

Effect of midrotation fertilization on growth and specific gravity of loblolly pine

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Abstract: Wood properties and growth were measured on breast-height cores and on disks collected at different heights from a thinned and fertilized midrotation loblolly pine (*Pinus taeda* L.) plantation in the lower Coastal Plain of North Carolina. The study was laid out in a randomized complete-block design receiving four levels of nitrogen (N) fertilizer: unfertilized control and 112, 224, and 336 kg/ha plus 28 kg/ha of phosphorus with each treatment. The effect of fertilization was analyzed for the whole-disk and for a 4 year average following fertilization on data collected from breast-height cores and from disks. The fertilization treatments did not significantly affect whole-disk wood properties but significantly increased radial growth. Fertilization rate of 336 kg/ha N significantly reduced 4 year average ring specific gravity and late-wood specific gravity. Wood properties of trees that received 112 and 224 kg/ha N were not affected following treatment. There was no height related trend in wood property changes due to fertilization. Fertilization significantly increased ring basal area and earlywood basal area. In summary, there was a decline in wood properties and an increase in basal area growth immediately after fertilization; both depended on the rate of fertilizer applied irrespective of height.

Résumé : Les auteurs ont mesuré les propriétés du bois et la croissance sur des carottes prélevées à hauteur de poitrine et des disques prélevés à différentes hauteurs dans une plantation à mi-révolution de pin à encens (*Pinus taeda* L.) éclaircie, fertilisée et située dans la basse plaine côtière de la Caroline du Nord. L'expérience était structurée en blocs complets aléatoires dans lesquels quatre niveaux de fertilisant azoté ont été appliqués : témoin, 112, 224 et 336 kg/ha, et 28 kg/ha de phosphore ont été ajoutés à chaque traitement. L'effet de la fertilisation a été analysé sur les moyennes des disques entiers et les moyennes des 4 années suivant le traitement à partir des données mesurées sur les carottes et les disques. Les traitements de fertilisation n'ont pas eu d'effet significatif sur les propriétés du bois à l'échelle du disque entier mais ont causé une augmentation significative de la croissance radiale. Un taux de fertilisation azotée de 336 kg/ha a entraîné une réduction significative de la densité relative moyenne des cerne annuels et du bois final des 4 années suivant le traitement. Les traitements de fertilisation azotée à 112 et 224 kg/ha n'ont pas eu d'effet sur les propriétés du bois. Les changements des propriétés du bois dus à la fertilisation n'ont suivi aucune tendance reliée à la hauteur dans l'arbre. La fertilisation a causé une augmentation significative de la surface terrière des cerne et du bois initial. En résumé, les propriétés du bois ont décliné et la croissance en surface terrière a augmenté immédiatement après la fertilisation mais chacun de ces effets dépendait du taux de fertilisation utilisé peu importe la hauteur.

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Introduction

Midrotation application of thinning and fertilization is a widely accepted management practice in pine plantations growing throughout world. In the southeastern United States the adoption of this practice has been rapid. The Forest Nutrition Cooperative (Forest Nutrition Cooperative 2006) reported a sevenfold increase in the annual area of pine plantations fertilized, from 81 000 ha in 1997 to 0.6×10^6 ha

in 2002, in the southeastern United States. This increase can be attributed to the capacity of midrotation fertilization to augment wood production in biologically and financially attractive ways.

Fertilization at midrotation in loblolly pine (*Pinus taeda* L.) stands has been found to have a strong positive influence on volume production. Data from various field trials established by the Forest Nutrition Cooperative pointed out that over 85% of fertilized stands responded to a combination of nitrogen (N) and phosphorus (P) fertilization (one-time application of 224 kg/ha N and 28 kg/ha P) with an average growth gain of 30% over a 6 year period (Forest Nutrition Cooperative 2006). A long-term monitoring study across a wide range of sites in Georgia reported that intensive practices such as vegetation control combined with fertilization in loblolly pine plantations can produce a mean annual increment of 23 to 32 $\text{m}^3 \cdot \text{ha}^{-1} \cdot \text{year}^{-1}$ by an age of 10–12 years, which was a 1.5- to 3.5-fold increase in annual increment compared with the values obtained in the control (Borders and Bailey 2001). Growth and yield models prepared from fertilized midrotation loblolly pine plantations also agreed with these conclusions (Amateis et al. 2000).

