SOIL CLASS, CULTURAL INTENSITY, AND PLANTING DENSITY: IMPACTS ON LOBLOLLY PINE PRODUCTIVITY THROUGH AGE 12 IN THE UPPER COASTAL PLAIN AND PIEDMONT

by

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(Under the Direction of Michael Kane)

ABSTRACT

Loblolly pine (*Pinus taeda*) plantations are commercially important in the southeastern United States. Understanding mechanisms that drive growth and development of loblolly pine plantations will improve management decisions. Soil class, cultural intensity, and planting density impacts on the productivity of loblolly pine and relationship between intensive culture response and site and stand attributes were examined at 20 locations. Soils with > 40 inches to the argllic horizon, were less able to support productivity at higher planting densities and exhibited the lowest productivity, however, these same sites tended to have the highest observed response to intensive culture. Intensive culture increased mean stem size and per acre productivity while decreasing survival, crown ratio, and relative spacing. Increases in planting density reduced mean tree size but increased productivity on a per acre basis. Several competing vegetation measures on operational plots were positively correlated with pine response at ages 4, 8, and 12.

INDEX WORDS: Loblolly pine; Upper Coastal Plain; Piedmont; Soil; Competing vegetation; Planting density; Intensive culture; Growth response

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1. **Purpose of Study**

Loblolly pine is an important tree species in the southeastern United States as it is used widely in commercial plantations. Due to its importance, the effects of silvicultural practices on loblolly pine growth and performance have been studied extensively. However, there is a lack of knowledge about how soil class, cultural intensity, and planting density affect and interact to impact plantation performance. The purpose of this study is to determine the effects of soil class, cultural treatment, and planting density and their interactions on the growth and development of loblolly pine stands in the Upper Coastal Plain and Piedmont. A secondary objective is to determine effects of individual site factors (soil attributes, base productivity, and competition levels) on loblolly pine growth response to intensive silvicultural practices in stands planted at 600 trees per acre (TPA). Both tree level and stand level attributes are examined to better understand the mechanisms that affect loblolly pine plantation growth and development. This research will provide a better understanding of the performance of loblolly pine plantations and associated stand development processes. This improved knowledge will help inform silvicultural decisions for loblolly pine plantations in the Upper Coastal Plain and Piedmont regions.

2. **Thesis Structure**

The first chapter describes the purpose of the study and provides a literature review on the topics associated with this research. Soil class, cultural intensity, and planting density effects on loblolly pine growth and development are presented in Chapter 2. Factors that affect growth response of loblolly pine to intensive culture are presented in Chapter 3. A summary of main findings is provided in Chapter 4.

3. **Literature Review**

3.1 Soil Effects

Loblolly pine has the ability to live and thrive on a variety of soil types and conditions from ridgetops to river bottoms (Guinness 1982). Soil physical properties are critical in the growth of the stand (Guinness 1982). Several soil properties have been related to determining the site index for a stand including : depth to the least permeable layer, depth of the surface soil layer, sand content in the subsoil, texture of the subsoil, pH, and slope position (Zahner 1957, Linnartz 1963). Coile and Schumacher (1953) found that site index for loblolly pine in the Piedmont was significantly affected by the depth of the surface soil and the imbibitional water value of the subsoil, but was not significantly associated with geographic location or burning. Imbibitional water value is defined as the difference between the moisture equivalent and the xylene equivalent of the soil and is highly correlated with the amount clays tend to shrink and swell (Coile and Schumacher 1953). Fisher and Garbett (1980) developed the CRIFF forest soil classification system based upon drainage class and the depth to and nature of the B horizon. They found that soil class had an effect on the growth and the growth response of loblolly pine and slash pine eight years after fertilization. Most of these sites were located in the Lower Coastal Plain but the classification can also be of use in the Upper Coastal Plain and Piedmont. Jokela (2004) indicated that understanding soil characteristics can be helpful in estimating responses but at times responses differ significantly within a soil grouping. Jokela et al. (2000) were not able to find a difference in loblolly pine growth response at age 5 to herbaceous weed control and fertilizer treatments among different CRIFF soil groups in the Lower Coastal Plain. They did observe non-significant, larger responses to fertilization on the CRIFF soil group A, a soil group associated with phosphorus deficiencies.

3.2 Competition Control

Competing vegetation has an adverse effect on many important growth factors for loblolly pine including moisture, light and nutrient availability, and rooting volume (Martin and Shiver 2002). Controlling either herbaceous vegetation and/or woody vegetation has been shown to provide growth gains. Miller et al. (2003) found that loblolly pine growth gains at age 15 on a series of 13 sites located across four physiographic provinces of the Southeast were greatest when competition control was focused on the most prominent type of competing vegetation on the site. Herbaceous weed control elevated the production of loblolly pine planted on lower quality sites to a level of production comparable to higher quality sites not receiving competition control through age 12 on study locations representing a range of site quality (Glover et al. 1989). Shiver and Martin (2002) found that the effects of woody and herbaceous competition control on the Upper Coastal Plain and Piedmont last at least until thinning age. The increase in production was assumed to be a result of the trees being able to access more of the available nutrients, moisture and growing space on the site. The amount of competing vegetation left on a site after treatment could be an explanation for site variation in response to fertilization treatments (Jokela et al. 2000). When higher levels of competing vegetation are left, more competition for the nutrients exists and the full benefits of applying fertilizer are not realized.

Controlling competing vegetation has an effect on most stand attributes of loblolly pine plantations. Stand attributes of basal area, total volume and merchantable volume per acre all increased with the removal of competing vegetation in loblolly pine plantations ranging from 5 to 12 years old (Fortson et al. 1996). Martin and Shiver (2002) found that competition control had a significant effect on dominate height and total stand volume of loblolly pine stands in the Coastal Plain and Piedmont and it also reduced the range in DBH in the Piedmont. Average

DBH was increased 14% and 13% at age 12 compared to an operational treatment in the Coastal Plain and Piedmont, respectively. Creighton et al. (1987) found that herbaceous weed control increased average height and DBH of loblolly pine, slash pine and longleaf pine from ages 2 to 7 years old on Coastal Plain and Piedmont sites. Miller et al. (2003) found that merchantable loblolly volume and hardwood basal area were related with merchantable loblolly pine volume decreasing around 1% for every 1 ft^2/ac of hardwood basal area present at age 15. Jokela et al. (2000) found that the effect of an herbaceous weed control only treatment at establishment began to decline after five years and that to maintain the response additional treatments of understory vegetation control or fertilization would be needed. The effects of controlling early competition control were still evident at 15 years old in loblolly pine plantations across four physiographic provinces of the southeastern United States (Miller et al. 2003). Competition control may not show as much response when a fertilization treatment is included on a site since more nutrients are readily available to the trees (Borders et al. 2004).

3.3 Fertilization

Fertilization is used to provide adequate nutrition to achieve target growth rates. Nutrient limitations can occur throughout the rotation of a stand and fertilization is often required more than once in the rotation (Fox et al. 2007a). A typical loblolly pine stand's demand for nitrogen (N) will typically exceed the supply of a site by ages 5 to 8 years old which leads to reduced productivity in the stand (Fox et al. 2007a). The typical mid-rotation fertilizer prescription for a loblolly pine plantation has been 150 to 200 lbs of N plus 25 lbs of P in the form of urea and diamonium phosphate (Fox et al. 2007b). Albaugh et al. (2004) found that in loblolly pine plantations located on well drained sandy soils, the impacts of fertilization were more important than reducing moisture limitations with irrigation during the age 8 to 16 year period. Other macronutrients such as potassium (K), calcium (Ca), and magnesium (Mg) also have the potential to become a limiting factor to growth on certain sites and these nutrients need to be added to alleviate the nutrient deficiencies on the site (Jokela 2004).

The response to fertilization often depends on the initial site nutrient supply with low available nutrient sites showing more growth response than sites with high nutrient availability (Tiarks and Haywood 1986, Allen 1987). Soil classification has been reported as a method to predict response to fertilization but response can be highly variable even within the same soil grouping (Allen 1987). Sites in the Lower Coastal Plain that are poorly drained, clayey and have phosphorus deficiencies have been shown to respond favorably to the addition of phosphorus at time of planting (Jokela 2004). The growth response of loblolly pine to the addition of P at time of planting can still be seen at age 13 although indications are that stands would benefit from a second application of P (Gent et al. 1986a).

Predicting the response to fertilization at mid-rotation in the Southeast is not as straight forward, since sites with similar soils can have completely different responses to fertilization (Allen 1987). Site index can be a useful tool when determining how a site will respond to fertilization having either a positive or negative relationship depending on the site conditions (Allen 1987). Recently, the use of leaf area index (LAI) has become a popular method in determining the potential for growth response. Knowing the potential LAI of a stand and the current LAI, potential response can be predicted. Stands with extremely low LAI have a larger potential to respond to fertilization than stands with LAI closer to the maximum (Fox 2007a). Loblolly pine growth responses to fertilization are maximized when there are moderate stocking levels since the trees have the ability to expand crowns and are not constrained by limiting conditions.

Fertilization treatments accelerate stand development, may cause an increase in expressed site quality, and also increase average DBH and height for a given stand (Gent 1986b, Jokela 2004). The mechanism behind fertilization response is increased leaf area of the stand which results in increased growth (Fox 2007a). The effects of fertilization will diminish over time therefore, repeated applications of fertilization during the life of the stand are necessary to maintain increased growth rates (Jokela et al. 2004).

3.4 Planting Density Effects

One of the first decisions a manger must make when planning a new stand is the number of trees per acre to plant. This decision will affect many of the future stand management decisions, most notably the timing of thinning treatments (Sharma et al. 2002). Planting density has a significant effect on many tree and stand level attributes (Harms et al. 2000, Carlson et al. 2009, Will et al. 2010, Zhao et al. 2011). Planting density for loblolly pine in the Lower Coastal Plain had significant effects at age 12 with average tree size generally decreasing and stand measures of basal area per acre and volume per acre increasing as planting density increased (Zhao et al. 2011). Under intensive culture, the lowest level of planting density 300 trees per acre (tpa) had an average DBH of 9.5 in. while the highest planting density of 1800 tpa had an average DBH of only 5.2 inches. In contrast, volume per acre increased from 3261 to 3871 ft^3 per acre for the 300 and 1800 tpa densities, respectively (Zhao et al. 2011). Intensive culture accelerated stand development across the planting density range (Zhao et al. 2011). The response to intensive culture in mean DBH was largest at the lowest planting density of 300 tpa as compared with DBH response at densities from 600 to 1800 tpa (Zhao et al 2011). Similarly, the effects of planting density on loblolly pine mean DBH and stand basal area were significant in the Piedmont at age 9 and began to be significantly different at age 5 (Carlson et al. 2009). Nine year old trees planted at 363 tpa averaged 0.9 inches larger in DBH than for trees planted at 726 tpa (Carlson et al. 2009). On the same study, the effects of planting density on basal area per acre were significant with higher density having increased basal area beginning at age 4.

The effects of planting density on DBH, crown length, and crown width can be seen very early in the stand but the effects on height are not seen until several years later (Sharma et al. 2002). Harms et al. (2000) found that as planting density increased, the average height and dominant height of loblolly pine in Hawaii had a tendency to decrease although differences were not significant. Loblolly pine mean height in the Lower Coastal Plain was significantly affected by planting density after age 4 with the higher densities of 1500 and 1800 tpa having significantly lower heights than tress planted at 300 and 600 tpa (Zhao et al. 2011). Increased planting densities will increase nutrient demands on a site and therefore, nutrient limitations may become noticeable sooner (Carlson et al. 2009).

Higher planting density stands will have density dependent mortality at younger ages than lower density stands. Loblolly pine mortality at ages of 10 and 12 years were significantly influenced by planting density on the Lower Coastal Plain with mortality increasing as planting density increased from 300 tpa to 1800 tpa (Zhao et al. 2011). Carlson et al (2009) did not find a difference in loblolly pine mortality related to density at age 9 on the Piedmont in stands planted at 363 tpa and 726 tpa.

3.5 Intensive Silviculture

Loblolly pine's importance as a commercial species in the southeastern United States has led to efforts to increase stand productivity and value of plantations through application of silvicultural regimes combining a number of beneficial practices. Common silvicultural practices to increase productivity and value are use of genetically improved stock, fertilization, and competition control. Several studies have found these methods to be effective ways to increase productivity by increasing average DBH, height, basal area, and volume (Tiarks and Haywood 1986, Borders and Bailey 2001, Martin and Shiver 2002, Albaugh 2004, Jokela 2004, McKeand et al. 2006). When fertilization and herbaceous weed control are combined the results are usually an additive effect (Jokela et al. 2000).

Plantation managers are routinely planting genetically improved stock. Most commercial plantations are currently established with genetically improved open pollinated seedlings (McKeand et al. 2006). Advances in technology have given growers the opportunity to explore the implementation of mass controlled pollinated and clonal genetic stocks that have the potential to significantly increase growth rates (Fox 2007b). Productivity and value gains from better genetic stock are greatest on more productive than less productive sites (McKeand et al. 2006). Good genetics should be combined with appropriate silviculture for maximum benefit.

Intensive silviculture regimes that include improved genetics and appropriate planting density combined with excellent competition control and needed fertilization produce high productivity rates in many instances. For example, regimes including yearly fertilization and complete competition control produced 2 to 4 times more than plantations not receiving the same intensive culture (Borders and Bailey 2001). Similarly, integrated intensive silvicultural regimes incorporating improved genotypes, appropriate densities, effective competition control and fertilization have yielded 10 tons/acre/year at age 12 on the Lower Coastal Plain (Zhao et al. 2011). These levels of growth in the southeastern United States rival the growth and production that can be produced by loblolly pine in favorable exotic locations (Borders and Bailey 2001).

Intensive culture regimes should be designed using knowledge of how different treatments such as fertilization, competition control and density interact with each other. For example, the best results from fertilization often result from combining it with other silvicultural practices such as competition control and site preparation (Allen 1987, Borders and Bailey 2001, Tiarks and Haywood 1986). This allows for loblolly pine to grow at its full potential when it does not have to compete for site resources. Unique combinations of planting density and cultural regime may provide specific stand responses. Loblolly pine mean DBH increases at age 12 in the Lower Coastal Plain were greater at a relatively low planting density where individual trees had ample space for crown development (Zhao et al. 2011).

The above findings indicate the importance of soil classification, competition control, fertilization, planting density, and intensive culture to loblolly pine plantation performance. The research described in the following chapters aims to advance knowledge on those influences on loblolly pine plantation development in the Upper Coastal Plain and Piedmont through age 12.

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CHAPTER 2

SOIL CLASS, CULTURAL INTENSITY, AND PLANTING DENSITY: IMPACTS ON LOBLOLLY PINE PRODUCTIVITY THROUGH AGE 12 IN THE UPPER COASTAL PLAIN AND PIEDMONT

Garrett,D.L., Kane, M., Zhao, D., and Markewitz, D. To be submitted to Southern Journal of Applied Forestry

Abstract

Effects of soil class, cultural intensity, planting density and their interactions on the growth and development of loblolly pine through age 12 in the Upper Coastal Plain and Piedmont were evaluated using 20 installations of the Plantation Management Research Cooperative Culture x Density Study. Installations contained six planting densities ranging from 300 to 1800 trees per acre and two cultural intensities: operational and intensive. The two cultures contained varying levels of fertilization and competition control. Soils were classified into four classes; Upper Coastal Plain with depth to the argillic horizon less than 20 inches or greater than 40 inches or Piedmont with either kaolinitic or non-kaolinitic subsoil mineralogy. Soil class had an effect on most stand attributes including DBH, height, dominant height, basal area per acre, volume per acre, green weight per acre, stand density index, survival and crown length. Culture and density affected most tree and stand attributes. Significant soil x density interactions for most attributes provided evidence that the Upper Coastal Plain soils, and especially those with greater than 40 inches to the argillic horizon, were less able to support higher densities than Piedmont soils. Culture x planting density interactions indicate that lower planting densities had larger responses than higher planting densities in mean DBH, basal area per acre, and mean live crown ratio to intensive culture. The soil x culture interaction was not significant for most attributes. Plantation managers should consider soil, planting density, and cultural level when making silvicultural prescriptions to meet their objectives.

