Effect of Fertilization on Growth and Wood Properties of Thinned and Unthinned Midrotation Loblolly Pine (*Pinus taeda* L.) Stands

Finto Antony, Laurence R. Schimleck, Richard F. Daniels, and Alexander Clark III

ABSTRACT

Growth and wood properties were measured on breast height cores collected from two stands, New Bern and Bertie, located in the lower Coastal Plain of North Carolina. The New Bern site was thinned before fertilizer application, and the Bertie site was not. The study was laid out in a randomized complete block design with each treatment replicated in four blocks at New Bern and two blocks at Bertie. The treatments were different levels of nitrogen fertilization: control (no nitrogen) and 112, 224, and 336 kg/ha. In addition, 28 kg/ha of phosphorus was included with each treatment. The objective of this study was to examine the response in growth and wood properties to midrotation fertilization in a thinned versus an unthinned stand. A significant decrease in latewood specific gravity was observed following nitrogen fertilization in the thinned stand but not in the unthinned stand. Whole ring width, latewood width, and earlywood width significantly increased following nitrogen fertilization at New Bern but not at Bertie. Whole ring specific gravity, earlywood specific gravity, latewood percentage, and earlywood:latewood ratio did not show any change due to fertilization in either stand. Responses in both growth and wood characteristics lasted for 2–3 years following fertilization and depended on the amount of fertilizer applied and whether or not the site was thinned. The response to nitrogen application was significant for the thinned stand only.

Keywords: wood density, specific gravity, ring width, repeated measure, mixed-effects model

Loblolly pine (*Pinus taeda* L.) is the most important plantation species in the southern United States, with a planted area of more than 13 million ha (Dickens et al. 2003). Intensive management is commonly used to improve the productivity of loblolly pine plantations throughout its growing range (Jokela et al. 2004). Midrotation thinning and fertilization is a widely used silvicultural practice, and by 2004 a total of 6.5 million ha of southern pine plantations had received fertilization with a peak annual midrotation fertilization of 0.64 million ha in 1999 (Albaugh et al. 2007).

Water availability and low soil nutrient availability are considered to be the two principal resources limiting pine productivity in the southern United States (Albaugh et al. 2004, Allen et al. 2005). Of these, low availability of soil nutrients such as nitrogen (N), phosphorus (P), potassium (K), and boron (B) are more important in limiting growth than water stress (Albaugh et al. 2004). Hence supplementing nutrient supply is an important silvicultural tool for increasing pine productivity (Allen et al. 2005, Fox et al. 2007). In studies established by the Forest Nutrition Cooperative throughout the southern United States, over 80% of intermediate-aged pine stands responded positively to the addition of N+P fertilizers (Allen et al. 2005), with reported growth gains of approximately 3,629 kg/ha per year averaged over a period of 8 years following the application of 224 kg/ha of N and 28 kg/ha of P (Fox et al. 2007).

Forest products industries are concerned with the potential effects of thinning and fertilization on wood properties, especially specific gravity (SG) because of its high correlation with strength of structural wood products and with the yield and quality of pulp produced from a given volume of wood. Early age fertilization (at ages 1 and 4) of loblolly pine did not change whole core average SG (Mora 2003). For trees at the age of 10–11, Jokela et al. (2004) found that fertilization combined with weed control decreased SG (compared with the control) for loblolly pine on some of the sites they examined based on the analysis conducted on data from seven individual studies established across the natural range of loblolly pine. Albaugh et al. (2004) reported a decrease in ring specific gravity and an increase in the earlywood:latewood ratio of rings produced immediately following fertilization of an 8-year-old loblolly pine stand. A similar decrease in specific gravity of rings produced immediately following fertilization has been reported by others (Zobel et al. 1961, Love-Myers et al. 2009). In comparison, operational thinning does not appear to produce a significant change in the specific gravity of loblolly pine (Burton and Shoulders 1974, Tasissa and Burkhart 1998).

Successful application of intensive forest management practices, including midrotation thinning and fertilization, requires an understanding of three basic things: resource limitation, which affects

Manuscript received March 28, 2010, accepted November 3, 2010.