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The effect of fertilization on wood quality is of concern to the forest products industry. Wood properties of interest that can be potentially affected by fertilization include specific gravity (SG), latewood and earlywood SG, percent latewood, microfibril angle, modulus of elasticity, and modulus of rupture. Of these, SG is considered to be a key wood property because of its strong correlation with strength and stiffness of solid wood products (Panshin and deZeeuw 1980), engineered wood products, and composite panels. SG is also highly correlated with pulp yield (Panshin and deZeeuw 1980). High SG wood will yield longer tracheids and paper with increased tear resistance, whereas low SG wood will generally have shorter tracheids with thinner walls and higher microfibril angle, and thus produce paper with good tensile, burst, fold, and sheet smoothness but with lower tear resistance and opacity (Smook 2002).

In conifers, the effect of fertilization at ages 1 and 4 at rates of 16 and 81 kg/ha, respectively, did not significantly affect the whole-core SG (Choong et al. 1970; Mora 2003). However, growth rings produced immediately following fertilization have shown a decrease in SG (Williams and Hamilton 1961; Zobel et al. 1961; Mallonee 1975; Morling 2002). The reduction in SG was observed for a variable period of time (reported to be 2–5 years) after fertilization and then reverted back to a pattern similar to that of unfertilized trees (Morling 2002; Nyakuengama et al. 2002). A similar pattern of decrease was observed for latewood SG in 12-year-old loblolly pine following annual fertilization (Clark et al. 2004). Researchers have also reported a reduction in percent latewood for a few years following fertilization (Williams and Hamilton 1961; Clark et al. 2004). However, a specific pattern of change due to fertilization was absent in earlywood SG. Specific gravity follows a declining trend with height. A limited number of studies have examined the effect of fertilization on wood properties at different heights, with Mallonee (1975) finding that fertilization has less influence at upper height levels.

In the last 20 years, midrotation fertilization following thinning has been widely used in loblolly pine plantation management. Based on the above research findings, from the perspective of volume growth and yield gains, these practices are promising. However, the quality of wood produced from fast-grown plantations is still a matter of concern. The main objective of this study was to examine the effects of midrotation fertilization on wood density and growth, including average whole-ring SG (WRSG), latewood SG (LWSG), earlywood SG (EWSG), percent latewood (WRLP), whole-ring basal area (WRBA), earlywood basal area (EWBA), and latewood basal area (LWBA). The second objective was to understand the presence of any trend in average wood properties and radial growth changes across height within a tree following midrotation fertilization. We presumed that wood SG would decrease and wood production would increase following midrotation thinning and fertilization in loblolly pine.

Materials and methods

The study was conducted on wood samples collected from an even-aged loblolly pine plantation planted in 1970 at New Bern, North Carolina, in the lower Coastal Plain. This

was one of the 19 installations of the Forest Nutrition Cooperative Regionwide 13 study established across the southeastern United States in site-prepared loblolly pine stands during 1984–1987 (Forest Nutrition Cooperative 1997). The experimental design was randomized complete block with four treatments replicated on four blocks (total of 16 plots). The treatments used in this study were an unfertilized control (000N) and 112 (112N), 224 (224N), and 336 (336N) kg/ha, with all treatments receiving 28 kg/ha P. The stand was thinned to 605 trees/ha in 1983 and treated with the different rates of N fertilizer in March 1984. All plots received an additional thinning to 346 trees/ha and fertilizer application of 224 kg/ha N in 1996, and the stand was harvested in 2003.

Increment cores of 12 mm in diameter were collected from nine standing trees at breast height (1.4 m) from each treatment plot (total $9 \times 4 \times 4 = 144$ trees) using a hydraulically driven increment core borer. Radial strips of 1.6 mm thick were sawn from these breast-height cores and conditioned to 8% moisture content. In addition to the breast-height cores, two trees representing the average DBH of the trees in the treatment plots were felled (total of 32 trees) to understand the effect of fertilization across heights within tree. Cross-sectional disks of 25 mm thick were cut at 1.4, 3.0, 4.5, 7.6, and 10.6 m up the stem of each felled tree. Two radial strips 13 mm thick were cut from each disk and dried at 50 °C. One strip was then sawn into a 1.6 mm thick radial strip and conditioned to 8% equilibrium 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 earlywood, latewood, and whole-ring width and SG. The densitometry data were also used to determine radial growth and percent 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 based on a green-volume and oven-dry-mass basis.

