



Assessment of Loblolly Pine Bark Physical Properties with Respect to Physiographic Region and Relative Tree Height

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Abstract

Plantation forests in the southeastern United States are dominated by loblolly pine (*Pinus taeda* L.) whose wood is used to supply the lumber, composite, pellet, and pulp and paper industries; processing of this timber affords bark as a major byproduct. To date, information is limited regarding the variation of loblolly pine bark properties with relative tree height and how these trends vary with physiographic region. For this study, 139 stands across the natural range of loblolly pine were destructively sampled with three trees felled from each stand. Bark properties, specific gravity (SG), moisture content (MC), green mass (kg m^{-3}), and percent (%) bark were determined from cross-sectional disks collected at multiple heights along the stem of each sampled tree. Values for bark MC and green mass increased with increasing height. Bark SG increased from the stump to a maximum at approximately 40% relative height before decreasing, whereas percent bark decreased to 40% relative height before increasing. While the trends in bark properties by relative height were consistent across all regions, significant differences by region were observed at some heights. Improved knowledge of bark properties will assist in efforts to valorize pine bark and refine calculations of carbon sequestered in it.

Study Implications Information regarding variation in bark properties (specific gravity (SG), moisture content (MC), green mass (kg m^{-3}), and percent (%) with tree relative height and physiographic region is provided for loblolly pine, a species that dominates plantation forests in the southeastern United States. Assessments provided herein are particularly relevant to refining calculations of carbon sequestered in one of the world's most important carbon sinks, plantation loblolly pine growing across the southeastern US, with the bark being a significant factor both in standing forests and as a residue generated by the forest products industry sector.

Keywords Bark thickness · Green mass · Loblolly pine · Moisture content · *Pinus taeda* · Regional variation · Specific gravity

Introduction

The highly productive forests of the southeastern United States have consistently produced more timber than any other country over the past few decades; approximately one third of the forests in this region are occupied by the southern pines, with roughly one half of the 28 million ha southern pine forest being comprised of plantation timber (Wear and Greis 2012). Since the 1950s, productivity of southern pine plantations increased fourfold (Fox et al. 2007) through genetic improvements coupled with the implementation of intensive forest management practices (Borders and Bailey 2001; McKeand et al. 2003; Jokela et al. 2010; Schultz 1999). The predominant southern pine species is loblolly pine (*Pinus taeda* L.), owing to its rapid growth, suitability to a wide range of site conditions, and responsiveness to treatments such as fertilization (Borders and Harrison 1989; Shiver et al. 2000; Fox et al. 2007; South and Harper 2016).

A significant volume of bark (10 to 12% of total stem weight on a dry-weight basis) accompanies the large volume of loblolly pine wood used to supply various forest product manufacturers in the southeastern United States (Antony et al. 2015; Zhao et al. 2016; Eberhardt et al. 2017). Interestingly, while a higher degree of intensive management of loblolly pine was shown to increase biomass production, the partitioning of that biomass between tree components (e.g., stem, bark, branches) was not affected (Zhao et al. 2012). Estimates of above-ground biomass often rely on calculations based on volume-to-weight conversions (Zhao et al. 2016), with allometric models for bark volumes being based on inside-bark and outside-bark diameter measurements (Gonzalez-Benecke et al. 2014).

There are two main perspectives regarding the importance of the volume (or mass) of tree bark as a resource generated by the southern pine forests. First, bark is major byproduct of the forest products industry sector, accumulated in large volumes at industrial mills since most southern pine timber is transported for processing as bark covered logs (Eberhardt and Reed 2006; So and Eberhardt 2006). Although valorization of pine bark continues to be investigated in studies using it as a chemical resource (Bianchi et al. 2015; Rajan et al. 2017), component of composites (Santos et al. 2021) or biofuel feedstock (Ben et al. 2019), most pine bark is still used directly in power boilers for its heat value (Eberhardt 2012). Second, bark is now recognized as a resource on the living tree as a key component contributing to sequestration of carbon in standing forests. Specific to loblolly pine, planting genetically improved trees over the last 40 years has increased stem wood volumes by 17% and carbon sequestration by 13% (Aspinwall et al. 2012). Nepal et al. (2012) estimated for an average loblolly pine stand harvested at age 25 years, 79% of the above-ground carbon in the bole will be sequestered in the resulting forest products produced from the tree. Although carbon sequestered in bark and other biomass is deemed a carbon neutral fuel source by many governments, combustion nonetheless returns the sequestered carbon to the atmosphere as greenhouse gases (Sterman et al. 2022).

Current allometric models for tree volumes often use outside bark diameters, and by doing so, estimates of biomass and carbon allocations do not account for

the fact that bark densities and carbon contents are different to those for the wood (Neumann and Lawes 2021); in cases where the bark specific gravity (SG) (density) is significantly lower than that of the wood, bark carbon content may be grossly overestimated (Billard et al. 2020; Neumann and Lawes 2021). Miles and Smith (2009) generated an extensive list of wood and bark SG values for North American tree species based on the green volume and oven-dry weight, with the average SG of the bark (0.33) being considerably lower than that reported for the wood (0.47). Looking into the older literature for loblolly pine, Martin (1969) reported the SG for loblolly pine bark to be 0.477, which is the same as that reported for the wood; however, this higher bark SG value can be attributed to the determination being based on the dry (not green) bark volume. Other values for loblolly pine bark SG values should be interpreted with caution given that the volume basis (green vs. dry) is not provided (Harder and Einspahr 1976), or the inner bark component is excluded from the determination (Martin and Crist 1968).

