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ARTICLE

Species comparison of the physical properties of loblolly and slash pine wood and bark

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Abstract: Composition of the southern pine forest is now predominated by two species, loblolly pine (*Pinus taeda* L.) and slash pine (*Pinus elliottii* Engelm.), owing to fire suppression activities, natural regeneration on abandoned agricultural lands, and extensive planting. Comparison of the wood and bark physical properties of these pines is of interest in terms of the yields of usable biomass and, for the bark, its ecological functionality on a living tree. Trees from a species comparison study were used to generate wood and bark property data, on a whole-tree basis, and for stem disks collected at breast height. Models were constructed to explain the effect of relative height on wood and bark properties. When comparing the whole-tree data, slash pine wood (0.523 versus 0.498) and bark (0.368 versus 0.311) specific gravity values were higher, both offset by lower moisture contents; slash pine also produced a higher percentage of bark on a dry-mass basis (17% versus 12.5%). Unlike wood properties, bark properties showed significant between-species differences when determined at breast height alone, the exception being moisture content. In terms of yield, harvests of a green tonne of loblolly pine and slash pine would give approximately the same dry mass of wood, but slash pine provides more bark.

Key words: bark thickness, moisture content, specific gravity, wood quality, yield.

Résumé : La composition de la forêt de pins du sud est maintenant dominée par deux espèces, le pin à encens (*Pinus taeda* L.) et le pin d'Elliott (*Pinus elliottii* Engelm.) à cause des activités de suppression des feux, de la régénération naturelle sur les terres agricoles abandonnées et de la plantation intensive. La comparaison des propriétés physiques du bois et de l'écorce de ces deux pins présente un intérêt en termes de rendement de la biomasse utile, et dans le cas de l'écorce, sa fonction écologique sur un arbre vivant. Les arbres faisant partie d'une étude comparative entre espèces ont été utilisés pour générer des données sur les propriétés de l'écorce et du bois sur une base d'arbre entier et pour des rondelles de tige prélevées à hauteur de poitrine. Des modèles ont été construits pour expliquer l'effet de la hauteur relative sur les propriétés du bois et de l'écorce. Lorsqu'on les compare sur une base d'arbre entier, les valeurs de densité du bois (0,523 versus 0,498) et de l'écorce (0,368 versus 0,311) du pin d'Elliott sont plus élevées, compensées dans les deux cas par une teneur en humidité plus faible; le pin d'Elliott produit également une plus forte proportion d'écorce (17% versus 12,5%) sur une base de masse anhydre. Contrairement aux propriétés du bois, les propriétés de l'écorce des deux espèces sont significativement différentes lorsqu'elles sont mesurées à hauteur de poitrine seulement, la teneur en humidité faisant exception. En termes de rendement, la récolte d'une tonne verte de pin à encens ou de pin d'Elliott donne approximativement la même masse anhydre de bois mais le pin d'Elliott produit plus d'écorce. [Traduit par la Rédaction]

Mots-clés : épaisseur de l'écorce, teneur en humidité, densité qualité du bois, rendement.

Introduction

The species composition of the pine forest of the southeastern United States has changed over the years, from the vast occurrence of longleaf pine (*Pinus palustris* Mill.) before colonial settlement to the current predominance of loblolly pine (*Pinus taeda* L.), favored by fire suppression activities and natural regeneration on abandoned agricultural lands (Stanturf et al. 2002; Fox et al. 2007). Loblolly pine was previously relegated to wet sites because of its susceptibility to fire when young and was only a minor species on upland sites dominated by longleaf pine and mixed hardwoods (Schultz 1999). Slash pine (*Pinus elliottii* Engelm.) accompanied longleaf pine along the lower coastal plain, but given its greater susceptibility to fire, this species was confined to wet sites too (Monk 1968).

Today, the ranges for both loblolly pine and slash pine have been expanded through extensive planting of seedlings from tree improvement programs (McKeand et al. 2003). In the southern region of the United States, loblolly and slash pines have been planted on more than 10 million and 4.2 million ha, respectively (Barnett and Sheffield 2004; Wear and Greis 2012; Huggett et al. 2013). Loblolly pine is generally favored because of its rapid growth, ability to grow well on a range of sites, and resistance to fusiform rust; thus, loblolly pine comprises more than one half of the total southern pine volume (Schultz 1999; Shiver et al. 2000).

Side-by-side studies conducted to compare loblolly and slash pines have led to the general conclusion that loblolly pine productivity is higher, the exception being on very poorly drained flatwood sites (Borders and Harrison 1989). For example, Shiver et al. (2000) found that loblolly pine had significantly greater total stand volume (130 versus 120 $m^3 \cdot ha^{-1}$) and total green mass per hectare (119 versus 105 tonnes (t)$\cdot ha^{-1}$) than slash pine when grown on the same site at age 14. Other comparisons of these two species

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have been extensive and include biomass allocation patterns (e.g., foliage, branch, and stem mass), physiological responses (e.g., stomatal conductance and photosynthesis), and productivity (e.g., aboveground biomass) determinations (Colbert et al. 1990; Dalla-Tea and Jokela 1991; Jokela and Martin 2000; Burkes et al. 2003; Chmura et al. 2007; Roth et al. 2007; Chmura and Tjoelker 2008; Vogel et al. 2011; Samuelson et al. 2012; Gonzalez-Benecke et al. 2014).

Wood properties for loblolly and slash pines, such as specific gravity (SG), are readily available in the literature and in some instances reflect mean values based on large pools of accumulated historical data (e.g., Forest Products Laboratory 2010); the caveat when making general comparisons of data from individual studies found in the literature is that geographic location has a significant influence on SG (Clark and Saucier 1991; Jordan et al. 2008). Therefore, when comparisons of wood properties for loblolly pine and slash pine are made, there is greater confidence in the significance of observed differences when trees from the same geographic region are used. Altogether, data in the literature show that the SG of slash pine is higher than that for loblolly pine (Cole et al. 1966; Phillips et al. 1976; Clark and Saucier 1991). Recent determinations of basic SG for these two southern pines by X-ray densitometry of wood cores showed the whole-core values for slash pine (0.65) to be higher than those for loblolly pine (0.61), with notable differences in the SG of juvenile wood (Eberhardt and Samuelson 2015). Since the trees used in this study were mature (50 years), the cores were solvent extracted to remove the contribution of heartwood extractives to the SG and scanned again; results showed the same trend in SG, save for slightly lower whole-core values (slash pine = 0.63, loblolly pine = 0.58). The difference in ring SG would appear to derive from the greater proportion of latewood in slash pine (68%) compared to loblolly pine (61%) given that the earlywood SGs of slash pine (0.36) and loblolly pine (0.35) are similar and the latewood SGs of slash pine (0.78) and loblolly pine (0.77) are also similar (Eberhardt and Samuelson 2015).