Finto Antony (fintoa@warnell.uga.edu), Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602. Laurence R. Schimleck and Richard F. Daniels, Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA 30602. Alexander Clark III, US Forest Service, Athens, GA 30602. *The Wood Quality Consortium of the University of Georgia (Athens, GA) funded this project. The US Forest Service (Athens, GA) provided valuable support in conducting this study. The wood samples were collected under a grant from the US Department of Energy. The Forest Nutrition Cooperative and Weyerhaeuser Company provided background information and access to the fertilization studies.*

This article uses metric units; the applicable conversion factors are: square centimeters (cm^2): 1 cm^2 = 0.155 $in.^2$; hectares (ha): 1 ha = 2.47 ac; kilograms (kg): 1 kg = 2.2 lb.

productivity; effects of different silvicultural treatments on the availability of limited resources; and the final consequence of resource availability on productivity and wood quality (Allen et al. 2005). An understanding of the effect of different management practices on productivity and quality of wood is of great importance both for wood growers and wood buyers. Therefore, our objectives were to examine the effects of midrotation fertilization on growth and wood properties, including average whole ring SG (WRSG), latewood SG (LWSG), earlywood SG (EWSG), percentage latewood (RLWP), whole ring basal area (WRBA), earlywood basal area (EWBA), latewood basal area (LWBA), and earlywood:latewood ratio (ELWR), in a thinned and an unthinned stand and to understand how these properties changed with time.

Materials and Methods

Origin of Samples

The study was conducted on wood samples collected from two loblolly pine plantations, New Bern and Bertie located on the lower Coastal Plain of North Carolina. The plantations were part of the regionwide-13 study, an extensive field trial established throughout the southeastern United States by the Forest Nutrition Cooperative (at the North Carolina State University) to identify the outcome of N and P fertilization in midrotation loblolly pine stands. The New Bern and Bertie stands were planted in 1970 and 1977, respectively, with approximately 1,482 trees/ha. The study was laid out in a randomized complete block design. The treatments used in this study were control (no nitrogen) (000N) and 112 (112N), 224 (224N), and 336 (336N) kg/ha of N, with all the treatments receiving 28 kg/ha of P. The treatments were replicated in four blocks at New Bern and in two blocks at Bertie. The New Bern stand was thinned to 605 trees/ha in 1983 and treated with different rates of N fertilizer in March 1984 at the age of 14. No thinning was conducted at Bertie, but the stand was treated with similar rates of N in April 1987 at the age of 10. All plots at the New Bern stand were thinned to 346 trees/ha in 1995, and a second fertilization treatment with 224 kg/ha N and 28 kg/ha P was applied in 1996. The two stands were harvested in 2003 (New Bern at the age of 33 and Bertie at the age of 26).

Increment cores (12 mm diameter) were collected at the time of harvest (in 2003) from a subsample of nine trees in each treatment plot from the two sites using a hydraulically driven borer. A total of 144 cores (36 cores per treatment) were collected from New Bern, and 72 cores (18 cores per treatment) were collected from Bertie. Only 66 cores from Bertie were analyzed for growth and wood properties using the X-ray densitometer. Owing to damage to the core and/or the presence of knots one core from the 112N treatment and 5 cores from the 224N treatment were omitted.

Growth and Wood Property Analysis

Radial strips (1.6 mm thick) were sawn from the breast height cores and conditioned to 8% moisture content. All the radial strips were then read on a scanning X-ray densitometer (Quintek Measurement Systems) at a resolution of 0.006 mm to determine the width and SG of the earlywood, latewood, and whole ring. The densitometry data were also used to determine radial growth and percentage latewood in each annual ring. A SG of 0.48 was used to distinguish between earlywood and latewood (Clark et al. 2004). Specific gravity values were computed on green volume and ovendry weight basis.

Statistical Analysis

The data collected from each tree can be considered as repeated measurements taken over time from an individual subject. A repeated-measures analysis of variance (ANOVA) with the main effects of treatment and time and their interaction was used to analyze this data set. The data collected from the 5-year postfertilization period were used for the analysis, i.e., 1984–1988 for New Bern and 1987–1991 for Bertie. Growth and SG data from the year before fertilization was used as covariate to adjust for any pretreatment differences (data from 1983 for New Bern and 1986 for Bertie). The data collected from each site was analyzed separately because the effect of thinning was not considered as a treatment and there is a possibility of confounding the effects of thinning and location (the thinned and unthinned sites were in different locations and fertilized at different times; hence, it is probable that the two sites are not identical in terms of growing conditions. Ideally, the trees would have all been growing on the same site and planted at the same time).

