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Whole-Tree Bark and Wood Properties of Loblolly Pine from Intensively Managed Plantations

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A study was conducted to identify geographical variation in loblolly pine bark and wood properties at the whole-tree level and to quantify the responses in whole-tree bark and wood properties following contrasting silvicultural practices that included planting density, weed control, and fertilization. Trees were destructively sampled from both conventionally managed stands and various designed experimental trials established across the southern United States by various research cooperatives and forest product industries to quantify the bark and wood properties of loblolly pine. Bark (percentage bark, specific gravity [SG], and moisture content [MC]) and wood (SG, MC, green weight of wood/m^3, and green weight of wood and bark/m^3 of volume) properties were measured from disks collected at multiple heights from sampled trees and used to compute the whole-tree bark and wood properties. Significant regional variation was observed for whole-tree bark and wood properties. Bark and wood SG showed an increasing trend from inland to coastal regions and vice versa for bark and wood MC. The effect of different silvicultural treatments on bark and wood properties were generally absent; but a significant effect on bark percentage, MC, and green weight of wood and bark/m^3 was observed for trees that received intensive treatments such as early age competition control plus multiple fertilizations.

Keywords: loblolly pine, *Pinus taeda* L., whole tree, wood properties, bark properties, intensive management

The southeastern United States is a an important region in terms of the manufacture and supply of wood products, producing approximately 60% of the wood used in the US and 16% used globally (Wear and Greis 2002). The majority of wood produced in this region is from plantation grown southern yellow pines, which currently cover a land area of 13 million ha, with a projected increase of 67% (to approximately 22 million ha) by 2040. Loblolly pine (*Pinus taeda* L.) is a commercial southern pine that occupies much of the standing pine volume (approximately 12 million ha) in the southern United States (Baker and Langdon 1994). Compared to other southern pines, its fast growth rate, ability to grow well on a wide range of sites, and responsiveness to various silvicultural treatments has made loblolly pine a primary plantation species in the southern United States.

Demand for timber products has grown considerably over the last few decades, mainly due to increase in world population and disposable income (Oswalt et al. 2010). To meet this demand, foresters now manage loblolly pine plantations intensively through a combination of silvicultural methods, such as initial site preparation, multiple weed control, thinning, and fertilization, along with planting genetically improved seedlings (Li et al. 1999, Allen et al. 2005). Today, pine plantations are harvested at a much younger age than in the past as trees attain merchantable size much quicker due to intensive management. Despite the improvement in growth and yield, tree growers and buyers are concerned about the quality of wood produced from trees rapidly grown under various management regimes (for example, a high proportion of low density and high microfibril angle juvenile wood) (Plomion et al. 2001, Watt et al. 2009).

Wood quality is a subjective term as its definition varies depending on intended end use (MacDonald and Hubert 2002). The quality of wood depends on its physical (for example, SG or density, MC), mechanical (e.g., stiffness and strength) and anatomical properties (e.g., microfibril angle, tracheid wall thickness) (Megraw

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1985, Briggs 2010). SG has been considered a key determinant of wood quality because of its strong correlation with the strength of solidwood products, as well as the yield and quality of pulp produced (Panshin and de Zeeuw 1980). MC is also a key variable determining the green weight of wood (Taras 1956), which is important for log transportation and value estimation. Taras (1956) reported that a 0.02 unit change in SG of wood at 100% MC will result in a weight change of 40 kg/m^3 and a 5% change in MC will result in weight change of around 25 kg/m^3. Different studies have identified regional variation in loblolly pine wood SG across its natural growing range (Zobel and van Buijtenen 1989, Daniels et al. 2002, Jordan et al. 2008, Antony et al. 2010). Some of these recent reports are based up on a subset of data used in the present study. All of these studies have observed a high wood SG for trees grown in the South Atlantic and Gulf Coastal Plain regions. Information about regional variation in wood MC is still lacking, however, which could be of interest to industries who procure wood on dry weight basis (actual fiber content basis).

The quality of bark produced from plantation grown loblolly pine is important, especially as an alternative fuel source (Corder 1976). The SG and MC of bark, and its percentage weight relative to wood are important criteria to be considered in the computation of total dry and green weight of a tree. Despite its importance, only limited information is available about loblolly pine bark properties (SG and MC) and bark proportion variation. For loblolly pine, McCormack (1955) reported that approximately 10% of the outside dbh (1.4 m) is bark. Based on the results from several past studies, Koch (1972) summarized that bark thickness (at breast height) of loblolly pine varies with physiographic location in which the tree grows and observed that it is correlated with breast height diameter. Phillips and Schroeder (1972) reported variation in bark properties with tree height and physiographic location based on loblolly pine and slash pine (*Pinus elliottii* Engelm.) wood and bark samples collected from stands distributed across the Coastal Plain and Piedmont regions of southeastern United States. They observed marginal differences in bark thickness and bark percentage by weight with location and tree height, but considerable differences in bark SG and MC. In another study, Miles and Smith (2009) reported the SG, MC, percentage content and green weight of loblolly pine bark and were 0.33, 99% (both on an oven-dry weight basis), 16.6% (percentage of wood volume) and 657 kg/m^3, respectively.

Several studies in the past have examined the effect of different silvicultural treatments on wood SG using samples collected from various growth and yield experimental trials. It was determined that low planting density stimulated production of low SG juvenile wood (Clark et al. 2008) affecting mechanical properties (stiffness and strength) and pulp yield. Clark et al. (2008) observed an increase in whole stem SG with increase in initial planting density. Similarly, early age competition control in loblolly pine was reported to increase (20% following complete control of herbaceous and woody vegetation compared to no treatment) the proportion of low SG juvenile core after 15 years of growth (Clark et al. 2006, Mora et al. 2007, Antony et al. 2011a). Midrotation fertilization along with thinning of loblolly pine resulted in a reduction of SG of annual rings produced for, 3–4 years following fertilization (Antony et al. 2009a, 2009b, Love-Myers et al. 2009). Most of the above studies examined the effect of silvicultural treatment using samples collected from multiple heights or at breast height (1.4 m) within a tree and not on the whole-tree properties. Unlike wood SG, few studies have examined the effect of silvicultural treatments on bark properties in loblolly pine. Sherrill (2005) reported the bark thickness of 13-year old loblolly pine trees sampled from a designed trial planted with 25 open pollinated families (as genotype) and two by two factorial combination of herbicide and fertilizer application. The effect of herbicide and fertilization on bark thickness was absent in this study after accounting for inside bark diameter of trees at breast height, though significant variation among families was observed.

The Wood Quality Consortium (WQC) at the University of Georgia (UGA), in collaboration with United States Department of Agriculture (USDA) Forest Service, industrial partners, and other research cooperatives in the southern United States have collected extensive data from both conventionally and intensively managed loblolly plantations growing across the southern United States. The goal was to quantify the variation that exists in bark and wood properties, including bark percentage and bark and wood SG and MC. The data collected by the WQC over the years were compiled and used in this study. Results from analysis of some of these data were published to describe regional and within tree variation in wood SG and the influence of various silvicultural treatments on annual ring SG but not on whole-tree bark and wood properties. The objectives of this study were to:

(i) identify geographical variation in bark and wood properties at the whole-tree level utilizing data collected from operationally and intensively managed stands.

