VARIATION IN LOBLOLLY PINE CROSS-SECTIONAL MICROFIBRIL ANGLE WITH TREE HEIGHT AND PHYSIOGRAPHIC REGION

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ABSTRACT

The effect of height and physiographic region on whole disk cross-sectional microfibril angle (CSMFA) in loblolly pine (*Pinus taeda* L.) in the southern United States was evaluated. Whole disk CSMFA was determined at 1.4, 4.6, 7.6, 10.7, and 13.7 m up the stem of 59 trees, representing five physiographic regions. A mixed-effects analysis of variance was performed to test the significance of height, region, and the height by region interaction on CSMFA. Height, region, and the height by region interaction terms were all found to be significant at the 0.10 level. Significant differences were found in CSMFA between 1.4 m and all other height levels in all regions. However, there was no difference between CSMFA at 1.4 m and 13.7 m in the Gulf Coastal Plain. No significant difference was found in CSMFA between 4.5, 7.6, and 10.7 meter-height levels in all regions. CSMFA was found to be significantly larger in the north Atlantic and Piedmont regions compared to the south Atlantic, Gulf, and Hilly regions at all heights. The analysis of variance also indicated that significant variation exists among trees within stands and across stands within regions. This is an indicator that aside from the distinct patterns of CSMFA within trees,

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other factors including site quality, length of growing season, rainfall, and genetics could possibly play a key role in CSMFA development.

Keywords: Analysis of variance, mixed-effects, repeated measures, spatial correlation.

INTRODUCTION

Microfibril angle (MFA) has a significant effect on both the mechanical properties and dimensional stability of wood, and as such is an important quality characteristic for solid wood products (MacDonald and Hubert 2002). MFA is highly inversely correlated with specific gravity (SG), modulus of elasticity, modulus of rupture, and tangential shrinkage, which is positively correlated with the longitudinal shrinkage of wood. In addition, MFA is highly correlated with stretch, stiffness, and strength properties of paper (Megraw 1985; Kellogg et al. 1975; Watson and Dadswell 1964).

Variations in MFA of any tree species can be attributed to variation within a tree, between trees in a particular stand, between different growing sites, and between different silvicultural regimes (Addis et al. 1995). MFA varies within each growth ring, from pith to bark, with height in the stem and among trees. Cave and Walker (1994) reported that the MFA decreases from the first earlywood cell to the last latewood cell. MFA in loblolly pine (*Pinus taeda* L.) is large near the pith and decreases rapidly out to 10 or more rings from the pith, and then continues dropping, regardless of height, but at a much slower rate until such time as it essentially stabilizes. The decrease in MFA with age takes place at a slower rate near the base of the tree than it does at upper heights. This results in higher MFA for a given number of rings from the pith at the butt and breast height regions than at several meters in height and above (Megraw 1985). Megraw (1999) found that the average MFA values of 24 loblolly pine trees decrease with increasing ring number all the way out through ring 20 at the base, 1 m, and 2 m. At heights of 3 m and above, MFA was found to decrease to ring 10, where it essentially stabilized near 10 degrees for all rings thereafter.

MFA varies considerably within the juvenile and mature zones of tree wood. MFA is characteristically greater in juvenile wood than in mature wood. In juvenile wood, MFA is large, ranging from 25 to 35 degrees and often up to 50 degrees near the pith, while MFA in mature wood is small ranging from 5 to 10 degrees (Larson et al. 2001). Pillow et al. (1953) found that MFA in the juvenile wood of open-grown loblolly pine averages 20 degrees larger than that of closely spaced natural stands. MFA has been found to decrease from 33 degrees at ring 1 to 23 degrees by age 10, and 17 degrees at age 22, in fast-grown loblolly pine (Ying et al. 1994).

The objective of this research was: (1) to identify the patterns of whole disk cross-sectional microfibril angle (CSMFA) variation with tree height and physiographic region, and (2) to estimate the components of variance attributable to variation among regions, stands within a region, and among trees within a given stand.