Separate ANOVA was conducted for each growth and wood property. Tukey's honestly significant difference test was used to conduct pairwise means comparisons of treatments where a significant result was obtained from ANOVA.

The full linear mixed model used for the analysis of the data can be written as follows:

$$y_{ijkl} = \mu + \beta y_{ijk0} + F_i + T_l + (FT)_{il} + b_j + (Fb)_{ij} + (FbT)_{ijl} + e_{ijkl} \quad (1)$$

$$i = 1, \ldots, 4, \quad j = 1, \ldots, 4, \quad k = 1, \ldots, 9, \quad l = 1, \ldots, 5,$$

where y_{ijkl} = the property measured from lth ring, of the kth tree, of the jth block, receiving the ith fertilization treatment; μ = the population mean; β is the coefficient associated with linear covariate y_{ijk0}, a prefertilization measurement; F_i = the ith fertilization effect; T_l = the lth ring or time effect; $(FT)_{il}$ = the interaction of the ith fertilization and lth ring/time effect; b_j = the random effect of the jth block with $b_j \sim \text{NID}(0, \sigma_b^2)$; $(Fb)_{ij}$ = the random interaction effect of the ith fertilization and jth block effects with $(Fb)_{ij} \sim \text{NID}(0, \sigma_{Fb}^2)$, the true error term for testing the treatment effect; $(FbT)_{ijl}$ = the random interaction of the ith fertilization, jth block and lth ring or time effect with $(FbT)ijl \sim \text{NID}(0, \sigma_{FbT}^2)$, the true error term for testing the main effect of time and treatment by time interaction; and e_{ijkl} = subsampling error, with $e_{ijkl} \sim \text{NID}(0, \sigma^2)$. Here, NID stands for normally and independently distributed with specified mean and variance.

Because measurements were taken from rings produced in adjacent years, we expect that correlation exists among the measurements taken from each sample tree. Observations closer together will tend to be more alike than observations farther apart. Correlation structures are used for modeling the dependence among observations. Different correlation structures considered to model the autocorrelation pattern were unstructured, compound symmetry, heterogeneous compound symmetry, Toeplitz, heterogeneous Toeplitz, first-order autoregressive, and heterogeneous first-order autoregressive. The model was fit to the data from each site with different correlation structures. The selection of the final model was based on Akaike's information criteria and Bayesian information criteria.

All the tests were conducted using the MIXED procedure with a restricted maximum likelihood estimation method available in SAS, version 9.1.3 (SAS 2004). The probability of making a type I error was set to 0.05, unless otherwise stated.

Table 1. Analysis of variance table for New Bern thinned fertilized site.[a]

Property	Source	Numerator d.f.	Denominator d.f.	*F* value	*P* value
WRSG	Fert	3	11.1	2.07	0.1627
	Time	4	44.1	1.45	0.2346
	Fert×time	12	44.3	1.59	0.1288
LWSG	Fert	3	9.05	5.58	0.0192
	Time	4	46.2	31.51	<0.0001
	Fert×time	12	46.1	2.81	0.0058
EWSG	Fert	3	8.41	1.1	0.4001
	Time	4	30.2	11.7	<0.0001
	Fert×time	12	30.4	1.4	0.2183
RLWP	Fert	3	107	0.59	0.6247
	Time	4	47.7	7.94	<0.0001
	Fert×time	12	48.2	1.08	0.3997
WRBA	Fert	3	11.9	10.61	0.0011
	Time	4	47.3	5.43	0.0011
	Fert×time	12	49	3.81	0.0004
EWBA	Fert	3	14.4	5.89	0.0078
	Time	4	41.8	6.69	0.0003
	Fert×time	12	43.2	3.23	0.0023
LWBA	Fert	3	10.4	12.59	0.0009
	Time	4	42	4.78	0.0029
	Fert×time	12	42.8	2.22	0.0278
ELWR	Fert	3	112	0.58	0.6265
	Time	4	49	5.79	0.0007
	Fert×time	12	49.8	0.83	0.6237

[a] d.f., degrees of freedom; Fert, fertilization; WRSG, whole ring specific gravity; LWSG, latewood specific gravity; EWSG, earlywood specific gravity; RLWP, ring latewood percentage; WRBA, whole ring basal area; EWBA, earlywood basal area; LWBA, latewood basal area; ELWR, earlywood:latewood ratio.

Table 2. Analysis of variance table for Bertie unthinned fertilized site.

