Regional variation in wood specific gravity of planted loblolly pine in the United States

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Abstract: Loblolly pine (*Pinus taeda* L.) is the most important plantation species in the southeastern United States and specific gravity (SG) is its most important wood quality trait. Analysis of annual ring SG of breast height (1.37 m) increment cores from 3957 trees representing 147 plantations across the species natural range showed that ring SG increases with increasing age and varies significantly among physiographic regions. The South Atlantic and Gulf regions had the highest ring SGs, while the Hilly and Piedmont regions had the lowest. Based on ring SG, the juvenile period averages 4.3 years, followed by 8.6 years of transition wood, with mature wood produced by year 13. Whole-core mean SG was significantly higher in the South Atlantic (0.486) compared with the other regions (mean = 0.455), which were not statistically different from each other. Trees from the South Atlantic have significantly higher whole-core SG because they contain significantly more latewood (40.1%) compared with trees growing in other regions (33.8%). Maps indicate that stands in the South Atlantic and Gulf regions have the highest SG at a given age. Stands growing on the northern and western fringe of the natural range of loblolly pine have the lowest whole-core SG.

Résumé : Le pin à encens (*Pinus taed*a L.) est la plus importante espèce plantée dans le sud-est des États-Unis d'Amérique et la densité est la plus importante caractéristique de la qualité du bois chez cette essence. L'analyse de la densité des cernes annuels dans des carottes prélevées à hauteur de poitrine (1,37 m) sur 3957 arbres provenant de 147 plantations établies partout dans l'aire naturelle de répartition de l'espèce montre que la densité des cernes annuels augmente avec l'âge et varie significativement entre les régions physiographiques. Les cernes annuels des régions de l'Atlantique Sud et du Golfe ont les densités les plus élevées tandis que ceux des régions de Hilly et du Piedmont ont les plus faibles. Sur la base de la densité des cernes annuels, la période juvénile dure en moyenne 4,3 ans, suivie d'une période de transition de 8,6 ans et du bois mature vers l'âge de 13 ans. La densité moyenne de l'ensemble de la carotte est significativement plus élevée dans la région de l'Atlantique Sud (0,486) que dans les autres régions (moyenne = 0,455) qui ne sont pas statistiquement différentes les unes des autres. Les carottes des arbres de la région de l'Atlantique Sud ont une densité significativement plus élevée parce qu'ils contiennent significativement plus de bois final (40,1 %) que les arbres qui croissent dans les autres régions (33,8 %). Pour un âge donné, les cartes indiquent que les peuplements des régions de l'Atlantique Sud et du Golfe ont la densité la plus élevée. Les carottes provenant des peuplements qui croissent aux limites nord et ouest de l'aire naturelle de répartition du pin à encens ont les plus faibles densités.

[Traduit par la Rédaction]

Introduction

In the United States, 58% of the timber harvested is produced in the southeast United States (Wear and Greis 2002). Currently there are more than 12.1×10^6 ha of pine plantations in the southeast United States, with the area projected to increase by 83% to over 22.2×10^6 ha in 2040. Loblolly pine (*Pinus taeda* L.) is the most important species planted and is used to produce both solid wood and fiber-based products. Many wood properties are important in determining the performance of products manufactured from loblolly pine, but the most universally important property is specific gravity (SG). Specific gravity is positively correlated with wood stiffness and strength (Panshin and deZeeuw 1980), important properties for southern pine lumber, engineered wood products, and composite panels. In addition, SG is positively correlated with pulp yield (Panshin and deZeeuw 1980) and is an important determinant of paper properties. Generally, higher SG wood has longer tracheids with increased tear resistance in liner board and kraft sack papers. Lower SG wood will generally have thinner walls and shorter tracheids, wider microfibril angles (MFA), and thus, produce paper with good tensile, burst, fold, and sheet smoothness, but lower tear and opacity (Smook 2002).

Wood properties vary considerably within a tree. 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

Received 9 July 2007. Accepted 7 August 2007. Published on the NRC Research Press Web site at cjfr.nrc.ca on 12 March 2008.

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 doi:10.1139/X07-158

wood are commonly referred to as juvenile wood. Juvenile wood differs from mature wood having a lower SG, shorter tracheids with larger MFA and a lower proportion of latewood (Larson et al. 2001). For loblolly pine, the length of juvenile wood production is shortest for the southeast portion of its natural range and increases in duration to both the north and west. Planting density or spacing also influences the proportion of stem basal area in juvenile wood, but not the age of transition from juvenile to mature wood.

Often, the difference between juvenile and mature wood has been determined by setting a threshold value for a specific wood property (Burdon et al. 2004); for SG, values ranging from 0.40 to 0.50 have been selected (Cown and Ball 2001; Clark and Saucier 1989; Clark et al. 2006). The number of years the cambium of loblolly pine produces juvenile wood, at a given height, based on ring specific gravity has been reported to range from 5 to 15 years (Zobel and McElwee 1958; Pearson and Gilmore 1980; Clark and Saucier 1989; Tasissa and Burkhart 1998; Mora et al. 2007). Researchers have reported that the length of juvenility in loblolly pine varies by geographic region with Clark and Saucier (1989) and Clark et al. (2006) finding the length of juvenile wood production based on a SG of 0.50 averaged from 4 to 8 years in the Atlantic Coastal Plain, and 10–14 years in the Piedmont, consistent with the findings of Tasissa and Burkhart (1998) who used a segmented modeling approach.

Recent work by Burdon et al. (2004) suggests that classifying zones within a tree as either juvenile or mature is an oversimplification of the physiological processes that are occurring within a tree. They propose that the stages of juvenility or maturity are vertically related, with wood produced in the radial direction being defined as deviates of corewood. Vertical deviations of wood for radiata pine (*Pinus radiata* D. Don) and loblolly pine, as defined by Burdon et al. (2004), are (*i*) juvenile wood is comprised of wood <3 m in height; (*ii*) transitional wood occurs between 3 and 5 m in height; and (*iii*) mature wood occurs at heights >5 m. Radial variation within a tree is subsequently defined in relation to vertical position and is comprised of varying zones of corewood, transition wood, and outerwood. For the duration of this paper, we adopt the terminology of corewood and outerwood as suggested by Burdon et al. (2004), with the distinction that the point of demarcation between corewood – transition wood and outerwood as defined by Burdon et al. (2004) is the age at which SG becomes stable.

The first wood density survey in the southern United States based on increment cores was conducted by the Forest Survey of the United States Forest Service (USFS) Southern Forest Experiment Station on natural pine species in Mississippi in the mid-1950s (Wheeler and Mitchell 1962). Results of the survey showed that SG increased from the northwest to the southeast across the state. The success of the Mississippi survey led to a regional survey of seven southern states conducted by the Forest Survey and the USFS Forest Products Laboratory (USDA Forest Service 1965). The southern wood density survey was expanded from 7 to 11 southern states and reported by Wahlgren and Schumann (1972, 1975). The results of these surveys showed that increment core SG of naturally regenerated loblolly pine decreased from the Atlantic and Gulf Coastal Plain to the Piedmont and Hilly Coastal Plain. Increment core SG of longleaf pine (*Pinus palustris* P. Mill.) and slash pine (*Pinus elliotii* Engelm.) were also found to decrease from south to north over their natural range.

Gilmore (1967) examined increment core SG of planted loblolly pine from the southern to the northern range in the Mississippi Valley in the 1960s and found that the SG of planted loblolly pine decreased from 0.480 in southern Mississippi to 0.403 in southern Illinois. Gilmore (1967) assumed the observed decrease was related to reduced late summer precipitation and a shorter growing season. Talbert and Jett (1981) found that the mean mature wood SG at 1.37 m for loblolly pine averaged 0.54 in North and South Carolina and 0.50 in northern Mississippi, west Tennessee, west Kentucky, and Virginia. Megraw (1985), when examining increment core SG of plantation loblolly pine in North Carolina compared with that in Arkansas, found the Arkansas SG to be 5%–8% lower than that of the North Carolina trees. Megraw (1985) reported that the difference was related to a higher percentage of latewood and higher latewood SG in the North Carolina trees.