(ii) quantify the responses in whole-tree bark and wood properties to combinations of intensive treatments based on data from designed experimental trials.

Materials and Methods

Data

The data used in this article were from a broad sampling effort conducted by the WQC, in collaboration with the Forest Service and other research cooperatives in the southeast. A description of the data used in this study along with relevant literature follows. In all studies, sampled trees were felled and 3.8-cm thick cross-sectional disks were collected at 0.15, 1.4, or 1.5, 3.0 m from the base and then at 1.5 m intervals along the stem up to 50 mm diameter outside bark (diameter outside bark) unless otherwise stated. The total height of all sampled trees was recorded.

Conventional Stands

Three data sets collected from traditionally managed stands in the southeastern United States were compiled as our Conventional Stand data. The first data set included trees sampled from 135 stands in six physiographic regions across the southeastern United States (see Table 1; referred to in Table 1 as Baseline). A minimum of 12 plantations of age 20–30 years that had been managed conventionally (planted with 1,112 to 1,779 trees per ha (TPH), thinned to 618 TPH, no fertilization except phosphorus at planting on deficient sites, and no competition control) were sampled from each region. At the time of sampling, stocking ranged from 494 to 1,483 TPH. Three trees were selected from each stand for destructive sampling, one representing the mean diameter class from the stand (from a diameter distribution with class interval of 25 mm) and two trees, each representing diameter classes above and below the mean diameter class.

The Conventional Stand data also included 40 13-year-old trees sampled from International Paper's Southland Experimental Forest

Table 1. Summary of field trials, along with information on treatments used, and trees sampled.

Study	Regions	Treatments	Type of treatments	No. of stands	No. of trees	Age (std. err.)	DBH (cm) (std. err.)	THT (m) (std. err.)
AubHerb	2	Banded, Broadcast	Weed control	1	70	15 (0)	18.0 (0.36)	13.1 (0.13)
Baseline	1, 2, 3, 4, 5, & 6	None	Conventional	135	407	23 (0.13)	23.1 (0.22)	19.3 (0.14)
CAPPS	1 & 4	Control, Herbicide, Fertilization, Herb & Fert	Weed + Fert	4	128	12 (0)	18.1 (0.25)	16.8 (0.20)
FastLob	4	988, 1483 & 1977 TPH	Planting density	1	96	14 (0)	22.9 (0.25)	18.2 (0.10)
IPSpacing	1	2244, 1794, 1495, 1344 1122, 897 & TPH	Planting density	1	132	21 (0)	25.9 (0.33)	25.5 (0.12)
NIRTIP3	5	None	Conventional	1	40	13 (0)	21.2 (0.41)	17.0 (0.17)
UGAPMRC	3 & 4	None	Conventional	173	247	16.6 (0.26)	16.2 (0.19)	13.1 (0.19)
VTThin	1, 4 & 6	Control, Low & High Thin	Thinning	12	180	37 (0.31)	29.9 (0.53)	23.4 (0.25)
Regions	1—South Atlantic Coastal Plain; 2—North Atlantic Coastal Plain; 3—Upper Coastal Plain; 4—Piedmont; 5—Gulf Coastal Plain; 6—Hilly Coastal Plain.							

Here, DBH represents diameter at breast height in cm and THT represents total tree height in m.

located on the Gulf Coastal Plain, with the objective of developing rapid nondestructive methods for estimating whole-tree wood properties (referred to in Table 1 as NIRTIP3). In addition, Conventional Study data included trees sampled by the Plantation Management Research Cooperative (PMRC) at UGA to develop taper equations and weight/m^3 factors (referred in Table 1 as UGAPMRC). Here, one or two trees were destructively sampled from 10- to 27-year-old conventionally managed stands in the Piedmont region of Georgia, South Carolina, and Alabama. Here, disk cross sections were collected from two heights (0.03 and 0.18 m) at the base of tree rather than from 0.15 m.

AubHerb Study

This study examined the effect of weed control on growth and yield of loblolly pine and was established by the Silvicultural Research Cooperative at Auburn University. Trees were sampled from 12 plots at age 15 from a North Atlantic Coastal Plain site located at West Point, Virginia. About 8–10 trees were sampled from each plot in proportion to the diameter distribution of all the trees in the plot, where the proportion was the ratio of trees in each dbh class to the total number of trees in the plot.

Consortium for Accelerated Pine Production (CAPPS) Study

This study was established by CAPPS at UGA to assess the impact of vegetation control and annual fertilization on growth and wood properties of loblolly pine. The study was established at two South Atlantic Coastal Plain sites in Dixon State Forest near Waycross, Georgia and two Piedmont sites in the B.F. Grant Experimental Forest near Eatonton, Georgia. The study consisted of four treatments: (1) control (mechanical site preparation); (2) herbicide (HerbWeed; herbicide application throughout the study period); (3) fertilization (Fert; annual fertilization with diammonium phosphate throughout the study period); and (4) herbicide and fertilization (HerbFert; both herbicide and fertilizer application combined together). At each location, the study was laid out in a randomized complete block design with four treatments replicated in two blocks. Borders et al. (2004) and Clark et al. (2004) provide more detail regarding the design of the study and treatments. Four trees, relative to the diameter distribution of all the trees in the plots, were destructively sampled from each plot. In this study, disk cross sections were collected from 0.91 and 2.4 m and then at 2.4 m intervals along the stem up to a 50 mm diameter outside bark.

FastLob Study

The study was established in UGA's B.F. Grant Memorial Forest in the Georgia Piedmont, with three initial planting densities (Table 1) along with complete competition control (Faust et al. 1999). A total of 32 trees marked for thinning were selected from each planting density at the age of 14 for wood property assessment. In this study, disk cross sections were collected from 0.15 m, and 25 and 50% of total tree height and at every 10% of total tree height to a 50 mm diameter outside bark.

IPSpacing Study

The trees were sampled from a loblolly pine spacing study located at Rincon, Georgia, on the South Atlantic Coastal Plain. The study was established in 1984 and laid out in a randomized complete block design, with seven initial spacing treatments (Table 1) replicated in three blocks. More details of this study were reported by Antony et al. (2012). Seven trees with dbh greater than or equal to 200 mm were destructively sampled from each plot in 2005. The trees sampled were selected in proportion to the diameter distribution of all the trees in the plot, where the proportion was the ratio of trees in each dbh class to the total number of trees in the plot.

VTThin Study

This is a region wide loblolly pine thinning study established during 1980–1982 period on 186 plantations by the Loblolly Pine Growth and Yield Research Cooperative at Virginia Polytechnic Institute and State University. At each stand, three plots of comparable site conditions (site index, TPH) were established and randomly assigned one of three thinning treatments: (1) no thin, (2) low thin (30% of the basal area removed), and (3) heavy thin (50% of basal area removed). For more details, see Burkhart et al. (1985) and Tasissa and Burkhart (1998a, 1998b). About five trees were destructively sampled from 30- to 45-year-old stands located in the South Atlantic, Hilly Coastal Plain and Piedmont regions (four stands per region) for wood property assessment.