Property	Source	Numerator d.f.	Denominator d.f.	*F* value	*P* value
WRSG	Fert	3	3.04	0.64	0.6359
	Time	4	16.1	19.71	<0.0001
	Fert×time	12	14.6	0.58	0.8225
LWSG	Fert	3	4.23	1.33	0.3779
	Time	4	123	29.19	<0.0001
	Fert×time	12	166	0.47	0.9285
EWSG	Fert	3	2.68	0.23	0.8737
	Time	4	17.3	3.44	0.0306
	Fert×time	12	15.7	0.64	0.7796
RLWP	Fert	3	3.03	0.5	0.7084
	Time	4	15.5	14.63	<0.0001
	Fert×time	12	14.3	0.87	0.5887
WRBA	Fert	3	5.73	1.01	0.4537
	Time	4	91.8	8.63	<0.0001
	Fert×time	12	138	1.38	0.1822
EWBA	Fert	3	4.38	0.5	0.6982
	Time	4	89.8	7.55	<0.0001
	Fert×time	12	135	1.25	0.2582
LWBA	Fert	3	62	1.11	0.3519
	Time	4	18	3.13	0.0405
	Fert×time	12	16.6	1	0.4905
ELWR	Fert	3	3.78	0.19	0.896
	Time	4	13.9	9.45	0.0007
	Fert×time	12	12.5	0.64	0.7764

[a] d.f., degrees of freedom; Fert, fertilization; WRSG, whole ring specific gravity; LWSG, latewood specific gravity; EWSG, earlywood specific gravity; RLWP, ring latewood percentage; WRBA, whole ring basal area; EWBA, earlywood basal area; LWBA, latewood basal area; ELWR, earlywood:latewood ratio.

Results

Results of the ANOVA for the New Bern and Bertie sites are presented in Tables 1 and 2, respectively. Plots of the estimated means from the ANOVA models are presented in Figures 1 and 2 for New Bern and Bertie, respectively. The covariate (data from the year prior to fertilization) used to adjust for pretreatment differences was found to be statistically significant for all the properties analyzed (not presented here). The main effect of time was significant for all growth and wood properties, except for WRSG at New Bern. Because our interest was to identify the influence of different midrotation fertilization regimes on growth and wood properties in a thinned site and an unthinned site, our results and discussion will be restricted to the main effect of treatment and treatment by time interaction terms.

Wood Properties

The treatment by time interaction was significant for LWSG at New Bern. In the first year following fertilization, significant differences were observed for the 224N ($P = 0.0095$) and 336N ($P <$

