Nine-Year Growth Responses to Planting Density Manipulation and Repeated Early Fertilization in a Loblolly Pine Stand in the Virginia Piedmont

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ABSTRACT

Achieving maximum stand leaf area early in the rotation can have large positive effects on plantation productivity. Two silvicultural management strategies that can enhance leaf area development are increasing planting density and improving nutrition. A trial was established to determine how these two silvicultural management strategies affect the growth of *Pinus taeda* L. in the Virginia Piedmont. The study was designed as a factorial with two planting densities (363 and 726 trees ac^{-1}) and three levels of nutrient additions. The three nutrient levels were aimed at maintaining the current site index (SI_{25}) of the stand (55 ft) or improving the SI_{25} to 70 and 80 ft. None of the treatments affected survival or height during the first 9 years. At age 9, the lower stand density treatment had a greater average diameter (6.03 in.) compared with the high stand density treatment (5.10 in.) averaged across all nutrient levels. The intermediate and high nutrient treatments increased diameter by 0.21 and 0.35 in., respectively, compared with the low nutrient treatment (5.38 in.), when averaged across both stand densities. Intraspecific competition affected diameter growth from age 5, whereas nutrient additions increased growth from age 4.

Keywords: *Pinus taeda*, planting density, nutrition

Stand density and nutrient management can influence plantation productivity by affecting stand leaf area. Stemwood production is correlated with stand leaf area (Vose and Allen 1988, Albaugh et al. 1998, Colbert et al. 1990). Manipulating stand density affects the rate at which site occupancy is achieved (Mead 2005), with higher-density stands reaching maximum stand leaf area faster than stands with low densities (Barron-Gafford et al. 2003). However, nutrient limitations can restrict leaf area development (Vose and Allen 1988, Albaugh et al. 1998, Fox et al. 2007).

Nutrient limitations result from an imbalance between nutrient demand and availability and can be overcome through fertilizer additions (Fox et al. 2007). Fertilization at time of planting in the southeastern United States has primarily been confined to phosphorus (P) applications on poorly drained clayey Ultisols of the lower Coastal Plain (Gent et al. 1986) and a limited number of well-drained clayey to loamy soils on the Citronelle and associated geological formations in the upper Gulf Coastal Plain (Leggett and Kelting 2006). Fertilizer studies conducted at time of planting in Piedmont loblolly pine (*Pinus taeda* L.) stands, using a range of elements, have yielded mixed responses. Some trials have shown no growth improvement (Moschler et al. 1970, Torbert and Burger 1984, Amishev and Fox 2006), whereas others have shown improvement (Carter and Lyle 1966, Haines and Haines 1979). Nitrogen (N) is generally sufficient in stands prior to canopy closure because of increased nutrient availability following harvesting and site preparation (the assart effect) (Vitousek and Matson 1985). However, at approximately the time of canopy closure, stand N requirements often begin to exceed soil N availability (Allen et al. 1990, Fox et al. 2007). Consequently, sites become increasingly responsive to N additions as they develop and mature.

Increasing stand density can lead to greater and faster utilization of site resources, particularly N (Barron-Gafford et al. 2003), through altered biomass allocation patterns (Dicus and Dean 1999, Burkes et al. 2003). Barron-Gafford et al. (2003) found significant decreases in foliar, fine root, and stemwood N concentrations when the stand density of 4-year old loblolly and slash pine (*Pinus elliottii*) increased from 300 to 900 to 1,500 trees per acre (TPA) in studies located in the lower Coastal Plain of southeastern Georgia. They found little difference in foliar and fine root P and potassium concentrations and concluded that N was the primary nutrient limiting growth in denser stands.

High initial stand densities, and associated high nutrient demands, may lead to stands becoming nutrient limited and hence responsive to fertilization at an earlier age. Understanding when in a rotation nutrients become limiting, and how factors such as stand density affect this relationship, is critically important to correcting deficiencies promptly and to managing stands optimally. We are unaware of any studies in the Piedmont that have investigated interactions between fertilization and planting density. Studies looking at the interaction of planting density and cultural intensity (Dicus and Dean 1998, Barron-Gafford et al. 2003, Rahman et al. 2006) have been located in other physiographic provinces in the southeastern United States.

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Table 1. Timing, rate, form of fertilizer applied, and method of application for each of the nutrient treatments.

