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Effects of planting density and cultural intensity on stand and crown attributes of mid-rotation loblolly pine plantations

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ABSTRACT

Loblolly pine (*Pinus taeda*) is an important timber species in the southeastern US and abroad. A better understanding of loblolly pine crown relationships with growth has implications for improving productivity estimates using process-based models or remote sensing techniques. Four study installations in the Upper Coastal Plain and Piedmont of Georgia were used to examine the effects of planting density and cultural intensity on loblolly pine stand growth and crown attributes. Treatments included six planting densities, ranging from 740 to 4440 trees ha^{-1}, in a split-plot design with two different levels of fertilization and competition control. The "low intensity (LI)" cultural treatment included relatively high nutrient inputs and early competition control. The "high intensity (HI)" cultural treatment included even greater nutrient inputs and complete sustained competition control. Treatment effects on stand and crown attributes were examined at age 13. Fertilization and competition control did not have a major influence on stand and crown attributes. Stands planted at lower densities resulted in significantly greater DBH and height but less standing volume per hectare, basal area per hectare, and current annual increment (CAI) volume growth compared to stands planted at higher densities. Stand-level foliar biomass, peak projected leaf area index (LAI), foliar nitrogen (N) content, specific leaf area (SLA), and intercepted photosynthetically active radiation (IPAR) were significantly greater for stands planted at higher densities, while live crown length and crown ratio were significantly greater for stands planted at the lower densities. IPAR efficiency (CAI per IPAR) was significantly affected by planting density, with values of 0.32–0.42 m^3 %IPAR^{-1} for 740 and 4440 trees ha^{-1}, respectively. At this stage of stand development, light limitations due to high stocking have a greater influence on growth than soil resource limitations for the loblolly pine plantations analyzed in this study. Higher density stands resulted in increased SLA and IPAR efficiency, supporting the idea that higher density stands utilize light more efficiently than lower density stands.

1. Introduction

Worldwide, plantation forests represent only 4% of all forests, yet they provide 50% of all wood production (Miller et al., 2009). The high productivity of many plantation forests can be attributed to advances in silvicultural and genetic technology (Borders and Bailey, 2001; McKeand et al., 2006). Almost half of all industrial forest plantations are located in the southern United States, where the most widely planted species is loblolly pine (*Pinus taeda*) (Fox et al., 2007a; Prestemon and Abt, 2002). Although loblolly pine is native to the southeastern US, plantations outside of the native range (e.g. Hawaii, South America, South Africa) have been very successful as well (Borders and Bailey, 2001; Samuelson et al., 2008). A substantial amount of research has focused on increasing productivity in loblolly pine plantations; and silvicultural practices such as fertilization, control of competing vegetation, and density management have become effective practices for manipulating growth rates (Borders and Bailey, 2001; Fox et al., 2007b; Jokela et al., 2004, 2000; Will et al., 2005). Fertilization and competition control practices (alone and combined) can significantly increase productivity in loblolly pine plantations, although the nature of the response is very site and age specific (Allen et al., 2005; Fox et al., 2007a; Jokela and Martin, 2000; Martin and Jokela, 2004b; Will et al., 2002). Planting density choices have implications for rotation length and wood product designations (Amateis and Burkhart, 2012; Huang et al., 2005). Loblolly pine wood production in response to common silvicultural inputs has been documented, however, the factors that drive those responses are not thoroughly understood (Jokela et al., 2004; King et al., 2008; Tyree et al., 2009; Will et al., 2005).

Many factors that influence stand growth are related to canopy size, structure, and nutritional status. Numerous studies have shown that loblolly pine stand productivity has a positive linear

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relationship with leaf area index (LAI) (Albaugh et al., 2004; Jokela and Martin, 2000; Samuelson et al., 2001, 2004; Will et al., 2005; Xiao et al., 2003). Studies have also shown the relationship to be curvilinear (Jokela et al., 2004; McCrady and Jokela, 1998; Sword Sayer et al., 2004), possibly due to increased shading within high LAI canopies (Martin and Jokela, 2004a; Will et al., 2005). The slope of the relationship between stem growth, or above-ground biomass production, per unit LAI is often referred to as "growth efficiency", and there is evidence that it can be altered through silvicultural practices (Albaugh et al., 2006; Borders et al., 2004; Burkes et al., 2003; Maier et al., 2002; Sword Sayer et al., 2004).

Perhaps one of the most intrinsic canopy measurements is intercepted photosynthetically active radiation (IPAR), which represents canopy photosynthetic energy capture (MacFarlane et al., 2002; Will et al., 2005). Studies have shown that IPAR is positively correlated with stem growth in loblolly pine, and is often linearly related to growth for a given site (Allen et al., 2005; Chmura and Tjoelker, 2008; Dalla-Tea and Jokela, 1991; McCrady and Jokela, 1998; Will et al., 2001, 2005). A stronger correlation between IPAR and volume growth compared to LAI and volume growth has been documented (Allen et al., 2005; Will et al., 2005). Radiation-use efficiency, defined as stem growth per annual IPAR ($\text{cm}^3\ \text{MJ}^{-1}$), was constant for 4-year old loblolly pine planted at a wide range of densities in the Upper Coastal Plain and Piedmont of Georgia, suggesting a functional relationship between IPAR and stand growth (Will et al. 2005).

