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Models to predict whole-disk specific gravity and moisture content in planted longleaf pine from cutover and old field sites

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Complete List of Authors:	Raut, Sameen; University of Georgia, Warnell School of Forestry and Natural Resources Dahlen, Joseph; University of Georgia, Warnell School of Forestry and Natural Resources Bullock, Bronson; University of Georgia, Warnell School of Forestry and Natural Resources Montes, Cristian; University of Georgia, Warnell School of Forestry and Natural Resources Dickens, David; University of Georgia, Warnell School of Forestry and Natural Resources
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Models to predict whole-disk specific gravity and moisture content in planted longleaf pine
from cutover and old field sites

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Sameen Raut¹
Joseph Dahlen¹
Bronson Bullock¹
Cristian Montes¹
E. David Dickens¹

iii
¹Warnell School of Forestry and Natural Resources, University of Georgia, 180 E Green St,
Athens, Georgia, 30602, USA

iv
Sameen Raut
Warnell School of Forestry and Natural Resources, University of Georgia, 180 E Green St,
Athens, Georgia, 30602, USA
sameen.raut@uga.edu

ABSTRACT

Efforts to restore longleaf pine across the southeast United States have occurred on two distinct site types, cutover forests and old agricultural fields. We measured wood and bark physical properties of unthinned planted longleaf pine from sixteen stands across Georgia, ages 12 to 25, with eight stands sampled from each site type. Three-hundred and twenty trees were felled and 3,572 disks collected from within the trees. Wood and bark specific gravity (SG), moisture content (MC), and proportion of bark were measured. Non-linear mixed effects models were developed to predict the variation in wood and bark SG with respect to relative height, age, and site type. Cutover sites had higher whole-tree wood SG (0.504 vs 0.455) and bark SG (0.374 vs 0.347) than old agricultural fields. The models explained 50% and 37% of the variability in wood and bark SG, respectively. Moisture content models were fitted as a function of SG for wood ($R^2 = 0.87$) and bark ($R^2 = 0.71$). Bark thickness, dry mass, and green volume were higher for cutover forest sites. Trees sampled included both non-defect and defect-containing trees, however, no significant differences in the wood physical properties were found. These results provide important information for the utilization of plantation longleaf pine.

Keywords

longleaf pine plantation, *Pinus palustris*, southern pine, wood and fiber quality, wood density.

INTRODUCTION

In the United States and worldwide, southern pine is one of the most commercially important species groups and it consists of longleaf pine (*Pinus palustris* Mill.), loblolly pine (*Pinus taeda* L.), slash pine (*Pinus elliottii* Engelm.), and shortleaf pine (*Pinus echinata* Mill.) (Wear and Greis 2012). In the 19th and early 20th century, forests across the South were lost due to urbanization or converted to agriculture lands (VanLear et al. 2005). Before that, longleaf pine was the dominant tree species in the southeastern U.S. where it occupied 30 million hectares in pure stands and 7 million hectares in mixed stands (Frost 1993; Landers et al. 1995), and loblolly pine was only confined to wet sites due to its poor tolerance to fire (Schultz 1999). Today, loblolly pine is the most important southern pine since it has been extensively planted because of its fast growth (Schultz 1999; McKeand et al. 2003), and the longleaf pine area has been reduced to a total of approximately 2 million hectares (Oswalt et al. 2012; McIntyre et al. 2018).

A major reason why longleaf pine was not replanted and instead replaced with loblolly pine or slash pine is because longleaf pine has a grass stage in which the plant allocates biomass growth to its roots rather than on above ground stem growth (Brockway et al. 2005). The grass stage lasts between 2 to 20 years depending upon factors including genetics, site quality, and forest management practices (Brockway et al. 2005; Dickens and Moorhead 2018), a much longer period when compared to other southern pine species. As a result, early growth in longleaf pine is slower than the other southern pines (Cram et al. 2010; Haywood et al. 2015; Dickens and Moorhead 2018). On sandy, excessively drained sites where the growing conditions are typically poor, longleaf pine can outcompete loblolly pine and slash pine which makes longleaf pine a suitable species for longer rotations (Outcalt 1993).

Longleaf pine forest ecosystems host a variety of unique species which include Bobwhite quail (*Colinus virginiana*), fox squirrels (*Sciurus niger*), deer (*Odocoileus virginiana*), wild turkeys (*Meleagris gallapavo*), gopher tortoises (*Gopherus polyphemus*), and scores of songbird species, wildflowers, and butterflies (Brockway and Lewis 1997; Johnson and Gjerstad 2006). Because of this, there has been a push to restore longleaf pine. Beginning in 1995 and continuing through today, numerous efforts have helped restore longleaf pine on private lands by providing technical assistance and financial incentives not available for other southern pines (Hains 2004). Collectively these efforts have led to the establishment of nearly 400,000 additional hectares of longleaf pine throughout the southeastern U.S. (Oswalt et al. 2012).

One of the touted advantages to growing longleaf pine is that it is typically considered to be a low risk species from pests and frequent forest fires, and it has high wood quality relative to the other southern pines (Landers et al. 1995; Dickens et al. 2018). Wood specific gravity (SG) (wood density divided by the density of water) is one of the most important indicators of wood quality for the southern pines, and is unitless (Megraw 1985; Larson et al. 2001). Wood SG increases radially as cambial age increases (Mora et al. 2007; Jordan et al. 2008; Dahlen et al. 2018; Schimleck et al. 2018) due to thickening of the cell walls (Larson et al. 2001). Wood SG is positively correlated with mechanical properties (Antony et al. 2010) and Kraft pulp yield (Koch 1972). The Wood Handbook (Forest Products Laboratory 2010; Kretschmann 2010) lists average wood SG values (basic SG) for longleaf pine that are equivalent to slash pine (0.54) and higher than loblolly pine or shortleaf pine (0.47). The Wood Handbook (Kretschmann 2010) does not provide origin information on the samples, however the samples were probably collected from naturally regenerated longleaf pine stands that were relatively old. Thus, these SG values do not necessarily reflect longleaf pine growing in plantations, because plantation trees reach merchantable size much sooner than

natural stands, and thus have a relatively high proportion of corewood (juvenile wood) which has low SG (Burdon et al. 2004; Mora et al. 2007; Moore and Cown 2017; Dahlen et al. 2018).

