# Regional variation in wood modulus of elasticity (stiffness) and modulus of rupture (strength) of planted loblolly pine in the United States

**Finto Antony, Lewis Jordan, Laurence R. Schimleck, Alexander Clark III, Ray A. Souter, and Richard F. Daniels**

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**Abstract:** Modulus of elasticity (MOE), modulus of rupture (MOR), and specific gravity (SG) are important properties for determining the end-use and value of a piece of lumber. This study addressed the variation in MOE, MOR, and SG with physiographic region, tree height, and wood type. Properties were measured from two static bending samples (dimensions 25.4 mm × 25.4 mm × 406.4 mm) representing each wood type (corewood and outerwood) at heights 2.4, 7.3, and 12.2 m from three trees sampled from 135 loblolly pine (*Pinus taeda* L.) stands distributed across the natural range of the species. An analysis of variance was conducted to detect the effect of physiographphic region, height, and wood type on each property. Significant regional variation was observed for MOE, MOR, and SG for both wood types with high values in the Gulf and South Atlantic Coastal Plains compared with other regions. A significant height-related trend in MOE, MOR, and SG within a tree was identified; MOE and MOR increased in corewood and decreased in outerwood with height. Maps showing regional variation in MOE and MOR at different heights by wood type were produced and showed significant variation for both properties.

**Résumé :** Le module d'élasticité (MOE), le module de rupture (MOR) et le poids spécifique (PS) sont des propriétés importantes pour déterminer l'usage final et la valeur d'une pièce de bois. Cette étude a porté sur la variation de ces propriétés en fonction de la région physiographique, de la hauteur de l'arbre et du type de bois. Les propriétés ont été mesurées en flexion statique sur deux éprouvettes (dimensions de 25,4 mm × 25,4 mm × 406,4 mm) représentant chaque type de bois (bois juvénile et bois mature) à des hauteurs de 2,4, 7,3 et 12,2 m dans trois arbres prélevés au sein de 135 peuplements de pin à encens (*Pinus taeda* L.) distribués dans l'ensemble de l'aire de répartition naturelle de l'espèce. Une analyse de variance a été réalisée afin de détecter les effets de la région physiographique, de la hauteur et du type de bois sur chaque propriété. Une variation régionale significative du MOE, du MOR et du PS a été observée dans les deux types de bois, avec des valeurs élevées dans le Golfe et dans les plaines côtières de l'Atlantique Sud comparativement aux autres régions. À l'intérieur de l'arbre, une tendance significative reliée à la hauteur a été identifiée pour le MOE, le MOR et le PS; le MOE et le MOR augmentaient dans le bois juvénile et diminuaient dans le bois mature en fonction de la hauteur. La cartographie des variations régionales du MOE et du MOR à différentes hauteurs et par type de bois montrent que ces deux propriétés varient grandement.

[Traduit par la Rédaction]

## Introduction

The southeastern United States is a critically important region of the world in terms of lumber manufacture, with production greater than any other single nation in the world. It is estimated that approximately 58% of the wood used in the United States and 16% of the wood consumed globally is produced in this region (Wear and Greis 2002). The majority of the timber produced in this region is from loblolly pine (*Pinus taeda* L.), a yellow pine species that has demonstrated good growth on a wide range of sites both within and outside the United States. Currently, there are more than 12.1 million hectares of pine plantations in the southeast United States, with the area projected to increase by 83% to over 22.2 million hectares in 2040.

In most of the plantation-grown coniferous species (e.g., loblolly pine in the United States, radiata pine (*Pinus radiata* D. Don) in New Zealand, etc.), the use of genetically improved planting stock combined with intensive silviculture has resulted in trees reaching merchantable size much quicker than in the past. As a consequence, trees with more corewood are being harvested from these plantations, resulting in deterioration in quality of wood produced from intensively managed plantations (Watt et al. 2009).

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Globally, forest product companies are under increasing pressure to optimize their resource use. Selection of suitable wood baskets for the delivery of appropriate raw materials is an important step towards achieving this objective. To successfully do so, a thorough knowledge of wood property variation in plantation-grown conifers across their growing range is required. Historically, regional variation in wood specific gravity (SG) in loblolly pine growing in the southern United States has been the subject of several studies (Zobel and McElwee 1958; USDA Forest Service 1965*a*; Talbert and Jett 1981; Jordan et al. 2008). Jordan et al. (2008) developed maps depicting the regional variation in ring SG with age using breast height increment cores collected from loblolly pine from 147 plantations distributed across the southern United States. Regional variation in SG of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) was also reported in the past (USDA Forest Service 1965*b*). Similarly, maps representing spatial variation in wood density of plantation-grown radiata pine in New Zealand have been developed that classified the country into three distinct wood density zones (Radiata Pine Breeding Co. 2003). These studies have mainly concentrated on SG because it is strongly related to many other wood properties, for example the stiffness and strength of wood, and is relatively inexpensive and easy to measure. The regional variation in other wood properties, for example microfibril angle (MFA), modulus of elasticity (MOE), modulus of rupture (MOR), pulp yield, and tracheid length, has not been reported primarily because of the difficulty and cost of measuring these wood properties compared with SG.

MOE, a measure of the deformation that wood undergoes when subjected to an applied load, and MOR, a measure of breaking strength, are properties of particular interest to the forest products industry. As already discussed, young fast-grown pines contain large volumes of corewood and lumber produced from existing short-rotation plantations may not have the stiffness or strength required to meet the design requirements for dimension lumber (MacPeak et al. 1990; Watt et al. 2009, 2010). Therefore, identifying zones of acceptable MOE and MOR for a particular product at a given age within the major wood-producing regions is important. SG can be considered as a reasonable indicator of MOE and MOR, but the within-tree variation in these properties is also influenced by properties such as MFA (Yang and Evans 2003; Donaldson 2008). The influence of MFA and density on MOE and MOR within a tree depends on the distance from pith (specifically the type of the wood, i.e., corewood or outerwood, following the terminology proposed by Burdon et al. 2004) and height from which samples were collected. In radiata pine, MFA was a major determinant of MOE than density in the corewood, but the trend was reversed in the outerwood zone with density being more important (Cown et al. 1999; Watt et al. 2010). In Douglas-fir, Lachenbruch et al. (2010) reported moderate to weak correlation between density and MOE ($r$ = 0.672) and MOR ($r$ = –0.498) and between MFA and MOE ($r$ = –0.498) and MOR ($r$ = –0.283) in the outerwood. In loblolly pine, SG and MFA together explained 76%–96% of the variation in MOE, although the relationship depended on the ring examined both with distance from the pith and with height within a tree (Megraw et al. 1999). Hence, regional maps for MOE and MOR based on SG only can be misleading, requiring either MFA to be measured along with SG or MOE and MOR to be measured directly, where the former method is expensive and time-consuming.

As the southern United States is an important region of the world in terms of both timber production and timber supply, the primary objective of this study was to examine the physiographical variation of MOE and MOR of loblolly pine growing across the southern United States. The variation in MOE and MOR with tree height and with wood type (corewood and outerwood) was also examined in this study.

## Materials and methods

### Data

Plantation-grown loblolly pine trees were sampled across the natural range of the species by the Wood Quality Consortium of the University of Georgia and the USDA Forest Service Southern Research Station to explore the variation in MOE, MOR, and SG. Based on edaphic and climatic factors, the natural range of loblolly pine in the southeastern United States has been classified into six physiographic regions: (*i*) South Atlantic Coastal Plain, (*ii*) North Atlantic Coastal Plain, (*iii*) Upper Coastal Plain, (*iv*) Piedmont, (*v*) Hilly Coastal Plain, and (*vi*) Gulf Coastal Plain (Fig. 1) (Miller and Robinson 1994). In this study, we utilized this physiographic regional classification system as a surrogate for site variables such as mean air temperature, precipitation, etc. A total of 135 plantations were selected for sampling from the natural range. Average stand and tree characteristics are presented in Table 1. The stands 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 and 1779 stems/ha. However, at the time of sampling, stocking ranged from 494 to 1483 stems/ha, with the majority of the stands having been thinned late (generally at midrotation); hence, the trees grew mostly under similar (relatively high) stand density levels.