Recently, the Wood Quality Consortium (WQC) of the University of Georgia and the USDA Forest Service Southern Research Station have completed a large-scale survey of SG across the natural range of planted loblolly pine. This survey represents the first detailed study of SG variation in loblolly pine for many years. Based on these data, the objectives of this research were to (*i*) examine the regional variation and trends of individual ring SG in planted loblolly pine; (*ii*) examine the regional variation in whole-core SG, earlywood SG, latewood SG, and latewood percentage; and (*iii*) develop regional maps depicting how SG changes across the southeastern United States.

Materials and methods

Data

Plantation loblolly pine trees were sampled across the natural range of the species by the WQC of the University of Georgia and the USDA Forest Service Southern Research Station to explore wood SG properties at breast height (1.37 m above ground). Plantations selected for sampling were conventionally managed having received no intensive management practices such as chemical competition control or fertilization except phosphorus on phosphorus-deficient sites. Stands selected for sampling had initial planting densities between 1112 to 1779 trees·ha^{-1}. However, at the time of sampling, stocking ranged from 494 to 1483 trees·ha^{-1}, with the majority of the stands having been thinned late, and grew most of their life under similar (relatively high) stand-density levels. Thus, the trees were producing wood under similar stocking conditions for most of their lives. One hundred and twenty-four of the plantations selected for sampling were commercial plantations aged 18–31 years from the WQC baseline study, 12 plantations were 30–45 years old and were sampled from a growth and yield study established by the Virginia Tech Growth and Yield Cooperative, and 11 plantations 21–24 years old were sampled from the species comparison study established by the University of Georgia Pine Management Research Cooperative (Fig. 1). A sample of 1530 trees was selected in pro-

Fig. 1. Plot of the 147 stands sampled for specific gravity (SG) analysis (●) and a subset of 38 stands (○ with star) for performing reduced knot kriging.

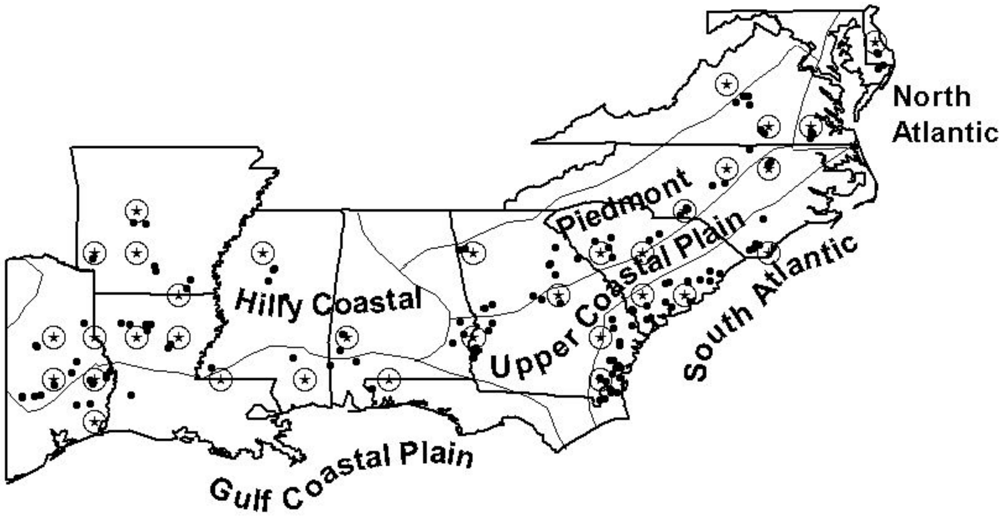


Table 1. Mean and standard deviation (in parentheses) of tree characteristics for the loblolly pine trees sampled for specific gravity analysis.

Region	No. of stands	No. of trees	DBH (cm)	Height (m)	Age (years)	Site index (m)
Gulf Coastal	17	492	20.6 (4.3)	18.9 (3.1)	23.5 (3.6)	20.5 (2.5)
Hilly Coastal	33	902	23.4 (5.6)	19.1 (3.1)	23.9 (4.3)	20.4 (2.6)
North Atlantic	7	207	21.6 (5.3)	17.4 (2.6)	22.4 (1.9)	19.4 (2.2)
Piedmont	30	813	23.1 (5.3)	17.9 (3.7)	24.2 (4.5)	18.9 (2.0)
South Atlantic	43	1048	24.6 (5.8)	20.9 (3.4)	23.4 (4.1)	22.6 (2.4)
Upper Coastal	17	495	22.3 (5.3)	18.4 (3.2)	23.0 (1.4)	20.0 (2.6)

portion to the diameter distribution of the trees in the stand. Regional, stand, and tree attributes are summarized in Table 1.

Increment cores, 12 mm in diameter, were collected from the trees chosen for analysis in each stand. The increment cores were dried, glued to core holders, and sawn into radial strips (12 mm tangentially and 2 mm longitudinally). Radial growth and SG of the earlywood and latewood of each annual ring for each radial strip was determined at 0.006 mm intervals using a direct-scanning X-ray densitometer (QTRS-01X, Quintek Measurement Systems, Knoxville, Tennessee). A SG value of 0.480 was used to separate earlywood and latewood. The densitometer was calibrated to express SG on a green volume and oven-dried mass basis.

Ring earlywood, latewood, whole-ring SG, and percentage of latewood were weighted by ring basal area to obtain a mean basal area weighted whole-core value for each tree sampled. For developing the SG maps, a mean stand value was calculated by averaging across the weighted ring SG of each sample tree at 1 year intervals. To account for the amount of time it took the trees to grow to a height of 1.37 m, 3 years were added to the ring count, such that ring 1 corresponds to a stand age of 4 years. We limited the number of rings used in this analysis to be ≤35 rings per tree.

Statistical analysis

Ring specific gravity

Often, trends over time are not adequately represented by a parametric modeling approach. A more modern and flexible approach to repeated measures analysis utilizes semiparametric analyses. Many frameworks for semiparametric modeling exist, but in this paper we model the relationship between SG and time via penalized smoothing splines, which have the advantage that they can be formulated within a linear mixed-effects modeling framework (Ngo and Wand 2004). Smoothing splines are curves that are formed by joining together several low-order polynomials at specified locations known as knots. Smoothing splines are extremely useful when modeling an intrinsically nonlinear relationship and have gained widespread popularity in the statistical literature (Verbyla et al. 1999; Ruppert et al. 2003; Durbán et al. 2004).

The trees selected for SG analysis can be considered a random sample of all trees within a given region, and their contribution to the variance of SG can be estimated. For analyzing the individual ring SGs, we chose to fit a penalized spline with a quadratic basis for examining regional differences in ring SG. More complex basis functions could be used, but a truncated line basis presents a simple mathematical form when formulating complex models (Durbán et al. 2004). Following Durbán et al. (2004), let y_{ij} ($i = 1, ..., m$ and $j = 1, ..., n_i$) denote ring SG observed at the jth ring from the pith of the ith tree. To fix ideas and facilitate explanation of the semiparametric models we utilize in this paper, we begin with a relatively simple example. Let

$$[1] \qquad y_{ij} = f(x_{ij}) + b_i + \varepsilon_{ij}; \qquad \varepsilon_{ij} \sim N(0, \sigma^2); \qquad b_i \sim N(0, \sigma_b^2)$$

where f is a smoothing function describing the trend of ring

SG with increasing ring number from the pith, b_i are independent, random tree-specific effects (or deviations from the pattern captured by f) that are assumed to be independent of the constant variance errors, ε_{ij}. The function f can be estimated by a penalized spline. Let $\kappa_1, \ldots, \kappa_K$ be a set of distinct knots in the range of x_{ij} and let $x_+ = \max(0, x)$. General rules of thumb regarding knot selection suggest the inclusion of one knot for every three or four predictor values, with no more than approximately 35 or so necessary overall. Evenly spaced knots or knots placed at the quantiles of x are often used (Kamman and Wand 2003; Ruppert et al. 2003; Durbán et al. 2004). The number of knots (K) for this problem were equally spaced such that $k = (2, 4, 6, ..., 34)$, for a total of 17 knots, ensuring the flexibility of the curve.