Studies on loblolly pine bark SG have been conducted to compare it to the bark of other southern pine species (Phillips et al. 1976; Gibson et al. 1986); in Gibson et al. (1986), the impact of site conditions (e.g., wet, intermediate, dry) was also investigated. Phillips and Schroeder (1972) carried out a detailed study whereby bark SG values were reported for loblolly and slash (*Pinus elliottii* Engelm.) pines at set percentages of merchantable height (0, 25, 50, 75, and 100%). It is interesting to note that although the thickness of the bark for both species decreased with height, the mean percent bark by weight reached a minimum at mid-height. In a recent study comparing both the wood and bark properties of these two species, in addition to seeing similarities in the data reported by Phillips and Schroeder (1972), we found that the bark SG for loblolly pine, but not slash pine, reached a definite maximum below the midpoint of relative height (Eberhardt et al. 2017). Raut et al. (2022) found that the bark SG trend for longleaf pine resembled the trend for wood SG, with the bark SG high at the base of the tree and then decreasing nonlinearly with height. Thus, it has been confirmed for the southern pines that bark SG can vary substantially with relative height, and that this variability can be species specific.

Plantation loblolly pine wood physical (SG) and mechanical (stiffness and strength) properties have been studied in detail to gain an understanding of the impact of forest management practices or physiographic region (Antony et al. 2015; Clark et al. 2006; Jordan et al. 2008; Dahlen et al. 2018, 2021; Eberhardt et al. 2022), however, very little information is available on the regional variation of loblolly pine bark (or the bark of any commercially important species), and specifically, how it might vary with height. Among the aforementioned studies, Antony et al. (2015) reported whole-tree values (percent by weight, SG, and moisture content (MC)) for the bark of trees from six physiographic regions. Briefly, results showed the two regions with the highest whole-disk wood SG values (Gulf Coastal, South Atlantic) to also have the highest bark SG values. To expand on the work of Antony et al. (2015), our objectives in the current study were to assess how bark percent, SG, MC, and green mass (kg m^{-3}) vary with relative height, and to examine if the within-tree trends also vary between physiographic regions. Indeed, when plotting the bark physical property data against relative height, Eberhardt et al. (2017) found

different trends in the data between loblolly and slash pine. Assessments provided herein are particularly relevant to refining calculations of carbon sequestered in one of the world's most important carbon sinks, plantation loblolly pine growing across the southeastern United States, with bark being a significant factor both in standing forests and as a residue generated by the forest products industry sector.

Materials and Methods

Source of Loblolly Pine Samples

Plantation loblolly pine trees were sampled across the natural range for the species by the University of Georgia Wood Quality Consortium (WQC) and the USDA Forest Service Southern Research Station between 1999–2004. Stands selected for sampling were conventionally managed, having received no intensive management practices (chemical competition control or fertilization) except for phosphorus applications on phosphorus-deficient sites. The stocking of the stands ranged from 494 to 1483 trees/ha (initial planting densities varied between 1112 to 1779 trees/ha). For the majority of stands, thinning had been delayed, hence most trees had grown under similar (relatively high) stand-density levels. A total of 139 loblolly pine stands were sampled for this study: 116 from the WQC baseline trial aged 18–31 years planted between 1970 and 1985 (due to low sample size and inherent variability in bark properties, the 7 North Atlantic Coastal stands were not included in this analysis), 12 from a thinning study with three treatments (control, light thinning, heavy thinning) established by the Virginia Tech Forest Modeling Research Cooperative (FMRC) aged 30–45 years and planted between 1960 and 1975, and 11 stands from the University of Georgia Plantation Management Research Cooperative (PMRC) species comparison trial (loblolly pine, slash pine) aged 21–24 years (Fig. 1) planted

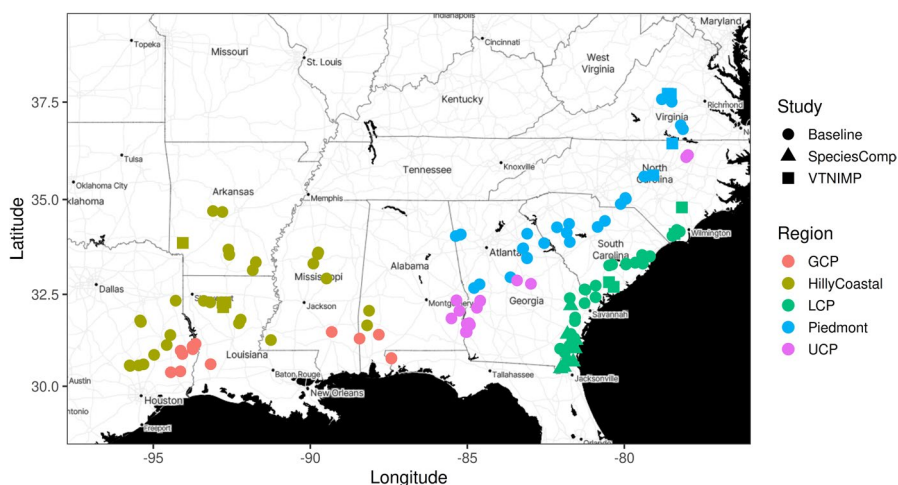


Fig. 1 Map of stand locations

between 1980 and 1981. From the FMRC trial, only the light thinning treatment was included; from the PMRC trial, only loblolly pine was included.

