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EFFECT OF MID-ROTATION FERTILIZATION ON STIFFNESS AND STRENGTH OF LOBLOLLY PINE WOOD

Finto Antony[1,*], **Laurence R. Schimleck**[2], **Richard F. Daniels**[1] and **Alexander Clark III**[3]

[1]Warnell School of Forestry and Natural Resources, The University of Georgia,
Athens, GA 30602, U.S.A.
[2]Department of Wood Science and Engineering, Oregon State University, Corvallis, OR 97331, U.S.A.
[3]USDA Forest Service, Southern Research Station, Athens, GA 30602, U.S.A. (*retired*)
*Corresponding author; e-mail: fintoa@warnell.uga.edu

ABSTRACT

Trees sampled from a loblolly pine mid-rotation fertilization trial were used in this study. The study was laid out in a randomized complete block design with four levels of nitrogen fertilizer as treatments: control (000N), 112 (112N), 224 (224N), and 336 (336N) kg/ha of nitrogen, with each treatment replicated in 4 blocks. Two trees were destructively sampled from each plot giving a total of 32 trees. Bolts 0.6 m in length were collected from each tree (3 bolts per tree); with the midpoint of each bolt at heights of 2.4, 7.3 and 12.2 m from the base of the tree (each bolt represented the midpoint of standard 4.9 m saw logs). Static bending samples with dimensions 25 by 25 by 406 mm (radial, tangential and longitudinal dimensions respectively) were cut from the bolts that included the 25 mm of wood produced immediately following fertilization. Data on modulus of elasticity (MOE, stiffness) and modulus of rupture (MOR, strength) were collected from clear static bending samples. Based on the analysis of variance, no significant treatment effect was observed on MOE and MOR. However, MOE and MOR decreased in wood produced immediately after fertilization for trees which received the highest level of fertilization (336N). A decreasing trend in MOE and MOR with height was also present.

Keywords: Loblolly pine, stiffness, strength, fertilization.

INTRODUCTION

Mid-rotation thinning and fertilization is a widely utilized silvicultural practice for the management of pine plantations. By 2004 a total of 6.5 million ha of pine plantations in the southeastern US had received fertilization with a peak annual mid-rotation ferti-lization of 0.64 million ha in 1999 (Albaugh *et al*. 2007). Mid-rotation fertilization of loblolly pine (*Pinus taeda* L.) stands has been found to have a strong positive influence on growth rate and volume production. Based on the studies established by the Forest Productivity Cooperative throughout the southern US, over 80% of stands responded positively to the addition of N+P fertilizers at mid-rotation (Allen *et al*. 2005), with re-ported growth gains of approximately 3630 kg/ha/year averaged over an 8-year period 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 and hence product quality. Several studies have identified the effect of fertilization on specific gravity (SG). Mora (2003) reported no change in whole core average SG in loblolly pine following early age fertilization (at ages 1 and 4). However, Jokela *et al.* (2004) observed a site-specific decrease in SG (compared to the control) following fertilization combined with weed control based on a data available from seven fertilization trials established across the natural range of loblolly pine. Several studies have reported a decrease in SG of rings produced immediately following fertilization in both loblolly pine (Albaugh *et al.* 2004; Antony *et al.* 2009a, 2009b; Love-Myers *et al.* 2009, 2010) and radiata pine (*Pinus radiata* D. Don) (Downes *et al.* 2002; Nyakuengama *et al.* 2002, 2003). Based on data from increment cores collected from the same trees as used in this study, Antony *et al.* (2009a) showed that modulus of elasticity (MOE, stiffness) estimated using near infrared (NIR) spectroscopy for wood produced in the three rings following the application of 336 kg/ha of nitrogen was decreased. The reduction in MOE in this region was explained by the combined effect of a decrease in SG and a slight increase in microfibril angle (MFA). However, little is known about the changes in modulus of rupture (MOR, strength) of wood following fertilization.

An understanding of the effect of fertilization on MOE and MOR of wood is of great importance to both wood growers and wood buyers as it determines the quality (and grade) of dimensional lumber. In this paper, we examine the effects of mid-rotation fertilization on static bending MOE and MOR for wood produced immediately following fertilization.