1. **Introduction**

Loblolly pine is grown throughout the southeastern United States and is considered the most important regional commercial pine species. Physical properties of a soil supporting a loblolly pine stand are critical in the growth of the stand (Guinness 1982). Several soil properties have been related to loblolly pine site index for a stand including depth to the least permeable layer, depth of the surface soil layer, sand content in the subsoil, texture of the subsoil, pH, and slope position (Zahner 1957, Linnartz 1963). Coile and Schumacher (1953) developed an equation to predict site index that included the site factors of depth of surface soil and the imbibitional water value of subsoil. Although these characteristics can be helpful in determining how loblolly pine will perform, variation can still be great within groupings (Zahner 1957, Linnartz 1968, Jokela 2004). Fisher and Garbett (1980) developed the CRIFF soil classification system that has proven useful in characterizing the effects of soils especially in the Lower Coastal Plain. Their system incorporates drainage class, depth to and nature of the B horizon. Using this system they were able to determine different growth and response patterns for loblolly pine 8 years after fertilization for different soils. Overall, soils can be a useful tool when examining a site and deciding the correct management actions, but pine stand performance within a soil class can be very variable and unpredictable.

The effects of intensive culture or planting density on the growth and productivity of loblolly pine have been studied (Harms et al 2000, Carlson et al. 2009, Will et al. 2010, Zhao et al. 2011). Intensive culture including competition control and fertilization provides managers the ability to accelerate growth and development of pine plantations and exceed inherent site productivity (Borders and Bailey 2001; Jokela et al. 2004). Competing vegetation affects many aspects of growth including available nutrients, available light and soil moisture, and rooting volume for loblolly pine by using site resources (Martin and Shiver 2002). Typical loblolly pine stand nutrient demand for nitrogen (N) will often exceed the available nutrients on a site between ages 5 and 8. Fertilization minimizes the effect of these nutrient limitations and multiple fertilizations during a rotation are often necessary to maintain increased growth rates (Fox et al.

2007). Albaugh et al. (2004) found that on a droughty, nutrient poor site in North Carolina the addition of nutrients was more beneficial to growth than irrigation for loblolly pine during the age 9 to 16 year period. The response to fertilization can be highly variable from site to site but some factors used to help predict response are soil class (Fisher and Garbett 1980) and leaf area index (Fox 2007).

Initial planting density will affect many of the future management decisions for the stand. Planting density has a significant effect on many tree and stand level attributes (Harms et al. 2000, Carlson et al. 2009, Will et al. 2010, Zhao et al. 2011). Carlson et al. (2009) found that the effect of planting density was significant for loblolly pine in the Piedmont at age 9 and that the effect began to be significant at age 5. Nine year old trees planted at 363 trees per acre (tpa) averaged 0.9 inches larger in DBH than trees planted at 726 tpa. Increasing loblolly pine planting density from 300 tpa to 1800 tpa in the Lower Coastal Plain generally resulted in smaller individual tree size but greater per acre basal area and weight at age 12 (Zhao et. al 2011). In this study the authors noted a significant difference in age 12 survival between stands planted at 300 tpa and 1800 tpa with the higher survival in the 300 tpa stand.

The interaction between soils, culture and density is also of interest to managers. Zhao et al. (2011) reported a significant interaction between cultural intensity and planting density for age 12 mean DBH of loblolly pine in the Lower Coastal Plain with greater mean DBH response on the lowest planting density (300 tpa) than on other densities. No culture x density interaction was reported for age 9 loblolly pine in the Piedmont when densities of 363 tpa and 726 tpa were examined (Carlson et al. 2009).

The PMRC established the Culture x Density Study on the Upper Coastal Plain and Piedmont during 1998 and 1999 to determine the effects of soils, culture, and density on the productivity of loblolly pine plantations. Due to insufficient soil information for many test installations, past analysis have not examined soil class effects or interactions. These past analyses indicate increased growth with intensive culture and mean individual tree size reductions but per acre yield increases with greater planting density (Zhao and Kane 2010).

The objectives of the present research were to incorporate soil class into the analysis of this regional study and determine effects and interactions of soil class, cultural intensity, and planting density on the growth and development of loblolly pine plantations at age 12 years in the Upper Coastal Plain and Piedmont. I hypothesize that soil class, cultural intensity, and planting density will significantly impact loblolly pine productivity.

2. Methods

2.1 Study Sites and Treatments

Twenty installations located in the Upper Coastal Plain and Piedmont of Alabama, Georgia, and South Carolina that were a part of the PMRC Culture x Density Study were examined (Table 2.1). The study originally contained 23 installations but 3 installations were lost due to harvest activities. The sites were planted in 1998 or 1999 with open-pollinated, bare-root seedlings chosen by the PMRC cooperator who owned the site. The seedlings were double planted to ensure adequate survival and to make sure the target planting density was met. Planting spots were reduced to one seedling at the end of the first growing season. The study was a split plot design with the main plots receiving one of two cultural intensities: operational or intensive (Table 2.2). Both intensities included broadcast chemical site preperation, tillage at some installations, fertilization and banded herbaceous weed control at time of planting. The intensive plots received continued complete competing vegetation control and fertilization almost every other year. The operational plots received fertilization in the 8th and 12th growing seasons with no further competing vegetation control. Within each main plot were six sub-plots of different planting densities: 300, 600, 900, 1200, 1500, and 1800 tpa. Tree spacing and plot size varied among each planting density (Table 2.3). Each measurement plot was surrounded by a buffer of 26 feet to form the gross plot.

2.2 Soil Classification

Soil information for classification was obtained through the USDA – NRCS Soil Survey Division. The accuracy of the soil survey system classification was verified by visits to 10 sites. Two augured soil profiles were examined at each site visited. It was concluded that the soil survey was accurate at placing soils into the appropriate soil class. The Culture x Density Study plan anticipated test establishment on four soil classes in the Piedmont (non-kaolinitc or kaolinitic argillic horizon mineralogy in combination with A horizon depth of either less than or greater than three inches) and three soil classes in the Upper Coastal Plain (depth to the argillic horizon less than 20 inches, between 20 and 40 inches, and greater than 40 inches). Only four of the seven classes are represented in the actual installations investigated (Table 2.4). Twelve installations were in the Upper Coastal Plain. Nine of these installations had soils < 20 inches to the argillic horizon and the remaining three having soils with > 40 inches to the argillic horizon. All eight installations in the Piedmont had an A horizon depth greater than three inches. Six Piedmont installations had kaolinitic argillic horizon mineralogy and two had non-kaolinitic mineralogy. Most installations were on well drained soils. Exceptions are two excessively drained soils (installations 2, 6) , one moderately well drained soil (installation 16), and one somewhat poorly drained soil (installation 19).

2.3 Stem and Stand measurements

Tree measurements were conducted at age 12. DBH was measured on all trees within the measurement plot and height was measured on every other tree. For trees not measured for height an equation in the form of ln (height)= $\beta 0 + \beta 1 \ DBH^{-1}$ was used to predict tree height. Dominant height was calculated as the mean of defect free trees with height measurements with DBH greater than the average DBH. Site index was calculated using age 12 dominant height on the operational culture 600 tpa planting density plot for each installation and the site index equation from Borders et al. (2004a). Trees measured for height were also measured for height to live crown. Crown length was calculated from total height and height to live crown measured. Live crown ratio was calculated as live crown length divided by total tree height. Total standing stem volume of living trees was calculated using a volume equation from Pienaar et al. (1987). Survival at age 12 was calculated by using the observed number of trees per acre divided by planting density for the plot. Stand density index was calculated for each plot using the following equation:

$$\mathrm{SDI} = \mathrm{N}\left(\frac{10}{\mathrm{Dq}}\right)$$

where SDI = stand density index; N = trees per acre surviving at age 12; and D_q= quadratic mean DBH in inches.

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

$$RS = \frac{\sqrt{43560/N}}{HD}$$

where RS= relative spacing; N= trees per acre surviving at age 12; and HD = average dominant height in feet.

2.4 Statistical Analysis

The arrangement of soil groups, cultural intensity, and planting density results in a split – split plot design. The main plots are soil class, subplots are cultural intensities, and planting densities are sub-subplots. Analysis of Variance (ANOVA) with a mixed effects model was used to test the effects of soil class, culture, planting density and the interactions. The installations and all factors containing installation are considered random. The model form is as follows:

$y_{ijkl} = \mu + \alpha_i + e_{l(i)} + \beta_j + (\alpha\beta)_{ij} + \delta_{jl(i)} + \gamma_k + (\alpha\gamma)_{ik} + (\beta\gamma)_{jk} + (\alpha\beta\gamma)_{ijk} + \varepsilon_{ijkl}$

Where

y_{ijkl} = the value of variable for plots at kth planting density in the jth cultural intensity of the lth installation in the ith soil class;

μ = the overall mean effect;

α_i = the effect of the ith soil class;

$e_{l(i)}$ = the random effect of installation with $e_{l(i)} \sim i.i.d.\ N(0, \sigma_e^2)$;

β_j = the effect of the jth culture;

$(\alpha\beta)_{ij}$ = the interaction effect between the ith level of soil and the jth level of culture;

$\delta_{jl(i)}$ = the random effect of culture and installation with $\delta_{jl(i)} \sim i.i.d.\ N(0, \sigma_\delta^2)$;

γ_k = the effect of the kth planting density;

$(\alpha\gamma)_{ik}$ = the interaction effect between the ith level of soil and the kth level of planting density;

$(\beta\gamma)_{jk}$ = the interaction effects between the jth level of culture and the kth level of planting density ;

$(\alpha\beta\gamma)_{ijk}$ = the interaction effects of the ith level of soil, the jth level of culture and the kth level of planting density;

ε_{ijkl} = the random effect of the kth planting density in the jth culture of the lth installation in the ith soil class with $\varepsilon_{ijkl} \sim i.i.d.\, N(0, \sigma_{\varepsilon}^2)$;

All random effects $e_{l(i)}$, $\delta_{jl(i)}$, and ε_{ijkl} are independent of each other. The analysis was conducted on average DBH, height, dominant height, survival, basal area per acre, volume per acre, green weight outside bark per acre, stand density index, relative spacing, mean live crown ratio, and mean live crown length. Survival and crown ratio were transformed using the arcsine of the square root prior to statistical analysis to address the assumption of a normal distribution.

3. Results

3.1 Soil Effects

Soil main effects were significant for all attributes except relative spacing and crown ratio (Table 2.5). Upper Coastal Plain soils with > 40 inches to the argillic horizon exhibited the lowest values for many individual tree and stand level attributes (Table 2.6). Survival at age 12 was lower on Upper Coastal Plain soils with < 20 in. to the argillic horizon (80%) than on Piedmont soils with a non-kaolinitic mineralogy (90%) or Upper Coastal Plain soils with > 40 inches to the argillic horizon (91%). Basal area per acre was significantly lower on the two Upper Coastal Plain soil classes than on the Piedmont classes. The basal area per acre for the Upper Coastal Plain soils with > 40 inches (145 ft^2/acre) to the argllic horizon was significantly lower than for the Upper Coastal Plain soil with < 20 inches to argillic (163 ft^2/acre). Crown length was significantly greater for the Upper Coastal Plain soil with < 20 inches to the argillic horizon than for the other soil classes.

3.2 Culture Effects

Culture main effects were significant for all attributes except mean crown length at age 12 (Table 2.5). All attributes were increased with increased culture except for survival, relative spacing, crown ratio and crown length (Table 2.6). Survival, relative spacing, and crown ratio were significantly lower for the intensive culture.

3.3 Planting Density Effect

The density main effect was significant for all attributes measured at age 12 (Table 2.5). Individual tree attributes of DBH, height, dominant height, relative spacing, crown ratio and crown length all decreased as the planting density increased. Per acre basal area, volume and green weight outside bark and stand density index all increased as density increased. Survival decreased as planting density increased.

3.4 Soil x Culture Interactions

The only significant soil x culture interaction was for crown ratio (Table 2.5). Loblolly pine on Piedmont, non-kaolinitic subsoil and Upper Coastal Plain with > 40 inches to the argillic horizon soil classes had more pronounced decreases in crown ratio in response to the intensive culture as compared with loblolly pine on the other two soil classes (Figure 2.1).

3.5 Soil x Density Interactions

There were significant soil x density interactions for height, dominant height, survival, basal area per acre, volume per acre, green weight outside bark, stand density index and relative spacing (Table 2.5). The height and dominant height interactions followed the same pattern of larger decreases in height as planting density increased on the Upper Coastal Plain, > 40 inches to the argillic horizon soils as compared with that on other soil classes (Figure 2.2). The survival interaction showed unusally low survival for the 300 and 600 tpa planting densities on the Piedmont non-kaolinitic soils (Figure 2.3). The basal area and stand density index interactions were very similar to each other. At 300 tpa soil classes had relatively similar basal area and stand density indexes but as planting density increased the relative increase in attributes was less for

Upper Coastal Plain than for Piedmont soil classes (Figure 2.4 and Figure 2.5). The volume and green weight outside bark interactions followed a similar pattern but differed slightly from that for basal area and stand density index in that they showed smaller decreases in attributes. The Upper Coastal Plain soils with > 40 inches to an argillic horizon did not gain volume (Figure 2.6) or green weight as planting densities increased at the same rate as the other three soil classes. Relative spacing on the Upper Coastal Plain soils decreased less as planting density increased than that on Piedmont soil classes (Figure 2.7).

3.6 Culture x Density Interactions

The culture x density interaction was significant for DBH, basal area per acre, stand density index, relative spacing, and crown ratio (Table 2.5). The DBH interaction reflects lower planting densities of 300 and 600 tpa having larger gains in mean DBH as cultural intensity increases as compared with higher densities (Figure 2.8). Basal area per acre on planting densities of 300 tpa and 600 tpa show relatively large gains with increased culture and the 1800 tpa showed the smallest gain of all planting densities (Figure 2.9). The stand density index interaction followed the same pattern as the basal area interaction (Figure 2.10). Relative spacing decreased more in response to intensive culture on lower planting densities than on the higher planting densities (Figure 2.11). The crown ratio interaction reflects planting densities of 300 and 600 tpa increasing their crown ratio with intensive culture at a higher rate than the higher planting densities (Figure 2.12).

4. Discussion

The sites used for this study represent highly productive sites in the Upper Coastal Plain and Piedmont, having an average operational expressed site index of 86 feet. In comparison, Miller et al. (2003) reported an average site index of 68 feet for 13 study sites across the four physiographic regions of the Southeast. The stands reported here provided stands in a range of different stand development stages resulting from the different planting densities and cultural treatments. Many stands at age 12 had achieved or passed traditional thinning thresholds and were experiencing self-thinning. Jokela et al. (2004) reported maximum current annual increment at 90 to 150 ft^2/acre basal area and initiation of competition related mortality at 130 ft^2/acre to 150 ft^2/acre basal area.

Soil class had a significant effect on the growth and development of loblolly pine stands in this study on upland sites in the Upper Coastal Plain and Piedmont. For most growth attributes, Upper Coastal Plain soils with > 40 inches to the argillic horizon consistently had the lowest growth. This was probably due to these soils having a low inherent nutrient supply and also low soil moisture holding capacity. Plantations on these soils did not perform as well as those on other soil classes even with intensive silviculture. Similarly, soil class effects were present on mean DBH and basal area per acre of loblolly pine at age 12 on poorly drained soils in the Lower Coastal Plain in a similar Culture x Density study (Harrison and Kane 2008). Certain sites in the Lower Coastal Plain have been identified by using the CRIFF soil classification system as responding better to fertilizer amendments or better supporting loblolly pine productivity without amendments (Fisher and Garbett 1980) although similar relationships between soil class and response in the Upper Coastal Plain in Piedmont have not been reported.