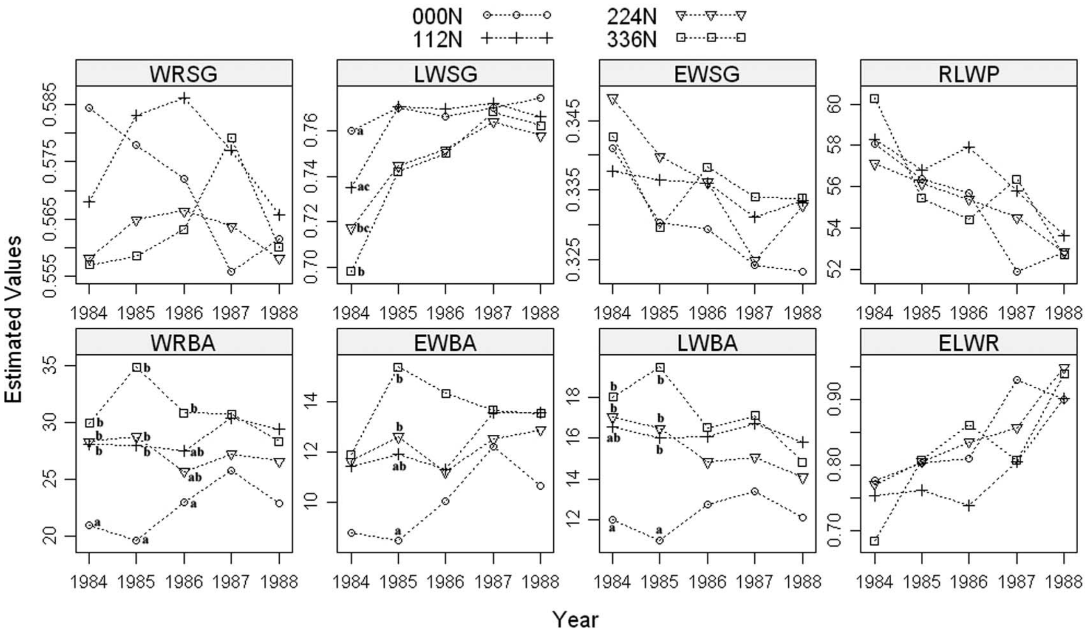

Figure 1. Plots of estimated mean growth and wood properties for different levels of nitrogen application by year at New Bern. WRBA, EWBA, and LWBA were measured in cm^2/tree. Treatments with different letters within a year were statistically significant. WRSG, whole ring specific gravity; LWSG, latewood specific gravity; EWSG, earlywood specific gravity; RLWP, percentage latewood; WRBA, whole ring basal area; EWBA, earlywood basal area; LWBA, latewood basal area; ELWR, earlywood:latewood ratio.

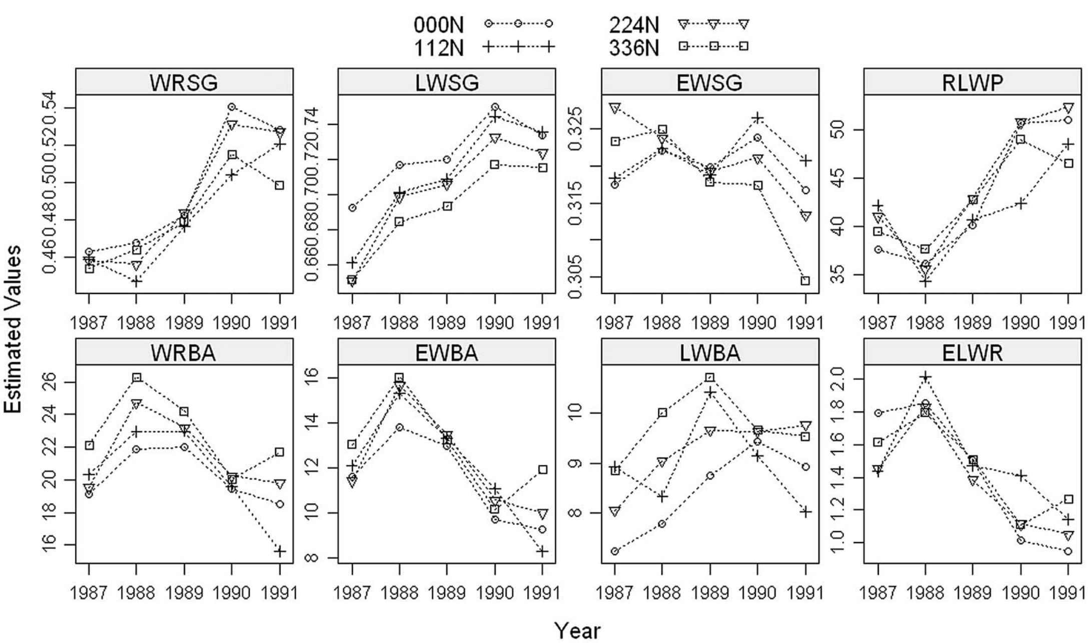

Figure 2. Plots of estimated growth and wood properties for different levels of nitrogen application by year at Bertie. WRBA, EWBA, and LWBA were measured in cm^2/tree. Treatments with different letters within a year were statistically significant. WRSG, whole ring specific gravity; LWSG, latewood specific gravity; EWSG, earlywood specific gravity; RLWP, percentage latewood; WRBA, whole ring basal area; EWBA, earlywood basal area; LWBA, latewood basal area; ELWR, earlywood:latewood ratio.

0.0001) treatments compared with the control, with LWSG decreasing by 0.062 (336N) and 0.043 (224N). In the same year, a significant difference in LWSG was also observed between treatments 336N and112N (decrease in LWSG = 0.037, $P = 0.0465$). Differences in LWSG were observed among fertilized and control trees in the second year postfertilization, but the differences were not statistically significant. After 3–4 years, LWSG of the fertilized and control trees became similar. At New Bern, the main effect of fertilizer treatment on LWSG was significant, with trees that received treatments of 336N ($P = 0.0313$) and 224N ($P = 0.0622$) having LWSG significantly lower than the control. At Bertie, the treatment by time interaction was not significant for LWSG, despite differences in LWSG of 0.031 (112N), 0.042 (224N), and 0.041 (336N) compared with the control being observed in the first year following fertilization. Significant treatment by time interaction and a treatment main effect was absent for WRSG, EWSG, and RLWP at both sites.

