EFFECTS OF CULTURAL INTENSITY AND DENSITY REGIME TREATMENT ON POST-THINNING LOBLOLLY PINE INDIVIDUAL TREE DEVELOPMENT IN THE LOWER COASTAL PLAIN OF THE SOUTHEASTERN UNITED STATES

by

JOHN THOMAS PERREN

(Under the direction of Dr. Michael Kane)

ABSTRACT

Four study installations from the Lower Coastal Plain were used to evaluate the effect of planting density, cultural intensity, and thinning treatment on loblolly pine (*Pinus taeda*) individual tree development during the six year post-thin period. The study has four initial densities combined with two cultural treatments that were thinned at age 12 to the current density on the lowest initial density. Results indicate that density significantly impacted the increment of all tree attributes examined. Cultural intensity had less effect and did not significantly alter increment. The effect of culture was greater on the growth response of individual stems when initial stand density and structure were accounted for. The linear increment and relative size-growth (RSG) were compared for estimating basal area by DBH class on two example plots. The RSG model produced more accurate estimations due to the inclusion of stand level basal area within the estimation parameter.

INDEX WORDS: Loblolly pine, Culture, Density, Thinning, Lower Coastal Plain

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Purpose of Study

The southeastern United States produces a large volume of commercially grown timber that comes from plantation systems. The most dominant species in the region is loblolly pine (*Pinus taeda*). In an attempt to maximize returns, many intensive silvicultural practices have been implemented to increase the production on any given site. Previous research has focused on the response of stand level attributes to silvicultural treatments. Of these silvicultural treatments, thinning is a well-understood concept when it comes to managing intraspecific competition. This study evaluates the effect of planting density, the intensity of silvicultural inputs (cultural intensity), and thinning treatment on post-thinning individual tree development. This research is different from many previous studies, because it examines thinning effect in conjunction with other treatments on individual trees within a particular stand. This information will allow for both more precise growth and yield models and better treatment regimes for future stands.

Significance

There have been substantial research efforts to quantify and better understand the effects of thinning on production in plantation systems. This research examines how cultural level, planting density, and thinning regimes impact individual tree attributes in highly productive plantations in the Lower Coast Plain. The Plantation Management Research Cooperative (PMRC) Coastal Plain Culture Density Study provides excellent data on how individual tree crowns, diameter growth, and basal area growth are affected by varying combinations of silvicultural treatments during the six-year period following thinning. With this knowledge, inferences about the development of trees of different diameter classes can inform selection of silvicultural treatments for commercial plantations.

This research provides results that further our understanding of the interactions between cultural treatments and density management on individual tree development. This information can be applied by commercial growers to increase the production capacity and improve resource use efficiency in loblolly pine plantations.

Thesis Structure

The remainder of this chapter is a literature review of research dealing with loblolly pine management. Research on individual tree DBH (diameter at breast height), basal area, and crown attributes response to cultural treatment and density management in thinned stands is presented in Chapter 2. Modeling individual tree basal area growth compared to stand level basal area growth using the relative size-growth (RSG) function is presented in Chapter 3. Main conclusions of the research are presented in Chapter 4.

Literature Review

Importance of loblolly pine

Plantation forests only account for 4% of all forests worldwide, yet they provide 50% of all the wood production (Food and Agriculture Organization of the United Nations 2007). Approximately 50% of all plantations are located in the southeastern United States, with loblolly pine (*Pinus taeda*) being the most widely utilized species (Fox et al. 2007a).

Loblolly pine was originally a small component of the largely forested landscape of the southern United States before the region was settled (Schultz, 1999). Due to its hardiness and ability to grow well across a wide range of sites, loblolly pine naturally regenerated and was extensively planted on cutover forestland and abandoned farmland between 1930 and 1990 (Schultz, 1999). Loblolly now dominates a tremendous range from Texas east to Florida and north along the Atlantic to Delaware (Schultz, 1997). This plasticity made loblolly the leading timber species in the United States, with 13.7 million hectares in commercial production (Schultz, 1997).

This large resource is unique in that approximately 90% of southern forests are privately owned with varying management objectives (Wear and Greis, 2002). With the increasing pressure to manage with auxiliary objectives in mind such as wildlife value (Miller et al. 2009) and the substantial threat that urbanization presents to the extent, condition, and health of the forests (Wear and Greis, 2002), there will be increasing pressures to produce more wood on a smaller land base. Southern pine plantations are some of the most intensively managed forests in the world, with productivity rivaling many of the exotic plantations of the Southern Hemisphere (Fox et al. 2007b). This type of intensive management will be needed to maintain the productive capacity of the US South forest industry and will become more economically attractive across larger area of the loblolly pine range (Borders and Bailey, 2001).

Planting Density

One of the most important considerations for an economically successful plantation is the planting density and how it corresponds with the appropriate rotation age for desired products (Bailey, 1986). For example, pulpwood regimes are more productive when planted at higher initial densities when compared to pure sawtimber regimes, which have lower initial densities (Amateis and Burkhart 2012).

Sharma et al. (2002) showed that all response variables (height, DBH, crown length, crown ratio, crown width, and survival) in a 16 years spacing trial were affected by density, with DBH being the most affected. With increasing planting density, average DBH of individual trees tends to decrease (Zhao et al. 2011; Will et al. 2010). A study in the Virginia Piedmont with two planting densities and three levels of nutrient additions showed that at age 9 the stands with lower initial planting density had greater average diameter across all nutrient addition levels (Carlson et al. 2009).

Planting density is also important in the development of crown characteristics. Much like DBH, crown length and crown ratio increase with decreasing planting densities (Sharma et al. 2002).

Competing Vegetation Control

Vegetation control, the exclusion of unwanted competing vegetation, most commonly by means of selective herbicides, is an important consideration in an intensively managed plantation system. McCullough et al. (2005) conducted a survey of herbicide distributors and estimated that 283,000 hectares of pine plantation in the Southeast received release treatments for years 2001 and 2002. Siry (2002) estimated a more impressive number of 800,000 hectares receive some type of herbicide treatments in the southeastern United States on an annual basis.

A strong positive effect of competition control on loblolly pine individual tree attributes (DBH and total height) and stand characteristics (basal area, total volume and merchantable volume) was demonstrated in both the Piedmont and Coastal Plain regions of Georgia and

Alabama. On average, when vegetation was controlled in established plantations, a gain of 9 to 18 m^3ha^{-1} per year was seen across 33 loblolly pine planation locations (Fortson et al. 1996). Miller et al. (1991) found that five years after planting, competing vegetation control resulted in an increase in loblolly pine diameter, height and volume on 13 locations distributed across the Southeast. Across this time period total control exhibited the greatest response followed by herbaceous control and woody control respectively. Woody control increased volume by 67% while herbaceous control increased volume by 171%. This indicates that during the establishment period, herbaceous competitors are a greater concern. After year 15, early woody control treatments remained significantly lower in hardwood basal area than check plots with an average of .91 m^2ha^{-1} or fewer for the woody control plots and .22 m^2ha^{-1} or less when woody control was done in conjunction with herbaceous weed control (Miller et al. 2003). A study by Martin and Shiver (2002) examining 12-year results from 31 sites across the Coastal Plain and Piedmont concluded that complete vegetation control in loblolly pine plantations increased total volume 45% and 39% in the Coastal Plain and Piedmont respectively. The effect of complete vegetation control and genetic improvement on volume production was shown to be additive.

Borders and Bailey (2001) found that complete competing vegetation control had higher yield production than annual fertilization in four out of six loblolly pine locations in Georgia. They also stated this type of response made intensive silviculture economically attractive with real returns from 8 to 12%. Fortson et al. (1996) also found that in most markets the magnitude of response from competing vegetation control was more than enough to justify the application costs of the treatment.

Fertilization

Fertilization is an important silvicultural activity to increase forest productivity by alleviating nutrient limitations. The amount of area treated has increased with the increase of management intensity, with an estimated 650,000 hectares fertilized in the southeastern United States on an annual basis (Siry 2002). The most limiting nutrients in the southeastern pine forests have been shown to be nitrogen and phosphorus (Fox et al. 2007a). From 1969 to 2004, approximately 6.5 million hectares were fertilized in the southeastern United States, primarily as urea and diammonium phosphate (Albaugh et al. 2007).

Nitrogen and phosphorous are important limiting factors of forest productivity even early in stand establishment (Fox et al. 2007a). Barron-Gafford et al. (2003) examined the effect of nutrition on stem biomass growth across three planting densities in loblolly and slash pine stands in the Lower Coastal Plain of the southeastern United States. In four-year-old plantations receiving intensive cultural treatments, stem biomass growth on a stand basis was not proportional to the increase in stand density, an indication that nitrogen acquisition was the most limiting factor impacting stem growth as stand density increased. A study in the Virginia Piedmont with two planting densities and three levels of nutrient additions showed that at age 9 the stands with lower initial planting density had greater average diameter across all nutrient addition levels, and average diameter increased as the level of nutrient additions increased when averaged across both densities (Carlson et al. 2009).

Another critical time in a rotation to consider the addition of nitrogen and phosphorous is at crown closure (Fox et al. 2007a). When nutrient amendments were applied, an average increase in loblolly pine growth response of roughly 3.6 tonnes ha^{-1} per year was achieved over the study period of eight years. This type of increase in production justifies the price of application in most markets when the price of fertilizer is moderate (Fox et al. 2007a). Average height and diameter growth following midrotation fertilization increased with increasing levels of fertilization (Hynynen et al. 1998). This response was most noticeable shortly after thinning (2 to 4 years) but began decreasing after this period.

Duzan et al. (1982) examined 44 North Carolina State Forest Fertilization Cooperative loblolly pine fertilization trials across the Piedmont and Coastal Plain. The set of installations represented a gradient of initial basal area and initial site index. The results from this study indicated that fertilization of stands with 112 kg ha^{-1} of nitrogen and 56 kg ha^{-1} of phosphorous resulted in an increased volume at lower initial basal area and increased initial site index. This demonstrates how important it is to manage density to receive the highest benefit from fertilization and that sites will respond differently to the same treatment.

Combining of Fertilization and Competing Vegetation Control

It has been shown that stand growth and the uptake of nitrogen and phosphorous are correlated under most circumstances. For this reason silvicultural treatments such as fertilization and vegetation control should be used to provide needed nutrient resources to crop trees (Will et al. 2006). Jokela et al. (2000) found that early fertilization and herbicide treatments resulted in a similar magnitude of response for loblolly pine and slash pine (*Pinus elliottii*) in the southeastern Lower Coastal Plain. The combination of the two treatments was significantly greater and was considered additive on 76% of the installations. They go on to warn that increasing the frequency and intensity of these treatment will likely result in a shift from additive to less than additive response by meeting the growth limiting requirements associated with production forests.

Swindel et al. (1988) showed that continuous elimination of either nutrient deficiencies or interspecific competition quintupled stand volume at age 4 in the flatwoods of north-central Florida for both loblolly and slash pine. The combination of both cultural treatments yielded a more than tenfold response in stand volume. These treatments complement one another and produce economically viable increases in forest productivity.

Thinning

Thinning is one of the most widely practiced midrotation silvicultural treatments in loblolly pine plantations (Amateis, 2000). When stands are grown at high levels of stocking, there are more trees competing for a fixed amount of resources. Competition for fixed resources leads to higher mortality rates in stands with greater stocking, as compared to those with lower levels (Hennessey et al. 2004). Thinning is often used in conjunction with other silvicultural treatments. Many studies have looked at thinning as a component of intensive management. A study in the Western Gulf region showed that with thinning alone, 50 % of the trees made it to the chip-and-saw class by age 17. When fertilization was added to the thinning regime, greater than 70% of the trees made it to the chip-and-saw class (Sword Sayer et al. 2004).