A map showing the sampled locations is presented in Figure 1. A summary of the stand characteristics along with the number of stands, trees sampled, mean dbh, and total tree height from each study is presented in Table 1.

Whole-Tree Property Estimation

The sampled disks were sealed in plastic bags and shipped to the Forest Service wood property laboratory for physical property analysis. Outside and inside bark diameters of all sampled disks were

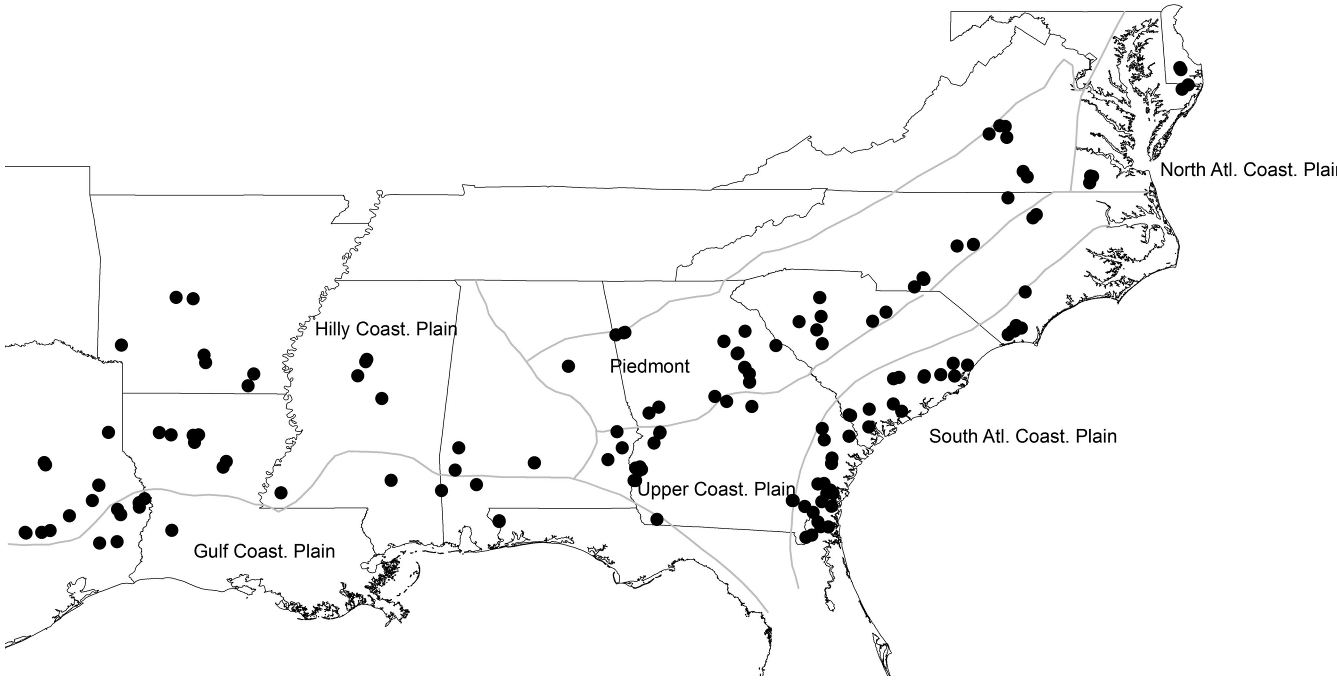

Figure 1. Location of the sampled stands.

measured. The percentage bark content in proportion to green weight of each disk was recorded. Bark and wood SG based on oven-dry weight and green volume and bark and wood MC based on green and oven-dry weight was measured for each disk. In addition, the green weight of wood per cubic meter (kg/m^3) and green weight of wood and bark per cubic meter (kg/m^3) of volume was measured for each sampled disk. The volume of the disks was measured using water displacement.

For each sampled tree, whole-tree volume weighted bark (bark percentage, SG, and MC) and wood (wood SG and MC, green weight of wood, green weight of wood and bark) properties were determined. Volume-weighted whole-tree bark properties and green weight of wood and bark were computed using the estimated outside bark volume for each stem segment. Volume-weighted whole-tree wood SG, MC, and green weight of wood were calculated using the estimated inside bark volume for each stem segment. The volume (both inside and outside bark) of each stem segment and the whole-tree was computed using the inside and outside bark diameter measured at each sampled height. The outside/inside bark volume of bolts between two sampled points (disk) was determined using Smalian's formula, except the bottom-most segment (below stump height; which was assumed to be a cylinder with volume $V = (0.00007854 \times D^2)L$, outside/inside bark diameter of the upper disk sampled was used) and the top most segment (assumed as a cone with volume $V = \frac{1}{3}(0.00007854 \times D^2)L$, where outside/inside bark diameter of lower disk sampled was used). Smalian's formula, which assumes each section of log as a frustum of a paraboloid, is given as

$$V = \left[\frac{(A_l + A_u)}{2}\right]L$$

where V is the volume of a section of the tree in m^3; A_l and A_u are the basal area of the lower and upper disks in square m of each log segment computed as $0.00007854 \times D^2$ (assumes the tree sections are circles), D is the outside/inside bark diameter in centimeters, and L is the length of the log section measured in meters. The total volume of the whole tree was calculated by summing the volume of each section. Whole-tree volume-weighted bark and wood properties were determined by taking weighted average bark and wood property values for each disk, where the weight used was a ratio of volume of each segment to the total volume of the tree. Since we have two measurements of bark and wood properties for most log segments (except the top and bottom log sections where we only had one observation each), we took an arithmetic average of the two observations before multiplying with the respective weight factor for each log segment.

Statistical Analysis

Separate analysis of variance (ANOVA) was conducted for each measured property from each of the above data sets. Since we are interested in estimates of stand-, block-, and plot-level variability in addition to regional and treatment differences, a mixed model ANOVA was used to conduct the analysis. Suitable models for each experimental trial were selected and are presented below (Equations 1–6). The effect of region (where trees sampled from multiple regions) and treatment were considered as fixed in all the models. In addition, variables such as stand age, dbh, and total tree height were used as covariates in the models. The effect of stand, block, and plot were treated as random effects in the model to properly account for variability as they were assumed to be randomly sampled from a large population.

Conventional Stand: $$y_{ijn} = \mu + R_i + A_{ijn} + D_{ijn} + HT_{ijn} + S_{ij} + \varepsilon_{ijn} \quad (1)$$

AubHerb Study: $$y_{kmn} = \mu + T_k + D_{kmn} + HT_{kmn} + p_{km} + \varepsilon_{kmn} \quad (2)$$

Table 2. F-values and *P*-values (in parenthesis) of fixed effects from models fitted to data.