Three trees were selected from the stand for destructive sampling, one tree representing the average diameter class and two trees each representing the upper and lower diameter class next to the average diameter class. The diameter at breast height (1.37 m) and total heights of the sampled trees were recorded and were used for the calculation of stem slenderness in the following sections. Each tree was felled and bolts of 0.6 m in length were destructively cut from 2.4, 7.3, and 12.2 m up the stem, representing the midpoint of each 4.9 m log, for processing into static bending samples. In some trees, these sampling heights were slightly adjusted to avoid larger knot clusters from the 0.6 m bolts. A 38.1 mm thick slab, from bark to bark through the pith, was cut from each 0.6 m bolt and kiln dried to 12% equilibrium moisture content. After drying, each slab was split through the pith into two boards and two clear static bending samples (one representing corewood and the other outerwood) of dimensions 25.4 mm × 25.4 mm × 406.4 mm were cut from each board. Corewood specimens were sawn from rings 2 to 4 (approximately) and outerwood specimens were sawn from next to the bark.

The 25.4 mm × 25.4 mm × 406.4 mm clear static bending samples were tested at 12% equilibrium moisture content



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**Fig. 1.** Map showing the sampled stand locations along with boundaries for six physiograpic regions.

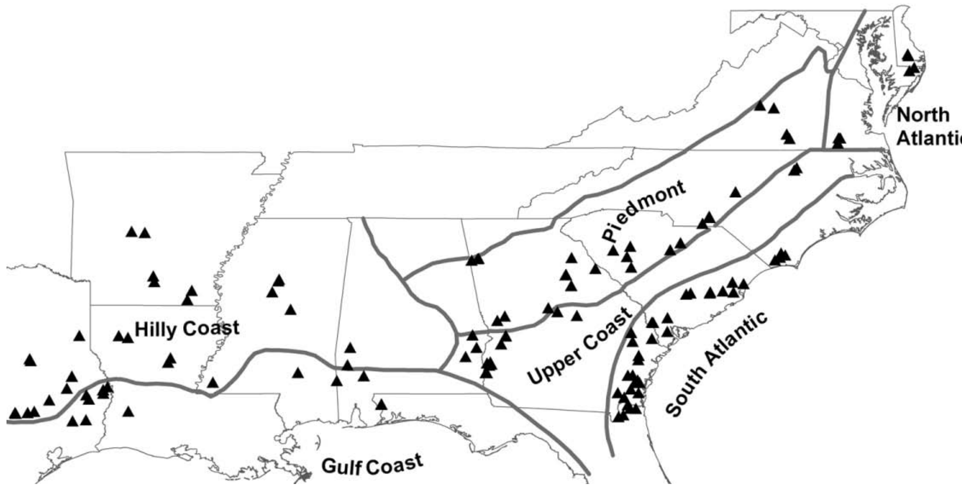


**Table 1.** Averages and standard deviations (in parenthesis) of stand and tree characteristics for the loblolly pine (*Pinus taeda*) trees sampled for analysis.

| Region | No. of stands | No. of trees | DBH (cm) | Height (m) | Age (years) | Site index (m) |
|---|---|---|---|---|---|---|
| Gulf Coastal | 17 | 46 | 21.2 (3.8) | 19.4 (2.8) | 23.1 (3.5) | 20.5 (2.6) |
| Hilly Coastal | 27 | 76 | 22.9 (4.1) | 19.2 (3.2) | 22.8 (3.0) | 20.5 (2.8) |
| North Atlantic | 7 | 21 | 24.3 (3.7) | 18.1 (2.7) | 22.3 (2.0) | 19.4 (2.4) |
| Piedmont | 29 | 82 | 24.2 (4.5) | 18.2 (2.1) | 23.0 (2.0) | 19.1 (2.1) |
| South Atlantic | 39 | 109 | 24.0 (4.5) | 20.7 (2.5) | 22.6 (1.7) | 22.6 (2.3) |
| Upper Costal | 16 | 45 | 23.6 (5.0) | 19.0 (3.2) | 23.0 (1.5) | 20.0 (2.7) |

**Note:** The average and standard deviation for diameter at breast height (DBH), height, and age were computed using tree-level values and the site index were computed using stand-level values.

over a 355.6 mm span with center loading and pith up on a Tinius Olsen Test Machine following the procedures for alternate sample size under ASTM D-143 (American Society for Testing and Materials 1980). A continuous load was applied at a head speed of 1.8 mm/min, rather than 1.3 mm/min, to reduce test time. Preliminary testing showed that specimens failed primarily in compression with no defined break or tension failure. After testing, each sample was oven dried at 103 °C and SG of the unextracted samples was calculated based on their dimensions at 12% equilibrium moisture content and oven-dry mass. MOE and MOR were calculated using procedures outlined in ASTM D-143 (American Society for Testing and Materials 1980). Data from static bending samples collected at different height levels (2.4, 7.3, and 12.2 m) by wood type (corewood and outerwood) within each tree were averaged and used for further analysis.

## Statistical analysis

To analyze the effect of physiographic region, height, and wood type on MOE, MOR, and SG, separate ANOVA was conducted for each property. The data follow a hierarchical structure, with stands sampled representing a random sample from all of the stands and trees sampled within a stand representing a random sample of trees from all of the trees within each stand within a physiographic region. Individual stand and tree effects can be represented as a random effect and their contribution to the variance of MOE, MOR, and SG can be estimated. These considerations dictate that a mixed-effects model should be employed to account for the distinct sources of variability in the experiment: stand-to-stand and tree-to-tree variability. The full linear mixed model used for the analysis can be written as

$$[1] \quad y_{ijklm} = \mu + R_i + H_l + W_m + (RH)_{il} + (RW)_{im} + (HW)_{lm} + (RHW)_{ilm} + s_j + t_k + u_{kl} + e_{ijklm}$$
$$i = 1, ..., N; j = 1, ..., N_i; k = 1, ..., N_{ij}; l = 1, ..., N_{ijk}; m = 1, ..., N_{ijkl}$$

where $y_{ijklm}$ is the property of interest of the *m*th wood type at the *l*th height of the *k*th tree of the *j*th stand in the *i*th physiographic region, $\mu$ is the population mean, $R_i$ is the *i*th region effect, $H_i$ is the *l*th sampling height effect, $W_m$ is the *m*th wood type effect, $(RH)_{il}$ is the interaction of the *i*th region and *l*th sampling height effects, $(RW)_{im}$ is the interaction of the *i*th region and *m*th wood type effects, $(HW)_{lm}$ is the interaction of the *l*th sampling height and *m*th wood type effects, $(RHW)_{ilm}$ is the interaction of the *i*th region, *l*th sampling height, and *m*th wood type effects, $s_j$ is the random effect of the *j*th stand with $s_j \overset{iid}{\sim} N(0, \sigma_s^2)$, $t_k$ is the random effect of the *k*th tree with $t_k \overset{iid}{\sim} N(0, \sigma_t^2)$, $u_{kl}$ is the random interaction between the *k*th tree and *l*th sampling height with $u_{kl} \overset{iid}{\sim} N(0, \sigma_u^2)$, the true error term for testing the sampling height effect, and $e_{ijkl}$ is the residual error with $e_{ijkl} \overset{iid}{\sim} N(0, \sigma_u^2)$.