	Nutrient treatment				
Date of application	F1	F2	F3	Form of fertilizer	Method of application
May 1999			50 lbs ac^{-1} P	Diammonium phosphate	4-ft circle around tree
			150 lbs ac^{-1} N	Ammonium nitrate	
April 2000	15 lbs ac^{-1} P	15 lbs ac^{-1} P	15 lbs ac^{-1} P	Triple superphosphate	4-ft circle around tree
		76 lbs ac^{-1} N	153 lbs ac^{-1} N	Urea	
April 2001	25 lbs ac^{-1} P			Triple superphosphate	
		25 lbs ac^{-1} P	25 lbs ac^{-1} P	Diammonium phosphate	Broadcast
		100 lbs ac^{-1} N	200 lbs ac^{-1} N	Ammonium nitrate	

Silvicultural treatments that affect height growth will lead to changes in expressed site index, implying a change in the site's quality or carrying capacity. Responses that modify the carrying capacity of the stand, known as type A responses (Nilsson and Allen 2003; equivalent to Snowdon's [2002] type 2 response), result in growth rates of the treated stands diverging over time relative to untreated stands. An example is P applied at planting on chronically deficient sites (Pritchett and Comerford 1982). The response to this type of treatment can be modeled by adjusting site index (Amateis et al. 2005). A treatment-induced change in site index is a major contributing factor to increased basal area (McTague 2008) and hence to changes in stand volume. In contrast, silvicultural treatments such as herbaceous competition control in young loblolly pine plantations or midrotation fertilizer applications increase diameter growth more than height, and the response is relatively short-lived. These responses are referred to as type B responses (equivalent to Snowdon's 2002 type 1 response) (Nilsson and Allen 2003, South and Miller 2007). In such cases, site quality or carrying capacity is not altered, but the growth rate of the stand is accelerated for a short period of time. Modeling these type B responses with a site index change is not appropriate, as the maximum carrying capacity of the site is not altered, and a better approach may be to use age shifts (South et al. 2006, South and Miller 2007, Carlson et al. 2008).

Understanding how silvicultural treatments affect growth and whether they fundamentally alter site index is important to comprehending the long-term effects of the treatment on stand growth. This understanding will help develop appropriate approaches to modeling growth responses. The objectives of our study were to (1) quantify the growth response of young loblolly pine to different stand density and fertilization management strategies in the Virginia Piedmont, (2) determine whether the effects of stand density and fertilization interact, and (3) determine the point in the rotation when intraspecifc competition begins. We report on the responses over the first 9 years after planting.

Methods

A trial was established as a randomized complete block design (three blocks) with a factorial combination of two planting densities (363 and 726 TPA) and three levels of nutrition. The nutrient treatments (Table 1) included low (F1), intermediate (F2), and high (F3) nutrient regimes, with the F1 expected to maintain a site index (SI_{25}) of 55, similar to the previous rotation, and the F2 and F3 treatments being fertilized at rates calculated to meet the nutrient requirements of stands with SI_{25} of 70 and 80 ft, respectively. Estimates of the nutrient requirements for the F2 and F3 treatments were made using the NUTREM model (North Carolina State Forest Nutrition Cooperative 2000) and assuming a stocking of 700 TPA. Plots were 0.4 ac in size, with an inner measurement area of 0.18 ac. Tree rows were 10 ft apart, with trees planted 12 or 6 ft apart within the row, resulting in 64 and 128 measurement trees in the 363 and 726 TPA treatments, respectively.

The study site, in Buckingham County, Virginia (37°34′59″N, 78°26′47″W; elevation 602 feet above sea level), has an average annual rainfall of 43.3 in., with snow (an average of 18.7 in. per year) potentially occurring between December and March. The mean annual temperature is 55°F, with a mean maximum of 87° F in July and minimum of 24°F in January. The frost-free period extends from mid-April to October. The soil is a Cecil series (clayey, kaolinitic, thermic, Kandiudult) with a gravelly loam A-horizon 4–8 in. deep and a clayey Bt horizon at a depth of 40 in. The upper 6 in. of the A-horizon contains 4% organic matter (unpublished data from company soil maps).

