ABSTRACT

MORA, CHRISTIAN RICARDO. Effects of early intensive silviculture on wood properties of loblolly pine. (Under the direction of Dr. H. Lee Allen)

Long-term effects of site preparation, early fertilization and weed control on selected wood properties of 22-23 year-old loblolly pine (*Pinus taeda* L.) were examined. Wood samples were obtained from four regeneration trials established by the North Carolina State Forest Nutrition Cooperative between 1978 and 1981 in southeastern USA. Twelve millimeter breast-height wood samples were extracted from a total of 675 trees (across sites) from five treatments: 1) low site preparation (control), 2) intensive site preparation, 3) intensive site preparation and fertilization, 4) intensive site preparation and weed control, and 5) intensive site preparation, fertilization and weed control. Specific gravity data were collected using an x-ray densitometer. All samples were scanned for ring specific gravity, ring earlywood specific gravity, ring latewood specific gravity and ring latewood proportion.

Across sites and treatments, the transition zone between juvenile and mature wood based on latewood specific gravity was between rings 4 and 15 and the demarcation point between both types of wood varied from rings 12 to 15. Silvicultural treatments did not affect the transition age on two out of the four sites (rings 14 and 15). An increase of 2 years on the transition age was associated to intensive cultural treatments on one site and a decrease of 3-4 years was observed on the remaining site, suggesting a relationship between the patterns of growth with age and the proportion of juvenile wood. The proportion of juvenile wood was not significantly affected by early silviculture on two sites (< 2%) and on one site a 10% decrease on the amount of juvenile wood was observed as a result of intensive cultural treatments. The results suggested that where strong growth responses to fertilization and weed control were observed, the transition age between juvenile and mature wood was unaffected or decreased and when the strong growth responses were related to herbaceous weed control, the transition age increased in intensive silvicultural plots compared to control plots.

Individual tree volume was significantly affected by intensive treatments. Positive responses ranged from 29 to 33%. Despite the increased growth showed by trees under intensive cultural treatments, wood properties were generally not significantly different from those observed on control plots. Intensive site preparation (HSP) and fertilization within intensive site preparation plots (F) resulted in reductions of earlywood specific gravity and total specific gravity, respectively. Weed control (H) showed little effect on most of the properties but on one site was related to an increase on weighted specific gravity. Intensive treatments, on average, resulted in small increases in weighted latewood specific gravity compared to low site preparation and the proportion of latewood was not affected by the treatments at all.

Keywords: *Pinus taeda* L., wood properties, intensive silviculture, specific gravity, x-ray densitometry, juvenile wood, transition age.

EFFECTS OF EARLY INTENSIVE SILVICULTURE ON WOOD PROPERTIES OF LOBLOLLY PINE

by

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DEDICATION

To my wife, Jimena

BIOGRAPHY

Christian Mora was born on March 03, 1971 in Santiago, Chile. He graduated from high school in December 1988. The author attended the Universidad de Chile (Santiago) and graduated with a BS degree in Forestry in December 1994. In January 1995, he started working with Bioforest S.A., the forest research company of the Arauco group, where he currently works as a research assistant. In 1996, after completing his BS thesis, he received the professional title of forest engineer with maximum honors. In fall 2001 the author came to North Carolina State University to pursue a Master of Science degree in Forestry. The author is married to Jimena Avirad.

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CHAPTER 1

Effects of early intensive silviculture on the juvenile-mature wood transition age and proportion of juvenile wood in loblolly pine trees using latewood specific gravity

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ABSTRACT

Long-term effects of site preparation, fertilization, and weed control on juvenile-mature wood transition age and proportion of juvenile wood of loblolly pine trees were examined in four regeneration trials established by the North Carolina State Forest Nutrition Cooperative in southeastern USA. Specific gravity data were collected from wood core samples using x-ray densitometry. Nonlinear models were applied to latewood specific gravity to estimate the juvenile-mature wood transition point. Heteroscedasticity and serial correlation of the data were considered by using generalized nonlinear regression models.

Across sites and treatments, the estimated transition zone based on latewood specific gravity was located between rings 4 and 15 and the juvenile-mature demarcation point varied from rings 12 to 15. Silvicultural treatments did not affect the transition age on two out of the four sites (rings 14 and 15). An increase of 2 years (physiological age) on the transition age associated to intensive cultural plots was observed on one site and a decrease of 3-4 years was found on the remaining site, suggesting that treatment effects on the patterns of growth with age are important in determining the proportion of juvenile wood.

The proportion of juvenile wood was not significantly affected by early silviculture on two sites (< 2%) and on one site a 10% decrease on the amount of juvenile wood resulted as effect of intensive silvicultural treatments. The results suggested that where strong growth responses to fertilization and weed control were observed, the transition age between juvenile and mature wood was unaffected or decreased and when the strong growth responses were related to herbaceous weed control, the transition age increased in intensive silvicultural plots compared to control plots.

Key Words: *Pinus taeda* L., nonlinear models, transition age, juvenile wood, latewood specific gravity.

INTRODUCTION

The forest industry faces many challenges. Reduced acreage for production of wood fiber and changing environmental policies will require more fiber production from fewer acres. The pressure to produce more wood fiber is leading to an increase of the proportion of intensively managed plantations. As forest management becomes more intensive (*e.g.* site preparation, fertilization, and weed control), trees will become of merchantable size at younger ages possibly resulting in material having different wood characteristics and properties compared with older ages. Future plantations that reach merchantability at younger ages will most likely contain a higher proportion of juvenile wood (Plomion *et al.* 2001).

Juvenile wood is defined as the zone of wood extending outward from the pith where wood characteristics undergo rapid and progressive changes in successively older growth rings (Larson *et al.* 2001, Amarasekara and Denne 2002). According to Clark and Saucier (1989) a radial cross-section of a pine stem typically contains three zones: a core or zone of crown-formed wood, a zone of transition wood, and a zone of mature wood. Both crown-formed wood and transition wood are commonly referred to as juvenile wood. The size of the juvenile wood region depends on ring physiological age (age of the cambium) and proximity to the crown (Larson 1969, Smith and Briggs 1986, Zobel and Sprague 1998).

Because of the gradual change in properties with age, the point at which a tree begins producing mature wood is not well defined and varies according to the characteristic being studied (Bendtsen and Senft 1986, Cown 1992).

Properties such as fiber length (Lee and Wang 1996), microfibril angle (Bendtsen and Senft 1986), and longitudinal stiffness (Roos *et al.* 1990) have been considered to determine the transition age. However, while the transition point or transition zone for each of these characteristics is of scientific interest, we are more concerned with those properties that can be repeatedly and economically measured (Sauter *et al.* 1999). This is the reason that most research into juvenile-mature transition has been based on wood specific gravity (*e.g.* Abdel-Gadir and Krahmer 1993, Hodge and Purnell 1993, Tassisa and Burkhart 1998).

From a practical perspective, the estimation of the transition age from juvenile to mature wood is needed to understand the effects of silvicultural treatments on wood quality. This allows the comparison between juvenile and mature wood properties, the evaluation of management regimes considering the amount of juvenile wood produced, and the appropriate classification and segregation of the material that will be processed by the industry.

For example, Clark and Edwards (1999) found variation in the diameter of the juvenile core with different site preparation techniques in loblolly pine planted in the lower Piedmont of Georgia. Clark *et al.* (1994) reported a recovery of more than 60% of number 2 and better graded lumber from 38-year old loblolly pine planted 1.8 × 1.8 m and thinned to $\leq$ 23 m^2 ha^{-1} compared to the recovery of less than 42% observed from trees of the same age planted 3.6 × 3.6 m and thinned to the same basal area, indicating the economic importance of changes in wood properties.

Several methods have been used to determine the age of demarcation between juvenile and mature wood. The simplest way to identify the region where mature wood starts is to visually locate a point on the density curves where the change in the property become less than in the juvenile wood as the ring number increases (Clark and Saucier 1989, Clark and Edwards 1999) or simply to assign a ring number from the pith at all stem levels, normally 5-15 rings in southern pines (Hodge and Purnell 1993, Cown and Ball 2001, Lindström 2002). An alternative approach is to use linear segmented regression models (Gallant and Fuller 1973, Loo *et al.* 1985, Di Lucca 1989, Szymanski and Tauer 1991, Abdel-Gadir and Krahmer 1993, Tassisa and Burkhart 1998, Sauter *et al.* 1999, Zhu *et al.* 2002) or nonlinear regression models (Hodge and Purnell 1993) to mathematically determine the point of transition.

A high proportion of the data used in previous studies consisted of x-ray densitometric observations that were collected on trees in repeated observations either in time and/or space. Since data collected from an individual tree tend to be more alike than different they tend to be correlated (Tassisa and Burkhart 1997). According to Sauter *et al.* (1999) possible interdependencies in data from adjacent rings could lead to poor estimates of the cambial age of the juvenile-mature wood transition and the use of methods that take into account these interdependencies can lead to estimates with smaller variability.

Tassisa and Burkhart (1997) indicated that one could consider the x-ray observations as if measurements were taken during several visits to the trees from year they are planted to the year they are sampled for the study. Since the correlation structure of the data resembles those encountered in longitudinal studies, analyses techniques designed for longitudinal data studies are appropriate.

Correlation problems have received little attention in the forestry literature. Gregoire *et al.* (1995) summarized this situation indicating that traditionally the main purpose of forest growth modeling is for prediction and it is well known that OLS (ordinary least squares) is inefficient but still consistent under correlated errors so the predicted response using OLS is still valid. West *et al.* (1994) indicate that when OLS analysis is conducted on data obtained from multiple measurements on individuals the covariance matrix of the parameter estimates and the residual variance of the regression are biased, producing biased confidence intervals and the tests of hypothesis operate at unknown levels of significance.

The objectives of this study were:

1. To estimate the transition point between juvenile and mature wood from x-ray densitometric observations using a nonlinear modeling approach accounting for heteroscedasticity and temporal interdependence of the data;
2. To evaluate the effects of early silvicultural treatments on the juvenile-mature wood transition age in loblolly pine; and
3. To evaluate the effects of early silvicultural treatments on the proportion of juvenile wood produced.

MATERIAL AND METHODS

Sample origin

Pinus taeda wood samples were obtained from four regeneration trials established by members of the North Carolina State Forest Nutrition Cooperative between 1978 and 1981 in southeastern United States. The selected sites were located in the Atlantic Coastal Plain from eastern Virginia to South Carolina. Three of the sites (sites 2, 3, and 4) were on poorly drained soils while one (site 1) was on well-drained soil (Table 1).

Each installation received a factorial combination of two levels of site preparation, fertilization, and herbicide treatment at establishment. These treatments were applied in a split-plot design with two site preparation treatments as main plots and fertilizer × herbicide treatments as subplots. All sites were originally established with four replications (blocks), however on site 2 one block had to be dropped due to fire. A complete description of the treatments is given elsewhere (Allen and Lein 1998, Nilsson and Allen 2003).

Five of the original eight treatments were selected for this study: 1. Control (low site preparation), 2. Intensive site preparation (SP), 3. Intensive site preparation plus fertilization (SP+F), 4. Intensive site preparation plus herbicide application (SP+H), and 5. Intensive site preparation plus fertilization and herbicide application (SP+F+H). The selection considered only treatments similar to those applied in current operational plantations. The intensity of the treatments was represented by the numbers 1 to 5 (in ascending order).

Fertilization included a control (no fertilizer) and nitrogen and phosphorus (N+P) applied as diammonium phosphate at establishment at a rate of 280 kg ha^{-1}. Herbicide treatments included a control (no weed control) and a banded (1.2 m) application of hexazinone applied once during each of the first two growing seasons following planting (Allen and Lein 1998).

Nine trees from each plot were sampled proportional to the diameter distribution of that plot. A power analysis approach (Cohen 1988) was utilized to determine the sample size (number of trees per plot) assuming a significance level (α) of 0.05, a power level ($1-\beta$) $\geq$ 0.80, and an effect size of 5% for a factorial design of $2 \times 2 + 1$ control.

Wood cores were collected at each site using a 12-mm increment hydraulic borer during the period March-June 2002. Increment cores were taken at 1.3 m (breast height) above the ground from each tree in the study. Trees that were suppressed, atypical in form, or infected by fusiform rust were excluded from sampling. Adjustments were made to avoid branches and knots. A total of 675 trees were sampled across sites.

Sample preparation and x-ray densitometry analysis

The increment cores were glued into yellow poplar (*Liriodendron tupilifera* L.) strips and sectioned longitudinally to produce strips of approximately 2-mm thick from the center of each core exposing transverse faces along the length of the sample. The samples were conditioned to a uniform moisture content of 8% for at least 48 hours prior to assessment.