Lacking in the literature are comparisons of the bark from these two southern pine species that would be of interest in terms of both the ecological functionality on a living tree (e.g., resistance to fire) and yields of usable biomass. Indeed, for some southern pine species, characterizations of the bark are relatively uncommon with detailed measurements of longleaf pine bark (e.g., thicknesses of the inner bark (secondary phloem) and outer bark (rhytidome) layers (Eberhardt 2013), and values for bark roughness (Eberhardt 2015)) only recently being reported. Whole-bark thicknesses, which are often determined from wood disk diameter measurements outside the bark, subtracting those determined inside the bark, were used to estimate bark volumes of disks taken along the bole for loblolly pine (Antony et al. 2015). Alternatively, bark thickness gauges have seen use in field studies involving southern pines, such as species comparisons (Dipesh et al. 2015) and assessments of the functionality of bark against insects (Hanula et al. 2000) and fire (Wang and Wangen 2011); note that the quality of the data from bark gauges is highly dependent upon the skill level of the operator (Laasasenaho et al. 2005).

Given the development of wood-bioenergy markets, there is increasing interest in determining bark quantities as a subset of aboveground biomass determinations. The yield of bark (on a dry-mass basis) from southern pines collectively is a little more than 10% along the bole (Cole et al. 1966) with up to 60% for small longleaf pine branches (Phillips et al. 1976). Specific to slash pine and loblolly pine, a recent biofuels study showed that slash pine had a higher bark content (14.1%) than loblolly pine (10.5%), determined by hand-sorting the material obtained following whole-tree chipping (Baker et al. 2012); note that these values provide only a relative comparison because only larger particles of wood and bark were partitioned, and since the moisture content (MC) of the bark was not determined, it is not possible to estimate any differences on a dry-mass basis. Likewise, bark fuel value and SG data seem to suggest higher values for slash pine, but the source of the bark was not reported and there was no statistical assessment of species differences (Harder and Einspahr 1976). In a recent report by Antony et al. (2015), bark measures including its percentage of the tree stem, SG, and MC were determined for loblolly pine for different physiographic regions as part of an extensive sampling program orchestrated through the Wood Quality Consortium led by the University of Georgia. The objective of the current study was to compare wood and bark physical property data from stands of loblolly pine and slash pine, grown on the same site within the South Atlantic Coastal Plain; measurements along the bole provide the most comprehensive between-species comparison to date. Data presented here are relevant to the development of a better understanding of the ecological functionality of bark in a southern pine forest ecosystem and physical properties impacting the utilization of a southern forest biomass resource.

Materials and methods

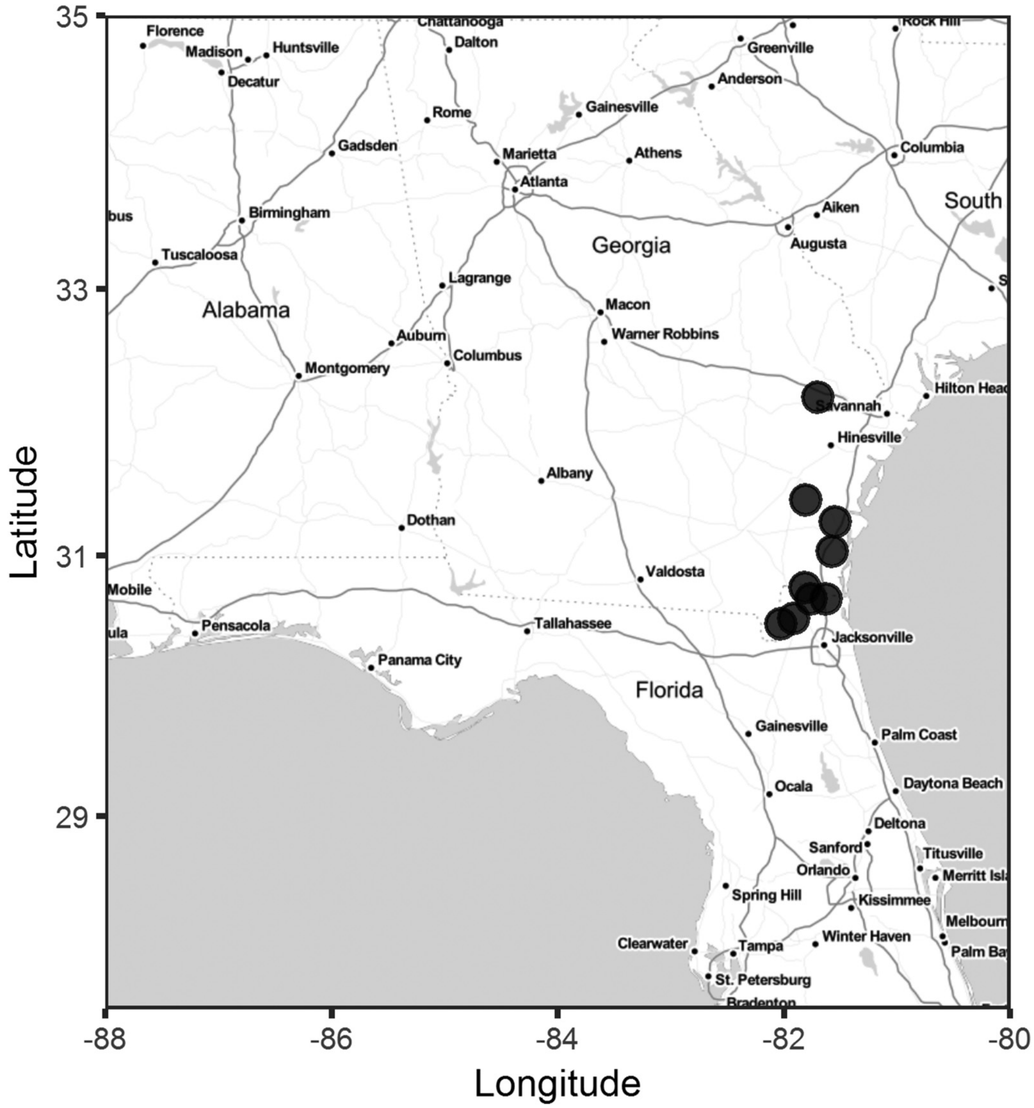
Trees used in the study

Ten plantations were sampled, ages 21–24 years, from a species comparison study established by the University of Georgia Pine Management Research Cooperative with the objective being to quantify growth differences between loblolly pine and slash pine when grown on the same site (Shiver et al. 2000). The 10 stands were located in the South Atlantic Coastal Plain (Georgia and Florida). The stand locations are shown in Fig. 1; note that stands 1 and 2 were located next to each other and share the same latitude and longitude (Table 1). The loblolly pine trees were included in the Wood Quality Consortium baseline study looking at regional differences in loblolly pine SG (Jordan et al. 2008). The plantations were conventionally managed with the exception of site preparation; the planting density was approximately 1779 trees·ha^{-1} and the trees were thinned following age 14. Table 1 shows the summary statistics for the stands with location, age, diameter at breast height, and height for the two pine species.

