WOOD VARIABILITY IN MATURE LONGLEAF PINE: DIFFERENCES RELATED TO CARDINAL DIRECTION FOR A SOFTWOOD IN A HUMID SUBTROPICAL CLIMATE[1]

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(Received February 2018)

Abstract. Mature longleaf pine (*Pinus palustris* Mill.) trees were harvested to compare wood property data for opposing bark-to-pith wood strips representing the northern and southern cardinal (or compass) directions. For each of the ten 70-yr-old trees used in the study, wood property data were compared at breast height (BH) and three relative heights: one-quarter height (1Q), midheight (MID), and three-quarter height (3Q). Scanning of the specimens by X-ray densitometry gave specific gravity (SG) profiles that were used to determine wood properties for comparison. No significant differences were determined for wood property data at BH, MID, or 3Q. However, data at 1Q showed higher ring SG ($p = 0.043$) and percent latewood ($p = 0.018$) for the northern side, although no differences were observed in the earlywood or latewood SG. This indicated that the higher ring SG for the northern direction results from a greater proportion of latewood. Partitioning the data into estimated juvenile-transition wood and mature wood zones demonstrated that the greater ring SG and percent latewood values in the northern direction occurred within the mature wood zone. Findings presented herein appear to provide the first demonstration of variation in wood properties with respect to cardinal direction for a pine species growing in a humid subtropical climate.

Keywords: Environmental impact, longleaf pine, radial profile, wood properties, wood quality.

INTRODUCTION

The southeastern United States produces more than one half of the country's volume of timber (Wear and Greis 2012). Among all of the southern pine species in the region, loblolly pine (*Pinus taeda* L.) is by far the most abundant across the current landscape. This was not always the case, with loblolly pine being a minor species before colonial settlement, often relegated to wet sites because of its susceptibility to fire when young (Schultz 1999). Indeed, at the time of colonial settlement, the southern pine forest was predominated by longleaf pine (*Pinus palustris* Mill.). Although efforts to restore

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Wood and Fiber Science, 50(3), 2018, pp. 323-336
https://doi.org/10.22382/wfs-2018-031

longleaf pine ecosystems are ongoing, the widespread occurrence of loblolly pine will undoubtedly remain from this point forward, with this pine species favored for planting because of rapid growth and adaptability to a wide range of sites (Schultz 1999; Shiver et al 2000); however, longleaf pine restoration efforts could double the area of this ecosystem type, from 3% to 6%, over the next few decades (Van Lear et al 2005). Restoration on private lands is incentivized by timber harvests (Landers et al 1995), warranting studies on the growth, yield, and wood properties of this renewed timber resource.

Given the aforementioned importance of the southern pine resource, significant effort has been expended toward assessments of loblolly pine solid wood (Jordan et al 2008; Antony et al 2015; Butler et al 2016) and fiber (Groom et al 2002a, 2002b; Mott et al 2002) properties. In a limited number of cases, variability of longleaf pine wood was investigated (Via et al 2003, 2009). Sampling schemes for wood property assessments typically involve the removal of wood cores at breast height (BH), thereby providing a practical means for widespread sampling to obtain representative data sets. Often such studies subject a subset of trees to destructive sampling, with disks cut from felled trees at regular distances measured along the tree bole; whole-tree mapping of wood properties has been reported for single trees and pooled data from several trees. Note that when sampling at BH, minor deviations from that height may be necessary to avoid branches (Mansfield et al 2009). In the vast majority of studies involving the collection of wood cores at BH, the process of collecting tree cores is often not specified, and particularly, whether any attention was given to sampling from a specific cardinal (or compass) direction. Thus, an increment borer entry point may be taken from a chosen cardinal direction, at a position in which a knowledgeable field worker can generate a core from bark to pith (ie across the widest diameter), on the uphill side of the tree at the point for determining the diameter at breast height (dbh), or randomly as a matter of convenient access to the tree. Further processing of wood cores, and wood disks, can afford thin strips of wood from bark to pith for scanning by X-ray densitometry, thereby generating wood specific gravity (SG) profiles to measure the SG for individual rings and the contributions from varying proportions of earlywood and latewood; note that for wood, the term density is often used interchangeably with SG. The various X-ray densitometry techniques available to scan wood specimens were recently reviewed by Jacquin et al (2017).