Unextracted specific gravity profiles were obtained from each sample using an x-ray densitometer (Quintek Measurement Systems™). Specific gravity was measured using a linear resolution of 0.06 mm and a reference standard (calibrated step wedge) was x-rayed along with every sample. The transition from earlywood to latewood was set at a specific gravity threshold of 0.480. All samples were scanned for ring specific gravity, ring earlywood specific gravity, ring latewood specific gravity and ring percentage of latewood. The specific gravity values were expressed on an oven-dry weight, green volume basis.

For the purpose of this study, ring latewood specific gravity was selected for the estimation of transition age. In several species, the latewood component is the most sensitive to environmental influences and its variation has the strongest effect on mechanical properties (Cown *et al.* 2002). In southern pines, along with latewood percentage, latewood specific gravity is the dominant factor determining overall ring specific gravity (Megraw 1985).

Nonlinear modeling and amount of juvenile wood

In loblolly pine, latewood specific gravity is characterized by low values near the pith increasing to a maximum value with increasing ring number or physiological age (Figure 1). Mean latewood specific gravity was estimated by fitting an asymptotic regression model to data from each plot.

The model had the form:

$$y(x)_i = \phi_{1i} + (\phi_{2i} - \phi_{1i})\exp[-\exp(\phi_{3i})x] \qquad [1]$$

where ϕ_{1i} represented the asymptote as $x \to \infty$, ϕ_{2i} the latewood specific gravity at $y_i(0)$, ϕ_{3i} the logarithm of the rate constant, y_i the latewood specific gravity, x_i the ring number from the pith, and i the treatment number. The parameterization of the model defined ϕ_{3i} as logarithm to enforce positivity of the rate constant so the model approached an asymptote (Pinheiro and Bates 2000).

Biological data usually exhibit autocorrelation and heteroscedasticity. The variances of errors around growth models are often found to be dependent on the means; large means usually have larger variance (Fang and Bailey 2001). Variance functions frequently used in growth modeling, the power function model

$$g(\mu_{ij}, \delta) = \left|\mu_{ij}\right|^{\delta} \qquad [2]$$

and the exponential function model

$$g(\mu_{ij}, \delta) = \exp(\delta\mu_{ij}) \qquad [3]$$

were used to account for heteroscedasticity. This is a standard way to account for variance that depends systematically on the level of response or some other factor (Davidian and Giltinan 1995). The within-subject autocorrelation was analyzed using an autoregressive of first order correlation structure (AR(1))

$$y_t = v + \theta y_{t-1} + \varepsilon_t \qquad [4]$$

a moving average of second order structure (MA(2))

$$y_t = v + \varepsilon_t - \sum_{i=1}^{2} \theta_i \varepsilon_{t-i} \qquad [5]$$

and an autoregressive-moving average (ARMA(1,1)) structure of the form

$$y_t = v + \phi y_{t-1} + \varepsilon_t - \theta\varepsilon_{t-1} \qquad [6]$$

The models were fitted using maximum likelihood and compared based on the Akaike's information criterion (AIC), the Schwarz's bayesian information criterion (BIC), and the log-likelihood ratio test (LRT).

A difference (incremental) parameterization (Bates and Watts 1988, Davidian 2001) was used to fit the models in R version 1.7 (Fox 2002). An incremental parameter accounts for a change in a parameter between blocks of cases and is associated with an indicator variable (Bates and Watts 1988). The treatments were represented by a set of indicator columns for the levels. In addition to the indicator variables for all levels, a constant column for an intercept was added. This creates a singular model matrix. The incremental or difference parameterization recognizes this singularity and constrains some coefficients to zero. For this reason, as a result of this fitting procedure an intercept (θ) and the effects associated to n-1 treatments (γ_i) were obtained. The intercepts and effects were combined to estimate the parameters of the asymptotic model for all treatments in the form

$$\phi_i = \theta + \gamma_i \times \delta_i \qquad [7]$$

where δ_i was an indicator variable assuming values 0 or 1. By using this approach it was possible to test whether or not different parameters were required for each treatment (Wald tests).

The transition age for latewood specific gravity was defined as the ring (physiological age) at which predicted latewood specific gravity reached 90% of the upper asymptotic value estimated for each treatment, calculated as $t_{0.9} = \ln(10)/\exp(\phi_3)$. Similarly, the corresponding half-life point of the curve (ring at which predicted latewood specific gravity was 50% of the upper asymptote), calculated as $t_{0.5} = \ln(2)/\exp(\phi_3)$, was assumed to indicate the beginning of the transition zone. The amount of juvenile wood was calculated as the ratio between the juvenile basal area and total basal area of the trees, using the estimated transition age ($t_{0.9}$) as the demarcation point between juvenile and mature wood.

Statistical analysis (linear model)

The proportion of juvenile wood was transformed using the Box-Cox family of power transformations in the form $x^{(\lambda)} = (x^{\lambda}-1)/\lambda$ if $\lambda \neq 0$ and $x^{(\lambda)} = \ln x$ if $\lambda = 0$ (Sokal and Rohlf 1995, Johnson and Wichern 2002).

A linear model representing a factorial design of 2 × 2 + 1 control was used for the analysis (Bergerud 1989). The model had the form

$$y_{ijk} = \mu + \beta_i + SP + F_j(SP) + H_k(SP) + FH_{jk}(SP) + \varepsilon_{ijk} \qquad [8]$$

where y_{ijk} was the proportion of juvenile wood (after transformation) associated to the levels ith, jth, and kth of the factors, μ was a fixed general mean, β_i was the random effect of the ith block, SP was the fixed effect associated to the control plot (low site preparation), F_j was the fixed effect of the jth level of the fertilizer treatment within the intensive site preparation plot, H_k was the fixed effect of the kth level of the herbicide treatment within the intensive site preparation plot, FH_{jk} was the fixed effect associated to the interaction between the jth level of the fertilizer treatment and the kth level of the herbicide treatment within the intensive site preparation plot, and ε_{ijk} was the random error. The model was fitted using the GLM procedure in SAS version 8.2 (SAS Institute Inc. 2001).

RESULTS

Nonlinear model fitting

Variance function

The likelihood ratio test (LRT) of both the power functions (Equation 2) and the exponential functions (Equation 3) were significant in all cases ($p<0.01$) indicating the necessity to account for heteroscedasticity (Table 2). The LRT values were calculated with respect to the model assuming a spherical variance-covariance structure (model 1, Table 2). The specification of power functions (models 2-3) resulted in smaller AIC and BIC compared to the exponential functions (models 4-5). Since both functions have the same number of parameters in the model, the power functions were judged superior.

A variance function using the ring number as a covariate (model 3) proved to be slightly superior to the specification corresponding to a variance covariate given by the fitted values (model 2) in all sites, but one (site 1). Because small differences on the fit statistics between model 2 and 3 were found, model 3 was also adopted on this site.

Serial correlation structure

There are a number of alternative parametric models that are commonly used for covariance matrices. One option is to consider explicitly the different sources of variation of the data, *i.e.* the among experimental units variation (*e.g.* biological variation) and the within experimental units variation (*e.g.* due to the way in which the data were collected on the unit). The strategy adopted in this work was to model the two sources of variation together (among and within units), emphasizing the fact that the data were collected over time, as shown in the plot of estimated autocorrelation against lags (time interval between y_t and y_{t+1}) for site 4 (Figure 2).

For the data examined in this study, the autoregressive-moving average ARMA(1,1) (Equation 6) was the best of the candidate correlation structures in all sites based on the LRT (calculated with respect to model 3) and AIC values (Table 3). The argument (p=1, q=1) described an autoregressive-moving average process of first order in which the data (latewood specific gravity) of year t depended on the data of the previous year (t-1) and the random component in year t depended on the random component of the previous year (Nemec 1996). The plot of the empirical autocorrelation function for the normalized residuals corresponding to model 7 (asymptotic regression model, power function with ring number as a covariate, and ARMA(1,1) structure to model the within-subject correlation) does not show any significant correlations, indicating that the ARMA(1,1) structure adequately represented the within-subject temporal dependence of the data (Figure 3).

Parameter estimation

Wald tests ($\alpha = 0.05$) conducted for H_0: $\theta_i = 0$ and for H_0: $\gamma_i = 0$ showed that most of the treatments shared identical estimates of the parameters on sites 2 and 4; however significant effects associated with intensive silvicultural treatments were observed on sites 1 and 3.

Maximum latewood specific gravity (ϕ_1, Equation 1) ranged from 0.700 to 0.758 (Table 4). The smallest values were observed on sites 2 and 3, both located in North Carolina. Site preparation plus fertilization plots (SP+F) showed a lower maximum specific gravity than control plots on sites 1 and 4. No differences in maximum latewood specific gravity were found among SP, SP+H, SP+F+H, and control plots on these two sites. No effects of intensive cultural treatments were observed on site 2. The maximum latewood specific gravity was higher for treatments SP, SP+H, and SP+F+H than control plots on site 3. Minimum latewood specific gravity (ϕ_2) varied from 0.414 to 0.440. These values correspond to $y(0)$ in Equation 1, so it was difficult to associate this variation with any treatment effect. The logarithm of the rate constant (ϕ_3, Equation 1) ranged from –2.016 to –1.423, indicating that the rate of change of latewood specific gravity differed by treatment. More intensive treatments consistently increased the rate of change of latewood specific gravity on site 1 compared to control plots, while the opposite effect was observed on site 3. No treatment differences in the rate constant were found on sites 2 and 4. Differences among treatments were observed only on site 1, in which the rate constant was greater in SP, SP+F, and SP+F+H compared to SP+H.

Estimation of transition age and transition zone

The estimated transition age ($t_{0.9}$) and transition zone (segment of the curve between $t_{0.5}$ and $t_{0.9}$) were calculated as a function of parameter ϕ_3 of the asymptotic regression model (Equation 1), so any difference in the point of demarcation between juvenile and mature wood or in the transition zone is explained by differences in the logarithm of the rate constant. As noted previously, ϕ_3 did not vary among treatments on sites 2 and 4, consequently no differences were observed in the transition zone and transition age on these sites (Table 5). The transition zone for latewood specific gravity was located between rings

5-15 and 4-14, respectively, with rings 14 and 15 corresponding to the transition age between juvenile and mature wood (Figure 4).

Differences associated with the silvicultural treatments were found on sites 1 and 3. On site 1, the transition zone for SP and SP+F+H was found between rings 4-14, for SP+H and C between rings 5-17, and for SP+F between rings 4-13. On site 3, the transition zone for control plots was located between rings 3-10, while for SP, SP+F, SP+H, and SP+F+H was between rings 4-12.

On average, the transition zones on sites 1, 2, 3, and 4 were found between rings 4-15, rings 5-15, rings 4-12, and rings 4-14, respectively. This information is consistent to that reported by other authors (Loo and Tauer 1985, Zobel and van Buijtenen 1989, Szymanski and Tauer 1991, Tassisa and Burkhart 1998, Zobel and Sprague 1998) indicating little or no effect of the silvicultural treatments on the transition from juvenile to mature wood on the sites considered in this study. Similar results are reported by Clark and Saucier (1989) and Clark and Edwards (1999) who found no effects of spacing and site preparation on the length of juvenility of loblolly pine plantations established in southeast USA.

Amount of juvenile wood

Analysis of the model presented in Equation 8 showed that site preparation, fertilization, and herbicide did not affect the amount of juvenile wood on sites 2 and 4 (Table 6). A significant effect ($p<0.01$) was associated with the interaction of fertilizer × herbicide on site 1. Fertilizer and herbicide resulted on an average of 66% of juvenile wood, compared to 72% observed in SP plots (which represented the “control” treatment within the intensive site preparation plots). When combined, these treatments increased the proportion of juvenile wood to 81%. Significant effects for fertilizer and site preparation ($p<0.01$) were obtained on site 3. On this site, an average of 55% of juvenile wood was found on fertilized plots while plots without fertilization presented an average proportion of juvenile wood of 60%. Plots with intensive site preparation (SP, SP+F, SP+H, SP+F+H) resulted on 57% of juvenile wood compared to 41% observed in plots with low site preparation (C).

On average, the amount of juvenile wood varied from 54% on site 3 to 75% on site 2. No trend associated to the geographic location was observed. The lowest proportion was 33% and the highest 85% (Table 7). On site 1, the percentage of juvenile wood decreased from 82% in control plots to an average of 72% in treatment plots. On site 2, the effects of silvicultural treatments resulted on an average of 75% of juvenile wood, only one point higher than control plots. A small variation was observed on site 4, for which the average proportion of juvenile wood was 65% and 67% for treatments and control plots, respectively. However, an increase from 41% in control plots to 57% in treatment plots was found on site 3. These results demonstrate how difficult it is to generalize about the effects of intensive silviculture on wood quality of trees.