METHODS AND MATERIALS

Fifty-nine loblolly pine trees from 20 stands, 20–27 years old, were sampled across the Southern United States for MFA analysis. Plantations were sampled in the south Atlantic Coastal Plain, north Atlantic Coastal Plain, Piedmont, Gulf Coastal Plain, and Hilly Coastal Plain physiographic regions (Fig. 1). The stands were located on land owned by forest products companies, and included only stands with similar silvicultural history: 1) site preparation with no herbaceous weed control; 2) no fertilization at planting except phosphorus on phosphorus-deficient sites; 3) stand density of at least 617 trees per hectare at the time of sampling. Trees larger than 12.7 cm in diameter were inventoried on 3, 0.04-hectare plots to determine stand stocking and diameter distribution. A sample of 3 trees was chosen for CSMFA analysis proportional to the diameter distribution of each stand

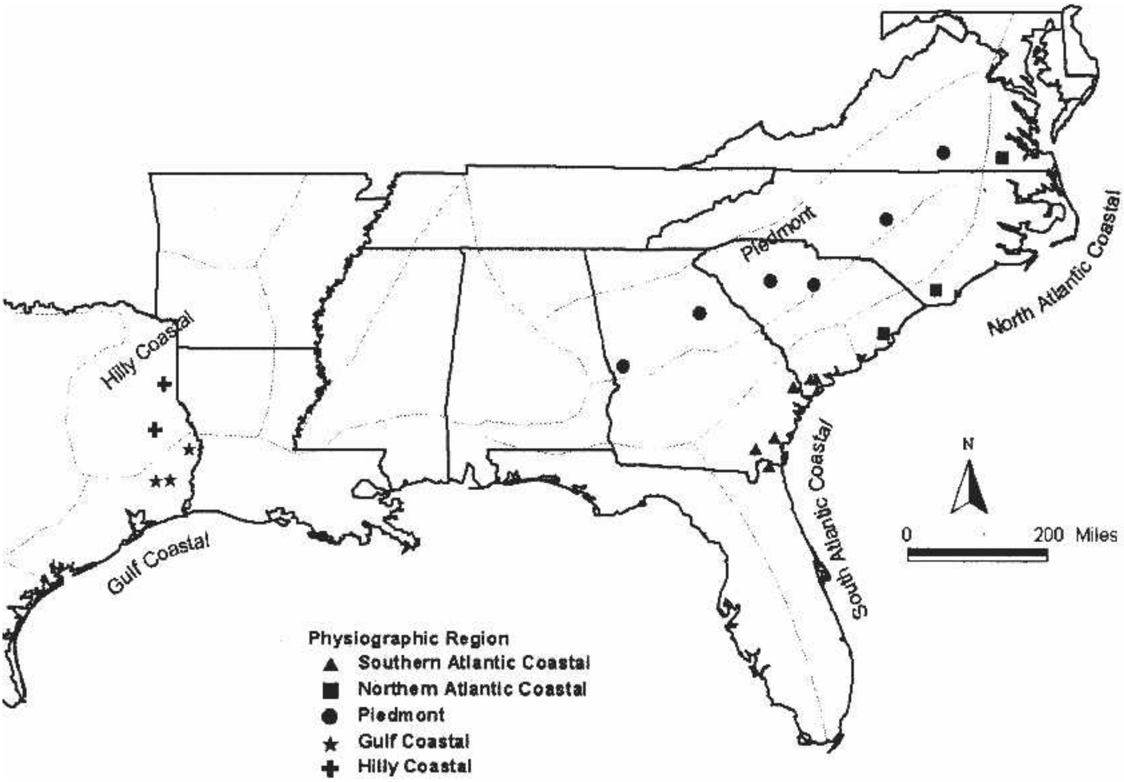

FIG. 1. Plot of the 20 stands selected for cross-sectional microfibril analysis.

to represent a range of tree sizes in the stand. Stand attributes are summarized in Table 1.