Tree sampling and bark measurements

Three trees from each species were felled from each of the 10 stands with one felled tree representing 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 immediately 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. Cross-sectional disks (3.8 cm thickness) were collected along the tree at 0.15 and 1.4 m (or 1.5 m) from the base and then at 1.5 m intervals up to an outside bark diameter of 5 cm. 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 masses were determined for the intact disks and the peeled wood disks, the latter prepared by carefully peeling the bark away with the aid of a chisel; the green mass of the bark was determined from the difference in green mass for the intact disk and the corresponding peeled wood disk. Basic SGs of bark and wood were based on the oven-dry masses and green volumes, the largest section of peeled bark used to determine the value for bark. Oven drying was carried out at 103 ± 2 °C until a constant mass was achieved (ASTM 2014). Green volumes were determined on the separated wood and bark components by water immersion after soaking in water to ensure full saturation. MCs were based on green and oven-dry masses of the wood and bark components and reported on a dry mass basis as done in Antony et al. (2015). The percentage of bark was calculated on the basis of the oven-dry masses of the bark and wood.

Fig. 1. Map of stand locations for the study.



Statistical analysis and tree reconstruction

The statistical analysis and associated graphics were done in R statistical software (R Core Team 2016) with RStudio interface (RStudio 2016) and the packages dplyr (Wickham and Francois 2016), ggmap (Kahle and Wickham 2013), and lmerTest (Kuznetsova et al. 2016). The disk measurements were used to reconstruct an estimate of the whole-tree bark properties using the dplyr package (Wickham and Francois 2016) within R (R Core Team 2016). For each tree, the areas of the wood and bark were calculated for each disk and the wood and bark properties then weighted on the basis of these individual disk areas, relative to the total area for all disks, to find the whole-tree properties. The proportions of bark were determined on both a mass basis and a green volume basis; note that the southern pines are typically bought and sold on a mass basis; thus, mass basis is more applicable to the forest industry sector.

The mean, standard deviation, and range of the values were calculated for each variable. For the wood, the SG, MC, and green mass were calculated. For the bark, the double bark thickness, SG, MC, green mass, percentage of dry mass, and percentage of green volume were calculated. For the wood and bark, the green mass of wood and bark to volume of wood and the green mass of wood and bark to volume of wood and bark were calculated. Analysis of variance was conducted using linear mixed-effects models to test the effect of species on the wood properties with stand and tree as random factors. A 0.05 significance level was used for all statistical tests. Models were developed by examining the plots and determining the general relationship between the dependent and independent variables; when nonlinear trends were found, the nonlinear model forms used were those discussed in Ratkowsky (1990). The regression models were evaluated by examining the plots and determining if the parametrized model fit to the general trend of the data. The coefficient of determination (R^2), based on the relationship between the actual variable and the predicted variable, was calculated, as was the root mean square error (RMSE). Linear models were constructed to explain the relationship between wood MC and wood SG:

$$\text{MC} = b_0 + b_1\text{SG} \quad (1)$$

where b_0 and b_1 are the regression model parameters. Quadratic and nonlinear models were constructed to explain the effect of wood properties by relative height. A quadratic model was used to explain the relationship between bark SG, or bark percentage, with relative height:

Table 1. Stand locations and characteristics for loblolly pine (*Pinus taeda*) and slash pine (*Pinus elliottii*).

					Diameter at breast height (cm)		Height (m)	
Stand	Latitude	Longitude	Age (years)	Species	Mean	SD	Mean	SD
1	31.4232	–81.8125	21	Loblolly	23.3	2.9	21.2	2.2
				Slash	21.5	0.5	20.9	0.2
2	31.4232	–81.8125	21	Loblolly	18.9	4.1	19.5	0.2
				Slash	15.9	4.8	16.2	4.7
3	30.6689	–81.6289	21	Loblolly	20.3	0.7	17.2	0.4
				Slash	23.1	3.9	19.7	0.3
4	30.5236	–81.9198	21	Loblolly	20.0	0.7	17.4	1.6
				Slash	22.1	2.0	18.9	0.4
5	30.6725	–81.7643	21	Loblolly	23.9	5.8	20.5	1.0
				Slash	20.5	1.7	21.5	0.8
6	30.7545	–81.8156	22	Loblolly	22.4	2.2	18.2	0.8
				Slash	25.5	3.2	21.1	1.5
7	32.19529	–81.7040	22	Loblolly	17.4	2.0	15.8	1.2
				Slash	17.6	2.7	16.0	0.8
8	30.48235	–82.02715	24	Loblolly	24.8	4.8	20.6	1.8
				Slash	16.4	1.3	17.2	1.6
9	31.2576	–81.5479	22	Loblolly	19.3	1.3	19.0	1.0
				Slash	20.0	1.6	20.1	0.3
10	31.02976	–81.57391	23	Loblolly	19.9	2.3	18.4	0.4
				Slash	19.1	1.7	20.4	0.2

$$y = b_0 + b_1\mathrm{rh} + b_2\mathrm{rh}^2 \quad (2)$$

where y is bark SG or bark percentage, rh is relative height, and b_0, b_1, and b_2 are the regression parameters. For the wood SG models, a nonlinear model was used:

$$y = b_0 + b_1 \times \log(\mathrm{rh}^{-b_2} - 1) \quad (3)$$

where y is wood SG, rh is relative height, and b_0, b_1, and b_2 are the regression parameters. For wood MC models, a nonlinear model was used:

$$y = \frac{b_0}{1 + \mathrm{e}^{((b_1 - \mathrm{rh})/b_2)}} \quad (4)$$

where y is wood MC, rh is relative height, and b_0, b_1, and b_2 are the regression parameters. For the bark MC models, a nonlinear model was used:

$$y = \mathrm{e}^{b_0 + b_1\mathrm{rh} + b_2\mathrm{rh}^2} \quad (5)$$

where y is bark MC, rh is relative height, and b_0, b_1, and b_2 are the regression parameters.

Results

Wood properties

Wood SG

The whole-tree values determined for wood SG (Table 2) showed a significant difference (P = 0.0001) between loblolly and slash pines, with the value for slash pine (0.523) being higher than that for loblolly pine (0.498). Stand-level data were also generated (Table 3) and showed higher values for wood SG in slash pine compared to loblolly pine for all but one stand. Since many studies rely on the sampling of tree cores collected at breast height alone, the data were processed accordingly for comparative purposes. In contrast with the whole-tree values discussed above, no significant difference (P = 0.1151) was observed between loblolly and slash pines for the breast height alone values (Table 4); no trends were observed in the corresponding stand-level data (Table 5). We attribute the higher wood SG values at breast height (loblolly pine = 0.557, slash pine = 0.570), relative to the whole-tree values, to the presence of mature wood that decreases in its contribution to total stem wood (juvenile and mature wood) with increasing tree height. Plotting wood SG for all disks against relative height shows wood SG to decrease for both species with relative height up the tree and wood SG data points for slash pine trending higher than those for loblolly pine (Fig. 2*a*).