DISCUSSION

The methodology presented in this paper is especially appropriate when the aim of the study is to describe a latewood specific gravity curve by fitting a mathematical model, since growth curves are usually nonlinear with growth approaching an asymptote. Fit, parsimony, and parameter interpretability are among the advantages of the nonlinear models over the linear ones. The approach used in this work was to model the mean latewood specific gravity profiles of each treatment without considering the individual trajectories of each tree. A more complete approach can still be applied. For example, Hall and Bailey (2001) and Fang and Bailey (2001) propose a multilevel nonlinear mixed models methodology to model growth curves of loblolly pine and slash pine, respectively.

By fitting an asymptotic regression model (Equation 1) to each treatment without any special attention to the correlation structure and heterogeneity present in the data (model 1, Table 2), similar estimates of the three parameters of the model (ϕ_1, ϕ_2, ϕ_3) were obtained compared to the estimates given by the model which considered both within-subjects correlation and heteroscedasticity (model 7, Table 3). However, the standard errors associated to each parameter and the inferences made about them were different, leading to different estimates of the transition age, confirming the observations given by West *et al.* (1994). The selection of the correlation structure and the specification of a variance function are data dependent. If the true covariance structure is simpler than the presented here, then no improvement will be obtained and tests can lack power.

Small differences on the position of the transition zone within trees were found among sites. Sites 1, 3, and 4 presented on average a transition zone located between rings 4 and 15 while site 2 presented a transition zone located between rings 5 and 15. There was no significant effect of the treatments on the transition zone on sites 2 and 4 compared to the control (low site preparation); however different effects were found on sites 1 and 3. On site 1 three of the four silvicultural treatments (SP, SP+F, SP+F+H) resulted on a smaller transition zone and transition age compared to the control and the fourth treatment, SP+H, led to the same transition zone than the control. On the other hand, all the silvicultural treatments resulted on higher transition zone (rings 4-12) than the control (rings 3-10) on site 3.

Megraw (1985) indicates that the position of the crown in the tree has a big impact on the specific gravity at a given height an any artificial means of accelerating normal crown recession has the effect of accelerating the transition from juvenile to mature wood below the point of the living crown. These sites were not thinned so a recession of the crown could accompany the increase in height growth on site 1 explaining the lower transition age in treatments compared to the control. Unfortunately data of crown length were not available on these sites to test this hypothesis.

The analysis of transition age on loblolly pine under different silvicultural treatments has been considered on several studies. Clark and Edwards (1999) reported no effects of different site preparation treatments on transition age of loblolly pine, which averaged ten years for all treatments. Tassisa and Burkhart (1998) found no effects of different thinning schemes on transition age, which was estimated to occur at approximately eleven to twelve years of cambial age. An interesting result of this study was the finding of a minor within-tree variation in the age of demarcation, which confirms the existence of a cylindrical core of juvenile wood in loblolly pine. Based on these results, we can appropriately estimate the proportion of juvenile wood using samples taken at one point along the stem, typically at DBH.

Although the identification of the demarcation point was important to adequately divide the zone corresponding to juvenile wood from that corresponding to outer wood, the effects of the treatments were better visualized analyzing the proportion of juvenile wood in trees. Interest in the amount of juvenile wood ultimately relates to how much of the merchantable volume is produced (Zobel and Sprague 1998). The results of this study showed that the silvicultural treatments did not statistically affect the proportion of juvenile wood (sites 2 and 4) and in site 1 a decrease of almost 10% compared to the control was found. Only on site 3 an increase of the amount of juvenile wood was observed. On average (across sites) C, SP, SP+F, SP+H, and SP+F+H resulted on 66, 68, 66, 67, and 69% of juvenile wood, respectively (Figure 5). Similar values for 20-year old loblolly pine are reported by Bendtsen and Senft (1986).

These results may be associated to growth differences. Data provided by the NCSFNC (1996) showed differences in standing volume at fourteen years between control plots (low site preparation) and treatment plots ranging from 15 to 49% (Table 8). Although some treatments led to an increase of the size of the juvenile core (Table 7), proportional to the total basal area, the increase did not represent more juvenile wood ($p>0.05$). Therefore, if the main concern is the amount of juvenile wood produced as a result of silvicultural treatments, the comparison must be based on the size of the juvenile core with respect to the final size of the trees and not on the size of the juvenile core alone. Of course, this comparison will be valid only in trees of the same age. Similar results are reported by Saucier (1990) and Zobel and van Buijtenen (1989) who found a larger diameter of juvenile wood in wider spaced pine plantations, but less percentage of the total volume of the tree.

Very large differences in growth during early years associated to site preparation and fertilization, herbicide, and fertilization plus herbicide resulted in a larger juvenile core on site 3 (Tables 7 and 8, Figure 6). No thinning was done on this site and the differences in diameter growth found during the first years of the study as a result of the treatments were not observed at sampling age (samples from control plots presented an average final diameter of 20 cm compared to the average of 22 cm of the treatment plots) resulting in trees with higher proportion of juvenile wood than control trees. This suggests that treatment effects on the patterns of growth with age are critically important in determining the proportion of juvenile wood.

In conclusion, intensive silviculture applied at the establishment of loblolly pine plantations can, under some specific circumstances, cause a significant change in the amount of juvenile wood. Site preparation, fertilization, and weed control applied at establishment had only a modest effect on the amount of juvenile wood, which agrees with the information reported by Zobel and Sprague (1998). The results suggested that where strong growth responses to fertilization and weed control were observed, the transition age between juvenile and mature wood was unaffected or decreased and when the strong growth responses were related to herbaceous weed control, the transition age increased in intensive silvicultural plots compared to control plots. These results can be extended to other silvicultural techniques when trees are of similar age. Because trees under intensive management will likely reach merchantable sizes at younger ages, a tradeoff between the amount of juvenile wood obtained and the most economical time to harvest must be considered as an important factor determining the presence or absence of cultural effects on wood quality of loblolly pine.

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Table 1. Description of the four test sites of loblolly pine used for wood sampling.

Site	Location	Lat.	Long.	Region[a]	Annual pp (mm)	Planted	Subsoil texture	Drainage
1	VA	37°62’N	76°78’W	UACP	1055	June 1979	Loam	Well
2	NC	34°87’N	77°25’W	LACP	1447	May 1980	Clay loam	Poorly
3	NC	35°00’N	78°35’W	LACP	1267	April 1979	Sandy loam	Poorly
4	SC	33°59’N	79°48’W	LACP	1281	April 1979	Clay	Poorly

[a] UAPC: Upper Atlantic Coastal Plain, LACP: Lower Atlantic Coastal Plain.

Table 2. Fit statistics for the asymptotic regression model considering five different variance-covariance structures for the four sites included in the study.

Site	Model	Variance-covariance structure	AIC	BIC	Log-likelihood	LRT	*p*
1	1	Spherical	-12185.21	-12085.89	6108.61	---	---
	2	Power	-12383.38	-12277.85	6208.69	200.17	<.01
	3	Power (~ring)	-12381.48	-12275.95	6207.74	198.27	<.01
	4	Exponential	-12374.91	-12269.38	6204.46	191.71	<.01
	5	Exponential (~ring)	-12312.69	-12207.16	6173.35	129.48	<.01
2	1	Spherical	-7827.20	-7734.18	3929.60	---	---
	2	Power	-7912.63	-7813.79	3973.32	87.43	<.01
	3	Power (~ring)	-7915.82	-7816.99	3974.91	90.62	<.01
	4	Exponential	-7908.68	-7809.85	3971.34	83.48	<.01
	5	Exponential (~ring)	-7883.22	-7784.38	3958.61	58.02	<.01
3	1	Spherical	-12273.19	-12174.03	6152.60	---	---
	2	Power	-12356.01	-12250.65	6195.01	84.82	<.01
	3	Power (~ring)	-12358.96	-12253.60	6196.48	87.76	<.01
	4	Exponential	-12354.14	-12248.78	6194.07	82.94	<.01
	5	Exponential (~ring)	-12338.19	-12232.83	6186.10	66.99	<.01
4	1	Spherical	-11696.39	-11597.56	5864.20	---	---
	2	Power	-11808.09	-11703.08	5921.04	113.70	<.01
	3	Power (~ring)	-11819.88	-11714.87	5926.94	125.49	<.01
	4	Exponential	-11805.25	-11700.25	5919.63	110.86	<.01
	5	Exponential (~ring)	-11801.65	-11696.65	5917.83	107.26	<.01

AIC: Akaike's information criterion, BIC: Schwarz's Bayesian information criterion, and LRT: Likelihood ratio test calculated with respect to model 1.

Table 3. Fit statistics for the asymptotic regression model considering four different within-subject correlation structures for the four sites included in the study.

Site	Model	Correlation structure	AIC	BIC	Log-likelihood	LRT	*p*
1	3	Independent	-12381.48	-12275.95	6207.74	---	---
	6	AR(1)	-13409.92	-13298.19	6722.96	1030.44	<.01
	7	ARMA(1,1)	-13733.54	-13615.60	6885.77	1356.06	<.01
	8	MA(2)	-13227.64	-13109.69	6632.82	850.16	<.01
2	3	Independent	-7915.82	-7816.99	3974.91	---	---
	6	AR(1)	-8792.17	-8687.52	4414.09	878.35	<.01
	7	ARMA(1,1)	-8868.82	-8758.35	4453.41	957.00	<.01
	8	MA(2)	-8676.42	-8565.95	4357.21	764.59	<.01
3	3	Independent	-12358.96	-12253.60	6196.48	---	---
	6	AR(1)	-13897.28	-13785.73	6966.64	1540.33	<.01
	7	ARMA(1,1)	-14202.99	-14085.24	7120.50	1848.03	<.01
	8	MA(2)	-13640.37	-13522.62	6839.19	1285.42	<.01
4	3	Independent	-11819.88	-11714.87	5926.94	---	---
	6	AR(1)	-12853.00	-12741.82	6444.50	1035.13	<.01
	7	ARMA(1,1)	-13088.82	-12971.46	6563.41	1272.94	<.01
	8	MA(2)	-12770.04	-12652.68	6404.02	954.16	<.01

AIC: Akaike's information criterion, BIC: Schwarz's Bayesian information criterion, and LRT: Likelihood ratio test calculated with respect to model 3.

Table 4. Estimated parameters for the asymptotic regression model 7 for each site-treatment combination.

		Treatments				
Site	Parameters[a]	C	SP	SP+F	SP+H	SP+F+H
1	ϕ_1	0.758	0.758	0.732	0.758	0.758
	ϕ_2	0.440	0.416	0.440	0.440	0.440
	ϕ_3	-2.016	-1.777	-1.726	-2.016	-1.772
2	ϕ_1	0.732	0.732	0.732	0.732	0.732
	ϕ_2	0.461	0.461	0.461	0.461	0.461
	ϕ_3	-1.886	-1.886	-1.886	-1.886	-1.886
3	ϕ_1	0.700	0.722	0.700	0.722	0.722
	ϕ_2	0.414	0.414	0.445	0.445	0.445
	ϕ_3	-1.423	-1.660	-1.660	-1.660	-1.660
4	ϕ_1	0.757	0.757	0.727	0.757	0.757
	ϕ_2	0.418	0.418	0.418	0.418	0.451
	ϕ_3	-1.809	-1.809	-1.809	-1.809	-1.809

[a] Treatment effects are represented by different values of the parameters within sites ($p<0.05$)

Table 5. Estimated transition age ($t_{0.9}$) and transition zone ($t_{0.5}$-$t_{0.9}$) obtained from the asymptotic regression model fitted to each site-treatment combination.

		Treatments				
Site	t	C	SP	SP+F	SP+H	SP+F+H
1	0.5	5	4	4	4	5
	0.9	17	14	13	14	17
2	0.5	5	5	5	5	5
	0.9	15	15	15	15	15
3	0.5	3	4	4	4	4
	0.9	10	12	12	12	12
4	0.5	4	4	4	4	4
	0.9	14	14	14	14	14

Table 6. Probability values from the analysis of variance for proportion of juvenile wood for the site preparation intensity, fertilization, and herbicide treatments on each site.

	Sites			
	1	2	3	4
Site preparation	**<0.01**[a]	0.56	**<0.01**[a]	0.78
Fertilization(SP)	**0.01**[a]	0.30	**<0.01**[a]	0.12
Herbicide(SP)	**<0.01**[a]	0.12	0.11	0.61
F×H(SP)	**<0.01**[a]	0.23	0.46	0.77

[a] Statistically significant effects (p<0.05)

Table 7. Proportion of juvenile wood (JW%) and diameter of the juvenile core in cm (DJC) for each site-treatment combination (mean values not followed by a common letter or number are significantly different from each other at α=0.05).