The site is typical of the Piedmont, with the area having been in agricultural production from 1800 to the mid-1900s. The previous stand was planted to loblolly pine, and the stand was likely the second or third pine rotation on this site, based on the amount of hardwood present in the previous stand. The previous plantation of loblolly pine was harvested in 1995 (age 29) and had a measured SI_{25} of 55 ft. The site was drum chopped and burned in the fall of 1997. The trial was planted in April 1998 with bare-root, open-pollinated loblolly pine seedlings. Intensive vegetation control was practiced after planting, which eliminated all woody vegetation from the plots and controlled the herbaceous vegetation for the first 3 years, achieving an almost bare-ground condition.

All tree measurements were conducted at the end of the growing season. Stem diameters were measured 6 in. above ground level at years 1, 2, and 3, with diameters at breast height (dbh) measured at years 4, 5, 7, and 9. Individual tree basal areas were determined and scaled to provide basal area estimates on a per-acre basis. Heights of all trees in each plot were measured annually through year 5. In years 7 and 9, heights were measured on a sample of 20 trees per plot. Trees were randomly selected across the diameter distribution within the plot. A regression for each plot was constructed, with the natural logarithm of height and the inverse dbh as the dependent and independent variables, respectively. This function was used to estimate heights of trees not measured. Site index calculations use the tallest 40 trees per acre, which are considered the dominant and codominant trees (Clutter et al. 1983). Using this definition, the dominant height was calculated as the mean height of the 16 tallest trees in each plot (irrespective of stand density treatment). SI_{25} was estimated using the function of Sharma et al. (2002), bearing in mind that the estimates in the current study were made for trees only 9 years old. Live crown length was estimated at age 9 using the difference between the total tree height and the height on the stem to the lowest branch with green needles. This was measured on the same trees for which height measurements were

Table 2. Results of the repeated measures analysis conducted with PROC MIXED indicating the *P* values of the main fixed effects and the fixed effect interactions.

	Survival[a]	Height	Ground-level diameter	dbh	Basal area[b]
Stand density × Nutrition × Age	0.543	0.060	0.807	0.947	0.600
Stand density × Nutrition	0.402	0.422	0.616	0.182	0.235
Stand density × Age	0.323	0.002	0.154	<0.001	<0.001
Nutrition × Age	0.180	0.004	0.155	0.183	0.004
Stand density	0.879	0.819	0.507	<0.001	<0.001
Nutrition	0.662	0.186	0.278	0.001	0.013
Age	0.001	<0.001	<0.001	<0.001	<0.001

[a] Arc sine transformed data was used in the analysis.
[b] Natural logarithmic transformations were used in the analysis.

taken. We did not consider it accurate to predict the live crown length on the trees that were not measured.

Analysis of variance (ANOVA) was conducted to test for treatment effects on live crown length (measured only at age 9) using PROC GLM (SAS 2005). Repeated measures analyses were performed on height, dbh and basal area measures using PROC MIXED (SAS 2005), to examine each growth metric over time using first-order autoregressive covariance matrices. When significant interactions were found (all occurred with age), then simple effects within each age class were investigated by running separate ANOVAs for each age. Heterogeneity of variances was tested using Levene's test. A logarithmic transformation of basal area was necessary to ensure homogeneity of variances. Survival percentages were transformed using an arc sine transformation prior to analysis. In all cases, an $\alpha = 0.05$ significance level was considered.

Results

Survival

Mortality in the trial was less than 3.3% at year 9. The high survival was partially attributable to the effective vegetation control practiced on the site. Most of the mortality (2.7%) occurred in the first year. There were no treatment effects on mortality with time being the only factor affecting survival (Table 2). There was no evidence of density-dependent mortality through age 9.