Growth Response

A treatment by time interaction was present at New Bern for WRBA but absent at Bertie. At New Bern, a significant increase was observed in WRBA for all treatments compared with the control for 2 years following fertilization. Compared with the control increases in WRBA of 7.1, 7.4, and 9.0 cm^2/tree in the first year ($P = 0.0189$, 0.0142, and 0.0007) and 8.4, 9.1, and 15.2 cm^2/tree in the second year ($P = 0.0279$, 0.0114, and <0.0001) were observed for the 112N, 224N, and 336N treatments respectively. By the third year after fertilization, only the 336N treatment showed a significant response in WRBA compared with the control (an increase of 7.9 cm^2/tree, $P = 0.0191$). At Bertie, the WRBA of trees which received the 336N treatment increased by 3 cm^2/tree compared with the control in the first year after fertilization and 2.8 (224N) and 4.4 (336N) cm^2/tree in the second, the differences were not statistically significant. A treatment by time interaction for EWBA was present at New Bern in the second year postfertilization but completely absent at Bertie with the EWBA of the 224N and 336N treatments, increasing significantly (4.1 and 6.9 cm^2/tree, respectively) compared with the control ($P = 0.0569$ and <0.0001).

A significant treatment by time interaction was present for LWBA at New Bern. In the first year following fertilization significant increases in LWBA (5 and 6 cm^2/tree) were observed for the 224N ($P = 0.0435$) and 336N ($P = 0.0050$) treatments compared with the control. In the second year, all treatments provided significant increases in LWBA (5, 5.5, and 8.5 cm^2/tree for treatments 112N, 224N, and 336N, with $P = 0.0368$, 0.0144, and < 0.0001, respectively) compared with the control. However, no differences in LWBA were observed among treatments at New Bern after the second year. The interaction between treatment and time for LWBA was absent at Bertie. The interaction between treatment and time was not significant for ELWR at either site.

Discussion

Several studies reported positive responses in growth following midrotation fertilization and thinning in loblolly pine (Amateis et al. 1996, Haywood and Tiarks 2002, Haywood 2005, Carlson et al. 2008). Generally, the response in wood properties following different silvicultural practices is secondary to the growth response. Thus, comparison of growth and wood property responses to any silvicultural treatment should be made simultaneously, but this has rarely been done. In this study, we examined growth and wood property responses following fertilization in a thinned and unthinned stand. We observed a significant increase in ring basal area growth (both EWBA and LWBA) and a reduction in LWSG for 2 to 3 years immediately following fertilization in the thinned stand. In the unthinned stand, responses to fertilization were observed, but they were not as apparent as in the thinned stand.

More often, it is assumed that the wood quality deteriorates and growth rate increases with increase in the intensity of silvicultural treatments applied to a stand. In this study, the response of both sites was in accordance with this assumption. The magnitude of decrease in LWSG and increase in WRBA, EWBA and LWBA was larger for the thinned and fertilized stand (New Bern) compared with the unthinned, fertilized stand (Bertie). The difference in response presumably is due to the additive effects of thinning and fertilization at New Bern. However, it is difficult to make definitive conclusions about the results observed in this study because of the confounding influence of stand location, climatic conditions, and age of the stands. The lack of fertilization response in the unthinned site (Bertie) suggests that this stand may not have been in a condition to respond to fertilization. High stand density levels in the unthinned stand may have restricted crown expansion and subsequent wood production. Thus, midrotation fertilization is often prescribed with thinning for this reason (Fox et al. 2007).

The response following silvicultural treatments can be classified as type A (a long-term response following the application of a limiting resource) and type B (a short term response following resource application) (Morris and Lowery 1988, Nilsson and Allen 2003). On the basis of the results presented here, it is evident that the response in SG and ring basal area following midrotation fertilization is transient in nature and typical of a type B response. Responses for LWSG lasted for a maximum of 2–3 years following fertilization in the thinned stand (Figure 1). A decrease in LWSG was present in the unthinned stand, but was smaller in magnitude compared with the thinned site (Figure 2). These results agree with findings for loblolly pine (Antony et al. 2009, Love-Myers et al. 2009) and radiata pine (*Pinus radiata* D. Don) (Nyakuengama et al. 2002, 2003) where a decrease in LWSG was observed in rings immediately following fertilization.