Study	Effects	Property: Bark %	Bark SG	Bark MC	Disk SG	Disk MC	Green weight of wood (kg/m³)	Green weight of wood and bark (kg/m³)
Conventional	Region	**2.98 (0.012)**	**21.93 (<0.001)**	**13.25 (<0.001)**	**14.11 (<0.001)**	**6.85 (<0.001)**	**7.38 (<0.001)**	**7.59 (<0.001)**
AubHerb	Treatment	0.36 (0.568)	1.68 (0.200)	0.39 (0.557)	0.07 (0.796)	0.11 (0.739)	0.06 (0.802)	0.00 (0.982)
Capps	Region	0.97 (0.427)	0.45 (0.571)	**29.95 (0.001)**	6.47 (0.122)	**9.37 (0.005)**	0.60 (0.515)	0.00 (0.953)
	Treatment	**4.07 (0.019)**	1.43 (0.256)	**3.25 (0.040)**	2.21 (0.113)	2.45 (0.082)	2.60 (0.072)	**3.56 (0.027)**
	Reg*Treat	1.91 (0.165)	1.41 (0.267)	1.38 (0.282)	0.83 (0.496)	0.85 (0.482)	0.33 (0.804)	0.95 (0.434)
FastLob	Treatment	2.97 (0.056)	0.77 (0.465)	2.18 (0.119)	0.43 (0.654)	1.63 (0.201)	1.86 (0.162)	0.82 (0.445)
IPSpacing	Treatment	0.09 (0.997)	1.28 (0.350)	0.56 (0.754)	1.30 (0.339)	2.08 (0.145)	0.71 (0.652)	0.49 (0.805)
VTThin	Region	0.78 (0.488)	4.24 (0.063)	2.80 (0.140)	**11.12 (0.015)**	2.01 (0.193)	0.06 (0.944)	0.19 (0.832)
	Treatment	0.86 (0.439)	0.66 (0.520)	1.58 (0.233)	0.88 (0.416)	2.23 (0.111)	1.74 (0.201)	1.75 (0.176)
	Reg*Treat	**3.85 (0.019)**	0.28 (0.890)	0.41 (0.802)	0.94 (0.443)	1.10 (0.358)	1.00 (0.431)	0.71 (0.590)

Significant effects are represented in bold. SG, specific gravity; MC, moisture content.

Table 3. Estimated means with standard error in parenthesis and results from multiple comparison tests, by physiographic region for trees from conventionally managed stands.

Region	Bark %	Bark SG	Bark MC	Disk SG	Disk MC	Green weight of wood (kg/m³)	Green weight of wood and bark (kg/m³)
South Atlantic	10.7ab (0.18)	0.316ac (0.004)	96.2a (2.6)	0.468a (0.004)	116.4ac (2.0)	993.9a (6.1)	1,113.2a (6.7)
North Atlantic	11.2ab (0.40)	0.297abcd (0.008)	100.1ac (5.8)	0.423b (0.008)	127.5ab (4.5)	948.7bc (13.6)	1,069.3abc (15.0)
Upper Coastal	11.1a (0.21)	0.300ad (0.004)	103.2ac (3.1)	0.454ac (0.004)	117.6abc (2.4)	979.9ab (7.2)	1,103.5ab (8.0)
Piedmont	10.4b (0.10)	0.275b (0.002)	118.8b (1.5)	0.436b (0.002)	124.8b (1.2)	968.9b (3.6)	1,081.9bc (3.9)
Gulf Coastal	10.7ab (0.24)	0.321c (0.005)	102.1ac (3.5)	0.464a (0.005)	109.0c (2.8)	958.6bc (8.3)	1,072.9bc (9.2)
Hilly Coastal	10.9ab (0.20)	0.295d (0.004)	114.4bc (2.9)	0.440bc (0.004)	117.6abc (2.3)	945.2c (6.8)	1,061.4c (7.5)
Partial regression coefficients, with standard error in parenthesis							
Age	0.051[1] (0.02)	0.003[1] (0.0004)	−2.69[1] (0.29)	0.002[1] (0.0004)	−1.69[1] (0.23)	−2.42[1] (0.70)	−2.05[1] (0.76)
DBH (cm)	−0.105[1] (0.01)	−0.001[1] (0.0003)	0.14 (0.21)	−0.001[1] (0.0004)	1.02[1] (0.17)	2.52[1] (0.52)	1.50[1] (0.56)
THT (m)	−0.328[1] (0.03)	0.002[1] (0.0006)	2.03[1] (0.42)	0.0005 (0.0007)	−0.173 (0.34)	0.44 (1.0)	−3.53[1] (1.10)
Variance estimates							
Stand	0.77	0.0003	151.3	0.0002	86.6	812.6	1003.7
Residuals	0.91	0.0006	221.8	0.0007	149.3	1312.8	1539.9

[1] Significant at 5% significance level.
Partial regression coefficients of covariates (age, diameter at breast height [DBH], and total tree height [THT]) from the models are also presented. Values with different letters in a column are significantly different.
SG, specific gravity; MC, moisture content.

$$\text{CAPPS study: } y_{ijkln} = \mu + R_i + T_k + (RT)_{ik} + D_{ijkln} + HT_{ijkln} + s_{ij} + b_{ijl} + (Tb)_{ijkl} + \varepsilon_{ijkln} \quad (3)$$

$$\text{FastLob Study: } y_{kmn} = \mu + T_k + D_{kmn} + HT_{kmn} + \varepsilon_{kmn} \quad (4)$$

$$\text{IPSpacing Study: } y_{kln} = \mu + T_k + D_{kln} + HT_{kln} + b_l + (Tb)_{kl} + \varepsilon_{kln} \quad (5)$$

$$\text{VTThin Study: } y_{ijkn} = \mu + R_i + T_k + (RT)_{ik} + A_{ijkn} + D_{ijkn} + HT_{ijkn} + s_{ij} + (Ts)_{ijk} + \varepsilon_{ijkn} \quad (6)$$

Where, y_{ijklmn} represents property value measured from n^{th} tree sampled from m^{th} plot, l^{th} block, received k^{th} treatment, in j^{th} stand from i^{th} region; μ is the population average; R_i is the region effect; T_k is the treatment effect; $(RT)_{ik}$ is the interaction effect of region and treatment; A_{ijklmn}, D_{ijklmn} and HT_{ijklmn} are respectively age, breast height diameter and total tree height of the sampled trees; s_{ij} is the random effect of stands sampled from i^{th} region distributed as $s_{ij} \sim N(0, \sigma_s^2)$; b_{ijl} is the random block effect distributed as $b_{ijl} \sim N(0, \sigma_b^2)$; $(Tb)_{ijkl}$ is random interaction effect of treatment and block distributed as $(Tb)_{ijkl} \sim N(0, \sigma_{Tb}^2)$; $(Ts)_{ijk}$ is the random interaction effect of treatment and stand distributed as $(Ts)_{ijk} \sim N(0, \sigma_{Ts}^2)$; p_{km} is the plot effect receiving k^{th} treatment distributed as $p_{km} \sim N(0, \sigma_p^2)$; and ε_{ijklmn} is the random error term distributed as $\varepsilon_{ijklmn} \sim N(0, \sigma_\varepsilon^2)$. Multiple comparison tests were conducted for significant fixed effects in the model using Tukey's Honestly Significant Difference test. All the models were fitted using the MIXED procedure in SAS 9.2 (SAS, Inc. 2008). $(Ts)_{ijk} \sim N(0, \sigma_{Ts}^2)$; p_{km} is the plot effect receiving k^{th} treatment distributed as $p_{km} \sim N(0, \sigma_p^2)$; and ε_{ijklmn} is the random error term distributed as $\varepsilon_{ijklmn} \sim N(0, \sigma_\varepsilon^2)$. Multiple comparison tests were conducted for significant fixed effects in the model using Tukey's Honestly Significant Difference test. All the models were fitted using the MIXED procedure in SAS 9.2 (SAS, Inc. 2008).