An additional factor that may influence the wood quality of planted longleaf pine is that the re-establishment has occurred on two primary land site types, on cutover forest sites where the prior rotation was trees (likely loblolly pine, slash pine, or natural longleaf pine), or on old agricultural fields where the prior crop was something other than a tree (Hains 2004; Johnson and Gjerstad 2006; Kush et al. 2006). Approximately 86% of the total longleaf pine plantations established through the Conservation Reserve Program (CRP) can be found on old agricultural fields (Paudel et al. 2021). Old agriculture fields have different soil characteristics, with significantly more available nutrients from the repeated fertilizer applications on the prior crops, and essentially no hardwood competition through the first thinning as compared to cutover forest sites (Clabo et al. 2020). Longleaf pine established on old agricultural fields has typically been planted at lower planting densities (e.g. less than 1235 trees ha⁻¹) compared to cutover forest sites (e.g. more than 1483 trees ha⁻¹) (South 2006; Dickens et al. 2018). Poor seedling survival averaging 51% in 21-year-old sites has been reported for planted longleaf pine stands established on old agricultural field sites (Hains 2004; Dickens et al. 2012; Dickens et al. 2018).

The abundant nutrients and lower planting densities result in a comparatively higher growth rates which could lower the SG compared to cutover forest sites (Clark et al. 2008). Generally, trees planted at lower planting densities show lower stem straightness, higher stem sinuosity, and more taper (Charlton et al. 2020). Generally, lowering planting densities results in reduced wood stiffness (Modulus of Elasticity) in *Pinus* species (Erasmus et al. 2018; Froneman and Wessels 2018; Erasmus and Wessels 2020). In loblolly pine, for a given cambial age, faster growth typically results in a subtle reduction in wood SG (Jordan et al.

2008; Dahlen et al. 2018). The lack of genetic improvement in longleaf pine combined with the rapid growth has also resulted in trees having a high amount of defects (Dickens et al. 2018). Dickens and Moorhead (2018) reported that some old field longleaf pine stands had over 50% stem defect rate with forking and ramicorn branches being the most common defects; other defects included significant sweep and fusiform rust. The high defect rate is likely to result in increased formation of low-quality compression wood, particularly for defects such as sweep (Zobel and van Bujitenen 1989). Compression wood is the reaction wood that is formed on the underside of leaning conifers; compression wood has higher wood SG, higher lignin content, high longitudinal shrinkage, higher microfibril angles, all of which greatly reduce the suitability of trees to produce high quality pulp or dimension lumber (Nicholls 1982; Timell 1986; Nyström and Kline 2000; Pont et al. 2007; Sharma et al. 2017).

The longleaf pine that was planted in the early 2000s as part of the restoration efforts are beginning to be harvested. Given the rapid growth rate and high defect rate, there are questions about the quality of planted longleaf pine and how it relates to current perceptions of longleaf pine, which are based on slow growing and naturally regenerated longleaf pine. A significant amount of information is available on the wood and fiber quality of planted loblolly pine (Mora et al. 2007; Jordan et al. 2008; Antony et al. 2015; Dahlen et al. 2018; Schimleck et al. 2018), and to a lesser extent slash pine (Eberhardt et al. 2017), however, there is little information available on the wood quality of planted longleaf pine. The wood quality information on planted longleaf pine that does exist (Baldwin and Saucier 1983; Gibson et al. 1986; Clark and Schmidting 1989) was measured prior to the recent restoration efforts and had much higher planting densities (2470 trees ha⁻¹ to 3700 trees ha⁻¹) (Baldwin and Saucier 1983; Gibson et al. 1986) compared to current practices for establishing planted longleaf pine (1235 trees ha⁻¹) (South 2006). Roundwood, consisting of both wood and bark, is sold or purchased on a green weight basis in the southern U.S., hence the moisture content

(MC) of the wood and bark is important (Eberhardt et al. 2017). Bark is typically burned for energy, however bark properties are also of interest with regards to other bioenergy applications and for bioproducts (Baker et al. 2012). Therefore, the objective of this study is to measure and model wood and bark SG and MC in planted longleaf pine trees grown in two specific site types (cutover forests and old agriculture fields) from samples collected from unthinned stands. This study will inform forest landowners and wood using industries on the wood and fiber quality of planted longleaf pine.

MATERIALS AND METHODS

Sample Locations

A total of 320 trees from 16 stands across south Georgia (Figure 1) were sampled in the summer of 2019. The ownership of the stands included private ($N = 9$), industrial ($N = 5$) and non-profit ($N = 2$) landowners. All the stands were planted and unthinned, between the ages of 12 to 25 years old (mean age 17.2 years, standard deviation (SD) 3.7 years), and growing on two site types: either a cutover forest site ($N = 8$) or a converted agricultural field in the prior crop (old field) ($N = 8$). For the cutover stands, 4 were prescribed burned once or multiple times, 3 were never burned, and 1 stand did not have prescribed burning information available. For the old field sites, 5 were burned, and the remaining 3 stands did not have burning information available. The overall average planting density was 1365 trees ha^{-1} (SD of 375 trees ha^{-1}) with the planting density ranging from 900 trees ha^{-1} to 2150 trees ha^{-1} . For cutover sites, the mean planting density was 1505 trees ha^{-1} (SD of 455 trees ha^{-1}) and for old field sites the mean planting density was 1220 trees ha^{-1} (SD of 225 trees ha^{-1}). The overall average stand density measured from the inventory plots was 775 trees ha^{-1} (SD of 225 trees ha^{-1}) which equates to an average survival rate of 57% compared to the reported planting density. The average stand density for cutover sites was 795 trees ha^{-1} (SD of 190 trees ha^{-1})

(mean survival rate of 53%) whereas for old field sites, average stand density was 755 trees ha^{-1} (SD of 265 trees ha^{-1}) (mean survival rate of 62%).

[Insert Figure 1 near here]

Figure 1. Map of the longleaf pine stand locations. Base map made with Natural Earth (free vector and raster map data @ [naturalearthdata.com](https://www.naturalearthdata.com)).