All of the models were fitted using the SAS MIXED procedure with the Kenward–Rogers approximation for computing the mean sum of square and denominator degrees of freedom for the fixed effects (SAS Institute Inc. 2004). Tukey's honestly significant difference test was used for pairwise comparisons between means.

### MOE and MOR maps

Maps showing regional variation in MOE and MOR at different height levels within a tree are important for making appropriate decisions on product categorization and utilization. Maps showing regional variation in SG at different stand ages and at different height levels within a tree have been published (Jordan et al. 2008; Antony et al. 2010) and are not considered in this study. Geostatistical methods, such as kriging, have been widely used to explain the spatial variation in a particular entity (here MOE or MOR). Kriging is an interpolation method that predicts the value of a variable (MOE or MOR) at an unknown spatial point using the spatial covariance information calculated from the available data. The data in this study were collected from trees spanning a large area in terms of latitude and longitude with information on covariates such as sampling height, wood type, stand age, total height, diameter at breast height, site index at age 25, and stems per hectare. It is important to model the spatial variation of MOE or MOR along with the available covariate information. A geoadditive approach, a combination of geostatistical and additive models under the assumption of additivity, proposed by Kamman and Wand (2003) was used in this study. These models can be implemented using the mixed-model framework.

Following Kamman and Wand (2003) and Ruppert et al. (2003), the geoadditive model can be formulated as follows. The additive model component for explaining the variation in MOE and MOR with tree-specific covariates is given as

$$[2]\qquad y_{ijklm} = \mu + H_l + H_l^2 + W_m + (HW)_{lm} + (H^2W)_{lm} + \mathrm{SL}_{jk} + A_j + \mathrm{SI25}_j + \mathrm{SPH}_j + e_{ijklm}$$
$$i = 1, ..., N; j = 1, ..., N_i; k = 1, ..., N_{ij};\quad l = 1, ..., N_{ijk}; m = 1, ..., N_{ijkl}$$

where $y_{ijklm}$ is the property of interest of the $m$th wood-type, at the $l$th height of the $k$th tree of the $j$th stand in the $i$th physiographic region, $\mu$ is the population mean, $H_l$ is the $l$th height effect, $H_l^2$ is the quadratic height term, $W_m$ is the $m$th wood type effect, $(HW)_{lm}$ is the interaction of the $l$th height and $m$th wood type effects, $(H^2W)_{lm}$ is the interaction of the quadratic height term with wood type, $\mathrm{SL}_{jk} = \mathrm{THT}_{jk}/\mathrm{DBH}_{jk}$, a measure of stem slenderness where $\mathrm{DBH}_{jk}$ is the diameter at breast height (metres) of the $k$th tree of the $j$th stand and $\mathrm{THT}_{jk}$ is the total height (metres) of the $k$th tree of the $j$th stand, $A_j$ is the age of the $j$th stand, $\mathrm{SI25}_j$ is the site index at age 25 of the $j$th stand, $\mathrm{SPH}_j$ is the stems per hectare of the $j$th stand, $e_{ijklm}$ is the residual error with $e_{ijklm} \overset{\text{iid}}{\sim} N(0, \sigma_u^2)$.

Given the data of form$(X_{ijk}, y_{ijk})$, where $y_{ijk}$ is a scalar and $X_{ijk} \in \Re^2$ represents geographical locations measured as latitude and longitude, a simple universal kriging model with linear covariates in it is

$$[3]\qquad y_{ijk} = \beta_0 + \beta_1^T X_{ijk} + S(X_{ijk}) + \varepsilon_{ijk}$$

where $\{S(X_{ijk}) : X \in \Re^2\}$ is a stationary mean zero stochastic process. Prediction to a new location $X_0 \in \Re^2$ within the sampling space is done by substituting the estimates of $\widehat{\beta}_0$ and $\widehat{\beta}_1$ and an empirical best linear predictor $\widehat{S}(X_0)$ for a known covariance structure for $S$ into model 3. The geographical component was fitted as a linear mixed model by using a bivariate thin plate spline to a geographic location (Ruppert et al. 2003). The covariance for $S$ is assumed to be isotropic, i.e., the covariance between two stands that are $\|h\|$ units apart is the same regardless of direction and the location of the stand.

The final geoadditive model can be obtained by merging models 2 and 3 as

$$[4]\qquad y_{ijklm} = \mu + H_l + H_l^2 + W_m + (HW)_{lm} + (H^2W)_{lm} + \mathrm{SL}_{jk} + A_j + \mathrm{SI25}_j + \mathrm{TPH}_j + \beta_1^T X_{ijk} + S(X_{ijk}) + \varepsilon_{ijklm}$$

which can be expressed as a linear mixed model as

$$[5]\qquad \boldsymbol{y} = X\beta + Zu + \varepsilon$$

where $\boldsymbol{y}$ is the vector of response (here MOE or MOR) and

$$X = [1\ H_l\ H_l^2\ W_m\ (HW)_{lm}\ (H^2W)_{lm}\ \mathrm{SL}_{jk}\ A_j\ \mathrm{SI25}_j\ \mathrm{TPH}_j\ X_{ijk}]$$

and $Z$ corresponds to the basis functions for $S$. The geographical component in the model was fitted using reduced knot kriging, where $\{\kappa_1, ..., \kappa_\kappa\}$ are a subset of knots selected from sample space $X_{ijk} \in \Re^2$. The knots were selected using the space-filling algorithm discussed by Kamman and Wand (2003) and Ruppert et al. (2003). Readers are referred to Ruppert et al. (2003) and Kamman and Wand (2003) for more detail regarding geoadditive model formulation, fitting, and prediction. Maps were produced by fitting the geoadditive model to the data. Model 4 was fitted using the SemiPar library in R (Wand et al. 2005).

## Results

The observed mean MOE, MOR, and SG from different physiographic regions at three height levels for both corewood and outerwood are presented in Table 2. The results from ANOVA are presented in Table 3. A sliced effect test was also conducted where the interaction terms were found to be significant. Estimated mean values for MOE, MOR, and SG from the fitted ANOVA models are presented in Figs. 2, 3, and 4, respectively. Interaction between region by height and region by height by wood type was not significant ($p > 0.05$) for all of the properties and is not considered further in the discussion.

### Stiffness (MOE)

The interaction between region and wood type was significant for MOE. Based on the sliced effect test of region by wood type interaction, significant regional differences were observed for MOE for both wood types with $p = 0.0140$ (corewood) and $p < 0.0001$ (outerwood). Significant differences for corewood and outerwood MOE were also found within each region based on sliced effect tests of region by wood type interaction, with $p < 0.0001$ for all regions. Based on multiple comparison tests, estimated corewood MOE was significantly higher ($p = 0.0242$) for trees from the Gulf Coastal Plain (MOE = 6.2 GPa) (the unit gigapascal (GPa) can be converted into pounds per square inch by multiplying

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**Table 2.** Average observed modulus of elasticity (MOE), modulus of rupture (MOR), and specific gravity (SG) of corewood and outerwood by physiographic region and height level.