An analysis of variance (ANOVA) was conducted on whole-disk radial growth (WRBA, EWBA, and LWBA) and wood properties (WRSG, LWSG, EWSG, and WRLP) averaged for all rings from the pith up to year 1995 (here after referred as whole-core). We confined our analysis of whole-disk averages on values from pith up to year 1995, because all the plots in the study received a second application of N (224 kg/ha in 1996). Limiting analysis on values up to year 1995 will avoid the effect of the second fertilization and confine the inference to the effects of the initial midrotation fertilization treatments. The stand was 25 years old in 1995, which would be a typical final rotation age for an intensively managed loblolly pine stand with thinning and fertilization treatments at midrotation. In addition, a 4 year average was calculated for years 1984–1987 to examine any differences in growth and wood properties manifest in rings produced immediately following fertilization. The rationale for restricting our analysis to a 4 year average is twofold. Similar studies of loblolly pine and other species observed a wood property response for 3–5 years following fertilization. In addition, the total width of four rings is approximately equivalent to the thickness of a board cut from this region. All wood property averages were calculated after weighting

the respective ring properties by the proportion of the basal area of each ring represented to the total basal area.

Separate ANOVAs were conducted on the breast-height core data collected from standing trees (hereafter referred as standing-tree data) and radial strip data collected from disks at five height levels in felled trees (hereafter referred as felled-tree data). The ANOVA was performed separately on all growth and wood properties at different fertilization regimes (whole core, 4 year). A sliced-effect test was conducted when a significant interaction term was found from ANOVA, in which we compared the mean differences among different levels of one factor keeping the levels of the second factor fixed in the interaction term. Tukey's honestly significant difference test was also used to conduct pairwise mean comparisons of treatments where a significant result was obtained from ANOVA. A 4 year pretreatment (1980–1983) average was calculated to use as covariate in the analysis of the 4 year posttreatment average. The trees selected for sampling represented a random sample of all trees in the corresponding plot. Here, trees within plots represent random effects, and their contribution to the variance of wood properties can be estimated, indicating that a mixed-effects model could potentially be employed to account for tree-to-tree variation.

The full linear mixed model used for the analysis of standing-tree data can be written as

$$[1] \quad y_{ijk} = \mu + F_i + b_j + (Fb)_{ij} + e_{ijk} \quad i = 1, \dots, 4; \\ j = 1, \dots, 4; k = 1, 2, \dots, 9$$

where y_{ijk} is the property of interest of the k th tree, of the j th block, receiving the i th fertilization treatment; μ is the population mean; F_i is the i th fertilization effect; b_j is the random effect of the j th block with $b_j \sim \text{NID}(0, \sigma_b^2)$; $(Fb)_{ij}$ is the random interaction effect of the i th fertilization and j th block effects with $(Fb)_{ij} \sim \text{NID}(0, \sigma_{Fb}^2)$, the true error term for testing the treatment effect; and e_{ijk} is the error due to subsampling, with $e_{ijk} \sim \text{NID}(0, \sigma^2)$.

The full linear mixed model used for the analysis of felled-tree data can be written as

$$[2] \quad y_{ijkl} = \mu + F_i + H_l + (FH)_{il} + b_j + T_{ijk} \\ + (Fb)_{ij} + (FbH)_{ijl} + e_{ijkl} \\ i = 1, \dots, 4; j = 1, \dots, 4; k = 1, 2; l = 1, \dots, 5$$

where y_{ijkl} is the property of interest of the l th height, of the k th tree, of the j th block, receiving the i th fertilization treatment; μ is the population mean; F_i is the i th fertilization effect; H_l is the l th height effect; $(FH)_{il}$ is the interaction of the i th fertilization and l th height effect; b_j is the random effect of the j th block with $b_j \sim \text{NID}(0, \sigma_b^2)$; T_{ijk} is the random effect of the k th tree of the j th block receiving the i th fertilization with $T_{ijk} \sim \text{NID}(0, \sigma_T^2)$; $(Fb)_{ij}$ is the random interaction effect of the i th fertilization and j th block effects with $(Fb)_{ij} \sim \text{NID}(0, \sigma_{Fb}^2)$, the true error term for testing the treatment effect; $(FbH)_{ijl}$ is the random interaction of the i th fertilization and the j th block and the l th height effect with $(FbH)_{ijl} \sim \text{NID}(0, \sigma_{FbH}^2)$; and e_{ijkl} is residual error, with $e_{ijkl} \sim \text{NID}(0, \sigma^2)$, the true error term for testing the main effect of height and interaction between treatment and height.