It is well documented that softwood species produce compression wood, and that this phenomenon results in asymmetries in the cross section of a tree stem (Timell 1986). In those circumstances, compression wood is readily distinguishable when looking at the cross section, and there is usually an obvious cause (eg a leaning stem). Apart from the occurrence of compression wood, the symmetry of a stem cross section is often not perfectly round, and this, along with other stem features (taper, sweep), impacts utilization (Tong and Zhang 2008). Mäkinen (1998) studied stem eccentricity in *Pinus sylvestris* and concluded that the orientation of the longest bole radius could not be associated with cardinal direction, slope direction, or wind direction; however, in that study, and subsequent work (Mäkinen and Vanninen 1999), it was acknowledged that the greatest bole radius was on the southern side of the stem. A limited number of studies in the older literature are discussed in Zobel and van Buijtenen (1989) and suggest that greater growth on the southern side of the tree, if any, may result from earlier cambial activity, particularly in temperate climates with the basic density of Norway spruce (*Picea abies*) wood being slightly higher on the southern side (Olesen 1973). In a recent study by Zeidler and Šedivka (2015), orientation (direction) provided a very minor contribution to the wood density variability for *Abies grandis* wood compared with tree width and height. Nevertheless, the density was found to be significantly higher ($p < 0.01$) on the southern side, even though the difference was small (400 vs 410 $kg \cdot m^{-3}$). Applying a resistance technique for the determination of wood density along the trunk of spruce (*Picea abies*), fir (*Abies alba*), and pine (*Pinus sylvestris*) trees grown in a common stand in the Czech Republic, Kloiber et al (2012) observed that density differences for the four cardinal directions were not statistically significant (based on Duncan's testing) and attributed this to the closed canopy conditions. Similarly, the same authors reported that the impact of the four cardinal directions on mechanical properties was not significant for selected trees grown in an approximately 100-yr-old stand with dense crown closure (Tippner et al 2016).

Studies on the cardinal direction of trees in temperate climates are indeed scarce and no such studies have been found in the literature for trees in a humid subtropical climate in the Northern Hemisphere, specifically in the southern United States. Notwithstanding, curious findings were obtained with longleaf pine where bark thicknesses were found to be greater on the northern side (Eberhardt 2013, 2015); no differences were observed in comparisons between eastern and western cardinal directions (Eberhardt 2013). In a preliminary investigation of wood disks from the same sample set of trees (So et al 2018), no significant differences in wood properties and ring width were obtained at BH; however, when including the data from all disks collected along the tree boles, ring SG was found to be slightly higher for the northern direction. Although ring width was not found to be significantly larger ($p = 0.096$) with whole-core data, partitioning the data into predominantly juvenile-transition wood and mature wood zones gave a seemingly higher northern ring width (1.83 vs 1.71 mm) with a probability value ($p = 0.058$) falling just short of statistical significance ($p < 0.05$). Given the potential for north vs south asymmetries in longleaf pine tree boles, ring width and wood property data were determined by analyzing wood strips at specific relative tree heights, with the primary objective being to assess whether cardinal direction variability may indeed occur in a pine species growing in a humid subtropical climate.

MATERIALS AND METHODS

Study Trees

Ten 70-yr-old longleaf pine (*Pinus palustris* Mill.) trees were harvested during a thinning operation in a spacing, thinning, and pruning study site in the Palustris Experimental Forest, LA (N31.176°, W92.677°). Soils are moderately drained, acidic, low in organic matter, and classified as Malbis fine sandy loam. The average annual rainfall at the site is 146.5 cm, with a fairly even monthly distribution; the average temperature at the site is 22°C, typically ranging from −5 to 35°C. Trees were selected to cover a range of dbh values (14.5-49.8 cm) and total heights (17.6-27.5 m); tree-specific data are shown in Table 1. At the time of harvest, the crown class was determined with one tree each as being dominant, intermediate, or suppressed and the remainder of the trees (seven total) being codominant. Although the treatments for the harvested trees were known, it was well beyond the scope of the present study to make any definitive assessments of the effect of treatment (eg spacing, thinning) on tree growth and wood property data, given the limited number of trees subjected to destructive sampling. Note that *t*-tests performed on dbh and height data showed that the study trees were a representative subsample of the trees harvested during the thinning operation and the preharvest population of trees in the stand.