Results

Conventional Stands

Physiographic regional differences were observed for bark percentage, bark SG, bark MC, disk SG, disk MC, green weight of wood, and green weight of wood and bark (Tables 2 and 3) for conventionally managed plantations. Significant differences among regions were observed in bark percentage of trees from conventionally managed stands, with trees from the Piedmont having lower

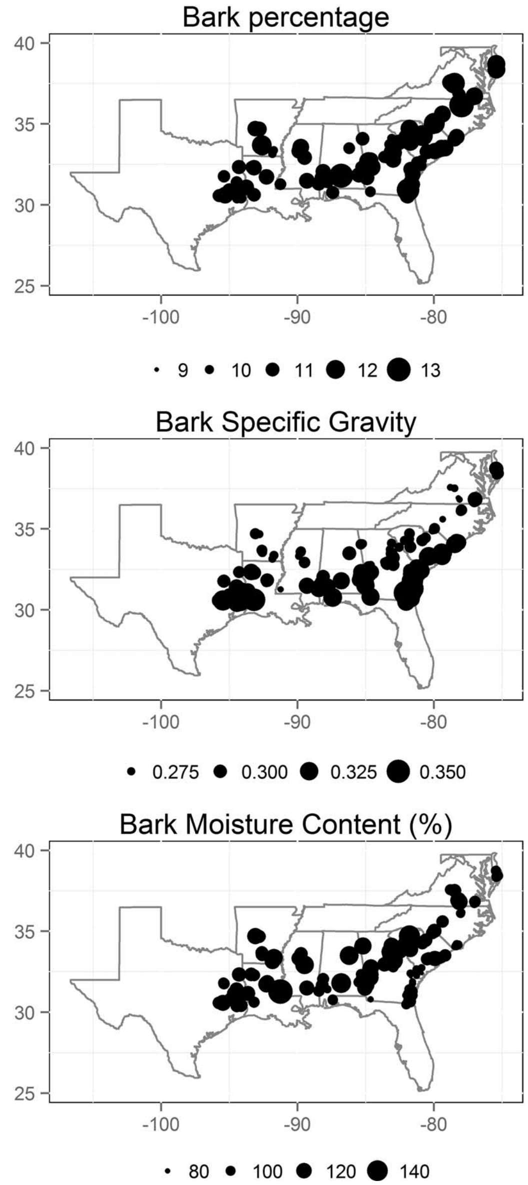

Figure 2. Map of estimated average bark properties (percentage bark, SG, and MC) of conventionally managed stands. Assumed an average age of 20 years, diameter of 20.6 cm, and total tree height of 16.9 m.

bark percentage compared to that of the Upper Coastal Plain (Figure 2). Differences across regions were also observed in bark SG and MC (Table 2). Bark SG follows an increasing trend from inland to coastal, with trees from the Piedmont having significantly lower bark SG than that of trees from all other regions, except the North Atlantic Coastal Plain (Table 3; Figure 2). Similarly, bark SG of trees from the Hilly Coastal Plain is significantly lower than that of trees from the Gulf and South Atlantic Coastal Plains (Table 3). In addition, bark SG of trees from the Upper Coastal Plain is lower than that of trees from the Gulf Coastal Plain. Unlike bark SG, a decreasing trend was observed from inland to the coastal for bark MC (Figure 2). Bark MC of trees from the Piedmont was significantly higher than that of trees from all other regions, except for trees from the Hilly Coastal Plain (Table 3). Higher bark MC was also observed for trees from the Hilly Coastal Plain compared to trees from the South Atlantic Coastal Plain.

Significant regional differences were observed in wood SG and MC of trees from conventionally managed stands (Table 2). The disk SG of trees from the North Atlantic Coastal Plain and Piedmont were significantly lower than that of trees sampled from sites in the South, Upper, and Gulf Coastal Plains (Table 3; Figure 3). Similarly, wood SG of trees from the Hilly Coastal Plain was lower than that of trees from the South Atlantic and Gulf Coastal Plains (Figure 3). Whole-tree MC was significantly different across regions, with lower disk MC observed for trees from the Gulf Coastal Plain compared to trees from the North Atlantic Coastal Plain and Piedmont. In addition, disk MC of trees from the Piedmont was higher than that of trees from the South Atlantic Coastal Plain (Table 3; Figure 3).

Significant regional differences were observed in green weight of wood/m^{3}and in green weight of wood and bark/m^3 (Table 2). The green weight of wood/m^3 was higher for trees from the South Atlantic Coastal Plain compared to trees from all other physiographic regions, except the Upper Coastal Plain (Table 3). Significantly lower green wood weight/m^3 was observed for trees from the Hilly Coastal Plain compared to trees from the Upper Coastal Plain and Piedmont (Table 3; Figure 3). The green weight of wood and bark/m^3 was higher for trees from the South Atlantic Coastal Plain compared to trees from the Piedmont and Gulf and Hilly Coastal Plains. Significantly higher green wood and bark weight/m^3 was also observed for trees from the Upper Coastal Plain compared to that of trees from the Hilly Coastal Plain (Table 3; Figure 3).

The linear effect of age and dbh was significant for all the bark and wood properties (Table 3), except the effect of dbh was not significant for bark MC. However, the effect of height was significant only for bark properties and green weight of wood and bark (Table 3). Based on the partial linear coefficients, bark percentage and SG and disk SG increased with tree age (i.e., as trees mature); but an opposite trend was observed for bark MC, disk MC, wood weight, and wood plus bark weight (Table 3). However, bark percentage and SG and disk SG decreased with dbh and bark MC, disk MC, wood weight, and wood plus bark weight increased with increase in dbh. Bark percentage decreased with increase in height; however, bark SG and MC increased with height (Table 3). The weight of wood and bark combined, based on the partial linear coefficients, decreased with increase in height. Large variability among stands and trees (based on the residual variance) was evident for all bark and wood properties, with tree-to-tree variability larger than stand variability (Table 3).

Managed Stands

Results from the ANOVA of each intensively managed study showed differences in banded and broadcast application of herbicide were absent for all properties examined based on the AubHerb Study data (Table 2; Figures 4 and 5). Similarly, differences among initial planting densities were also absent for whole-tree bark and wood properties based on data from the IPSpacing Study (Table 2; Figures 4 and 5). The effect of age (where multiple ages were present), dbh, and total tree height (tht) did not show a consistent result like the conventional stand analysis, which might be due to the narrow range of dbh and tht covered in each of these individual studies. For that reason, age, dbh, and tht were not considered further. The variance estimates in these studies were primarily used to account for differences across stands, blocks, plots within blocks in the study, and to correctly specify the error term to test for each of the fixed effects in these studies and, hence, are not presented.