Kellison and Gingrich (1983) generally recommended that thinning should be implemented to reduce stocking often between ages 11 to 15, dependent on site index, when the trees are 40 feet tall on average. To maintain high average growth rates throughout the life of the rotation, densities must be managed at levels that maintain large crowns with high mean live crown ratios (Dean and Baldwin, 1996; Ginn et al. 1991; Kellison and Gingrich 1983). Research indicates that stands where density was reduced by thinning had smaller or slower crown recession and larger crown ratios (Liu et al. 1995; Short and Burkhart, 1992).

The management of density and manipulation of crown through thinning are important because the crown is the driver of productivity. Studies show that trees that received thinning produced more foliar biomass and total leaf area, which lead to higher photosynthetic rates and greater production (Yu et al. 2003). Research by Peterson et al. (1997) showed that increased bole diameter growth is likely due to the large increase in foliar biomass, as well as initially higher physiological activity in the lower crowns of thinned stands.

Relative Size-Growth (RSG) Function

Zhang et al. (1993) originally developed the RSG function as a disaggregation function for interior Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) to distribute stand volume growth to a list of individual trees. The shape of the function is determined by initial stand density, mean tree size, and stand structure. It was speculated that the function could be used for distributing stand basal area growth (Zhang et al. 1993). Moore et al. (1994) used the basic function to model the relative basal area response of Douglas-fir in the Inland Northwest United States to different silvicultural treatments. They found that the RSG function's characteristic relationships between tree size, stand density, stand structure, and relative distribution of growth across size classes within a stand were not altered by thinning or fertilization.

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CHAPTER 2

EFFECTS OF CULTURAL INTENSITY AND DENSITY REGIME TREATMENT ON POST-THINNING LOBLOLLY PINE INDIVIDUAL TREE LINEAR INCREMENT IN THE LOWER COASTAL PLAIN OF THE SOUTHEASTERN UNITED STATES[1]

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Abstract

This study evaluates the effect of planting density, cultural intensity, and thinning treatment on loblolly pine post-thinning individual tree development. The Lower Coastal Plain Culture/Density Study has four initial densities, in combination with two cultural treatments, which were thinned at age 12 to the current density on the lowest initial density. Analysis of data six years post-thin focuses on cultural intensity and density regime effects alone or in combination on individual tree development in DBH, height, basal area, crown length, and crown ratio. Thinning intensity effects on individual tree development were evaluated by using linear regression to compare the initial size of the tree to the increment for each tree attribute. Results indicate that density regime has the largest effect on the development of diameter growth following thinning with trees from higher densities and associated greater thinning intensity having a greater response in diameter increment. Basal area growth followed the same trend as diameter growth. Height increment was variable and height at the time of thinning proved to be a poor predictor of height response over the treatment period. Thinning had a similar effect on both crown length and crown ratio, with smaller crowns having greater increment than larger crowns and larger crowns remaining the same or receding in size.

Introduction

The southeastern United States produces a large volume of commercially grown timber that comes from plantations. The most dominant species in the region is loblolly pine (*Pinus taeda*). In an attempt to maximize returns on investment, many intensive management practices have been implemented to increase the production on any given site. One of the first considerations is planting density. Initial planting density has a strong effect on diameter growth.

As planting density increases, mean diameter of individual stems declines (Zhao et al. 2011). Another consideration for initial planting density is the desired products from the stand, with high densities being more appropriate for lower value product classes such as pulpwood (Amateis and Burkhart 2012). Fertilization and weed control have both been shown to have large impacts on the productive capacity of a stand. Nutrients are limiting in most southern timberlands, with nitrogen and phosphorous being of primary concern. Fertilization (Fox et al. 2007a) and the removal of competing vegetation (Fortson et al. 1996) to increase the availability of nutrients to crop trees have been shown to more than justify the price of application in most markets. Thinning is often used to maintain vigorously growing stands. When stands reach high levels of stocking, there is more competition for a fixed amount of resources. Competition leads to a higher mortality rate in stands with a greater stocking, as compared to those with lower levels (Hennessey et al. 2004). Thinning is often used in conjunction with other silvicultural treatments. Many studies have looked at thinning as a component of intensive management. A study in the Western Gulf region showed that with thinning alone, 50 % of the trees were classified as chip-and-saw by age 17. When fertilization was added to the thinning regime, greater than 70% of the trees were classified as chip-and-saw (Sword Sayer et al. 2004).

The Plantation Management Research Cooperative (PMRC) established the Lower Coastal Plain Culture Density Study to evaluate the effect of initial density and cultural intensity on loblolly pine and slash pine stand development. At age 12, selected plot on a subset of four installations from the original study were thinned to further evaluate the relationship between density management and stand development in loblolly pine plantations. A stand level analysis of these installations for the age 12 to 18 year period was completed by the PMRC (Zhao et al. 2014), but analysis at the individual tree scale is needed to better explain the relationship between thinning and individual stem development. Understanding individual tree response to treatment will lead to better prescriptions at the stand level.

Individual tree attributes during the age 12 to 18 year period were evaluated to test the following hypotheses.

a. Culture and density regime will have a significant effect on age 12 and age 18 mean individual tree DBH, height, basal area, live crown length, live crown ratio, and the increment of each attribute over the 6-year post-thin period.
b. The initial size of the tree will significantly affect the relative growth of the tree. Individual tree DBH, height, basal area, live crown length, and live crown ratio increment will increase with increasing initial age 12 size.

Methods

Study Site Description

The data used in this analysis is a subset from the PMRC's Lower Coastal Plain Culture Density Study that was established in 1996. There were four installations with thinning, two in South Carolina, one in Georgia, and one in Florida, representing a variety of soils and site qualities (Table 2.1). Installations were planted with first generation, open-pollinated family 7-56 loblolly pine. This family was known to be a fast grower. All seedlings were grown at the same nursery. The installations were arranged in a split-plot design with four initial densities of interest (740, 1480, 2220, and 2960 trees ha^{-1}) and two cultural treatments (operational and intensive). The two cultural levels served as the main plots with the four density regimes being the subplots. The operational plots received bedding, banded chemical site preparation, and first year banded herbaceous weed control. These plots also received fertilization at planting, year eight, year twelve, and year sixteen. The intensive culture plots included the same treatments as the operational plots with the addition of tip moth control, complete vegetation control, and fertilization in year three and even aged years starting in the fourth year. Specifics about the treatment details are presenting in Table 2.2. Measurement plots varied in number of trees per plot and total area by initial density and were surrounded by a treated buffer (Table 2.3). Thinning was imposed on the 1480, 2220, 2960 trees ha^{-1} plots under both operational and intensive culture during the dormant season of year 12. Plots were thinned to match age 12 trees ha^{-1} on the corresponding 740 trees ha^{-1}-planting density and cultural intensity plot for each installation, which provided the non-thinned counterpart. Thinning consisted of third row removal with selection in the leave rows. The felled trees were left in place on the plot.

Thinning to a standard number of trees per hectare for a given installation and cultural intensity resulted in different levels of mean residual basal area and percent of the initial stand basal area removed (Table 2.4). The combination of planting density and thinning are referred to as the thinning regime. The impact of the thinning regime on mean DBH, height, basal area, total volume outside bark, stand density index, relative spacing, crown ratio, crown length, and index of suppression for the 1480, 2220, and 2960 TPH thinned density plots before and immediately following thinning at age 12 and the 740 TPH non-thinned counterpart as reported by Zhao et al. (2014) presented in Table 2.5.

Data collection

Each installation was measured at age 12 prior to thinning and at age 18. DBH was taken on every tree within the measurement plot, while total height and height to live crown were taken on every other tree within the measurement plot. Total height and height to live crown of unmeasured trees was estimated using the linear regression equation $\ln(Y) = \beta 0 + \beta 1\ DBH^{-1}$ for each plot, where Y represents total height and height to live crown. Live crown length was then calculated by subtracting the height to live crown from total height. Crown ratio was calculated for every tree by dividing the live crown length by the total height.

Analysis

This study was established as a split-plot design with culture as the main plot and density regime as the subplots. For the analysis, trees that died prior to age 18 were omitted from the data set. Mean DBH, height, basal area, live crown length, crown ratio at age 12 (post-thin) and age 18, and the change in the attributes over the 6-year post-thin period were evaluated by an analysis of variance with a mixed-effects model (SAS version 9.3 SAS Institute, Cary, NC) to determine if there were statistically significant density regime, cultural intensity, or interaction effects. Least squared means comparison using Fishers LSD test was used to compare the means for culture and density treatments.

Linear regression was used to evaluate the effect of initial tree condition, density regime, and cultural intensity on the change in DBH, height, basal area, crown length, and crown ratio during the post-thinning period. DBH, height, basal area, crown length, and crown ratio increment for each tree were calculated by subtracting the age 12 attribute value from the age 18 attribute value. Data from all four installations for density regime and cultural level (management) combination was aggregated. A full model was created for each of the tree level variables, with indicator variables for both slope and intercept to test the effect of management, density regime, and combinations of density regimes.

$$\Delta Y = \left(a_0 + a_1(I_1) + a_2(I_2) + a_3(I_3) + a_4(I_M)\right) + \left(b_0 + b_1(I_1) + b_2(I_2) + b_3(I_3) + b_4(I_M)\right) * Y$$

Where

Y = tree attribute at age 12

ΔY = increment in tree attribute from age 12 to age 18

$a_0, \ldots, a_4$ = intercept parameter estimates

$b_0, \ldots, b_4$ = slope parameter estimates

$$I_1 = \begin{cases} 1 & \text{if density regime 1480 trees ha}^{-1} \\ 0 & \text{otherwise} \end{cases}$$

$$I_2 = \begin{cases} 1 & \text{if density regime 2220 trees ha}^{-1} \\ 0 & \text{otherwise} \end{cases}$$

$$I_3 = \begin{cases} 1 & \text{if density regime 2960 trees ha}^{-1} \\ 0 & \text{otherwise} \end{cases}$$

$$I_M = \begin{cases} 1 & \text{if management level is intensive} \\ 0 & \text{otherwise} \end{cases}$$

Results

Mean Tree Attributes

Management intensity, density regime, and the interaction of management intensity and density regime showed a significant effect on both age 12 and 18 DBH. Density regime and the interaction of density regime and management had a significant effect on DBH increment, while management alone did not (Table 2.6). More intensive management resulted in increased mean DBH across density regimes of 1.4 cm and 1.3 cm for age 12 and age 18, respectively (Table 2.7). Mean DBH at ages 12 and 18 decreased with increasing density across management intensity (Table 2.7). DBH increment increased from the 740 trees ha^{-1} non-thinned through the 2960 trees ha^{-1} thinned density regime (Table 2.7).

Management intensity, density regime and their interaction showed a significant effect on age 12 mean height per tree, while density regime and the interaction of density regime and management were the only significant effects on age 18 height and height increment (Table 2.6). Mean age 12 height increased 1.6 m from operational to intensive management (Table 2.7). The 740 trees ha^{-1} non-thinned density regime produced the largest mean height at age 18 and had the largest mean age 12 to 18 increment (Table 2.7).

Management intensity, density regime and their interaction showed a significant effect on age 12 mean basal area per tree, while density regime and the interaction of density regime and management were the only significant effects on age 18 basal area and basal area increment (Table 2.6). Mean age 12 basal area increased 0.0044 m^2 from operational to intensive management and increased with decreasing density ranging from 0.0239 m^2 at 2960 trees ha^{-1} to 0.0439 m^2 at 740 trees ha^{-1} (Table 2.7). Mean basal area increment was significantly higher for the 740 trees ha^{-1} non-thinned density regime than the other density regimes, which were not significantly different from one another (Table 2.7).

Only density regime and the interaction of density regime and management had a significant effect on age 12 and age 18 crown length and crown length increment (Table 2.6). Mean crown length increment significantly increased with density regime, ranging from 1.4 m for 740 trees ha^{-1} non-thinned to 2.5 m for the 2960 trees ha^{-1} thinned regime (Table 2.7).