The interactions between soil class and planting density offer interesting insights. Loblolly pine on Upper Coastal Plain soils with > 40 inches to an argillic horizon consistently performed worse relative to stands on other soil classes as planting density increased. Sharp contrasts in growth attribute slopes as planting density increased among different soil classes were evident for most growth attributes. This probably results from the Upper Coastal Plain soils with > 40 inches to the argillic horizon having relatively less nutrient and lower available moisture resources. The increase in density increased the demand for these resources causing the differences in site quality among soil classes to be magnified at the higher planting densities. Higher planting densities will shorten the period from planting when nutrition will limit pine growth. In the present study, the differences in mean height are especially pronounced at very high planting densities. Carlson et al. (2009) hypothesized that increased density would make stands become more responsive to nutrient amendments earlier. In contrast to the results of the present study, these authors did not find any significant interaction between nutrition amendments and density in age 9 loblolly pine stand attributes when evaluating planting densities of 363 and 726 tpa probably because they did not examine extreme high densitites.

Intensive culture consistently increased tree and stand attribute values with the exception of relative spacing, crown ratio and survival which decreased with increased culture due to accelerated stand development. This result is consistent with other studies that have found intensive culture increased growth over less intensive treatments (Albaugh et al. 2004, Borders et al. 2004b, Zhao et al. 2011). Intensive culture increased tree growth and accelerated stand development resulting in increased competition. Zhao et al. (2011) reported the same trend of accelerated stand development with intensive culture in loblolly pine at age 12 in the Lower Coastal Plain.

There was not a significant difference in the response to intensive culture on the different soil classes with the exception of crown ratio. The general lack of significant interactions suggests that the improved resource availability with intensive culture was effective across the soil classes tested. Fox et al (2007) reported that over an 8 year period the growth gains to a one time application of fertilization in well stocked loblolly pine stands averaged 50 ft^3/ac/year on sites throughout the South. Jokela et al. (2000) found the interaction of a fertilization treatment and soils to be significant at age 5 for loblolly pine on several different CRIFF soil classes. Fertilization response was greater on CRIFF A soils which are poorly drained and have an argillic horizon. Such a strong impact of soil class on response to intensive culture was not apparent in the Upper Coastal Plain and Piedmont in the present study. The operational culture regime used in this study is considered to be a very good operational culture as implemented by commercial growers who are managing land intinsively. The intensive culture regime was designed to eliminate interspecific competition and nutritional growth constraints and is beyond current operational practice. The consistent growth gains from intensive culture suggest that operational culture leaves resource limitations to loblolly pine productivity on many sites.

Planting density had a significant effect on the growth and development of loblolly pine in the Upper Coastal Plain and Piedmont. The densities evaluated represent a wide range of possible planting densities, but most field operations use a range of planting densities of 420 to 750 tpa when multiple products are desired. Increasing planting density caused individual tree attributes to decrease while stand attributes increased because of more individuals per acre. Several other studies have reported similar results on loblolly pine (Sharma et al. 2002, Carlson et al. 2009, Zhao et al. 2011). The trees on the higher planting densities experienced more intraspecific competition and were unable to grow as fast as the trees on the lower planting densities. Consistent differences were seen between the lowest and highest planting densities, but the differences between the intermediate densities were not as pronounced in every attribute.

The interaction between culture and planting density at age 12 was significant for DBH, basal area, stand density index, mean crown ratio and survival. Interactions other than survival and relative spacing followed a similar pattern of the lower planting densities showing larger increases from intensive culture than higher densities. With intensive culture survival on the higher planting densities decreased significantly more than on the lower planting densities since increased culture stimulated growth and competition. Similarly, Zhao et al. (2011) reported that the combination of intensive culture and high planting density significantly increased age 12 loblolly pine mortality in the Lower Coastal Plain. As in the current study, they also found that the lower planting densities showed larger gains in DBH with increased culture over the higher planting densities.

5. Conclusions

Soils class, cultural intensity and planting density have significant effects on loblolly pine plantation performance in the Upper Coastal Plain and Piedmont. Soils are important when determining how loblolly pine will perform. Productivity at age 12 was less on Upper Coastal Plain soils with> 40 inches to an argillic horizon than on the other soil classes evaluated. Intensive culture increased individual tree and stand growth. Intensive culture will accelerate the stand development process and require earlier thinning or final harvest to reduce the effect of density related competition and mortality. Planting density has a strong effect on individual tree and stand attributes. As planting density increased, individual tree size decreased but stand attributes of basal area and volume increased due to more individuals per acre. Lower planting densities also exhibited larger age 12 mean DBH, basal area per acre and stand density responses to the intensive culture than higher planting densities. Stand density is an important decision for forest managers especially on Upper Coastal Plain soils with > 40 inches to the argillic horizon. Plantations on these soils show larger decreases in mean height, mean dominant height, and less increase in basal area per acre, volume per acre, and green weight outside bark per acre as planting density increases than plantations on the other soil classes, especially those in the

Piedmont. This effect is probably a result of these soils having a relatively lower inherent nutrient and available water supply and the increased demand on the soil with increased density causes nutrient and/or moisture deficiencies to be magnified. Managers should consider thinning and final harvest options when making decisions on planting density and cultural intensity combinations.

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Table 2.1. Location, soil information, and site index for 20 installations of the PMRC Culture x Density Study located in the Upper Coastal Plain and Piedmont.

Installation	Location	Physiographic Province	Soil Series	Soil Taxonomy	Site Index*
1	Hancock Co., Ga	Upper Coastal Plain	Bonifay/Cowarts	Loamy, siliceous, subactive, thermic Grossarenic Plinthic Paleudults	79
2	Baldwin Co, Al	Upper Coastal Plain	Lakeland	Thermic, coated Typic Quartzipsamments	79
3	Escambia Co., Al	Upper Coastal Plain	Freemanville	Fine, kaolinitic, thermic Plinthic Kandiudults	85
4	Escambia Co., Al	Upper Coastal Plain	Orangeburg	Fine-loamy, kaolinitic, thermic Typic Kandiudults	89
5	Harris Co., Ga	Piedmont	Lloyd	Fine, kaolinitic, thermic Rhodic Kanhapludults	95
6	Marion Co., Ga	Upper Coastal Plain	Lakeland	Thermic, coated Typic Quartzipsamments	75
8	Laurens Co., SC	Piedmont	Cecil	Fine, kaolinitic, thermic Typic Kanhapludults	86
9	Monroe Co., Al	Upper Coastal Plain	Bama - Malbis	Fine-loamy, siliceous, subactive, thermic Typic Paleudults	85
11	Greene Co, Ga	Piedmont	Cecil	Fine, kaolinitic, thermic Typic Kanhapludults	87
12	Barbour Co, Al	Upper Coastal Plain	Orangeburg - Springhill	Fine-loamy, kaolinitic, thermic Typic Kandiudults	94
13	Jasper Co, Ga	Piedmont	Lloyd - Pacolet	Fine, kaolinitic, thermic Rhodic Kanhapludults	88
15	Talladega Co., Al	Piedmont	Decatur - Tupelo	Fine, kaolinitic, thermic Rhodic Paleudults	85
16	St. Clair Co, Al	Piedmont	Conasauga and Firestone	Very-fine, mixed, active, thermic Chromic Vertic Hapludalfs	76
17	Harolson Co., Ga	Piedmont	Grover	Fine-loamy, micaceous, thermic Typic Hapludults	86
18	Chatooga Co., Ga	Piedmont	Fullerton	Fine, kaolinitic, thermic Typic Paleudults	83
19	Perry Co., MS	Upper Coastal Plain	Susquehanna/Freest	Fine, smectitic, thermic Vertic Paleudalfs	93
20	McCulloch, Al	Upper Coastal Plain	Benndale	Coarse-loamy, siliceous, semiactive, thermic Typic Paleudults	90
21	Burke Co. Ga	Upper Coastal Plain	Tifton	Fine-loamy, kaolinitic, thermic Plinthic Kandiudults	91
22	Burke Co. Ga	Upper Coastal Plain	Tifton	Fine-loamy, kaolinitic, thermic Plinthic Kandiudults	93
23	Clarke Co. Al	Upper Coastal Plain	Okeelala - Brantley	Fine-loamy, siliceous, semiactive, thermic Ultic Hapludalfs	87

*Based on age 12 dominant height on plots with operational culture and 600 tpa planting density

Table 2.2. Description of operational and intensive cultures in the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.

Treatment	Growing season	Operational Culture	Intensive Culture
Site prep		Tillage including subsoiling on some sites	Tillage including subsoiling on some sites
		Broadcast chemical site preparation	Broadcast chemical site preparation
Competition control	1st year	4 oz/ac sulfometuron methyl Banded + direct spraying of glyphosate and triclopyr for hardwood control	4 oz/ac sulfometuron methyl broadcast + direct spraying of glyphosate and triclopyr for complete control
	2nd		12 oz/ac imazapyr broadcast
	3rd-12th		Repeated direct spraying of glyphosate and triclopyr for complete control
Fertilization	At Planting	500 lbs of 10-10-10 per acre	500 lbs of 10-10-10 per acre
	2nd		-600 lbs of 10-10-10 per acre + 117 lbs of NH_4NO_3 per acre + micronutrients
	4th		117 lbs of NH_4NO_3 per acre
	6th		300 lbs of NH_4NO_3 per acre
	8th	200 lbs N + 25 lbs P per acre	200 lbs N + 25 lbs P per acre
	10th		200 lbs N + 25 lbs P per acre
	12th	200 lbs N + 25 lbs P per acre	200 lbs N + 25 lbs P per acre

Table 2.3. Spacing and plot size for different planting densities in the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.

Planting Density	Orginal Spacing	Measurement Plot Size	Gross Plot Size
Trees/ac	(ft x ft)	(ac)	(ac)
300	12 x 12	0.26	0.56
600	8 x 9	0.13	0.37
900	8 x 6	0.11	0.31
1200	6 x 6	0.10	0.30
1500	6 x 4.8	0.11	0.32
1800	6 x 4	0.10	0.31

Table 2.4. Soil classes, installations per class, and individual installation by soil class for the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.*

Soil Class	Installations per Class	Installations in Class
Piedmont, Non-Kaolinitic subsoil	2	16,17
Piedmont, Kaolinitic subsoil	6	5,8,11,13,15,18
Upper Coastal Plain, Argillic < 20"	9	3,4,9,12,19,20,21,22,23
Upper Coastal Plain, Argillic > 40"	3	1,2,6

*See Table 2.1 for installation details.

Table 2.5. P-values for soil, culture and density main effects and associated interactions on loblolly pine stem and stand attributes at age 12 from 20 installations in the Upper Coastal Plain and Piedmont.*

Effects	DBH	Height	Dominant Height	Survival	Basal Area	Volume	Green Weight Outside Bark	Stand Density Index	Relative Spacing	Mean Crown Ratio	Mean Crown Length
Soil	**0.0044**	**0.0205**	**0.0164**	**0.0130**	**0.0007**	**0.0091**	**0.011**	**0.0008**	0.1794	0.4400	**0.002**
Culture	**<.0001**	**<.0001**	**<.0001**	**0.0152**	**<.0001**	**<.0001**	**<.0001**	**0.0005**	**0.0017**	**0.0016**	0.1939
Soil x Culture	0.22	0.1058	0.1089	0.7623	0.1819	0.2976	0.3408	0.1611	0.1229	**0.0601**	0.6596
Density	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**
Soil*Density	0.5579	**<.0001**	**<.0001**	**0.0960**	**0.0043**	**<.0001**	**<.0001**	**0.0077**	**0.0748**	0.8943	0.1662
Density x Culture	**0.0102**	0.8271	0.8405	0.1486	**0.0902**	0.673	0.6847	**0.0586**	**0.0371**	**0.0301**	0.1077
Soil*Density*Culture	0.8883	0.83	0.599	0.6582	0.6445	0.7277	0.7587	0.5451	0.7118	0.1019	0.1529

*Values in bold indicate significance at α=0.10 level.

Table 2.6. Means for main effects of soil class, cultural intensity, and planting density at age 12 for 20 installations in the Upper Coastal Plain and Piedmont.

Soil Class	DBH (Inches)	Height (ft)	Dom. Height (ft)	Survival	Basal Area (ft^2/acre)	Volume (ft^3/acre)	Green Weight (tons/acre)	Stand Density Index	Relative Spacing	Crown Ratio	Crown Length (ft)
Piedmont, non-kaolinitic subsoil	6.62a	45.9ab	47.6ab	0.90a	192.6a	4267a	110a	422.6a	0.16a	0.42a	19.22ac
Piedmont, kaolinitic subsoil	6.64a	47.6a	49.6a	0.85a	181.2a	4151a	107a	397.6a	0.16a	0.41a	19.73a
Upper Coastal Plain, Argillic < 20”	6.48a	48.5a	51.5a	0.80b	162.7b	3832a	99a	360.0b	0.16a	0.43a	21.03b
Upper Coastal Plain, Argillic > 40”	5.70b	41.0b	43.7b	0.91a	144.7c	2982b	75b	336.5b	0.17a	0.45a	18.60c
Culture											
Intensive	6.73a	48.8a	51.3a	0.82a	177.8a	4168a	108a	387.5a	0.16a	0.42a	20.48a
Operational	6.11b	44.9b	47.4b	0.87b	159.2b	3519.b	90b	360.56b	0.17b	0.44b	19.70a
Density											
300	9.10a	49.1a	50.9a	0.93a	128.8a	2867a	77a	243.7a	0.25a	0.55a	27.09a
600	7.24b	48.6b	50.6a	0.90a	158.3b	3637b	96b	328.0b	0.18b	0.45b	21.64b
900	6.28c	47.7b	50.0ab	0.84b	167.2c	3870c	100c	366.5c	0.15c	0.42c	19.89c
1200	5.72d	46.2c	49.2b	0.82b	181.1d	4158d	107d	411.7d	0.14d	0.40c	18.57d
1500	5.26e	45.0d	47.9c	0.78c	181.9d	4129d	105d	427.5e	0.13e	0.37d	16.99e
1800	4.95f	44.5d	47.6c	0.78c	193.8e	4402e	111e	466.5f	0.12f	0.36d	16.36e

*Means within a column and main effect not followed by a same letter are significantly different at α=.10.

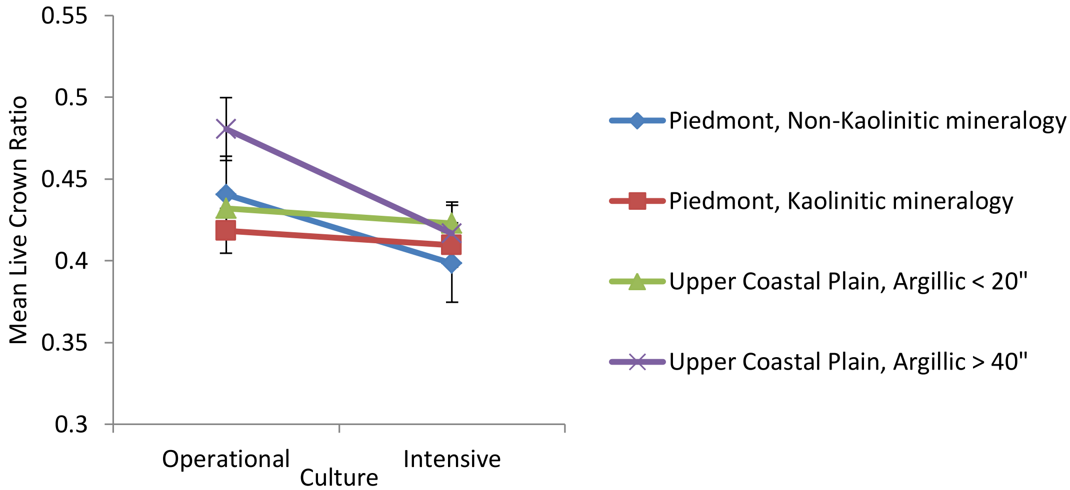

Figure 2.1. Interaction of soil class and cultural intensity on loblolly pine age 12 crown ratio in the Upper Coastal Plain and Piedmont. Symbols indicate mean values. Bars indicate standard errors.