MATERIALS AND METHODS

Trees were sampled from a loblolly pine plantation established at New Bern, North Carolina, USA by the Forest Productivity Cooperative as part of their regionwide mid-rotation fertilization trial. The site is a poorly drained lower Coastal Plain site with leafy soil and has a site index of 21 m at age 25. The annual maximum and minimum temperatures of this location are 22.9 and 11.3 °C (climate average from 1971–2000). The average annual rainfall is 1423 mm, with summer rainfall being 580 mm and winter rainfall being 428 mm. The study was laid out in a randomized complete block design with four levels of nitrogen fertilizer as treatments: control (000N), 112 (112N), 224 (224N), and 336 (336N) kg/ha of nitrogen. Each treatment was randomly allocated to 4 plots within each block, giving 16 plots for the whole study. In addition to nitrogen fertilizer, all plots in the study received 28 kg/ha of phosphorous. The operational rate of fertilization is generally 224 kg/ha of nitrogen along with 28 kg/ha phosphorous. The blocking was based on soil property variation existing in the field. All study plots were thinned to 613 trees/ha at age 13 (in 1983) and fertilized at age 14 (in March 1984). The trees for the present study were harvested at age 33 (in May 2003).

Two trees representing the average diameter at breast height of all the trees in the treatment plot were destructively sampled from each plot (a total of 32 trees). From the felled trees, bolts 0.6 m in length were collected (3 bolts per tree) with the midpoint of

each bolt at heights of 2.4, 7.3 and 12.2 m from the base of tree (each bolt representing the midpoint of standard 4.9 m saw logs). From each 0.6 m bolt, a 3.8 cm thick radial slab was cut from bark-to-bark through the pith and the slabs were kiln dried to 12 percent moisture content. After drying, each slab was split in half through the pith and a static bending sample with dimensions 25 by 25 by 406 mm (radial, tangential and longitudinal dimensions respectively) was cut from each board. The static bending samples were cut from each board to include the 25 mm of wood (in the radial direction) produced immediately following fertilization, *i.e.* the 25 mm of wood produced following fertilization in 1984. Depending on the height at which we sampled, the number of annual rings that the 1984 ring was from the pith differed. The approximate number of rings for each treatment by height combination is presented in Table 1. A total of 192 samples were collected (32 trees, 3 heights, and 2 sides of each bolt), but only 162 clear static bending samples were used for further testing (30 samples were not tested owing to defects).

Table 1. The approximate number of annual rings that the 1984 ring was from the pith for each height sampled and fertilizer treatment combination.

	Treatments			
Height	000N	112N	224N	336N
2.4	11	11	10	10
7.3	7	7	6	6
12.2	4	4	4	3

The clear static bending samples were tested at 12 percent EMC over a 355.6 mm span with center loading and pith side up on a Tinius Olsen Test Machine following the procedures for alternate sample size under ASTM D143-94 (ASTM Standard D143, 2009). A continuous load was applied at a head speed of 1.8 mm per minute, rather than 1.3 mm per minute, to reduce test time. MOE and MOR of each sample were calculated using procedures outlined in ASTM D-143 (ASTM Standard D143, 2009). MOE, MOR and number of rings per 25 mm of static bending samples collected from two sides of the board at each height was averaged and used for further statistical analysis.

Separate analyses of variance (ANOVA) were conducted on MOE and MOR data. A linear mixed-effects model was utilized to account for block-to-block variability and the variance due to subsampling of trees from each plot. The number of rings in each sample might vary with the level of fertilizer applied and height at which the sample was collected and may have an influence on the samples used to determine MOE and MOR. We used number of rings in the sample (an average from two static bending samples collected from samples at each height) as a covariate in the analysis. The full linear mixed model used for the analysis can be written as:

$$y_{ijkl} = \mu + F_i + H_l + (FH)_{il} + b_j + (Fb)_{ij} + (FbH)_{ijl} + \beta x_{ijkl} + e_{ijkl} \tag{1}$$

$$i = 1,\ldots,4,\ j = 1,\ldots,4,\ k = 1,2,\ l = 1,\ldots,3,$$

where y_{ijkl} = the property of interest of the lth height, of the kth tree, of the jth block, receiving the ith fertilization treatment; μ = the population mean; F_i = the ith fertilization effect; H_l = the lth height effect; $(FH)_{il}$ = the interaction of the ith fertilization and l^{th} height effect; b_j = the random effect of the jth block with $b_j \sim NID(0, \sigma_b^2)$; $(Fb)_{ij}$ = the random interaction effect of the ith fertilization and j^{th} block effects with $(Fb)_{ij} \sim NID(0, \sigma_{Fb}^2)$, the true error term for testing the treatment effect; $(FbH)_{ijl}$ = the random interaction of the ith fertilization j^{th} block and l^{th} height effect with $(FbH)_{jl} \sim NID(0, \sigma_{FbH}^2)$, the true error term for testing the main effect of height and interaction between treatment and height; β is the coefficient associated with the linear covariate number of rings in sample, x_{ijkl}; and e_{ijkl} = subsampling error, with $e_{ijkl} \sim NID(0, \sigma^2)$. A sliced effect test was used to compare the mean differences among fertilization treatments at a fixed height level and *vice versa*, where the interaction term $(FH)_{il}$ was found to be significant. Tukey's Honestly Significant Difference (HSD) test was used to conduct pairwise mean comparisons of treatments where a significant (p-value < 0.05) result was obtained from ANOVA.