We expected that correlation existed among the measure-

ments up the stem of each sample tree. Observations closer together will tend to be more alike than observations farther apart. If correlation among the repeated measurements exists, its autocorrelation pattern can be modeled with an appropriate spatial correlation model. Correlation structures are used for modeling dependence among observations. In the context of mixed-effects models, they are used to model the correlation among the within-subject errors. For our felled-tree data, we had unequally spaced measurements taken along the tree stem, so a spatial correlation structure could be used to account for the autocorrelation of wood properties within a tree. Equation 2 was fit to the complete data set with different spatial correlation structures. The spatial structures chosen included Gaussian, log linear, power, and linear models. The final model selection was based on the improvement made on the model using the Akaike information criterion and Bayesian information criterion. Based on these criteria, inclusion of correlation structure did not produce a significant improvement in the model fitting in the felled-tree data other than the improvement provided by the tree random effect.

All the tests were conducted using the MIXED procedure with a restricted maximum likelihood estimation method available in SAS version 9.1 (SAS Institute Inc. 2004). The level of significance used in all tests was 0.05, unless otherwise stated.

Results

The results of the ANOVA from standing-tree data and felled-tree data are presented in Tables 1 and 2, respectively. Large within-tree trends in growth and wood properties across the tree, from stump to tip, reported by previous studies were corroborated in the present study by the significant height term in all tests conducted (Table 2). Since many of the growth and wood properties did not seem to be significantly influenced by fertilization treatments, we have restricted the results section to the significant fertilizer effects and fertilizer by height interaction terms observed from the ANOVA.

The influence of fertilization on whole-disk average wood properties was absent in general. However, as can be seen in Table 2, there are instances where significant fertilization effects were found. The interaction between fertilizer and height was significant in the analysis of WRSG (Table 2) for felled-tree data. Further analysis on this interaction term revealed considerable variation in WRSG across heights within each treatment level, but differences among treatments within each level of height were absent. A significant fertilization effect was observed in whole-disk LWSG of felled trees (Table 2). Tukey's mean comparisons indicated that whole-disk LWSG was lower in treatment 336N than in treatment 112N ($P = 0.034$). However, for the felled trees, fertilizer treatments increased growth, as can be seen by the considerable increases in average WRBA and EWBA production (Table 2). The WRBA of trees that received the 224N treatment was significantly greater than that of the control ($P = 0.024$); this result can be attributed to the significant increase in EWBA for the 224N treatment when compared with values obtained in the control ($P = 0.043$).

Table 1. Analysis of variance results for mean radial growth and wood properties conducted on data collected from pith up to year 1995 (whole core) and 4 year postfertilization period from breast-height increment cores.

Property	Whole core		4 year	
	<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
WRSG	1.03	0.423	3.52	0.062
LWSG	0.83	0.509	9.69	0.004
EWSG	0.64	0.606	1.23	0.356
WRLP	3.14	0.079	2.69	0.109
WRBA	2.15	0.164	11.45	0.002
LWBA	2.09	0.173	15.35	<0.001
EWBA	2.17	0.161	8.27	0.006

Note: WRSG, whole-ring specific gravity; LWSG, late-wood specific gravity; EWSG, earlywood specific gravity; WRLP, whole-ring latewood percent; WRBA, whole-ring basal area; LWBA, latewood basal area; EWBA, earlywood basal area. WRSG, LWSG, and EWSG are unitless. WRLP is measured as a percentage. WRBA, LWBA, and EWBA are measured in square metres per hectare. The main effect of fertilizer test in the table has three numerator degrees of freedom (df) and nine denominator df.