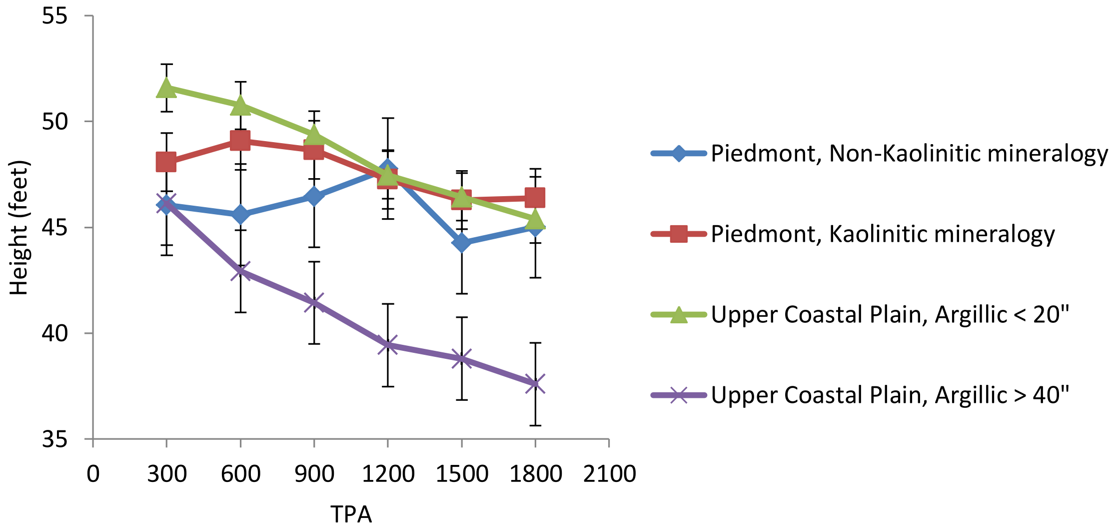

Figure 2.2. Interaction of planting density and soil class on loblolly pine age 12 mean height in the Upper Coastal Plain and Piedmont. Symbols indicate mean values. Bars indicate standard error.

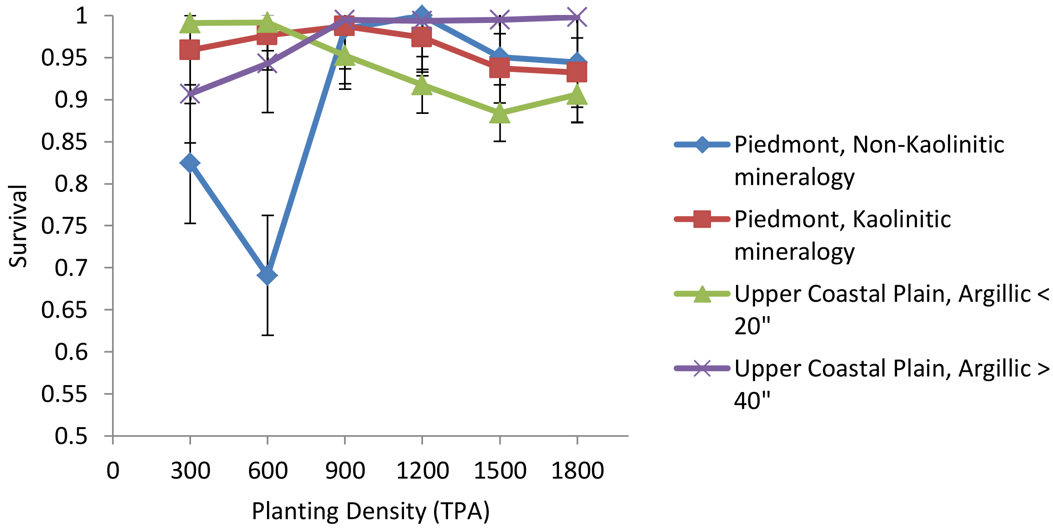

Figure 2.3 Interaction of planting density and soil class on loblolly pine age 12 survival in the Upper Coastal Plain and Piedmont. Symbols indicate mean values. Bars indicate standard error.

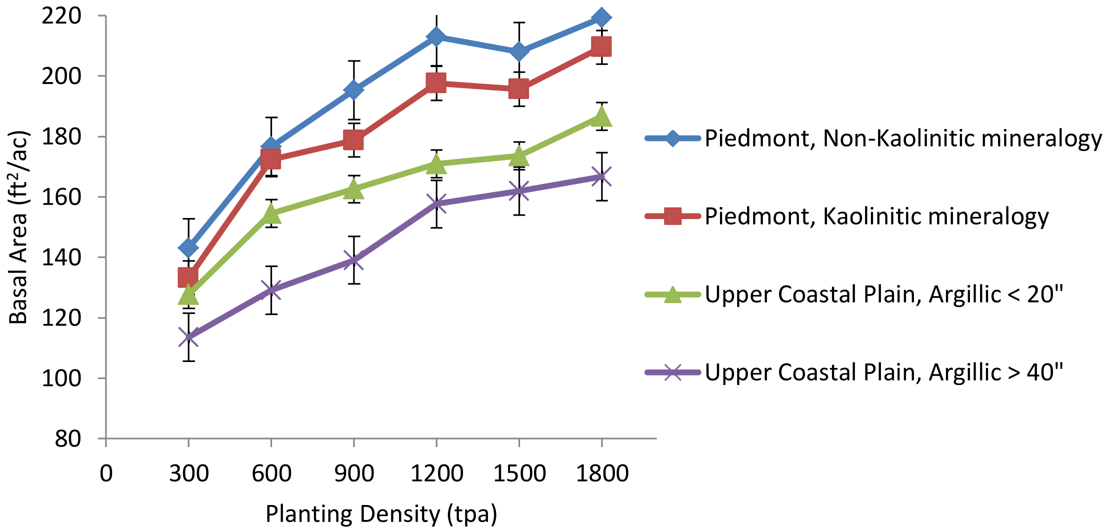

Figure 2.4. Interaction of planting density and soil class on loblolly pine at age 12 basal area per acre in the Upper Coastal Plain and Piedmont. Symbols indicate mean values. Bars indicate standard error.

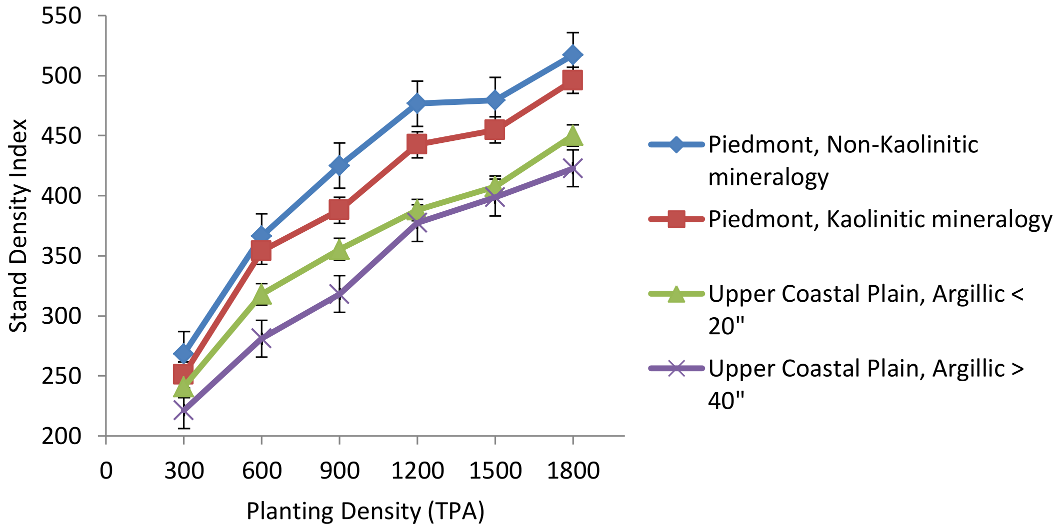

Figure 2.5. Interaction of planting density and soil class on loblolly pine age 12 stand density index in the Upper Coastal Plain and Piedmont. Symbols indicate mean values. Bars indicate standard error.

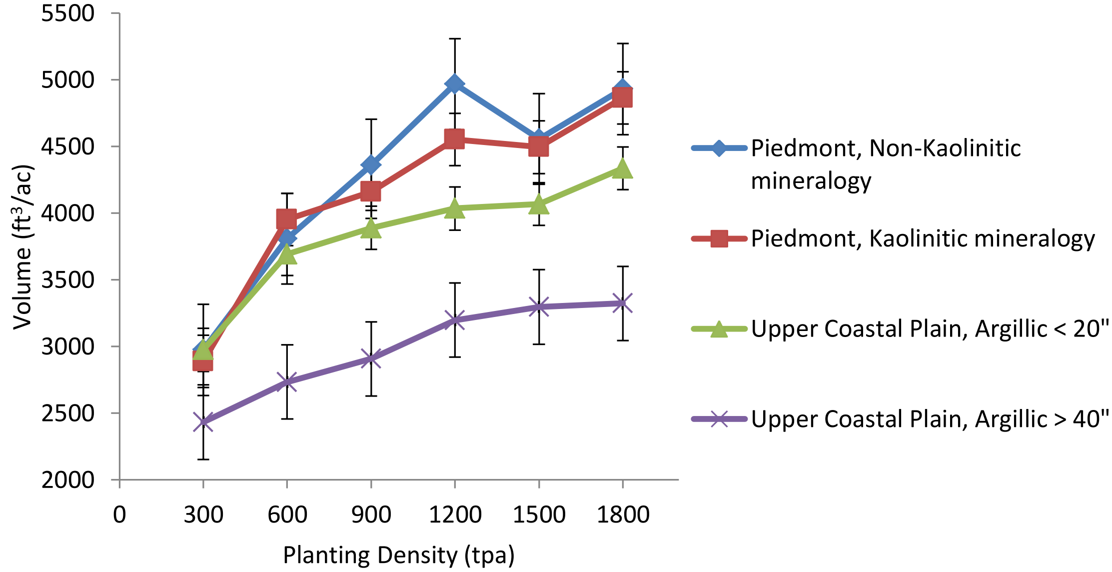

Figure 2.6. Interaction of planting density and soil class on loblolly pine age 12 volume per acre in the Upper Coastal Plain and Piedmont. Symbols indicate mean values. Bars indicate standard error.

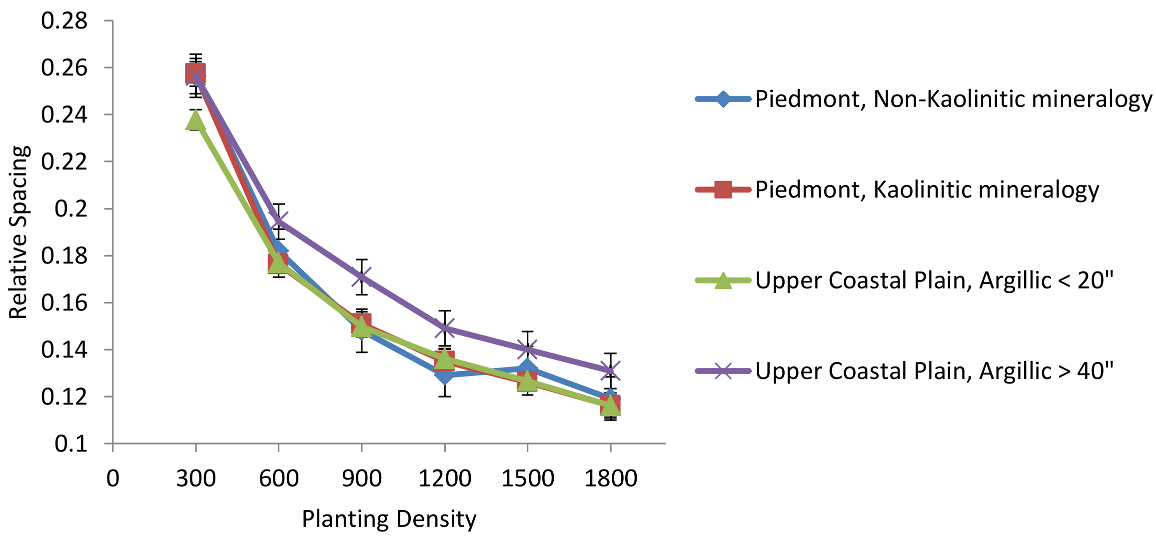

Figure 2.7. Interaction of planting density and soil class on loblolly pine age 12 relative spacing in the Upper Coastal Plain and Piedmont. Symbols indicate mean values. Bars indicate standard error.

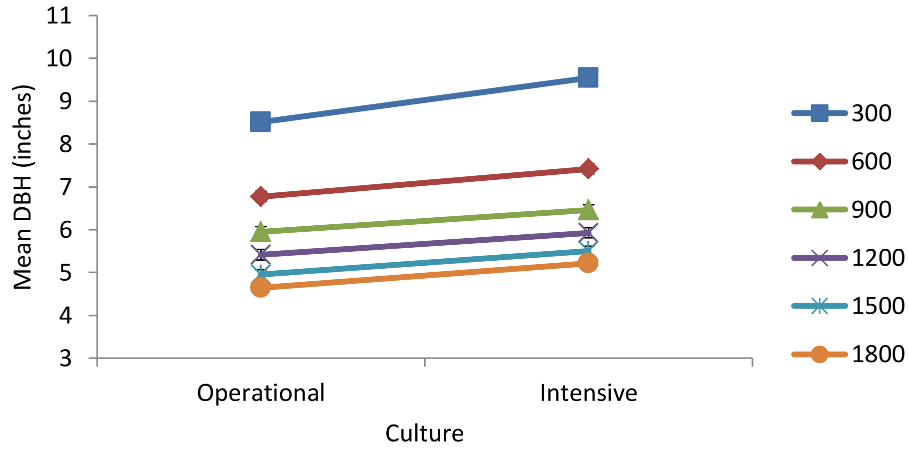

Figure 2.8. Interaction of cultural intensity and planting density on loblolly pine age 12 mean DBH in the Upper Coastal Plain and Piedmont. Symbols indicate mean values. Bars indicate standard error.

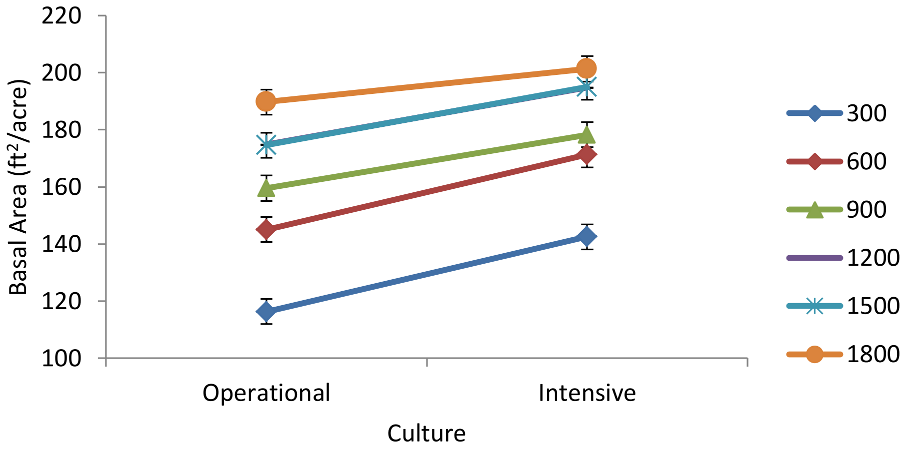

Figure 2.9. Interaction of cultural intensity and planting density on loblolly pine age 12 basal area per acre in the Upper Coastal Plain and Piedmont. Symbols indicate mean values. Bars indicate standard error. The 1200 and 1500 lines are identical and therefore only the 1500 tpa line shows on the graph.