| | 2.4 m | | | | 7.3 m | | | | 12.2 m | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Region | *N* | MOE (GPa) | MOR (MPa) | SG | *N* | MOE (GPa) | MOR (MPa) | SG | *N* | MOE (GPa) | MOR (MPa) | SG |
| **Corewood** | | | | | | | | | | | | |
| North Atlantic | 28 | 3.60 | 50.86 | 0.405 | 16 | 5.33 | 53.59 | 0.368 | 8 | 4.85 | 52.41 | 0.362 |
| South Atlantic | 113 | 4.64 | 52.30 | 0.413 | 91 | 6.38 | 60.38 | 0.394 | 46 | 6.39 | 59.70 | 0.385 |
| Upper Coastal | 48 | 4.42 | 49.34 | 0.404 | 39 | 6.16 | 59.97 | 0.385 | 22 | 6.07 | 60.78 | 0.389 |
| Piedmont | 86 | 4.45 | 52.97 | 0.417 | 79 | 5.98 | 58.81 | 0.392 | 46 | 6.14 | 60.75 | 0.399 |
| Gulf Coastal | 43 | 5.58 | 58.39 | 0.409 | 36 | 6.47 | 64.80 | 0.403 | 8 | 6.64 | 63.49 | 0.394 |
| Hilly Coastal | 78 | 4.93 | 56.26 | 0.417 | 62 | 6.12 | 59.41 | 0.391 | 38 | 6.41 | 61.94 | 0.394 |
| **Outerwood** | | | | | | | | | | | | |
| North Atlantic | 28 | 8.07 | 85.13 | 0.522 | 5 | 8.50 | 84.38 | 0.479 | 1 | 5.48 | 75.84 | 0.486 |
| South Atlantic | 153 | 10.70 | 97.02 | 0.593 | 68 | 10.45 | 90.20 | 0.524 | 20 | 10.29 | 87.39 | 0.514 |
| Upper Coastal | 67 | 9.82 | 88.93 | 0.551 | 16 | 9.89 | 85.00 | 0.499 | 5 | 9.07 | 79.79 | 0.469 |
| Piedmont | 113 | 9.39 | 86.34 | 0.539 | 29 | 10.05 | 88.76 | 0.509 | 8 | 8.93 | 80.90 | 0.505 |
| Gulf Coastal | 58 | 10.93 | 97.68 | 0.573 | 33 | 10.53 | 94.84 | 0.527 | 7 | 10.54 | 86.27 | 0.499 |
| Hilly Coastal | 116 | 9.87 | 91.97 | 0.538 | 43 | 9.67 | 85.50 | 0.487 | 6 | 8.49 | 78.70 | 0.457 |

**Table 3.** ANOVA results for modulus of elasticity (MOE), modulus of rupture (MOR), and specific gravity (SG).

| | MOE | | MOR | | SG | |
|---|---|---|---|---|---|---|
| Effect | *F* | *p* | *F* | *p* | *F* | *p* |
| Region | 9.16 | **<0.0001** | 4.81 | **0.0004** | 7.5 | **<0.0001** |
| Height | 19.42 | **<0.0001** | 2.36 | 0.0955 | 190.95 | **<0.0001** |
| Wood type | 736.42 | **<0.0001** | 902.59 | **<0.0001** | 1247.44 | **<0.0001** |
| Region × height | 1.40 | 0.1768 | 1.23 | 0.2672 | 1.30 | 0.2299 |
| Region × wood type | 5.21 | **0.0001** | 6.24 | **<0.0001** | 14.16 | **<0.0001** |
| Height × wood type | 42.71 | **<0.0001** | 50.45 | **<0.0001** | 46.77 | **<0.0001** |
| Region × height × wood type | 0.88 | 0.553 | 0.85 | 0.5787 | 1.58 | 0.1095 |

**Fig. 2.** Plots showing estimated modulus of elasticity (MOE) with sampling height for six physiographic regions for both corewood and outerwood.

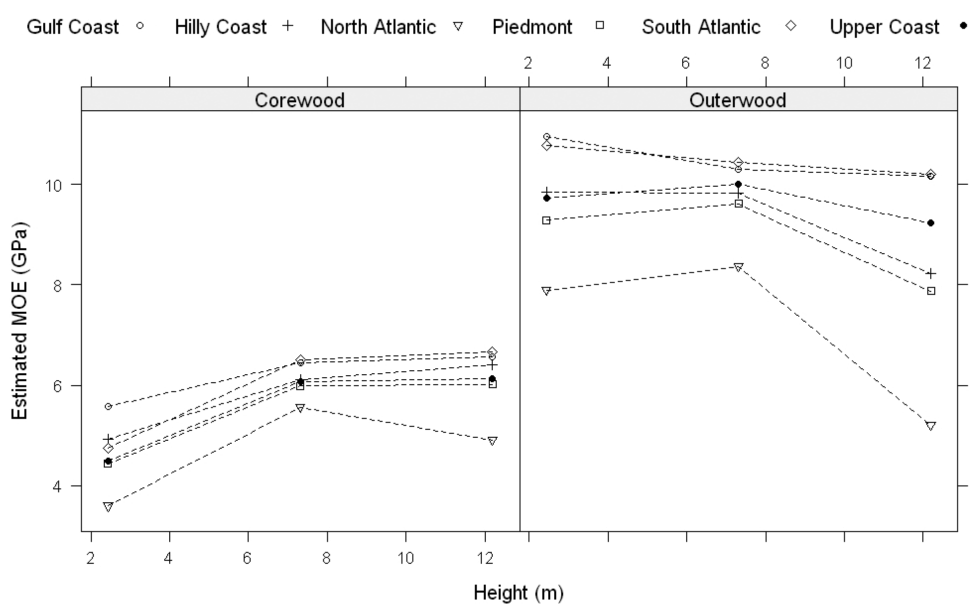


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**Fig. 3.** Plots showing estimated modulus of rupture (MOR) with sampling height for six physiographic regions for both corewood and outerwood.

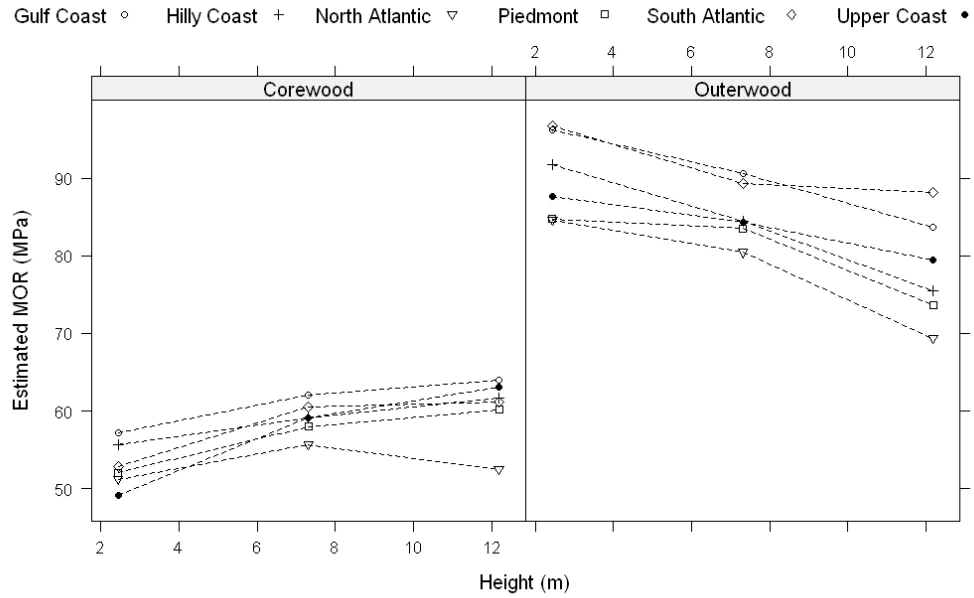
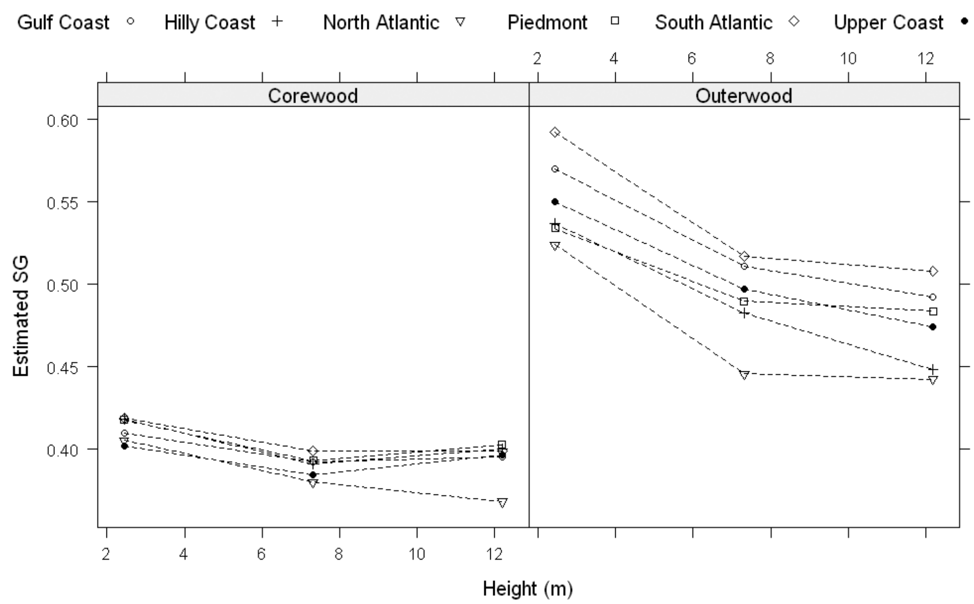