Nonlinear models were constructed to explain wood SG based on relative height. The model for loblolly pine is

$$\text{Loblolly pine wood SG} = 0.472 + 0.036 \times \log(\mathrm{rh}^{-0.683} - 1) \quad (6)$$

where rh is the relative height. The R^2 was 0.77 for the model with a RMSE of 0.027. The model for slash pine is

$$\text{Slash pine wood SG} = 0.496 + 0.027 \times \log(\mathrm{rh}^{-0.788} - 1) \quad (7)$$

where rh is relative height. The R^2 was 0.60 for the model with a RMSE of 0.034. A comparison of the two models reveals that the inflection point for the slash pine model (0.496) is higher than for loblolly pine (0.472).

Wood MC

Wood MC determined on a whole-tree basis (Table 2) also showed a significant difference (P < 0.0001), with the value for loblolly pine (106%) being higher than for slash pine (96%). Stand-level data were also generated (Table 3) and show higher wood MC in loblolly pine compared to slash pine for all stands. The higher MC for wood with lower SG is consistent with the theoretical maximum MC (MC_{max}) calculation for wood:

$$\mathrm{MC}_{max} = \frac{1}{\mathrm{SG_g}} - \frac{1}{1.54} \quad (8)$$

where SG_g is the green SG and 1.54 is the SG of the cell wall (Forest Products Laboratory 2010). Thus, within a species, lower SG wood

Table 2. Comparison of overall wood and bark properties between loblolly pine (*Pinus taeda*) and slash pine (*Pinus elliottii*): whole-tree values based on disks taken along the entire tree bole.

		Loblolly				Slash				
Tissue	Property	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	*P* value
Wood	Specific gravity	0.498	0.022	0.447	0.548	0.523	0.029	0.475	0.572	0.0001
	Moisture content (%)	106	9	93	128	96	10	78	120	<0.0001
	Green mass (kg·m^{-3})	1026	25	974	1085	1023	32	922	1067	0.6425
Bark	Double bark thickness (cm)	0.88	0.18	0.67	1.45	0.90	0.20	0.57	1.35	0.7148
	Specific gravity	0.311	0.024	0.271	0.365	0.368	0.022	0.330	0.412	<0.0001
	Moisture content (%)	78	17	47	110	69	18	43	102	0.0007
	Green mass (kg·m^{-3})	553	66	432	685	619	59	499	766	<0.0001
	Dry mass (%)	12.5	2.7	8.9	19.1	17.0	3.2	12.3	23.7	<0.0001
	Green volume (%)	18.7	4.2	12.5	26.9	22.5	4.1	16.3	32.5	<0.0001
Wood and bark	Green mass of wood and bark to volume wood (kg·m^{-3})	1151	37	1072	1228	1202	53	1090	1304	<0.0001
	Green mass of wood and bark to volume wood and bark (kg·m^{-3})	935	36	856	990	930	36	864	1003	0.5041

Table 3. Comparison of stand-level values for wood and bark properties between loblolly pine (*Pinus taeda*) and slash pine (*Pinus elliottii*): whole-tree values based on disks taken along entire tree bole.

		Wood			Bark						Wood and bark	
Stand	Species	Specific gravity	Moisture content (%)	Green mass (kg·m^{-3})	Double bark thickness (cm)	Specific gravity	Moisture content (%)	Green mass (kg·m^{-3})	Dry mass (%)	Green volume (%)	Green mass of wood and bark to volume wood (kg·m^{-3})	Green mass of wood and bark to volume wood and bark (kg·m^{-3})
1	Loblolly	0.495	105	1014	0.91	0.284	88	535	11.3	18.2	1133	926
	Slash	0.487	98	963	0.81	0.341	89	642	14.7	19.8	1122	900
2	Loblolly	0.486	118	1060	0.79	0.322	87	600	12.8	18.1	1193	976
	Slash	0.530	95	1033	0.82	0.346	76	609	17.7	24.7	1234	928
3	Loblolly	0.513	103	1042	0.82	0.306	70	520	12.5	19.3	1166	940
	Slash	0.531	97	1042	0.99	0.386	62	625	17.1	22.1	1220	950
4	Loblolly	0.495	111	1043	1.18	0.289	61	466	15.7	24.0	1190	904
	Slash	0.518	95	1006	1.13	0.364	45	527	19.6	25.6	1188	882
5	Loblolly	0.506	106	1038	0.76	0.298	106	616	9.3	14.8	1145	975
	Slash	0.537	93	1037	0.71	0.367	85	682	13.2	18.3	1188	971
6	Loblolly	0.507	99	1009	0.85	0.322	81	584	11.9	17.5	1133	934
	Slash	0.534	90	1011	1.18	0.376	66	623	17.9	23.5	1203	920
7	Loblolly	0.507	102	1024	1.00	0.310	50	465	17.0	25.1	1179	884
	Slash	0.541	93	1042	0.96	0.380	45	549	21.2	27.8	1252	903
8	Loblolly	0.478	112	1010	0.76	0.336	83	616	10.6	14.5	1113	952
	Slash	0.514	101	1033	0.83	0.377	60	600	18.0	23.0	1214	933
9	Loblolly	0.497	106	1020	0.92	0.311	69	525	13.3	19.8	1150	921
	Slash	0.523	96	1027	0.86	0.371	78	659	16.4	21.7	1212	947
10	Loblolly	0.495	102	1000	0.79	0.331	84	607	11.0	15.7	1113	938
	Slash	0.518	100	1035	0.68	0.374	80	674	14.1	18.5	1188	968

tends to have a higher MC. The relationship between wood MC and wood SG was linear for both species. The model for loblolly pine is

$$\text{(9)} \qquad \text{Loblolly pine wood MC} = 326 - 440\text{SG}$$

where the R^2 was 0.90 for the model with a RMSE of 9%. The model for slash pine is

$$\text{(10)} \qquad \text{Slash pine wood MC} = 308 - 403\text{SG}$$

where the R^2 was 0.87 for the model with a RMSE of 8%.

In contrast with the whole-tree values for wood MC, no significant difference (P = 0.2576) was observed between loblolly and slash pines for the breast height values (Table 4), and no trends were observed in the corresponding stand-level data (Table 5). The lack of significant differences in MC mirrors the lack of differences in SG at breast height. We attribute the lower wood MC values at breast height (loblolly pine = 80%, slash pine = 77%), relative to the whole-tree values, to the presence of mature wood that decreases in its contribution to total stem wood (juvenile and mature wood) with increasing tree height.

Plotting wood MC for all disks against relative height shows wood MC for both species increases with relative height up the tree, with wood MC for slash pine being consistently lower than that for loblolly pine (Fig. 2*b*). Data points for loblolly pine were evenly distributed above those for slash pine, except for disks taken at 0.15 m. A nonlinear model was constructed for wood MC as a function of relative height. The model for loblolly pine is

$$\text{(11)} \qquad \text{Loblolly pine wood MC} = \frac{150}{1 + e^{((0.017 - \text{rh})/0.239)}}$$

where rh is relative height. The R^2 was 0.77 for the model with a RMSE of 13%. The model for slash pine is

Table 4. Comparison of wood and bark properties between loblolly pine (*Pinus taeda*) and slash pine (*Pinus elliottii*): whole-disk values based on disks taken at breast height alone.