	Treatments									
Site	C		SP		SP+F		SP+H		SP+F+H	
	JW%	DJC	JW%	DJC	JW%	DJC	JW%	DJC	JW%	DJC
1	82^a	15.5^3	72^b	15.4^3	65^c	15.1^3	67^c	17.2^2	81^a	19.0^1
2	74^a	20.3^1	74^a	16.4^2	80^a	18.8^2	73^a	18.6^2	73^a	19.9^1
3	41^c	12.7^2	59^a	16.4^1	54^b	16.7^1	60^a	16.7^1	56^b	16.3^1
4	65^a	14.3^1	68^a	15.4^1	66^a	16.1^1	68^a	14.6^1	64^a	15.2^1

Table 8. Standing volume per hectare (m^3 ha^{-1}) 14 years after planting for the different site-treatment combination.

	Treatments				
Site	C	SP	SP+F	SP+H	SP+F+H
1	116	134	147	117	168
2	174	163	216	191	248
3	127	192	175	226	196
4	68	126	138	127	141

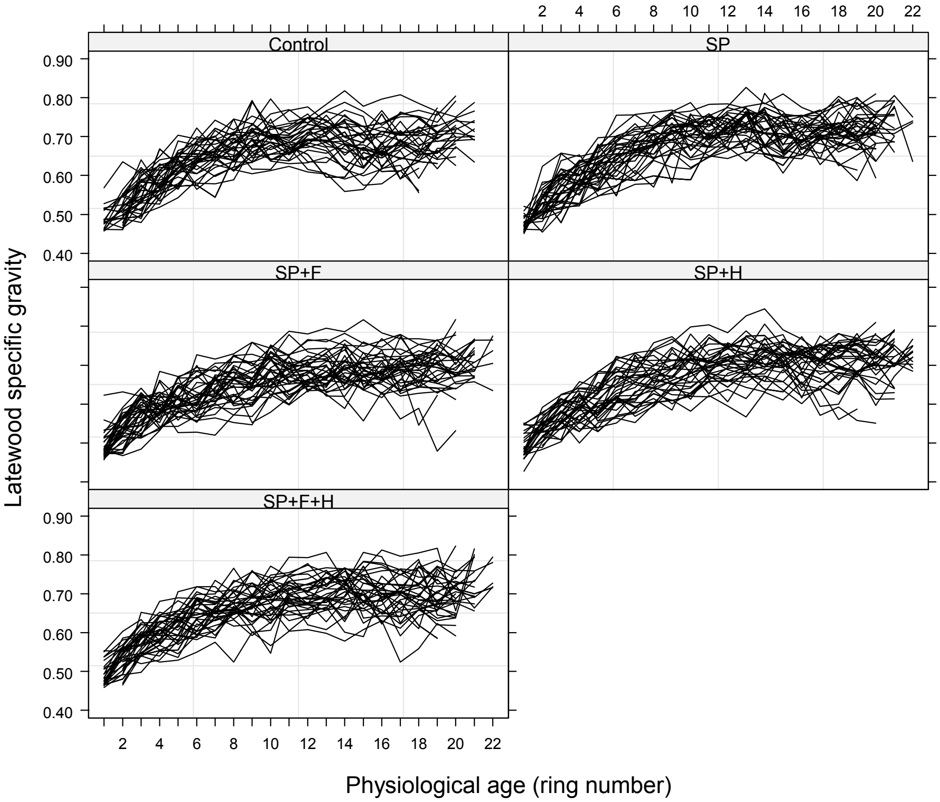

Figure 1. Latewood specific gravity profiles of individual trees on site 3.

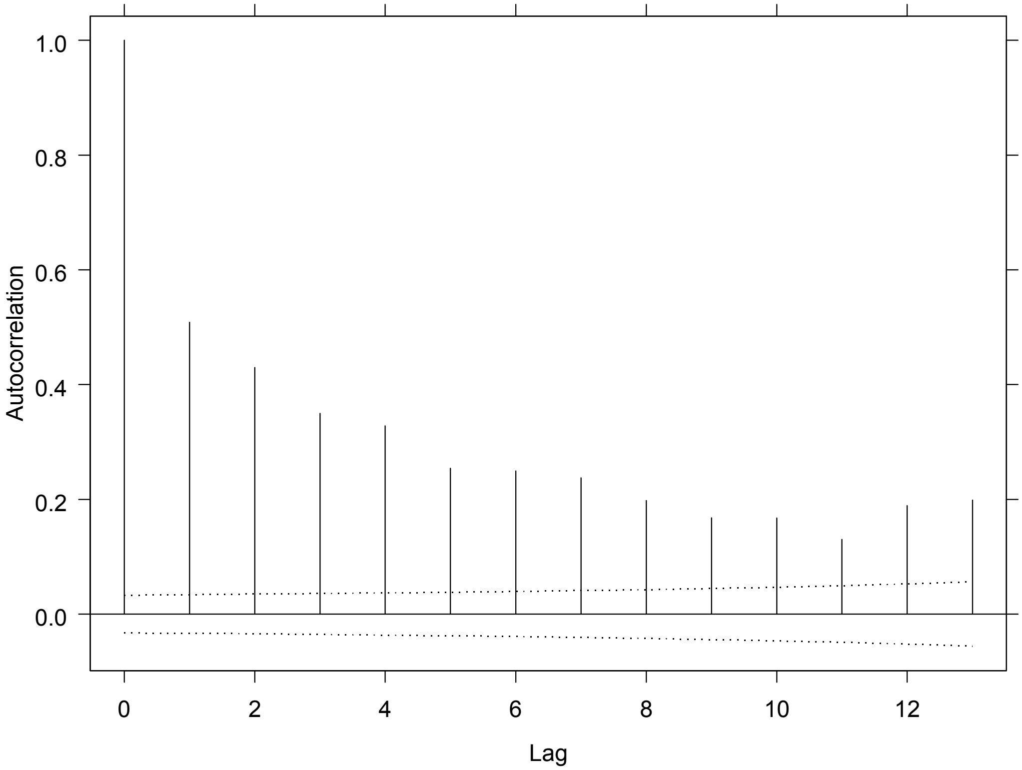

Figure 2. Empirical autocorrelation function corresponding to the standardized residuals of the asymptotic regression model on site 4.

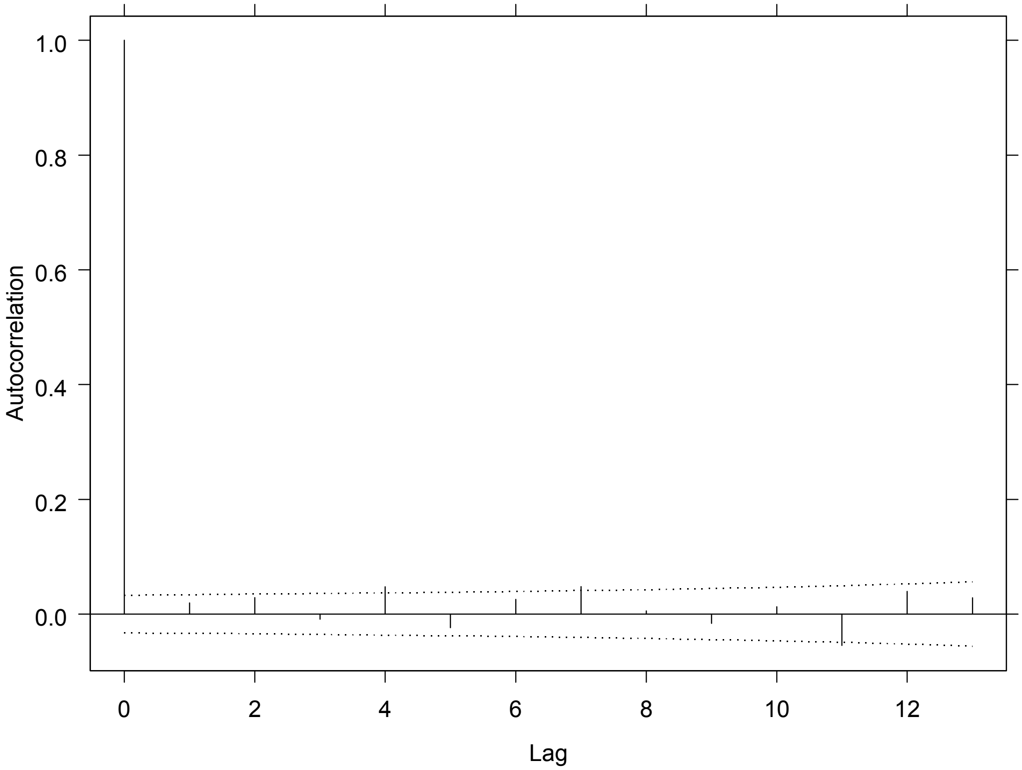

Figure 3. Empirical autocorrelation function corresponding to the normalized residuals of the asymptotic regression model on site 4.

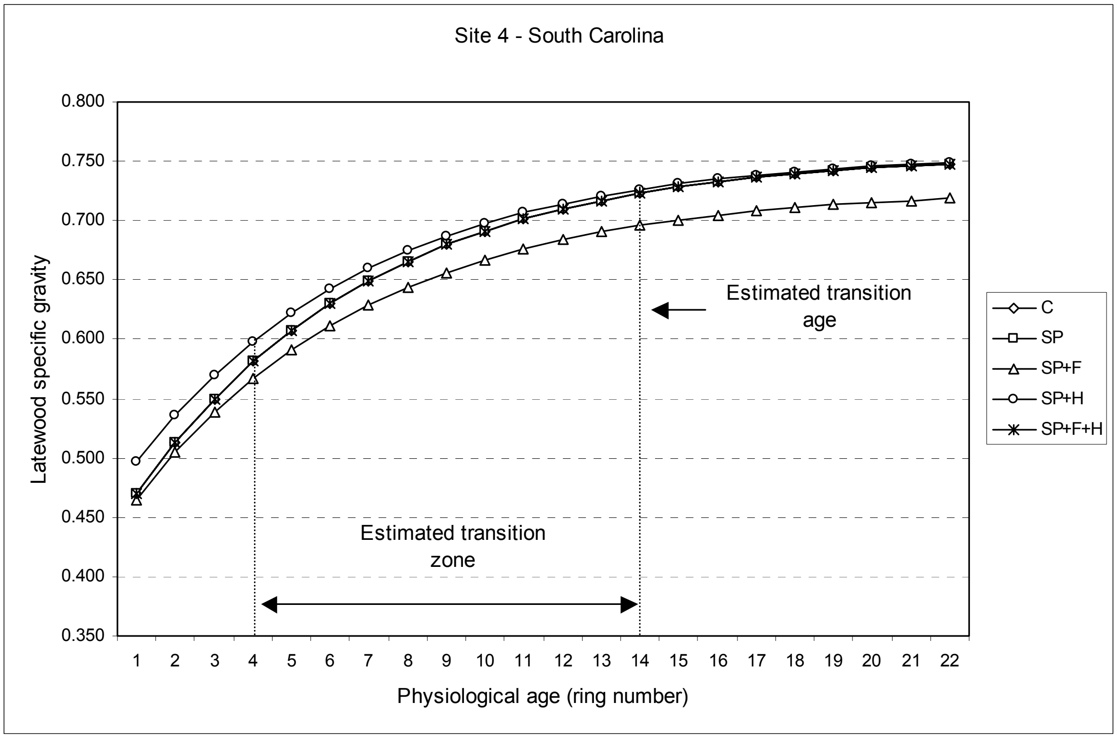

Figure 4. Asymptotic regression models for latewood specific gravity and estimated transition zone and transition age on site 4.

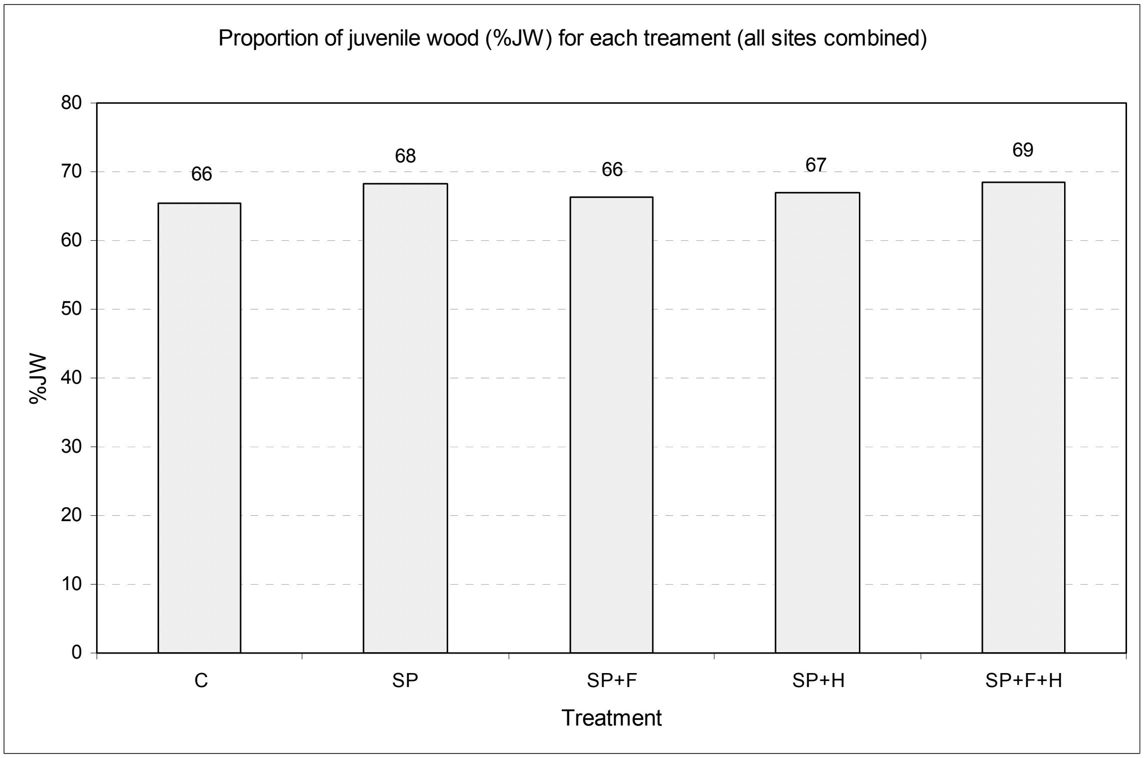

Figure 5. Proportion of juvenile wood for each treatment and all sites combined.