**Fig. 4.** Plots showing estimated specific gravity (SG) with sampling height for six physiographic regions for both corewood and outerwood.

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by 145037.74) compared with trees from the North Atlantic Coastal Plain (MOE = 4.7 GPa). However, for outerwood, the MOE of trees from the Gulf Coastal Plain (MOE = 10.5 GPa) was significantly higher than that of trees from the Hilly Coastal Plain (MOE = 9.3 GPa, $p$ = 0.0273), North Atlantic Coastal Plain (MOE = 7.2 GPa, $p < 0.0001$), and Piedmont (MOE = 8.9 GPa, $p$ = 0.0014). Similarly, the MOE of trees from Hilly Coastal Plain was significantly higher than that of trees from the North Atlantic Coastal Plain ($p$ = 0.0120) and lower than that of trees from the South Atlantic Coastal Plain (MOE = 10.5 GPa, $p$ = 0.0021). Significantly lower outerwood MOE for trees from the North Atlantic Coastal Plain was observed compared with that of trees from the South Atlantic Coastal Plain ($p < 0.0001$) and Upper Coastal Plain (MOE = 9.7 GPa, $p$ = 0.0033). Also, outerwood MOE of trees from the Piedmont was significantly lower than that of trees from the South Atlantic Coastal Plain ($p < 0.0001$).

The interaction between height by wood type was significant for MOE. Significant differences in MOE were observed with height within each wood type, with $p < 0.0001$ (corewood) and $p$ = 0.0003 (outerwood) based on the sliced effect test. In addition, MOEs from wood types were significantly different at each height, with $p < 0.0001$ at all heights. Based on the multiple comparison tests, corewood MOE measured at height 2.4 m (MOE = 4.6 GPa) was significantly lower than that of wood from 7.3 m (MOE = 6.1 GPa, $p <$ 0.0001) and 12.2 m (MOE = 6.1 GPa, $p < 0.0001$). Outerwood MOE measured at 12.2 m (MOE = 8.5 GPa) was significantly lower compared with that of wood from 2.4 m (MOE = 9.7 GPa, $p$ = 0.0003) and 7.3 m (MOE = 9.8 GPa, $p$ = 0.0006).



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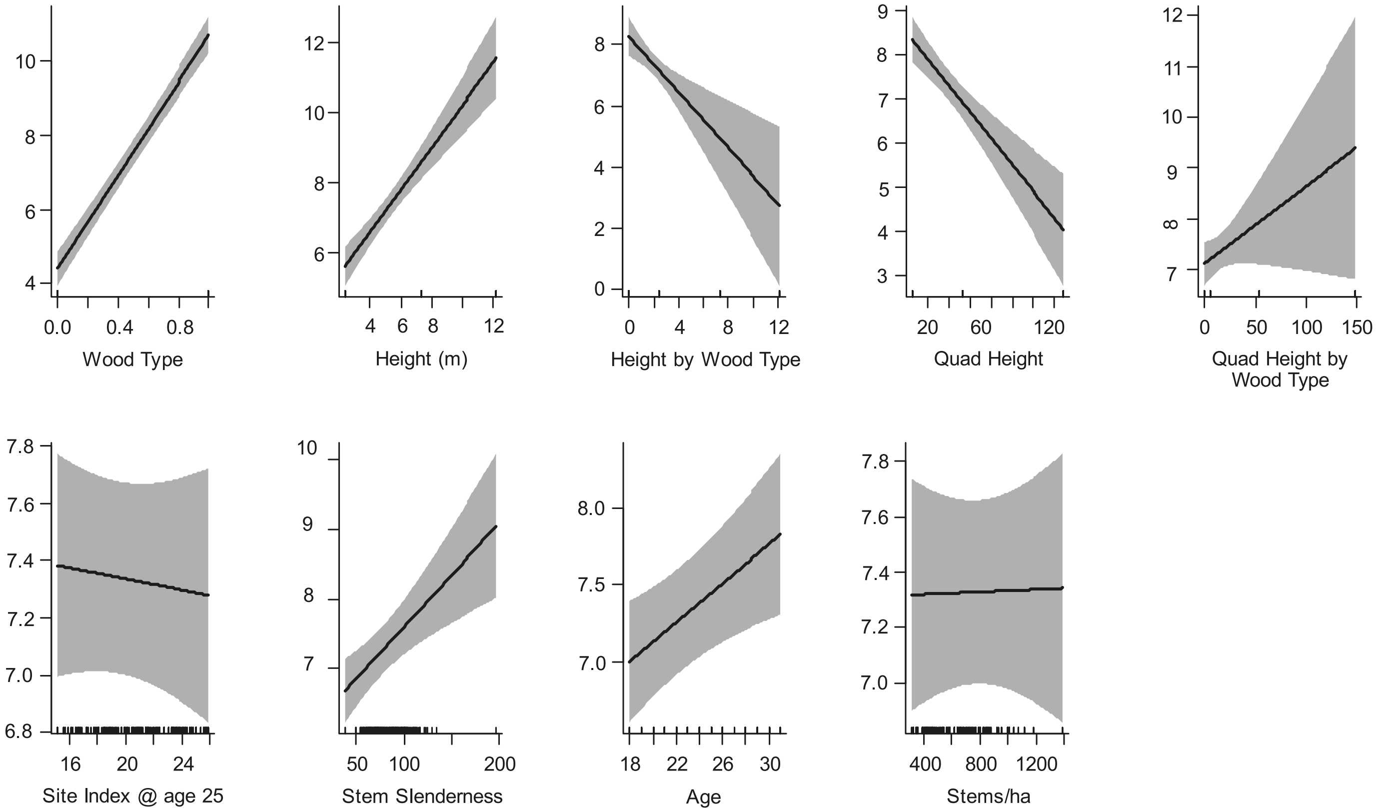
**Fig. 5.** Plots showing the effects of different explanatory variables on modulus of elasticity with plus and minus twice the standard error (shaded region). The vertical tick marks on the horizontal axis represent the observed points. Wood type: 0, corewood; 1, outerwood.