A temporary reduction in LWSG and thus WRSG was observed for the 4 years immediately following fertilizer application. Over the 4 years, WRSG and LWSG were significantly affected by fertilization (Tables 1 and 2). In the breast-height core data set, the effect of fertilizer treatments on 4 year average WRSG was significant at a 0.1 significance level (Table 1). The Tukey's mean comparison revealed a decrease in WRSG for treatment 336N compared with treatment 112N, with a *P* value of 0.065 (Fig. 1). A significant fertilization effect was detected in 4 year average WRSG in felled trees. The mean comparison tests revealed that WRSG was lower in treatment 336N than in the control (*P* = 0.014), 112N (*P* = 0.004), and 224N (*P* = 0.039) (Fig. 2). The 4 year average LWSG of fertilized trees was found to be significantly lower, by an amount of 0.09, than that of unfertilized trees in the breast-height cores collected. In the breast-height cores, higher rates of fertilization (224N and 336N) produced wood with lower LWSG, by approximately 0.05, compared with the treatment 112N. Mean comparison tests indicated a significant decrease in LWSG in treatments 224N (*P* = 0.016) and 336N (*P* = 0.004) compared with the control (Fig. 1) and a significant difference between treatments 112N and 336N (*P* = 0.039) on the breast-height core data. In the felled-tree data, the 4 year average LWSG of trees that received treatment 336N was significantly lower than that of trees in the control (*P* = 0.007) and 112N treatment (*P* < 0.001), and the average LWSG of trees that received a fertilizer rate of 224N was lower than that of trees receiving 112N (*P* = 0.016) (Fig. 2). A treatment effect was absent on whole-core and 4 year average EWSG in both standing-tree and felled-tree data. The effect of fertilizer was significant on 4 year average WRLP on felled-tree data at a 0.1 significance level. However, no significant treatment difference was observed in Tukey's mean comparison test.

The amount of wood produced in the fertilized plots during the 4 year period following treatment was significantly

Table 2. Analysis of variance results for mean radial growth and wood properties conducted on data collected from pith up to year 1995 (whole core) and 4 year postfertilization period from disks collected at different height levels in felled trees.

Property	Source	Whole core		4 year	
		<i>F</i>	<i>P</i>	<i>F</i>	<i>P</i>
WRSG	H	167.46	<0.001	36.13	<0.001
	F	1.64	0.249	8.96	0.005
	H × F	2.29	0.021	0.27	0.992
LWSG	H	5.78	<0.001	4.00	0.007
	F	4.32	0.038	14.53	<0.001
	H × F	1.46	0.174	1.23	0.292
EWSG	H	24.66	<0.001	9.81	<0.001
	F	1.26	0.344	1.73	0.231
	H × F	1.88	0.062	1.05	0.419
WRLP	H	184.35	<0.001	38.64	<0.001
	F	0.86	0.496	3.75	0.054
	H × F	1.19	0.316	0.62	0.815
WRBA	H	2.87	0.033	2.82	0.035
	F	5.27	0.023	16.52	<0.001
	H × F	1.07	0.407	2.38	0.017
LWBA	H	51.85	<0.001	7.45	<0.001
	F	2.51	0.125	15.73	<0.001
	H × F	0.48	0.916	4.46	<0.001
EWBA	H	15.18	<0.001	17.63	<0.001
	F	5.31	0.022	15.28	<0.001
	H × F	1.95	0.052	2.16	0.029

Note: The trees in this study received four levels of nitrogen fertilizer (unfertilized control and 112, 224, and 336 kg/ha), and the disks were collected from five height levels (1.4, 3.0, 4.5, 7.6, and 10.6 m). All notations and measurement units are the same as those described in Table 1. The main effect of height (H) has four numerator degrees of freedom (df) and nine denominator df; the main effect of fertilization (F) has three numerator df and 48 denominator df; the interaction between height and fertilization effect (H × F) has 12 numerator df and 48 denominator df.

greater than that in the unfertilized plots (Tables 1 and 2). The increase in the 4 year average WRBA was due to the cumulative increase in LWBA and EWBA during the period following fertilization (Tables 1 and 2). A height-related trend in basal area growth was present in the 4 year averages of WRBA, LWBA, and EWBA, as indicated by significant treatment by height interactions (Table 2). All fertilization treatments (112N, 224N, and 336N) produced a significant increase in 4 year average WRBA, LWBA, and EWBA compared with the control in the breast-height cores (Fig. 1). For the felled-tree data, the 336N treatment consistently produced an increase in 4 year average WRBA at all heights and an increase in LWBA and EWBA at all heights except 10.6 m when compared with the unfertilized trees (Fig. 2).