A penalized spline formulation of model [1] can be written as

$$[2] \qquad y_{ij} = \underbrace{\beta_0 + \beta_1 x_{ij} + \beta_2 x_{ij}^2 + \sum_{k=1}^{K} u_k (x_{ij} - \kappa_k)^2}_{f(x_{ij})} + b_i + \varepsilon_{ij}$$

Penalized least-squares estimates of ($\boldsymbol{\beta}$, $\mathbf{u}$) can be obtained via standard fitting methodology by formulating model [2] as a linear mixed model in which we assume $u_k \sim N(0, \sigma_u^2)$. The penalized spline smoother is given by $f(x_i)$ evaluated at $(\hat{\boldsymbol{\beta}}, \hat{\mathbf{u}})$, where these quantities are the maximum likelihood (ML) estimate (MLE) of $\boldsymbol{\beta}$ and the empirical best linear unbiased predictor (EBLUP) of $\mathbf{u}$, respectively, obtained by fitting model [2] as a linear mixed model (e.g., with SAS PROC MIXED or other mixed-model software). In this approach, the parameter that controls the smoothness in the estimate of $f(x_i)$ (the "smoothing parameter'') is $\lambda = \sigma^2/\sigma_u^2$ and is selected automatically via the restricted MLEs of σ^2 and σ_u^2. The semiparametric model [2] can be written in the general form of a linear mixed model given by

$$[3] \qquad \boldsymbol{Y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{Z}\mathbf{u} + \varepsilon$$

where

$$\mathbf{Y} = \begin{bmatrix} y_{11} \\ \vdots \\ y_{mn_m} \end{bmatrix}$$

$$\mathbf{X} = \begin{bmatrix} \mathbf{X}_1 \\ \vdots \\ \mathbf{X}_m \end{bmatrix}$$

$$\mathbf{X}_i = \begin{bmatrix} 1 & x_{i1} & x_{i1}^2 \\ \vdots & \vdots & \vdots \\ 1 & x_{in_i} & x_{in_i}^2 \end{bmatrix}$$

$$\mathbf{Z} = \begin{bmatrix} \mathbf{Z}_1 & \mathbf{1}_1 & 0 & \cdots & 0 \\ \mathbf{Z}_2 & 0 & \mathbf{1}_2 & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \mathbf{Z}_m & \vdots & \vdots & \cdots & \mathbf{1}_m \end{bmatrix}$$

$$\mathbf{Z}_i = \begin{bmatrix} (x_{i1} - k_1)_+^2 & \cdots & (x_{i1} - k_K)_+^2 \\ \vdots & \ddots & \vdots \\ (x_{in_i} - k_1)_+^2 & \cdots & (x_{in_i} - k_K)_+^2 \end{bmatrix}$$

$$\mathbf{u} = [u_1, \ldots, u_K, b_1, \ldots, b_m]^T$$

Examining regional differences in the dependence of SG on ring number is relatively straightforward by the addition of interaction terms to the model. In particular, we generalize model [2] as

$$[4] \qquad y_{ij} = \beta_0 + \beta_1 x_{ij} + \beta_2 x_{ij}^2 + \sum_{k=1}^{K} u_k (x_{ij} - \kappa_k)_+^2 + \sum_{r=2}^{R} z_{ir}(\gamma_{0r} + \gamma_{1r} x_{ij} + \gamma_{2r} x_{ij}^2) + \sum_{r=2}^{R} z_{ir} \left[\sum_{k=1}^{K} w_k^r (x_{ij} - \kappa_k)_+^2 \right] + b_i + \varepsilon_{ij}$$

$z_{ijr} = 1$ if $z_{ij} = r$ and 0 otherwise for $r = 2, ..., R$, ($R = 6$), and $w_k^r \sim N(0, \sigma_w^2)$. The first four terms in eq. 4 specify the fitted curve for r = 1, the Gulf region, and the fifth and sixth terms correspond to differences of the fitted curves for each of the other regions as compared with the Gulf.

Similar to the trees selected for sampling, the stands selected for sampling represent a random sample of all stands in the corresponding region, and the between-stand variation may be accounted for by the addition of stand-level random-effects to model [4]. This leads to a three-level model of the form

$$[5] \qquad y_{ijl} = \beta_0 + \beta_1 x_{ijl} + \beta_2 x_{ijl}^2 + \sum_{k=1}^{K} u_k (x_{ijl} - \kappa_k)_+^2 + \sum_{r=2}^{R} z_{ijr}(\gamma_{0r} + \gamma_{1r} x_{ijl} + \gamma_{2r} x_{ijl}^2) + \sum_{r=2}^{R} z_{ijr} \left[\sum_{k=1}^{K} w_k^r (x_{ijl} - \kappa_k)_+^2 \right] + s_i + b_{ij} + \varepsilon_{ijl}$$

where y_{ijl} ($i = 1, ..., m$; $j = 1, ..., m_i$; $l = 1, ..., n_{ij}$) denotes ring SG observed at the lth ring, in the jth tree, of the ith stand. Here, s_i and b_{ij} are stand- and tree-specific random effects, respectively.

The derivative of eq. 5 is of interest because it allows us to explore the rate at which SG changes with increasing ring number from the pith. From this, we can answer such questions as (*i*) How fast is SG increasing?; (*ii*) At what age does SG plateau?; and (*iii*) Can we estimate the age at which SG changes from corewood to transition wood to outerwood?

Differentiating eq. 5 with respect to x_{ijl} yields

$$[6] \quad \frac{\partial y_{ijl}}{\partial x_{ijl}} = \beta_1 + 2\beta_2 x_{ijl} + \sum_{k=1}^{K} 2u_k (x_{ijl} - \kappa_k)_+ + \sum_{r=2}^{R} z_{ijr}(\gamma_{1r} + 2\gamma_{2r} x_{ijl}) + \sum_{r=2}^{R} z_{ijr} \left[\sum_{k=1}^{K} 2w_k^r (x_{ijl} - \kappa_k)_+ \right]$$

Predicted values and corresponding standard errors for eqs. 5 and 6 can easily be obtained by utilizing the solutions of the mixed-model equations. A more thorough review of prediction and inference in the sort of penalized spline model we use here is given by Ruppert et al. (2003).

The models in this paper were fitted using the MIXED procedure in SAS (SAS Institute Inc. 2004). For simplicity, we assume a common variance parameter for all curves ($\sigma_u^2 = \sigma_w^2$), meaning that the curves are different but with the same amount of smoothing. Also, the deviation of the ith stand and jth tree is modeled through a random intercept. A more complex structure assuming that the curves are not parallel could be employed by incorporating random slope effects, however, the memory requirements of fitting such a model become prohibitive, e.g., the size of the random effects' design matrix (**Z**) necessary for such a model would be of the dimension $[N(RK + 2m + 2\sum m_i)] = (76\,317 \times 8310)$, which would require approximately 5.0 GB of RAM just to hold in memory for the required calculations.

Whole-core properties

An analysis of variance (ANOVA) was used to test for regional differences in whole-core, early, and latewood SG, and latewood percentage. Let y_{ijk} represent the wood property of interest measured on the kth tree in the jth stand in the ith region, the model can be written as

$$[7] \quad y_{ijk} = \mu + R_i + s_{ij} + \varepsilon_{ijk}$$

where μ denotes the population mean, R_i denotes the fixed effect of the ith region, s_{ij} denotes the random effect of the jth stand in the ith region where we assume $s_{ij} \sim \mathrm{N}(0, \sigma_s^2)$, and ε_{ijk} are independent $N(0, \sigma^2)$ experimental errors. All tests were performed at the 0.05 level, and Tukey's honestly significant different (HSD) test was used for pairwise comparisons among region-specific means.

Specific gravity maps

One of the primary objectives of this study was the development of maps detailing how loblolly pine SG changes over the southeast United States. Methods for modeling geostatistical data have gained widespread popularity in recent years and are often employed with a method known as kriging (Cressie 1993). Kriging is a method of interpolation that predicts unknown values from data observed at known locations. This method uses the semivariogram to express spatial covariance, and it minimizes the error of the predicted values, which are estimated from the spatial distribution of the observed values. A reasonable approach for development of SG maps would be to employ a kriging-based model; however, since the stand data in this study were collected across both space (i.e., latitude and longitude) and time, the effects of stand age also need to be considered. Kriging can be extended to incorporate covariates; however, the covariates are often assumed to be linear (Kamman and Wand 2003). For this data set, mean stand SG was found to be highly nonlinear with age, thus, we chose the geoadditive approach of Kamman and Wand (2003), which combines kriging with additive models allowing for general smooth functional covariate effects and is implemented in a mixed-model framework.