Tree Harvesting and Disk Collection

Before felling, the trees were marked to identify the northern cardinal direction. Trees were felled, delimbed, and bucked with a chainsaw to give 5-cm-thick disks cut at stump height, followed by 77 cm, and then every 61 cm along the tree bole,

Table 1. General characteristics of 70-yr-old longleaf pine trees used in study.

Tree number	Diameter at breast height (cm)	Total height (m)	Height to live crown (m)	Diameter at live crown (cm)
1	49.8	25.5	11.8	40.9
2	33.0	27.3	17.9	17.3
3	36.8	26.3	15.4	23.6
4	14.5	17.6	14.0	5.8
5	42.7	26.6	14.8	30.7
6	42.2	26.3	18.4	22.1
7	26.2	27.5	20.0	13.2
8	34.8	22.9	13.1	20.8
9	34.0	25.4	15.5	27.2
10	28.7	26.2	19.8	12.7

including BH. Each disk was assigned a unique number for identification and marked as such to retain cardinal directions (eg north, south, east, and west). A wood strip (1 cm × 1 cm) was sectioned along a north-to-south line, through the center of each disk, encompassing the pith. Both as wood disks and later as wood strips, specimens were allowed to dry under ambient conditions in an air-conditioned laboratory with good airflow. Only the disks taken at BH, one-quarter height (1Q), mid-height (MID), and three-quarter height (3Q) were analyzed in this present study. The 3Q height was within the live crown (Table 1) for most of the trees. In three instances, the next disk above was used to avoid a 3Q disk with major defects.

Wood Specimen Processing

The bark-to-pith wood strips were soaked in acetone at room temperature to remove resinous extractives (Eberhardt and Samuelson 2015). Bark adhering to the specimens was not removed. Using a crosswise pattern, the wood strips were carefully positioned in a large glass tank and held in place with a perforated ceramic disk serving as a weight. Over a 2-wk period, the spent solvent was periodically removed every second or 3rd day with a siphon, followed by the addition of fresh solvent. Spent solvent was recycled by rotary evaporation and redistillation. Only a small trace of solid residue was recovered from the spent solvent from the final extraction cycle; this indicated that the extraction process was complete.

Extractive-free wood strips were placed in core holders machined from yellow poplar wood, dried (50°C, 24 h), and then permanently glued (Gorilla Glue, Cincinnati, OH). Mounted cores were sawn into 2.3-mm-thick strips, from bark to pith, ensuring that the transverse surface of the specimen, bordered by adhering wood from the core holders, would be orthogonal to the X-ray beam.

X-ray Densitometry

Densitometry was performed using a Quintek Measurement Systems X-ray densitometer (Knoxville, TN) to measure SG values at 0.06 mm intervals. An SG of 0.48 was used to differentiate between earlywood and latewood zones (Koubaa et al 2002; Clark et al 2006; Antony et al 2012). Specimens were scanned along the radial direction from bark to pith and the data automatically processed to provide wood properties (ring SG, earlywood SG, latewood SG, percent latewood) and width for each growth ring. Densitometer calibration was on a green volume and oven-dried mass basis.

Statistical Analysis and Curve Fitting

Wood properties (eg ring SG, latewood SG) were averaged at each ring number for the 10 trees and plotted using PROC GPLOT (SAS/STAT 9.3, Cary, NC). Data points were excluded when only one tree represented a given ring number, as observed with the highest ring numbers. Curve fitting was also applied using a cubic spline fitted by the method of Reinsch (1967) with a smoothing factor of 60. A smoothing factor can be between 0 and 99 with higher values producing smoother curves (SAS/STAT 9.3). For statistical analysis, wood properties were weighted by ring area, for each ring number, to obtain a mean basal area–weighted whole-core value for each tree, in each direction, at each sampling position. These two values for each tree were used in a paired t-test to determine the significant difference by direction and averaged to show how they compare. This was also repeated for the herein designated juvenile wood ($\leq$20 rings) and mature wood ($>$20 rings) zones, with said juvenile wood zone likely including some transition wood. Paired t-tests were conducted using PROC MEANS (SAS/STAT 9.3) with $p < 0.05$ used as the criterion for significance.