Discussion

Basal area growth of loblolly pine increased following midrotation fertilization. A similar response in 10 year cumulative basal area and volume growth was reported from the same site following N fertilization (Forest Nutrition Cooperative 1997). Based on the Forest Nutrition Cooperative's report, the greatest response was observed for the higher rates of fertilization (224N and 336N). These results

Fig. 1. Plots of estimated 4 year postfertilization means (1984–1987) of growth and wood properties by treatment. The data were collected from breast-height increment cores obtained from trees that received four levels of nitrogen fertilizer (unfertilized and 112, 224, and 336 kg/ha). The error bars represent ± 2 standard error. All notations and measurement units are as described for Table 1.

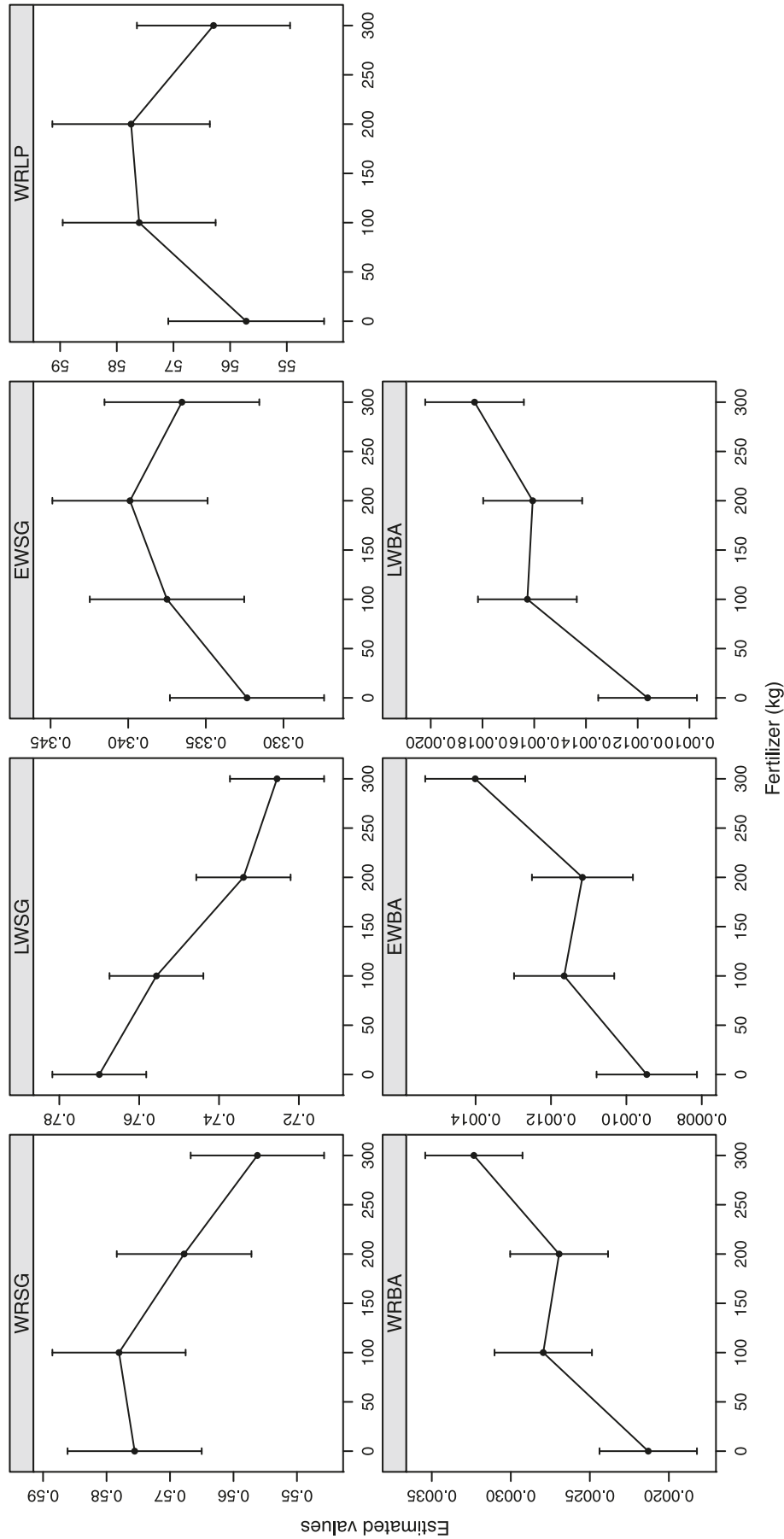
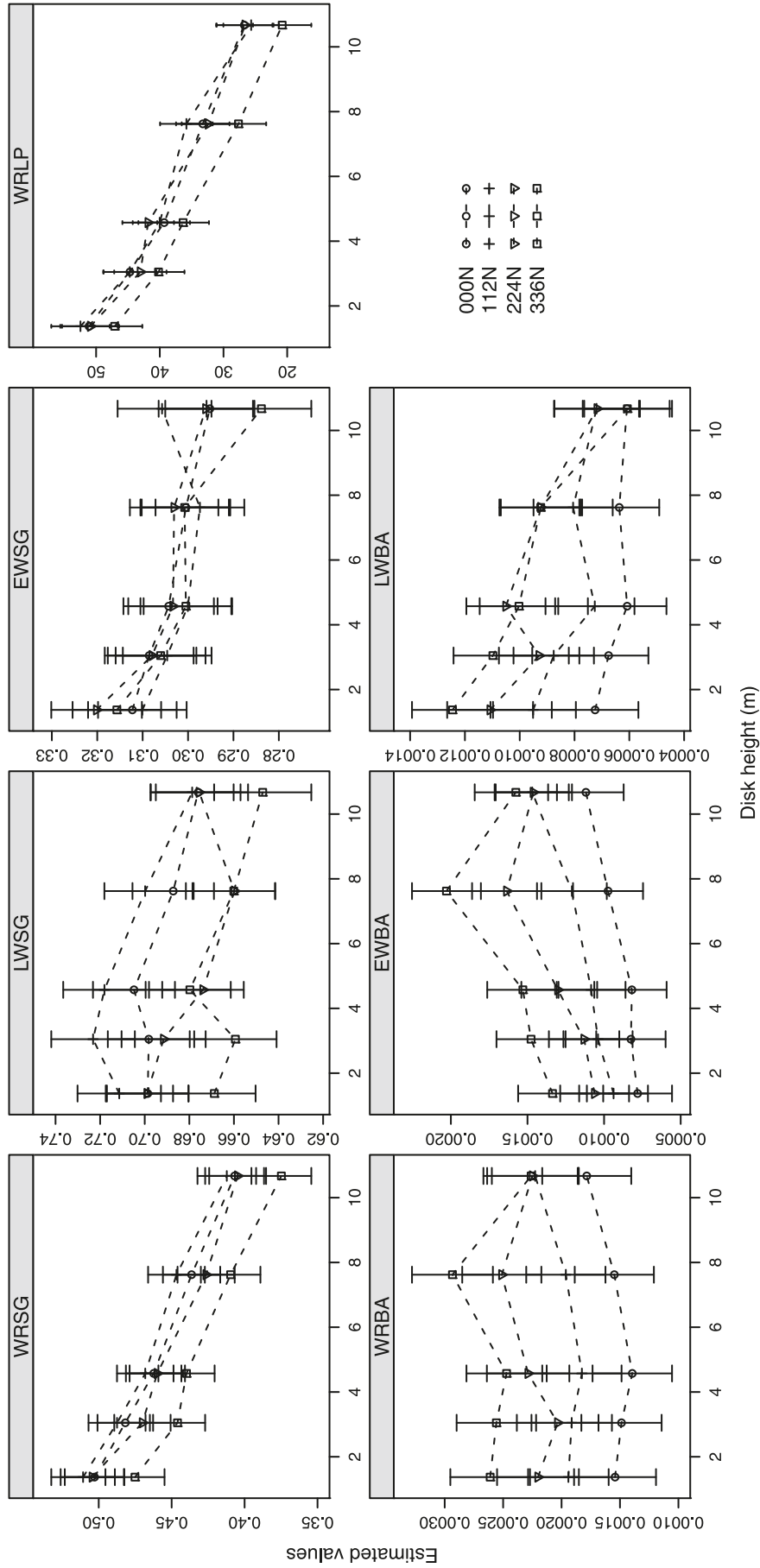


Fig. 2. Plots of estimated 4 year postfertilization means (1984–1987) of growth and wood properties with heights by treatment. The data were collected from disks sampled at five height levels (1.4, 3.0, 4.5, 7.6, and 10.6 m). The sampled trees received four levels of nitrogen fertilizer (unfertilized and 112, 224, and 336 kg/ha). The error bars represent ± 2 standard error. All notations and measurement units are as described for Table 1.



were supported by the results presented in this study. Many studies have already discussed in detail growth responses following fertilization, and consequently we will confine our discussion to the effects of fertilization on wood properties.