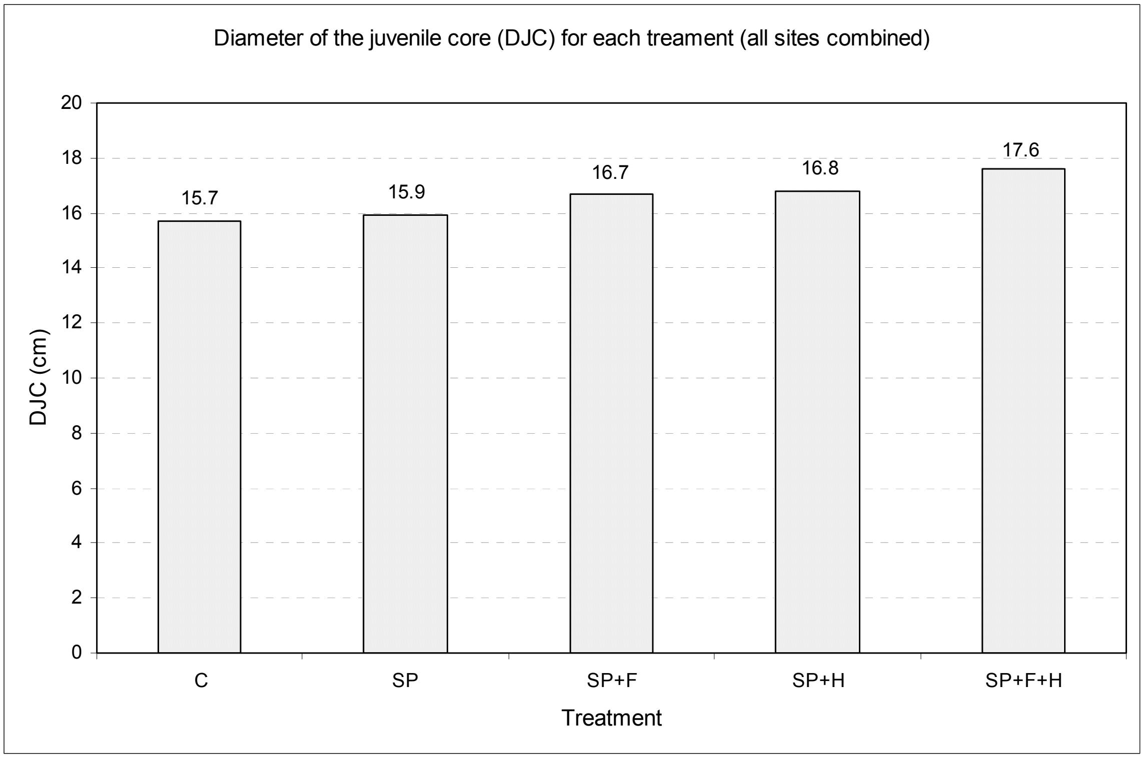

Figure 6. Diameter of the juvenile core for each treatment and all sites combined.

CHAPTER 2

Wood properties responses to early intensive silviculture in loblolly pine

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ABSTRACT

Long-term effects of site preparation, early fertilization, and weed control on selected wood properties of loblolly pine trees were examined in four regeneration trials established by the North Carolina State Forest Nutrition Cooperative in southeastern USA. Wood properties data consisted of specific gravity measurements collected from wood core samples using x-ray densitometry. Weighted specific gravity values at age of sampling and trends of the wood properties over time were examined. More than twenty years after applied the treatments, individual tree volume was significantly affected by intensive treatments. Positive responses ranged from 29 to 33%. Despite the increased growth showed by trees under intensive cultural treatments, wood properties were generally not significantly different from those observed on control plots. Intensive site preparation (HSP) and fertilization within intensive site preparation plots (F) resulted in reductions of earlywood specific gravity and total specific gravity, respectively. Weed control (H) showed little effect on most of the properties but on one site was related to an increase on weighted specific gravity. Intensive treatments, on average, resulted in small increases on weighted latewood specific gravity compared to low site preparation and the proportion of latewood was not affected by the treatments at all.

Key Words: *Pinus taeda* L., intensive silviculture, site preparation, fertilization, weed control, specific gravity, wood properties.

INTRODUCTION

The primary objective of most current timber management strategies is optimization of wood fiber volume. The key to optimizing production is to use the best genetic material available and to provide resources in quantities sufficient to allow the trees' genetic potential to be realized (Allen and Albaugh 2000). As the pressure to produce wood fiber increases, the role of intensively managed loblolly pine plantations takes on greater significance. Combinations of silvicultural treatments such as site preparation, weed control and fertilization enable foresters to grow more wood fiber on a given area (Moore and Allen 1999, Martin and Shiver 2002). At the same time, with the increasing global interest in rehabilitating degraded forests in many countries, intensive silviculture will become the promising choice in creating and maintaining productive, efficient, competitive and sustained forests (Agus *et al.* 2001, Borders and Bailey 2001).

The results and benefits of using intensive silvicultural treatments such as site preparation, weed control and fertilization to improve the growth of forest plantations have been well documented. For example, Mead (1990) reported that after eleven years, site preparation and fertilization applied at planting increased site index from 22 to above 30 m height of a radiata pine plantation established in New Zealand. Working with the same specie, Mason and Milne (1999) found that weed control and early fertilization resulted in initial growth gains that were maintained at midrotation ages. Similar results have been reported for white spruce (Sutton 1995) and eucalypts plantations (Boden 1984, Florence 1996). In the case of southern pines, Edwards (1994) reported that after ten growing seasons, intensive site preparation increased the survival, height growth and volume production of a loblolly pine plantation established in the lower Piedmont of Georgia. Shiver and Martin (2002) found that after twelve years, intensive site preparation resulted in trees with higher dimensions and volume than trees from low site preparation plots in loblolly pine plantations established in the Piedmont and Upper Coastal Plain regions of South Carolina, Georgia, and Alabama. More recently, Nilsson and Allen (2003) reported that after eighteen growing seasons, intensive site preparation resulted in higher stand volume than low site preparation treatments in several loblolly pine plantations across southeastern USA.

The response of a forest stand to silvicultural treatments imposed at time of planting varies over time as both resource availability and stand's demand for resources change. The types of long-term growth response to early silvicultural treatments vary according to the treatments applied and site characteristics and have been described in detail by Snowdon and Waring (1984) for radiata pine and by Morris and Lowery (1988) and Nilsson and Allen (2003) for southern pines. Briefly, site preparation and weed control treatments typically result gains achieved early in the rotation that are maintained until harvest. Fertilization, on the other hand, may result in either short or long term increases in nutrient availability and increased growth (Allen 1990). Nitrogen (N) additions usually result in short term increases in soil N availability, while phosphorus (P) fertilization on P-deficient soils often results in long-term increases in P availability and a continued gain in tree growth is observed throughout the rotation (Nilsson and Allen 2003).

Intensive silviculture has increased yields and returns on investment, but concerns have arisen about wood stem quality, especially that of fast-grown softwoods (Dinus and Welt 1997). The concept of wood quality is not fixed and is dependent on the intended use of the wood (Downes *et al.* 1997); however, high specific gravity is almost universally considered a desirable wood quality trait because of its high correlation with wood strength and stiffness and pulp yields (Haygreen and Bowyer 1996, Faust *et al.* 1999).

Tillage can improve tree growth by increasing the availability of water and nutrients in the soil (Allen *et al.* 1990). Schmidtling (1973) reported that after nine years of response, cultivation increased growth of loblolly pine compared to control plots but, despite the increase in growth rate, specific gravity values were not significantly different from that observed in untreated plots. Mann (1999) found little or no effect of soil moisture (irrigation treatment) on ring specific gravity and latewood proportion in a 7-year-old loblolly pine plantation established in a sandy site in North Carolina. On the other hand, Cregg *et al.* (1988) reported that in a year with high soil moisture and below average evapotranspiration, the transition from earlywood to latewood in a 10-year-old loblolly pine stand in southeastern Oklahoma was delayed in about three months compared with a year with low soil moisture; however, sustained growth rates in the late season during the wet year resulted in higher latewood proportion and specific gravity.

The effects of fertilization on wood properties are difficult to generalize. If height growth and crown development are promoted, increased wood growth will usually be accompanied by a decrease in latewood proportion and specific gravity. If foliage mass and photosynthetic efficiency are promoted, then the proportion of latewood and specific gravity may be unaltered (Larson *et al.* 2001). Several studies have reported short-term reductions in specific gravity and other properties following fertilization but they have concluded that these reductions are outweighed by large gains in volume growth (Megraw 1985, Megraw

1986, Blanche *et al.* 1992). The most consistent change in wood properties attributed to fertilization appears to be a short-term adjustment in the earlywood/latewood ratio (Blair and Olson 1984, Zobel and van Buijtenen 1989).

Vegetation control plays a critical role in crop establishment and, as a management practice, often increases tree growth. The use of herbicides to reduce competing vegetation will increase soil moisture and nutrients available for pine growth. Therefore, from a wood quality perspective, competition control could significantly influence the earlywood/latewood proportion resulting in similar effects to those of site preparation (Clark and Edwards, 1999).

As a result of the growth differences associated to intensive silviculture, wood properties may be affected in a form that is not always predictable (Zobel and van Buijtenen 1989). The impact of intensive silviculture on both solid and fiber wood products is still matter of controversy largely because only few studies have been followed long enough to determine the true effect of these activities on wood quality.

Established in the late 1970s, the North Carolina State Forest Nutrition Cooperative's Regionwide 7 installations are the oldest replicated study in the Southeast USA with regionally distributed installations designed to quantify the magnitude and duration of growth and nutritional responses to site preparation, early fertilization, and weed control. Eighteen years after planting, individual tree and stand growth were dramatically increased in the plots that combined all these practices at establishment (Nilsson and Allen 2003). Considering the significant response to the treatments, these studies provided an excellent opportunity to examine the effects of long-term silvicultural management on wood properties of loblolly pine plantations. The objectives of this study were to examine the long-term effects of site preparation, weed control and fertilization at planting on selected wood properties of loblolly pine. In addition, the effects of the early silvicultural treatments on the trends over time for ring specific gravity, ring earlywood specific gravity, ring latewood specific gravity, and ring latewood proportion were examined.

MATERIAL AND METHODS

Wood samples

Wood samples were obtained from four Regionwide 7 trials established by members of the North Carolina State Forest Nutrition Cooperative between 1978 and 1981 in southeastern United States. The sites were located from eastern Virginia to South Carolina (Table 1).

Each field trial received a factorial combination of two levels each of mechanical site preparation (SP), fertilization (F), and herbaceous weed control (H), for a total of eight treatments per installation. These treatments were applied at establishment in a split-plot design with the two site preparation treatments comprising the main plots and the 2 × 2 fertilization by weed control factorial being subplots. All trials were initially established with four blocks based on uniformity of soil and site conditions; however, on site 2 one block was dropped due to fire. Treatment plots were 29 × 29 m, with twelve rows of twelve seedlings planted at a 2.4 × 2.4 m spacing (Allen 1990, Allen and Lein 1998).

The treatments used in this study were: 1. Control (LSP), 2. Intensive site preparation (HSP), 3. Intensive site preparation and fertilization (HSP+F), 4. Intensive site preparation and weed control (HSP+H), and 5. Intensive site preparation, fertilization and weed control (HSP+F+H). Numbers 1 to 5 represented the intensity of the treatments (in ascending order).