Tree Sampling and Bark Measurements

From each stand, three trees were felled and included in this analysis (one stand had incomplete data for one tree so data here includes a total of 416 trees). One felled tree represented the mean diameter class from the stand (the diameter class being determined in 25 mm intervals), the other two felled trees were selected as representing diameter classes that were above and below the mean diameter class. Trees were felled with a chainsaw, their branches removed, and the total height of the main bole recorded. The number of stands, trees sampled per region, and tree attributes (diameter and height) are summarized in Table 1.

Cross-sectional disks (38-mm thick) were collected along the tree at 0.15 and 1.37 m heights from the base and then at 1.5 m intervals up to an outside bark diameter of 50 mm. Disks were sealed in plastic bags and transported back to the laboratory for further processing. Outside and inside bark diameters were measured for the green disks with the difference providing a measure of double-bark thickness. Green weights were determined for the intact disks and then subsequently for the peeled-wood disks, the latter prepared by carefully peeling the bark away with the aid of a chisel; the green weight of the bark was determined from the difference in green weight for the intact disk and the corresponding peeled wood disk. Bark basic SG values were calculated from the oven-dry weights and green volumes of the largest sections of peeled bark. Green volumes were determined on the bark sections by water immersion after soaking in water to ensure full saturation. Oven drying of the wood and bark components was carried out at 103 ± 2 °C until a constant mass was achieved (ASTM International 2014). Moisture contents were determined from the green and oven-dry weights of the wood and bark components and reported on an oven-dry weight basis as conducted by Antony et al. (2015). Bark green mass was determined from the SG and MC measurements. Percent bark values were calculated on the basis of the oven-dry weights of the bark and wood.

Table 1 Summary statistics (standard deviation (SD), minimum (Min), maximum (Max)) for number of stands, trees sampled, total tree height and diameter at breast height by region

Region	Number		Total height (m)				Diameter at breast height (mm)			
	Stands	Trees	Mean	SD	Min	Max	Mean	SD	Min	Max
Lower Coastal Plain	43	129	21.1	3.1	15.0	30.2	244	51	155	384
Upper Coastal Plain	17	51	18.9	3.1	12.8	27.0	235	48	150	356
Piedmont	30	90	18.7	2.9	13.3	26.9	245	51	145	371
Gulf Coastal Plain	16	48	18.8	2.7	12.6	23.4	204	38	145	290
Hilly Coastal	33	98	19.6	3.0	13.7	26.3	239	50	140	376
Overall	139	416	20.2	3.2	12.6	30.2	243	51	140	384

Statistical Analysis

Statistical analysis was conducted using the R statistical software (R Core Team 2023) with RStudio interface (RStudio 2023); data processing and plotting was conducted using the tidyverse series of packages (Wickham 2023). The mean, standard deviation, and range of the values were calculated for each variable (SG, MC, green mass, percent bark).

Bark properties varied nonlinearly with relative height within tree, and the nonlinear trends appeared different between some of the physiographic regions. To model these differences, we fit generalized additive mixed models (GAMM) (Hastie and Tibshirani 1986) using the mgcv package in R (Wood 2023). For each response variable (SG, MC, green mass, percent bark), a GAMM model was constructed with the bark properties first predicted from relative height, and secondly with relative height and region (predictor variables). For the relative height and region model, the model structure contained an intercept for each region, a smoothed function which varied by relative height and region, and two random effects, stand (sampled from within region), and tree (sampled within stand):

$$y_{ij} = \alpha_0 + \alpha_{1j} \text{Region}_{ij} + f_j(RH_i) + b_{0k} + b_{1l} + \varepsilon_{ij}, \varepsilon_{ij} \sim N(0, \sigma^2) \quad (1)$$

where y_{ij} is the mean value for each relative height (RH) (i) and region (j), α_0 is the intercept (mean response) for the reference region (Lower Coastal Plain), α_{1j} is the difference between the intercept for the jth region and the reference region, $f_j()$ are smoothed functions for each region using relative height (RH_i), b_{0k} is the random effect of stand, b_{1l} is the random effect of tree, and ε_{ij} are the residuals for the model which are normally distributed with a mean of 0 and a variance of σ^2 (Wood 2017). The same structure was used for the relative height model with the parameters related to regions being omitted. We also fit a GAMM model between bark MC and SG but without the effect of region included. To predict the total dry weight of bark at the individual tree level, a model based on Schumacher and Hall (1933) was fit with inputs of DBH and total height:

$$y = \alpha_0 \times DBH^{\alpha_1} \times HT^{\alpha_2} + \varepsilon, \varepsilon \sim N(0, \sigma^2) \quad (2)$$

where y is the total dry weight of the bark (kg), DBH is the diameter at breast height (mm), HT is the total height (m), α_0 , α_1 , and α_2 are the model parameters, and ε is the residuals for the model which are normally distributed with a mean of 0 and a variance of σ^2 . The model was fit both with and without varying the parameters by region and the models compared using analysis of variance. This fit was done using the `gnls` function within the `nlme` package in R (Pinheiro et al. 2025).