		Loblolly				Slash				
Tissue	Property	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	*P* value
Wood	Specific gravity	0.557	0.029	0.486	0.6	0.570	0.034	0.491	0.62	0.1151
	Moisture content (%)	80	11	66	112	77	10	57	107	0.2576
	Green mass (kg·m^{-3})	1000	39	928	1077	1007	44	908	1082	0.4960
Bark	Double bark thickness (cm)	1.08	0.25	0.70	1.80	1.01	0.34	0.10	1.90	0.1896
	Specific gravity	0.295	0.029	0.244	0.368	0.364	0.031	0.318	0.426	<0.0001
	Moisture content (%)	52	16	26	89	53	16	30	82	0.8245
	Green mass (kg·m^{-3})	448	62	348	561	554	56	426	650	<0.0001
	Dry mass (%)	14.8	4.1	9.4	26.8	16.5	5.1	2.5	27.8	0.0645
	Green volume (%)	24.6	5.7	15.6	39.1	23.6	7.0	3.1	41.2	0.4882
Wood and bark	Green mass of wood and bark to volume wood (kg·m^{-3})	1147	68	1043	1292	1181	81	1036	1352	0.0336
	Green mass of wood and bark to volume wood and bark (kg·m^{-3})	863	47	762	956	897	48	795	1004	0.0011

Table 5. Comparison of stand level values for wood and bark properties between loblolly pine (*Pinus taeda*) and slash pine (*Pinus elliottii*): whole-disk values based on disks taken at breast height alone.

		Wood			Bark						Wood and bark	
Stand	Species	Specific gravity	Moisture content (%)	Green mass (kg·m^{-3})	Double bark thickness (cm)	Specific gravity	Moisture content (%)	Green mass (kg·m^{-3})	Dry mass (%)	Green volume (%)	Green mass of wood and bark to volume wood (kg·m^{-3})	Green mass of wood and bark to volume wood and bark (kg·m^{-3})
1	Loblolly	0.556	76	979	1.20	0.268	56	417	13.5	24.5	1115	841
	Slash	0.526	77	931	0.97	0.328	75	574	15.4	22.6	1099	850
2	Loblolly	0.560	84	1029	0.97	0.322	55	494	15.1	23.8	1186	902
	Slash	0.568	77	1005	0.80	0.355	59	566	15.9	23.0	1179	905
3	Loblolly	0.554	87	1038	1.07	0.292	54	451	14.9	24.9	1186	891
	Slash	0.563	83	1026	1.13	0.388	46	564	17.6	23.7	1204	917
4	Loblolly	0.543	94	1049	1.40	0.275	42	393	19.6	32.1	1233	835
	Slash	0.568	75	995	1.27	0.356	36	486	18.7	26.9	1173	856
5	Loblolly	0.570	76	998	1.00	0.279	64	457	11.1	20.4	1115	888
	Slash	0.579	75	1013	0.73	0.362	65	596	11.5	17.2	1136	940
6	Loblolly	0.567	69	959	0.87	0.285	55	442	10.2	18.5	1060	864
	Slash	0.594	67	991	1.43	0.375	41	529	18.4	26.3	1181	869
7	Loblolly	0.563	78	1001	1.30	0.300	41	422	20.7	32.8	1211	812
	Slash	0.598	74	1040	1.33	0.369	33	490	24.9	35.1	1306	846
8	Loblolly	0.552	81	1000	0.93	0.311	51	470	11.7	19.3	1110	895
	Slash	0.555	89	1042	0.63	0.355	48	522	12.4	18.5	1169	940
9	Loblolly	0.536	81	964	1.10	0.294	44	427	16.7	26.7	1122	821
	Slash	0.577	75	1010	1.00	0.348	75	609	15.8	23.7	1201	914
10	Loblolly	0.571	72	984	0.97	0.319	61	513	14.0	22.6	1134	878
	Slash	0.573	77	1012	0.77	0.407	49	605	14.4	19.1	1157	935

$$\text{(12)}\qquad \text{Slash pine wood MC} = \frac{144}{1 + e^{((-0.00574 - \text{rh})/0.354)}}$$

where rh is relative height. The R^2 was 0.71 for the model with a RMSE of 12%. The asymptote parameter is slightly higher for loblolly pine (150%) than for slash pine (144%), indicating that at the tops of the trees, the MC will be higher for loblolly pine than for slash pine.

Bark properties

Bark SG

Data collected through the present study also provided the opportunity to directly compare bark properties for loblolly and slash pines on a whole-tree basis. Whole-tree bark SG for slash pine was significantly higher (0.368 versus 0.311, $P < 0.0001$) than for loblolly pine (Table 2). Stand-level data were also generated (Table 3), and for all stands, slash pine had higher bark SG than loblolly pine. Similar to the whole-tree values for bark SG, a significant difference ($P < 0.0001$) was observed between loblolly pine (0.295) and slash pine (0.364) for the samples collected at breast height (Table 4); the corresponding stand-level data showed consistently higher values for slash pine relative to loblolly pine (Table 5). Bark SG values for both species were only slightly lower at breast height relative to the whole-tree values.

Plotting bark SG against relative height shows that the data for slash pine trend higher than those for loblolly pine (Fig. 3*a*). Simple linear correlation coefficients were essentially zero (not shown). Quadratic models were constructed for bark SG. The loblolly pine model is

$$\text{(13)}\qquad \text{Loblolly pine bark SG} = 0.291 + 0.218\text{rh} - 0.256\text{rh}^2$$

where rh is relative height. The R^2 was 0.18 for the model with a RMSE of 0.034. The slash pine model is

$$\text{(14)}\qquad \text{Slash pine bark SG} = 0.366 + 0.026\text{rh} - 0.042\text{rh}^2$$

Fig. 2. Wood (*a*) specific gravity and (*b*) moisture content plotted against relative height along the tree bole.