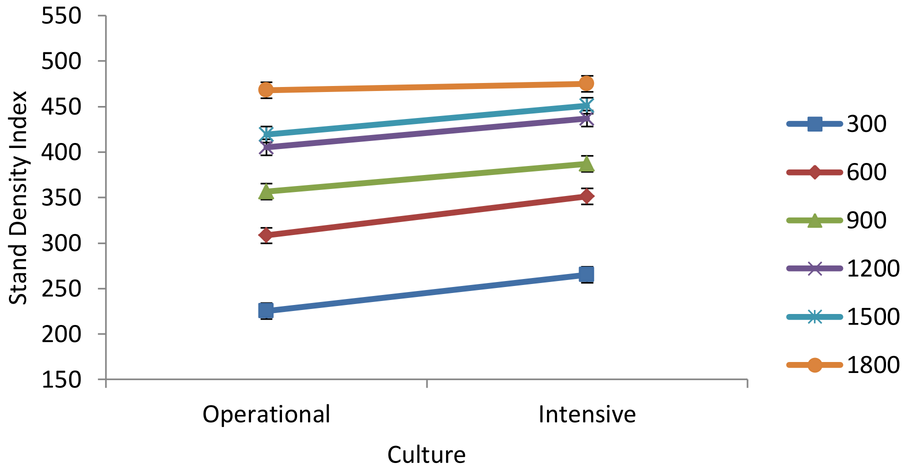

Figure 2.10. Interaction of cultural intensity and planting density on loblolly pine age 12 stand density index in the Upper Coastal Plain and Piedmont. Symbols indicate mean values. Bars indicate standard error.

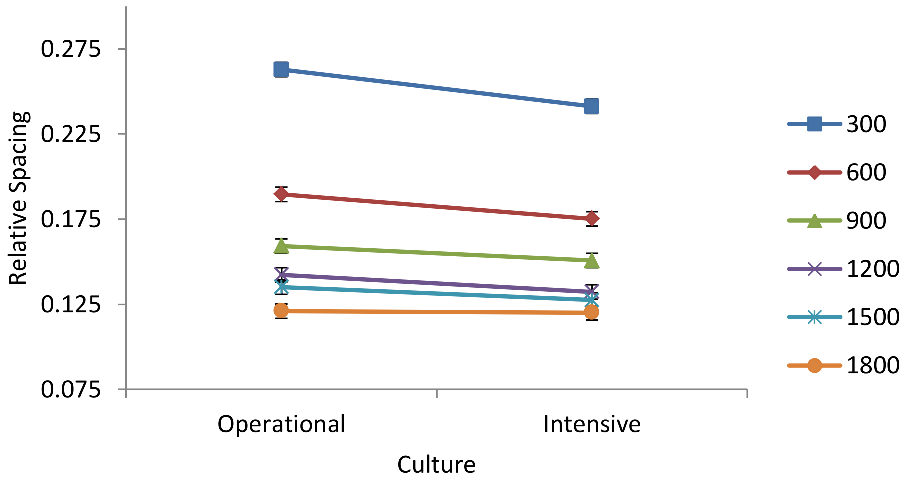

Figure 2.11 Interaction of cultural intensity and planting density on loblolly pine age 12 relative spacing in the Upper Coastal Plain and Piedmont. Symbols indicate mean values. Bars indicate standard error.

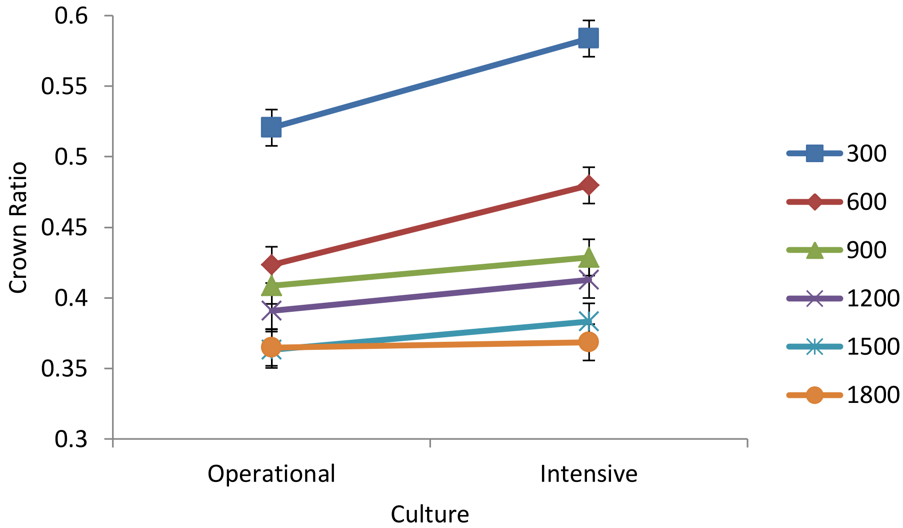

Figure 2.12 Interaction of cultural intensity and planting density on loblolly pine age 12 crown ratio in the Upper Coastal Plain and Piedmont. Symbols indicate mean values. Bars indicate standard error.

CHAPTER 3

PRODUCTIVITY RESPONSE OF LOBLOLLY PINE PLANTATIONS TO INTENSIVE CULTURE THROUGH AGE 12 IN THE UPPER COASTAL PLAIN AND PIEDMONT

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Abstract

Understanding how existing site conditions affect response to intensive culture will improve silvicultural decisions. Twenty installations of the Plantation Management Research Cooperative Culture x Density Study in the Upper Coastal Plain and Piedmont were examined for relationships between magnitude of growth response to intensive culture through age 12 in stands planted at 600 tree per acre and soil attributes, site index under operational culture, and competing vegetation measures. Each installation tested two cultural intensities, operational and intensive, with differing levels of fertilization and competition control. Age 12 loblolly pine productivity with operational culture and response to intensive culture varied among soil class. Upper Coastal Plain soils with > 40 inches to the argllic horizon had the lowest productivity under operational culture but tended to have the largest response to intensive culture although few observed differences in response were statistically significant. It should be noted that the response was to an increase in culture that is considered to be intensive. Soil attributes of depth to Bt and subsoil texture were weakly correlated with response; response tended to increase with increased depth to Bt and decrease with finer subsoil textures. Age 12 pine response was positively correlated with operational plot measures of small woody competition at age 8 and percent grass, broadleaf or herbaceous cover and grass height at age 4. Age 4 and 8 pine responses were positively correlated with several measures of non-woody competition cover at younger ages. These results imply that competition levels could be used to develop treatment thresholds, and soils could be used to guide treatment decisions.

1. Introduction

Loblolly pine is an ecologically and economically important tree species in the southeastern United States. Its importance has led to the development of many silviculture practices to increase growth and production rates. Typical silvicultural practices used on loblolly pine plantations in the southeastern United States are fertilization and controlling competing vegetation. Several studies have shown that these treatments are effective ways to increase individual tree growth and whole stand production but it is not well understood how site factors affect the response to these treatments (Tiarks and Haywood 1986, Borders and Bailey 2001, Jokela et al. 2004).

Fertilization is used to minimize the effect of nutrient limitations and is often needed more than once in a rotation (Fox et al. 2007). The response to fertilization can vary from site to site depending on soil or initial nutrient status of the site (Tiarks and Haywood 1986, Jokela 2004). Although these factors can be guides for predicting fertilization response, it is still difficult to accurately predict the response for a given site due to variability that can occur even within soil groupings (Jokela 2004).

Competing vegetation has an adverse effect on all important growth factors for loblolly pine including moisture, light and nutrient availability, and rooting volume (Martin and Shiver 2002). Controlling competing vegetation allows loblolly pine to capture the full potential of the site. Glover et al. (1989) found that the use of competition control can increase the expressed site index at age 12 of a lower quality site to the same level of a higher quality site not receiving competition control. The level of competing vegetation present on a site could be a factor in determining the magnitude of response to competing vegetation control (Jokela et al. 2000). The combination of complete vegetation control and annual fertilization has been shown to yield very productive loblolly pine stands on appropriate sites (Borders and Bailey 2001).

The Plantation Management Research Cooperative (PMRC) established a Culture x Density Study to examine the effects of cultural intensity and planting density on loblolly pine plantation performance in the Upper Coastal Plain and Piedmont. At age 12, intensive culture increased average DBH, height and dominant height, basal area per acre, volume per acre, green and dry weight per acre across planting densities while increased planting density resulted in lower average DBH, height and crown length, but increased basal area per acre, volume per acre, total stem green and dry weight per acre (Zhao and Kane 2010).

The research reported here strives to provide a better understanding of the processes that drive loblolly pine growth response to intensive culture in the Upper Coastal Plain and Piedmont. The increased knowledge will allow managers to make more informed decisions when deciding how to manage plantations of loblolly pine in these regions. The objective of this research was to determine how soil attributes, base site productivity, and competing vegetation level were related to growth response to intensive culture in the Plantation Management Research Cooperative's (PMRC) Culture x Density Study. An additional objective was to examine soils and their relation to growth attributes on operational culture plots. Hypotheses tested include:

1. Growth on operational plots will vary depending on soil class and soil attributes.
2. Different soil classes will show varying levels of response to intensive culture.
3. The response to intensive culture will decrease as site index under operational culture increases.
4. Increased competing vegetation as indicated by levels under operational culture will result in larger growth response to intensive culture.

2. Methods

2.1 Study Sites and Treatments

Twenty installations located in the Upper Coastal Plain and Piedmont of Alabama, Georgia, and South Carolina that were a part of the PMRC Culture x Density Study were examined (Table 3.1). The study originally contained 23 installations but three installations were not active at age 12. The sites were planted in 1998 or 1999 with open-pollinated bare-root seedlings chosen by the PMRC cooperator who owned the site. The trees were double planted to insure adequate survival and to make sure target planting density was met. Planting locations were reduced to one seedling at the end of the first growing season. The study was a split plot design with the main plots receiving one of two cultural intensities: operational or intensive (Table 3.2). Both intensities included broadcast chemical site prep, tillage at some installations, fertilization and banded herbaceous weed control at time of planting. The intensive plots received continued complete competing vegetation control and fertilization almost every other year. The operational plots received fertilization in the 8th and 12th growing seasons with no further competing vegetation control. Within each main plot were six sub-plots of different planting densities: 300, 600, 900, 1200, 1500, and 1800 trees per acre (tpa). Plot size varied among each planting density (Table 3.3). Each measurement plot was surrounded by a buffer of 26 feet to form the gross plot. The study focused on the 600 tpa planting density to reduce the effects of density dependent stand development on variability in response to intensive culture.

2.2 Soil Classification

Soil information was obtained from the USDA – NRCS Soil Survey. To check the accuracy of the soil survey, soils were field checked on ten sites. Two soil profiles were examined at each site field checked. It was concluded that the soil survey was accurate at placing soils into the appropriate soil class. Each site was classified in several ways according to its soil properties including a study specific classification system, depth to the argillic horizon (Bt), subsoil texture, and drainage class. The study specific classification system included four classes (Table 3.4). The depth to the Bt and subsoil texture was assumed to be the value for the standard NRCS soil series classification. Subsoil textures were assigned values ranging from 1 to 6 with 1 being the coarsest texture and 6 being the finest texture. There were two installations with sandy subsoil texture (class 1), one with sandy loam texture (class 2), two with silty clay loam texture (class 3), two with loam texture (class 4), five with sandy clay loam texture (class 5), and eight with clay texture (class 6). A similar system was used when assigning values to drainage class, with values ranging from 1 for excessively drained soils to 4 for somewhat poorly drained soils. There were two installations in the excessively drained class (class 1), 16 in the well drained class (class 2), one in the moderately well drained class (class 3) and one in the somewhat poorly drained class (class 4).

2.3 Stem and Stand measurements

Tree measurements were conducted every two years beginning with age 2. DBH was measured on all trees within the measurement plot and height was measured on every other tree. For trees not measured for height an equation in the form of $\ln(\text{height}) = \beta 0 + \beta 1\ \text{DBH}^{-1}$ was used to predict height for each plot and measurement period. Total standing stem volume of living trees was calculated using a volume equation from Pienaar et al. (1987). Response for a given installation was calculated as the attribute (mean DBH, mean height, basal area per acre, volume per acre) value for the intensive culture minus the attribute value for the operational culture for a given age.

2.3 Site Index

Dominant height was calculated as the mean of defect free trees with height measurements and DBH greater than the average DBH. Site index was calculated using age 12 dominant height on the operational culture 600 planting density plots for each installation and the site index equation from Borders et al. (2004).

2.4 Competing Vegetation Assessments

Competing vegetation was assessed only on the operational plots only since the intensive culture plots had complete competition control. Each measurement plot contained competing vegetation subplots representing 4 to 5 percent of the total measurement area. Each subplot was marked with a 2' pipe around which a 4 foot radius circular plot was established. All vegetation within each sub-plot was assessed. Depending on plot size, there were 9 to 20 subplots in a measurement plot. Competing vegetation was classified into two main classes: herbaceous or woody. Herbaceous material was further classified as andropogon grasses (*Andropogon* sp.), other grasses and broadleaf vegetation. For each category of herbaceous vegetation, percent coverage was estimated and heights were measured to obtain mean height. The woody vegetation was classified into small and large woody categories. Small woody vegetation was less than 1.6 in. DBH and/or shorter than 4.5 feet. Large woody material was greater than 1.6 in. DBH and taller than 4.5 feet. Attributes measured for small woody material included height, crown length, average crown width, and number of rootstocks. Large woody material measurements included DBH, height, height to live crown, and average crown width. Measurements were taken every two years with data available for the present study through age 8. Small woody sum height and small woody sum crown height was the sum of the total height and crown length, respectively of the small woody material on the plot. Small woody crown area was estimated using the following formula: crown area in ft^2=(crown width/2)^2 x π. Small woody crown volume was calculated using the following formula: crown volume in ft^3= crown area* crown length. The large woody bole volume was calculated as an index using the following formula: bole volume in $ft^3 = (dbh/24)^2 * \pi *$bole height. Large woody crown volume was calculated using the formula: crown volume in ft^3 = (crown width/2)* π*(total height-bole height).

2.5 Statistical Analysis

The effects of soil class on mean DBH, mean height, basal area per acre and volume per acre with operational culture and the response of these attributes to intensive culture were analyzed using an analysis of variation (ANOVA) test. The GLM procedure in the SAS (version 9.3 SAS Institute Inc. Cary North Carolina) operating system was used to perform the ANOVA and significance with a $\alpha \leq 0.10$ was noted. Fishers LSD test was used to determine least square means comparison of significant effects. Prior to statistical analysis it was determined that response attributes were normally distributed using the Shapiro Wilk test. Linear relationships between the response magnitude at plantation ages 4, 8, and 12 years and depth to Bt, and subsoil texture were examined using Pearson correlations. The response and drainage class relationship was not evaluated because the great majority of soils evaluated were well drained. The relationship between expressed site index on the operational plots and growth response to intensive culture was analyzed with a simple regression using the REG procedure in SAS. Pearson correlations were used to determine linear relationships between growth response measures at ages 8 and 12 years and competition measures at ages 2, 4 and 8 years and response measures at age 4 and competition measures at ages 2 and 4. Only six of the 20 installations had large woody competitors at age 8. Correlations between response and large woody attributes were performed but did not provide any insights due to the general absence of this competition class.