Since stands were sampled from five physiographic regions, and the model structure contains an intercept term for each region and a smoothed function for relative height for each region, we simplified comparisons between regions by constructing 95% confidence intervals for the prediction of the bark properties, and thereby, we were able to compare each region to the other 4 regions for each relative height (Rose et al. 2012). We then calculated the similarity between

regions, with score of 100 representing complete overlap of the confidence intervals (i.e. 100% overlap) over all relative heights, and a score of 0 representing no overlap (i.e. 0% overlap) for any relative height. We then constructed plots of the predictions showing the 95% confidence intervals.

Bark Scenarios by Region and Location Within Tree

Five scenarios for bark properties were constructed to illustrate how bark properties vary regionally and with different parts of the tree being utilized. These represented (1) whole tree utilization, (2–4) individual 5 m saw log utilization (logs 1–3), and (5) the top portion of the tree at final harvest which is typically sold to the pulp and paper or fuel pellet industries. For the first scenario, bark properties for the whole merchantable tree from the stump height (0.15 m) to the top diameter (50 mm diameter) were calculated. Scenarios two through four represented three saw logs 5 m in length, with log 1 being from 0.15 m to 5.15 m, log 2 from 5.15 m to 10.15 m, and log 3 from 10.15 m to 15.15 m. The fifth scenario represented the top of the tree, i.e. material above 15.15 m and below the 50 mm diameter top. To calculate these scenarios, we used the mean total height and DBH for the sampled trees for each region as the representative tree. Each tree was constructed with RH varying from 0 to 1 in 0.0005 increments. To predict the diameter inside bark and diameter outside bark for each tree, two GAMM taper models fit with 5 knots were constructed on the data using the methods described above for bark properties (Robinson et al. 2011). These models were then used to predict the outside and inside bark diameters as a function of relative height and region. For outside bark diameter the RMSE was 38 mm and the coefficient of determination was 0.70; for inside bark diameter the RMSE was 37 mm and the coefficient of determination was 0.68.

Bark properties were then predicted using the constructed GAMM models for each relative height. Heights below 0.15 m (stump) and above a 50 mm top were removed from the scenario analysis. At each relative height, the predicted bark area was calculated from the diameter inside and outside bark:

$$\text{BarkArea}_{ij} = \pi \times \left(\left(\frac{\text{DOB}_{ij}}{2} \right)^2 - \left(\frac{\text{DIB}_{ij}}{2} \right)^2 \right) \quad (3)$$

where BarkArea_{ij} is the area of the bark in mm^2 for each relative height (i) and region (j), DOB_{ij} is the diameter outside bark, and DIB_{ij} is the diameter inside bark. Then for each scenario, the predicted weighted average bark properties were calculated:

$$W_j = \frac{\sum (\text{BarkArea}_{ij} \times X_{ij})}{\sum \text{BarkArea}_{ij}} \quad (4)$$

where W_j is the weighted bark property (SG, MC, green mass, or percent bark) for each region, and X_{ij} is the bark property (SG, MC, green mass, or percent bark).

Table 2 Summary statistics (standard deviation (SD), mean) for bark specific gravity (SG), bark moisture content (MC), bark green mass, and percent bark (dry bark weight versus dry wood and bark weight) by region collected from disks

	SG		MC		Green mass (kg m ⁻³)		Percent bark	
Region	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Lower Coastal Plain	0.327	0.048	120	58	707.0	161.1	9.8	3.1
Upper Coastal Plain	0.308	0.041	129	56	698.9	163.2	10.2	3.1
Piedmont	0.293	0.036	130	53	670.2	153.5	11.3	3.3
Gulf Coastal Plain	0.329	0.044	121	57	717.7	164.8	10.5	2.5
Hilly Coastal	0.308	0.044	129	56	693.0	144.8	10.8	3.1
Overall	0.313	0.046	125	56	696.2	157.1	10.5	3.1

Table 3 Generalized additive mixed model (GAMM) fit statistics for bark specific gravity, bark moisture content, bark green mass, and percent bark, each as a function of relative height, and relative height and region

Property	Relative height		Relative height and region	
	R ²	RMSE	R ²	RMSE
Specific gravity	0.09	0.043	0.18	0.041
Moisture content (%)	0.63	34.2%	0.64	33.8%
Green mass (kg m ⁻³)	0.65	93.3 kg m ⁻³	0.66	92.0 kg m ⁻³
Percent (Dry)	0.28	2.51%	0.31	2.44%

Results and Discussion

Bark Properties—Generalized Additive Models

Bark properties averaged across all stands are summarized in Table 2 and are comparable with those reported in earlier studies with loblolly pine (Phillips and Schroeder 1972; Gibson et al 1986; Antony et al. 2015; Eberhardt et al. 2017). For the GAMM models, the intercept variables and smoothed terms were significant (p -value < 0.001) for all models constructed (bark SG, bark MC, bark green mass, and percent bark). The GAMM fit statistics (R^2 and root mean square error) are presented in Table 3 with the R^2 for the fixed effects for the relative height models ranging from 0.09 (bark SG) to 0.65 (bark green mass), and relative height and region models ranging from 0.18 (bark SG) to 0.66 (bark green mass). The weaker R^2 for bark SG can be attributed to the relatively large variation in the minimum and maximum bark SG values, and because the maximum bark SG was found at different relative heights depending on specific stands and trees (Fig. 2); accordingly, this property was not as consistent as other bark properties. Region was a significant term for each model, with the bark SG model having the greatest improvement in R^2 (0.18 vs 0.09) relative to percent bark (3% improvement), and moisture content and green mass (1% improvement for both models).