The diameter distribution of each stand was obtained from cruise data by establishing three 11.3 m fixed radius plots prior to destructive sampling. Twenty trees in each stand were selected and felled across the diameter distribution of the stands, the number of trees sampled from each diameter class was based on the proportion of trees present in that particular diameter class during the inventory. Trees sampled included trees from both within and

outside the three inventory plots, and consisted of trees from the extreme ends of the diameter distributions as well. Typically, wood and fiber quality studies focus on sampling only defect-free trees (Schimleck et al. 2019), however, due to the high proportion of longleaf pine with defects (Dickens and Moorhead 2018; Dickens et al. 2018), we also sampled trees with defects including forks, excessive sweep, ramicorn branches, and fusiform rust. From each stand, not more than 6 defect trees were sampled with the number determined based on the proportion of trees that had a visible stem defect during the inventory work. For the cutover sites, a total of 25 defect trees were sampled and for old field sites a total of 31 defect trees were sampled. Supplementary Table S1[†] shows the summary of the stands with location, age, site type, mean diameter at breast height (DBH), and mean total height from felled trees.

Tree Sampling and Disk Measurements

Trees were felled using a chainsaw and delimbed. The total height of the main stem was measured using a logger's tape. Cross-sectional disks of approximately 5 cm thickness were collected at 0.15 m (stump height), 0.6 m, 1.37 m (breast height), 2.44 m from the base, and then at every 1.22 m intervals up to an outside bark diameter of 7.6 cm. For the forked trees, cross-sectional disks were collected at the same heights from the base as the other trees up to the crotch base. One disk was taken at the crotch base, one from the base of each of the forks, and one at the 7.6 cm top from both the forks. When the fixed disk height overlapped branch whorls, the height was adjusted, and the exact height recorded. A total of 3,572 cross-sectional disks were sampled for this study, placed in individual plastic bags, and transported back to the Wood and Fiber Quality Laboratory at the University of Georgia in Athens, GA, USA and frozen until sample processing began.

Disks were thawed prior to measurements. Outside bark diameters of the disks were measured using a diameter tape. Green weight was measured using a digital scale. Bark was

[†] Supplementary data are available with the article at <https://>

peeled off the green disks and then the inside bark diameters were measured. Double bark thickness was calculated as the difference of outside and inside bark diameters. Green weight of the wood was measured after bark removal and the difference between green weight of the unpeeled and peeled disks gave the total green weight of bark. The largest piece of bark (having intact inner and outer bark) from each disk was weighed to determine the green weight. Green volume of the largest bark pieces and wood disks were measured using water displacement using ASTM D2395 (ASTM International 2017) after soaking the samples in water for at least 48 hours to ensure that the cell lumens were saturated with water; this reduces the possibility for water to be absorbed into the samples during the water displacement process. The bark pieces and the disks were then oven dried at $103 \pm 2^\circ\text{C}$ until the weight stabilized and then the oven dry weights were recorded using a digital scale. Wood and bark SG and MC were then calculated:

$$SG = \left(\frac{\text{Weight}_{\text{OD}}}{\text{Volume}} \right) \times \left(\frac{1}{K} \right) \#(1)$$

where, SG is the basic specific gravity of the material, $\text{Weight}_{\text{OD}}$ is the oven-dry weight (in grams) of that material, Volume is the green volume (in cm^3) of that material, and K is the density of water (1 g cm^{-3}). Moisture content was calculated as:

$$MC = \left(\frac{\text{Weight}_G - \text{Weight}_{\text{OD}}}{\text{Weight}_{\text{OD}}} \right) \times 100 \#(2)$$

where, MC is the moisture content of the material in percentage, Weight_G is the green weight (in grams), and $\text{Weight}_{\text{OD}}$ is the oven-dry weight (in grams).

Statistical Analysis and Model Fitting

Given the type of data, a mixed effects analysis was selected as the test for the hypothesis. Whole-tree wood and bark values were obtained by calculating the average of individual disks from a tree weighted by wood and bark surface area of those disks, relative to the total area for all the disks from a particular tree. Whole-tree SG, MC, and green mass

were calculated for the wood, and whole-tree SG, MC, green mass, dry mass, and double bark thickness were calculated for bark. For all the wood and bark variables, mean, standard deviation, minimum, and maximum values were calculated. Analysis of variance (ANOVA) using a linear mixed effects model with stands and trees sampled as random factors was done to test for differences in wood and bark SG and MC between cutover and old field sites, and between non-defect and defect-containing trees. Linear and nonlinear models were fitted to predict the trends in dependent variables with respect to the independent variables. Models were examined for their form using plots and compared based on their coefficient of determination (R^2) of the fixed and random (stand, tree) effects, Akaike Information Criterion (AIC) values, likelihood ratio tests, and root mean square error (RMSE). The parameter in the models that varied randomly was selected based on the best fit to the data. All statistical analyses and graphics were done in the R statistical software (R Core Team 2020) using the RStudio Interface (RStudio 2020). Packages used were ggspatial (Dunnington 2020), maps (Becker et al. 2018), needs (Katz 2016), nlme (Pinheiro et al. 2018), rgeos (Bivand and Rundel 2019), rnaturalearth (South 2017), rnaturalearthdata (South 2017), sf (Pebesma 2018), and tidyverse series of packages (Wickham 2019). The base map for Figure 1 was made with Natural Earth (free vector and raster map data @ naturalearthdata.com).

Wood Specific Gravity Model Development

A three parameter nonlinear model from Ratkowsky (1990) was chosen for predicting the trend in wood SG (SGWood) with respect to relative height. Here, the base wood SG model was:

$$\text{SGWood}_{ijk} = (\beta_0 + b_{0i} + b_{0ij}) - \beta_1 \times \ln(\text{RHeight}_{ijk} + \beta_2) + \varepsilon \quad \#(3)$$

where, SGWood_{ijk} and RHeight_{ijk} are the wood SG and relative height of the k th disk from the j th tree in the i th stand, respectively, $\ln$ is the natural logarithm, β_0 , β_1 , and β_2 are the fixed effects parameters, the nested random effects of the asymptote β_0 at the stand and tree levels

are represented by b_{0i} and b_{0ij} , respectively, and ε is the error term. Because SG increases with cambial age (Megraw 1985), the effect of age on wood SG was incorporated into the model as:

$$SGWood_{ijk} = (\beta_0 + b_{0i} + b_{0ij}) - \beta_1 \times \ln(RHeight_{ijk} + \beta_2) + \beta_3 \times AGE_i + \varepsilon \quad \#(4)$$

where, β_3 is the added fixed effect regression parameter which explains the effect of age on wood SG and AGE_i is the age of the i th stand. Wood SG appeared to increase linearly with age for these samples. The other terms are as previously defined.