3. Results

3.1 Tree and Stand Attributes Under Operational Culture and Response to Intensive Culture

Statistics for loblolly pine mean DBH, mean height, basal area per acre and volume per acre for intensive and operational culture are presented in Table 3.5. The operational culture plots averaged 6.9 in. in DBH, 47 feet in height, 146 ft^2/acre in basal area, and 3256 ft^3/acre in volume. Statistics for loblolly pine response to intensive culture at ages 4, 8, and 12 years are presented in Table 3.6. Pronounced positive mean responses were apparent during the age 4 to 12 period. The age 12 response to intensive culture averaged 0.6 in. in DBH, 3.5 feet in mean height, 24 ft^2/acre in basal area, and 762 ft^3/acre in volume. Volume growth response was highly variable ranging from -644 ft^3/acre to 1665 ft^3/acre. Two study sites exhibited no or negative growth response to intensive culture.

3.2 Soil Effects on Stand Attributes for Operational Culture and Response to Intensive Culture at Age12

Age 12 stand attributes on the operational culture plots with the exception of survival differed significantly among soil classes (Table 3.7). Mean DBH, basal area per acre and volume per acre were all significantly lower for the Upper Coastal Plain soils with > 40 in. to the argillic horizon than for other soil classes (Table 3.8). Mean height was significantly lower for this soil class and Piedmont non-kaolinitic mineralogy soils as compared with the other two soil classes. Survival on the Upper Coastal Plain soils with < 20 inches to the argllic horizon (84%) was substantially lower than survival on the other soil classes (94% to 100%).

Although differences in response attributes were not statistically significant (Table 3.9) observed response values were consistently greater for Upper Coastal Plain soils with > 40 in. to the argillic horizon and least for Piedmont soils with kaolinitic mineralogy (Table 3.9). Mean separation test suggests the difference in height response between these two soils was significant.

There were no strong significant linear relationships between age 12 response attributes and depth to the Bt horizon, or subsoil texture (Table 3.10). There was a trend of increased dominant height response with greater depth to the Bt($p=0.11$) and with coarser subsoil texture ($p=0.12$).

3.3Base Site Productivity

Expressed operational culture site index ranged from 75 feet to 95 (Table 3.1). A simple linear regression between operational culture site index and volume growth response showed no correlation ($R^2 = 0.03$ p-value= 0.40). Although not significant, response tended to decrease as site index increased (Figure 3.1).

3.4 Competition Levels and Age 12, 8 and 4 Year Responses

3.4.1 Competing Vegetation Levels

There was a wide range of competing vegetation levels on the operationally managed plots (Table 3.11). Percent andropogon per acre and percent grass per acre decreased from age 2 to 8 years while percent broadleaf cover had a small increase. Small woody competition measures increased from age 2 to 8 years. The range for all competing vegetation measures was considerable. Large woody bole volume averaged 4.05 ft^3/acre and ranged from 0 to 26 ft^3/acre. Large woody crown volume averaged 9135 ft^3/acre and ranged from 0 to 45376 ft^3/acre. Basal area of large woody competition averaged 1.2 ft^2/ acre and ranged from 0 to 8.7 ft^2/acre. Number of large woody stems per acre averaged 38.5 and ranged from 0 to 193 stems per acre.

3.4.2 Age 12 Pine Response

Correlations were not significant at (p=0.10) between age 2 competition values and age 12 response (Table 3.12). A negative trend (p=0.12) between loblolly pine height response to intensive culture and percent cover of andropogon was evident.

There were a number of significant correlations between age 12 pine response to intensive culture and competing vegetation attributes on the operational plots at ages 4 or 8. Age 12 pine response was generally positively correlated with age 4 percent grass cover and grass height on operational culture plots (Table 3.13). Height response was positively correlated with percent broadleaf cover and percent herbaceous cover. Basal area and volume response were negatively associated with broadleaf and herbaceous mean height on operational culture plots. Measures of woody competition at age 4 were not strongly correlated with age 12 pine response variables.

Age 12 height response was significantly correlated with several measures of competing vegetation at age 8 (Table 3.14). Basal area response at age 12 was positively correlated with age 8 percent andropogon, percent herbaceous, and the sum of small woody crown height. Pine volume response at age 12 was positively correlated with percent andropogon, mean andropogon height, percent broadleaf, and percent herbaceous. Pine volume response also tended to increase as the sum of small woody competition heights and the sum of crown heights increased on operational culture plots.

3.4.3 Age 8 Pine Response

The only significant correlation between age 8 growth response and age 2 competition values was a trend of increased dominant height response to increased sum of small woody competition height on operational plots (Table 3.15). There were consistent trends of greater age

8 loblolly pine response with increasing age 4 mean grass height and decreasing mean broadleaf or mean herbaceous height (Table 3.16). There was also a generally consistent trend of greater age 8 loblolly pine response with increasing percent cover of grasses, broadleaf or herbaceous competitors on operational plots at age 4. Small woody competition at age 4 was not significantly correlated with age 8 loblolly pine response. The most consistent significant trends between age 8 pine response and age 8 competition values were increasing pine response with increasing percent broadleaf or percent herbaceous cover on the operational plots (Table 3.17). There were positive correlations between height response and measures of small woody competition.

3.4.4 Age 4 Pine Response

The most consistent relationship between age 4 pine response and age 2 competition values were positive relationships between response measures and percent herbaceous cover at age 2 on the operational plots (Table 3.18). Similar trends with response were found with percent grass, percent broadleaf or mean andropogon height at age 2.

The relationship between age 4 response and age 4 competition values were similar to those for age 8 response with age 8 competition. There were consistent trends of greater age 4 response with increasing age 4 mean grass height and decreasing age 4 mean broadleaf or mean herbaceous height (Table 3.19). Response increased as percent cover of broadleaf or herbaceous competition increased. No significant relationships between small woody competition at age 4 and age 4 pine response was observed.

4. Discussion

Age 12 was an appropriate time to evaluate soils, site index, and competing vegetation relationships with pine performance on the 600 tpa planting density because the stands had not encountered significant mortality from overcrowding. Zhao and Kane (2010) reported basal area per acre for this study to be entering the range of 120 to 150 ft^2/acre as reported by Jokela et al. (2004) where density related competition becomes significant.

Growth on the operational culture plots was significantly affected by soil class. The Upper Coastal Plain soils with >40 inches to the argillic horizon had lower performance in most attributes as compared to the other soil classes. This may be attributed to the fact that these soils are inherently less fertile and are unable to support the nutrient demand of the trees (Allen 1987, Fox et al. 2007).

Soil class did not have a statistically significant effect on loblolly pine mean DBH or volume per acre response, although observed responses were greatest for Upper Coastal Plain soils with > 40 in. to the argillic horizon. Height and basal area response were significantly larger (p=0.10, p=0.11 respectively) on this soil class. Mean survival was lowest on the Upper Coastal Plain soils with < 20 inches to the argillic. One site within this soil class (Installation 21) had extremely low survival (42%) on the operational culture 600 tpa plot. The average survival for this soil class without this site was 89%; only slightly lower than mean survival on other soil classes. Research in the Lower Coastal Plain confirmed that pine plantation responses to cultural treatment vary with soil class. Fisher and Garbett (1980) found that the CRIFF soil classification system proved useful in characterizing Lower Coastal Plain soils for loblolly and slash pine response to fertilization. Harrison and Kane (2008) reported significant soil class effects on loblolly pine performance as did Zhao et al. (2007) for slash pine.

Pine response tended to increase as the subsoil texture became coarser or depth to the Bt increased but the correlations were low. The relationships between height response at age 12 and subsoil texture or depth to Bt were the strongest correlations (p=.12).

Other soil classification approaches may prove better predictors for pine growth and response to cultural intensity. Also, incorporating measures of soil moisture and rainfall records could provide additional insight into pine growth response. There were uneven numbers of sites in the various soil classes with some classes only having one or two installations. A larger sample size may allow for subtle differences to become more apparent. Also the response measured here was to an increase of an already intensive culture. The high level of operational culture may have masked response possibly apparent using a lower intensity operational culture as a base

Expressed site index on the operational plots did not provide a strong prediction of volume growth response to intensive culture. The two levels culture each provided significant resources to the planted pine and reduced the potential effect of native site differences. The operational cultural regime used in this study provided good competition control and nutrition; therefore sites were very productive even under operational culture. There was a weak non-significant trend of pine response decreasing as site index increased. This pattern could be expected because sites with the higher base productivity would require fewer inputs to obtain and sustain maximum growth. Scott et al. (2004) found that site index was a useful predictor of determining nutrient status of a site since they were able to relate it to the decreased growth on sites that had more intensive harvest.

Most of the competing vegetation measures were not strongly correlated with loblolly pine growth response at ages 12, 8 or 4 years. Small woody competition was correlated with pine height response at multiple age combinations. Percent cover of grass, andropogon or herbaceous competition was positively correlated with pine response. When examined across multiple pine response ages of 4, 8, and 12 the positive correlation between mean grass height at age 4 and pine volume response increased with increasing pine age (Pine age 4: $r = 0.41$ and $p = 0.08$; Pine age 8: $r = 0.47$ and $p = 0.04$; Pine age12: $r = 0.55$ and $p = 0.02$). This indicates that complete sustained competition control continues to provide benefits to the stand. Other studies have found relationships between competing vegetation levels and the growth of loblolly pine (Miller et al 2003, Jokela et al 2000). Harrison and Shiver (2006) found that the growth response of loblolly pine to competing vegetation control in the Piedmont and Upper Coastal Plain was highly variable and even negative at times with gains in basal area averaging 9 ft^2/ac at age 15.

Only linear associations between pine response and competing vegetation measures were examined. Simple correlations were evaluated to identify the relationships between growth response and competition attributes.

This research can be used by managers to make stronger site specific silvicultural plans. Since there is some evidence that Upper Coastal Plain soils with > 40 inches to the argllic horizon tend to have greater growth responses to intensive culture, managers can evaluate if use of intensive culture on these sites helps meet objectives. Knowing that the percent cover of grass at age 4 is correlated with growth response at age 12 will allow managers to target sites with greater cover of competing vegetation. Understanding that sum of small woody height and sum of small woody crown height on plantations provides an indicator of growth response potential and might be incorporated into guideline development for early release treatments.

5. Conclusions

The results from this study provide insights into productivity of loblolly pine plantations established at 600 trees per acre in the Upper Coastal Plain and Piedmont through age 12. Loblolly pine plantation performance with operational culture and response to intensive culture varied significantly among soil classes. Age 12 survival for operational culture tended to be lower on Upper Coastal Plain sites with < 20 inches to the argillic horizon. Mean tree size tended to be less on Upper Coastal Plain sites with > 40 inches to the argillic horizon than on the other soil classes. This soil class tended to exhibit the greatest observed response to intensive culture although differences among soil classes were only significant for height. Most observed responses to intensive culture tended to be smallest on Piedmont sites with kaolinitic mineralogy. Specific soil attributes of depth to Bt and subsoil texture were not strongly related to pine response to intensive culture. Pine response tended to increase as subsoil texture became coarser and depth to the Bt increased but the correlations were weak. Pine response to intensive culture was not significantly related to expressed site index under operational culture.

Age 12 pine response was positively correlated with operational plot measures of small woody competition at age 8 and percent grass, broadleaf or herbaceous cover, and mean grass height at age 4. Competition measures at age 2 were generally not significantly correlated with age 12 pine response. Age 4 and 8 pine responses were positively correlated with several measures of non-woody cover at younger ages.

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Table 3.1. Location, soil information, and site index on operational plots planted at 600 trees per acre for 20 installations of the PMRC Culture x Density Study located in the Upper Coastal Plain and Piedmont.

Installation	Location	Physiographic Province	Soil Series	Soil Taxonomy	Site Index*
1	Hancock Co., Ga	Upper Coastal Plain	Bonifay/Cowarts	Loamy, siliceous, subactive, thermic Grossarenic Plinthic Paleudults	79
2	Baldwin Co, Al	Upper Coastal Plain	Lakeland	Thermic, coated Typic Quartzipsamments	79
3	Escambia Co., Al	Upper Coastal Plain	Freemanville	Fine, kaolinitic, thermic Plinthic Kandiudults	85
4	Escambia Co., Al	Upper Coastal Plain	Orangeburg	Fine-loamy, kaolinitic, thermic Typic Kandiudults	89
5	Harris Co., Ga	Piedmont	Lloyd	Fine, kaolinitic, thermic Rhodic Kanhapludults	95
6	Marion Co., Ga	Upper Coastal Plain	Lakeland	Thermic, coated Typic Quartzipsamments	75
8	Laurens Co., SC	Piedmont	Cecil	Fine, kaolinitic, thermic Typic Kanhapludults	86
9	Monroe Co., Al	Upper Coastal Plain	Bama - Malbis	Fine-loamy, siliceous, subactive, thermic Typic Paleudults	85
11	Greene Co, Ga	Piedmont	Cecil	Fine, kaolinitic, thermic Typic Kanhapludults	87
12	Barbour Co, Al	Upper Coastal Plain	Orangeburg - Springhill	Fine-loamy, kaolinitic, thermic Typic Kandiudults	94
13	Jasper Co, Ga	Piedmont	Lloyd - Pacolet	Fine, kaolinitic, thermic Rhodic Kanhapludults	88
15	Talladega Co., Al	Piedmont	Decatur - Tupelo	Fine, kaolinitic, thermic Rhodic Paleudults	85
16	St. Clair Co, Al	Piedmont	Conasauga and Firestone	Very-fine, mixed, active, thermic Chromic Vertic Hapludalfs	76
17	Harolson Co., Ga	Piedmont	Grover	Fine-loamy, micaceous, thermic Typic Hapludults	86
18	Chatooga Co., Ga	Piedmont	Fullerton	Fine, kaolinitic, thermic Typic Paleudults	83
19	Perry Co., MS	Upper Coastal Plain	Susquehanna/Freest	Fine, smectitic, thermic Vertic Paleudalfs	93
20	McCulloch, Al	Upper Coastal Plain	Benndale	Coarse-loamy, siliceous, semiactive, thermic Typic Paleudults	90
21	Burke Co. Ga	Upper Coastal Plain	Tifton	Fine-loamy, kaolinitic, thermic Plinthic Kandiudults	91
22	Burke Co. Ga	Upper Coastal Plain	Tifton	Fine-loamy, kaolinitic, thermic Plinthic Kandiudults	93
23	Clarke Co. Al	Upper Coastal Plain	Okeelala - Brantley	Fine-loamy, siliceous, semiactive, thermic Ultic Hapludalfs	87

*Based on age 12 dominant height on plots with operational culture and 600 tpa planting density

Table 3.2. Description of operational and intensive cultures in the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.

Treatment	Growing season	Operational Culture	Intensive Culture
Site prep		Tillage including subsoiling on some sites	Tillage including subsoiling on some sites
		Broadcast chemical site preparation	Broadcast chemical site preparation
Competition control	1st year	4 oz/ac sulfometuron methyl Banded + direct spraying of glyphosate and triclopyr for hardwood control	4 oz/ac sulfometuron methyl broadcast + direct spraying of glyphosate and triclopyr for complete control
	2nd		12 oz/ac imazapyr broadcast
	3rd-12th		Repeated direct spraying of glyphosate and triclopyr for complete control
Fertilization	At Planting	500 lbs of 10-10-10 per acre	500 lbs of 10-10-10 per acre
	2nd		-600 lbs of 10-10-10 per acre + 117 lbs of NH_4NO_3 per acre + micronutrients
	4th		117 lbs of NH_4NO_3 per acre
	6th		300 lbs of NH_4NO_3 per acre
	8th	200 lbs N + 25 lbs P per acre	200 lbs N + 25 lbs P per acre
	10th		200 lbs N + 25 lbs P per acre
	12th	200 lbs N + 25 lbs P per acre	200 lbs N + 25 lbs P per acre

Table 3.3. Spacing and plot size for different planting densities in the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.

Planting Density	Orginal Spacing	Measurement Plot Size	Gross Plot Size
Trees/ac	(ft x ft)	(ac)	(ac)
300	12 x 12	0.26	0.56
600	8 x 9	0.13	0.37
900	8 x 6	0.11	0.31
1200	6 x 6	0.10	0.30
1500	6 x 4.8	0.11	0.32
1800	6 x 4	0.10	0.31

Table 3.4. Soil classes, installations per class, and individual installation soil class for the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.