## Strength (MOR)

For MOR, the interaction between region by wood type was significant. Based on the sliced effect tests of the region by wood type interaction, significant regional differences were observed for outerwood MOR ($p < 0.0001$) but not for corewood MOR. Corewood MOR (53.1–61.1 MPa) (the unit megapascal (MPa) can be converted into pounds per square inch by multiplying by 145.04) was significantly lower than outerwood MOR (78.2–91.4 MPa) for all regions ($p < 0.0001$ regardless of regions). Based on the multiple comparison tests, outerwood MOR of trees from the Gulf Coastal Plain (MOR = 90.2 MPa) was significantly higher compared with trees from the Piedmont (MOR = 80.6 MPa, $p = 0.0062$). Outerwood MOR of trees from the South Atlantic Coastal Plain (MOR = 91.4 MPa) was significantly higher than that of trees from the Hilly Coastal Plain (MOR = 83.9 MPa, $p = 0.0054$), North Atlantic Coastal Plain (MOR = 78.2 MPa, $p = 0.0203$), Upper Coastal Plain (MOR = 83.8 MPa, $p = 0.0374$), and Piedmont (MOR = 80.6 MPa, $p < 0.0001$).

The interaction between height by wood type was significant for MOR. Significant differences in mean MOR was observed with height for both wood types ($p < 0.0001$ for both) based on the sliced effect test of the height by wood type interaction term. Significantly lower MOR was observed for corewood compared with outerwood at all heights ($p < 0.0001$ at all heights). Based on the multiple comparison tests, corewood MOR at 2.4 m (MOR = 53.0 MPa) was significantly lower than corewood MOR at 7.3 m (MOR = 59.1 MPa, $p < 0.0001$) and 12.2 m (MOR = 60.4 MPa, $p < 0.0001$). Outerwood MOR at 2.4 m (MOR = 90.3 MPa) was significantly higher compared with outerwood MOR at 7.3 m (MOR = 85.4 MPa, $p = 0.0002$) and 12.2 m (MOR = 78.3 MPa, $p < 0.0001$). In addition, outerwood MOR measured at 7.3 m was significantly higher than outerwood MOR at 12.2 m ($p = 0.0038$).

## SG

The interaction between region by wood type was significant for SG. Significant regional differences were observed in outerwood SG ($p < 0.0001$) but not in corewood SG based on the sliced effect test of region by wood type interaction term. Significantly lower SG ($p < 0.0001$ at all regions) was observed in corewood (0.39–0.41) compared with outerwood (0.47–0.54). Based on the multiple comparison tests, outerwood SG of trees from the Gulf Coastal Plain (SG = 0.52) was significantly higher than that of trees from the Hilly Coastal Plain (SG = 0.49, $p = 0.0009$) and North Atlantic Coastal Plain (SG = 0.47, $p = 0.0041$). Outerwood SG from the South Atlantic Coastal Plain (SG = 0.54) was also significantly higher compared with outerwood SG from the Hilly Coastal Plain ($p < 0.0001$), North Atlantic Coastal Plain ($p < 0.0001$), Upper Coastal Plain (SG = 0.51, $p = 0.0028$), and Piedmont (SG = 0.50, $p < 0.0001$)

The interaction between height by wood type was significant for SG. Based on the sliced effect test of height by wood type interaction, significant differences with height were observed for corewood and outerwood SG ($p < 0.0001$). Significantly lower SG was observed for corewood compared with outerwood at all heights ($p < 0.0001$ for all heights). Based

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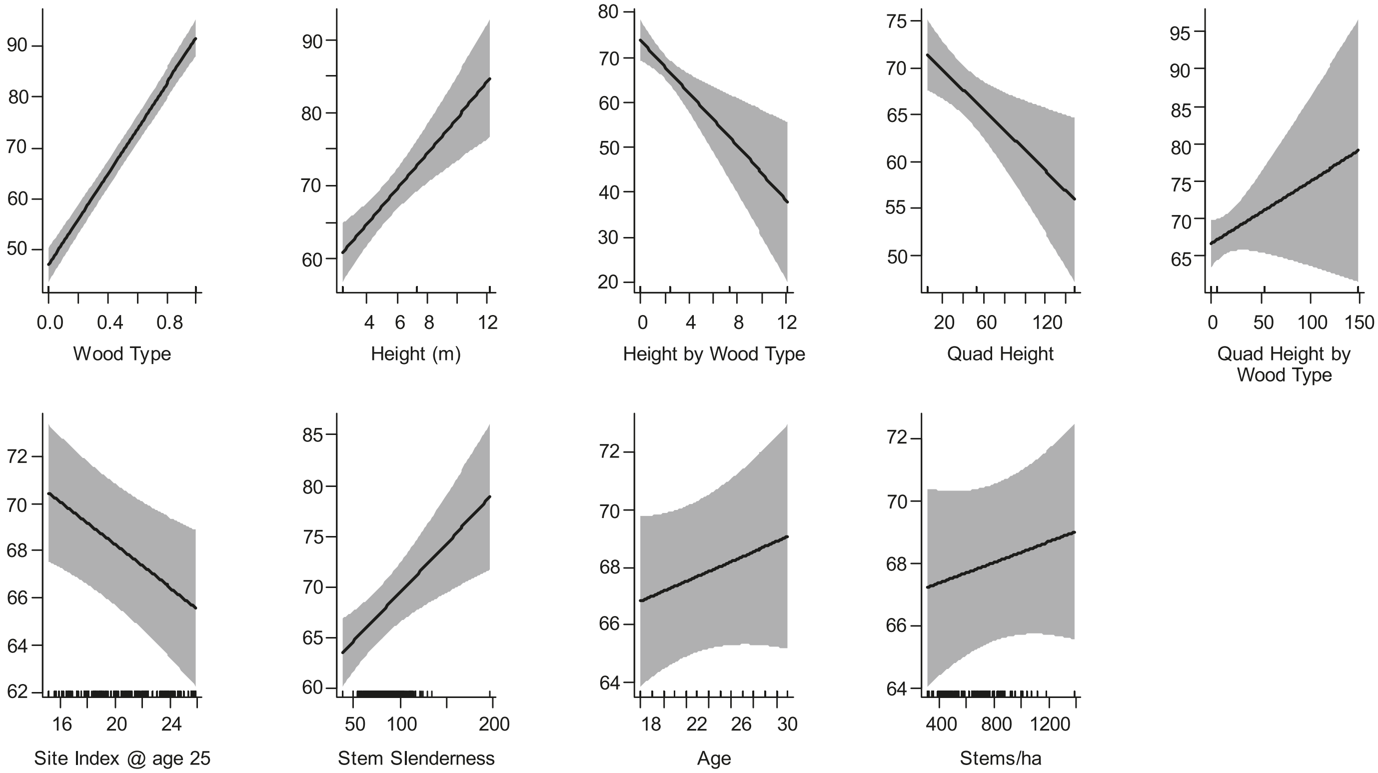
**Fig. 6.** Plots showing the effects of different explanatory variables on modulus of rupture with plus and minus twice the standard error (shaded region). The vertical tick marks on the horizontal axis represent the observed points. Wood type: 0, corewood; 1, outerwood.

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on the multiple comparison tests, significant differences in corewood SG were observed at 2.4 m (SG = 0.41) compared with 7.3 m (SG = 0.39, $p < 0.0001$) and 12.2 m (SG = 0.39, $p < 0.0001$). Significant difference were also observed for outerwood SG at 2.4 m (SG = 0.55) compared with that at 7.3 m (SG = 0.49, $p < 0.001$) and 12.2 m (SG = 0.47, $p < 0.0001$).

### MOE and MOR maps

Based on the fitted geoadditive model, a significant difference was observed between corewood and outerwood MOE ($p < 0.0001$), with MOE increasing from corewood to outerwood (Fig. 5). Significant linear ($p < 0.0001$) and quadratic ($p < 0.0001$) trends in average MOE with height were present. A significant difference was observed in the linear trend of corewood and outerwood MOE with height ($p = 0.0004$), but no such difference was observed in the quadratic trend of MOE with height. The effect of stand age ($p = 0.0054$) and stem slenderness ($p = 0.0002$) on MOE was also significant,with an increasing trend observed with age (partial regression coefficient = 0.064) and with stem slenderness (partial regression coefficient = 0.015) (Fig. 5). The influence of other factors such as site index and stems per hectare on mean MOE was not significant.