Impressive increases in loblolly pine productivity can be realized by reducing soil nutrient limitations (Albaugh et al., 2004; Borders and Bailey, 2001; Fox et al., 2007b; Martin and Jokela, 2004b; Samuelson et al., 2008). Nitrogen (N) is one of the nutrients most commonly limiting to loblolly pine growth (Fox et al., 2007a). Increases in foliar N concentration do not lead to a consistent observable increase in photosynthetic capacity for loblolly pine (Munger et al. 2003). Additional N acquired by the foliage, however, may serve as a source for subsequent foliage development, which may consequentially drive additional stem growth (Borders et al., 2004; Munger et al., 2003; Tyree et al., 2009; Will et al., 2002).

The objective of this study was to determine relationships between silvicultural practices, stand growth, and crown attributes including live crown length, crown ratio, specific leaf area (SLA), LAI, foliar biomass, IPAR, and foliar nitrogen (N) concentration and content. Hypotheses include:

(1) High intensity silviculture will (a) increase stem growth, live crown length, LAI, foliar biomass, SLA, foliar N concentration and content, IPAR, nitrogen-use efficiency (NUE), and growth efficiency, (b) decrease survival and crown ratio, and (c) have no effect on IPAR efficiency compared to low intensity silviculture.

(2) Lower planting density will (a) increase individual stem growth, live crown length, crown ratio, foliar N concentration, and survival, (b) decrease stem growth per hectare, LAI, foliar biomass, SLA, foliar N content, IPAR, NUE, and growth efficiency, and (c) have no effect on IPAR efficiency compared to higher planting density.

(3) The cultural intensity × planting density interaction effect will not be significant for the attributes analyzed.

2. Methods

2.1. Study sites and treatments

This study utilized four loblolly pine research installations maintained by the University of Georgia Plantation Management Research Cooperative (PMRC). Two installations were located in the Upper Coastal Plain region of Georgia and two installations were located in the Piedmont region of Georgia (Table 1).

Soils at all four installations are typical for the region and characterized by translocated silicate clay and base saturation less than 35%. They are described as very deep, well-drained, and moderately permeable (Soil Survey Staff, 2013). Based on climate data accumulated at stations in the vicinity of the research installations, average annual precipitation typically exceeds 110 cm and is well-distributed throughout the year (Southeast Regional Climate Center, 2013).

The installations were planted in 1998 with open-pollinated, bare-root loblolly pine seedlings chosen by the PMRC cooperator for that site. Only one half-sib family was planted within each installation, although the exact family designation for each installation is unknown. Each installation was arranged in a split-plot design, with two main plots that received one of two cultural treatments and six sub-plots that were planted at one of six densities (740, 1480, 2220, 2960, 3700, and 4440 trees ha^{-1}). The two cultural treatments were termed "high intensity (HI)" and "low intensity (LI)" (Table 2). The combination of two cultural intensities and six planting densities resulted in 12 plots per installation, where main plots were randomly assigned and sub-plots were randomly assigned within main plots. The HI treatment included frequent fertilization and complete sustained competition control. The LI treatment included less frequent fertilization and only early competition control. To ensure adequate first-year survival, planting spots were double-planted and reduced to a single surviving seedling after the first growing season. Plot size varied to accommodate the different planting densities (Table 3). Gross plots contained an interior measurement plot surrounded by an approximate 8 m wide buffer. The entire gross plot received the designated planting density and cultural regime. Measurements were obtained only from trees in the interior measurement plots.

2.2. Stand and crown measurements

In the measurement plots, diameter at breast height (DBH) was measured on all trees and total height and live crown length (distance from the top of the tree to the lowest living branch) were measured on every other tree in the dormant season at age 13. Crown ratio was calculated as live crown length divided by stem height. For the trees that were not measured for height, estimates of height were made using an equation fit for trees with both measured height and DBH for each plot using the model form: $\ln(\text{height}) = \beta 0 + \beta 1\ \text{DBH}^{-1}$.

Total outside-bark stem volume was estimated for all trees at age 13 using the volume equation developed by Pienaar et al. (1987). Gross current annual increment (CAI) of stem volume growth per hectare was estimated by subtracting volume at age 12 from volume at age 13. When estimating gross CAI, tree volume lost to mortality from age 12 to age 13 years old was included in the volume at age 13 to ensure that CAI reflected the growth rate of the remaining trees. Basal area ($\text{m}^2\ \text{ha}^{-1}$) and percent survival were also determined at age 13.

Circular leaf litter traps ($0.46\ \text{m}^2$) were used to estimate plot level foliar biomass. Eight traps were randomly distributed throughout each of the plots on all four installations. Litter was collected from the traps over the course of the 13th year (March 2010–March 2011). Litter was dried in a drying oven at 65 °C to a constant weight and then hand-sorted to remove debris (bark, weeds, reproductive material, etc.). Pine needles were weighed to estimate previous-year (2009) age-class foliar biomass for each plot; as loblolly in the southeastern US typically retains needles for 2 growing seasons (Wells and Metz (1963)). Foliar biomass estimates were then doubled to represent peak foliar biomass (two foliar age classes) for each plot.