Our observations support the conclusion that the magnitude and duration of the response depends on the amount of N applied (Amateis et al. 2000) and whether or not the site was thinned (Figures 1 and 2). The decline in LWSG for the fertilized trees compared with the control in the first year following fertilization was in the following order: 336N $>$ 224N $>$ 112N, with estimated values of 0.062, 0.043, and 0.025, respectively, in the thinned stand, and 0.041, 0.041, and 0.031, respectively, in the unthinned stand. The response lasted for approximately 3 years following fertilization in trees which received 336N and slowly converged to the LWSG profile of control trees (Figure 1) in the thinned stand.

In loblolly pine, the transition from earlywood to latewood in an annual ring largely depends on changes in the concentration of the growth hormone auxin (Larson et al. 2001). Latewood formation commences when height growth (shoot elongation) ceases and new needles become mature allowing a large amount of photosynthetic material to become available for secondary wall thickening (Megraw 1985). Fertilization in a midrotation stand following thinning generally results in increased foliar growth with increased auxin production and a subsequent reduction in the availability of photosynthate for secondary cell wall thickening. An increase in the number of cells produced (increased auxin production) and a decrease in wall thickness (reduced photosynthate availability) might explain the temporary reduction in LWSG and subsequent reduction in WRSG with corresponding growth increases (WRBA, EWBA, and LWBA) following midrotation fertilization.

In summary, we evaluated the effect of midrotation fertilization on growth and wood properties in thinned and unthinned loblolly pine stands. A temporary reduction in LWSG was observed for 2–3 years immediately following the application of nitrogen in the thinned stand but was not as apparent in the unthinned stand. WRBA, EWBA, and LWBA also showed similar behavior with a distinct response (increase) in the thinned stand only. ELWR in both thinned and unthinned stands did not change significantly following midrotation fertilization. The decrease in LWSG for a short period of time following fertilization may impact ring SG and hence the strength of wood produced and pulp yield. For instance, according to Mitchell 1964 a SG difference of 0.02 units can lead to differences of 22.7 kg (50 lb) in pulp yield per ton of round wood, emphasizing the importance of changes in wood properties (here SG) on pulp productivity. We might also speculate that the decrease in ring SG following change in LWSG for a period of 2–3 years at midrotation may produce a weak band of mature wood and hence the strength of products made from it. For example, Downes et al. (2002) observed a decrease in density; increase in microfibril angle and a slight decrease in stiffness following midrotation application of N and P in thinned radiata pine (*P. radiata* D. Don) stands. However, in loblolly pine further studies are needed to confirm these assumptions.

Literature Cited

ALBAUGH, T.J., H.L. ALLEN, P.M. DOUGHERTY, AND K.H. JOHNSEN. 2004. Long term growth responses of loblolly pine to optimal nutrient and water resource availability. *For. Ecol. Manag.* 192:3–19.

ALBAUGH, T.J., H.L. ALLEN, AND T.R. FOX. 2007. Historical patterns of forest fertilization in the southeastern United States from 1969 to 2004. *South. J. Appl. For.* 31(3):129–137.

ALLEN, H.L., T.R. FOX, AND R.G. CAMPBELL. 2005. What is ahead for intensive pine plantation silviculture in the South? *South. J. Appl. For.* 29(2):62–69.

AMATEIS, R.L., J. LIU, M.J. DUCEY, AND H.L. ALLEN. 2000. Modeling response to midrotation nitrogen and phosphorus fertilization in loblolly pine plantation. *South. J. Appl. For.* 24(4):207–212.

AMATEIS, R.L., P.J. RADTKE, AND H.E. BURKHART. 1996. Growth and yield of thinned and unthinned plantations. *J. For.* 94(12):19–23.

ANTONY, F., L. JORDAN, R.F. DANIELS, L.R. SCHIMLECK, A. CLARK, AND D.B. HALL. 2009. Effect of midrotation fertilization on growth and specific gravity of loblolly pine. *Can. J. For. Res.* 39(5):928–935.

BURTON, J.D., AND E. SHOULDERS. 1974. Fast-grown, dense loblolly pine saw logs: A reality. *South. J. Appl. For.* 72(10):637–641.

CARLSON, C.A., T.R. FOX, H.L. ALLEN, AND T.J. ALBAUGH. 2008. Modeling mid-rotation fertilizer responses using the age-shift approach. *For. Ecol. Manag.* 256(3):256–262.