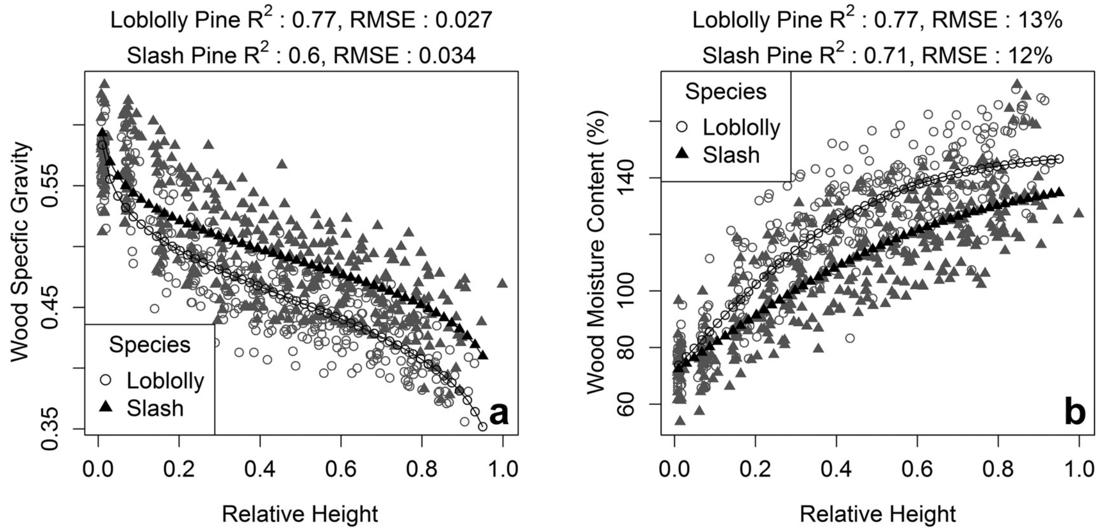
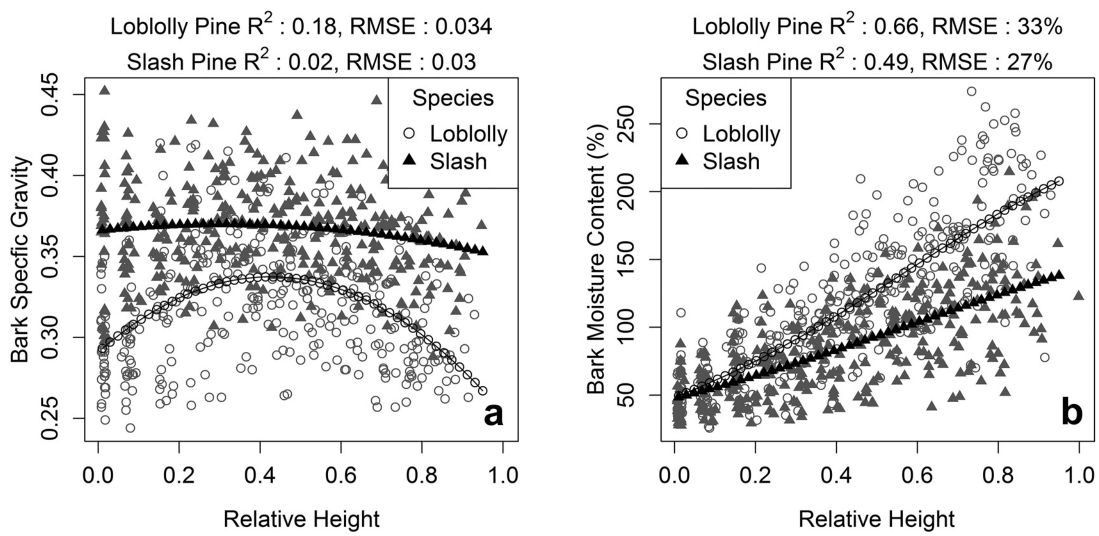


Fig. 3. Bark (*a*) specific gravity and (*b*) moisture content plotted against relative height along the tree bole.



where rh is relative height. The R^2 was 0.02 for the model with a RMSE of 0.03. The maximums were near midheight for both species; however, the trend by relative height for loblolly pine was much more pronounced than what was found for slash pine.

Bark MC

Bark MC determined on a whole-tree basis (Table 2) also showed a significant difference (P = 0.0007), with the value for loblolly pine (78%) being higher than that for slash pine (69%). While there were strong linear relationships between wood SG and MC, the bark relationships were apparent neither for loblolly pine (R^2 = 0.03) nor for slash pine (R^2 = 0.18). In contrast with the whole-tree values for bark MC, no significant difference (P = 0.8245) was observed between loblolly pine (52%) and slash pine (53%) for the breast height values (Table 4); likewise, while the stand-level data showed mostly higher values for loblolly pine relative to slash pine for the whole-tree data (Table 3), this was not apparent for the breast height alone data (Table 5). Plotting bark MC for all disks against relative height (Fig. 3*b*) clearly shows increases with relative height up the tree, similar to that for wood (Fig. 2*b*); however, the bark MC data diverge to a greater extent with height than observed for wood with the MC data. Plotting bark MC against wood MC showed weak linear correlations for both loblolly pine (R^2 = 0.51) and slash pine (R^2 = 0.44) (plots not shown).

Nonlinear models were constructed for bark MC. The loblolly pine model is

$$\text{(15)} \qquad \text{Loblolly pine bark MC} = e^{3.879+2.382\text{rh}-0.892\text{rh}^2}$$

where rh is relative height. The R^2 was 0.66 for the model with a RMSE of 33%. The slash pine model is

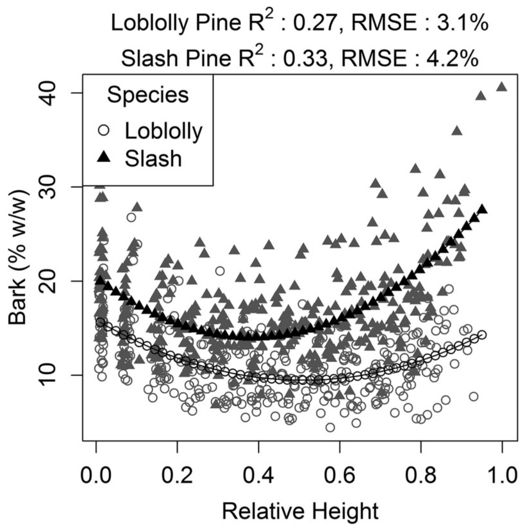
$$\text{(16)} \qquad \text{Slash pine bark MC} = e^{3.864+1.6\text{rh}-0.505\text{rh}^2}$$

where rh is relative height. The R^2 was 0.49 for the model with a RMSE of 27%. The model starting points are similar (3.879 versus 3.864) but the parameters allow separation as relative height increases.

Bark percentages and thickness

The whole-tree values determined for bark percentage on a dry-mass basis (Table 2) showed a significant difference (P < 0.0001)

Fig. 4. Percentage of bark plotted against relative height along the tree bole.



between loblolly and slash pines, with the value for slash pine (17.0%) being higher than that for loblolly pine (12.5%); results on a dry-mass basis are common to biomass allocation studies (e.g., Phillips et al. 1976). Parallel results were obtained on data based on green bark volumes. Plotting the bark percentage values (dry-mass basis) against relative height showed that for loblolly pine, the values at the base of the tree and at the top of the tree were above 10%, offset by some values at midheight being lower than 10% (Fig. 4); bark percentage values for slash pine trended in a similar manner except for being shifted roughly 5 percentage points higher.

Quadratic models were constructed for bark percentages (dry-mass basis). The loblolly pine model is

$$\text{(17)} \qquad \text{Loblolly pine bark \%} = 15.883 - 25.175\text{rh} + 24.735\text{rh}^2$$

where rh is relative height. The R^2 was 0.27 for the model with a RMSE of 3.1%. The slash pine model is

$$\text{(18)} \qquad \text{Slash pine bark \%} = 20.307 - 32.647\text{rh} + 42.392\text{rh}^2$$

where rh is relative height. The R^2 was 0.33 for the model with a RMSE of 4.2%.