RESULTS AND DISCUSSION

The objective of this study was to assess whether there were significant differences in wood properties between the northern and southern cardinal directions for mature longleaf pine at four heights (BH, 1Q, MID, and 3Q). Similar data selection was used for comparisons of northern and southern directions for *Abies grandis* and involved disks representing the basal, middle, and crown segments of the tree (Lukšáek et al 2012; Zeidler and Šedivka 2015). Values for the wood properties are presented here as basal area–weighted whole-core values, averaged for the tree disks at each of the four heights. Ring SG, earlywood SG, and latewood SG were previously reported to be similar between the northern and southern directions for the disks taken at BH (So et al 2018); these data are included in Table 2 for comparison. It should be noted that the sample size for trees subjected to destructive sampling is often smaller than field-sampling regimes involving the collection of wood cores at BH alone. North–south differences were noted by Trendelenburg (1935) on a full stem map generated for a single tree; statistically significant north–south differences have been observed with as few as four trees (Zeidler and Šedivka 2015). Perhaps, the most comprehensive study on north–south differences, at different relative heights, was conducted by Olesen (1973) with 26 trees. In the present study, the data from the 10 trees used were compared by paired *t*-tests to limit tree-to-tree variability from obscuring the detection of differences with our given sample size.

Moving up the tree bole, the disks taken at 1Q height showed significant differences in both ring SG ($p = 0.043$) and percent latewood ($p = 0.018$), in which higher values were obtained in the northern direction. Because values for percent latewood generally coincide with ring SG (Clark and Saucier 1991; Tasissa and Burkhardt 1998), it would be inconsistent to see a difference in one of these values and not the other. No differences were observed in the earlywood SG or latewood SG, thereby, indicating that the higher ring SG for the northern direction resulted from a greater proportion of latewood and not differences in the mean values for earlywood SG and latewood SG. Note that greater ring SG at lower latitudes is associated with longer growing seasons and extended photosynthate production in loblolly pine (Jokela et al 2004; Samuelson et al 2013). Cell formation ceases during winter dormancy of the southern pines but photosynthesis (Gough et al 2004) and cell wall thickening continues (Nix and Villiers 1985). With the likelihood of warmer temperatures along the southern side of the tree, it would be counterintuitive to suggest greater winter metabolic activity on the northern side of the tree bole. Because no difference was observed in ring width between the northern and southern directions, the greater percentage latewood would not appear to result in protracted cambial activity

Table 2. Paired *t*-test for effect of direction on wood property and ring width data, including mean values, standard deviations (in parentheses), and probabilities (*p*) of rejecting the null hypothesis for the whole core.

Relative height	Direction	Ring SG	Latewood SG	Earlywood SG	Percent latewood	Ring width (mm)
BH	North	0.580 (0.031)	0.774 (0.028)	0.346 (0.020)	54.8 (5.0)	2.81 (0.73)
	South	0.577 (0.040)	0.767 (0.038)	0.349 (0.017)	54.5 (6.9)	2.68 (0.67)
	Difference	0.003 (0.020)	0.007 (0.028)	0.003 (0.014)	0.3 (5.0)	0.13 (0.35)
	p	0.650	0.479	0.526	0.860	0.267
1Q	North	0.531 (0.025)	0.747 (0.039)	0.330 (0.014)	48.1 (4.2)	2.64 (0.61)
	South	0.517 (0.028)	0.743 (0.049)	0.329 (0.012)	45.2 (3.6)	2.80 (0.83)
	Difference	0.014 (0.019)	0.004 (0.036)	0.001 (0.008)	2.9 (3.2)	0.16 (0.37)
	p	**0.043**	0.728	0.545	**0.018**	0.199
MID	North	0.511 (0.017)	0.738 (0.032)	0.328 (0.020)	44.3 (4.1)	2.51 (0.56)
	South	0.499 (0.021)	0.717 (0.033)	0.332 (0.021)	43.9 (6.0)	2.53 (0.50)
	Difference	0.012 (0.029)	0.021 (0.035)	0.004 (0.013)	0.4 (4.2)	0.02 (0.66)
	p	0.247	0.087	0.323	0.807	0.526
3Q	North	0.507 (0.037)	0.699 (0.029)	0.344 (0.031)	46.3 (8.8)	2.28 (0.63)
	South	0.500 (0.033)	0.687 (0.033)	0.337 (0.030)	47.2 (9.2)	2.20 (0.63)
	Difference	0.007 (0.041)	0.011 (0.045)	0.007 (0.031)	0.9 (12.6)	0.08 (0.36)
	p	0.595	0.470	0.552	0.832	0.549