Cross-sectional disks 2.54 cm thick were cut at 1.4, 4.6, 7.6, 10.7, and 13.7 m up the stem of each sample tree. Two radial strips 1.27 cm square were cut from each disk and dried at 122 degrees Celsius. One strip was sawn into a 2-mm-thick radial strip for X-ray densitometry for measurement of earlywood and latewood as well as radial growth and specific gravity at 0.0060-cm intervals. The second strip was sawn into a 2-×7-mm strip for CSMFA analysis. MFA was determined by Silviscan® using X-ray diffraction at 0.10-cm intervals on the radial surface. The MFA data were assigned to an annual ring based on the radial measurements collected on the densitometer and during X-ray diffraction. CSMFA was calculated, by weighting ring MFA with respect to the proportion of the basal area of the total that each ring made up. Model performance was evaluated utilizing informative statistics including twice the negative log-

TABLE 1. *Range and average (in parentheses) tree size characteristics for 59 loblolly pine trees sampled for cross-sectional microfibril angle analysis.*

Region	Trees sampled	DBH (cm)	Total height (m)	Age (years)	MFA (degrees)
S. Atlantic	15	15.5–32.2 (23.9)	17.7–25.3 (22.1)	21–24 (22.3)	10.2–28.4 (16.2)
N. Atlantic	9	16.8–28.7 (22.7)	15.5–21.9 (19.0)	21–24 (22.7)	13.7–36.7 (19.4)
Piedmont	17	15.7–36.1 (25.6)	15.1–19.9 (18.3)	21–25 (23.4)	12.0–30.5 (18.1)
Gulf	9	14.5–24.9 (18.8)	12.6–18.7 (16.5)	20–27 (23.7)	12.7–25.0 (16.0)
Hilly	9	14.2–29.0 (21.3)	11.4–21.7 (17.7)	20	12.6–22.2 (15.9)

likelihood, Akaike information criterion (AIC), and Bayesian information criterion (BIC).

Statistical analysis and model development

The stands selected for sampling represent a random sample of all stands in the corresponding region. Conversely, the trees within a stand represent a sample of all trees from the corresponding stand located within a distinct physiographic region. Here, stands and trees within stands represent random-effects, and their contribution to the variance of CSMFA can be estimated. From the plot of CSMFA versus disk height by physiographic region (Fig. 2), it can be seen that CSMFA varies not only with disk height but from tree to tree, indicating that a mixed-effects model could potentially be employed to account for the variation of CSMFA within stands and from tree to tree. It can also be seen from Fig. 2 that CSMFA is initially large at 1.4 m, decreases and stabilizes from 4.6 to 10.7 m, and then increases at 13.7 m. Generally, CSMFA appears to be larger in the north Atlantic and Piedmont regions compared to the south Atlantic, Hilly, and Gulf regions.

Assuming that the effects of the sampling strata are additive at the different levels, an individual observation of CSMFA, y_{ijkl} can be defined as

$$y_{ijkl} = \mu + R_i + H_l + (RH)_{il} + S_{ij} + T_{ijk} + e_{ijkl},$$
$$i = 1, \ldots, M, j = 1, \ldots, M_i,$$
$$k = 1, M_{ij}, l = 1, \ldots, n_{ijk} \qquad (1)$$