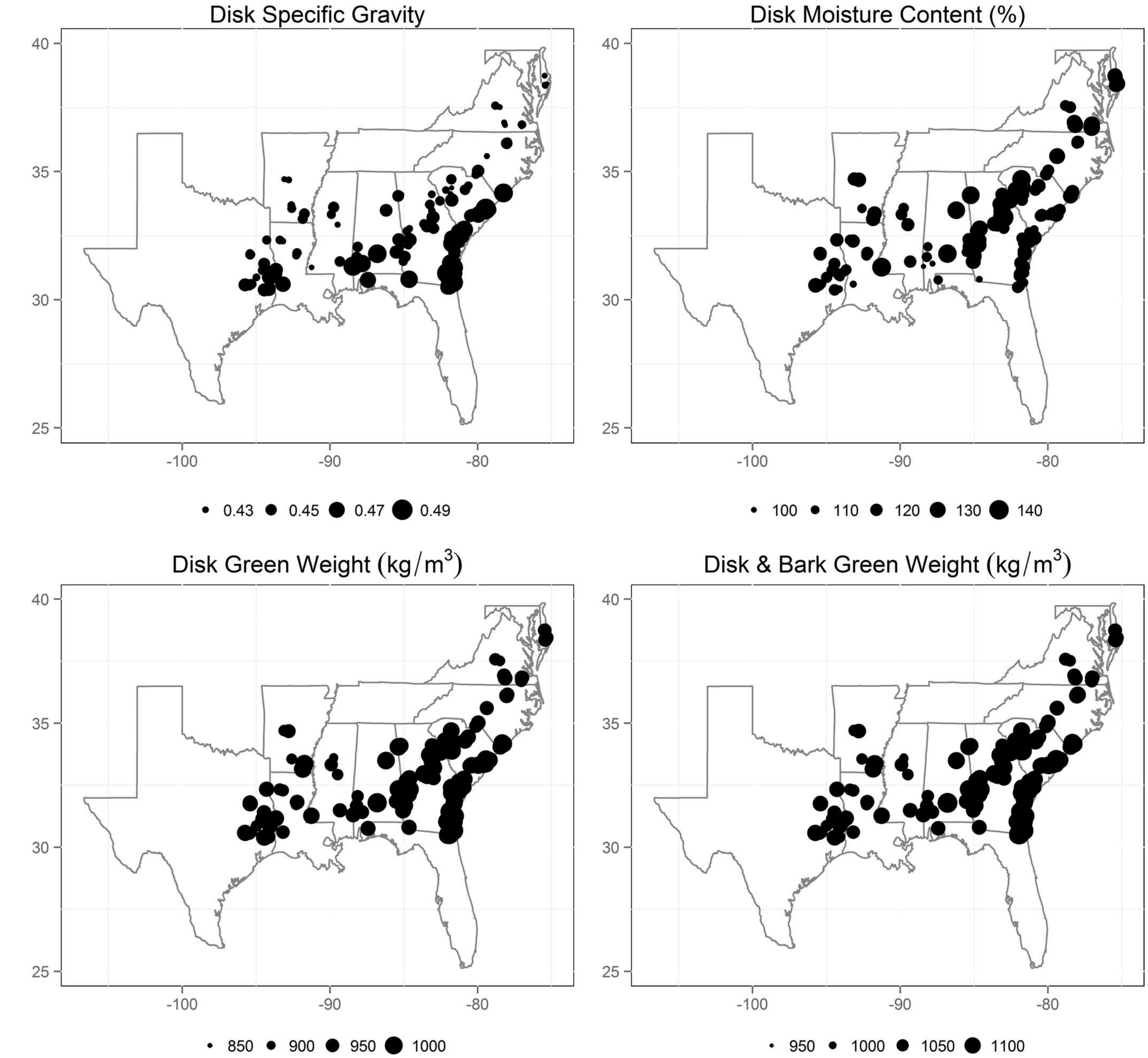

Figure 3. Map of estimated average wood properties (SG, MC, and green weight) of conventionally managed stands. Assumed values were an average age of 20 years, diameter of 20.6 cm, and total tree height of 16.9 m.

CAPPS study

The effect of region and the interaction between region and treatment was absent for whole-tree bark percentage, but the treatment effect was significant (Table 2). Percentage bark of trees from control plots was significantly higher than that of trees that received annual fertilization (Figure 4). The effects of region, treatment, and their interaction was absent for bark SG. The effect of region was significant for bark MC. The treatment effect on bark MC was marginal and multiple comparisons did not show any treatment differences.

The effect of region, treatment and their interaction was absent for whole-tree weighted wood SG and green weight of wood/m^3. The effect of region was significant for whole-tree wood MC (Table 2; Figure 5), with trees from the South Atlantic Coastal Plain having lower MC than trees from the Piedmont. Treatment and the interaction between region and treatment did not significantly affect wood MC. Significant treatment effects were observed for green weight of wood and bark/m^3 (Table 2) with significantly higher wood and bark weight for trees from the control plot compared to trees that received the fertilization alone and both herbicide and fertilizer together (Figure 5).

FastLob Study

A marginal treatment difference was observed for whole-tree bark percentage (Table 2), with a higher bark percentage observed for trees from an initial spacing of 988 TPH compared to 1,977 TPH (Figure 4). No difference was observed among treatments for any other bark and wood properties (Figures 4 and 5).