One of the main objectives of this study was to determine the impact of site type on wood SG and therefore, this effect was incorporated into the model:

$$SGWood_{ijk} = (\beta_0 + b_{0i} + b_{0ij}) - \beta_1 \times \ln(RHeight_{ijk} + \beta_2) + \beta_3 \times AGE_i + \beta_4 \times SITETYPE_i + \varepsilon \quad \#(5)$$

where, β_4 is the added fixed effect regression parameter to explain the effect of the type of site where the trees are grown on wood SG, $SITETYPE_i$ specifies whether the i th stand is an old field site ($SITETYPE_i = 1$) or a cutover site ($SITETYPE_i = 0$). The other terms are as previously defined.

In defect trees, such as trees with heavy sweep, reaction wood forms on the underside of leaning trees in softwood species, the resulting compression wood has noticeably higher wood SG than normal or opposite wood (Timell 1986; Sharma et al. 2017). Therefore, the effect of the defects on wood SG was also incorporated into the model to give:

$$SGWood_{ijk} = (\beta_0 + b_{0i} + b_{0ij}) - \beta_1 \times \ln(RHeight_{ijk} + \beta_2) + \beta_3 \times AGE_i + \beta_4 \times SITETYPE_i + \beta_5 \times DEFECT_{ij} + \varepsilon \quad \#(6)$$

where, β_5 is the fixed effect regression parameter added to explain the effect of defects on wood SG. $DEFECT_{ij}$ defines whether the j th tree in the i th stand has a defect ($DEFECT = 1$) or not ($DEFECT = 0$). The other terms are as previously defined.

Wood Moisture Content Model Development

As wood SG increases, the amount of water within the cell decreases as does the maximum MC (Glass and Zelinka 2010). Within a species, higher SG wood tends to have lower green MC (Antony et al. 2015; Eberhardt et al. 2017; Dahlen et al. 2020b). Because of this, we fitted wood MC as a function of wood SG rather than fitting wood MC as a function of relative height. The model was adapted from Ratkowsky (1990), the model for wood MC was:

$$MCWood_{ijk} = (\beta_0 + b_{0i} + b_{0ij}) \times (1 + SGWood_{ijk})^{\beta_1} + \varepsilon \quad \#(7)$$

where, $MCWood_{ijk}$ and $SGWood_{ijk}$ are the wood MC and SG of the k th disk from the j th tree in the i th stand, respectively. β_0 and β_1 are the fixed effects parameters. The nested random effects of the parameter β_0 at the stand and tree levels are represented by b_{0i} and b_{0ij} , respectively, and ε is the error term. We observed non-constant variance (heteroscedasticity) in the data (perhaps due to the limited number of points at the extreme values) and thus we accounted for this in the model (Pinheiro and Bates 2000). To avoid error propagation when applying multiple models, we fit equation 7 two ways, the first using the measured wood SG data which would be used when wood SG data is measured, and the second using the predicted wood SG values from equation 5 which would be used when wood SG data is predicted.

Bark Specific Gravity Model Development

To predict the trend in the data for bark SG with respect to relative height, a three-parameter nonlinear model used by Eberhardt et al. (2017) and adapted from Ratkowsky (1990) was used. The base bark SG model was:

$$SGBark_{ijk} = (\beta_0 + b_{0i} + b_{0ij}) + \beta_1 \times \ln(RHeight_{ijk}^{-\beta_2} - 1) + \varepsilon \quad \#(8)$$

where, $SGBark_{ijk}$ and $RHeight_{ijk}$ are the bark SG and relative height of the k th disk from the j th tree in the i th stand, respectively, β_0 , β_1 , and β_2 are the fixed effects parameters. Nested

random effects of the asymptote β_0 at the stand and tree levels are represented by b_{0i} and b_{0ij} , respectively, and ε is the error term. Incorporating the effect of age on bark SG, the model was:

$$\text{SGBark}_{ijk} = (\beta_0 + b_{0i} + b_{0ij}) + \beta_1 \times \ln(\text{RHeight}_{ijk}^{-\beta_2} - 1) + \beta_3 \times \text{AGE}_i + \varepsilon \#(9)$$

where, β_3 is the added fixed effect parameter to explain the effects of age on bark SG and AGE_i is the given age of the i th stand, the other terms are as previously defined. To determine if the site type has any effect on longleaf pine bark SG, a site type term was incorporated into equation 9 to give the model:

$$\text{SGBark}_{ijk} = (\beta_0 + b_{0i} + b_{0ij}) + \beta_1 \times \ln(\text{RHeight}_{ijk}^{-\beta_2} - 1) + \beta_3 \times \text{AGE}_i + \beta_4 \times \text{SITETYPE}_i + \varepsilon \#(10)$$

where, β_4 is the added fixed effect regression parameter to explain the effects of the type of site where the trees are grown on bark SG, SITETYPE_i represents either an old field site ($\text{SITETYPE}_i = 1$) or a cutover site ($\text{SITETYPE}_i = 0$). The other terms are as previously defined. Trees affected by defects such as sweep show asymmetry in the cross sectional samples which can be explained by reaction wood development, however changes in bark are not noted in the literature (Scurfield 1973) and thus were not explored here.

Bark Moisture Content Model Development

A similar approach to modeling wood MC was done for modeling bark MC where bark MC was predicted as a function of bark SG. Using a model adapted from Ratkowsky (1990) and modified, the model for bark MC was:

$$\text{MCBark}_{ijk} = \frac{1}{\beta_0 + \beta_1 \times \text{SGBark}_{ijk}^2 + (\beta_2 + b_{2i} + b_{2ij}) \times \text{SGBark}_{ijk}^4} + \varepsilon \#(11)$$

where, MCBark_{ijk} and SGBark_{ijk} are the bark MC and SG of the k th disk from the j th tree in the i th stand, respectively. β_0 , β_1 , and β_2 are the fixed effects parameters. The nested random effects of the parameter β_2 at the stand and tree levels are represented by b_{2i} and b_{2ij} ,

respectively, and ϵ is the error term. The non-constant variance in the data was accounted for in the model (Pinheiro and Bates 2000). To avoid error propagation when applying multiple models, we fit equation 11 two ways, the first using the measured bark SG data, and the second using the predicted bark SG values from equation 10.