A significant difference was observed between corewood and outerwood MOR ($p < 0.0001$) based on the fitted geoadditive model (Fig. 6). The linear ($p < 0.0001$) and quadratic ($p = 0.0052$) trends in MOR with height were found to be significant. A significant difference was observed in the linear trend ($p = 0.0007$) of corewood and outerwood MOR with height, but the difference was absent for the quadratic trend. The effect of site index ($p = 0.0044$) and stem slenderness ($p = 0.0004$) of trees was significant on MOR (Fig. 6). A decreasing trend in MOR was observed with an increase in site index (partial regression coefficient = –0.456). However, an increasing trend in MOR was observed with stem slenderness (partial regression coefficient = 0.097), indicating that as trees become older and taller, MOR tends to increase (Fig. 6).

Predicted MOE and MOR from the geoadditive model at heights 2.4 and 7.3 m (the middle portion of the first two logs) are presented in Figs. 7 and 8. For simplicity, the models were refitted with linear terms for wood type, height, interaction between height and wood type, and quadratic height as explanatory variables along with the bivariate geographical component (longitude and latitude). The maps indicated a significant regional trend in MOE and MOR, with the Gulf and South Atlantic Coastal Plains having the highest MOE and MOR and the North Atlantic Coastal Plain having the lowest MOE and MOR for a given height and wood type.

## Discussion

Significant regional trends in MOE, MOR, and SG were observed in this study. MOE, MOR, and SG were higher for trees from the Gulf and South Atlantic Coastal Plains compared with all other regions at all height levels irrespective of wood type (Figs. 2, 3, and 4). Low MOE, MOR, and SG were observed for trees from the North Atlantic Coastal Plain for both corewood and outerwood. Regional variation in corewood SG was absent (Fig. 4). MOE and MOR regional trends from ANOVA agree with those of the geoadditive maps.

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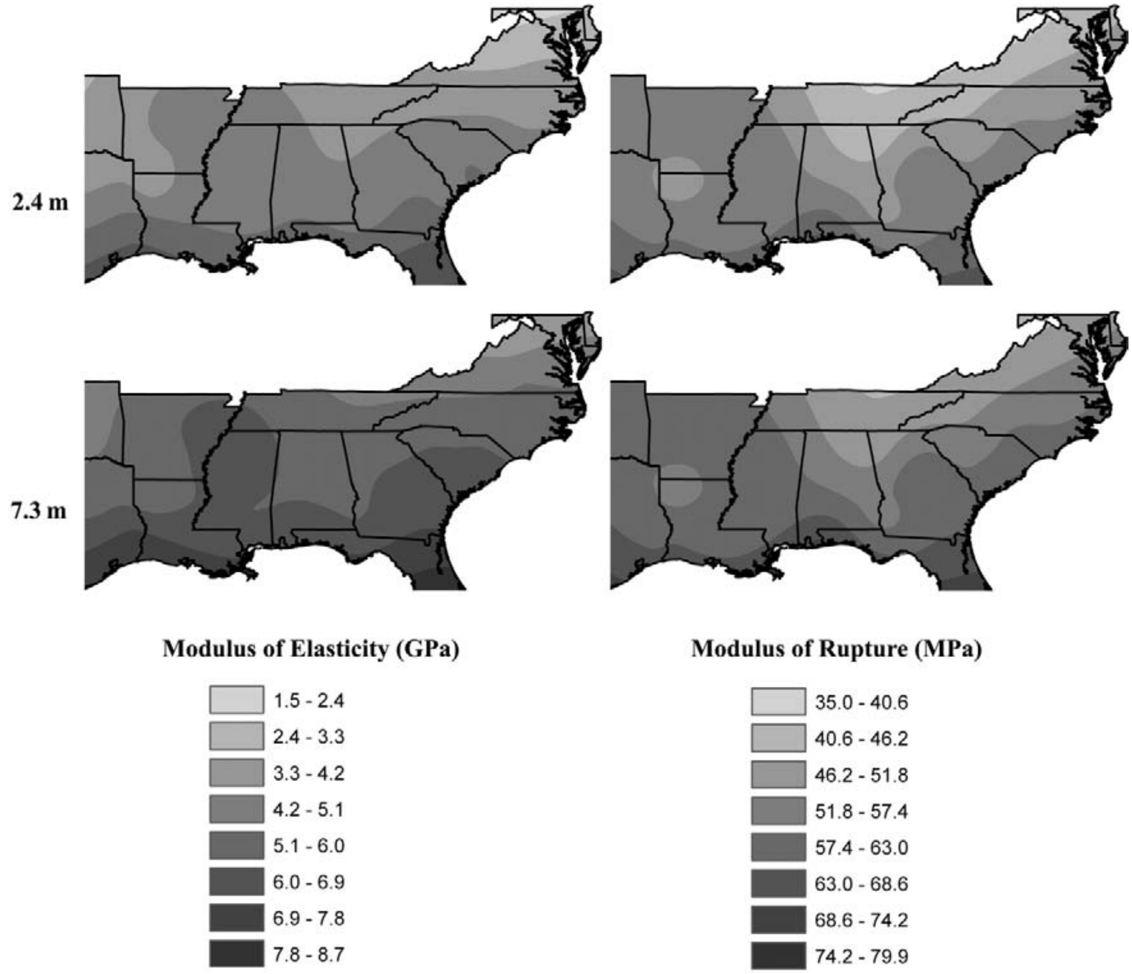
**Fig. 7.** Maps showing the regional variation in modulus of elasticity and modulus of rupture for corewood at heights of 2.4 and 7.3 m.




A distinct regional trend in MOE and MOR was evident from the maps, with stands in the Gulf and South Atlantic Coastal Plains having the highest MOE and MOR and stands in the North Atlantic Coastal Plain having the lowest MOE and MOR for a given height and wood type (Figs. 7 and 8). Generally, MOE and MOR showed a decreasing trend from south to north and from east to west in both corewood and outerwood, with more pronounced variation in the outerwood. These trends in MOE and MOR agree with the SG maps published in earlier studies (Jordan et al. 2008; Antony et al. 2010). Based on the MOE and MOR maps, we can broadly divide the loblolly pine resources in the southern United States into three sections: (*i*) the southern parts of the South Atlantic and Gulf Coastal Plains with high MOE and MOR, (*ii*) the northern parts of the South Atlantic and Gulf Coastal Plains and parts of the Upper and Hilly Coastal Plains with medium MOE and MOR, and (*iii*) Piedmont and the Hilly and North Atlantic Coastal Plains characterized by relatively low MOE and MOR.