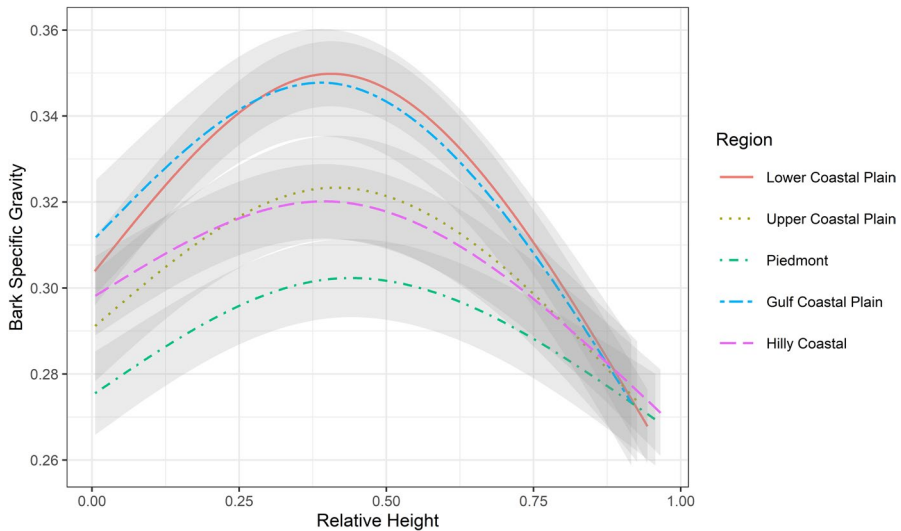


Fig. 2 Variation in loblolly pine bark specific gravity (SG) with relative height for each physiographic region. The 95% confidence intervals for the predictions are shown by the grey bands surrounding each line

Bark Specific Gravity

For all physiographic regions, bark SG increased initially and reached maximum values at relative heights ranging from 0.35–0.45 before decreasing to a minimum (similar across all regions) near the top of trees. The maximum bark SG values occur at much lower relative height values versus the height to live crown (median=0.64, mean=0.63). For the median tree, the bark SG maximum is 3.6 to 5.6 m below the live crown. This pattern of bark SG having a maximum within these relative heights has been demonstrated before in two prior studies comparing loblolly and slash pines (Phillips and Schroeder 1972; Eberhardt et al. 2017); note that unlike loblolly pine, slash pine does not show a definite maximum in bark SG plotted against relative height. Lower Coastal and Gulf Coastal Plain trees had the highest maximum bark SG values (0.35), observed at a relative height of approximately 0.4. Curve shapes were also very similar and comparison of 95% confidence intervals (Table 4) for bark SG models for each region showed no difference in bark SG variation with relative height for Lower Coastal and Gulf Coastal Plain trees, i.e. there was 100% overlap in confidence intervals at all heights. Hilly Coastal and Upper Coastal Plain trees also had similar maximum bark SG values (0.32). Confidence intervals for these regions also largely overlapped (82% of relative heights) but differed from Lower Coastal and Gulf Coastal Plain trees at greater than 50% of heights. In contrast, Piedmont trees had the lowest bark SG for most heights and had a maximum value that was lower (0.30, relative height=0.45) than those for the other regions. This result was consistent with Phillips and Schroeder (1972) whereby the maximum they observed for Piedmont loblolly pine trees (South Carolina) was

Table 4 Bark property (specific gravity (SG), moisture content (MC), green mass, percent bark (dry bark weight versus dry wood and bark weight)) confidence interval similarities by relative height. A value of 100 means complete overlap (i.e. 100%) of the modeled predictions across all relative heights, whereas a value of 0 means no overlap (i.e. 0%) of the modeled predictions across any relative height

Region	Compared region	SG	MC	Green mass (kg m ⁻³)	Percent bark
Lower Coastal Plain	Upper Coastal Plain	42	67	100	100
Lower Coastal Plain	Piedmont	12	43	26	0
Lower Coastal Plain	Gulf Coastal Plain	100	100	100	70
Lower Coastal Plain	Hilly Coastal	31	59	100	18
Upper Coastal Plain	Piedmont	82	82	100	61
Upper Coastal Plain	Gulf Coastal Plain	80	100	100	100
Upper Coastal Plain	Hilly Coastal	22	57	85	79
Piedmont	Gulf Coastal Plain	14	100	18	80
Piedmont	Hilly Coastal	62	97	100	85
Gulf Coastal Plain	Hilly Coastal	38	71	90	63

lower than those from the Coastal Plain (“south Georgia”). There was little overlap of confidence intervals between Piedmont trees and those from the Lower Coastal and Gulf Coastal Plains (Table 4).

Antony et al. (2015) reported average bark SG values for these trees and observed significant differences (at 5% level) between some regions, with regions already noted above as being the most different. Average whole-tree values obtained by Antony et al. (2015), in order of decreasing bark SG (values with different letters are significantly different), were Gulf Coastal Plain (0.321c), Lower Coastal Plain (0.316ac), Upper Coastal Plain (0.300ad), Hilly Coastal Plain (0.295d) and Piedmont (0.275b).