Crown ratio at age 12 and crown ratio increment were only affected significantly by density regime and the interaction of density regime and management, while age 18 crown ratio was significantly affected by management intensity, density regime and their interaction (Table 2.6). Age 12 mean crown ratio deceased with increasing density from 0.51 at 740 trees ha^{-1} to

0.38 at 2960 trees ha^{-1} (Table 2.7). By age 18 crown ratio continued to be greater for the 740 trees ha^{-1} (0.42) as compared to the higher planting density-thinned regimes (0.39-0.40). Mean crown ratio at age 18 significantly decreased as management increased with a mean difference of 0.04 (Table 2.7). Mean crown ratio increment was least for the 740 trees ha^{-1} non-thinned (-0.091) and most for the 2960 trees ha^{-1} thinned regime (0.019) (Table 2.7).

Linear Increment Models

The full model was significant ($p<0.01$) for DBH, height, basal area, crown length, and crown ratio increment, indicating that the age 12 attribute value has a significant effect on the increment from age 12 to 18. The coefficient of determination (r^2) was 0.27, 0.36, 0.46, 0.30, and 0.74 for the DBH, height, basal area, crown length and crown ratio increment models, respectively. Management had a significant effect on the model slope, but not on intercept for DBH increment and basal area increment. Management had a significant effect on the model slope and intercept for both crown length increment and crown ratio increment.

Density regime and management intensity effects and parameter estimates for DBH, height, basal area, crown length, and crown ratio are presented in Tables 2.8, 2.9, 2.10, 2.11, and 2.12 respectively. For both the operational and intensive treatments, trees with larger initial DBH had greater DBH increment than smaller trees, and the higher initial planting density-thinned regimes had a higher level of growth response in DBH increment (Figure 2.1). Increment increased with increasing initial planting density-thinned regimes for both the operational and intensive management. DBH increment had significantly different slopes for each density regime (Table 2.8). For management intensity, the slope was significantly different between the operational and intensive treatment with the intensive treatment having a flatter slope (Table 2.8).

Height increment did not demonstrate a consistent trend across density regime or management intensity (Figure 2.2). Height increment had variable responses with the 1480 trees ha^{-1} and 2220 trees ha^{-1} thinned densities having significantly different slopes and intercepts compared to the 740 trees ha^{-1} non-thinned density (Table 2.9). The 2960 trees ha^{-1} thinned density intercept was significantly different from the 740 trees ha^{-1} non-thinned density, while the slope was not (Table 2.9). Management intensity had a significant effect on slope, but not intercept.

Basal area increment demonstrated similar trends as DBH increment, with increment increasing with increasing initial size and increasing initial planting density thinned regimes (Figure 2.3). Basal area increment slope was least for the 740 trees ha^{-1} non-thinned density and greatest for the 2960 trees ha^{-1} thinned. There were no significant differences in the intercepts among density regime. For management intensity the slope was significantly different between operational and intensive culture, while the intercept was not. (Table 2.10).

Crown length increment responded differently than both DBH and basal area increment. Crown length increment decreased with increasing initial crown length with noted negative values indicating receding crowns (Figure 2.4). Slope for crown length increment was significantly different between management and for the 2960 trees ha^{-1} thinned density regime. The 1480 trees ha^{-1} thinned and 2960 trees ha^{-1} thinned density regime and management intensity had significantly different intercepts from the 740 trees ha^{-1} non-thinned density regime, while the 2220 trees ha^{-1} thinned density did not (Table 2.11).

Crown ratio increment followed a similar trend as crown length increment. Crown ratios decreased with increasing initial crown ratios (Figure 2.5). Crown ratio increment had a significantly different slope and intercept for management intensity (Table 2.12). The 1480 trees ha^{-1} thinned density regime and the 2220 trees ha^{-1} thinned density regime had a significantly different intercept compared to the 740 trees ha^{-1} non-thinned density regime, but they were significantly different from one another (Table 2.12).

Discussion

Our first hypothesis that culture and density regime would have significant effects on mean individual tree attributes was partially supported. Density regime and the interaction of density regime and culture were significant for all attributes. Culture was found to have a significant effect on individual tree mean age 12 DBH, mean age 18 DBH, mean age 12 height, mean age 12 basal area, and mean age 18 crown ratio. The lack of significance of culture in many of the attributes is not surprising due to the relatively high levels of input in the operational treatment, which would be considered relatively intensive in commercial forestry in the southeastern United States (Fox et al. 2007b). For the second hypothesis, initial age 12 size did have a significant effect on the increment of individual trees for every attribute. Though initial size had a significant effect, height increment did not consistently increase with increasing initial size, and crown length increment and crown ratio increment decreased with increasing initial size.

Individual tree DBH growth follows similar trends reported by Johnson (2013) and Lock (2015) for loblolly pine in the Upper Coastal Plain and Piedmont with DBH decreasing with increasing density regime and increment increasing with increasing initial age 12 size. Trees in each density regime and management combination responded differently to thinning due to the different stages of stand development at the time of thinning and the relative thinning intensity imposed (Table 2.4). Though management intensity does not seem to affect individual tree DBH response to thinning, it has a large effect on the pre-thinned basal area ha^{-1} of the 740 trees ha^{-1} non-thinned and 1480 trees ha^{-1} thinned density regimes. When this specific thinning method was imposed to the 1480 trees ha^{-1} thinned density regime, there was a large difference in residual basal area between cultural intensities with 20 m^2 ha^{-1} in the intensive and 18 m^2 ha^{-1} in the operational due to smaller individual stem DBH. This led to different growing conditions post thinning with the intensive plot having a higher average residual basal area, leading to less available resources per tree. Once trees have similar room to grow, nutrient availability seems to become a more important influence impacting growth. This is seen on the 2220 and 2960 thinned density regimes, where cultural intensity has a more noticeable impact. The range in residual basal area was 15 to 16 m^2 ha^{-1} for the 2220 and 2960 thinned density regimes for both management treatments. Due to the small range in average residual basal, trees in the intensive plots had more available resources and more competitive trees responded with greater DBH increment growth. Across all management and density regime combinations, there was a common trend of trees with larger initial DBH having larger DBH increments in response to thinning than trees with smaller initial DBH. Because of the correlation between basal area and DBH, the response of basal area across this period follows the same rationale as DBH.

Height response to treatment did not yield consistent trends across the age 12 to 18 post thin period. In general the non-thinned counterpart produced the highest level of both increment and total height at age 18. Initial height at the time of thinning is not a good indicator for the amount of individual tree height growth to expect. The height response to thinning is similar to the results presented by Hennessey et al. (2004) showing that height response to thinning did not differ significantly among the various post-thinning residual basal area treatments.

Sharma et al. (2002) reported that crown length and crown ratio increase with decreasing planting densities. This general trend was evident in both the age 12 and 18 mean crown length and crown ratio. Crown length increment and crown ratio increment showed the same general response over the age 12 to 18 post thin period. Crowns that were more suppressed prior to thinning, smaller crown lengths and smaller crown ratios, responded more than larger crowns already in a more dominant position. Stands with higher levels of stocking prior to thinning had smaller, more suppressed crowns. This relationship explains why mean crown length increment increased with increasing density regime. Crown ratio increment followed the same trend with lower density regimes losing crown on average and the higher densities gaining crown.

Conclusion

Managing intraspecific competition was the most important factor in this study for maintaining vigorously growing individual trees and consequently stands. Improving the nutrient availability of a stand will also increase the growth of individual trees that have room to grow. Trees with larger initial diameter and basal area per tree at the time of thinning have a greater ability to obtain more resources needed to increase growth, and are thus more competitive. The nutrient availability at stand establishment, up to the time of thinning, has a large effect on the initial condition of the stand. It also determines when thinning should occur and the level of response that should be expected. Thinning should also be triggered by the receding of crowns before the size of the crown seriously limits the ability of the trees to continue growing at a productive rate. Thinning releases crowns from these suppressed conditions and allows for significant recovery in growth potential under high resource conditions.

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Tables and Figures

Table 2.1. Location, soil information, and site index for the four thinned installations of the Lower Coastal Plain Culture/Density study.

Installation	State	County	CRIFF	NRCS Soil Series	Soil Taxonomy	Site Index (m)
7	SC	Georgetown	A	Cape Fear	fine, mixed, semiactive, thermic typic umbraquult	24
8	SC	Williams	A	Yemassee-Eunola	fine-loamy, siliceous, semiactive, thermic aeric endoaquults	27
12	GA	Ware	B2	Albany-Leefield	loamy, siliceous, subactive, thermic aquic arenic paleudult	24
13	FL	Putnam	C	Pomona	sandy, siliceous, hyperthermic ultic alaquods	28

*Site index (SI) was calculated using age 18 dominant height on plots with operational culture and 1480 TPH planting density and Zhao 2011 site index model for the Lower Coastal Plain:

$$SI = exp\left[5.4185 + (\ln H_D - 5.4185)\left(\frac{A}{25}\right)^{0.5235}\right]$$

Table 2.2. Silvicultural treatments for each cultural regime.

Operational Regime	Intensive Regime
Bedding	Bedding
Fall banded chemical site preparation	Fall broadcast chemical site preparation
	Tip moth control 1st and 2nd growing seasons
Herbaceous weed control: 1st yr. banded	Repeated herbicide application to achieve complete vegetation control
Fertilization: at planting, 560 kg ha^{-1} of 10-10-10; spring of 8th, 12th, and 16th growing season, 224 kg ha^{-1} of N and 28 kg ha^{-1} of P	Fertilization: at planting, 560 kg ha^{-1} of 10-10-10; spring 3rd growing season, 673 kg ha^{-1} 10-10-10 + micronutrients + 131kg ha^{-1} NH_4NO_3; spring 4th growing season 131kg ha^{-1} NH_4NO_3; spring 6th growing season 336 kg ha^{-1} NH4NO3; spring 8th, 10th, 12th, 14th, 16th and 18th growing season 224 kg ha^{-1} of N and 28 kg ha^{-1} of P

Table 2.3. Measurement and gross plot size by density regime at PMRC culture density installations.

Planting Density (Trees ha-1)	Planting Spacing (m x m)	Gross Plot Size (ha)	Measurement Plot Size (ha)
740	3.66 x 3.66	0.227	0.105
1480	2.44 x 2.74	0.150	0.053
2220	2.44 x 1.83	0.125	0.046
2960	1.83 x 1.83	0.121	0.040

Table 2.4. Mean basal area and standard deviation pre- and post-thinning by culture and density regime.

Management	Density Regime	BA Age 12 Pre-Thin (m^2ha^{-1})	BA Age 12 Post-Thin (m^2ha^{-1})	BA % Removal
Operational	740	26(3.8)	26(3.8)	No Thin
	1480	33(5.0)	19(2.6)	41%(5.4)
	2220	38(4.8)	17(2.8)	55%(2.0)
	2960	39(5.0)	15(3.2)	61%(4.0)
Intensive	740	30(4.2)	30(4.2)	No Thin
	1480	39(4.6)	20(2.2)	48%(2.6)
	2220	40(6.2)	18(1.6)	56%(3.4)
	2960	46(5.6)	16(0.6)	65%(5.6)

*Standard deviation is presented within the parentheses.