Soil Class	Installations per Class	Installations in Class
Piedmont, Non-kaolintic subsoil	2	16,17
Piedmont, Kaolinitic subsoil	6	5,8,11,13,15,18
Upper Coastal Plain, Argillic < 20"	9	3,4,9,12,19,20,21,22,23
Upper Coastal Plain, Argillic > 40"	3	1,2,6

*See Table 3.1 for installation details.

Table 3.5. Summary statistics for loblolly pine age 12 mean DBH, mean height, basal area per acre and volume per acre for intensive culture and operational culture, at the 600 trees per acre planting density for 20 study locations in the Piedmont and Upper Coastal Plain.

Culture	Attribute	Mean	Std. Dev.	Range
Intensive	DBH (in)	7.5	0.6	5.9 - 8.3
	Height (ft)	50	4	41 - 57
	BA(ft^2/ac)	170	23	111 - 215
	Volume (ft^3/ac)	4018	715	2286 - 5169
	Survival (%)	89	9	73 -100
Operational	DBH (in)	6.9	0.7	5.6 - 8.9
	Height (ft)	47	4	39 - 53
	BA(ft^2/ac)	146	24	98 -187
	Volume (ft^3/ac)	3256	688	1878 - 4482
	Survival (%)	91	13	42-100

Table 3.6. Loblolly pine response to intensive culture at ages 4 , 8 and 12 years for mean DBH, mean height, basal area per acre and volume per acre for the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.

Attribute	Age 4			Age 8			Age 12		
	Mean	Std. Dev.	Range	Mean	Std. Dev.	Range	Mean	Std. Dev.	Range
DBH (in)	1.1	0.48	-0.12 - 1.81	0.8	0.49	-0.44 - 1.6	0.6	0.69	-1.4-1.5
Height (ft)	3.5	2.1	-1.5 - 6.8	4.1	3.1	-2.6 - 8.7	3.7	3.7	-4.6 – 9.7
BA(ft^2/Ac)	21.4	10.7	-3.4 - 37.1	31.1	14.6	5.2 - 60.3	24.3	17.8	-15.7 - 53.5
Volume (ft^3/Ac)	235	142	-69 - 487	695	376	-71 - 1331	762	608	-644 - 1665
Survival (%)	4.4	13.3	-7.6 - 55	1.7	15.6	-2.3 - 54	-1.0	13.6	-2.3-34

Table 3.7. P-values for soil class effects on loblolly pine age 12 DBH, height, basal area per acre, volume per acre, and survival on operational culture plots and in response to intensive culture at a 600 tpa planting density.

	DBH (in)	Height (ft)	BA (ft^2/ac)	Volume (ft^3/ac)	Survival (%)
Operational	0.0179	0.0016	0.0024	0.0071	0.1871
Response	0.6802	0.3682	0.2936	0.4596	0.9205

Table 3.8. Mean and standard error for loblolly pine age 12 mean DBH, mean height, basal area per acre, volume per acre and survival on operational plots with 600 tpa planting density by soil class in the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.

	DBH (in)		Height (ft)		BA (ft^2/ac)		Volume (ft^3/ac)		Survival (%)	
Soil Class	mean	S.E.	mean	S.E.	mean	S.E.	Mean	S.E.	mean	S.E.
Piedmont, Non-kaolinitic mineralogy	6.9a	0.4	43.3b	2.1	161.2ab	12.0	3337.7a	367.5	100.0a	8.6
Piedmont, kaolinitic mineralogy	7.3a	0.2	48.1a	1.2	165.8a	6.9	3734.3a	212.2	94.2a	5.0
Upper Coastal Plain, Argillic < 20"	7.1a	0.2	48.8a	1.0	140.9b	5.6	3269.4a	173.2	84.2b	4.0
Upper Coastal Plain, Argillic > 40"	5.8b	0.3	39.7b	1.7	112.2c	9.8	2208.0b	300.1	97.4a	7.0

*Means within a column not followed by a common letter are significantly different at $\alpha \leq 0.10$.

Table 3.9. Mean age 12 loblolly pine response to intensive culture for mean DBH, mean height, basal area per acre, volume per acre, and survival for the 600 tpa planting density by soil class for the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.*

	DBH (in)		Height (ft)		BA (ft^2/ac)		Volume (ft^3/ac)		Survival (%)	
Soil Class	mean	S.E.	mean	S.E.	mean	S.E.	mean	S.E.	Mean	S.E.
Piedmont, Non-kaolinitic mineralogy	0.7a	0.5	4.5a	2.5	30.9a	12.2	943.1a	433.2	-0.6a	10
Piedmont, kaolinitic mineralogy	0.4a	0.3	1.9b	1.5	12.9a	7.1	434.4a	250.1	-2.4a	6
Upper Coastal Plain, Argillic < 20"	0.6a	0.2	3.8ab	1.2	27.3a	5.8	844.3a	204.2	1.1a	4.8
Upper Coastal Plain, Argillic > 40"	1.0a	0.4	6.5a	2.0	33.8a	10	1050.9a	353.7	-5.1a	8.4

*Means within a column not followed by a common letter are significantly different at $\alpha \leq 0.10$.

Table 3.10. Results for Pearson correlations of soil attributes with loblolly pine age 4, 8 and 12 mean DBH, mean height, mean dominant height, basal area per acre and volume per acre response for a 600 tpa planting density on the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.*

		Age 4		Age 8		Age 12	
Attribute	Statistic	Depth to BT	Subsoil Texture	Depth to BT	Subsoil Texture	Depth to BT	Subsoil Texture
DBH	r	0.0419	-0.0070	0.2361	-0.2696	0.2263	-0.3026
	p-value	0.8609	0.9766	0.3163	0.2503	0.3374	0.1948
Height	r	0.1003	-0.0477	0.3240	-0.3023	0.3569	-0.2946
	p-value	0.6739	0.8417	0.1635	0.1952	**0.1224**	0.2073
Dom. Height	r	0.0930	-0.0533	0.2541	-0.2511	0.3778	-0.3606
	p-value	0.6967	0.8235	0.2796	0.2855	**0.1005**	**0.1183**
BA	r	-0.0764	0.0608	0.0341	0.0549	0.2613	-0.2739
	p-value	0.749	0.7989	0.8865	0.8182	0.2658	0.2425
TVOB	r	-0.099	0.109	0.053	0.003	0.242	-0.229
	p-value	0.678	0.6474	0.8257	0.9889	0.3045	0.3325

*Values in bold indicate significance at α=0.10

Table 3.11. Competing vegetation at ages 2, 4, and 8 years with operational culture and 600 tpa planting density on the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.

	Age 2			Age 4			Age 8		
Attribute	Mean	Std. Dev.	Range	Mean	Std. Dev.	Range	Mean	Std. Dev.	Range
Percent Andropogon Cover	8	9.6	0 - 34	22	20.2	0 - 62.2	2	3.2	0 - 13
Mean Andropogon Height (ft)	1.3	1.1	0 - 3.3	1.9	1.1	0 - 4.5	0.4	0.5	0 - 2.4
Percent Grass Cover per acre	22	17.3	1 - 63	15	13.2	0 - 52.8	7	5.7	0 - 24
Mean Grass Height (ft)	0.6	0.4	0.1 - 2.2	2.3	0.3	0 - 0.8	3.5	0.2	0 - 0.9
Percent Broadleaf Cover per Acre	37	15.8	17 - 69	41	18.0	4 - 79	42	15.7	4 - 72
Mean Broadleaf Height (ft)	1.9	0.7	0.6 - 3.6	2.7	0.6	1.6 - 3.6	1.9	0.7	0.4 -3.5
Percent Herbaceous Cover per Acre	66	22.7	22 - 89	78	21.3	7 - 94	51	16.7	7 - 77
Mean Herbaceous Height (ft)	1.5	0.4	0.9 - 2.4	2.3	0.7	1.2 - 3.7	1.4	0.5	0.5 - 2.4
Small Woody Sum Height (ft)	1349	1772	0 - 6113	2060	2486	0 - 8245	4690	4294	0 - 15,495
Small Woody Sum Crown Height (ft)	864	1161	0 - 4281	1543	2062	0 - 7550	3524	3432	0 - 13,158
Small Woody Crown Area (ft^2/acre)	743	1092	0 - 4263	1829	3007	0 - 10,714	4468	7376	0 - 33,720
Small Woody Crown Volume per Acre (ft^3/acre)	2415	3961	0 - 14,540	13035	23663	0 - 76,632	36441	71996	0 - 328,307
Small Woody Stem Count (Stems per Acre)	568	824	0 - 3178	481	564	0 - 2118	1088	896	0 - 2985

Table 3.12. Results for Pearson correlations between age 12 loblolly pine response to intensive culture and age 2 competing vegetation values on operational culture plots in the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.*

Attribute		Percent Andropogon	Mean Andropogon Ht	Percent Grass per acre	Mean Grass Height	Percent Broadleaf per Acre	Mean Broadleaf Height	Percent Herbaceous per Acre	Mean Herbaceous Height	Small Woody Sum Height	Small Woody Sum Crown Height	Small Woody Crown Area	Small Woody Crown Volume	Small Woody Stem Count per Acre
DBH	r	-0.329	-0.049	0.001	0.044	0.140	-0.055	-0.041	-0.108	0.247	0.185	0.098	0.087	0.286
	p-value	0.156	0.839	0.997	0.855	0.557	0.818	0.865	0.651	0.293	0.434	0.682	0.716	0.222
Height	r	-0.363	0.148	0.188	0.045	0.235	-0.018	0.154	0.067	0.321	0.260	0.144	0.150	0.331
	p-value	**0.116**	0.533	0.428	0.852	0.319	0.941	0.517	0.781	0.168	0.268	0.544	0.528	0.154
Dom. Height	r	-0.362	0.129	0.193	0.017	0.255	0.055	0.172	0.124	0.269	0.254	0.176	0.199	0.285
	p-value	**0.116**	0.587	0.415	0.944	0.278	0.818	0.468	0.604	0.251	0.280	0.458	0.400	0.223
BA	r	-0.231	0.253	0.171	0.020	0.313	0.090	0.251	0.153	0.184	0.132	0.098	0.132	0.135
	p-value	0.328	0.282	0.471	0.934	0.180	0.707	0.286	0.519	0.437	0.579	0.681	0.578	0.571
Volume	r	-0.268	0.231	0.183	0.022	0.325	0.069	0.253	0.148	0.219	0.164	0.123	0.160	0.169
	p-value	0.254	0.327	0.439	0.926	0.162	0.773	0.281	0.532	0.353	0.490	0.605	0.500	0.476

*Values in bold indicate significance at α=0.10

Table 3.13. Results for Pearson correlations between age 12 loblolly pine response to intensive culture and age 4 competing vegetation on operational plots in the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.*

Attribute		Percent Andropogon	Mean Andropogon Ht	Percent Grass per acre	Mean Grass Height	Percent Broadleaf per Acre	Mean Broadleaf Height	Percent Herbaceous per Acre	Mean Herbaceous Height	Small Woody Sum Height	Small Woody Sum Crown Height	Small Woody Crown Area	Small Woody Crown Volume	Small Woody Stem Count per Acre
DBH	r	-0.359	-0.111	0.251	0.415	0.328	-0.254	0.093	-0.333	0.158	0.121	-0.003	-0.074	0.181
	p-value	0.121	0.641	0.286	**0.069**	0.159	0.281	0.696	0.152	0.506	0.610	0.989	0.758	0.446
Height	r	-0.294	-0.003	0.439	0.545	0.374	-0.478	0.311	-0.439	0.268	0.254	0.111	0.003	0.333
	p-value	0.209	0.99	**0.053**	**0.013**	**0.104**	**0.033**	0.182	**0.053**	0.253	0.280	0.642	0.990	0.152
Dom. Height	r	-0.259	0.042	0.432	0.498	0.399	-0.399	0.360	-0.336	0.241	0.251	0.091	0.003	0.282
	p-value	0.27	0.86	**0.057**	**0.025**	**0.082**	**0.081**	0.119	0.148	0.307	0.286	0.703	0.989	0.229
BA	r	-0.187	0.069	0.514	0.609	0.230	-0.486	0.337	-0.533	0.242	0.224	0.213	0.103	0.307
	p-value	0.43	0.771	**0.02**	**0.004**	0.329	**0.03**	**0.147**	**0.016**	0.304	0.343	0.367	0.665	0.188
Volume	r	-0.206	0.060	0.467	0.551	0.308	-0.464	0.355	-0.461	0.220	0.208	0.169	0.069	0.274
	p-value	0.383	0.803	**0.038**	**0.012**	0.186	**0.039**	**0.124**	**0.041**	0.352	0.378	0.477	0.772	0.243

*Values in bold indicate significance at α=0.10

Table 3.14. Results for Pearson correlations between age 12 loblolly pine response and age 8 competing vegetation on operational plots in the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.*

Attribute		Percent Andropogon	Mean Andropogon Ht	Percent Grass per acre	Mean Grass Height	Percent Broadleaf per Acre	Mean Broadleaf Height	Percent Herbaceous per Acre	Mean Herbaceous Height	Small Woody Sum Height	Small Woody Sum Crown Height	Small Woody Crown Area	Small Woody Crown Volume	Small Woody Stem Count	Large Woody Bole Vol	Large Woody Crown Volume	Large Woody Basal Area	Large Woody Stem Count
DBH	r	0.157	0.080	-0.499	-0.156	0.365	0.107	0.203	0.128	0.088	0.143	0.140	0.161	0.090	-0.096	-0.092	-0.095	-0.025
	p-value	0.508	0.737	0.025	0.510	0.114	0.652	0.390	0.591	0.713	0.547	0.556	0.499	0.707	0.687	0.700	0.692	0.918
Height	r	0.415	0.376	-0.072	0.181	0.437	0.285	0.465	0.261	0.452	0.462	0.324	0.300	0.411	-0.052	-0.131	-0.089	0.071
	p-value	**0.069**	**0.103**	0.764	0.445	**0.054**	0.224	**0.039**	0.267	**0.046**	**0.040**	0.164	0.199	**0.072**	0.829	0.581	0.709	0.767
Dom. Height	r	0.397	0.389	-0.092	0.098	0.485	0.347	0.500	0.357	0.396	0.403	0.270	0.245	0.370	-0.079	-0.161	-0.088	0.071
	p-value	**0.083**	**0.090**	0.700	0.681	**0.030**	**0.134**	**0.025**	**0.122**	**0.084**	**0.078**	0.250	0.297	**0.108**	0.740	0.497	0.712	0.765
BA	r	0.384	0.332	0.043	0.196	0.313	0.217	0.381	0.218	0.362	0.379	0.284	0.258	0.278	0.064	0.037	0.033	0.203
	p-value	**0.095**	0.153	0.856	0.408	0.180	0.359	**0.097**	0.356	0.117	**0.099**	0.225	0.271	0.235	0.789	0.877	0.889	0.390
Volume	r	0.359	0.332	0.031	0.204	0.350	0.274	0.407	0.264	0.360	0.367	0.245	0.218	0.287	0.049	-0.005	0.008	0.191
	p-value	**0.121**	**0.153**	0.895	0.387	**0.131**	0.242	**0.075**	0.260	**0.119**	**0.111**	0.297	0.356	0.219	0.838	0.984	0.974	0.419

*Values in bold indicate significance at α=0.10

Table 3.15. Results for Pearson correlations between age 8 loblolly pine response and age 2 competing vegetation on operational culture plots in the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.*