For our purposes, the covariates that may be of potential interest are site index and stand age, both of which may enter into the model in an additive manner. However, the relationship between site index and SG was found to be linear, thus, we restricted site index to be a linear covariate. Following Kamman and Wand (2003) and Ruppert et al. (2003), the general formulation of the additive model for stand age is given as

$$[8] \quad y_{ij} = \beta_0 + f(\mathrm{age}_{ij}) + \varepsilon_{ij}$$

where y_{ij} is the SG of the jth measurement occasion (stand age) made on the ith stand, and f is a smooth function of age. The penalized spline version of model [8] is similar to model [2], except that truncated linear spline basis functions were used rather than truncated quadratics, and the model does not include the random intercept, b_i. For the sake of brevity, we omit further details.

The geostatistical component is incorporated by fitting a bivariate thin plate spline to a geographical location. Given that the data are of the form ($\mathbf{x}_{ij}$, y_{ij}), where y_{ij} is scalar and $\mathbf{x}_{ij} \in \Re^2$ represents the geographical location, the general kriging model with linear covariates is

$$[9] \quad y_{ij} = \beta_0 + \boldsymbol{\beta}_1^{\mathrm{T}} \mathbf{x}_{ij} + S(\mathbf{x}_{ij}) + \varepsilon_{ij}$$

where $\{S(\mathbf{x}) : \mathbf{x} \in \Re^2\}$ is a stationary stochastic process with mean zero. Prediction at a location $\mathbf{x}_0$ across the sampling space is achieved using the estimates of $\widehat{\beta}_0, \widehat{\boldsymbol{\beta}}_1$, and $\widehat{S}(\mathbf{x}_0)$ for a given covariance structure (i.e., model) for S. It is assumed that the covariance between stands is isotropic, indicating that the covariance between stands $\|\mathbf{h}\|$ units apart is the same, regardless of direction or location (Ruppert et al. 2003). The development of the covariance function of S and estimation of its parameters is beyond the scope of this paper and the readers are referred to Kamman and Wand (2003). Equation 9 is fitted using reduced knot kriging, where $\{\kappa_1, \ldots, \kappa_K\}$ are a subset of knots selected from the sample space, $\mathbf{x}_i$. The knots are selected by a space filling algorithm discussed in Nychka et al. (1996) and Ruppert et al. (2003). The number of knots to be selected was chosen by evaluating $K = \max\{10, \min[50, \mathrm{round}(\mathbf{x}_i/4)]\}$ (Fig. 1). Combining eqs. 8 and 9 yields the geoadditive model

$$[10] \quad y_{ij} = \beta_0 + f(\mathrm{age}_{ij}) + \boldsymbol{\beta}_1^{\mathrm{T}} \mathbf{x}_{ij} + S(\mathbf{x}_{ij}) + \varepsilon_{ij}$$

which, again, can be written as a linear mixed model

$$[11] \quad \mathbf{Y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{Z}\mathbf{u} + \varepsilon$$

where $\mathbf{Y}$ is the overall response vector, $\mathbf{X} = [1 \quad \mathrm{age}_{ij} \quad \mathbf{x}_{ij}^{\mathrm{T}}]$ and $\mathbf{Z}$ is the matrix of spline basis functions corresponding to f and S. For our data, we found it necessary to model only stand age nonparametrically. However, the inclusion of more additive components is easily implemented. Similarly, the addition of linear terms (e.g., effects of site index) can be introduced into eq. 11 through $\mathbf{X}\beta$. The main reason for using the geoadditive model is to account for the highly nonlinear trend of whole stand SG with age. Higher resolution maps were produced by increasing the number of knots and also utilizing every location within the data set. However, we were interested in generating maps that could be used to identify broad regional trends (low resolution). The geoadditive model was implemented using the SemiPar library in R (Wand et al. 2005).

Results

Plots of ring earlywood SG from pith to bark show earlywood SG decreases slightly from $\sim$0.37 to 0.32 from rings 1 to 10, respectively, and then levels off (Fig. 2). Earlywood SG is highest in the Gulf and South Atlantic regions compared with the Piedmont, North Atlantic, and Hilly regions. Mean ring latewood SG increases rapidly from ring 1 to 10 and approaches an upper limit (Fig. 2). When compared with the plot of earlywood SG, latewood SG does not appear to differ among regions. The plots of annual ring SG and latewood percentage show that these two properties follow the same pattern (Fig. 2). Both increase rapidly from the pith to about ring 13, before stabilizing. Whole-ring SG and percentage of latewood are highest in the South Atlantic and Gulf regions and lowest in the Piedmont and Hilly regions. The sporadic nature of the curves in Fig. 2, from rings 20 to 35, can be attributed to a reduction in the number of trees sampled that had more than 20 rings.

Ring specific gravity

A plot of predicted SG (eq. 5) versus ring number from the pith is given in Fig. 3. All regions have similar patterns characterized by a rapid increase in SG for approximately 12 rings, followed by a series of rolling dips, but generally all regions approach some "quasi-asymptote" as described by Burdon et al. (2004). Specific gravity is generally higher in the Gulf and South Atlantic regions beginning at ring 5, compared with the other regions. Ring SG also increases much more rapidly in the Gulf and South Atlantic compared with all other regions. To compare the six curves, we refit the full model (eq. 5) with one common curve. Comparison of this model with model [5] corresponds to testing the null hypothesis $H_0 : \gamma_{jr} = 0$, where j = 0, 1, 2 and r = 2, 3, 4, 5, or 6. The difference in the values of –2LL for the two models was found to be 2672.3 and is asymptotically distributed as χ^2_{15}. This test indicates highly significant differences between regions at any conventional significance level.

Specific gravity in rings 1–5 were found to be similar among all regions, with the exception of the South Atlantic having statistically higher SGs compared with all other regions excluding the Gulf at rings 4 and 5 (Figs. 4 and 5). Similarly, SG at ring 5 was found to be higher in the Gulf compared with the Hilly and North Atlantic regions. At rings 6–10, where the fitted curves begin to diverge (Fig. 5), ring SG was found to be significantly higher in the Gulf and South Atlantic compared with all other regions, with no differences observed between the South Atlantic and Gulf regions. Similarly, SG in the Upper Coastal region was found to be significantly higher than the Hilly and Piedmont regions across rings 6–10. No significant differences were detected when comparing the Hilly, Piedmont, and North Atlantic regions.

For rings 11–15, ring SG was found to be significantly higher in the South Atlantic, compared with all other regions (Fig. 5). Ring SG was found to be higher in both the Gulf and Upper Coastal regions compared with the Hilly and Piedmont regions. As opposed to the results in rings 6–10, no significant differences were found when comparing the Gulf and Upper Coastal regions. Figure 4 indicates that SG in the Gulf region appears to be leveling off at ring 10, whereas SG continues to increase in the Upper Coastal region. No significant differences were detected between the Hilly, Piedmont, and North Atlantic regions. Ring SG was found to be significantly higher in the South Atlantic compared with all other regions in rings 16–20. No differences were detected when comparing the Gulf, Upper Coastal, and North Atlantic regions, but both the Gulf and Upper Coastal regions had significantly higher SGs compared with the Hilly and Piedmont regions. Ring SG was found to be significantly lower in the Hilly region when compared with all other regions. Beyond 20 rings, the patterns observed in rings 16–20 generally hold, with the highest SGs found in the South Atlantic, Gulf, and Upper Coastal regions, and lower values found in the Hilly, North Atlantic, and Piedmont regions.

Visual inspection of the mean (Fig. 2) and fitted (Figs. 3–5) curves of ring SG indicate a series of "rolling dips" in all regions. These trends are not seen before approximately ring 11, but become more readily apparent past this ring number for all regions. Closer inspection of the data indicated no significant outliers of magnitude that would increase or decrease the mean value of SG at any one particular ring. However, this is not true especially for the largest ring numbers from pith where the frequency of trees with those rings is reduced (the Upper Coastal region had only six trees that had up to 24 rings).