Table 2.5. Mean DBH (cm), height (HT,m), basal area (BA, m^2ha^{-1}), total volume outside bark (TVOB, m^3ha^{-1}), stand density index (SDI), relative spacing (RS), crown ratio (CR), crown length (CL, m), and index of suppression (IS) for the 1480, 2220, and 2960 TPH thinned density plots before and immediately following thinning at age 12 and the 740 TPH non-thinned counterpart. (From Zhao et al. 2014)

Management	Density Regime	DBH	HT	BA	TVOB	SDI	RS	CR	CL	IS
Pre-thinning age 12										
Operational	740	21.8	15.2	26	180.7	554	0.24	0.54	8.2	
	1480	18	14.9	33	230.6	746	0.18	0.43	6.4	
	2220	15.5	14.9	38	255.2	872	0.15	0.37	5.6	
	2960	14.2	14.6	39	272.4	961	0.13	0.37	5.4	
Intensive	740	24.4	17.1	30	232.1	610	0.23	0.48	8.2	
	1480	19.6	17.2	39	315.3	870	0.16	0.39	6.8	
	2220	16.8	16.2	40	293.1	892	0.14	0.37	5.9	
	2960	15.5	16	46	340.6	1082	0.12	0.35	5.6	
Immediate post-thinning										
Operational	1480	18.8	15.3	19	127.6	403	0.25	0.44	6.7	0.32
	2220	17.5	15.4	17	111.2	358	0.25	0.39	6.1	0.41
	2960	17	15.6	15	107.1	343	0.25	0.40	6.2	0.44
Intensive	1480	20.3	17.4	20	159.4	430	0.23	0.40	7.0	0.34
	2220	18.3	16.7	18	120.0	348	0.24	0.39	6.6	0.49
	2960	17.5	16.8	16	114.9	334	0.24	0.36	6.1	0.51

Table 2.6. P-values for the effects of management, density regime, and their interaction on mean DBH, mean HT, mean BA, mean crown length, and mean crown ratio at ages 12 and 18 and the mean 6-year increment in thinned loblolly pine plantations.

Source	DBH Age 12	DBH Age 18	DBH Increment
Management	**0.0117**	**0.0428**	0.6514
Density Regime	**<.0001**	**<.0001**	**<.0001**
Man x Den Reg	**<.0001**	**0.0419**	**0.0244**
Source	**HT Age 12**	**HT Age 18**	**HT Increment**
Management	**0.0064**	0.0879	0.0723
Density Regime	**0.0002**	**<.0001**	**<.0001**
Man x Den Reg	**<.0001**	**<.0001**	**0.0002**
Source	**BA Age 12**	**BA Age 18**	**BA Increment**
Management	**0.0131**	0.051	0.5181
Density Regime	**<.0001**	**<.0001**	**0.0017**
Man x Den Reg	**<.0001**	**0.01**	**0.3935**
Source	**Crown Length Age 12**	**Crown Length Age 18**	**Crown Length Increment**
Management	0.4966	0.3167	0.3726
Density Regime	**<.0001**	**<.0001**	**<.0001**
Man x Den Reg	**0.0004**	**<.0001**	**<.0001**
Source	**Crown Ratio Age 12**	**Crown Ratio Age 18**	**Crown Ratio Increment**
Management	0.1199	**0.0404**	0.8992
Density Regime	**<.0001**	**<.0001**	**<.0001**
Man x Den Reg	**<.0001**	**<.0001**	**<.0001**

*Values in bold indicate significant effect at α=0.05

Table 2.7. Main effects of management and density regime on age 12, age 18, and 6-year increment for mean DBH, mean HT, mean BA, mean crown length, and mean crown ratio in thinned loblolly pine plantations. Means in the same age/treatment combination with the same letter are not significantly different.

		DBH (cm)	HT (m)	BA (m^2)	Crown Length (m)	Crown Ratio
		Age 12 measurements				
Culture	Operational	18.8 a	15.5 a	0.0287 a	6.8 a	0.44 a
	Intensive	20.2 b	17.1 b	0.0331 b	7.0 a	0.41 a
Density Regime	740 (non-thinned)	23.4 a	16.3 a	0.0439 a	8.3 a	0.51 a
	1480 (thinned)	19.5 b	16.5 b	0.0305 b	6.9 b	0.42 b
	2220 (thinned)	17.8 c	16.1 a	0.0253 c	6.2 c	0.39 c
	2960 (thinned)	17.3 d	16.3 a	0.0239 c	6.1 c	0.38 d
		Age 18 measurements				
Culture	Operational	24.4 a	21.6 a	0.0482 a	9.0 a	0.42 a
	Intensive	25.7 b	22.7 a	0.0533 a	8.7 a	0.38 b
Density Regime	740 (non-thinned)	28.4 a	23.0 a	0.0651 a	9.7 a	0.42 a
	1480 (thinned)	25.0 b	22.0 b	0.0410 b	8.6 b	0.39 b
	2220 (thinned)	23.5 c	21.8 c	0.0443 c	8.4 b	0.39 bc
	2960 (thinned)	23.3 c	21.8 c	0.0436 c	8.6 b	0.40 b
		Age 12 to 18 increment measurements				
Culture	Operational	5.6 a	6.2 a	0.0195 a	2.2 a	-0.025 a
	Intensive	5.5 a	5.5 a	0.0202 a	1.8 a	-0.023 a
Density Regime	740 (non-thinned)	5.0 a	6.7 a	0.0212 a	1.4 a	-0.091 a
	1480 (thinned)	5.4 b	5.5 b	0.0195 b	1.7 b	-0.025 b
	2220 (thinned)	5.7 bc	5.6 b	0.0189 b	2.2 c	0.001 c
	2960 (thinned)	6.0 c	5.5 b	0.0196 b	2.5 d	0.019 d

Table 2.8. Parameter estimates for individual tree DBH increment linear regression analysis from age 12 to 18.

Variable	Parameter Estimate	Standard Error	P-Value
Intercept (a_0)	-1.22712	0.34491	0.0004
Slope (b_0)	0.28543	0.01558	<.0001
	Indicator Variables		
Management Slope (b_4)	-0.0339	0.00449	<.0001
1480 trees ha^{-1} thinned slope (b_1)	0.07057	0.00639	<.0001
2220 trees ha^{-1} thinned slope (b_2)	0.11869	0.00793	<.0001
2960 trees ha^{-1} thinned slope (b_3)	0.14637	0.00858	<.0001

Table 2.9. Parameter estimates for individual tree height increment linear regression analysis from age 12 to 18.

Variable	Parameter Estimate	Standard Error	P-Value
Intercept (a_0)	9.78069	0.45186	<.0001
Slope (b_0)	-0.16895	0.02867	<.0001
	Indicator Variables		
Management Slope (b_4)	-0.03545	0.00415	<.0001
1480 trees ha^{-1} thinned intercept (a_1)	-4.29331	0.71208	<.0001
2220 trees ha^{-1} thinned intercept (a_2)	-9.63125	0.97458	<.0001
2960 trees ha^{-1} thinned intercept (a_3)	-1.22475	0.08099	<.0001
1480 trees ha^{-1} thinned slope (b_1)	0.18891	0.04304	<.0001
2220 trees ha^{-1} thinned slope (b_2)	0.52886	0.06024	<.0001

Table 2.10. Parameter estimates for individual tree basal area increment linear regression analysis from age 12 to 18.

Variable	Parameter Estimate	Standard Error	P-Value
Intercept (a_0)	-0.00252	0.00074293	0.0007
Slope (b_0)	0.58539	0.01936	<.0001
Indicator Variables			
Management Slope (b_4)	-0.08344	0.01067	<.0001
1480 trees ha^{-1} thinned slope (b_1)	0.17595	0.01586	<.0001
2220 trees ha^{-1} thinned slope (b_2)	0.30465	0.02117	<.0001
2960 trees ha^{-1} thinned slope (b_3)	0.37901	0.02362	<.0001

Table 2.11. Parameter estimates for individual tree crown length increment linear regression analysis from age 12 to 18.

Variable	Parameter Estimate	Standard Error	P-Value
Intercept (a_0)	6.18863	0.25751	<.0001
Slope (b_0)	-0.58243	0.03394	<.0001
Indicator Variables			
Management Intercept (a_4)	-1.78822	0.34633	<.0001
Management Slope (b_4)	0.22232	0.04683	<.0001
1480 trees ha^{-1} thinned intercept (a_1)	-0.31285	0.08208	0.0001
2960 trees ha^{-1} thinned intercept (a_3)	1.52561	0.57908	0.0085
2960 trees ha^{-1} thinned slope (b_3)	-0.22997	0.09065	0.0113

Table 2.12. Parameter estimates for individual tree crown ratio increment linear regression analysis from age 12 to 18.

Variable	Parameter Estimate	Standard Error	P-Value
Intercept (a_0)	0.39737	0.00993	<.0001
Slope (b_0)	-0.94484	0.02009	<.0001
Indicator Variables			
Management Intercept (a_4)	-0.10267	0.01352	<.0001
Management Slope (b_4)	0.19004	0.03012	<.0001
1480 and 2220 trees ha^{-1} thinned intercept (a_{12})	-0.01435	0.00268	<.0001

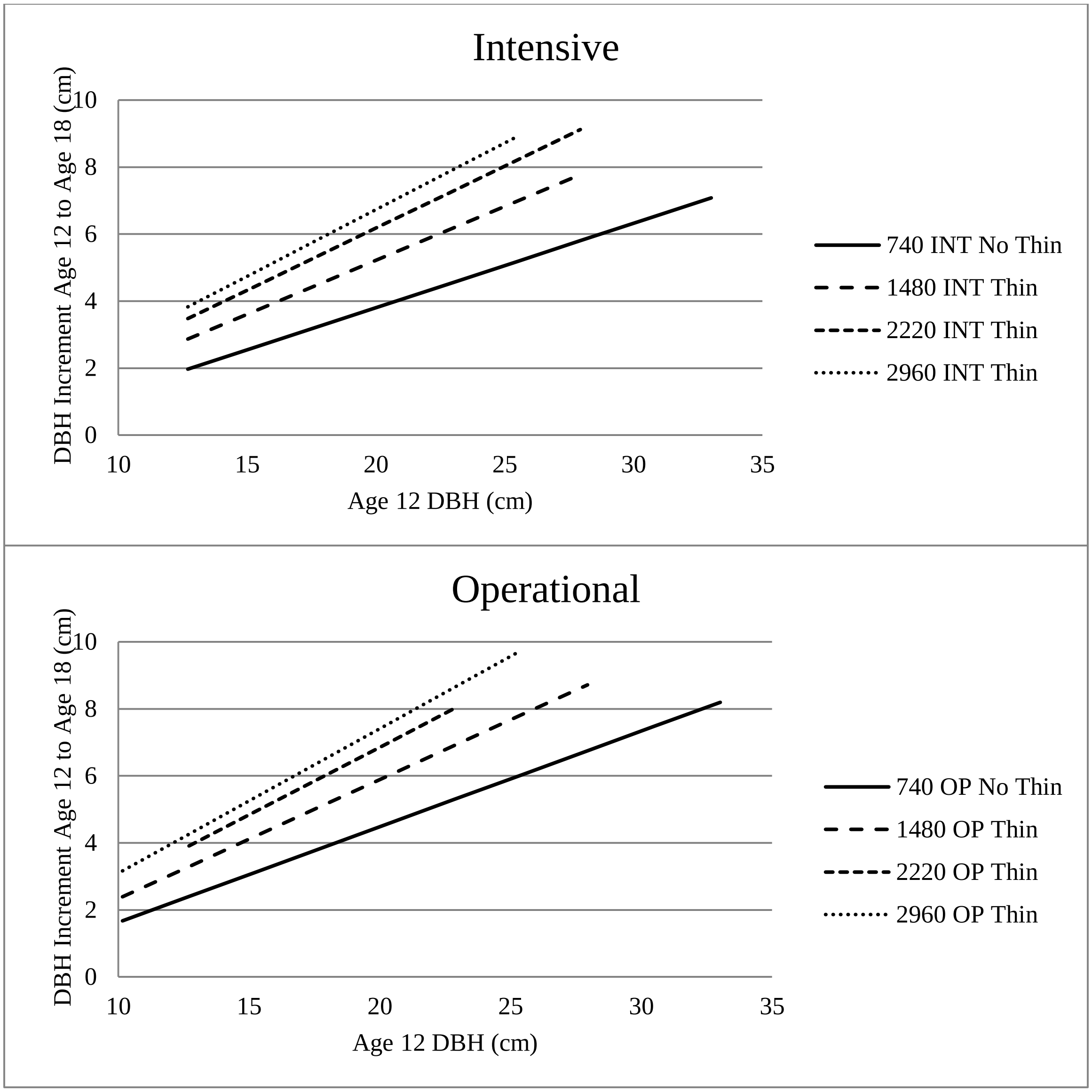

Figure 2.1. Linear relationship for DBH increment from age 12 to 18 by age 12 DBH for density regimes by management intensity.