The application of different levels of N fertilizer did not produce a significant change in average whole-ring specific gravity (WRSG), averaged from the pith up to year 1995 for breast-height cores and for disks taken at five height levels. This finding agrees with earlier studies that examined the effects of early-age fertilization on the average SG of breast-height cores (Choong et al. 1970; Megraw 1985; Mora 2003). In general, all four wood properties averaged from the pith to the year 1995 remained essentially unaffected by midrotation fertilization.

The effect of midrotation fertilization on wood properties is considered to be transient and may last for a few years following treatment (Posey 1964; Ross et al. 1979). Changes to wood properties due to midrotation N application could possibly be explained on the basis of averages taken over a short time period following fertilization. The decrease in 4 year average WRSG and latewood SG (LWSG) for the 336N treatment compared with the other treatments clearly indicates the formation of a weak band of wood inside the trees following heavy fertilization. This change in WRSG may be attributed to the cumulative effects of changes in other properties such as a decrease in LWSG and tracheid wall thickness. This explanation agrees with the findings of Nyakuengama (1991) and Nyakuengama et al. (2002, 2003), who reported a decrease in density and a corresponding decrease in tracheid wall thickness following midrotation fertilization in radiata pine (*Pinus radiata* D. Don).

The change in wood properties following fertilization depends on the amount of fertilizer applied. A decline in 4 year average WRSG and LWSG was observed for the 336N treatment. However, the 4 year weighted average wood property values of treatments 112N and 224N were not significantly different from those of the control. The decline in 4 year average LWSG for the 336N treatment explains the decrease in WRSG during this period and is indicative of reduced secondary wall thickening of latewood tracheids following fertilization (Erickson and Harrison 1974; Nyakuengama et al. 2003; Clark et al. 2004). This short-term change in SG can be attributed to a large response in the crown (specifically needle formation) that produced a temporary change in wood formation, i.e., a higher earlywood-to-latewood ratio (Larson et al. 2001).

Few studies have examined the effect of fertilization on wood properties at different heights. The present study did not show any significant interaction of fertilizer treatment with height for wood properties. Mallonee (1975) also concluded that there was no significant interaction between fertilizer treatment and height for different wood properties. However, the wood properties examined in the present study all follow, to some extent, a trend with height, which has been observed and explained in earlier studies (Megraw 1985; Zobel and van Buijtenen 1989; Megraw et al. 1999). WRSG, LWSG, and percent latewood all decreased with height, while earlywood specific gravity remained relatively constant.

Any decision regarding optimum midrotation fertilization

practice should be made by examining wood properties and growth responses following fertilization. The 4 year average whole-ring basal area (WRBA) for the treatments 112N and 224N increased considerably when compared with the WRBA for the control, while little change was observed in wood properties. However, the 336N treatment produced a much larger increase in WRBA growth and a decrease in SG compared with the control. Hence, midrotation fertilization, at an appropriate level, can produce substantial gains in radial growth without negatively affecting wood properties. However, the results from the present study are restricted to one site. More studies involving diverse site conditions and treatment regimes are needed before making broad generalizations regarding the effects of fertilization on different wood properties.

In summary, a significant change was absent for ring specific gravity, latewood specific gravity, earlywood specific gravity, and percent latewood averaged from the pith up to 12 years after fertilization. Midrotation fertilization changed ring specific gravity and latewood specific gravity averaged over a 4 year postfertilization period. Lower rates of fertilization (112 and 224 kg/ha) did not change wood properties significantly. However, the highest rate of fertilization (336 kg/ha) resulted in a significant decline in ring specific gravity and latewood specific gravity averaged over 4 years posttreatment. Basal area growth was highly and positively influenced by fertilization with greater responses following higher rates of N.

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