CLARK, A., B.E. BORDERS, AND R.F. DANIELS. 2004. Impact of vegetation control and annual fertilization on properties of loblolly pine wood at age 12. *For. Prod. J.* 54(12):90–96.

DICKENS, D.E., D.J. MOOREHEAD, AND B. MCELVANY. 2003. Pine plantation fertilization. *Better Crops* 87(1):12–15.

DOWNES, G.M., J.G. NYAKUENGAMA, R. EVANS, R. NORTHWAY, P. BLAKEMORE, R.L. DICKSON, AND M. LAUSBERG. 2002. Relationship between wood density, microfibril angle and stiffness in thinned and fertilized *Pinus radiata*. *IAWA J.* 23(3):253–265.

FOX, T.R., H.L. ALLEN, T.J. ALBAUGH, R. RUBILAR, AND C.A. CARLSON. 2007. Tree nutrition and forest fertilization of pine plantations in the southern United States. *South. J. Appl. For.* 31(1):5–11.

HAYWOOD, J.D. 2005. Influence of precommercial thinning and fertilization on total stem volume and lower stem form of loblolly pine. *South. J. Appl. For.* 29(4):215–220.

HAYWOOD, J.D., AND A.E. TIARKS. 2002. Response of second-rotation southern pines to fertilizer and planting on old beds: Fifteenth-year results. P. 497–502 in *Eleventh biennial southern silvicultural research conference*, Outcalt, K. (ed.). US For. Serv., South. Res. Stn., Asheville, NC.

JOKELA, E.J., P.M. DOUGHERTY, AND T.A. MARTIN. 2004. Production dynamics of intensively managed loblolly pine stands in the southern United States: A synthesis of seven long-term experiments. *For. Ecol. Manag.* 192:117–130.

LARSON, P.R., D.E. KRETSCHMANN, A. CLARK, AND J.G. ISEBRANDS. 2001. *Formation and properties of juvenile wood in southern pines: A synopsis.* US For. Serv. Gen. Tech. Rep. FPL-GTR-129. 42 p.

LOVE-MYERS, K.R., A. CLARK III, L.R. SCHIMLECK, E.J. JOKELA, AND R.F. DANIELS. 2009. Specific gravity responses of slash and loblolly pine following mid-rotation fertilization. *For. Ecol. Manag.* 257(12):2342–2349.

MEGRAW, R.A. 1985. *Wood quality factors in loblolly pine.* TAPPI Press, Atlanta, GA. 88 p.

MITCHELL, H. 1964. Patterns of variation in specific gravity of southern pines and other coniferous species. *TAPPI J.* 47:276–283.

MORA, C.R. 2003. *Effects of early intensive silviculture on wood properties of loblolly pine.* M.Sc. thesis. North Carolina State Univ., Raleigh, NC. 92 p.

MORRIS, L.A., AND R.F. LOWERY. 1988. Influences of site preparation on soil conditions affecting stand establishment and tree growth. *South. J. Appl. For.* 12:170–178.

NILSSON, U., AND H.L. ALLEN. 2003. Short- and long-term effects of site preparation, fertilization and vegetation control on growth and stand development of planted loblolly pine. *For. Ecol. Manag.* 175(1–3):367–377.

NYAKUENGAMA, J.G., G.M. DOWNES, AND J. NG. 2002. Growth and wood density responses to later-age fertilizer application in *Pinus radiata. IAWA J.* 23(4):431–448.

NYAKUENGAMA, J.G., G.M. DOWNES, AND J. NG. 2003. Changes caused by midrotation fertilizer application to the fiber anatomy of *Pinus radiata. IAWA J.* 24(4):397–409.

SAS. 2004. *SAS OnlineDoc version 9.1.3.* SAS Institute Inc., Cary, NC. Available online at support.sas.com/onlinedoc/913/docMainpage.jsp; last accessed Mar. 2, 2011.

TASISSA, G., AND H.E. BURKHART. 1998. Modeling thinning effects on ring specific gravity of loblolly pine (*Pinus taeda* L.). *For. Sci.* 44(2):212–223.

ZOBEL, B.J., G.F. GROGGANS, T.E. MAKI, AND F. HENSON. 1961. Some effects of fertilizers on wood properties of loblolly pine. *TAPPI* 44(3):187–191.