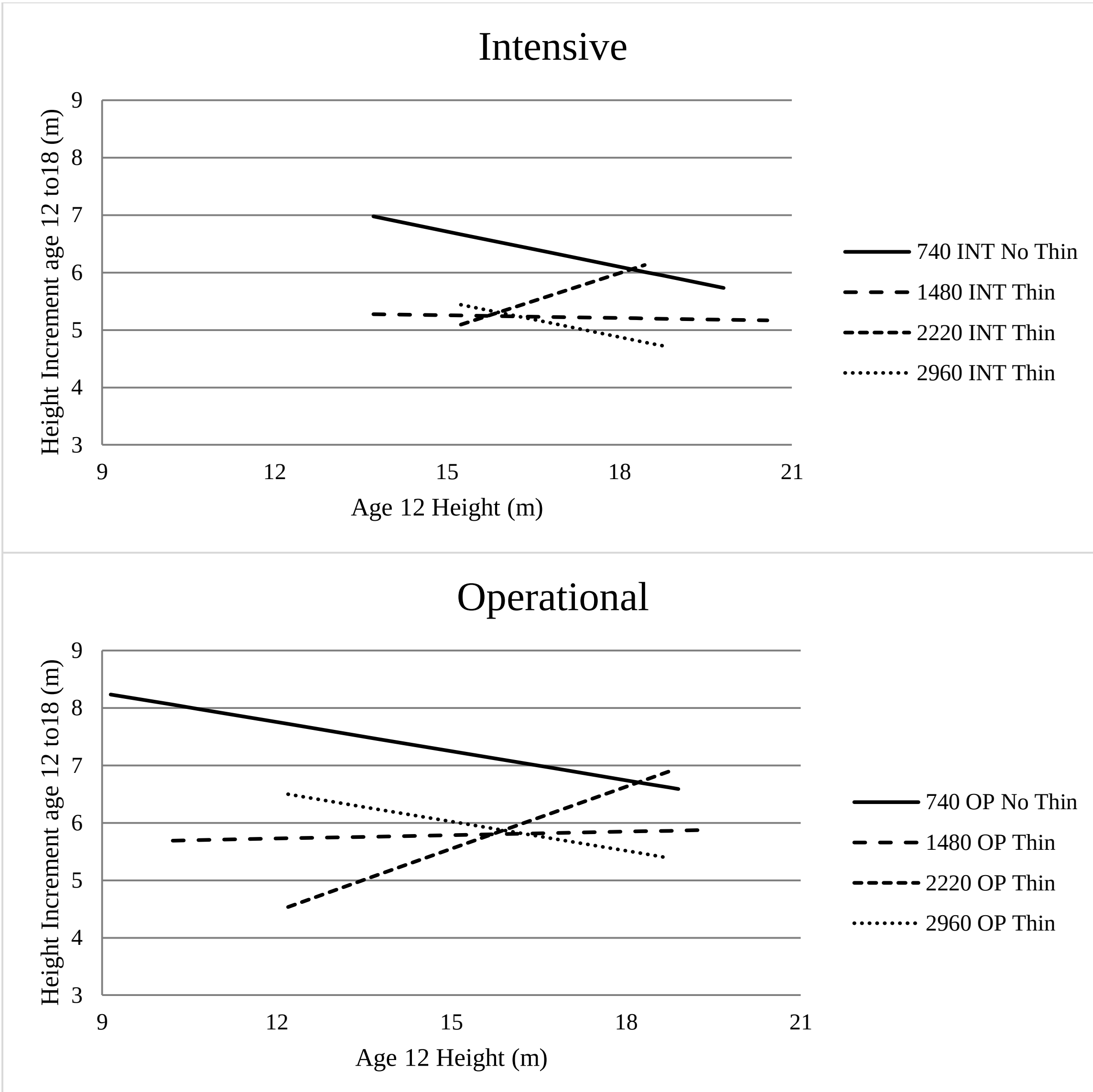

Figure 2.2. Linear relationship for height increment from age 12 to 18 by age 12 height for density regimes by management intensity.

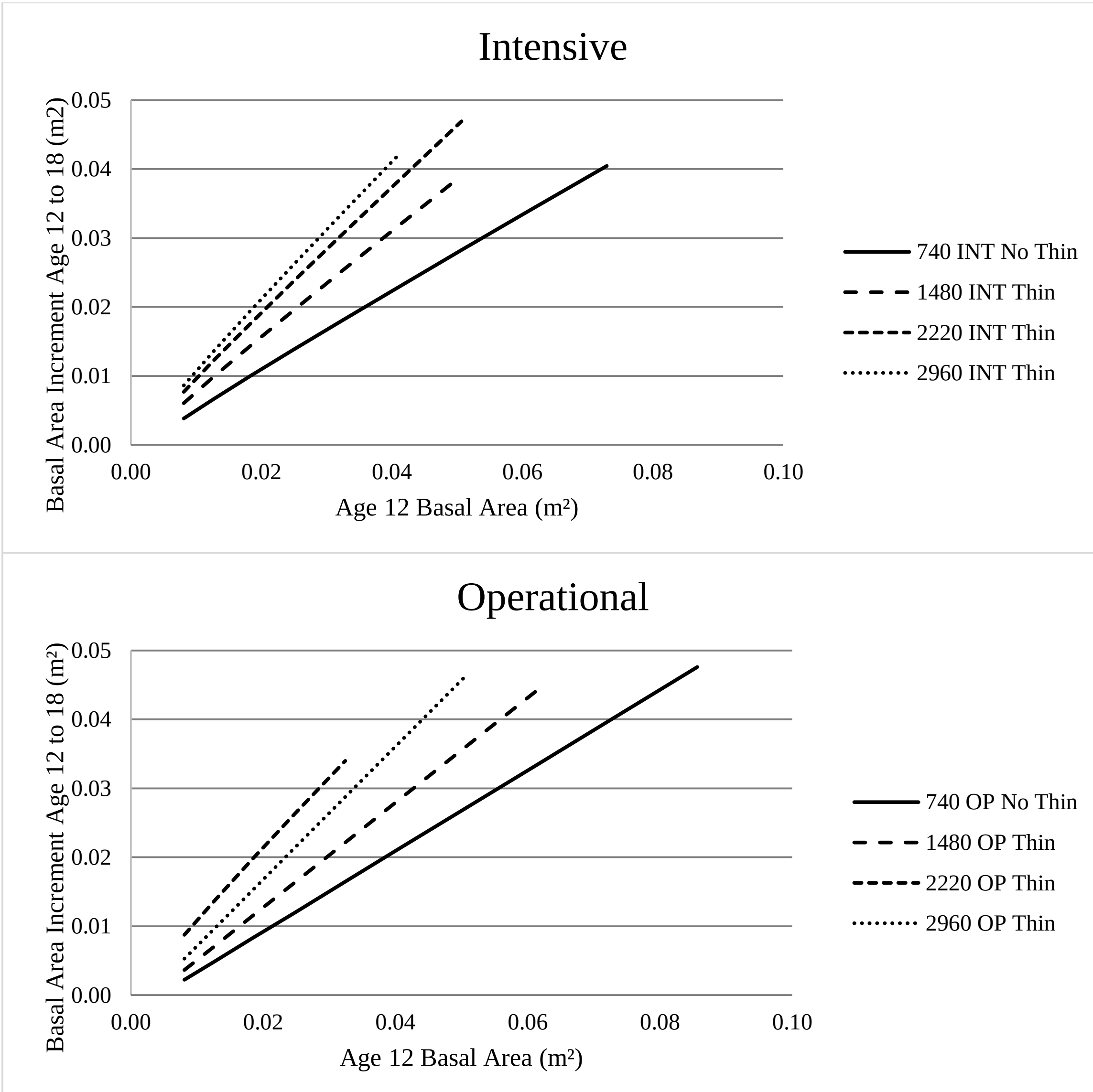

Figure 2.3. Linear relationship for basal area increment from age 12 to 18 by age 12 basal area for density regimes by management intensity.

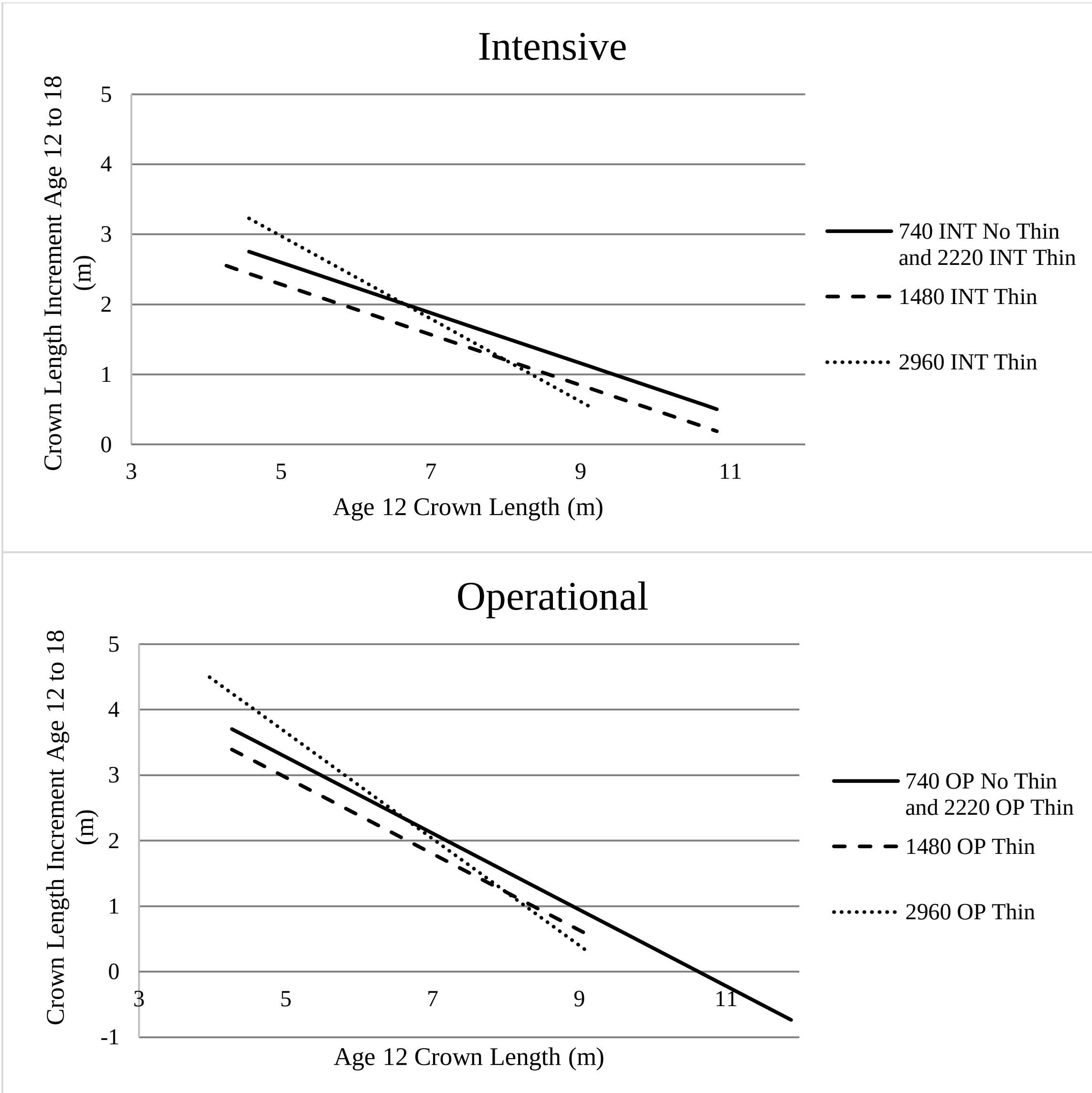

Figure 2.4. Linear relationship for crown length increment from age 12 to 18 by age 12 crown length for density regimes by management intensity.