In the current study, no difference in double bark thickness was observed for loblolly pine and slash pine on a whole-tree basis (P = 0.7148) or at breast height (P = 0.1896). However, given that bark thickness is influenced by tree diameter, a more appropriate comparison is the volume of bark of which slash pine had significantly higher green volume (P = < 0.0001, 22.5% versus 18.7%).

Green weights of wood and bark

The green mass of wood (kilograms per cubic metre) was determined on on a whole-tree basis (Table 2) and at breast height alone (Table 4). No significant differences (whole tree, P = 0.6425; breast height, P = 0.4960) were observed in either case for green mass of wood between the two species. The whole-tree green mass of bark was also determined (Table 2) and found to be higher (P < 0.0001) for slash pine (619 kg·m^{-3}) than for loblolly pine (553 kg·m^{-3}). Similar results were obtained with the breast height green mass values (Table 4) with the value for slash pine (554 kg·m^{-3}) being significantly higher (P < 0.0001) than that for loblolly pine (448 kg·m^{-3}).

Another related measure is the green mass of wood and bark to the volume of wood (Miles and Smith 2009), a measure most commonly used for scaling logs manually. Here we found significant differences (P < 0.0001) with slash pine (1202 kg·m^{-3}) having higher green mass than loblolly pine (1151 kg·m^{-3}). Alternatively, the green mass of wood and bark can be reported using the combined volume of wood and bark, which is likely more appropriate for the southern pines, which are sold on the basis of mass. We did not find significant differences when using the green volume of wood and bark (P = 0.5041). The whole-tree and breast height data are provided in Tables 2 and 4, respectively, given that they have a practical application for wood sales.

Discussion

Wood physical property differences

The higher whole-tree wood SG value for slash pine, compared to loblolly pine, is consistent with literature reports (Harder and Einspahr 1976; Clark and Saucier 1991; Forest Products Laboratory 2010). Unique to the current study is that we demonstrate a statistically significant difference for trees of similar age, diameter, and height, with all trees sampled being within the same physiographic region. In a prior study comparing only loblolly pine in six physiographic regions, significant differences in whole-tree wood SG were observed between some of the regions (Antony et al. 2015); likewise, significant differences between some of the physiographic regions were observed with whole-core wood SG values determined at breast height alone (Jordan et al. 2008). The consequences of including additional physiographic regions (and (or) age classes) in the current study are not known; the number of physiographic regions in any such assessment would be limited by the fact that the range for slash pine is not as widespread as it is for loblolly pine. Among the physiographic regions encompassed in the range of slash pine, results are conflicting with Antony et al. (2015) observing differences in loblolly pine whole-tree wood SG as opposed to Jordan et al. (2008) not observing differences using whole-disk data determined at breast height alone. Given the potential for the data variability to be impacted by sampling from different physiographic regions, it is plausible that the statistically significant between-species difference that we demonstrate here may not occur in other physiographic regions.

Wood MC determined on a whole-tree basis was higher for loblolly pine (106%) than for slash pine (96%), similar to the findings of Baker et al. (2012) who reported a significant difference for the MC of loblolly pine and slash pine chips (110 versus 103%, P = 0.004). Within a species, lower SG wood tends to have a higher MC. This trend was observed in a study examining the regional differences in wood properties of loblolly pine (Antony et al. 2015), where the inverse relationship between wood SG and MC is accentuated with lower values for wood SG (0.423–0.468) than those reported here, coinciding with higher values for wood MC on a dry-mass basis (109%–128%).

Bark physical property differences

Whole-tree bark SG for slash pine was higher (0.368 versus 0.311) than for loblolly pine, similar to values in the literature (0.373 versus 0.329), albeit these volume-weighted values were reported with no statistical comparison (Phillips et al. 1976). Higher bark SG was reported for slash pine (0.474) and loblolly pine (0.477) by Martin (1969), with those values being even higher than the maximums that we observed for slash pine (0.412) and loblolly pine (0.365). It should be noted that the values determined by Martin (1969) were based on an oven-dry basis (oven-dry mass and oven-dry volume) and not a green basis (oven-dry mass and green volume) as done in the present study. We can attribute these higher bark density values to a significantly lower volume for dry bark relative to green bark. Specifically, in a study on longleaf pine bark, it was found that radial shrinkage for the inner bark on the northern face of the tree was nearly 23% upon drying green bark under ambient conditions (Eberhardt 2013); the corresponding value for the outer bark was nearly 13%. With bark samples used by Martin (1969) being in an oven-dry state, significantly lower volumes would have resulted in significantly higher bark SG values. Similar to the whole-tree values for bark SG, a significant difference was observed between loblolly pine (0.295) and slash pine (0.364) for the samples collected at breast height. Bark SG values for both species were only slightly lower at breast height relative to the whole-tree values.

Consistent with the above results, plotting bark SG against relative height (Fig. 3) showed that the data for slash pine trend higher than those for loblolly pine, with maximums near midheight for both species. The exact reason for the bark SG values to show maximums as such may be the result of bark anatomy related to the proportions of living inner bark (functional phloem) and essentially dead outer bark (rhytidome) along the length of the tree bole; the inner bark transports the products of photosynthesis, while the outer bark seals in moisture and provides a protective barrier (Trockenbrodt 1990; Eberhardt 2013, 2015). In very simplified terms, the development of new periderms results in the oldest zones of inner bark being transformed into an ultimately dead layer in the outer bark. The layers in outer bark differ from xylem in that they are not specifically formed annual layers, nor do they all remain for the life of the tree, with the outermost layers of outer bark sloughed off with time (Eberhardt 2013). Moving up from the base of the tree, the proportion of outer bark decreases, as does the degree of weathering. It is plausible that the SG of the outer bark decreases upon weathering, thereby reversing the trend of increasing SG with increasing outer bark thickness. Further work is needed to determine the SG of the inner and outer bark components, and the impact of aging on bark SG, to validate this rationalization of the aforementioned midheight maximums in bark SG.

Bark MC determined on a whole-tree basis gave a higher value for loblolly pine (78%) compared to slash pine (69%). Slightly lower values were reported by Phillips et al. (1976) for loblolly pine (65%) and slash pine (52%). Following the same inverse relationship between wood MC and wood SG, a higher bark MC coincided with a lower bark SG. In general terms, this inverse relationship was reported for loblolly pine (Antony et al. 2015) when making side-by-side comparisons of bark MC and bark SG data for different physiographic regions. The data reported by Phillips et al. (1976) showed the inverse relationship to hold true when comparing the data for slash pine and loblolly pine, but not necessarily the other two southern pines (longleaf pine and shortleaf pine) included in that study.