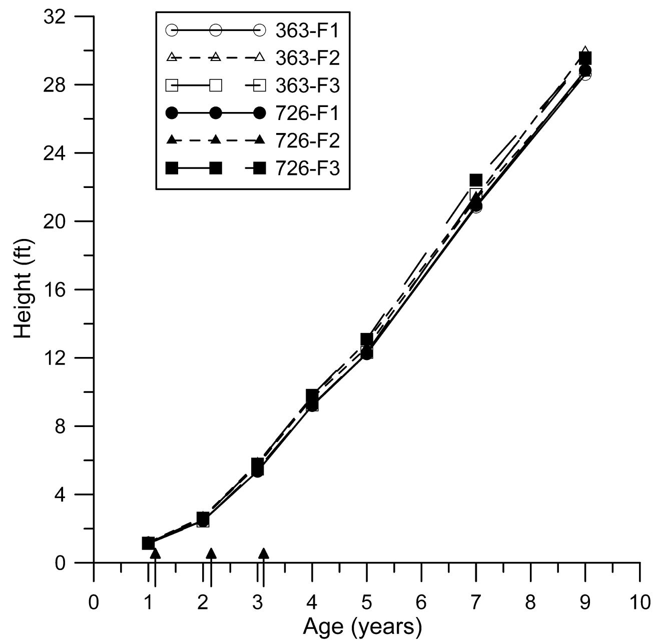

Figure 1. Height growth over time. Open and closed symbols indicate the 363 and 726 trees per acre treatments, respectively. Arrows along the *x*-axis indicate the timing of fertilizer applications.

Height

The repeated measures analysis (Table 2) indicated that both stand density by age and nutrient by age interactions were significant ($P = 0.002$ and 0.004, respectively), indicating that trees planted at different stand densities or with different nutrient additions had different height growth rates (Figure 1). Differences in growth rates (as evidenced by the significant interactions) were small, however, and the treatments did not significantly affect mean plot height at any point in time (Figure 1). Significant age by treatment interactions do, however, indicate the potential for treatment differences to become significant at some time in the future. Similar results were obtained when only the heights of the dominant and codominant trees in the plots were considered.

Although 9 years may be considered too young for accurate site index estimates, we estimated the SI_{25} for the stand (averaged across all plots) to be 71 ft. This is an improvement over that of the previous rotation (SI_{25} of 55 ft). Since height at age 9 was not affected by treatment, there is no evidence that these treatments will affect the expressed site index.

Live Crown Length

At year 9, mean live crown length was significantly greater in the 363 TPA treatment compared with the 726 TPA treatment ($P <$ 0.001), with a difference, averaged across nutrient treatments, of 3.76 ft. Average live crown length in the 726 TPA was 18.67 ft, which equated to 64.0% of the tree height, whereas average live crown length was 22.42 ft (76.0% of the tree height) in the 363 TPA treatment. Nutrition also significantly ($P = 0.040$) affected live crown length, with longer crowns occurring with higher levels of nutrient additions. The difference in crown length between the F1 treatment (19.86 ft) and F3 treatment (21.09 ft) was significant, with F2 (20.70 ft) being intermediary and not significantly different from the F1 or F3 treatment. Average live crown lengths equated to 68.8%, 70.0%, and 71.1% of the total tree height in the F1, F2, and F3 treatments, respectively.

Tree Diameter

Mean stem diameter measured at 6 in. above ground level during the first 3 years after planting did not show any significant treatment effects (Figure 2). The only factor affecting ground level diameter was tree age (Table 2).

The repeated measures analysis on the dbh (Table 2) indicated a highly significant stand density by age interaction ($P < 0.001$). The treatment by age interaction indicates a difference in growth rates, which can be seen in Figure 2, particularly at years 7 and 9, where

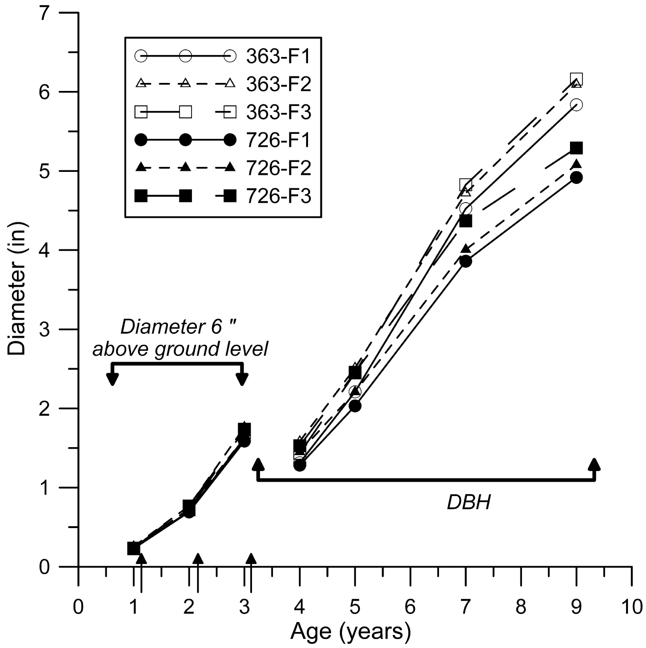

Figure 2. Diameter development over time. Open and closed symbols indicate the 363 and 726 trees per acre treatments, respectively. Arrows along the *x*-axis indicate the timing of fertilizer applications.