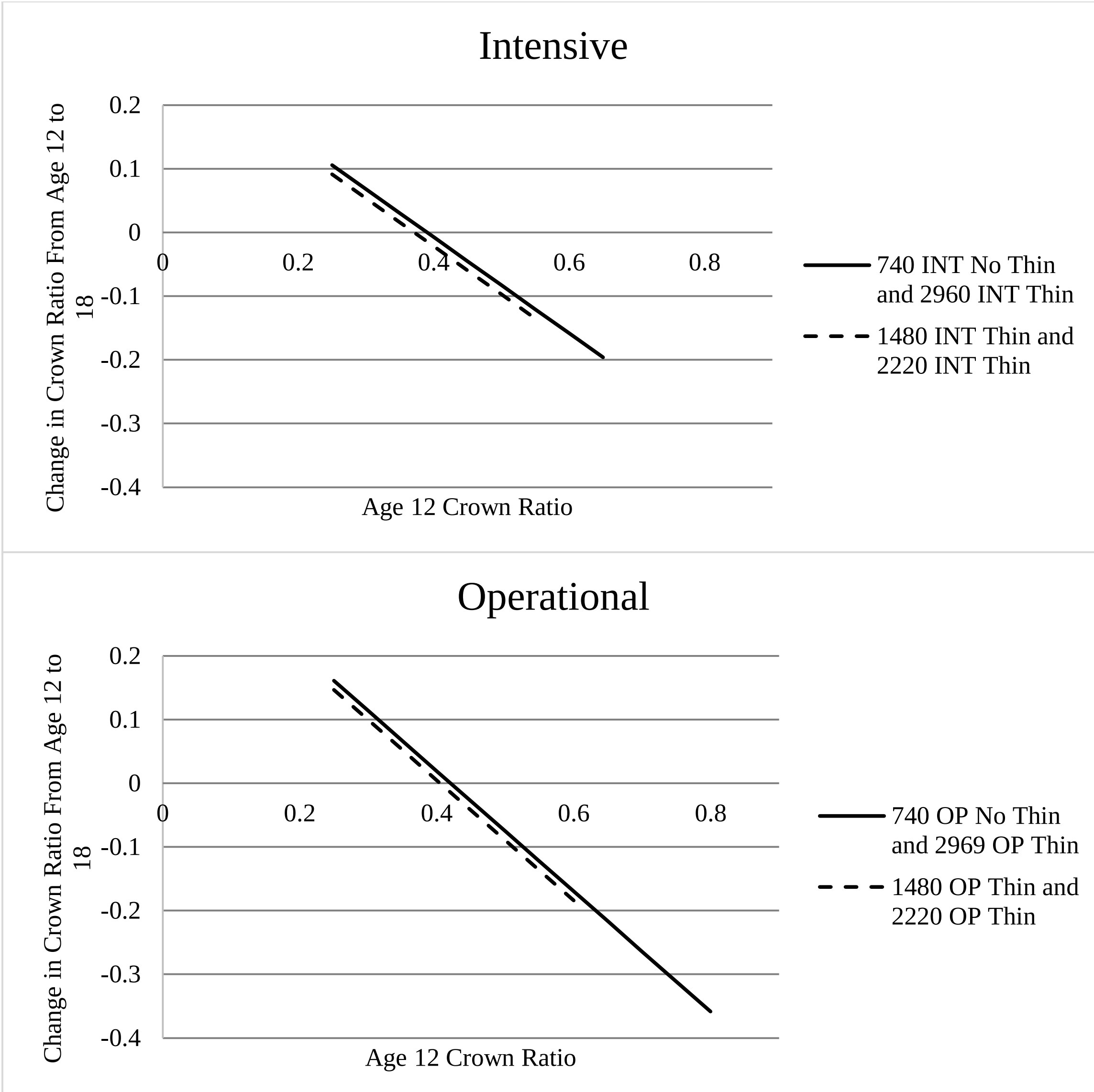

Figure 2.5. Linear relationship for crown ratio increment from age 12 to 18 by age 12 crown ratio for density regimes by management intensity.

CHAPTER 3

EFFECTS OF CULTURAL INTENSITY AND DENSITY REGIME TREATMENT ON POST-THINNING LOBLOLLY PINE INDIVIDUAL TREE RELATIVE SIZE-GROWTH IN THE LOWER COASTAL PLAIN OF THE SOUTHEASTERN UNITED STATES [2]

[2] Perren, J.T., Kane, M., Zhao, D., and Daniels, R. To be submitted to Forest Ecology and Management.

Abstract

Four existing installations from the Plantation Management Research Cooperative's Lower Coastal Plain Culture/Density Study were used to evaluate the effect of planting density, cultural intensity, and thinning treatment on loblolly pine (*Pinus taeda*) post-thinning individual tree development. The study has four initial densities in combination with two cultural treatments that were thinned at age 12 to the current density on the lowest initial density. Analysis of data six years post-thin for the Lower Coastal Plain focuses on the effects of cultural intensity and density regime effects alone or in combination on individual tree basal area growth. Density regime and cultural intensity effects were evaluated on individual tree basal area development using the relative basal area growth (RBAG) function. Results indicate that the function has a positive, linear relationship for this data set, initial density was not a significant influence on the function, and cultural intensity significantly impacted both the slope and intercept of the function. The RBAG function produced better basal area growth estimates by initial DBH class than the linear increment method from Chapter 2, due to the inclusion of stand level basal area parameters in the function.

Introduction

Plantation forests produce a disproportionally high amount of wood to the relative area on a global scale (Food and Agriculture Organization of the United Nations 2007). The southeastern United States has approximately 50% of these plantations, with the primary species being loblolly pine (Fox et al. 2007). Across the region, approximately 13.7 million hectares of loblolly pine are in commercial production (Schultz, 1997). With the threat of urbanization (Wear and Greis, 2002) and loss of the land base in the future to other uses, intensive management will be necessary to maintain current production levels. Density management by means of planting density and thinning, and cultural treatments such as competing vegetation control and fertilization have been shown to significantly increase the productivity of a site and yield higher value products (Amateis, 2000; Sword Sayer et al. 2004; Will et al.2006). Efforts to quantify the growth response to these treatments led to the creation of the relative size-growth (RSG) function (Zhang et al. 1993). This function was meant to distribute stand growth from a whole stand model to individual trees. Further research was conducted that looked at the ability of the RSG function relative to modeling intermediate silvicultural treatments (Moore et al. 1994). This later research quantifies the basal area RSG relationship rather than volume RSG relationship examined in previous research. The RSG function for tree basal area distribution will be used to evaluate the effects of density management and cultural intensity on loblolly pine stand development in the Plantation Management Resource Cooperative's (PMRC) Lower Coastal Plain Culture Density Study.

Hypotheses

a. Culture and density regime will have a significant effect on the relative size-growth of basal area for the post-thin period.
b. Relative basal area growth will increase with increasing initial relative size over the post-thin period.

Methods

Study Site Description

The data used in this analysis is a subset from the PMRC's Lower Coastal Plain Culture Density Study that was established in 1996. There were four installations with thinning, two in South Carolina, one in Georgia, and one in Florida, representing a variety of soils and site qualities (Table 3.1). Each installation was arranged in a split-plot design with four initial densities of interest (740, 1480, 2220, and 2960 trees ha^{-1}) and two cultural treatments (operational and intensive). The two cultural levels served as the main plots with the four density regimes being the subplots. The operational plots received bedding, banded chemical site preparation, and first year banded herbaceous weed control. These plots also received fertilization at planting, year eight, year twelve, and year sixteen. The intensive culture plots included the same treatments as the operational plots with the addition of tip moth control, complete vegetation control, and fertilization in year three and even aged years starting in the fourth year. Specifics about the treatment details are presenting in Table 3.2. Measurement plots varied in number of trees per plot and total area by initial density and were surrounded by a treated buffer (Table 3.3). Thinning was imposed on the 1480, 2220, 2960 trees ha^{-1} plots under both operational and intensive culture during the dormant season of year 12. Plots were thinned to match age 12 trees ha^{-1} on the corresponding 740 trees ha^{-1}-planting density and cultural intensity plots for each installation, which provided the non-thinned counterpart. Thinning consisted of third row removal with selection in the leave rows. The felled trees were left in place on the plot. Thinning to a standard number of trees per hectare for a given installation and cultural intensity resulted in different levels of mean residual basal area and percent of the initial stand basal area removed (Table 3.4). The combination of planting density and thinning are referred to as the thinning regime.

Data collection

Each installation was measured at age 12 prior to thinning and at age 18. DBH was taken on every tree within the measurement plot. Only tree records with both age 12 and 18 measurements were used, and trees that died during the study period were omitted.

Analysis

The model that was used is a relative size-growth (RSG) model that utilizes basal area. Individual tree basal area was calculated using the DBH for each tree record with the equation: (basal area / tree) =0.00007854 DBH^2. Relative basal area growth (RBAG) is defined as the ratio of individual tree basal area growth to stand total basal area growth on a unit area. RBAG was calculated by dividing the difference in individual tree basal area growth from age 12 to age 18 by the total stand basal area per hectare growth from age 12 to age 18. Relative basal area (RBA) is defined as the ratio of individual tree basal area to stand total basal area on a unit area. RBA was calculated by dividing the age 12 individual tree basal area by the total stand basal area per hectare. The RSG function for tree basal area distribution is expressed as a quadratic equation relating RBAG to RBA. The form of the equation is:

$$RBAG = \beta_0 + \beta_1 RBA + \beta_2 RBA^2$$

A full model was created with indicator variables for both slope and intercept to test the effect of management, density regime, and combinations of the different density regimes.

$$RBAG = \left(a_0 + a_1(I_1) + a_2(I_2) + a_3(I_3) + a_4(I_M)\right) + \left(b_0 + b_1(I_1) + b_2(I_2) + b_3(I_3) + b_4(I_M)\right) * RBA + \left(c_0 + c_1(I_1) + c_2(I_2) + c_3(I_3) + c_4(I_M)\right) * RBA^2$$

Where

$RBAG =$ relative basal area growth

$RBA =$ relative basal area

$a_0, \ldots, a_4 =$ intercept parameter estimates

$b_0, \ldots, b_4 =$ slope parameter estimates

$c_0, \ldots, c_4 =$ quadratic parameter estimates

$$I_1 = \begin{cases} 1 & \text{if density regime 1480 trees ha}^{-1} \\ 0 & \text{otherwise} \end{cases}$$

$$I_2 = \begin{cases} 1 & \text{if density regime 2220 trees ha}^{-1} \\ 0 & \text{otherwise} \end{cases}$$

$$I_3 = \begin{cases} 1 & \text{if density regime 2960 trees ha}^{-1} \\ 0 & \text{otherwise} \end{cases}$$

$$I_M = \begin{cases} 1 & \text{if management level is intensive} \\ 0 & \text{otherwise} \end{cases}$$

Reduced models using the indicator variables were then compared to the full model using a F-test.