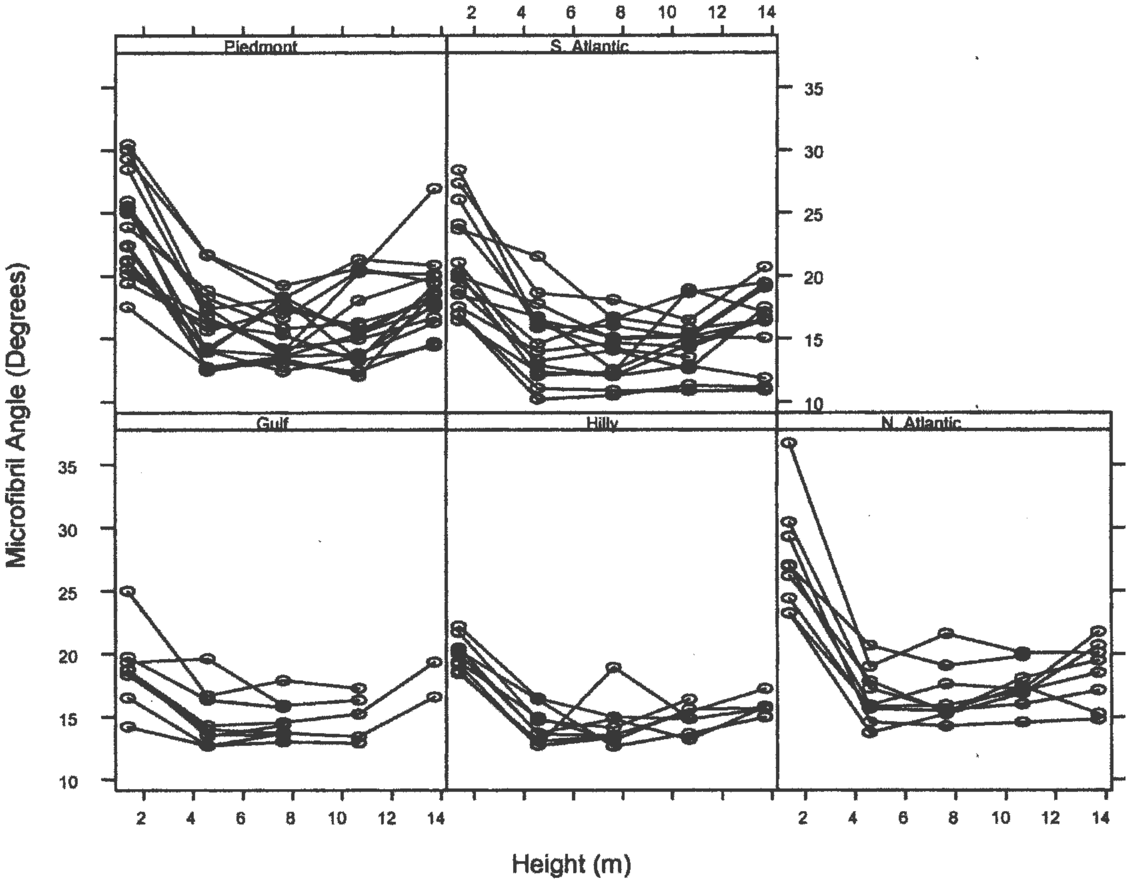

FIG. 2. Plot of observed cross-sectional microfibril angle versus disk height by physiographic region for the 59 trees selected for analysis.

where,

y_{ijkl} = CSMFA of the l^{th} height level, of the k^{th} tree, of the j^{th} stand, in the i^{th} region,
μ = the population mean,
R_i = the i^{th} region effect,
H_l = the l^{th} height level effect,
$(RH)_{il}$ = the interaction of the i^{th} region and l^{th} height effects
S_{ij} = the effect of the j^{th} stand in the i^{th} region with $S_{ij} \overset{iid}{\sim} N(0, \sigma_S^2)$,
T_{ijk} = the effect of the k^{th} tree of the j^{th} stand in the i^{th} region, with $T_{ijk} \overset{iid}{\sim} N(0, \sigma_T^2)$ and
e_{ijkl} = residual error, with $e_{ijkl} \overset{iid}{\sim} N(0, \sigma^2\mathbf{I}_{ijk})$

We first fit Eq. (1) with differing combinations of random-effects (Table 2). From Table 2, it can be seen that inclusion of the stand and tree random-effects components improves model performance based on AIC, BIC, and twice the negative log-likelihood values. According to the statistical criterion indices, AIC, BIC, and the log-likelihood values all indicate the Model 4 is preferred. We expect that correlation exists among the almost equally spaced CSMFA measurements, or observations closer together will tend to be more alike than observations farther apart. If correlation among the repeated measurements exists, its autocorrelation pattern can be modeled with an appropriate spatial correlation model.

The correlation structure

Correlation structures are used for modeling dependence among observations. In the context of mixed-effects models, they are used to model the correlation among the within-subject errors.

TABLE 2. *Selection criteria values for Eq. (1) fit with differing combinations of random-effects.*

Model	Random	AIC	BIC	−2(Log-likelihood)
1	None	1267.3	1269.4	1265.3
2	S_{ij}	1214.4	1216.3	1210.4
3	T_{ijk}	1180.6	1184.7	1176.6
4	S_{ij}, T_{ijk}	1176.0	1179.0	1170.0

Correlation structures can be categorized as time series or spatial correlation structures, and the latter can be considered a generalization of the former. The time series correlation structure is most suitable for equally or continually spaced time series data, but can be applied to distance data. If we use vector H_{ijkl} to denote the position vector of within subject error e_{ijkl} and model the within subject correlation of e_{ijkl} and e_{ijkl}' as a function of relative distance (d) between H_{ijkl} and H_{ijkl}', then the correlation of the errors can be defined as, $corr(e_{ijkl}, e_{ijkl}') = h[d(H_{ijkl}, H_{ijkl}'), \rho]$, where ρ are correlation parameters and $h(.)$ is a specified correlation function.