Regional trends in MOE and MOR may be explained by regional variation in SG and MFA. SG is positively correlated with MOE and MOR, and regional trends in SG with age and tree height were examined by Jordan et al. (2008) and Antony et al. (2010). Both studies found that the SG of trees sampled from stands in the South Atlantic and Gulf Coastal Plains (southern regions) was higher than that of trees from the North Atlantic Coastal Plain and Piedmont (northern regions). Unlike SG, MFA is negatively correlated with MOE and MOR (Megraw et al. 1999), with high MFA associated with low MOE and MOR and vice versa. Jordan et al. (2006) reported significant regional variation in whole-disk cross-sectional MFA in the southern United States. They reported significantly larger MFA for trees from the North Atlantic Coastal Plain and Piedmont regions compared with the South Atlantic, Gulf, and Hilly Coastal Plains at different height levels. The regional variation in MOE and MOR is consistent with the regional trends observed for SG and MFA, i.e., high MOE and MOR in areas with high SG and low MFA and low MOE and MOR in areas with low SG and high MFA. The regional variations in SG and MFA are ultimately driven by different environmental factors, such as high summer rainfall and an extended growing season for trees growing in the southeastern parts of the loblolly pine growing region, which results in a high percentage of latewood and low MFA for trees growing in this region compared with stands in the northwestern parts of the loblolly pine growing region (Clark and Daniels 2004). It should be noted here that the lowest sampling height is 2.4 m, and based on the evidence from Megraw et al. (1999) and Jordan et al. (2005), there is considerable variation in MFA below this height. So it is reasonable to assume that regional differences would be more pronounced for wood produced near



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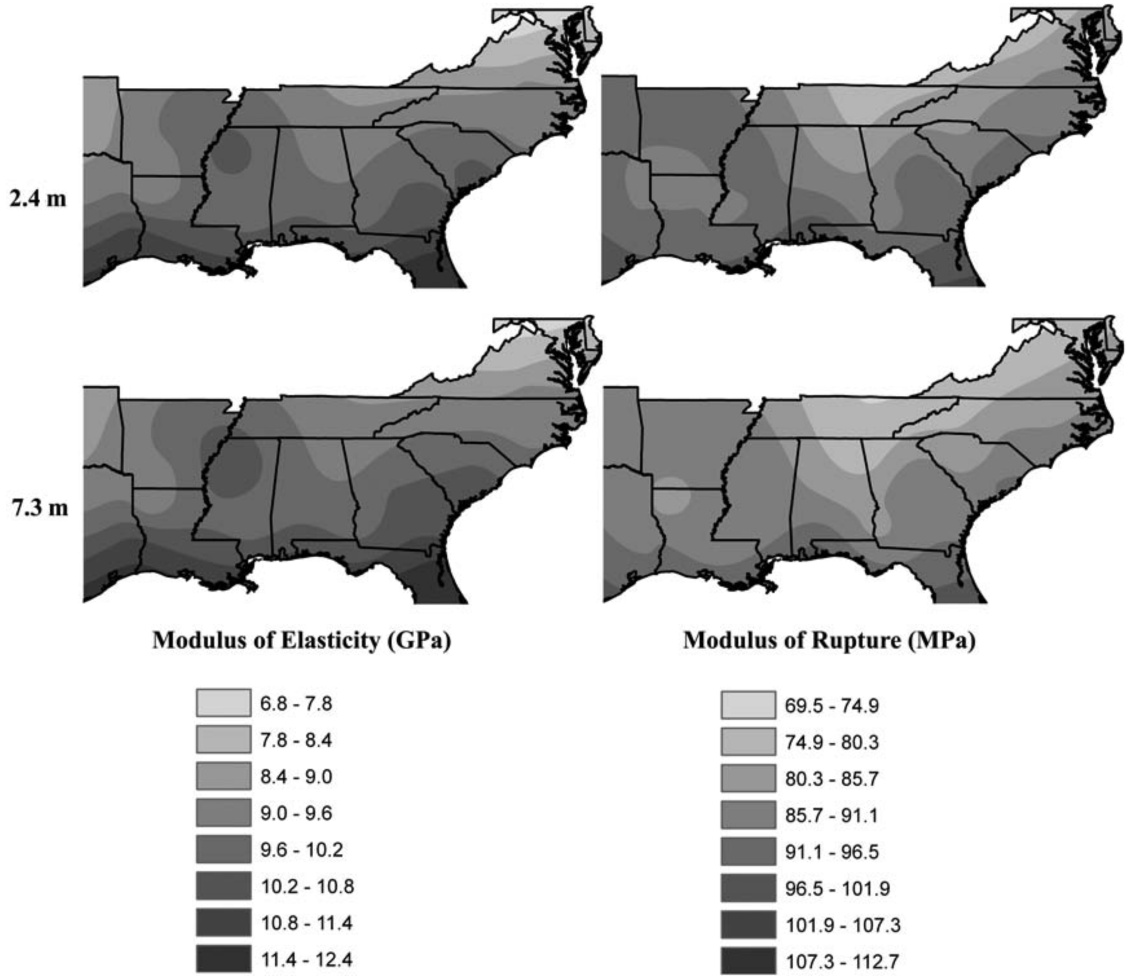
**Fig. 8.** Maps showing the regional variation in modulus of elasticity and modulus of rupture for outerwood at heights of 2.4 and 7.3 m.




the base of the tree, but further studies are required to verify this assumption.

Based on the present study, MOE and MOR exhibit considerable within-tree variation in loblolly pine. Generally, high MOE and MOR were observed for outerwood compared with corewood (Figs. 2 and 3). Within-tree variation in SG and MFA may explain this variability. We observed higher SG in the outerwood portions of trees compared with the corewood (Fig. 4). Larson et al. (2001) observed high MFA (ranging from 25 to 35°) in the corewood of loblolly pine compared with the outerwood (ranging from 5 to 10°). A height-related trend in MOE and MOR was also found in this study. The magnitude and direction of variation in each of these mechanical properties with height depend on the wood type (corewood or outerwood). Both MOE and MOR increased with tree height in the corewood portion of the stem, while MOE and MOR decreased with height in the outerwood portion of the stem (Figs. 2 and 3). Unlike MOE and MOR, SG decreased with height in both corewood and outerwood but had less variation with height in the corewood (Cown 1992) (Fig. 4). Megraw et al. (1999) found that MFA values decreased from pith to bark up to ring 20 at the base and at heights of 1 and 2 m in loblolly pine trees, i.e., a slower rate of decrease in MFA at the base of the tree from pith to bark. However, they observed a fast rate of decrease from pith to bark in MFA at heights of 3 m and above where it reached a stable value at ring 10. This suggests a higher average MFA in corewood static bending samples at the base of the tree than as we move up in the tree (Jordan et al. 2005, 2006). So the opposite trends in MOE and MOR with height in the corewood and outerwood portions of the stem might be due to the combined effect of an overall SG decrease in both wood types and the difference in rate of decrease in MFA at different heights in the corewood and outerwood portions of the stem. Similar trends were observed in radiata pine where density alone explained the majority of variation in outerwood MOE, while corewood MOE was influenced by both density and MFA, with MFA sometimes having a stronger relationship with MOE than density (Cown et al. 1999; Ivković et al. 2009; Watt et al. 2010). In comparison, density explains the majority of variation in MOR in *Eucalyptus* and radiata pine (Yang and Evans 2003; Ivković et al. 2009); however, in a recent study by Lachenbruch et al. (2010), the relationship between MOR and density was moderate (ranged from 0.62 to 0.69 and depended on the samples used to determine the relationship).

Apart from density and MFA, both MOE and MOR are highly influenced by stem form (Watt and Zoric 2010), stand density (Clark et al. 2008; Watt and Zoric 2010), silvicultural practices (Watt et al. 2009), and the presence of any weak-



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nesses in wood, such as knots, stress risers at pits, rays, and compression wood (Cown et al. 2004). In this study, we found that stem slenderness had a significant influence on both MOE and MOR, which agrees with the observed trends in radiata pine from New Zealand (Watt et al. 2009; Watt and Zoric 2010). We did not observe a significant influence of stocking on MOE and MOR, which might be due to the narrow range of stand densities used in this study. However, further studies of loblolly pine are necessary to unveil the nature of the relationship between MOE and MOR and extraneous variables such as stem slenderness, stand density, and silvicultural management practices.

In summary, significant variation was observed for MOE and MOR over the natural range of loblolly pine. A height-related trend in MOE and MOR within a tree was also identified in this study. It was also observed that the height-related trend in MOE and MOR depends on the wood type (corewood or outerwood). An understanding of variation in MOE and MOR is important for forest product industries for the segregation of raw material and the optimization of manufacturing processes.

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