Fertilizer treatments included a control (no fertilizer) and diammonium phosphate (DAP) applied immediately following planting at a rate of 280 kg ha^{-1} in a 1.2 meter wide band centered over the planting row. Weed control treatments included a control (no herbicides) and a banded (1.2 m) application of hexazinone (Velpar™) applied once during each of the first two growing seasons following planting (rates varied by installation). Site preparation methods varied by site and interest of the landowner but included a low intensity site preparation (LSP) and a high intensity site preparation treatment (HSP). See Allen (1990), Allen and Lein (1998), and Nilsson and Allen (2003) for a complete description of the treatments.

A power analysis approach was utilized to determine the number of trees per plot required for sampling using a significance level (α) of 0.05, a power level ($1-\beta$) ≥ 0.80, and an effect size of 5% for a factorial design of $2 \times 2 + 1$ control (Cohen 1988). Nine trees from each plot were sampled proportional to the diameter distribution of that plot.

From March to June 2002, 12 mm bark-to-bark increment cores were extracted at breast height (1.3 m) from the nine trees selected on each plot using a 12-mm increment hydraulic borer. Trees that were suppressed, atypical in form, or infected by fusiform rust were excluded from sampling. A total of 675 trees were sampled across sites.

Diameter at breast height in cm (DBH) and total height in m (HTO) were measured on each tree. These data provided the basis for calculating individual tree volume as

$$VOL = 0.00748 + (0.0000353 \times DBH^2 \times HTO) \qquad [1]$$

where VOL represented the total stem wood volume outside bark in cubic meters (Shelton *et al.* 1984).

Sample preparation and specific gravity measurements

Each core was divided at the pith and one radial half of each core was prepared for specific gravity data collection. The radial cores were dried at 50ºC for 24 hours, glued into yellow poplar strips and sectioned longitudinally to produce strips of approximately 2-mm thick from the center of each core exposing transverse faces along the length of the sample. The samples were conditioned to a uniform moisture content of 8% for at least 48 hours before they were scanned.

Specific gravity profiles were obtained from each sample using an x-ray densitometer (Quintek Measurement Systems™) with a linear resolution of 0.06 mm. The cores were not resin extracted. The transition from earlywood to latewood within a ring was set at a specific gravity threshold of 0.480. All samples were scanned for ring specific gravity (RSG), ring earlywood specific gravity (REW), ring latewood specific gravity (RLW), and ring percentage of latewood (RLP). The specific gravity values were expressed on an oven-dry weight, green volume basis.

Specific gravity values at age of sampling based on the basal area of the ring produced (WSG) were calculated as

$$WSG = \left(\sum_{i=1}^{n} \pi (r_i^2 - r_{i-1}^2) \rho_i \right) / \pi r_n^2 \qquad [2]$$

where r_i was the outer radius of the ith ring and ρ_i the ring specific gravity of the ith ring (Hoag and Kramer 1991). The same formula was used to calculate weighted earlywood specific gravity (WEW), latewood specific gravity (WLW), and latewood proportion (WLP).

Statistics

The linear model

$$y_{ijk} = \mu + \beta_i + SP + F_j(SP) + H_k(SP) + FH_{jk}(SP) + \varepsilon_{ijk} \qquad [3]$$

representing a factorial design of 2 × 2 + 1 control, was utilized for the analyses of weighted wood properties at age of sampling. The response y_{ijk} was modeled as a function of a fixed general mean (μ), a random block effect (β_i), a fixed control plot effect (SP), a fixed fertilizer effect within the intensive site preparation plot (F_j), a fixed weed control effect within the intensive site preparation plot (H_k), a fixed fertilizer × weed control interaction effect within the intensive site preparation plot (FH_{jk}), and a random error term (ε_{ijk}). The same model was used for the analysis of treatment effects on diameter, total height and volume of the trees.

The time-dependent nature of RSG, RLW, REW, and RLP was analyzed using repeated measures analysis of variance to account for serial correlation of measurements collected from the same trees over time (Moser *et al.* 1990, Meredith and Stehman 1991, Gumpertz and Brownie 1993, King *et al.* 2002). RLP was transformed prior to analysis using the Box-Cox family of power transformations (Sokal and Rohlf 1995, Johnson and Wichern 2002).

The multivariate repeated-measures model used was

$$y_{ijk} = \mu + \beta_i + A_j + \varepsilon_{ij} + T_k + AT_{jk} + \beta T_{ik} + \delta_{ijk} \qquad [4]$$

where $\mu + \beta_i + A_j + \varepsilon_{ij}$ represented the between-plot part of the model and $T_k + AT_{jk} + \beta T_{ik} + \delta_{ijk}$ represented the within-part of the model (Appendix 1). The between-plot part of the model consisted of an overall mean (μ), a random block effect (β_i), a fixed treatment effect (A_j), and a random plot to plot variation (ε_{ij}). The treatment effect was partitioned into SP, F, H, and F × H effects, reflecting the factorial treatment structure. The within-plot part of the model was estimated by fitting linear, quadratic and cubic orthogonal polynomials to the data and consisted of a fixed time effect (T_k), a fixed time by treatment interaction (AT_{jk}), a random block by time effect (βT_{ik}), and a random effect for observations on the same plot (δ_{ijk}). Both models (2 and 3) were fitted using the GLM procedure in SAS version 8.2 (SAS Institute Inc. 2001).

RESULTS

Twenty two (site 2) and twenty three (sites 1, 3, 4) years after planting, individual volume responses were positive for intensive silvicultural treatments on all sites but one (site 2). On site 2, the responses varied from negative (-18%) in HSP to slightly positive (8%) in HSP+F+H plots compared to the control treatment (Table 2).

On site 1, intensive cultural treatments increased individual tree volume in 33% compared to LSP plots (0.242 m^3). The responses were also positive on site 3 (Table 2 and 3). Intensive treatments resulted in mean tree volume of 0.505 m^3, 32% more than LSP plots (0.383 m^3). Similarly, early intensive silviculture on site 4 resulted in trees with 29% more volume than trees from control plots (0.237 m^3). Except for site 2, these results demonstrate the positive and long-term effects of early intensive silviculture on growth of individual loblolly pine. Furthermore, they are in qualitative agreement with the stand level responses reported previously for the same study sites (NCSFNC 1996, Nilsson and Allen 2003).

Despite the differences in tree volume, WSG measured at DBH generally did not vary significantly among treatments (Table 2). For example, WSG of LSP and HSP plots on site 1 was 0.472 and 0.471, respectively. No statistical effects of site preparation, fertilization or weed control were observed for this variable (Table 3). On site 2, LSP plots resulted in a mean WSG of 0.476, similar to that observed on intensive silvicultural plots (0.475). The highest WSG was observed in HSP+H plots (0.486); however this value was not statistically different from that observed in LSP plots. Within HSP plots, the addition of fertilizer resulted in a significant reduction of WSG (Table 3), with an average of 0.468 in HSP+F and HSP+F+H plots, 0.014 (equivalent to 14 kg m^{-3}) less than the mean value of HSP and

HSP+H. On site 3, WSG measured on LSP and HSP plots was 0.494 and 0.493, respectively. Similar to site 2, fertilization within intensive site preparation plots resulted in a reduction of 0.012 (12 kg m^{-3}) on this property. On site 4, LSP resulted in trees with WSG of 0.494, 0.3% less than the average from HSP plots. A significant fertilization × weed control interaction was observed on this site (Table 3). In this case, the greatest value was observed in HSP+F+H plots (0.506) and the smallest on HSP+F plots (0.483) (Figure 1, Table 2).

The between-plot part of the repeated measures analysis (Equation 4) of RSG on site 1 indicated that, averaged over twenty three years, there were no effects of site preparation, fertilization or weed control (Table 4). Trends of RSG over time (Figure 2) were examined in the within-plot analysis. In this case, the analyses were focused on the specific gravity of individual rings rather than in the weighted specific gravity at DBH. A significant linear (L) and quadratic (Q) time components were observed on this site (Table 4). Averaged over treatments, the trend of RSG over time had a linear component that depended on the weed control levels (lower coefficient associated to weed control) and the response over time leveled-off at a similar physiological age for all treatments (Table 5).

A similar analysis was performed on the other three sites. For example, on site 2, averaged over twenty two years, no effects of intensive silvicultural treatments were found on RSG. However, on this site the time effect not only included a linear and a quadratic component but also a cubic one (C). L was the same for all treatments; Q was negatively affected by high site preparation and C was negatively affected by fertilization (Table 4 and 5). On site 3, averaged over twenty three years, a strong negative effect of fertilization on RSG was found. L and Q terms were significant but only L showed differences depending on the fertilization level; in other words, the rate of change of RSG with age was negatively influenced by the presence of fertilizers. On site 4, the between-plot analysis of RSG showed a significant interaction between fertilization and weed control. On this site, the time effect was decomposed on L and Q terms. L did not depend on the treatments; however, Q was negatively affected by HSP and weed control (Table 4 and 5).

Silvicultural treatments did not affect WEW on three out of the four sites. On site 4, a strong negative effect of HSP on WEW was observed. On average, LSP plots resulted in WEW of 0.325, 2.5% more than intensive cultural treatments (Table 2 and 3). On this site, the lowest value was found on HSP plots (0.313).

Site preparation, fertilization and weed control did not affect REW on sites 1 and 2. Statistical effects of fertilization and site preparation were observed on sites 3 and 4, respectively. Trends over time showed a significant L, Q and C component on sites 1, 3 and 4. On site 2, only L and Q were significant (Appendix 2). In general, the linear coefficient was common to all treatments except for the L×SP interaction that was positively affected by HSP on site 4. The quadratic term was also common to all sites except for the Q×H interaction that was negatively affected by weed control on site 4. C did not show variation among treatments on sites 2 and 4, but was positively affected by weed control on site 1 and by the interaction F × H on site 3.

Similar to WSG, no effects of site preparation, fertilization or weed control on WLW were found on sites 1, 2 and 3. A strong interaction effect between fertilization and weed control was observed on site 4. On average, HSP and HSP+F+H plots presented a WLW of

0.714, 2% more than the average of HSP+F and HSP+H plots (Table 2 and 3). On this site, intensive cultural treatments resulted in an increase of 2% of WLW compared to LSP plots.

Results of the analyses of trends over time for RLW showed that L, Q and C components were significant on all sites. L was common to all treatments on sites 1 and 2 (parallel profiles) and varied negatively with fertilization on site 3. On site 4, L was negatively affected by both, intensive site preparation and weed control. The quadratic component of the trend was negatively associated to HSP on sites 2 and 4. Smaller C coefficients were associated to HSP on sites 3 and 4, and to weed control on site 1 (Appendix 3).

WLP was not affected by intensive cultural treatments (Table 3). Trends of RLP over time were almost identical to those observed for RSG. Significant L and Q terms were found on sites 1, 3 and 4. On site 2, RLP was represented by a third-order polynomial function. No time effects were observed on L, Q and C, except for the interaction Q×H on site 4 and the interaction C×F on site 1 (Appendix 4).

DISCUSSION

At the end of the study period, individual tree volumes were higher in intensively treated plots than in control plots in three out of the four sites. The increase in volume (ranging from 29 to 33%) may be due in part to better early growth associated to intensive site preparation, early fertilization and weed control and also to an increased tree growth throughout the period of analysis. Results from previous analysis on these sites (Allen and Lein 1998, Nilsson and Allen 2003) and in other sites (Martin and Shiver 2002, Shiver and Martin 2002) reinforce these ideas. On site 2, negative responses to HSP have been reported previously and they were related to a piling effect that was applied before bedding (NCSFNC 1996).

Increases in tree volume as a result of intensive silviculture have been traditionally associated to decreases on wood properties. Results from the analysis of weighted specific gravity measured at breast height showed no significant differences of this property among most of treatments. This is an interesting result, considering that specific gravity has been recognized as a key property for both, solid and fiber wood products. Similar results on specific gravity were reported by Clark and Edwards (1999) on a 15-year old loblolly pine plantation established with different site preparation treatments. Weighted specific gravity ranged from 0.465 to 0.506 and, averaged over all treatments, varied from 0.471 on site 1 to 0.495 on site 4. The lowest value was found on the site in Virginia and the highest on the site located in South Carolina. This sort of geographical variation has been reported in the literature before. Several studies have demonstrated a general trend for wood specific gravity values to decrease from south to north and east to west. These regional differences have been associated to rainfall patterns and length of the growing season (Talbert and Jett 1981, Clark and Saucier 1989).

Phosphorus fertilization at time of planting resulted in small reductions of weighted specific gravity at two sites. These reductions ranged from 12 to 14 kg m^{-3}. The analysis of the impact of these reductions on the quality of final products is beyond the scope of this work; however, differences as low as of 0.05 units on specific gravity can result in 5% increase or decrease in pulp yields (Zobel and van Buijtenen 1989). Larson *et al.* (2001) indicated that tree age at the time of fertilizer application apparently has a pronounced effect on the nature of the response. Fertilization at time of planting, especially if combined with site preparation, increases height and crown development which usually result in a temporal decrease of specific gravity. The application of DAP at establishment (phosphorus source) and the long-term effects associated to P-fertilization on P-deficient soils (Gent *et al.* 1986) may be the reason of the observed variation on wood specific gravity.