Diameter Ratio Model

We found that cutover sites and old field sites had slightly different bark diameter ratios, as such, a simple linear model with no intercept but having a slope term was used to fit diameter inside bark (DIB) with respect to diameter outside bark (DOB) separately for both cutover and old field sites. Hence, the diameter outside bark can be converted to diameter inside bark using:

$$DIB = \beta_1 \times DOB + \epsilon \quad \#(12)$$

where, DIB is the inside bark diameter at a height in the tree where the outside bark diameter is DOB, β_1 is the regression parameter, which was fit separately by site type, and ϵ is the error term.

RESULTS

Whole-Tree Wood Specific Gravity and Moisture Content

The overall average whole-tree wood SG for this study was 0.480 (Table 1). Trees grown on cutover sites had significantly higher wood SG (0.504) than trees grown on old field sites (0.455) (p-value = 0.0013). Both the minimum and maximum whole-tree wood SG values were higher for cutover sites than old field sites. Seven out of the eight cutover stands had higher average whole-tree wood SG values than any of the old field stands, irrespective of age (Supplementary Table S2[†]). For a given site type, generally as stand age increased, there was a gradual increase in wood SG.

The mean whole-tree wood MC for the study was 113% (Table 1) with the lowest whole-tree wood MC of 69% from one of the cutover sites, and the maximum value of 172% from an old field site. There was a significant difference in wood MC values among longleaf pine trees grown on cutover and old field sites (p -value = 0.0068). The mean whole-tree wood MC for cutover sites was 104% and 123% for old field sites.

[Insert Table 1 near here]

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Table 1. Whole-tree wood and bark properties for longleaf pine in cutover and old field sites. Significant differences due to site types are indicated by the p-values for each tissue.

Tissue	Property	Overall (N= 320)				Cutover (N=160)				Old Field (N=160)				p-value
		Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	
Wood	Specific gravity	0.480	0.046	0.376	0.620	0.504	0.041	0.424	0.620	0.455	0.035	0.376	0.533	0.0013
	Moisture content ¹	113	20	69	172	104	17	69	141	123	17	86	172	0.0068
	Green mass ²	1016	35	864	1088	1022	27	929	1081	1011	40	864	1088	0.3429
Bark	Specific gravity	0.360	0.035	0.254	0.519	0.374	0.026	0.306	0.460	0.347	0.037	0.254	0.519	0.0215
	Moisture content ¹	93	23	43	173	82	18	43	136	105	22	50	173	0.0034
	Green mass ²	691	57	501	841	677	59	501	797	704	53	553	841	0.0986
	Dry mass ¹	17.8	3.8	8.8	33.0	19.4	3.7	11.5	33.0	16.1	3.1	8.8	29.3	0.0127
	Green volume ¹	22.3	4.5	12.8	42.7	24.4	4.6	14.7	42.7	20.1	3.2	12.8	27.8	0.0061
	Double bark thickness ³	2.02	0.42	1.05	4.24	2.08	0.45	1.17	4.24	1.96	0.38	1.05	3.19	0.2094
Wood and Bark	Green mass of wood and bark to volume wood ²	1216	64	1011	1417	1242	62	1101	1417	1189	55	1011	1310	0.0274
	Green mass of wood and bark to volume wood and bark ²	942	37	783	1013	936	35	812	998	948	38	783	1013	0.3227

¹ %
²kg m⁻³
³cm

Whole-Tree Bark Specific Gravity and Moisture Content

The average whole-tree bark SG was 0.360 (Table 1). Trees on cutover sites had a significantly higher mean bark SG (0.374) compared to those in old field sites (0.347) (p-value = 0.0215). The average whole-tree bark MC was 93% with the lowest whole-tree bark MC value at 43% for a tree from one of the cutover sites and the maximum whole-tree bark MC value at 173% for a tree from one of the old field sites. There was a significant difference in bark MC values of trees from cutover sites (82%) and old field (105%) sites (p-value = 0.0034).

Whole-Tree Green Weights of Wood and Bark

For the wood and bark, whole-tree green mass, dry mass, green volume, double bark thickness, green mass of wood and bark to volume wood, and green mass of wood and bark to volume wood and bark were calculated (Tables 1 and S2[†]). Cutover sites had significantly higher amounts of dry bark yield than old field sites. The difference here being that old field sites had higher bark MC than cutover sites. Cutover sites also had significantly higher bark green volumes as compared to old field sites. For a given volume of wood, wood and bark from longleaf pine trees harvested from cutover sites yielded significantly more green mass on average than old field sites.

Comparison Between Straight Trees and Defect Trees

For the overall data, there was no significant difference in wood SG, wood MC and bark SG between trees with and without defects (Table 2). The only significant difference was for bark MC where defect trees had lower values than non-defect trees. There was a significant difference between defect and non-defect trees for bark SG in cutover sites where defect trees had higher values than non-defect trees. There was also a significant difference between defect and non-defect trees for bark MC in old field sites where defect trees had

lower values than non-defect trees. Generally, the p-values for cutover sites (except for bark MC) were lower than in old-field sites, even though the sample size was smaller for cutover sites (N = 25) than old field sites (N = 31).

[Insert Table 2 near here]

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386 **Table 2.** Whole-tree specific gravity (SG) and moisture content (MC) values for different longleaf pine tissues in defect and non-defect trees.
 387 Significant differences due to defects are indicated by the p-values for each tissue.

Site Type	Tissue	Property	Non-Defects (N=135)				Defects (N=25)				<i>p</i> -value
			Mean	SD	Min	Max	Mean	SD	Min	Max	
Cutover	Wood	SG	0.502	0.039	0.424	0.612	0.520	0.049	0.444	0.620	0.1577
		MC (%)	105	17	70	140	99	17	69	130	0.1121
	Bark	SG	0.371	0.025	0.305	0.460	0.387	0.028	0.334	0.435	0.0248
		MC (%)	84	17	43	136	71	16	49	114	0.1448
Old field	Wood	SG	Non-Defects (N=129)				Defects (N=31)				<i>p</i> -value
			Mean	SD	Min	Max	Mean	SD	Min	Max	
	Bark	SG	0.456	0.035	0.376	0.533	0.453	0.033	0.388	0.528	0.3088
		MC (%)	123	18	87	172	122	16	86	162	0.5092
		SG	0.346	0.036	0.254	0.412	0.350	0.043	0.262	0.519	0.7133
		MC (%)	106	21	67	160	99	24	50	173	0.0048
Overall	Wood	SG	Non-Defects (N=264)				Defects (N=56)				<i>p</i> -value
			Mean	SD	Min	Max	Mean	SD	Min	Max	
	Bark	SG	0.479	0.044	0.376	0.612	0.482	0.052	0.388	0.620	0.8425
		MC (%)	113	19	70	172	112	20	69	162	0.5580
	Bark	SG	0.359	0.033	0.254	0.460	0.366	0.041	0.262	0.519	0.2549
		MC (%)	95	22	43	160	86	25	49	173	0.0029