The derivative (eq. 6) plots for all regions are characterized by a rapid increase in SG from ring 1 to approximately ring 5 (Fig. 6). Past ring 5, SG is increasing, but at a decreasing rate, until the point at which SG essentially stabilizes or reaches the quasi-asymptote as suggested by Burdon et al. (2004). The ring number at which SG begins producing outerwood, or when SG stabilizes, is approximately ring 12. The derivative plots clearly indicate the three zones of wood formation: (*i*) corewood, being produced in rings 1–5; (*ii*) transition wood being produced in rings 5–12; and (*iii*) outerwood being produced after ring 12. We then constructed Table 2, which contains the estimated length of juvenility using a prespecified threshold value of 0.50, and the three zones of wood as described above for each physiographic region. The length of juvenility or corewood, using eq. 6, was defined as ring 1 up to the ring number where the rate of change begins to decrease. Transition wood was defined as the ring number where the rate of change begins to decrease up to the ring number where the confidence intervals of the derivative function first intersect the y axis at 0. Outerwood was defined as all rings greater than the ring number where the confidence intervals of the derivative function first intersect the y axis at 0.

Fig. 2. Plot of mean ring, earlywood, and latewood specific gravity (SG), and percentage of latewood by region.

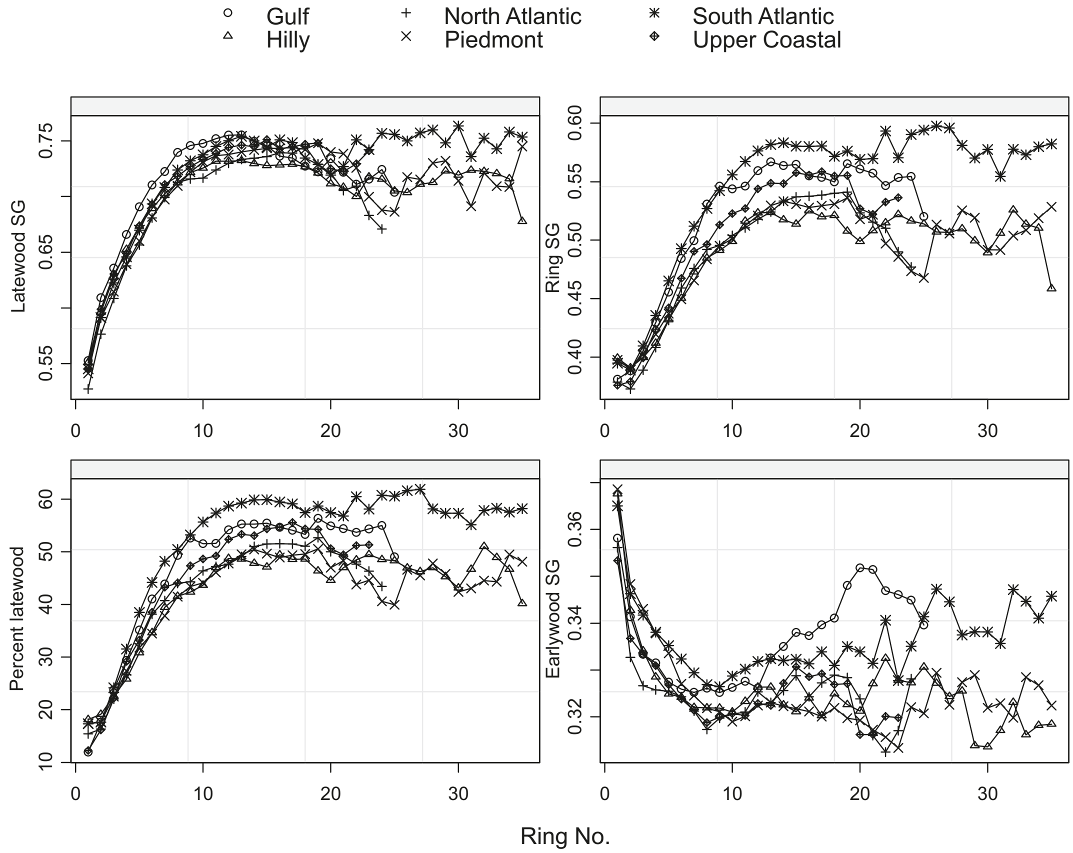
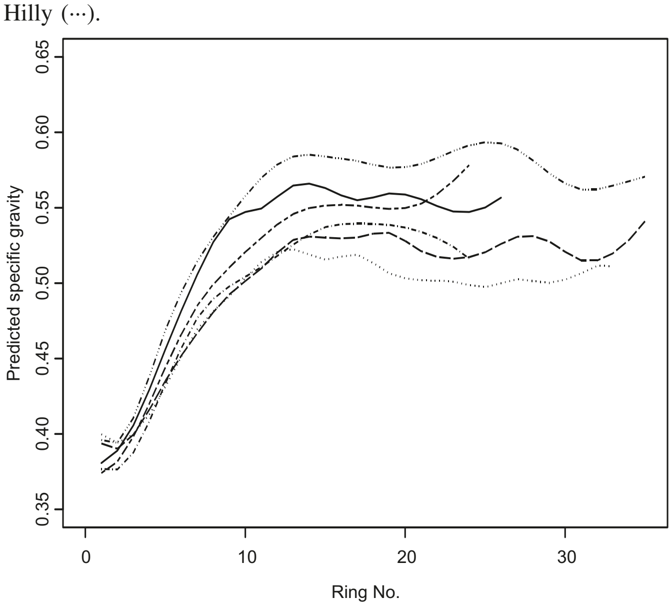


Fig. 3. Plot of predicted specific gravity versus ring number from the pith by physiographic region: South Atlantic (– ··· –), Gulf (—), Upper Coastal (– — –), North Atlantic (- · - · ·), Piedmont (- - -), and Hilly (···).



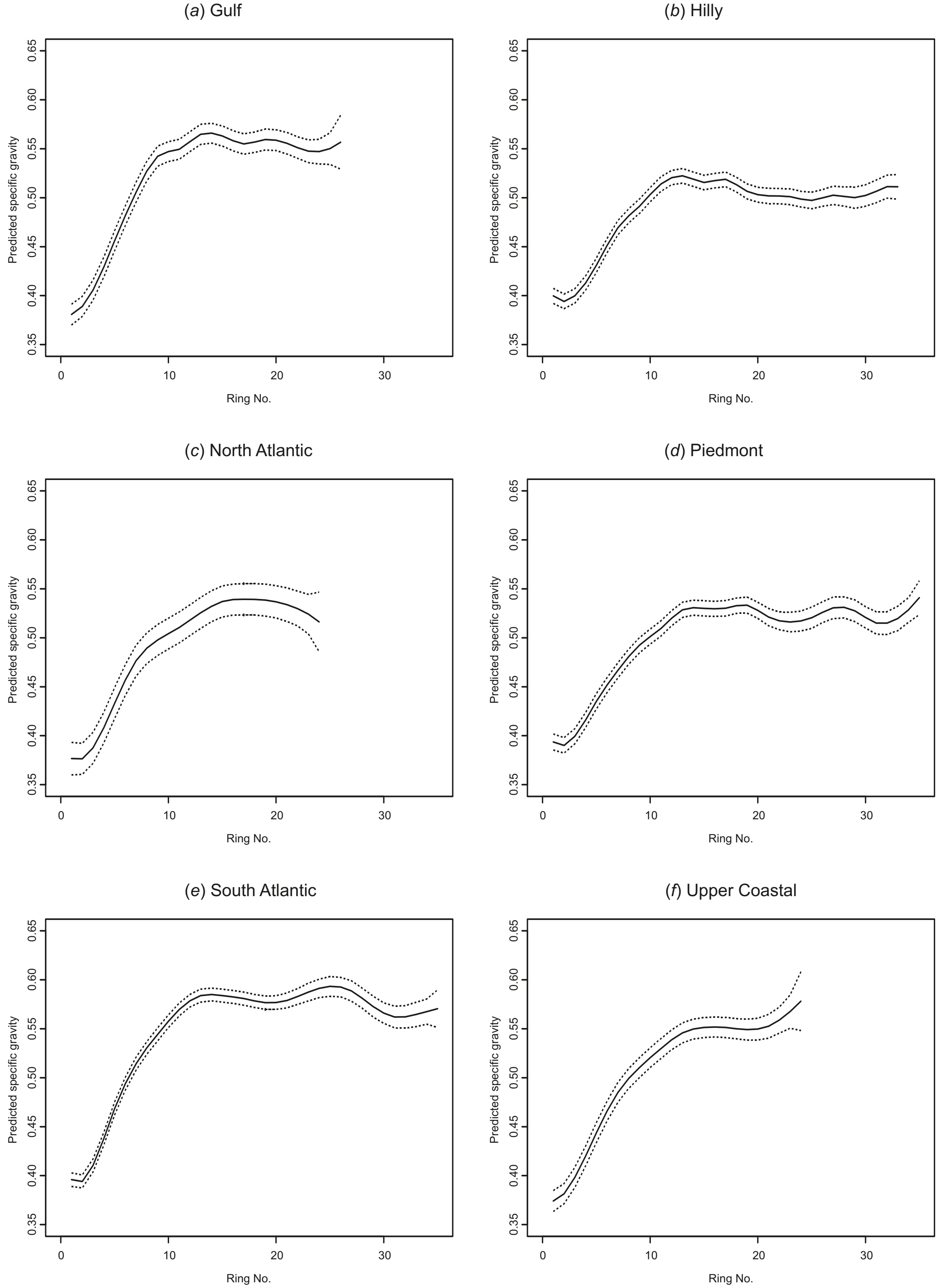
The estimated length of juvenility based on the threshold method ranges from 6.5 years in the South Atlantic to 10 years in the Hilly and Piedmont regions. Using eq. 6, the length of juvenility or corewood was found to range from 4.0 years in the North Atlantic and Piedmont regions to 6.0 years in the Hilly region. The length of the transition wood period ranged from 5.6 (9.6 – 4.0) years in the Gulf region to 11.3 (15.2 – 4.0) years in the North Atlantic region. The ring number at which trees started to produce outerwood according to eq. 6 ranges from 9.6 years in the Gulf region to 15.2 years in the North Atlantic region.