Bark Moisture Content

Variation in bark moisture content with relative height for each physiographic region is shown in Fig. 3. Bark MC increased with relative height for all regions with values ranging from 55–65% initially to maximums approaching 225% at the highest sampling level. Eberhardt et al. (2017) also reported that bark MC for loblolly pine (and slash pine) increased with increasing relative height.

Differences in bark MC at a given relative height amongst the physiographic regions was apparent, but as noted with bark SG, there were also very strong similarities between some regions. For example, at a relative height of 0.50, Gulf Coastal and Lower Coastal Plain trees both had moisture contents of approximately 125%; there was complete (100%) overlap of the confidence intervals for the fitted curves. In comparison, higher bark MC values were observed for Hilly Coastal and Upper Coastal Plain trees up to a relative height of 0.7, and at most heights (82%), the confidence intervals overlapped for these regions. At lower relative heights, Piedmont

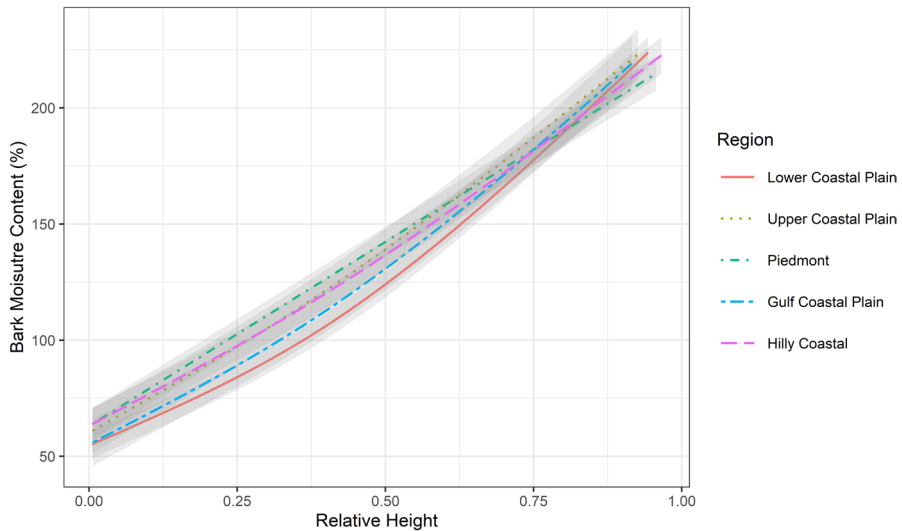


Fig. 3 Variation in loblolly pine bark moisture content (MC) with relative height for each physiographic region. The 95% confidence intervals for the predictions are shown by the grey bands surrounding each line

trees had the highest MC of any region. Regional differences were not as great as with bark SG as shown by a greater overlap of the confidence intervals (Table 4).

As with bark SG, Antony et al. (2015) observed significant differences amongst regions for average bark moisture content, in order of increasing bark MC, were Lower Coastal Plain (96.2%a), Gulf Coastal Plain (102.1%ac), Upper Coastal Plain (103.2%ac), Hilly Coastal Plain (114.4%bc) and Piedmont (118.8%b).

Regions that had the highest average bark SG (Gulf Coastal Plain, Lower Coastal Plain) were amongst the regions having the lowest average bark MC (Table 2). Similarly, Piedmont and Hilly Coastal trees (lowest average bark SG's) had the highest average bark MC's. For the Upper Coastal Plain, average bark MCs were very similar to those of the Gulf Coastal Plain (100% overlap of confidence intervals), even though the bark SG of Gulf Coastal Plain trees was considerably higher (0.329 vs. 0.308). There is a negative relationship between bark SG and MC, although the prediction fit statistics were poor ($R^2=0.14$, 52% RMSE).

Bark Green Mass

Because of the inverse relationship between bark SG and bark MC, bark green mass values were calculated and compared between the regions. Bark green mass increased from approximately 450–500 kg/m³ at the base of the tree (relative height of 0.0) to values that ranged from 860–900 kg/m³ at the top of the tree (relative height of 0.9) (Fig. 4). The Gulf Coastal Plain consistently had the highest values at all relative heights but 100% overlap in confidence intervals was observed with