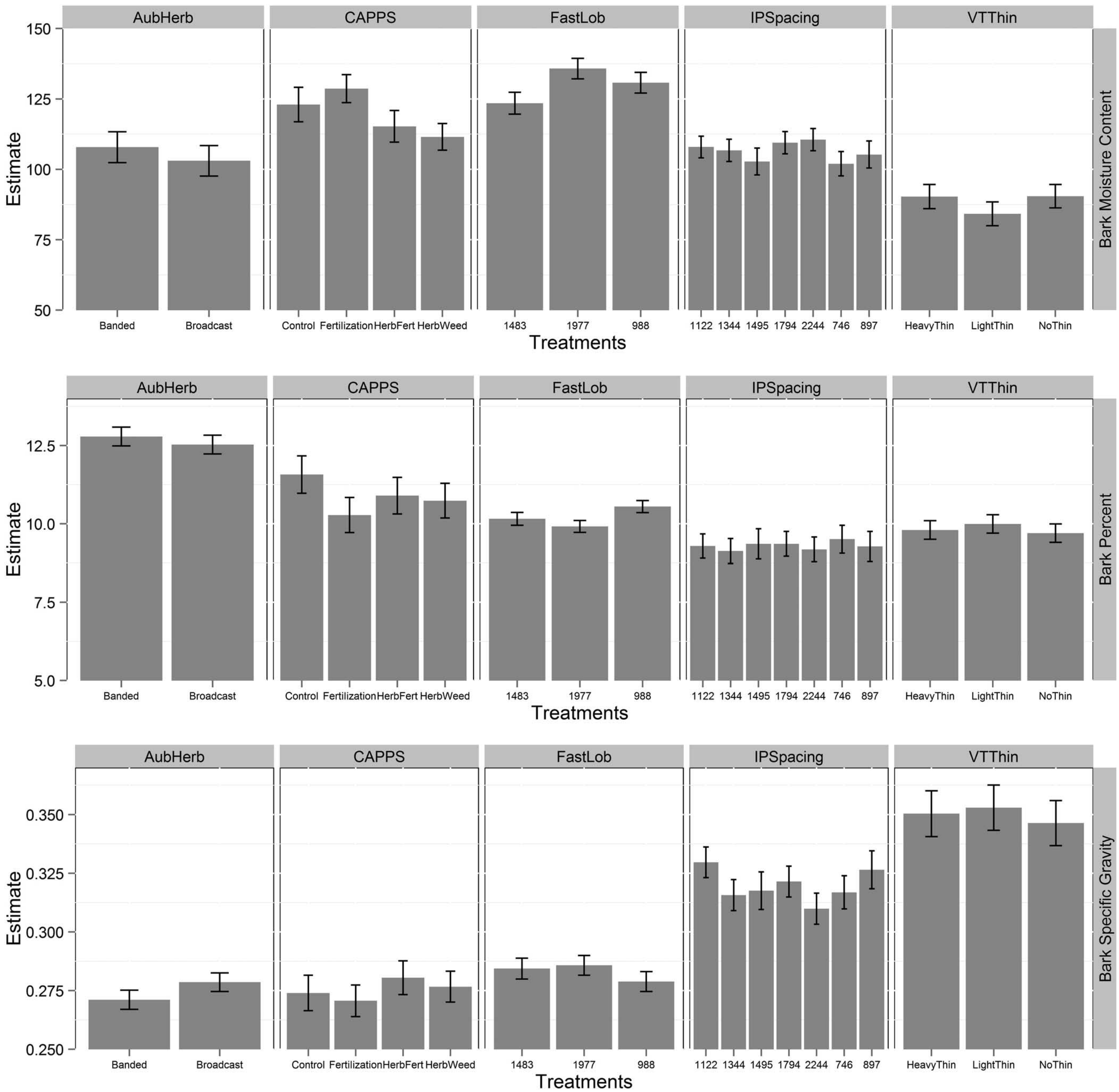

Figure 4. Estimated mean with standard error (± 1) for bark properties by treatments from various intensively managed studies. Here, FastLob and IPSpacing studies were spacing trials and treatments were initial planting density in trees per ha.

VTThin Study

The interaction of region by treatment was significant for whole-tree bark percentage (Table 2), but no difference was observed among treatments within each region on further analysis. The main effects of thinning and region were absent for whole-tree bark percentage (Table 2; Figure 4). A marginal regional effect was observed for whole-tree bark SG (Table 2), with trees from the South Atlantic Coastal Plain having higher bark SG than Piedmont trees. However, the effect of thinning and the interaction between thinning and region on bark SG was absent. The effect of thinning, region, and their interaction was absent for bark MC.

A significant regional difference was observed for whole-tree disk SG (Table 2), with trees from the South Atlantic Coastal Plain having higher disk SG than Piedmont trees. Marginal differences in whole-tree SG were also observed between trees from the Piedmont versus Hilly Coastal Plain. The interaction between region and treatment and the main effect of treatment was not significant for whole-tree wood SG. The main effect of region, treatment, and their interaction (region by treatment) were not significant for whole-tree wood MC, green weight of wood/m^3, and green weight of wood and bark/m^3 (Figure 5).

Discussion

Wood properties, primarily SG, of loblolly pine and their variation within-tree and across the physiographical range have been

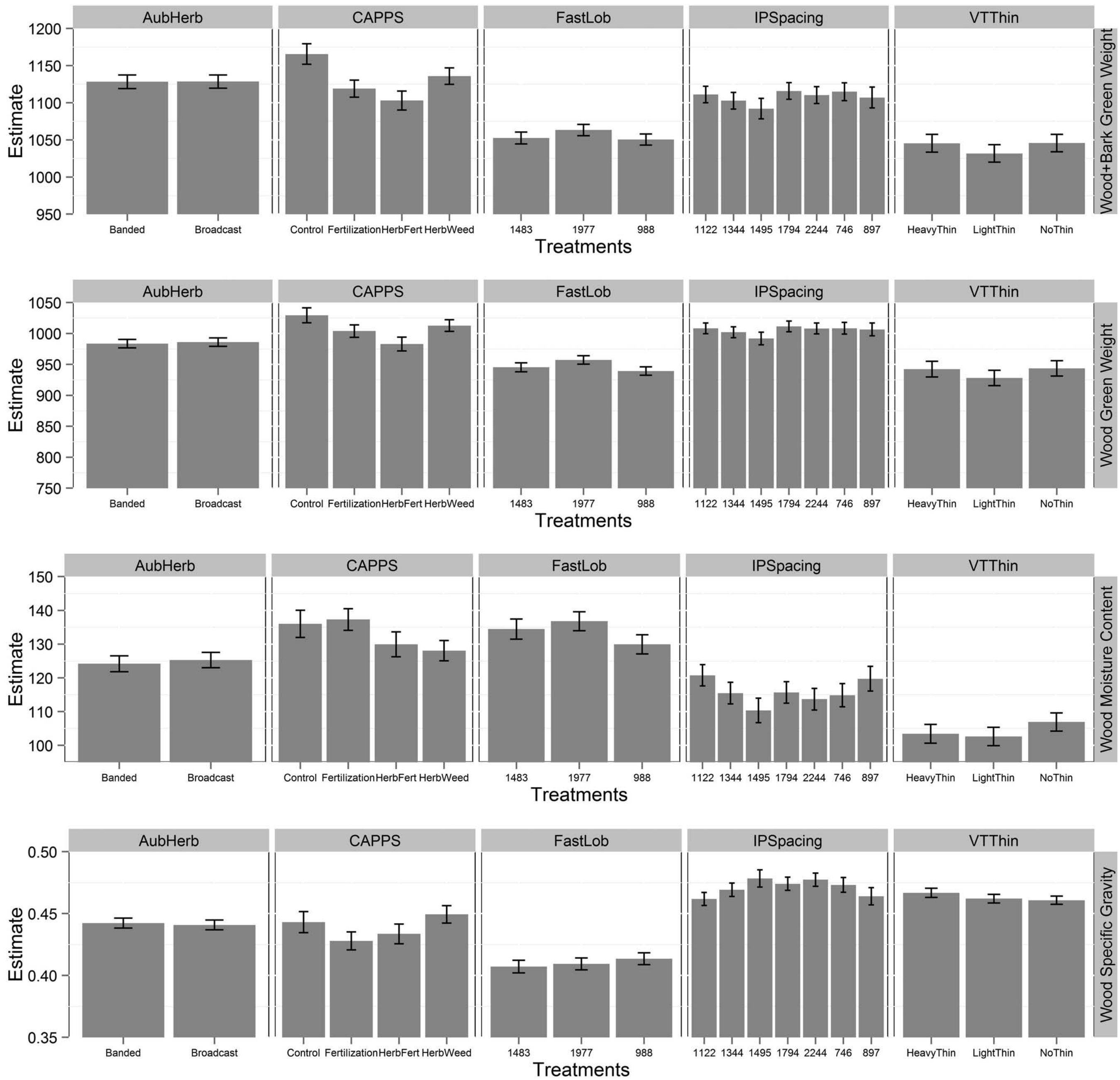

Figure 5. Estimated mean with standard error (± 1) for wood properties by treatments from various intensively managed studies. Here, FastLob and IPSpacing studies were spacing trials and treatments were initial planting density in trees per ha.