Whole-core properties

Results from the ANOVA for the whole-core properties are found in Table 3. Whole-core SG was found to be significantly higher in the South Atlantic region when compared with all other regions. Aside from this result, no other statistically significant differences were found when comparing whole-core SG among regions. Clearly, the higher whole-core SGs in the South Atlantic region is linked to the fact that the trees in this region have significantly higher ring SGs and a higher percentage of latewood compared with all other regions (Table 3). The percentage of latewood in the South Atlantic region was found to be 6.3 percentage points higher on average than all other regions.

Table 3 indicates that whole-core earlywood SG is significantly lower in the Upper Coastal region compared with the South Atlantic region. The differences in whole-core earlywood are negligible ranging from 0.329 in the North Atlantic and Upper Coastal regions to 0.338 in the South Atlantic region. Whole-core latewood SG was found to differ only between the South Atlantic and Hilly regions, but the overall differences between regions was quite small, with the difference between the South Atlantic and Hilly regions being only 0.017.

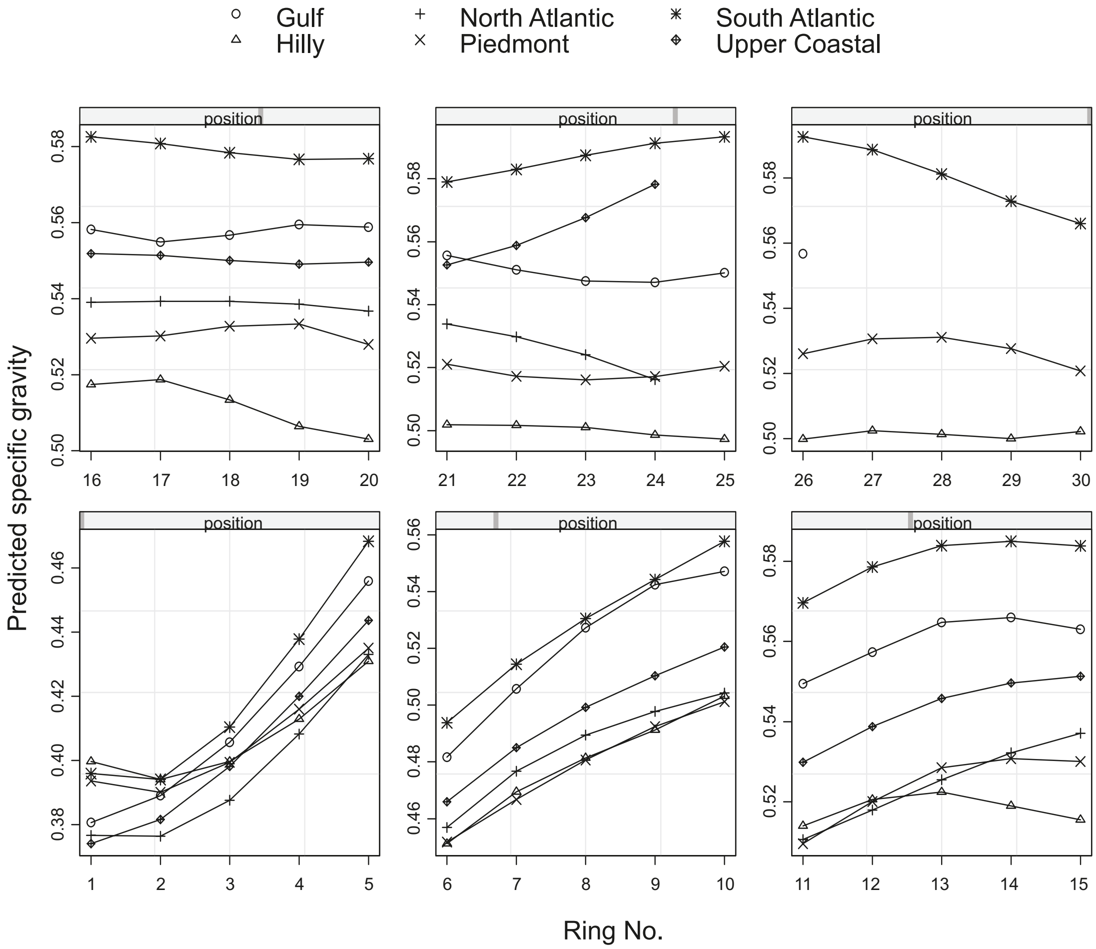
Fig. 4. Plot of predicted population mean curves and corresponding 95% pointwise confidence intervals for the (*a*) Gulf region, (*b*) Hilly region, (*c*) North Atlantic region, (*d*) Piedmont region, (*e*) South Atlantic region, and (*f*) Upper Coastal region.



Specific gravity maps

Results of SG map development indicated that mean stand SG increases in a highly nonlinear fashion with stand age (P = 0.0001) (Fig. 7). Site index was also found to be highly significant (P = 0.0001) and indicates that whole-stand SG decreases with increasing site index (coefficient = –0.00053). Plots of the residuals were constructed and indicated no significant trends. Mean stand SG increases rapidly to

Fig. 5. Plot of predicted population mean curves by five ring intervals.