In addition, we expect that measurements taken across the tree at different heights are correlated. For our data, we have equally spaced measurements taken along the tree stem and different covariance structures may be used to account for the autocorrelation of wood properties within a tree. The model was fitted to the data with different correlation structures such as compound symmetry, first order autoregressive (AR(1)), first order autoregressive heterogeneous (ARH(1)) and unstructured. Final model selection was based on the improvement made in the model using the Akaike's information criteria (AIC) and Bayesian information criteria (BIC). Based on AIC and BIC, an ARH(1) structure was selected for MOE and no correlation structure was favored for MOR in addition to the random effects.

All the tests were conducted using the MIXED procedure with a restricted maximum likelihood estimation (REML) method available in SAS version 9.2 (SAS Institute Inc. 2008). The level of significance used in all tests is 0.05, unless otherwise stated.

RESULTS

The results from analysis of variance are presented in Table 2. The effect of fertilization and its interaction with height was not significant for either MOE or MOR in wood produced immediately after fertilization. Based on polynomial contrasts, linear and

Table 2. Results from analysis of variance for both modulus of elasticity (MOE) and modulus of rupture (MOR).

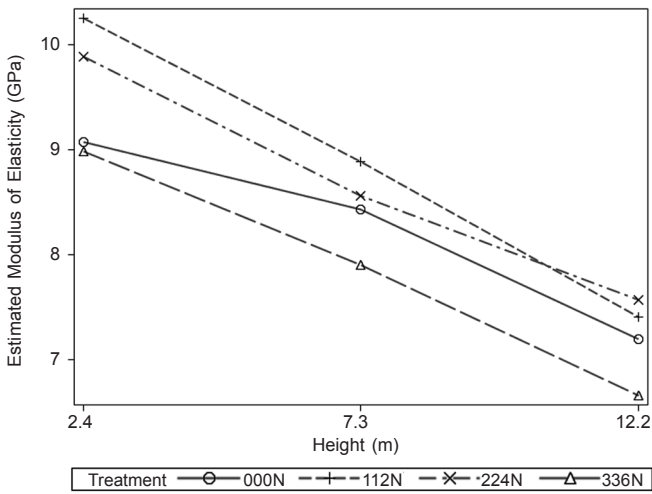| Effect	Modulus of Elasticity		Modulus of Rupture	
	F-value	p-value	F-value	p-value
Fertilization	1.96	0.1606	1.39	0.3025
Height	17.23	<0.0001	50.52	<0.0001
Fertilization*Height	0.32	0.9171	1.96	0.1122
Number of rings	10.72	0.0017	2.11	0.1517

Figure 1. Estimated modulus of elasticity (MOE) with sampled height for each fertilization treatment (000N - Control; 112N – 112 kg/ha; 224N – 224 kg/ha and 336N – 336 kg/ha).

quadratic trends in MOE and MOR with treatment were absent. Though not statistically significant, after adjusting for number of rings within samples, a drop in mean MOE and MOR was evident at all heights for trees that received 336N compared to the control, 112N and 224N (Fig. 1). The difference in MOE between the control and the 336N treatment was negligible (0.09 GPa) at 2.4 m, but a consistent decrease in MOE (0.53 GPa) was observed between these two treatments at the other two heights
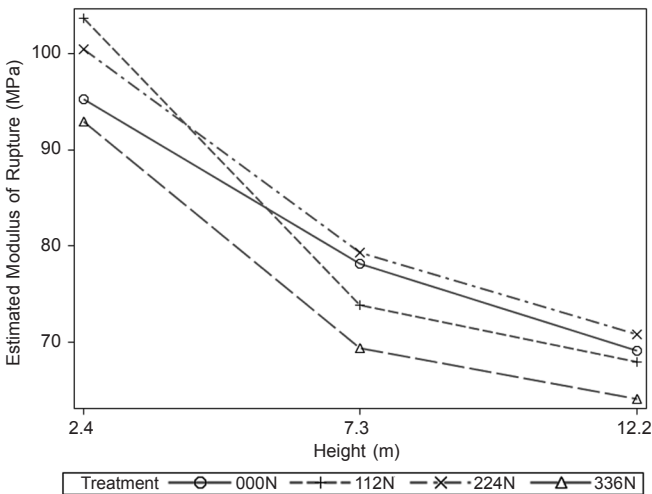

Figure 2. Estimated modulus of rupture (MOR) with sampled height for each fertilization treatment (000N - Control; 112N – 112 kg/ha; 224N – 224 kg/ha and 336N – 336 kg/ha).