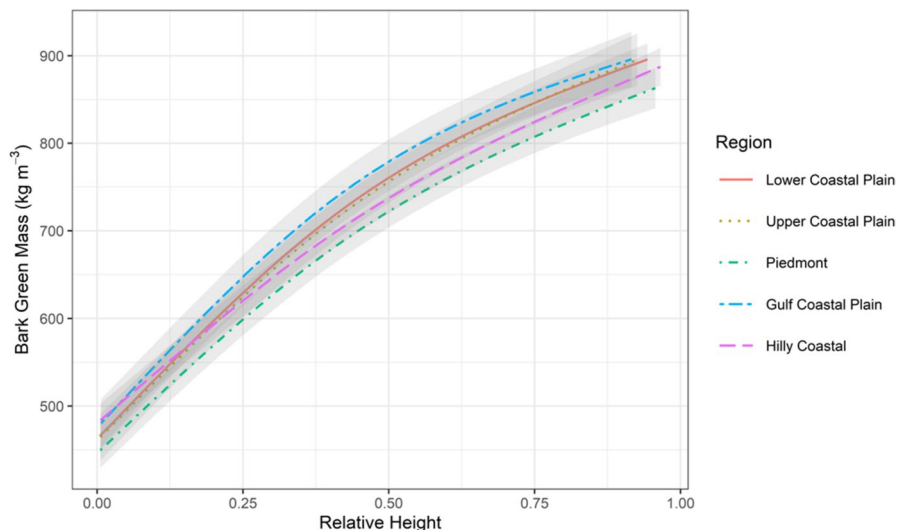


Fig. 4 Variation in loblolly pine bark green mass with relative height for each physiographic region. The 95% confidence intervals for the predictions are shown by the grey bands surrounding each line

the Lower and Upper Coastal Plains. Similarly, 100% overlap was also observed for the Lower Coastal Plain and the Hilly Coastal, and Upper Coastal Plain (Table 4). Piedmont trees consistently had the lowest bark green mass and there was little overlap between the Piedmont, Lower Coastal plain, and Gulf Coastal Plain confidence intervals (Table 4).

Percent Bark

Percent bark (Fig. 5) had initial values in the range of 12.5–14%, decreased to 8.5–9.3% at a relative height of 0.40 (approximately) before increasing to values that ranged from 13.4–17.5%. Trees from the Piedmont consistently had the highest percent bark values, whereas those from the Lower Coastal Plain consistently had the lowest; there was 24% overlap in confidence intervals for these two regions (Table 4). There was also some overlap (49%) between the Upper and Hilly Coastal Plain. In comparison, Lower and Upper Coastal Plain, Lower and Gulf Coastal Plain, Lower and Hilly Coastal Plain, and Upper and Gulf Coastal Plain regions had 100% overlap.

Few significant differences amongst regions were reported by Antony et al. (2015) for average percent bark determined on a whole-tree basis. Values they reported, in order of increasing percent bark, were Piedmont (10.4%b), Gulf Coastal Plain (10.7%ab), Lower Coastal Plain (10.7%ab), Hilly Coastal Plain (10.9%ab), and Upper Coastal Plain (11.1%a). Excluding the trees from the Lower Coastal Plain, the overlap in the confidence intervals for the trees from the remaining regions was high, ranging from 61 to 100% (Table 4), also showing limited between-region

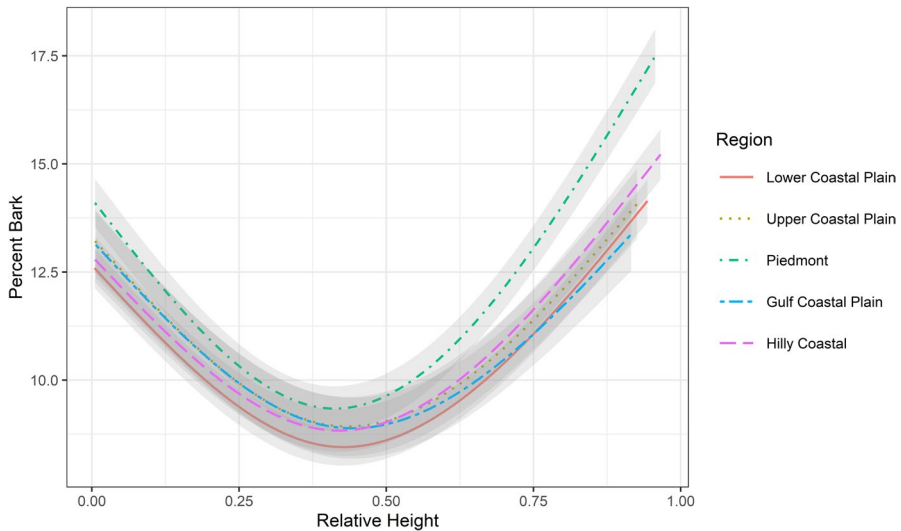


Fig. 5 Variation in loblolly pine percent bark with relative height for each physiographic region. The 95% confidence intervals for the predictions are shown by the grey bands surrounding each line

differences; however, while Antony et al. (2015) found a significant difference in whole-tree values between the Piedmont and Upper Coastal Plain, our observations revealed considerable overlap (61%) in the confidence intervals between these two regions, with this being at the lower relative heights (Fig. 5).

Patterns in Bark SG and Percent Bark

Patterns of a maximum (bark SG) and a minimum (percent bark) within intermediate relative heights (0.35–0.45), as shown in Figs. 2 and 5, were expected given results from prior studies comparing loblolly and slash pine (Phillips and Schroeder 1972; Eberhardt et al. 2017); slash pine, unlike loblolly pine, does not show a definite maximum in bark SG when plotted against relative height. Unlike the aforementioned studies that were restricted to a single physiographic region each, we see that the patterns for loblolly pine are consistent across regions throughout the southeastern United States. As for the regional differences, it is difficult to speculate specifically on what factors (e.g. climate, soils, etc.) are important. Water availability has been shown to affect bark thickness in Aleppo pine (*Pinus halepensis* Mill.) (Martín-Sanz et al. 2019) on contrasting sites and Nie et al. (2023) observed that precipitation in the wettest quarter of the year had a significant effect ($P < 0.05$) on phloem thickness across 23 *Picea* species. Nie et al. (2023) also observed that *Picea* phloem thickness was related ($P < 0.01$) to mean temperature over the driest three months.