For our data, we have approximately equally spaced MFA measurements taken at 3-m intervals along the tree stem, so a time series or spatial correlation structure may be used to account for MFA autocorrelation within a tree. For sample data, we can use an empirical autocorrelation function (Box et al. 1994) to estimate the serial correlation, and gain insight into choosing an appropriate correlation structure. A plot of the estimated autocorrelation coefficients against lags with critical value boundary lines at the 0.05 level for the linear mixed-effects model (Model 4) is given in Fig. 3. From the scatter-plot, we can see that the empirical correlation coefficients at the first 3 lags are mildly significant, indicating that an appropriate correlation structure could potentially improve model performance.

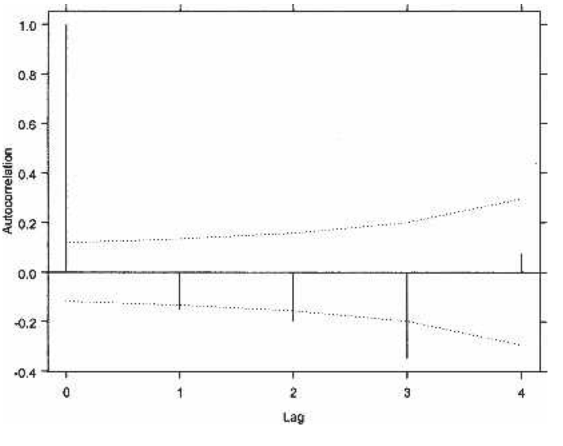

FIG. 3. Scatter-plot of the empirical autocorrelation versus lag from the linear mixed-effects model.

We proceed by updating the linear mixed-effects model (Model 4) by fitting several spatial and time correlation functions. The spatial structures chosen included: Gaussian, Log linear, Power, and Linear models. For the time series structure, we fit an autoregressive structure of order 1 [$AR(1)$]. The AIC, BIC, and twice the negative log-likelihood values from the correlated structure model fits are given in Table 3. When compared to Model 4, we can see that the addition of a Power correlation structure improves model performance. Model 4.3 was found to have the lowest AIC and BIC values when compared to the Model 4. This reaffirms that mild autocorrelation among the disks exists, and it is of sufficient magnitude to warrant the addition of an autocorrelation structure. The Power correlation structure assumes $\mathrm{cov}(e_{ijkl_1}, e_{ijkl_2}) = \sigma^2[h\{d(ijkl_1,ijkl_2)\}]$, where $d(ijkl_1,ijkl_2) = H_{ijkl_1} - H_{ijkl_2}$, is the Euclidean distance between two adjacent disks, and the correlation function is given as $h\{d(ijkl_1,ijkl_2)\} = \rho^{d(ijkl_1,ijkl_2)}$.

RESULTS

The results of the linear mixed-effects model analysis of variance with a Power correlation structure (Model 4.3) along with estimates of the random-effects components of variance are presented in Table 4. The region main effect was found to be statistically significant at the 0.1 level, but not at the 0.05 level. The finding of a significant regional result in the mean value of CSMFA at the 0.1 level can be attributed to larger values in the north Atlantic and Piedmont regions, compared to the south Atlantic, Gulf, and Hilly regions. Average CSMFA was found to decrease 3.2, 3.1, and 3.6 degrees when moving from the north Atlantic to the south Atlantic, Gulf, and Hilly regions, respectively. The mean value of CSMFA was found to be similar in the south Atlantic, Gulf, and Hilly regions. Similarly, CSMFA was found to be non-significant when comparing the north Atlantic to the Piedmont region.