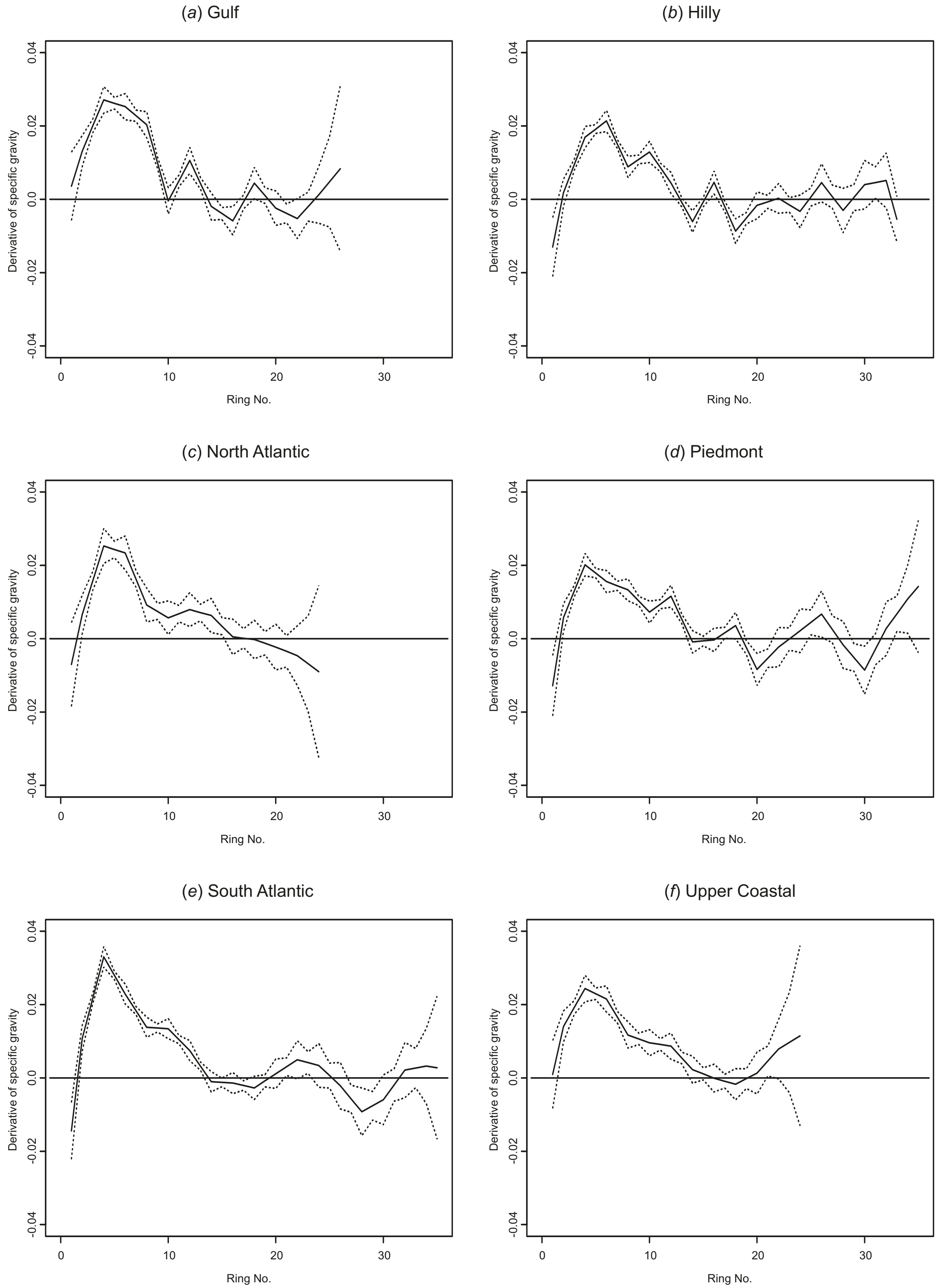
~20 years then begins leveling off until age ~28 years where SG begins to increase again. Only 20 stands had ages >27 years, thus, values of SG beyond this point are potentially biased, which can also be seen by an increase in the variability bars for age (Fig. 7). The degrees of freedom for the geographical component were found to be 34.60, indicating a high degree of nonlinearity (a planar fit corresponds to 3 df). The natural full model for this data could be a three-dimensional smoothing model, thus, such a large degree of freedom value may be suspect. However, when we implemented a bivariate smoothing spline for ages 5, 15, and 20 years separately, results indicated that SG is best described by a nonlinear component.

Predicted SGs and corresponding standard errors of the geoadditive fit for whole-stand SG at 16, 22, and 28 years of age are shown in Fig. 8. For simplicity, the models were refitted without the inclusion of site index. The results show that SG generally decreases along two gradients: south to north and east to west. SG was found to be highest along the South Atlantic coast, from the southern tip of Georgia to the northern tip of South Carolina. The Gulf also exhibits high stand SGs, extending from mid-Louisiana west to Texas. The maps also indicate a high band of SG along the western edge of Mississippi extending into northern Arkansas and south into Louisiana. However, this area is also characterized by larger standard errors, as much of this part of the region was not covered in the survey. Higher standard error values are typically found in those regions with sparse coverage such as the southern Gulf, northern Texas and Arkansas, northern Alabama and eastern Mississippi, the southern Atlantic coast of North Carolina, and Maryland. Figure 8 also suggests that predicted SG generally falls in line with the predefined regions located in Fig. 1. However, it is apparent that a more thorough survey would be required to delineate the gradients of change in whole-stand SG.

Discussion

This analysis showed that ring SG increases with increasing ring number from the pith and varies significantly among the physiographic regions. Ring SG was generally found to be higher in the South Atlantic and Gulf regions when compared with all other regions at an earlier age (ring 5). Overall, these results suggest that ring SG is greatest in the South Atlantic, Gulf, and Upper Coastal regions, with the Hilly region possessing the lowest ring SGs. This work also suggests that wood within a tree can potentially be split into three unique groups based on derivatives of mean ring SG. On average, the length of the periods were found to be 4.3 years of corewood, 8.6 years of transition wood, with outerwood being produced after 12.9 years. Plots of the mean and fitted curves both indicate a series of rolling dips

Fig. 6. Derivatives of the population mean curves and corresponding 95% pointwise confidence intervals for the (*a*) Gulf region, (*b*) Hilly region, (*c*) North Atlantic region, (*d*) Piedmont region, (*e*) South Atlantic region, and (*f*) Upper Coastal region. Derivative, solid line; and lower and upper 95% CIs, dotted line.



in all regions. The presence of these observed dips in ring SG suggests that, under the absence of limiting resources, individual tree ring SG is potentially physiologically driven. As nutrients become limiting and competition increases with the onset of crown closure, SG may be more sensitive to environmental factors.

Table 2. Estimated length of juvenility (ring No.) using a prespecified threshold value of 0.50, and the three-zones of wood as described by eq. 6.

	Method				
	Threshold		Equation 6		
Region	Corewood	Outerwood	Corewood	Transition wood	Outerwood
Gulf Coastal	1–7.0	>7.0	1–4.0	4.0–9.6	>9.6
Hilly Coastal	1–10.0	>10.0	1–6.0	6.0–12.4	>12.4
North Atlantic	1–9.5	>9.5	1–4.0	4.0–15.2	>15.2
Piedmont	1–10.0	>10.0	1–4.0	4.0–13.5	>13.5
South Atlantic	1–6.5	>6.5	1–4.0	4.0–13.2	>13.2
Upper Coastal	1–8.0	>8.0	1–4.0	4.0–13.6	>13.6

Table 3. Results of whole-core wood properties ANOVA including the probability of a significant difference (*P* value), estimated values, corresponding standard errors (in parentheses), and pairwise comparisons.

Region	Whole-core SG*	Earlywood SG*	Latewood SG*	Percent latewood*
Gulf Coastal	0.462b (0.0043)	0.336ab (0.0021)	0.706ab (0.0056)	34.18b (0.6939)
Hilly Coastal	0.453b (0.0031)	0.333ab (0.0015)	0.691b (0.0040)	33.79b (0.5013)
North Atlantic	0.447b (0.0067)	0.329ab (0.0033)	0.687ab (0.0087)	33.33b (1.0797)
Piedmont	0.457b (0.0032)	0.335ab (0.0016)	0.693ab (0.0042)	33.94b (0.5266)
South Atlantic	0.486a (0.0027)	0.338a (0.0014)	0.708a (0.0036)	40.13a (0.4465)
Upper Coastal	0.456b (0.0043)	0.329b (0.0021)	0.700ab (0.0056)	34.09b (0.6937)
P	0.0001	0.0047	0.0101	0.001

Note: SG, specific gravity.

*Values within the column with the same letter are not significantly different.

Whole-core SG averaged 0.486 in the South Atlantic region and was significantly higher than all other regions. Whole-core SG did not differ significantly among the North Atlantic, Upper Coastal, Piedmont, Gulf, or Hilly regions and averaged 0.455. The SG of the whole-core when averaged across regions was 0.460 for the trees in this study. This is considerably lower than the whole-core SG of 0.503 reported for 12 453 natural loblolly pine trees sampled in the 1970s (Wahlgren and Schumann 1975). This difference in increment core SG is probably due to differences in the proportion of corewood, age of the trees sampled, extractive content, and the distribution of the trees bored across the natural range of the species. The age of the natural trees sampled in the 1970s' study ranged from 5 to 100 years and averaged 28 years, compared with the planted trees sampled in this study that ranged in age from 18 to 45 years and averaged 23.4 years.