As discussed above, bark is comprised of inner and outer bark components with differences in anatomy, percentage of living cells, and functionality. Specific to the MC of inner and outer bark components, Reifsnyder et al. (1967) determined average values for red pine (*Pinus resinosa* Aiton), on a dry-mass basis, to be 182% for the inner bark and 25% for the outer bark. This led to the conclusion that determinations of bark MC are "strongly influenced" by the inner and outer bark proportions. In longleaf pine, the thickness of the inner bark is relatively constant, while that for the outer bark declines from the base of the tree upwards (Eberhardt 2013, 2015). It is likely that the two southern pines in this study have similar distributions of inner to outer bark; thus, the increase in bark MC with relative height can be attributed to an increasing proportion of inner bark.

Bark percentages and yields

The whole-tree values determined for bark percentage on a dry-mass basis showed the value for slash pine (17.0%) being higher than that for loblolly pine (12.5%); Phillips et al. (1976) also observed the percentage of bark, determined on a dry-mass basis, to be higher in slash pine relative to loblolly pine. Specifically, the values were 1.4 percentage points higher for slash pine (12.7%) relative to loblolly pine (11.3%) in the stem and 11.3 percentage points higher in the branches (32.5% versus 21.2%). Baker et al. (2012) also compared loblolly and slash pines and found the percentage of bark, on a wet-mass basis, to be 3.6 percentage points higher for slash pine (14.1%) compared to loblolly pine (10.5%).

Plotting the bark percentage values against relative height (Fig. 4) showed that loblolly pine and slash pine trended in a similar manner except for the values for slash pine being shifted roughly 5 percentage points higher. In terms of utilization, slash pine would provide a higher amount of bark residue, irrespective of where the roundwood is taken (i.e., butt log and tree tops).

Fire ecology of thicker bark

No difference in double bark thickness was observed for loblolly pine and slash pine on a whole-tree basis or at breast height. In terms of its adaptation to the environment, it has been widely hypothesized that thicker bark is a response to more frequent fires (e.g., Pausas 2015). Of the southern pines, longleaf pine, which previously dominated forests in the southeastern United States, is considered a fire climax species and displays a number of adaptations (thick bark and grass stage) that allow it to tolerate frequent, low-intensity fires (Haywood 2000; Hardin et al. 2001; Wang and Wangen 2011). Slash pine and loblolly pine can tolerate fire to some degree but are not as resistant as longleaf pine (Hardin et al. 2001), while south Florida slash pine (*Pinus elliottii* var. *densa* Little & Dorman) displays adaptions similar to longleaf pine (Hardin et al. 2001; Menges and Deyrup 2001). The important role of thick bark in surviving fire was demonstrated by Hare (1965) who exposed the bark of standing loblolly and slash pine trees to a flame and reported significantly longer times for the cambium of slash pine trees to reach 140 °C than for loblolly pine (Hare 1965). Since the thermal conductivity of bark is a function of its density, MC, and temperature (Martin 1963; Bauer et al. 2010), it may not be appropriate to attribute fire resistance to any single attribute. Hare (1965) did not measure bark density or MC.

At this juncture, it should be mentioned that southern pine bark is not smooth and thus given that there are plates of bark with crevices between, a simple measurement of double bark thickness may not truly represent the amount of bark that would separate a fire from the cambium it is protecting. Determinations of bark "roughness" of longleaf pine wood disks were only recently conducted by measuring maximum and minimum bark thicknesses and showed bark roughness values to be constant to a relative height of 60%, decreasing up through the crown (Eberhardt 2015). It was beyond the scope of the current study to conduct such measurements; however, we can say that since bark structure (appearance) varies among the southern pines, and its roughness varies along the stem for a given species, fire resistance cannot be simply attributed to the thickness (or percent of dry mass or percent of green volume) of bark for any given species.

Green masses and roundwood processing

Roundwood is frequently sold on the basis of its "green mass," a value with units of mass, and volume, being pounds per cubic foot or kilograms per cubic metre (Miles and Smith 2009). Along with results for SG and MC, Antony et al. (2015) reported green masses for wood. Parallel to that study, the green mass of wood (kilograms per cubic metre) was determined both on a whole-tree basis and at breast height alone, with no significant between-species differences. These results can be rationalized by the higher wood SG for slash pine being offset by lower wood MC relative to the corresponding values for loblolly pine. Intuitively, with similar green masses, costs associated with the transportation of green wood should be the same for both species, especially after debarking, as done for pulp-grade chips produced during lumber manufacturing. The mill buying the chips would receive more wood with slash pine given the higher SG and lower MC; however, these values are taken for the whole tree and do not reflect the outer portion of the bole, which is where these chips are typically produced.

The whole-tree green mass of bark was determined to be higher for slash pine (619 kg·m^{-3}) than for loblolly pine (553 kg·m^{-3}); similar results were obtained with the breast height green mass values. Only very limited data are available that specify the MC of the inner and outer bark components. Reifsnyder et al. (1967) determined average values for red pine MC, on a dry-mass basis, to be 182% for the inner bark and 25% for the outer bark; similar results were reported by Martin (1969) for loblolly, longleaf, and slash pines. Accordingly, the MC of a whole-bark sample is a reflection of the proportions of inner bark and outer bark. We can attribute the higher whole-tree green mass of bark to the increasing proportion of higher MC inner bark with increasing relative height. Since prior work has shown that the proportions of inner and outer bark present in bark residues obtained during industrial processing are dependent upon the debarking method applied (Eberhardt 2012), transportation costs based on mass may be subtly impacted by pine species composition and compounded by how the roundwood was processed.

Using the values found here, a tonne (1000 kg) of green loblolly pine wood and bark would produce 494 kg of dry biomass of which 432 kg would be wood and 62 kg would be bark. A tonne of green slash pine wood and bark would produce 522 kg of dry biomass of which 433 kg would be wood and 89 kg would be bark. Thus, a tonne would yield essentially the same mass of wood but the slash pine tonne would result in more bark. It is important to note that these samples were collected in the summer months from May to August, and thus, variation is likely to be found if these same stands were to be sampled in different seasons. Doruska and Patterson (2006) found that loblolly pine significantly varied with the highest mass scaling factors found in the spring and fall months compared to the summer and winter months. It is also important to note that the wood/bark SG and MC of different age trees and different silvicultural treatments will yield different values.

Summary

The destructive sampling of trees from a species comparison study provided wood property data for loblolly pine and slash pine showing differences on a whole-tree basis but not for disks collected at breast height alone. Particularly unique to this study was the parallel collection of bark property data that are of interest in terms of both ecological functionality and biomass yields. Whole-tree bark SG was significantly higher for slash pine offset by the bark MC being significantly higher for loblolly pine; the percentage of bark for slash pine was significantly higher than that for loblolly pine. Unlike the wood properties, bark properties showed significant between-species differences when determined at breast height alone, the exception being MC. Altogether, results demonstrate that a harvest of loblolly pine and slash pine would yield the same masses of dry wood; however, slash pine would yield more bark, irrespective of harvesting location. Higher processing costs would be associated with drying the additional moisture in loblolly pine wood compared to that in slash pine wood. Also, facilities that utilize the bark for generating energy would also have greater energy yields from slash pine than from loblolly pine.

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