The height main effect was found to be significant at the 0.0001 level, indicating a significant difference between mean CSMFA values at the different height levels. The difference in height can be mostly attributed to differences in CSMFA at 1.4 and 13.7 m compared to all other heights. Pairwise comparisons were conducted to evaluate the change in CSMFA with changing height across all regions (Table 5). From Table 5, it can be seen that across regions, CSMFA differs significantly at 1.4 and 13.7 m compared to the other height levels. At 1.4 m, CSMFA was found to be significantly larger, on the order of 7 degrees when moving to 4.6, 7.6, or 10.7 m in height, and 5 degrees larger than that at 13.7 m. No significant difference was found when comparing CSMFA values at 4.6, 7.6, and 10.7 m. However, CSMFA was found to be significantly larger at 13.7 m in height versus 4.6, 7.6, and 10.7 m. The increase of CSMFA at 13.7 m is of interest. Average tree height across all re-

TABLE 3. *Comparisons of linear mixed-effects model performance with different within-tree correlation structures.*

Model	Correlation structure	AID	BIC	−2(Log-likelihood)
4	Independent	1176.0	1179.0	1170.0
4.1	Gaussian	1174.3	1178.3	1166.3
4.2	Log Linear	1183.9	1187.9	1175.9
4.3	Power	1173.1	1177.1	1165.1
4.4	Linear	1202.9	1205.9	1196.9
4.5	AR(1)	1173.5	1177.4	1165.5

TABLE 4. *Analysis of variance for the linear mixed-effects model with a power autocorrelation structure.*

Source	Numerator *d.f.*	Denominator *d.f.*	F-value	P-value
Region	4	14.5	2.70	0.0725
Height	4	155	129.38	0.0001
Region*Height	16	172	3.33	0.0001

$\hat{\sigma}_S^2 = 2.06$, $\hat{\sigma}_T^2 = 1.93$, $\hat{\sigma}_S = 4.03$

TABLE 5. *Pairwise comparisons and estimated change in CSMFA (in degrees) when moving across height levels (from left to right) across all regions.*

Height (m)	1.4	4.6	7.6	10.7	13.7
1.4		−6.92[a]	−7.22[a]	−6.81[a]	−4.74[a]
4.6			−0.30	0.10	2.12[a]
7.6				0.41	2.48[a]
10.7					2.07[a]

[a] Significant at the 0.05 level

gions was found to be 18.4 m, meaning that the average distance from the last CSMFA measurement was only 4.7 m from the top of the tree, and possibly well into the tree crown. This could substantially influence the values of CSMFA since the wood at this height would be comprised mostly of juvenile corewood resulting in significantly higher CSMFA values.

The region by height interaction effect was found to be significant at the 0.0001 level, implying that region has a significant effect on CSMFA, but its effect depends on the height level. Mean CSMFA values vary with disk height and by physiographic region (Fig. 4). CSMFA values were found to be larger at all height levels in the north Atlantic and Piedmont regions compared to the south Atlantic, Gulf, and Hilly regions. Pairwise comparisons showed CSMFA was significantly larger at 1.4 m (3.30 degrees) in the north Atlantic compared to the Piedmont region. Aside from differences at 1.4 m, no other statistically significant differences were found when comparing respective height levels between the north Atlantic and Piedmont regions. No significant differences were found at respective height levels when comparing the south Atlantic, Gulf, and Hilly regions. Since CSMFA values are similar in the north Atlantic and Piedmont regions, and in the south Atlantic, Gulf, and Hilly regions, joint comparisons were conducted to determine if significant differences in CSMFA occurred between the two groups at the respective height levels. The joint comparisons at 1.4 and 10.7 m were found to be significant at the 0.05 level, and all other comparisons were significant at the 0.10 level. Estimates of the joint comparisons for the regions indicated that on average, CSMFA is 5.9, 1.8, 1.8, 2.2, and 1.8 degrees larger in the north Atlantic and Piedmont regions compared to the south Atlantic, Gulf and Hilly at 1.4, 4.6, 7.6, 10.7, and 13.7 m in height respectively.

The variance estimate (σ^2) was found to be 4.03 degrees. The variance components of trees within stands (σ_T^2), and stands within regions (σ_S^2) were found to be 1.93 and 2.06 degrees, respectively. From these estimates, it can be concluded that the trees within stands and stands