In general, trends of ring specific gravity over time (ring-by-ring basis) were appropriately described by linear and quadratic terms. In other words, the statistical evidence suggested that specific gravity patterns over time (or physiological age) were well described by second-order polynomials. The use of polynomial responses does not imply acceptance of this function as the true underlying response curve. Rather, polynomials are used to investigate characteristics of the response curve such as trend, humps and troughs, or asymmetry (Meredith and Stehman 1991). The linear component of the orthogonal polynomials was not affected by site preparation, fertilization or weed control on sites 2 and 4, indicating that the profiles of ring specific gravity over time were parallel for the different treatments. However, the significant L×H and L×F interactions observed on site 1 and site 3, respectively, resulted in a reduction of the coefficient of the linear term and, consequently; a lack of parallelism of the ring specific gravity profiles among treatments was observed. The quadratic terms of the polynomial functions fitted to the data from sites 2 and 4 were negatively affected by intensive site preparation. These results reflected differences on the curvature of the specific gravity profiles associated to the levels of these two factors.

Wood specific gravity can be thought of as a direct combination of its three seasonal determinants: earlywood specific gravity, latewood specific gravity and latewood percentage. Early silvicultural treatments resulted in a significant decrease (less than 3%) on weighted earlywood specific gravity on 4. This reduction was exclusively associated to the levels of site preparation (LSP vs. HSP). The interaction time × earlywood specific gravity was described by third-order polynomials in most of the sites. However, ring earlywood specific gravity plotted against time showed little variation and remained more or less constant with age. This pattern was observed on all sites; therefore, the significance of the linear and quadratic terms must be interpreted with caution as may be the result of a scale effect. The relative constant pattern of earlywood specific gravity over time has been reported previously (*e.g.* Megraw 1985, Hodge and Purnell 1993, Bucur *et al.* 1994). A similar geographic trend to that observed on weighted specific gravity, was found on weighted earlywood specific gravity with values ranging from 0.314 to 0.320 from north to south.

Although not statistically significant, the early effects of weed control and site preparation on soil moisture may have contributed to the small increase (1 to 4%) of weighted latewood specific gravity observed on the study sites. The highest values of summerwood were observed on HSP and HSP+H plots. Fertilization did not statistically affected latewood specific gravity; however, small reductions (ranging from 1 to 3%) were associated to this treatment. In contrast with weighted specific gravity and weighted earlywood specific gravity, latewood specific gravity did not show any geographical trend. Megraw (1985) indicates that latewood specific gravity increases rapidly with ring number from the pith until values are almost up to their characteristically high level. This trend was consistently fitted by third-order polynomial functions on all sites. Site preparation, fertilization and weed control affected the parameters of these curves differently on the different sites.

One of the anticipated effects of intensive silviculture was the extension of summerwood formation (therefore latewood proportion) by increasing the late-season availability of soil moisture. The increase of soil moisture is principally related with a decrease of the levels of competition, especially that from hardwoods (Nilsson and Allen 2003). Intensive silvicultural treatments did not affect the weighted proportion of latewood of the trees. This result was consistently observed on all sites, indicating that the temporal adjustment earlywood/latewood suggested in the literature as the most likely result of intensive cultural treatments was not the reason for the differences found in some of the wood properties analyzed. Rather, they may be the result of changes in the absolute values of earlywood and latewood specific gravity. This idea was confirmed by the analysis of the trend of ring latewood specific gravity over time (see also Chapter 1). In general, latewood proportion was appropriately described by a second-order polynomial function and the parameters showed practically no variation associated to the treatments, even during the first years that followed the application of the treatments where this adjustment on the latewood proportion was expected.

In conclusion, intensive silvicultural treatments applied at time of planting, did not significantly affect wood properties measured at diameter at breast height in 22- and 23-year old loblolly pine plantations established in southeastern USA. Intensive site preparation (HSP) and fertilization (F) resulted in small reductions of earlywood specific gravity and total specific gravity, respectively. Herbaceous weed control (H) showed little effect on most of the properties but resulted in slightly increased weighted specific gravity on one site. Intensive treatments, on average, resulted on small increases on weighted latewood specific gravity compared to low site preparation and the proportion of latewood was not affected by the treatments at all.

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Table 1. Description of the four test sites of loblolly pine used for wood sampling.

Site	Location	Lat.	Long.	Region[a]	Annual pp (mm)	Planted	Subsoil texture	Drainage
1	VA	37°62'N	76°78'W	UACP	1055	June 1979	Loam	Well
2	NC	34°87'N	77°25'W	LACP	1447	May 1980	Clay loam	Poorly
3	NC	35°00'N	78°35'W	LACP	1267	April 1979	Sandy loam	Poorly
4	SC	33°59'N	79°48'W	LACP	1281	April 1979	Clay	Poorly

[a] UAPC: Upper Atlantic Coastal Plain, LACP: Lower Atlantic Coastal Plain

Table 2. Means for selected wood properties, diameter, total height and tree volume of sampled loblolly pine trees for each site-treatment combination.

Site	Treatment	WSG	WLW	WEW	WLP (%)	DBH (cm)	HTO (m)	VOL (m^3)
1	LSP	0.472	0.696	0.315	42	21.3	18.6	0.242
	HSP	0.468	0.707	0.311	41	22.0	18.9	0.265
	HSP+F	0.473	0.694	0.313	43	22.7	20.0	0.300
	HSP+H	0.466	0.694	0.315	41	25.3	19.3	0.353
	HSP+F+H	0.476	0.695	0.318	43	25.2	21.2	0.383
2	LSP	0.476	0.644	0.323	49	27.6	19.7	0.430
	HSP	0.478	0.675	0.315	47	23.2	18.0	0.289
	HSP+F	0.471	0.666	0.316	46	26.2	20.1	0.402
	HSP+H	0.486	0.682	0.314	48	25.5	19.5	0.366
	HSP+F+H	0.465	0.653	0.313	46	27.9	20.6	0.466
3	LSP	0.494	0.679	0.320	59	24.0	22.4	0.383
	HSP	0.499	0.697	0.322	59	26.1	23.7	0.463
	HSP+F	0.487	0.676	0.317	56	28.2	24.4	0.554
	HSP+H	0.498	0.689	0.322	58	27.1	23.9	0.490
	HSP+F+H	0.487	0.686	0.320	58	27.3	24.4	0.514
4	LSP	0.494	0.693	0.325	47	21.4	17.7	0.237
	HSP	0.493	0.709	0.313	47	22.2	19.1	0.271
	HSP+F	0.483	0.689	0.315	46	23.9	20.3	0.335
	HSP+H	0.500	0.710	0.322	47	21.8	18.8	0.261
	HSP+F+H	0.506	0.719	0.316	49	23.0	20.2	0.308

WSG: Weighted specific gravity, WLW: Weighted latewood specific gravity; WEW: Weighted earlywood specific gravity; WLP: Weighted latewood proportion; DBH: Diameter at breast height; HTO: Total height; VOL: Tree volume.

Table 3. Probability values from the analysis of variance of selected wood properties, diameter, total height and tree volume at the age of sampling for each site.

Site	Source of variation	WSG	WLW	WEW	WLP	DBH	HTO	VOL
1	Site preparation	0.81	0.78	0.82	0.70	**<0.01** [a]	**0.04** [a]	**<0.01** [a]
	Fertilization(SP)	0.24	0.27	0.52	0.06	0.62	**0.01** [a]	0.15
	Weed control(SP)	0.95	0.29	0.20	0.95	**<0.01** [a]	0.10	**<0.01** [a]
	F×H(SP)	0.69	0.19	0.99	0.90	0.49	0.43	0.90
2	Site preparation	0.94	0.08	0.12	0.14	0.24	0.91	0.38
	Fertilization(SP)	**0.03** [a]	0.11	0.99	0.20	0.08	0.06	0.05
	Weed control(SP)	0.91	0.78	0.63	0.40	0.20	0.23	0.17
	F×H(SP)	0.21	0.39	0.80	0.60	0.83	0.50	0.90
3	Site preparation	0.83	0.45	0.94	0.64	**0.03** [a]	**0.05** [a]	0.06
	Fertilization(SP)	**0.04** [a]	0.18	0.07	0.41	0.32	0.40	0.30
	Weed control(SP)	0.87	0.89	0.46	0.85	0.95	0.95	0.91
	F×H(SP)	0.85	0.34	0.38	0.25	0.41	0.87	0.54
4	Site preparation	0.72	0.06	**0.01** [a]	0.90	0.23	**<0.01** [a]	0.07
	Fertilization(SP)	0.50	0.36	0.44	0.90	0.17	**0.01** [a]	0.05
	Weed control(SP)	**<0.01** [a]	**0.02** [a]	0.07	0.08	0.52	0.62	0.48
	F×H(SP)	**0.04** [a]	**0.03** [a]	0.13	0.25	0.80	0.91	0.75

[a] Statistically significant effects (p<0.05)

Table 4. Probability values from the repeated measures analysis of variance of ring specific gravity (RSG) for each site.

Variable: RSG	Site			
Source of variation	1	2	3	4
	Between-plot analysis			
Mean	**<0.01**[a]	**<0.01**[a]	**<0.01**[a]	**<0.01**[a]
Site preparation	0.86	0.42	0.97	0.65
Fertilization(SP)	0.11	0.24	**0.03**[a]	0.49
Weed control(SP)	0.85	0.65	0.60	**<0.01**[a]
F×H(SP)	0.90	0.13	0.47	**0.01**[a]
	Within-plot analysis			
Time linear	**<0.01**[a]	**<0.01**[a]	**<0.01**[a]	**<0.01**[a]
Linear×SP	0.35	0.79	0.27	0.11
Linear×F	0.41	0.98	**0.04**[a]	0.15
Linear×H	**0.05**[a]	0.45	0.33	0.13
Linear×F×H	0.30	0.45	0.78	0.21
Time quadratic	**<0.01**[a]	**0.01**[a]	**<0.01**[a]	**<0.01**[a]
Quadratic×SP	0.98	**0.02**[a]	0.21	**0.05**[a]
Quadratic×F	0.23	0.88	0.58	0.29
Quadratic×H	0.57	0.35	0.21	**0.04**[a]
Quadratic×F×H	0.44	0.57	0.36	0.74
Time cubic	0.35	**0.04**[a]	0.13	0.61
Cubic×SP	**0.01**[a]	0.13	**<0.01**[a]	0.95
Cubic×F	0.63	**0.02**[a]	0.79	0.43
Cubic×H	0.97	0.80	0.44	0.14
Cubic×F×H	0.25	0.43	0.56	**0.02**[a]

RSG: Ring specific gravity ; [a] Statistically significant effects (p<0.05);

Table 5. Estimated orthogonal polynomial coefficients for RSG by site and treatment.

Variable: RSG				
Site	Treatment	L	Q	C
1	LSP	0.344	-0.044	-0.023
	HSP	0.353	-0.037	0.005
	HSP+F	0.334	-0.044	0.000
	HSP+H	0.321	-0.034	-0.004
	HSP+F+H	0.323	-0.063	0.008
2	LSP	0.292	-0.030	-0.002
	HSP	0.299	-0.076	-0.003
	HSP+F	0.314	-0.084	-0.036
	HSP+H	0.299	-0.105	-0.008
	HSP+F+H	0.283	-0.091	-0.027
3	LSP	0.297	-0.088	0.036
	HSP	0.329	-0.093	0.010
	HSP+F	0.293	-0.097	0.003
	HSP+H	0.352	-0.112	-0.001
	HSP+F+H	0.306	-0.100	0.001
4	LSP	0.299	-0.087	0.003
	HSP	0.332	-0.098	0.021
	HSP+F	0.295	-0.107	0.002
	HSP+H	0.337	-0.120	-0.022
	HSP+F+H	0.334	-0.136	0.013

RSG: Ring specific gravity; L: Linear, Q: Quadratic, and C: Cubic polynomial coefficients.