The 1480 trees ha^{-1} thinned density regime and 2960 trees ha^{-1} thinned density regime with operational culture from installation 8 were chosen to demonstrate the ability of the RSG function to distribute basal area growth across a range of initial densities and DBH classes. Installation 8 was used for illustrative purposes because it best represented the mean site index across all four installations. The linear increment model will also be used to predict basal area growth by DBH class on the same plots, and will then be compared to both the observed values and the RSG function predictions.

Results

The quadratic parameter estimates, $c_0,\ldots, c_4$, were not significant. The terms were dropped and the model was run as a linear function. The overall linear model was significant ($p<0.01$), indicating that the relative basal area has a significant effect on the relative basal area growth over the post-thin period from age 12 to 18. The coefficient of determination (r^2) was

0.49 for the model. Culture had a significant effect on both the model intercept ($p<0.01$) and slope ($p<0.01$) (Table 3.5). Density regime did not significantly affect either slope or intercept for the relative growth of basal area. Relative basal area growth increased with increasing relative basal area for both cultural intensities (Figure 3.1).

The observed and predicted age 18 basal area ha^{-1} by age 12 DBH class utilizing the linear increment equation from Chapter 2 and the RSG function for the operational culture 1480 trees ha^{-1} thinned density regime and 2960 trees ha^{-1} thinned density regime from installation 8 are presented in Tables 3.6 and 3.7, respectively. The linear increment method tended to over predict basal area for most DBH classes for the 1480 trees ha^{-1} thinned density regime and 2960 trees ha^{-1} thinned density regime, resulting in a higher stand level basal area estimation than the observed value. The RSG function had a smaller difference between the observed and predicted age 18 basal area than the linear increment model predicted and observed age 18 basal area for both the 1480 trees ha^{-1} thinned density regime and 2960 trees ha^{-1} thinned density regime.

Discussion

The first hypothesis that culture and density regime would significantly affect the relative size-growth of basal area for the post-thin period was partially supported. Culture was found to have a significant impact on relative size-growth of basal area, while the density regime effect was not significant. The second hypothesis was accepted with both cultural treatments producing higher relative basal area growth with increasing initial relative size across the post-thin period. This general trend is supported by the results of Moore et al. (1994), though their relationship was non-linear.

The RSG function for basal area growth takes into account differences in stocking by comparing ratios that have the stand level basal area value for both relative size and growth. This is important for this study due to the variability of residual basal area following the thinning treatment (Table 3.4). With this difference accounted for in the model, the different density regimes were not significantly different from one another. Culture was found to be the significant driver in the differences in relative growth. Culture was not a simple increase in total relative growth between the two management levels, rather the relationship between relative basal area and relative basal area growth varied between management levels across the relative basal area range (Figure 3.1). Intensive management produced an equation that started with less relative growth than the operational management at the low end of the relative basal area range and more relative growth at the high end of the relative basal area range. This relationship indicates that larger trees are contributing a higher proportion of relative growth in the intensive plots compared to the operational plots. When comparing the numbers of stems per hectare for each DBH class (Figure 3.2) and the amount of stand level basal area for each DBH class (Figure 3.3), it is evident that larger DBH classes contribute higher amounts of basal area per stem to stand level basal area. The RSG does a good job allocating basal area growth to individual stems when the stand level basal area at the beginning of treatment is known and stand level basal area growth can be accurately predicted (Table 3.6, Table 3.7). When comparing the RSG function predicted age 18 basal area to the linear increment predicted age 18 basal area, both methods produce good estimates for the 1480 trees ha^{-1} thinned density regime. The RSG function produces more accurate age 18 basal area predictions for both the 1480 trees ha^{-1} thinned density regime and the 2960 trees ha^{-1} thinned density regime than the linear increment method.

Conclusion

Thinning alters stand density and allocates more resources to fewer individual residual stems. When thinning is conducted on a stem per area basis across different initial densities, the impact of thinning on residual basal area and stand structure is variable. The RSG function, utilizing basal area, adequately characterizes the allocation of growth to a range of initial stem sizes. Density regime does not significantly impact the function because initial stand level basal area is inherently included in the RBA parameter that the function utilizes. Culture has a greater effect on the growth response of individual stems when the initial stand density and structure is accounted for. Trees with larger initial size contribute more absolute growth than smaller trees. The initial varied distribution of individual stem size impacted the response that occurred due to higher culture with more homogenous stands having a more stable response to treatment. This method is a valuable tool for allocating growth to individual trees when the initial stand basal area is known and a good prediction of stand level basal area for the future can be obtained.

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Tables and Figures

Table 3.1. Location, soil information, and site index for the four thinned installations of the Lower Coastal Plain Culture/Density study.

Installation	State	County	CRIFF	NRCS Soil Series	Soil Taxonomy	Site Index (m)
7	SC	Georgetown	A	Cape Fear	fine, mixed, semiactive, thermic typic umbraquult	24
8	SC	Williams	A	Yemassee-Eunola	fine-loamy, siliceous, semiactive, thermic aeric endoaquults	27
12	GA	Ware	B2	Albany-Leefield	loamy, siliceous, subactive, thermic aquic arenic paleudult	24
13	FL	Putnam	C	Pomona	sandy, siliceous, hyperthermic ultic alaquods	28

*Site index (SI) was calculated using age 18 dominant height on plots with operational culture and 600 TPA planting density and Zhao 2011 site index model for the Lower Coastal Plain:

$$SI = exp\left[5.4185 + (\ln H_D - 5.4185)\left(\frac{A}{25}\right)^{0.5235}\right]$$

Table 3.2. Silvicultural treatments for each cultural regime.

Operational Regime	Intensive Regime
Bedding	Bedding
Fall banded chemical site preparation	Fall broadcast chemical site preparation
	Tip moth control 1^{st} and 2^{nd} growing seasons
Herbaceous weed control: 1st yr. banded	Repeated herbicide application to achieve complete vegetation control
Fertilization: at planting, 560 kg ha^{-1} of 10-10-10; spring of 8th, 12th, and 16th growing season, 224 kg ha^{-1} of N and 28 kg ha^{-1} of P	Fertilization: at planting, 560 kg ha^{-1} of 10-10-10; spring 3rd growing season, 673 kg ha^{-1} 10-10-10 + micronutrients + 131kg ha^{-1} NH_4NO_3; spring 4th growing season 131kg ha^{-1} NH_4NO_3; spring 6th growing season 336 kg ha^{-1} NH4NO3; spring 8th, 10th, 12th, 14th, 16th and 18th growing season 224 kg ha^{-1} of N and 28 kg ha^{-1} of P

Table 3.3. Measurement and gross plot size by density regime at PMRC culture density installations.

Density Regime (Trees ha-1)	Planting Spacing (m x m)	Gross Plot Size (ha)	Measurement Plot Size (ha)
740	3.66 x 3.66	0.227	0.105
1480	2.44 x 2.74	0.150	0.053
2220	2.44 x 1.83	0.125	0.046
2960	1.83 x 1.83	0.121	0.040

Table 3.4. Mean basal area and standard deviation pre- and post-thinning by culture and density regime.

Management	Density Regime	BA Age 12 Pre-Thin (m^2ha^{-1})	BA Age 12 Post-Thin (m^2ha^{-1})	BA % Removal
Operational	740	26(3.8)	26(3.8)	No Thin
	1480	33(5.0)	19(2.6)	41%(5.4)
	2220	38(4.8)	17(2.8)	55%(2.0)
	2960	39(5.0)	15(3.2)	61%(4.0)
Intensive	740	30(4.2)	30(4.2)	No Thin
	1480	39(4.6)	20(2.2)	48%(2.6)
	2220	40(6.2)	18(1.6)	56%(3.4)
	2960	46(5.6)	16(0.6)	65%(5.6)

*Standard deviation is presented within the parentheses.

Table 3.5. Parameter estimates for fitting the RBAG model.

Variable	Parameter Estimate	Standard Error	P-Value
Intercept (a_0)	-0.0000063	0.00007216	0.9305
Slope (b_0)	1.004	0.04415	<.0001
	Indicator Variables		
Management Intercept (a_4)	-0.00050318	0.00011674	<.0001
Management Slope (b_4)	0.29549	0.06869	<.0001

Table 3.6. Observed and predicted age 18 basal area (m^2ha^{-1}) by age 12 DBH class (cm) utilizing the linear increment equation from Chapter 2 and the relative size growth (RSG) function for the operational culture 1480 trees ha^{-1} thinned density regime from installation 8.

Age 12 DBH Class	Stems per hectare	Observed Age 18 basal area	Chapter 2 Predicted BA	Difference observed and Chapter 2 predicted	RSG Predicted BA	Difference observed and RSG predicted	Difference Chapter 2 predicted and RSG predicted
16	75	2.19854	2.52770	-0.32916	2.56109	-0.36255	-0.03339
17	57	2.21011	2.19011	0.02000	2.20253	0.00757	-0.01243
18	94	4.22747	4.04510	0.18237	4.04763	0.17985	-0.00253
19	208	9.91207	9.91994	-0.00788	9.87584	0.03623	0.04410
20	113	5.82217	5.87100	-0.04883	5.82360	-0.00143	0.04740
21	75	4.50760	4.32724	0.18036	4.27383	0.23377	0.05341
22	75	4.99585	5.01336	-0.01750	4.92207	0.07378	0.09129
26	19	1.49383	1.70341	-0.20958	1.65377	-0.15994	0.04964
Totals=	717	35.4	35.6	-0.23022	35.4	0.00728	0.23750

Table 3.7. Observed and predicted age 18 basal area (m^2ha^{-1}) by age 12 DBH class (cm) utilizing the linear increment equation from Chapter 2 and the relative size growth (RSG) function for the operational culture 2960 trees ha^{-1} thinned density regime from installation 8.

Age 12 DBH Class	Stems per hectare	Observed Age 18 basal area	Chapter 2 Predicted BA	Difference observed and Chapter 2 predicted	RSG Predicted BA	Difference observed and RSG predicted	Difference Chapter 2 predicted and RSG predicted
15	75	2.27386	2.55746	-0.28360	2.42602	-0.15216	0.13144
16	175	5.94053	6.52695	-0.58642	6.16256	-0.22203	0.36439
17	125	4.65957	5.22531	-0.56574	4.90565	-0.24608	0.31966
18	150	6.85374	7.16231	-0.30857	6.68226	0.17148	0.48005
19	50	2.58472	2.70206	-0.11734	2.50716	0.07756	0.19490
20	50	2.79729	2.89300	-0.09572	2.67655	0.12073	0.21645
21	100	6.24518	6.50446	-0.25928	5.98925	0.25594	0.51521
Totals=	725	31.4	33.6	-2.21667	31.3	0.00543	2.22210