Modeling Wood Specific Gravity

The parameters for the wood SG models are shown in Table 3 and the fit indices and error statistics are given in Table 4. Within a tree, the disk from the stump height had the highest wood SG and it gradually decreased with increasing height (Figure 2). The rate of decrease in wood SG was slightly higher at relative heights from 0 to 0.10 and the rate of decrease slowed as relative height increased to the top of the tree bole. The base model for predicting wood SG as a function of relative height (equation 3) explained 23% of the variation (fixed effects only) with an RMSE of 0.045 (Table 4). Incorporating the effect of age in the model (equation 4) significantly improved the fit statistics over the base model (p-value = 0.0030) with the R^2 improving to 38% (RMSE = 0.040). Incorporating the effect of site type (equation 5) further improved the model where the fixed effects explained 50% of the variation in the SG of wood (RMSE = 0.036) and this model was significantly improved over the model with relative height and age (p-value <0.0001). Incorporating site type into the model reduced the random stand effect to account for 6% of the variation. Incorporating the effect of the tree defects on the wood SG (equation 6) did not result in a significant parameter (p-value = 0.8420).

[Insert Table 3 near here]

[Insert Table 4 near here]

[Insert Figure 2 near here]

Table 3. Parameter estimates for the longleaf pine wood and bark specific gravity (SG) models with their respective standard error (SE) values.

Property	Parameter	Model					
		Base model (Eq. 3)	SE	+Age effect (Eq. 4)	SE	+Site type effect (Eq. 5)	SE
Wood SG	β_0	0.432	0.008	0.335	0.029	0.365	0.018
	β_1	0.042	0.002	0.042	0.002	0.042	0.002
	β_2	0.145	0.019	0.145	0.019	0.145	0.019
	β_3	-	-	0.005	0.002	0.005	0.001
	β_4	-	-	-	-	-0.038	0.007
	Parameter	Base model (Eq. 8)	SE	+Age effect (Eq. 9)	SE	+Site type effect (Eq. 10)	SE
Bark SG	β_0	0.327	0.007	-	-	0.341	0.007
	β_1	0.018	0.001	-	-	0.018	0.001
	β_2	0.887	0.105	-	-	0.888	0.106
	β_3	-	-	-	-	-	-
	β_4	-	-	-	-	-0.029	0.009

Table 4. Fit indices and error statistics for the longleaf pine wood and bark specific gravity (SG) models.

Property	Model	Fit Indices (R ²)			AIC	RMSE
		Fixed	Random			
		Stand	Tree			
Wood SG	Base (Eq. 3)	0.23	0.56	0.86	-16977	0.045
	+Age (Eq. 4)	0.38	0.56	0.86	-16984	0.040
	+Site type (Eq. 5)	0.50	0.56	0.86	-16999	0.036
Bark SG	Base (Eq. 8)	0.29	0.50	0.66	-14359	0.043
	+Site type (Eq. 10)	0.37	0.50	0.66	-14364	0.040

Figure 2. Longleaf pine wood specific gravity fitted as a function of relative height, age, and site type for all the disks. The lines represent the modeled response for each site type for the mean age (17.2 years) of the sites.

Modeling Wood Moisture Content

All the factors which affect wood SG (relative height, age, site type) directly or indirectly affect wood MC as wood SG and wood MC follow an inverse relationship. The model predicting wood MC as a function of wood SG (equation 7) explained 87% of the variation (fixed effects only) in wood MC with an RMSE of 8.6%. Four percent of the variability in wood MC was due to stand, and 4% was due to tree within stand. The model parameters for equation 7, β_0 and β_1 are 926.633 and -5.409 for measured wood SG and 791.674 and -4.973 for predicted wood SG, respectively. The plot of wood MC as a function of measured wood SG is shown in Figure 3.

[Insert Figure 3 near here]

Figure 3. Longleaf pine wood moisture content fitted as a function of measured wood specific gravity for all the disks. The line represents the modeled response.

Modeling Bark Specific Gravity

Bark SG decreased as a function of relative height, with a rapid decrease when relative height was less than 0.1 (Figure 4). The base model for bark SG (equation 8) explained 29% of the variation (fixed effects only) with an RMSE of 0.043 (Table 4). Incorporating age into the model (equation 9) was not significant (p-value = 0.1079). Adding site type to the model (equation 10) resulted in a significantly improved model (p-value = 0.0061). The model with added site type effect was able to explain 37% of the variation

(RMSE = 0.040). Figure 4 shows the final model where bark SG is a function of relative height and site type.

[Insert Figure 4 near here]

Figure 4. Longleaf pine bark specific gravity fitted as a function of relative height and site type for all the disks. The lines represent the modeled response for each site type.

Modeling Bark Moisture Content

The model predicting bark MC as a function of bark SG (equation 11) explained 71% of the variation (fixed effects only) in bark MC with an RMSE of 27.6%. Five percent of the variability in bark MC was due to stand, and 9% was due to tree within stand. The model parameters for equation 11, β_0 , β_1 , and β_2 are 0.003, -0.022, and 0.653 for measured bark SG and 0.006, -0.123, and 1.277 for predicted bark SG, respectively. The plot of bark MC as a

function of measured bark SG is shown in Figure 5 which shows that bark SG and bark MC follow an inverse relationship.

[Insert Figure 5 near here]

Figure 5. Longleaf pine bark moisture content fitted as a function of measured bark specific gravity for all the disks. The line represents the modeled response.

Diameter Inside Bark as a Function of Diameter Outside Bark

A simple linear model with no intercept (equation 12) was used to fit DIB as a function of DOB, separately, for both cutover and old field sites as the difference between them was significant ($p < 0.0001$). For the cutover sites, the β_1 parameter was 0.877 (R^2 of 0.98 and RMSE of 0.523 cm). For old field sites, the β_1 parameter was 0.897 (R^2 of 0.99 and RMSE of 0.427 cm).