Whole-core SG was significantly higher in the Southern region because trees growing in this region contain significantly more latewood (40%) when compared with that of trees growing in the other regions (34%). The amount of latewood produced is highly correlated with summer precipitation, mean annual temperature, and number of growing days (Zobel and McElwee 1958; Mitchell 1964; Clark and Daniels 2004). The South Atlantic region receives, on average, more summer precipitation in July through October, has a higher mean annual temperature and more growing days than the other regions in the loblolly pine range. Thus, trees growing in the South Atlantic region have lower levels of water stress during the summer months and when coupled with the longer growing season, the period of latewood production is longer relative to other regions.

Maps of mean stand whole-core SG show that stand SG increases in a nonlinear fashion with stand age. Stands in the South Atlantic and Gulf regions have the highest SG at a given age followed by a band of high SG west of the Mississippi River in the Hilly Coastal Plain in Louisiana and Arkansas. This area has been referred to as the flood-plain region and consists generally of highly productive farmland, characterized by loessial soils all having site index values ranging from 22.9 to 33.5 m (Baker and Langdon 2006). This band is also characterized by a "hot spot" surrounding two stands located in the southeast corner of Arkansas. At age 16 years, these two stands were in the 80th and 90th percentiles of all stands located in the Gulf and Hilly regions, suggesting that the hot spot may not be an anomaly. Stands growing on the fringe of the natural loblolly pine range have the lowest whole-core SG.

Clearly, great variation in SG exists over the natural range of loblolly pine. An understanding of this variation is crucial for the forest products industry if the resource is to be used to its full potential. Differences in SG can have a large impact on product yields and properties. For example, an increase of 0.02 in SG is reported to translate into a 22.7 kg increase in dry pulp yield per ton of round wood (Mitchell 1964) or an increase of 35.15 and 3516 kg/cm^2 in modulus of rupture and modulus of elasticity, respectively (Wahlgren and Schumann 1975). Thus, lumber from trees harvested from the fringe of the loblolly pine range in the North Atlantic, Piedmont or Hilly regions will, on average, be weaker and less stiff than lumber cut from the same age and size of trees harvested in the South Atlantic and Gulf regions or along the west side of the Mississippi River in the Hilly Coastal region. From a biomass standpoint, for trees similar in size to those used in this study, Jordan et al. (2006) reported that a 0.05 increase in whole-core SG at

Fig. 7. Effect of (*a*) stand age and (*b*) site index, with corresponding variability bars, for whole-stand specific gravity.

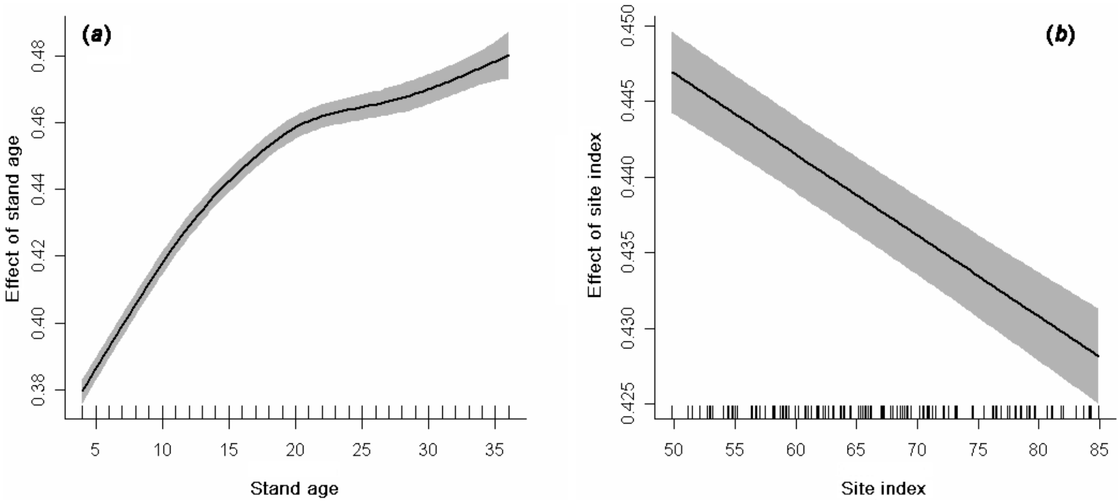
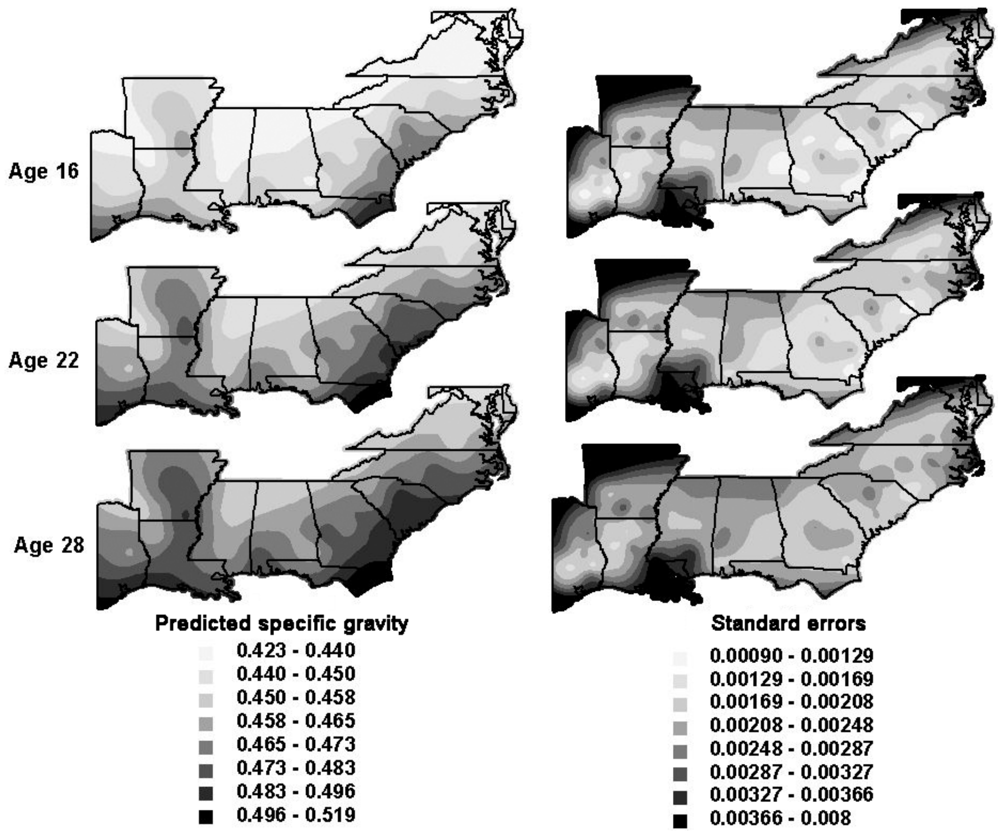


Fig. 8. Plot of estimated whole-stand Specific gravity (SG) and corresponding standard errors at 16, 22, and 28 years of age.



1.37 m resulted in a 20 kg increase in total tree biomass in slash pine.

Conclusions

Analysis of annual ring SG of breast height increment cores collected from 3957 loblolly pine trees growing in 147 plantations located across the natural range of the species showed that ring SG increases with increasing age and varies significantly among physiographic regions, with the highest ring SGs found in the South Atlantic and Gulf regions. Based on ring SG, three distinct zones were identified: juvenile or corewood, which is produced, on average, for the first 4.3 years, transition wood (produced in the following 8.6 years), and mature wood (produced after year 13).

Whole-core mean SG was found to be significantly higher in the South Atlantic region when compared with the other regions, which were not statistically different from each other. Trees growing in the South Atlantic region have higher whole-core SGs because they contain significantly more latewood (40.1%) than trees growing in the other regions (33.8%). The higher percentage of latewood for the

South Atlantic region can be attributed to consistent late-summer rainfall and a longer growing season.

Maps of mean whole-stand core SG indicate that SG generally decreases from south to north and east to west. Stands in the South Atlantic and Gulf regions have the highest SG at a given age followed by stands west of the Mississippi River in the Hilly Coastal Plain in Louisiana and Arkansas. Stands growing on the fringe of the natural range of loblolly pine have the lowest whole-core SG. The maps also show that mean stand SG increases in a nonlinear fashion with stand age.

Acknowledgements

The authors gratefully acknowledge the support from the sponsors of the Wood Quality Consortium of the University of Georgia and the USDA Forest Service. Thanks are also extended to the Associate Editor and three anonymous reviewers.

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