Response		Percent Andropogon	Mean Andropogon Ht	Percent Grass per acre	Mean Grass Height	Percent Broadleaf per Acre	Mean Broadleaf Height	Percent Herbaceous per Acre	Mean Herbaceous Height	Small Woody Sum Height	Small Woody Sum Crown Height	Small Woody Crown Area	Small Woody Crown Volume	Small Woody Stem Count per Acre
DBH	r	-0.234	0.052	-0.018	-0.067	0.241	-0.069	0.056	-0.140	0.253	0.164	0.088	0.088	0.281
	p-value	0.321	0.828	0.940	0.777	0.306	0.773	0.815	0.557	0.282	0.491	0.711	0.714	0.230
Height	r	-0.291	0.091	0.168	-0.017	0.268	0.086	0.193	0.007	0.365	0.268	0.173	0.154	0.388
	p-value	0.214	0.702	0.478	0.942	0.254	0.719	0.416	0.976	**0.114**	0.253	0.467	0.516	0.091
Dom. Height	r	-0.255	0.042	0.191	-0.036	0.307	0.157	0.252	0.030	0.380	0.303	0.236	0.226	0.381
	p-value	0.277	0.862	0.42	0.879	0.187	0.509	0.284	0.899	**0.099**	0.194	0.317	0.337	0.098
BA	r	-0.007	0.324	0.257	0.028	0.245	-0.031	0.364	0.095	0.064	-0.033	-0.035	0.003	0.008
	p-value	0.978	0.163	0.273	0.908	0.298	0.898	0.115	0.692	0.790	0.889	0.884	0.989	0.974
TVOB	r	-0.100	0.276	0.264	0.036	0.271	0.000	0.348	0.082	0.166	0.049	0.036	0.067	0.110
	p-value	0.676	0.239	0.260	0.882	0.248	1.000	0.133	0.733	0.485	0.837	0.881	0.778	0.644

*Values in bold indicate significance at α=0.10

Table 3.16. Results for Pearson correlation between age 8 loblolly pine response and age 4 competing vegetation on operational culture plots in the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.*

Response		Percent Andropogon	Mean Andropogon Ht	Percent Grass per acre	Mean Grass Height	Percent Broadleaf per Acre	Mean Broadleaf Height	Percent Herbaceous per Acre	Mean Herbaceous Height	Small Woody Sum Height	Small Woody Sum Crown Height	Small Woody Crown Area	Small Woody Crown Volume	Small Woody Stem Count per Acre
DBH	r	-0.268	0.018	0.333	0.459	0.347	-0.334	0.246	-0.372	0.143	0.114	-0.016	-0.079	0.185
	p-value	0.253	0.939	0.151	**0.042**	**0.134**	**0.151**	0.296	**0.106**	0.548	0.631	0.947	0.741	0.434
Height	r	-0.254	0.058	0.463	0.592	0.370	-0.543	0.359	-0.500	0.352	0.322	0.135	-0.004	0.455
	p-value	0.279	0.807	**0.04**	**0.006**	**0.108**	**0.013**	**0.12**	**0.025**	0.128	0.166	0.570	0.985	0.044
Dom. Height	r	-0.227	0.061	0.495	0.569	0.407	-0.531	0.435	-0.457	0.355	0.335	0.168	0.049	0.434
	p-value	0.335	0.799	**0.027**	**0.009**	**0.075**	**0.016**	**0.056**	**0.043**	0.125	0.148	0.479	0.839	0.056
BA	r	0.067	0.265	0.438	0.447	0.060	-0.450	0.385	-0.382	0.009	-0.011	-0.016	-0.086	0.113
	p-value	0.778	0.260	**0.054**	**0.048**	0.803	**0.046**	**0.093**	**0.097**	0.971	0.963	0.946	0.718	0.637
TVOB	r	-0.006	0.236	0.418	0.473	0.180	-0.470	0.405	-0.395	0.061	0.033	-0.020	-0.107	0.163
	p-value	0.981	0.317	**0.067**	**0.035**	0.449	**0.036**	**0.076**	**0.085**	0.799	0.891	0.935	0.655	0.493

*Values in bold indicate significance at α=0.10

Table 3.17. Results for Pearson correlations between age 8 loblolly pine response and age 8 competing vegetation on operational culture plots in the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.*

Attribute		Percent Andropogon	Mean Andropogon Ht	Percent Grass per acre	Mean Grass Height	Percent Broadleaf per Acre	Mean Broadleaf Height	Percent Herbaceous per Acre	Mean Herbaceous Height	Small Woody Sum Height	Small Woody Sum Crown Height	Small Woody Crown Area	Small Woody Crown Volume	Small Woody Stem Count	Large Woody Bole Vol	Large Woody Crown Volume	Large Woody Basal Area	Large Woody Stem Count
DBH	r	0.198	0.121	-0.396	-0.073	0.556	0.383	0.427	0.341	0.108	0.152	0.135	0.152	0.049	-0.043	0.004	-0.029	0.017
	p-value	0.403	0.612	**0.084**	0.760	**0.011**	**0.095**	**0.061**	0.141	0.650	0.522	0.571	0.522	0.839	0.857	0.987	0.902	0.944
Height	r	0.295	0.197	-0.038	0.133	0.528	0.321	0.540	0.246	0.494	0.513	0.422	0.400	0.419	0.035	-0.052	0.001	0.092
	p-value	0.206	0.405	0.874	0.576	**0.017**	0.168	**0.014**	0.296	**0.027**	**0.021**	**0.064**	**0.080**	**0.066**	0.882	0.829	0.997	0.700
Dom. Height	r	0.206	0.147	-0.012	0.122	0.579	0.336	0.580	0.268	0.441	0.462	0.362	0.345	0.395	0.104	-0.011	0.060	0.163
	p-value	0.383	0.536	0.961	0.607	**0.008**	0.148	**0.007**	0.254	**0.052**	**0.040**	**0.116**	**0.137**	**0.085**	0.662	0.964	0.802	0.493
BA	r	0.319	0.326	0.413	0.411	0.303	0.302	0.486	0.206	0.280	0.240	0.130	0.089	0.192	0.059	0.032	-0.001	0.097
	p-value	0.171	0.161	0.071	0.072	0.195	0.195	0.030	0.383	0.232	0.309	0.584	0.709	0.419	0.805	0.894	0.996	0.684
Volume	r	0.283	0.282	0.307	0.350	0.353	0.294	0.491	0.203	0.298	0.265	0.151	0.113	0.218	0.090	0.022	0.014	0.121
	p-value	0.226	0.229	0.188	**0.131**	**0.127**	0.209	**0.028**	0.391	0.202	0.260	0.525	0.636	0.356	0.706	0.926	0.955	0.612

*Values in bold indicate significance at α=0.10

Table 3.18. Results for Pearson correlations between age 4 loblolly pine response and age 2 competing vegetation on operational culture plots in the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.*

Response		Percent Andropogon	Mean Andropogon Ht	Percent Grass per acre	Mean Grass Height	Percent Broadleaf per Acre	Mean Broadleaf Height	Percent Herbaceous per Acre	Mean Herbaceous Height	Small Woody Sum Height	Small Woody Sum Crown Height	Small Woody Crown Area	Small Woody Crown Volume	Small Woody Stem Count per Acre
DBH	r	-0.063	0.318	0.257	0.072	0.343	0.163	0.408	0.211	0.340	0.211	0.121	0.117	0.315
	p-value	0.793	0.172	0.275	0.764	**0.138**	0.494	**0.074**	0.371	0.143	0.372	0.612	0.622	0.176
Height	r	-0.173	0.224	0.186	0.033	0.393	0.229	0.343	0.267	0.334	0.239	0.149	0.150	0.301
	p-value	0.465	0.343	0.431	0.889	**0.087**	0.332	**0.139**	0.254	0.150	0.310	0.530	0.529	0.197
Dom. Height	r	-0.148	0.172	0.142	-0.004	0.405	0.269	0.328	0.263	0.367	0.299	0.238	0.242	0.304
	p-value	0.533	0.468	0.552	0.987	**0.076**	0.252	0.158	0.264	0.111	0.201	0.312	0.304	0.193
BA	r	-0.035	0.394	0.413	0.207	0.144	0.054	0.400	0.248	0.309	0.158	0.087	0.084	0.266
	p-value	0.883	**0.085**	**0.07**	0.381	0.545	0.823	**0.081**	0.292	0.186	0.505	0.717	0.725	0.257
TVOB	r	0.012	0.421	0.422	0.208	0.196	0.112	0.463	0.292	0.337	0.192	0.131	0.135	0.289
	p-value	0.961	**0.065**	**0.064**	0.379	0.407	0.638	**0.04**	0.211	0.146	0.417	0.581	0.570	0.216

*Values in bold indicate significance at α=0.10

Table 3.19. Results for Pearson correlations between age 4 loblolly pine response and age 4 competing vegetation on operational culture plots in the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.

Response		Percent Andropogon	Mean Andropogon Ht	Percent Grass per acre	Mean Grass Height	Percent Broadleaf per Acre	Mean Broadleaf Height	Percent Herbaceous per Acre	Mean Herbaceous Height	Small Woody Sum Height	Small Woody Sum Crown Height	Small Woody Crown Area	Small Woody Crown Volume	Small Woody Stem Count per Acre
DBH	r	-0.044	0.159	0.342	0.470	0.471	-0.426	0.569	-0.414	0.191	0.162	0.126	0.053	0.237
	p-value	0.855	0.505	**0.14**	**0.037**	**0.036**	**0.061**	**0.009**	**0.07**	0.421	0.495	0.598	0.825	0.314
Height	r	-0.151	0.129	0.348	0.436	0.499	-0.406	0.495	-0.349	0.244	0.228	0.211	0.136	0.267
	p-value	0.526	0.588	**0.133**	**0.055**	**0.025**	**0.076**	**0.027**	**0.132**	0.301	0.335	0.373	0.566	0.255
Dom. Height	r	-0.138	0.099	0.326	0.373	0.511	-0.357	0.503	-0.291	0.297	0.289	0.296	0.238	0.287
	p-value	0.562	0.679	0.16	**0.106**	**0.021**	**0.122**	**0.024**	0.213	0.204	0.216	0.206	0.312	0.220
BA	r	0.108	0.261	0.262	0.409	0.338	-0.377	0.551	-0.339	0.070	0.029	0.022	-0.037	0.124
	p-value	0.65	0.267	0.264	**0.073**	**0.145**	**0.102**	**0.012**	**0.143**	0.770	0.904	0.928	0.876	0.604
TVOB	r	0.067	0.243	0.256	0.406	0.322	-0.371	0.495	-0.316	0.068	0.025	-0.001	-0.058	0.114
	p-value	0.778	0.301	0.277	**0.076**	0.166	**0.107**	**0.027**	0.175	0.777	0.917	0.995	0.807	0.634

*Values in bold indicate significance at α=0.10

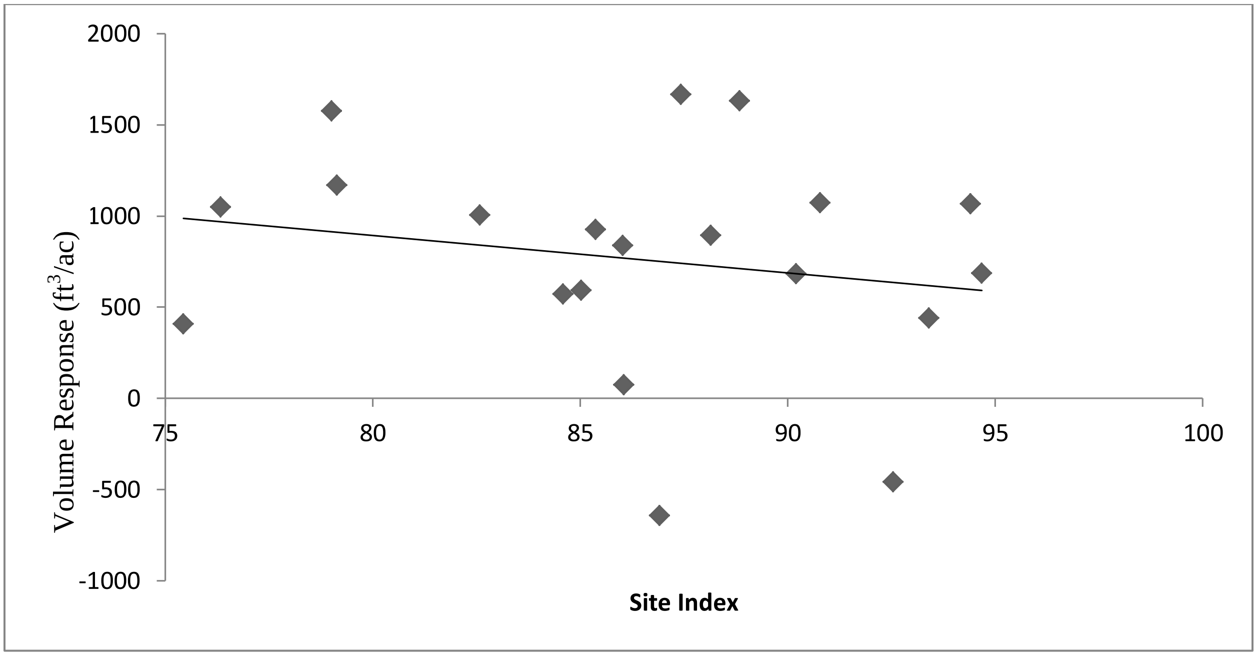

Figure 3.1. Relationship between age 12 loblolly pine volume growth response to intensive culture and expressed site index with operational culture at the 600 tpa planting density for the PMRC Culture x Density Study in the Upper Coastal Plain and Piedmont.

CHAPTER 4

CONCLUSIONS

This study examined twenty research installations in the Upper Coastal Plain and Piedmont for soil, cultural intensity and planting density effects on loblolly pine plantation productivity through age 12.

Soil class was important in determining loblolly pine productivity. Productivity at age 12 was lower on Upper Coastal Plain soils with > 40 inches to the argillic horizon than on the other soil classes examined. The importance of stand density was magnified on the Upper Coastal Plain soils with > 40 inches to the argillic horizon. Loblolly pine performance on this soil class relative to other soils was poorer at higher planting densities than lower planting densities.

Intensive culture affected most stand and stem attributes at age 12. It increased all attribute means except for survival, live crown ratio and relative spacing which decreased with intensive culture due to increased intraspecific competition. Increasing planting density decreased individual tree size and increased stand attributes of basal area per acre and volume per acre. Lower planting densities also exhibited larger age 12 responses to intensive culture in mean DBH and basal area per acre.

Loblolly pine growth observed with operational culture and response to intensive culture for the 600 tpa planting density varied among soil class at age 12. Operational growth varied significantly among soil classes with the Upper Coastal Plain soils with > 40 inches to the argillic horizon having the lowest productivity. This soil class tended to exhibit the largest responses to intensive culture although observed differences among soil classes were generally not statistically significant. Specific soil attributes of depth to Bt or subsoil texture did not have strong correlations with pine response to intensive culture although pine response tended to increase with increased depth to Bt and decrease with finer subsoil texture. Pine response to intensive culture was not significantly related to expressed site index under operational culture. It should be noted that response measured here resulted from increased culture relative to an "operational" level with considerable competition control and fertilization inputs.

There were significant linear correlations between loblolly pine response to intensive culture and measures of competing vegetation with operational culture. Age 12 pine response was positively correlated with operational culture small woody competition at age 8 and percent grass, broadleaf or herbaceous cover and grass height at age 4. Competition measures at age 2 were generally not strongly correlated with pine response. Age 4 and 8 pine responses were positively correlated some measures of non-woody cover at younger ages.

The results of this thesis suggest that forest managers should consider soil class effects when developing productivity estimates. Recognize that more intensive culture will generally promote levels of productivity greater than that resulting from lower operational culture and adjust planting density and associated thinning and harvest regimes to achieve desired productivity and product targets. Several soil and competing vegetation attributes may also prove useful in developing estimates of pine plantation response to intensive culture.

APPENDIX 1. PICTURES OF AUGERED SOIL PROFILES.

Installtion 11, Greene Co, Ga Piedmont Cecil Fine, kaolinitic, thermic Typic Kanhapludults

Installation 13 Jasper Co, Ga   Piedmont   Lloyd – Pacolet Fine, kaolinitic, thermic Rhodic Kanhapludults