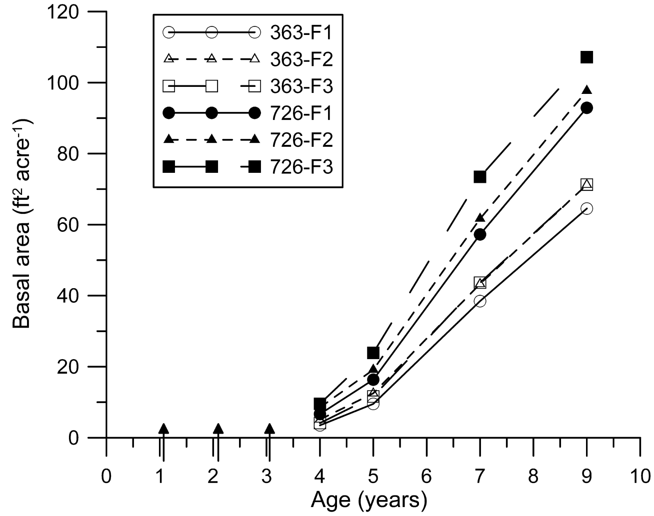

Figure 3. Basal area development over time. Open and closed symbols indicate the 363 and 726 trees per acre (TPA) treatments, respectively. Note that the F2 and F3 treatments in the 363 TPA have similar values and lie almost on top of each other. Arrows along the *x*-axis indicate the timing of fertilizer applications.

the stand density treatments diverge, with the 363 TPA treatment having a much higher diameter growth rate (slope) than the 726 TPA treatment. The mean dbh in the 363 TPA treatment was significantly greater than in the 726 TPA treatment in years 5, 7, and 9 (P values of 0.049, $<$0.001, and $<$ 0.001, respectively). At age 9, the mean dbh of trees in the 363 TPA treatment was 0.93 in. greater than those in the 726 TPA treatment (5.10 in.).

The repeated measures analysis (Table 2) showed a highly significant effect of nutrition ($P = 0.001$) on dbh, with F2 and F3 being significantly greater than F1. The mean dbh increased significantly as a result of increased nutrient levels from year 4 (the first year of dbh measurement) through year 9 ($P = 0.036$, 0.009, 0.004, and 0.005 for years 4, 5, 7, and 9, respectively). At age 9, the mean dbh in the F2 and F3 treatments were significantly greater (0.21 and 0.35 in., respectively) than the F1 treatment (5.38 in.), but no statistical differences were found between the F2 and F3 treatments.

Basal Area

The repeated measures analysis (Table 2) on the basal area data showed significant stand density by age ($P < 0.001$) and nutrition by age ($P = 0.004$) interactions. These age interactions indicate different rates of basal area growth as a result of both the stand density and the different nutrient levels. Simple effect analysis at each age indicated that basal area was significantly affected by both stand density and nutrition at each measurement point ($P < 0.001$ for the stand density effect at all time points; $P = 0.030$, 0.008, 0.004, and 0.005 for years 4, 5, 7, and 9, respectively, for the nutrition treatments) (Figure 3). At 9 years, mean basal area in the F2 and F3 treatments were significantly greater (5.8 and 10.5 $ft^2\ ac^{-1}$, respectively) than the F1 treatment (78.7 $ft^2\ ac^{-1}$), and the 726 TPA was 30.2 $ft^2\ ac^{-1}$ greater than the 363 TPA treatment (69.0 $ft^2\ ac^{-1}$).

Discussion

Mortality was not affected by any of the treatments up through year 9. This is similar to the study of Land et al. (2004), who, prior to year 9, did not observe differences in the mortality of loblolly pine planted at densities of 436, 681, and 1,743 TPA. Land et al. (2004) found that at age 9, the 1,743 TPA treatment had higher mortality than the other two treatments, whereas differences in the survival between the 436 and 681 TPA treatments was observed only at age 13. Buford (1991) similarly observed little mortality when the planting density was less than 705 TPA in the South Carolina Piedmont until the trees were more than 15 years old. Although no density-dependent mortality has been observed in our study, we expect treatment-related mortality in the future as competition for resources becomes greater.