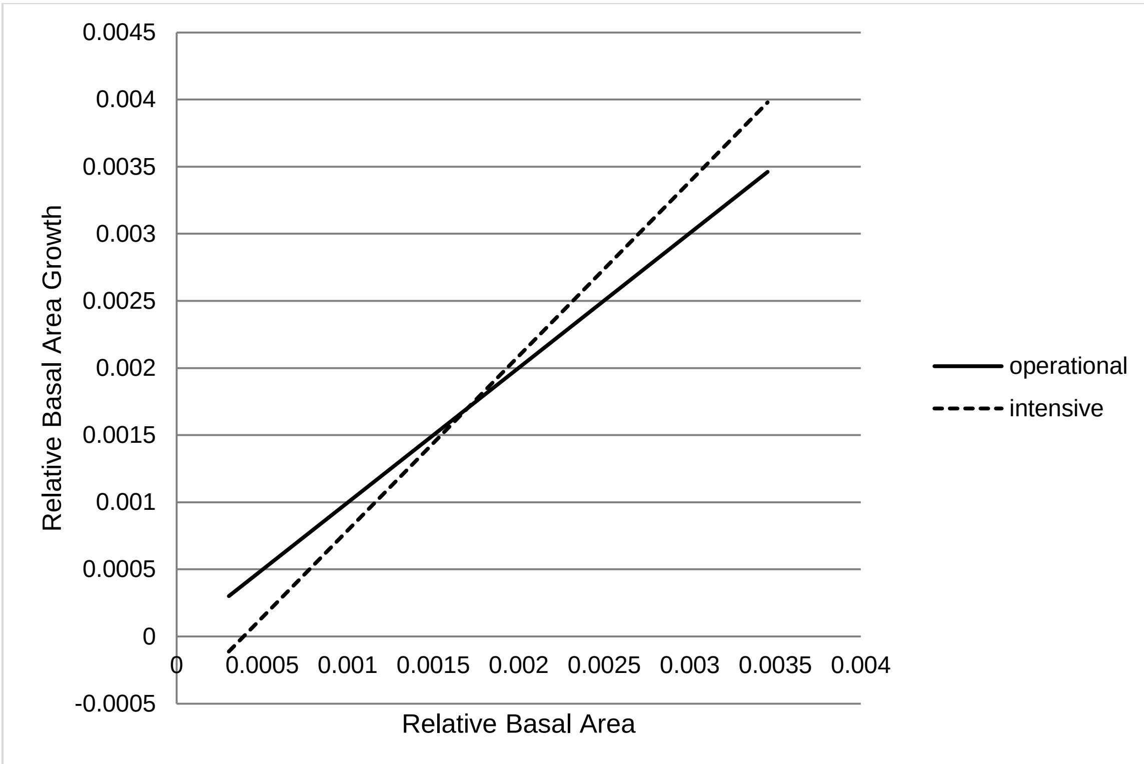

Figure 3.1. Relative size growth (RSG) function for relative basal area growth for the age 12 to 18 post-thin period by management intensity.

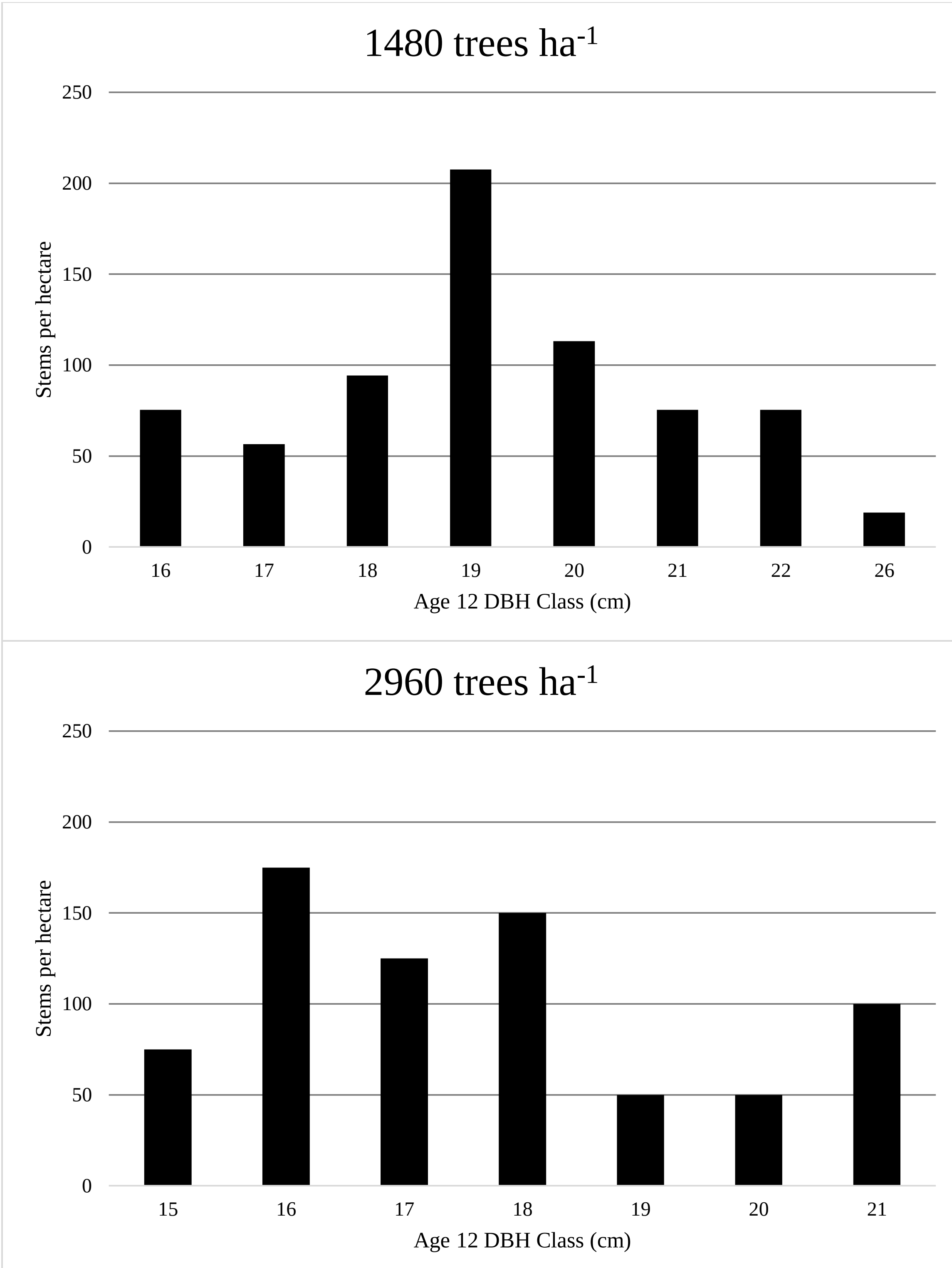

Figure 3.2. Observed number of stems per hectare by age 12 DBH class for the 1480 trees ha^{-1} and 2960 trees ha^{-1} operational thinned plots from installation 8.

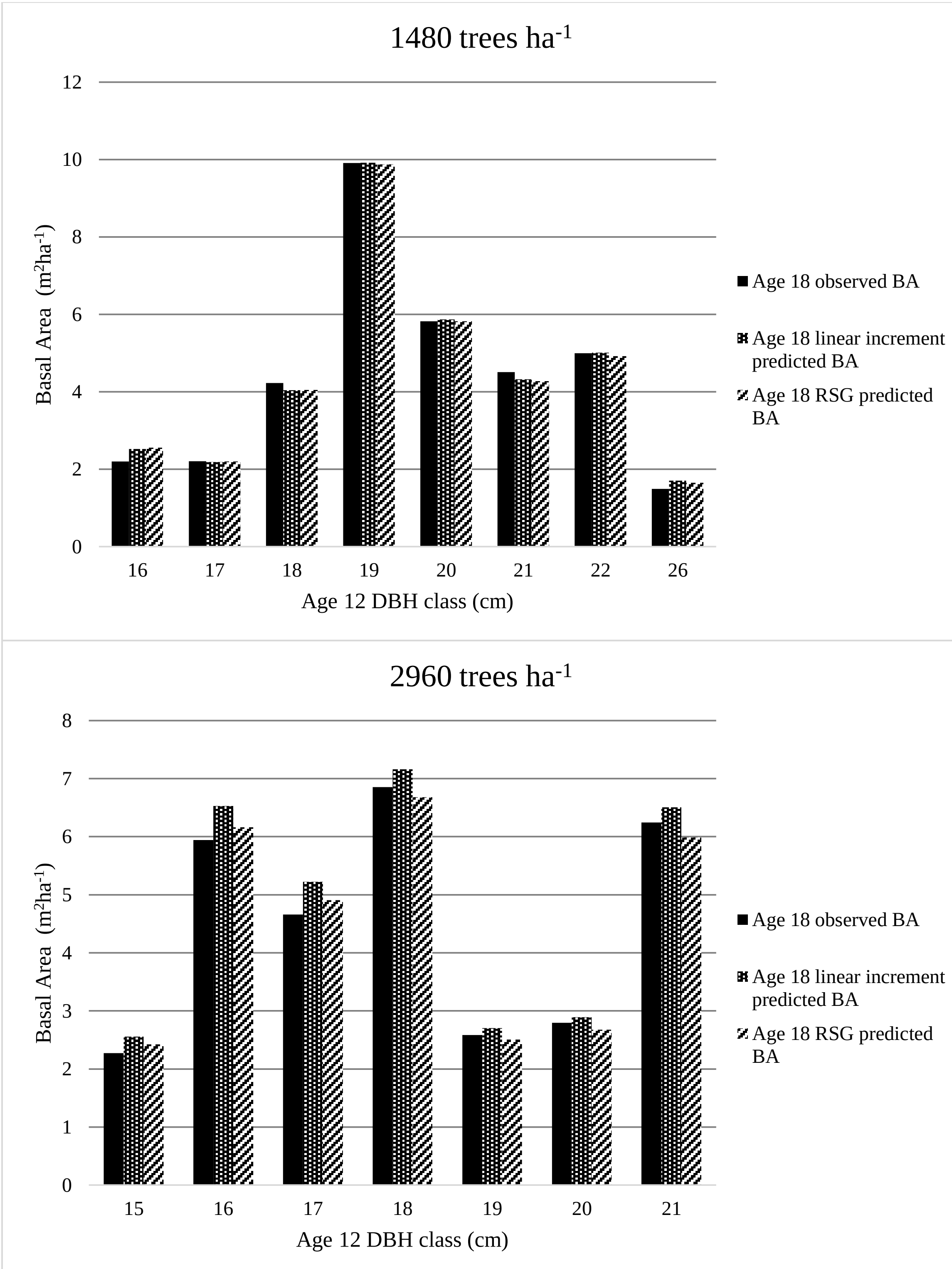

Figure 3.3. Comparison between the age 18 observed basal area, the age 18 linear increment predicted basal area, and the age 18 relative size growth (RSG) predicted basal area by the age 12 DBH class for the 1480 trees ha^{-1} and 2960 trees ha^{-1} operational thinned plots from installation 8.

CHAPTER 4

CONCLUSIONS

This study was conducted on four installations from the Lower Coastal Plain Culture x Density study.

The effect of density was the most important factor in the response of individual tree DBH, height, basal area, crown length, and crown ratio both before and after thinning. Density played a large role in the size and distribution of stems prior to thinning with higher initial densities producing smaller individuals. The density prior to thinning had a large effect on the residual stand following thinning. Stands with lower levels of stocking following thinning were able to have a higher growth response due to the reduced intraspecific competition. This resulted in the higher planting density thinned regimes having a greater increment over the age 12 to 18 post-thin period. Across all density regimes, larger individuals contributed proportionally more to stand level growth than smaller individuals.

Cultural intensity impacted growth less than density management and was not statistically significant for individual tree DBH, height, basal area, crown length, and crown ratio increment across the study period. Culture may have been more significant if there was a larger difference between the two management levels. The operational treatment was relative high intensity when compared to common practices in commercial plantations. Though the growth response to intensive culture was not statistically significant, mean values at both age 12 and 18 tended to be greater for intensive than operational management. Culture played a significant role in the rate of stand development. The intensive plots reached higher levels of stocking prior to thinning than the operational plots. The different stand condition between management levels within the same density regime led to the significance of the interaction of management and density regime throughout the study. Culture has a greater effect on the growth response of individual stems when the initial stand density and structure is accounted for, and significantly impacted basal area growth using the RSG function.

The RSG function consistently produced more accurate age 18 basal area predictions by DBH class than the linear increment method. The RSG function includes stand level basal area growth and initial stand level basal area into its estimation parameters, giving it more consistent and accurate estimations of how each individual stem grows in context to the stand.

These results indicate that proper density management is essential to maintaining vigorously growing stands, and must considered before the effects of higher levels of culture can be realized.