reported in several past studies (Megraw 1985, Zobel and van Buijtenen 1989, Clark and Saucier 1989, McAlister et al. 1997). Many recent studies have examined the within-tree variation (from pith-to-bark and stump-to-tip within a tree) of SG (Daniels et al. 2002, Jordan et al. 2008, Antony et al. 2010), microfibril angle (Jordan et al. 2006, 2007) and mechanical properties (Antony et al. 2011b) of loblolly pine. The effect of silvicultural practices on loblolly pine ring wood SG has also been studied by several authors (Clark et al. 2004, 2006, 2008, Antony et al. 2009a, 2009b, Love-Myers et al. 2009, Antony et al. 2011a, 2011c). These studies have addressed the within-tree variation (stump-to-tip and pith-to-bark variation) of wood SG, microfibril angle, stiffness and strength of loblolly pine, and not the bark property variation or wood MC variation, despite the importance of these traits for utilization of resources. Though information on within-tree SG variation is available, wood growers and buyers are more likely concerned with whole-tree bark and wood properties than within tree property variation (e.g., ring-by-ring-level variation as reported in cited studies) for their decision-making and transactions. In this article, we have compiled data collected by the WQC over the years to summarize the whole-tree bark and wood properties of loblolly pine from both conventionally and intensively managed stands distributed across the natural range of loblolly pine.

Limited information about regional variation in bark and wood properties, except wood SG, of loblolly pine is available in the literature. Most of the available information is based on old-growth plantations established using completely different planting materials and silviculture than those currently being used. This study is especially timely because it is based on a large number of samples from trees that "best" represents current silvicultural practices across the native range of loblolly pine. Based on the analysis of data collected from conventional and intensively managed loblolly pine stands, we observed significant regional trends in bark and wood properties. Bark and wood SG was lower for trees from most of the inland areas compared to coastal regions, and we observed a decreasing trend in bark and wood SG in a northwest direction. It was observed that trees from the South Atlantic, and the Upper and Gulf Coastal Plains have higher wood SG than trees from the Piedmont, the North Atlantic, and Hilly Coastal Plains. The trend in wood SG variation across the loblolly pine natural range agrees with that reported by others (Zobel and van Buijtenen 1989, Jordan et al. 2008, Antony et al. 2010). The observed regional variation in bark SG also agreed with previous studies of loblolly pine (Phillips and Schroeder 1972). Unlike SG, higher bark and wood MC for trees from the inland, especially Piedmont and Hilly Coastal Plain, indicated an increasing trend in MC in the northwest direction. Regional differences in SG and MC were attributed primarily to site-to-site variation in climate and soil conditions. Environmental variables, primarily water availability and temperature, significantly influenced the temporal variation in wood properties (Drew et al. 2009). The high wood SG of coastal plain trees is mainly due to a high latewood percentage, which is caused by high summer precipitation in this region and a long growth period (Clark and Daniels 2002). As reported by Koch (1972), an inverse relation between SG and MC exists because wood with high SG is less porous and holds less water than low SG wood. The condition of the soil also plays a role in the variation of SG and MC within trees. To corroborate this, Gibson et al. (1986) reported the influence of site on wood and bark SG and MC of four major southern US pine species from three sites in Louisiana. Based on their study, wet sites (poorly drained soil) produced wood with low SG and high MC compared to dry sites (well-drained soil). They also observed a high bark SG on wet sites.

Despite large variation in wood SG and MC, regional variation in wood green weight was marginal, which was essentially due to the inverse trends of wood SG and MC variation (Figures 2 and 3). If the SG of wood is assumed to be constant, then variation in wood MC is the only factor that drives variability in the green weight of wood across the region, and it should be accounted for during tree weight scaling. In addition, a regional trend in wood plus bark green weight was evident, with trees from the South Atlantic Coastal Plain having the highest green weight followed by Upper Coastal Plain trees. Unlike our results, Bullock (2002) reported no difference in green weight of wood and bark of loblolly pine sampled from east Texas, central Louisiana, Piedmont Georgia, and Piedmont and Coastal Plain Virginia. This study, however, was based on a limited sample size.

Intensive silviculture was reported to have a negative impact on wood quality, either through increasing the proportion of low quality juvenile wood (early age application of silviculture treatments) (Clark et al. 2004) or by significantly altering pith-to-bark wood property profiles (for example, decreasing SG and increasing microfibril angle) (Antony et al. 2011c). Here, we presented the effect of different silvicultural practices on whole-tree bark and wood properties. Notable among the studies was the CAPPS study, where trees received early age herbaceous weed control and multiple application of fertilizer. It is evident from the CAPPS result that treatments of such intensity might considerably impact the percentage bark and green weight of wood plus bark for loblolly pine. On the other hand, the effect of silvicultural treatments on whole-tree bark and wood properties were generally absent, especially herbaceous weed control, initial planting density, and thinning. The effect of silvicultural treatments may not be expressed on a whole-tree basis except in situations where trees are managed intensively (for example, the CAPPS study). Local responses within a tree may occur (such as annual rings produced following midrotation fertilization) but the overall effect of the response when determined on a whole-tree basis was small. One example would be a decrease in latewood SG (LWSG) following midrotation fertilization in loblolly pine (Antony et al. 2009a, 2011c).

The wood and bark properties in this study showed considerable variability from stand to stand. In addition, significant tree-to-tree variability was also evident for wood and bark properties, based on estimates of residual variance. The compiled data could be used for answering questions related to wood and bark property variation (regional and within tree), however, it should be noted that the trees are sampled from plantations with different management histories and ownerships. Although attempts were made to sample from stands that were managed similarly and were uniform (e.g., Baseline study), some information about these stands was still missing. For example, information was lacking about the genetic material used in each study (except the IPSpacing study). The large stand-level variation observed in this study might be due partly to differences in planting material used, environmental conditions, and genotype by environment interactions (Byram and Lowe 1988, Jett et al. 1991, Zobel and Jett 1995). In the past, studies identified the variability of seed source materials across the geographic range of loblolly pine (Byram and Lowe 1988, Jett et al. 1991); further studies are required to identify the phenotypic (both growth and wood properties) performance of different genotypes across the growing range of loblolly pine. For intensively managed stands, few studies (e.g., CAPPS and VTThin) have sampled stands from a range of geographical locations. Generalization of conclusions regarding silviculture across loblolly pine growing range is not possible on wood properties until more stands can be sampled. In summary, significant regional variation in bark and wood properties were evident at the whole-tree level. Any effect of silvicultural treatments on whole-tree bark and wood properties was restricted to situations where trees received weed control and multiple fertilizer treatments. Responses in bark and wood properties following a single application of a treatment such as early age weed control, thinning, and/or midrotation fertilization were absent at the whole-tree level.

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