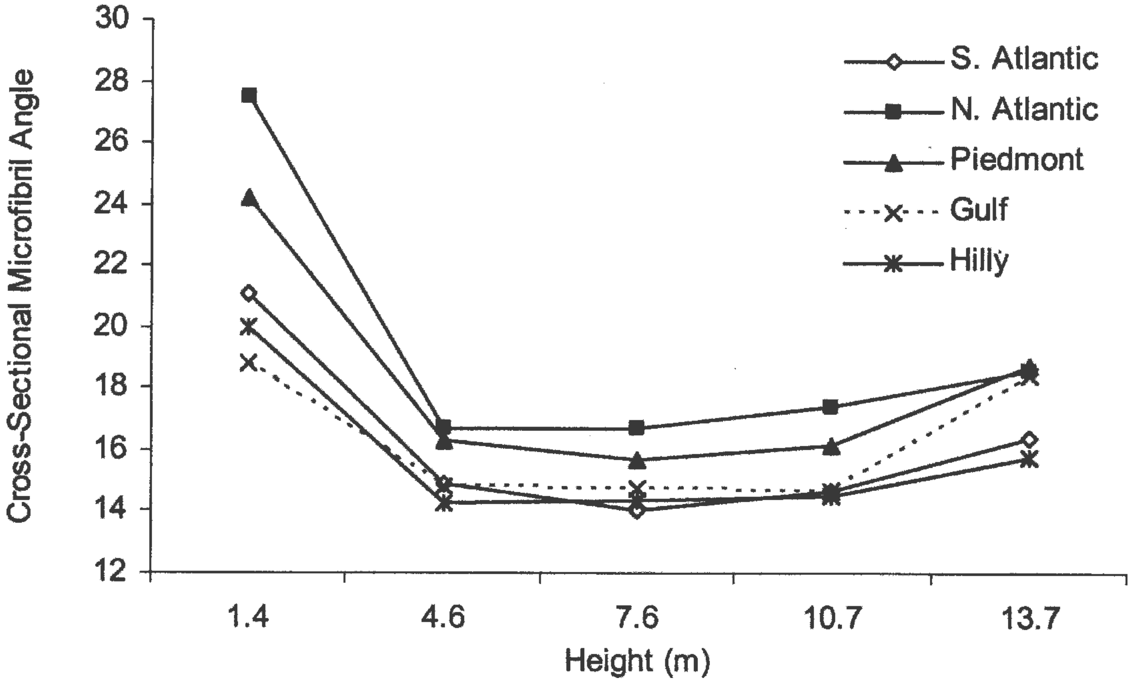

FIG. 4. Plot of estimated mean cross-sectional microfibril angle versus disk height by physiographic region.

within regions random-effects contribute a significant amount to the variation of CSMFA.

DISCUSSION AND CONCLUSIONS

An analysis of variance was conducted to evaluate the effect of region and height on cross-sectional microfibril angle in plantation-grown loblolly pine in the southern United States. CSMFA was found to differ significantly by region and height. CSMFA was highest at 1.4 m, decreased at 4.6 m where it stabilized at 4.6, 7.6, and 10.7 m height levels and then increased at 13.7 m. The increase in CSMFA at 13.7 m can be attributed to the disks being in or near the tree crown and thus containing large volumes of juvenile wood and therefore higher CSMFA values.

The finding of higher CSMFA values in the north Atlantic and Piedmont regions is consistent with higher specific gravity findings by Clark and Daniels (2004). Clark and Daniels (2004) found that specific gravity values, which are highly inversely correlated with MFA, were on average lower in the north Atlantic and Piedmont regions compared to the south Atlantic, Gulf, and Hilly regions. With the south Atlantic region receiving more summer rainfall and an extended growing season, trees in this area have a greater percentage of latewood and conversely lower MFA values. Lower CSMFA values in the Gulf and Hilly regions may be attributed to site quality. Trees from the Gulf and Hilly regions were found to be on average 0.7 cm smaller in diameter and 2.1 m shorter in height than the trees in the north Atlantic and Piedmont regions. Slow growth could produce a more compact fiber structure with less earlywood, resulting in lower CSMFA values. Regional weather patterns or site quality differences are not the sole factor influencing CSMFA. Initial stocking density and the number of trees per acre at the time of sampling could influence the size of the juvenile core, resulting in higher CSMFA at low planting densities and low CSMFA values at high planting densities.

The majority of variation in CSMFA was found to be attributed to the differences between trees within stands and stands within regions. This is a highly plausible scenario, given the unique patterns of CSMFA within trees (Fig 2). The large estimate of the stand random-effects component may be due to environmental differences including site quality, length of growing season, and rainfall, or any number of environmental factors.

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