DISCUSSION

Wood

The mean whole-tree wood SG that we found (0.480) is similar to the value reported by Baldwin and Saucier (1983) (0.500) for trees from cutover sites in Louisiana and Texas that were planted at a density of 2470 trees ha⁻¹ to 3700 trees ha⁻¹. Gibson et al. (1986) reported an average whole-tree wood SG of 0.482 in longleaf pine aged 26 years growing in dry sites in Louisiana (initial planting density of 3000 trees ha⁻¹). All these wood SG values are less than the whole-tree wood SG (0.570) of 25-year-old longleaf pine trees planted at a density of 1075 trees ha⁻¹ on cutover sites on the Mississippi coast (Clark and Schmidting 1989). From this study, the cutover stand 8 (age 25) had an average whole-tree wood SG of 0.547, similar to what Clark and Schmidting (1989) reported. Because ring SG increases with cambial age for southern pines, as stand age increases so too will whole-tree wood SG (Larson et al. 2001; Dahlen et al. 2018).

We found that cutover sites had higher whole-tree wood SG than old field sites even though the age was similar. Clark and Schmidting (1989) found that fertilization and site preparation increased the period of corewood (juvenile wood) production which reduced wood SG in longleaf pines planted on cutover sites. Love-Myers et al. (2010) found that fertilization lowered the overall wood SG in loblolly pine. An increase in corewood proportion (having low SG) as a result of competition control of woody and herbaceous weeds was reported in loblolly pine by Antony et al. (2011). The old field sites likely had a lower wood SG because of the presence of residual nutrients from repeated fertilizer treatments and the absence of competition from hardwoods in the initial growing years (Clabo et al. 2020). From a wood utilization perspective, the cutover sites had higher SG and

lower MC wood and thus a forest products manufacturing facility purchasing wood by the ton would be buying more wood and less water compared to old field sites.

Trees from cutover sites in our study, despite being younger, had higher whole-tree wood SG values than planted loblolly pine whole-tree wood SG values reported by Gibson et al. (1986), Clark and Schmidting (1989), and Eberhardt et al. (2017). However, the values reported for loblolly pine in these studies are higher than what we found here for trees from old field sites. Cutover sites in our study had lower wood SG values as compared to slash pine values reported in Clark and Schmidting (1989) and Eberhardt et al. (2017) as these studies showed that slash pine tends to have higher whole-tree wood SG values than loblolly pine. Compared to the Wood Handbook (Kretschmann 2010) wood SG values for longleaf pine and slash pine (0.540), and loblolly and shortleaf pine (0.470), our values for wood SG in cutover sites were higher than loblolly pine and shortleaf pine but lower than longleaf pine or slash pine; however the age of our specimens is likely younger than the samples listed in the Wood Handbook.

Wood SG decreased with an increase in relative height. This trend in SG by height is common for other southern pines, including work by Eberhardt et al. (2017) on loblolly pine and slash pine, and Dahlen et al. (2018) on loblolly pine. Wood properties undergo rapid changes in the first 5 m from the base of the tree (Burdon et al. 2004), and for southern pines the trend with increasing height on SG is negative (Megraw 1985). Previous studies have shown that the wood SG in planted loblolly and slash pines decreases rapidly from the base of the tree to a relative height of around 0.1 and from there onwards, decreases gradually (Antony et al. 2010; Eberhardt et al. 2017). For planted longleaf pine, we found that the decrease in wood SG with height was not as drastic as in loblolly or slash pine.

The final wood SG model explained 50% of the variation with the variables relative height, age, and site type. The high tree to tree variation (30%) versus stand type variation (6%) is typical for wood properties in *Pinus* species (Auty et al. 2013, 2014; Moore et al. 2014, 2015; Dahlen et al. 2018). The longleaf pine wood SG model has lower prediction statistics than what was found by Eberhardt et al. (2017) for loblolly pine ($R^2 = 0.77$) and slash pine ($R^2 = 0.60$). The Eberhardt et al. (2017) samples came from a designed experiment with a narrow age range (21-24 years) whereas the trees sampled here were from operational stands with a much wider age range. At the ring level, wood SG increases non-linearly with cambial age (Jordan et al. 2008; Dahlen et al. 2018). For whole-disk SG measured here, we found that disk SG increased linearly with age. However, it is important to not extrapolate the results of this linear increase in whole-disk SG with age to younger or older cambial ages.

Overall wood MC values found in this study are similar to those reported by Baldwin and Saucier (1983) (110%) and slightly higher than the generic value Koch (1972) reported for longleaf pine (100%). Cutover sites had wood MC values similar to loblolly pine whereas old field sites had greater wood MC than both loblolly (106%) and slash pine (96%) (Eberhardt et al. 2017). The higher wood MC in trees from old field sites would result in higher drying costs compared to cutover sites, as well as for a given green weight of wood, cutover sites would yield more dry weight. Wood MC results correspond to wood SG results as it was expected for old field sites to have higher wood MC because they were found to have lower wood SG than cutover sites.

Defect vs Non-Defect Wood Differences

We did not find significant differences in wood SG or MC with regard to non-defect or defect-containing trees. The defect trees sampled in this study consisted of forked trees, trees that had ramicorn branches, and trees that had rust, in addition to the trees with

excessive sweep. Occurrence of higher SG compression wood is expected for trees with excessive sweep but it is not always present in wood from trees having other defects (Sharma et al. 2017). It is important to note that not every disk cut from a defect tree will have compression wood, and we did not separate disks with and without compression wood as this is difficult to determine on rough cut disks, except in cases where compression wood formation is severe. It should also be noted that the adverse effect of stem defects such as forking and ramicorn branches on wood SG and MC likely depends on the height at which the defect occurs, with defects occurring at lower heights along the main stem having severe impact on the stem wood quality as compared to when the defects occur higher up the main stem. A study specifically focused on defect trees with a larger sample size could differentiate between the defects and help to draw more informed conclusions.

Bark

The mean whole-tree bark SG that we found is slightly lower than what was reported by Baldwin and Saucier (1983) (0.389) and slightly higher than what was reported by Gibson et al. (1986) (0.334). We found that longleaf pine has similar bark SG as slash pine (0.368), and higher bark SG than loblolly pine (0.311) (Eberhardt et al. 2017). We found overall bark MC values similar to those reported by Baldwin and Saucier (1983) (90%) while Eberhardt et al. (2017) reported lower bark MC values for both loblolly (78%) and slash (69%) pines. Just like the relationship between wood MC and wood SG, bark MC also decreased as the bark SG increased (Figure 5). Bark MC is heavily influenced by the proportion of inner and outer bark because they have different MC values (Reifsnyder et al. 1967; Koch 1972; Graves et al. 2014), for longleaf pine the inner bark thickness remains relatively constant but the outer bark thickness decreases along the length of the tree (Eberhardt 2013).