Regarding southern bark structural features, we are aware of only isolated reports for longleaf pine. Measurements of inner bark and outer bark thicknesses decline to an asymptote with relative height, with the change in thickness for the inner bark

being small compared to that for the outer bark (Eberhardt 2013, 2015). As noted by Eberhardt et al. (2017) it is likely that the distribution of inner to outer bark is similar in loblolly pine and changes in the ratio of the two bark types with height likely influence when bark SG reaches its maximum. Interestingly, in longleaf pine there is a transition in bark roughness, assessed by maximum and minimum total bark thicknesses, that is constant to a relative height of 60%, steadily increasing further up. It remains to be determined if loblolly pine exhibits a similar feature for bark roughness and if so, whether this coincides with the maximum and minimum values for bark SG and percent bark, respectively.

Total Bark Weight of an Individual Tree

To predict the total weight of dry bark of an individual tree, Eq. 2 was fit using inputs of DBH, total height, with the parameters varying both with and without region. Including region significantly (p -value = 0.0297) improved the model results with the a_2 parameter varying by region, however the AIC values were very similar between the region (2169) and non-region model (2171) (Table 4). The models had the same R^2 (0.87) and essentially the same RMSE (region model = 3.2 kg vs non-region = 3.3 kg). Given the minor difference in the RMSE we conclude the model is statistically better but not practically better. The parameters for the final non-region model are $a_0 = 0.0000838$, $a_1 = 1.7501850$, $a_2 = 0.8939792$. The lack of differences found here for region might be attributed to the equation used.

Bark Scenarios

For the five simulated scenarios (Table 5), bark SG was greater in logs 2 and 3 than log 1 and the top of the tree, and the opposite pattern was true for percent bark whereby log 1 and the top of the tree had higher percent bark. Bark moisture content increased with height within tree, as did bark green mass. The Lower Coastal Plain (0.328) and Gulf Coastal Plain (0.330) had greater values for whole tree bark SG than the other regions.

The present study clearly augments prior investigations of the regional variation in various properties of the loblolly pine resource by providing the first comparison of bark properties relative to height along the tree bole for different physiographic regions. This study and future studies considering relative height has practical applications for managing, quantifying, and simulating the quantities and properties of bark in standing trees and when utilized by the forest products industry. Specifically, in tree harvesting operations whereby different logs (stem sections) from the same tree are routed to different facilities based on minimum end diameter requirements, factoring in relative height with bark measurements may allow a better understanding of the bark resource and its potential for utilization. The data we present can also be added to existing allometric models to improve regional estimates of carbon sequestered in loblolly pine bark.

Table 5 Bark scenarios across region for whole tree, logs 1, 2, and 3, and the top of trees for the modeled predictions of specific gravity (SG), moisture content (MC), green mass and percent bark (dry bark weight versus dry wood and bark weight)

Region	Log	SG	MC	Green mass (kg m ⁻³)	Percent bark
Lower Coastal Plain	Whole Tree	0.328	90	622	10.4
	1	0.320	66	532	11.2
	2	0.347	99	688	8.8
	3	0.337	142	793	9.3
	Top	0.303	186	856	11.6
Upper Coastal Plain	Whole Tree	0.308	99	613	10.9
	1	0.303	77	537	11.7
	2	0.322	120	703	9.2
	3	0.310	167	811	10.2
	Top	0.288	203	869	12.5
Piedmont	Whole Tree	0.290	103	589	11.6
	1	0.285	81	517	12.3
	2	0.301	126	674	9.6
	3	0.295	166	776	11.5
	Top	0.281	196	832	14.9
Gulf Coastal Plain	Whole Tree	0.330	94	638	10.8
	1	0.326	70	553	11.7
	2	0.346	113	729	9.1
	3	0.324	161	831	10.1
	Top	0.291	200	878	12.2
Hilly Coastal	Whole Tree	0.310	103	621	10.6
	1	0.307	78	544	11.4
	2	0.319	117	684	9
	3	0.309	159	783	10.1
	Top	0.289	196	847	12.8

Conclusions

Detailed information on the variation of loblolly pine bark percent, SG, MC, and green mass with relative tree height is reported herein and modeled for the first time for different physiographic regions, thereby allowing a comparison of trends throughout the southeastern United States. Unlike bark MC and green mass, which both increased with relative height, bark SG increased to a maximum at approximately 40% relative height before decreasing; the trend for percent bark was the opposite of SG. It has now been confirmed that bark SG can vary substantially with relative height and that this variability is not limited to species differences alone. Since current allometric models often ignore the difference between bark SG and wood SG, as well as the variability of bark SG with tree height, there is the opportunity to greatly improve estimates of bark yields during wood harvesting and assess

bark quality parameters for specific applications; the whole tree and log-specific results presented herein validate this need. In terms of carbon sequestration in standing timber, our results reinforce the need to collect data for other southern pine species to establish estimates tailored to both the species and differences between regions for a given species.

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Data Availability The data underlying this article will be shared on reasonable request to the corresponding author if given permission by the members of the Wood Quality Consortium.

Declarations

Competing interests The authors declare no conflict of interest.

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