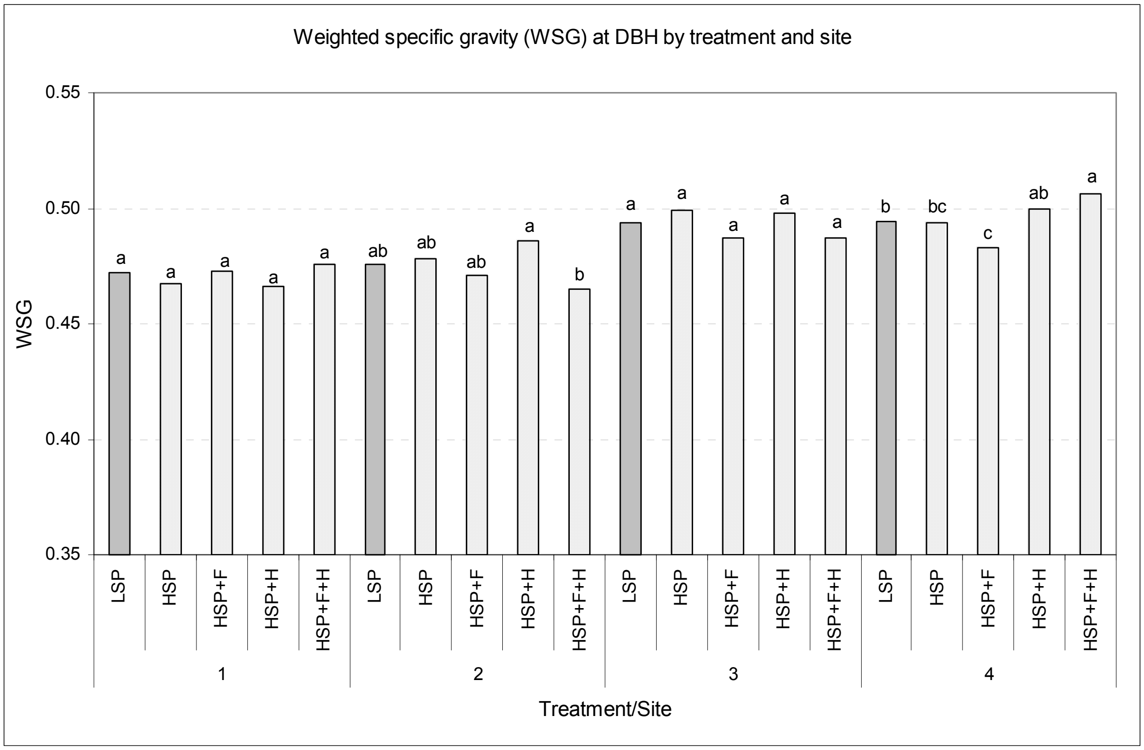

Figure 1. Weighted specific gravity (WSG) measured at DBH for each site-treatment combination.

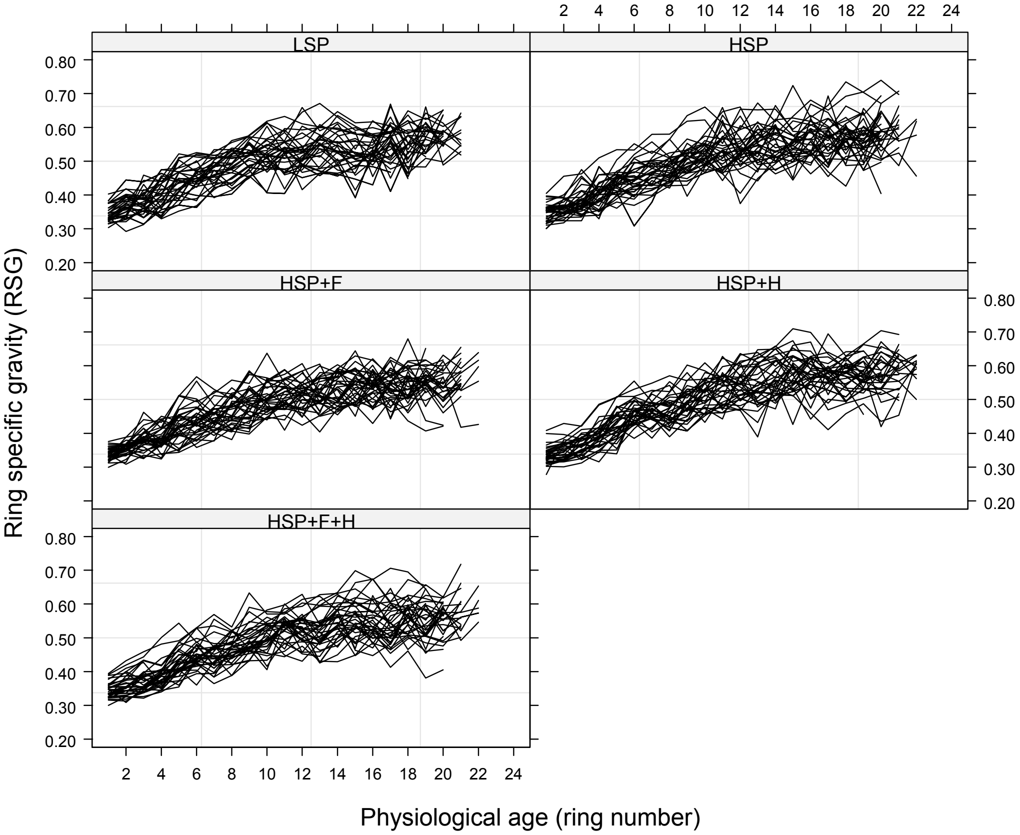

Figure 2. Ring specific gravity (RSG) profiles of individual trees at site 3.

APPENDICES

Appendix 1. Repeated measures analysis of variance for the wood quality study.

Source	df	MS	F
	Between-plot analysis		
Mean	1	MS(M)	MS(M)/MS(B)
Block	(r-1)	MS(B)	
Treatment	4		
Site preparation	1	MS(SP)	MS(SP)/MS(B×T)
Fertilization(SP)	1	MS(F)	MS(F)/MS(B×T)
Weed control(SP)	1	MS(H)	MS(H)/MS(B×T)
Fertilization×weed control(SP)	1	MS(F×H)	MS(F×H)/MS(B×T)
Block×treatment	4(r-1)	MS(B×T)	
	Within-plot analysis		
Time linear	1	MS(L)	MS(L)/MS(L×B)
Linear×block	1(r-1)	MS(L×B)	
Linear×site preparation	1	MS(L×SP)	MS(L×SP)/ MS(L×T×B)
Linear×fertilization	1	MS(L×F)	MS(L×F)/ MS(L×T×B)
Linear×weed control	1	MS(L×H)	MS(L×H)/ MS(L×T×B)
Linear×fertilization×weed control	1	MS(L×F×H)	MS(L×F×H)/ MS(L×T×B)
Linear×treatment×block	1×4(r-1)	MS(L×T×B)	
Time quadratic	1	MS(Q)	MS(Q)/MS(Q×B)
Quadratic×block	1(r-1)	MS(Q×B)	
Quadratic×site preparation	1	MS(Q×SP)	MS(Q×SP)/ MS(Q×T×B)
Quadratic×fertilization	1	MS(Q×F)	MS(Q×F)/ MS(Q×T×B)
Quadratic×weed control	1	MS(Q×H)	MS(Q×H)/ MS(Q×T×B)
Quadratic×fertilization×weed control	1	MS(Q×F×H)	MS(Q×F×H)/ MS(Q×T×B)
Quadratic×treatment×block	1×4(r-1)	MS(Q×T×B)	
Time cubic	1	MS(C)	MS(C)/MS(C×B)
Cubic×block	1(r-1)	MS(C×B)	
Cubic×site preparation	1	MS(C×SP)	MS(C×SP)/ MS(C×T×B)
Cubic×fertilization	1	MS(C×F)	MS(C×F)/ MS(C×T×B)
Cubic×weed control	1	MS(C×H)	MS(C×H)/ MS(C×T×B)
Cubic×fertilization×weed control	1	MS(C×F×H)	MS(C×F×H)/ MS(C×T×B)
Cubic×treatment×block	1×4(r-1)	MS(C×T×B)	

Appendix 2. Probability values from the repeated measures analysis of variance of ring earlywood specific gravity (REW) for each site.

Variable: REW	Site			
Source of variation	1	2	3	4
	Between-plot analysis			
Mean	**<0.01**[a]	**<0.01**[a]	**<0.01**[a]	**<0.01**[a]
Site preparation	0.70	0.08	0.51	**0.01**[a]
Fertilization(SP)	0.42	0.86	**0.02**[a]	0.39
Weed control(SP)	0.57	0.52	0.29	0.13
F×H(SP)	0.89	0.70	0.32	0.15
	Within-plot analysis			
Time linear	0.63	**<0.01**[a]	**0.02**[a]	**<0.01**[a]
Linear×SP	0.47	0.75	0.51	**<0.01**[a]
Linear×F	0.36	0.46	0.12	0.89
Linear×H	0.13	0.78	0.19	0.42
Linear×F×H	0.20	0.84	0.18	0.42
Time quadratic	**<0.01**[a]	**0.01**[a]	**0.02**[a]	**<0.01**[a]
Quadratic×SP	0.13	0.81	0.60	0.66
Quadratic×F	0.54	0.74	0.27	0.31
Quadratic×H	0.40	0.50	0.32	**0.01**[a]
Quadratic×F×H	0.44	0.71	0.48	0.35
Time cubic	**0.02**[a]	0.20	**0.01**[a]	**0.04**[a]
Cubic×SP	**0.01**[a]	0.31	0.79	0.28
Cubic×F	0.39	0.20	0.46	0.81
Cubic×H	**<0.01**[a]	0.86	0.08	0.61
Cubic×F×H	0.20	0.89	**<0.01**[a]	0.21

REW: Ring earlywood specific gravity ; [a] Significant effects ($p<0.05$);

Appendix 3. Probability values from the repeated measures analysis of variance of ring latewood specific gravity (RLW) for each site.

Variable: RLW	Site			
Source of variation	1	2	3	4
	Between-plot analysis			
Mean	**<0.01**[a]	**<0.01**[a]	**<0.01**[a]	**<0.01**[a]
Site preparation	0.59	0.09	0.53	0.06
Fertilization(SP)	0.76	0.20	0.22	0.78
Weed control(SP)	0.43	0.72	0.89	**0.02**[a]
F×H(SP)	0.28	0.36	0.33	<**0.01**[a]
	Within-plot analysis			
Time linear	**<0.01**[a]	**<0.01**[a]	**<0.01**[a]	**<0.01**[a]
Linear×SP	0.76	0.84	0.28	**<0.01**[a]
Linear×F	**0.03**[a]	0.24	**0.04**[a]	0.08
Linear×H	0.95	0.16	0.94	**0.03**[a]
Linear×F×H	0.89	0.98	0.40	0.63
Time quadratic	**<0.01**[a]	**0.01**[a]	**<0.01**[a]	**<0.01**[a]
Quadratic×SP	0.74	**0.01**[a]	0.75	**0.03**[a]
Quadratic×F	0.81	0.71	0.13	0.26
Quadratic×H	0.72	0.93	0.68	0.82
Quadratic×F×H	0.23	0.64	0.13	0.83
Time cubic	**0.01**[a]	**0.01**[a]	**<0.01**[a]	**0.02**[a]
Cubic×SP	0.24	0.55	**0.01**[a]	**0.02**[a]
Cubic×F	0.70	0.58	0.66	0.56
Cubic×H	**0.02**[a]	0.87	0.66	0.61
Cubic×F×H	0.77	0.43	**0.03**[a]	0.84

RLW: Ring latewood specific gravity ; [a] Significant effects ($p<0.05$);

Appendix 4. Probability values from the repeated measures analysis of variance of ring latewood proportion (RLP) for each site.

Variable: RLP	Site			
Source of variation	1	2	3	4
	Between-plot analysis			
Mean	**<0.01** [a]	**<0.01** [a]	**<0.01** [a]	**<0.01** [a]
Site preparation	0.83	0.83	0.43	0.30
Fertilization(SP)	**0.02** [a]	0.90	**0.04** [a]	0.98
Weed control(SP)	0.59	0.64	0.32	0.06
F×H(SP)	0.71	0.11	0.48	**0.05** [a]
	Within-plot analysis			
Time linear	**<0.01** [a]	**<0.01** [a]	**<0.01** [a]	**<0.01** [a]
Linear×SP	0.23	0.52	0.89	0.56
Linear×F	0.39	0.31	0.16	0.12
Linear×H	0.14	0.58	0.52	0.96
Linear×F×H	0.91	0.36	0.98	0.99
Time quadratic	**<0.01** [a]	**<0.01** [a]	**<0.01** [a]	**<0.01** [a]
Quadratic×SP	0.37	0.17	0.17	0.92
Quadratic×F	0.20	0.99	0.74	0.07
Quadratic×H	0.32	0.43	0.40	**0.04** [a]
Quadratic×F×H	0.99	0.64	0.17	0.97
Time cubic	0.16	**0.03** [a]	0.83	0.77
Cubic×SP	0.07	0.89	**0.05** [a]	0.50
Cubic×F	0.45	**0.01** [a]	0.99	0.83
Cubic×H	0.78	0.88	0.62	0.05
Cubic×F×H	0.17	0.98	0.38	**<0.01** [a]

RSG: Ring latewood proportion ; [a] Significant effects (p<0.05);