The effect of relative height on bark SG found here was very different from what Eberhardt et al. (2017) found for loblolly and slash pine. Here, we found that the bark SG was highest at the stump, whereas Eberhardt et al. (2017) found little variation for slash pine, and loblolly pine had highest bark SG around mid-height, however the data was highly variable compared to the results found here. Here, the final bark SG model explained 37% of the variation with relative height and site type as the fixed effects. There was more variability by stand (13% vs 6%) and less variability by tree (16% vs 30%) for bark than for wood, perhaps some of these differences could be due to specific silvicultural prescriptions done at the stand level, such as prescribed burning. Lower prediction statistics as compared to the bark SG model in this study were reported for planted loblolly ($R^2 = 0.18$) and slash pine ($R^2 = 0.02$) by Eberhardt et al. (2017) which shows that bark SG is more predictable for planted longleaf pine, however we are not sure why this is the case. With regards to the ratio between DOB and DIB, the amount of bark found here for cutover ($\beta_1 = 0.877$) and old field ($\beta_1 = 0.897$) was higher than what Stängle et al. (2015) reported for Norway spruce (*Picea abies*) ($\beta_1 = 0.944$) and Dahlen et al. (2020a) reported for loblolly pine ($\beta_1 = 0.932$). In a different study in Norway spruce, Laasasenaho et al. (2005) found that the bark proportion varied with height, with bark proportion at the top of the tree being 15% and 7.5% at the base of the stump. The relative accuracy of the DOB to DIB model ($R^2 = 0.98$ for cutover sites and 0.99 for old field sites) allows for precise predictions of DIB when measuring DOB.

Wood and Bark Green Weight

In the southern U.S., roundwood is typically sold on a green weight basis and thus accurate estimates of SG and MC of wood and bark help inform procurement decisions for forest products facilities (Taras 1956; Antony et al. 2015; Eberhardt et al. 2017). Cutover sites had higher wood and bark SG and lower wood and bark MC as compared to old field

sites, and thus utilizing trees from cutover sites would result in an industry buying less water on a weight basis. The mean whole-tree wood green mass yield for this study was lower than what was reported for loblolly and slash pines which is likely due to the younger age of our sample trees, however, the overall average wood and bark green mass yield for a given volume of wood and bark from both site types in our study was still higher than the corresponding values reported for loblolly and slash pines in Eberhardt et al. (2017).

Fire Protection and Comparison to Loblolly and Slash Pine

Wang and Wangen (2011) in 33-year-old longleaf pines subjected to biennial fire regimes concluded that frequent burning did not influence bark thickness or bark production. While not conclusive, our results appear to follow this conclusion. The double bark thickness values from this study are almost twice as that reported for loblolly and slash pine by Eberhardt et al. (2017), and the bark MC is also higher here (93%) than for loblolly pine (78%) or slash pine (69%). Fast growth as a result of good site quality which then translates to relatively thinner bark has been observed in European silver fir (*Abies alba* Mill.) and Norway spruce trees (Stängle et al. 2017; Stängle and Dormann 2018). If this trend in bark thickness also holds true for southern pines, it might help explain why loblolly and slash pines tend to have thinner bark compared to longleaf pine because they grow faster (Dickens et al. 2018). For a given bark MC, bark thickness is the most significant indicator of a tree's fire resistance (Bauer et al. 2010) and thus the relatively high bark MC and the high bark thickness might help explain the higher fire resistance in longleaf pine compared to other southern pines (Hardin et al. 2001). A more detailed study comparing bark properties in planted and naturally regenerated longleaf pine trees is necessary before drawing conclusions regarding the fire tolerance of planted longleaf pine trees.

Utilization of Bark

Bark is an important raw material worldwide with the annual utilization amount exceeding 350 million m³ (Pásztor et al. 2016). On a green weight basis, most conifer trees have 5% to 15% bark (Nosek et al. 2016). On a dry weight basis, energy content in bark averages 2% higher as compared to that of wood (Kauter et al. 2003). In the southeastern United States, nearly all forest product facilities burn bark for energy, however bark can be made into durable pellets (Lehtikangas 2001; Pásztor et al. 2016) and there is interest in utilizing bark in higher value products (Baker et al. 2012; Nosek et al. 2016; Pásztor et al. 2016; Eberhardt et al. 2017). On a dry weight basis, we found that planted longleaf pine had 17.8% dry mass of bark, which is higher than what Eberhardt et al. (2017) found for both loblolly pine (12.5%) and slash pine (17%). Therefore, a bio-energy facility specifically focused on maximizing bark consumption would benefit more from planted longleaf pine bark as compared to loblolly or slash pine, and the bark from cutover sites would be preferred over old field sites due to the lower moisture content which makes drying less expensive (Lehtikangas 2001).

CONCLUSIONS

Whole-tree specific gravity and moisture content of wood and bark were measured for planted, unthinned longleaf pine trees grown on cutover forest and old field sites. Trees from cutover forest sites had higher wood and bark specific gravity than trees from old field sites. Wood and bark moisture content were higher for trees grown on old field sites because moisture content has an inverse relationship with specific gravity for both wood and bark. Models were developed to describe the effects of relative height, stand age, and site type on wood and bark specific gravity. Relative height and site type had a significant effect on both wood and bark specific gravity whereas age had significant effect on wood specific gravity only. We did not find a significant difference between wood specific gravity in trees with and

without defects (forking, sweep, ramicorn branching, and rust). The results indicated that trees from cutover forest sites produced higher quality wood that would be more suitable for lumber or Kraft pulp (for linerboard or dissolving pulp) than trees from old field sites. For a given green ton of wood and bark, cutover forest sites had a higher yield of wood and bark dry mass than old field sites. This work focused on the wood quality data for unthinned planted longleaf pine at the whole-disk level. Future work could be directed towards the use of X-ray densitometry to calculate ring by ring wood specific gravity on older material to understand how wood specific gravity changes with cambial age for longleaf pine from planted trees. Future research can also be done to better understand why the bark specific gravity variability within tree was much more consistent for planted longleaf pine compared to planted loblolly or slash pine.

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