(7.3 and 12.2 m). MOE of trees which received the 112N and 224N treatments was better than that of the control trees at all heights, especially at the base of the tree. MOR following the 336N treatment was decreased by 2.3, 8.8 and 5 MPa respectively at heights of 2.4, 7.3 and 12.2 m (Fig. 2) compared to the control. MOR of the treatments 112N (8.4 MPa) and 224N (5.2 MPa) was higher than the control trees at 2.4 m and was consistent at other height levels for treatment 224N. However, for treatment 112N a decrease in MOR was observed at other heights (7.3 and 12.2 m) compared to the control (Fig. 2).

A significant height-related trend was observed for both MOE and MOR. For MOE there was a linear decreasing trend with height (p-value < 0.0001), while for MOR linear (p-value < 0.0001) and quadratic (p-value < 0.0001) decreasing trends with height were observed.

The covariate, number of rings within a sample, had a significant linear effect on MOE, but not on MOR. We allowed the slope of the relationship to vary with sampled height and fertilization level, but it was not significant in model development and subsequently dropped. Based on the partial linear coefficient (β = 0.58), MOE increased as the number of rings within each sample increased.

DISCUSSION

Based on the short clear static bending samples collected in this study from the zone of wood produced immediately after fertilization at three heights, a statistically significant difference in MOE and MOR among fertilization treatments was absent. Though not significant, a decrease in MOE and MOR of wood produced following the 336N fertilizer treatment was evident at all heights. This supports the conclusions of Antony *et al*. (2009a), who reported a significant drop in estimated MOE (from a NIR-based calibration using SilviScan MOE data) for three rings produced after fertilization using data collected from increment cores sampled at five heights for trees used in this study. Similarly, Downes *et al*. (2002) observed a decrease in MOE of boards cut from wood produced immediately after fertilization in radiata pine, but no change was observed in MOR. As deduced from previous studies, MOE and MOR of wood are largely influenced by the density and MFA (Megraw *et al*. 1999; Downes *et al*. 2002). Hence, the reduction in MOE and MOR for treatment 336N observed in this study might be due to a decrease in density (Nyakuengama *et al*. 2002; Antony *et al*. 2009b) and an increase in MFA (Antony *et al*. 2009a, 2009b). The decrease in density, to a certain extent, can be related to changes in the earlywood:latewood ratio and in tracheid anatomical characteristics such as a decrease in wall thickness and an increase in radial diameter (Nyakuengama *et al*. 2003; Antony *et al*. 2009a).

In this study, we observed that the MOE and MOR of trees receiving the 112N and 224N treatments were higher than that of the control, at least at the base of the tree. One reason for the observed increase in both properties might be that wood produced following mid-rotation fertilization is in the mature wood zone near the bottom of the tree with lower MFA and higher density (Downes *et al*. 2002). In previous studies, Antony *et al*. (2009a, 2009b) observed that the density of wood produced immediately

following these treatments increased or was unchanged compared to the control. In addition, the increase in MFA for treatments 112N and 224N was minimal. A possible explanation for the increase or no change in MOE and MOR for trees receiving the 112N and 224N treatments is the absence of change in density and MFA. This might be due to continued production of latewood cells even after fertilization which is plausible considering the relatively high summer precipitation observed at the site.

The decreasing trend in MOE and MOR with height agrees with that observed by Antony *et al*. (2011), where they examined within-tree variation of MOE and MOR using static bending samples collected from conventionally managed loblolly pine plantations. The decrease in MOE and MOR with height is primarily due to the interaction of change in density and MFA with height (Cown 1992; Megraw *et al*. 1999; Jordan *et al*. 2005, 2006), which is influenced by the transition from mature to juvenile wood that occurs with height within the sheath of wood produced annually. The number of rings from the pith for the 1984 ring was approximately 10, 7 and 4 at 2.4, 7.3 and 12.2 m respectively.

We also observed that the covariate number of rings in the 25 mm short clears had a significant effect on MOE but not on MOR. Based on this study, MOE increased with an increase in rings within the sample (a linear trend was observed). Number of rings within a sample is an important criterion in conifer lumber grading and is a significant predictor of MOE of loblolly pine (Schumsky *et al*. 2006). The positive effect of the number of rings on MOE has been shown in previous studies, for example for samples from redwood species (*Sequoia* sp.; Mascia & Cramer 2009).

In summary, there was no significant decrease in MOE and MOR immediately following fertilization at this site. However, there was a tendency for MOE and MOR to decrease in trees which received the highest rate of N fertilization. A decreasing trend with tree height was observed for both MOE and MOR.

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