Conventional wisdom suggests that stand density does not affect height growth (Clutter et al. 1983, Pienaar and Shiver 1993, Rahman et al. 2006) unless stand density is at an extreme (i.e., less than 400 TPA or greater than 1,000 TPA) (Pienaar and Shiver 1993). Land et al. (2004) found significant differences in tree height at ages 5, 9, and 13 in their study with three different spacing treatments (436, 681, and 1,743 TPA) and concluded that height was temporarily stimulated at the time of canopy closure. However, Land et al. (2004) found, at age 17, no significant differences in height as a result of the different stand density treatments. The lack of height response to stand density treatments in our study, which were not extreme, was thus not unexpected.

On the other hand, differences in diameter between the two density treatments in our study became significant at age 5. We interpret this to mean that the cumulative effects of the intraspecific competition have resulted in significant reductions in diameter growth at this time. The onset of detectable growth reductions indicating intraspecific competition is comparable to those observed with similar treatments in other studies (Pienaar and Shiver 1993, Land et al. 2004, Rahman et al. 2006).

Nutrient additions improved diameter growth with significant fertilizer treatment effects being observed from the initial dbh measurements taken at year 4. However, there were no effects of the nutrient treatments on height at any time. Phenology studies in midrotation loblolly pine stands have suggested that height is less responsive to nitrogen additions than is diameter growth (Zhang et al. 1997). This is likely to be similar in the young trees in our study, where competition was controlled.

Although accurate estimates of site index are difficult when the trees are 9 years old, the site index estimated across all treatments showed a marked increase over that observed in the previous rotation (increasing from SI_{25} 55 to 71). This improvement could be ascribed to improved genetic material, as well as competition control practiced across all treatments at the site. As the nutrient applications did not affect either mean tree height or mean height of the dominant and codominant trees at age 9, we conclude that the nutrient additions have not altered the expressed SI_{25} of the stand at this time, and consequently the carrying capacity of the site has not been changed by the nutrient additions. Nutrient additions did, however, significantly improve diameter growth in our study. Thus it appears that the addition of nutrients early in the rotation in the Piedmont is a type B response with stand development being accelerated. This response is similar to that observed with herbaceous competition control in young loblolly pine plantations and midrotation fertilizer applications and is best modeled through age shifts (South et al. 2006, South and Miller 2007, Carlson et al. 2008) as opposed to site index changes.

The increase in live crown length due to fertilization is consistent with Albaugh et al. (2006), who observed similar increases due to fertilization in mid-rotation stands. Increased crown length resulting from slower foliage and branch abscission may be one mechanism whereby trees improve their growth as a result of nutrient additions. Similarly, increased available space per tree at the lower stand density allows more light to reach the lower branches. As a result, branches remain alive longer in a manner analogous to the way thinning increases crown length and width (Peterson et al. 1997). Peterson et al. (1997) ascribe the improved growth after thinning to greater horizontal crown expansion and longer crown lengths, which continues until physical interaction between crowns occurs and shading results in lower light levels to the base of the crown. We suggest that longer crowns in the 363 TPA treatment led to greater leaf areas, which in turn resulted in improved diameter growth at the lower stand density.

Although no significant interactions between nutrition and stand density treatments were found in the first 9 years, we hypothesize that if the current growth trends continue, this interaction may become significant in the future. This hypothesis is based on the finding of Barron-Gafford et al. (2003), who showed significant decreases in foliar, fine root, and stem nitrogen concentrations when stand densities of 4-year-old loblolly and slash pine increased from 300 TPA to 1,500 TPA. Thus we suggest that higher stand densities will result in greater nutrient demand and nutrient limitations becoming evident sooner, which will result in significant nutrient and stand density interactions in the future.

Conclusions

Up through year 9, there were no treatment-related differences in mortality, and survival in the trial was good (greater than 96%). Treatments did not affect mean tree height or dominant tree height. Thus, elevated nutrition has not altered the site index of the stand. Diameter growth appeared to be more responsive to treatments than height growth, as dbh was affected by both stand density and nutrient level. This trial identified the time at which intraspecific competition starts to affect growth at the densities examined (namely at 5 years). Nutrient limitations appeared to affect tree growth from approximately year 4. Early interventions, such as thinning and fertilization, should be considered if growth is to be optimized throughout the rotation. No interaction between nutrition and stand density was observed.

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