Significance ($p < 0.05$) is in boldface. SG, specific gravity; BH, breast height; 1Q, one-quarter height; MID, midheight; 3Q, three-quarter height.

for the northern direction, particularly that occurring later into the growing season until winter dormancy.

Notwithstanding, the onset of latewood formation and the formation of false rings are associated with reduced moisture availability. However, if moisture is provided late in the growing season, wood formation continues, affording higher ring SG (Gonzalez-Benecke et al 2010). No attempt was made to determine the MC of the wood as carried out in other studies with whole disks (Antony et al 2015; Eberhardt et al 2017). Measurements of inner and outer bark thicknesses for longleaf pine from the same study site were previously conducted on intact disks (Eberhardt 2013) and gave greater inner and outer bark shrinkage in the northern cardinal direction; this was attributed to higher inner and outer bark moisture contents. By extension, if the MC of bark has any relationship to the MC of the wood beneath, greater latewood formation on the northern side could coincide with greater moisture availability, particularly if later in the growing season. To the best of our knowledge, no study to date has attempted to discern any differences in wood MC (or shrinkage) relative to cardinal direction for standing trees or wood specimens. Guyot et al (2013) collected samples in all cardinal directions but pooled the data for MC; electrical resistivity tomography afforded east to west traces, but no statistical comparison between the cardinal directions was conducted.

Moving further up the tree bole, the wood SG data (Table 2) for both the MID and 3Q disks showed a trend similar to that for the 1Q disks, although this was not the case with the percent latewood and ring width data. Regardless, no further significant differences were observed between the northern and southern directions. It could be suggested that the differences noted for the 1Q disks are an anomaly; however, similar to other demonstrations of within-tree wood variability, different wood properties between compass headings may also vary with relative height. A preliminary whole-tree (all heights) analysis (So et al 2018) of the study trees showed that the ring SG in the northern direction was significantly ($p = 0.002$) higher than in the southern direction. The whole-tree analysis averaged up to 44 disks for each tree, as compared with the present study in which only one disk at each of the four heights was used for each tree. Demonstration of a whole-tree difference in the absence of a difference at BH is not without precedent. In a recent species comparison study between loblolly and slash (*Pinus elliottii*) pines, differences in wood physical properties were observed for the full data set using tree disks taken as 1.5-m intervals; however, no differences based on species were observed when using the disks at BH alone (Eberhardt et al 2017).

The potential north–south differences from pith to bark at each height was also examined both statistically (Tables 3 and 4) and visually (Figs 1-4) after partitioning the data into that assigned to juvenile and mature wood zones. The juvenile (and transition) wood zone was set at ring number 20 and below. This was based on adaptations of the juvenile (and transition) wood to mature wood demarcations for loblolly pine, being the concurrent points at which ring SG and percent latewood data at BH begin to plateau in plots along cambial age (Clark et al 2006). In that study, thresholds for ring SG and percent latewood were assigned values of 0.5 and 50%, respectively, with these thresholds being crossed at similar cambial ages. In the present study, inflection points for ring SG and percent latewood data both occurred near ring number 20 at BH, providing evidence for a change in wood properties, designated as being indicative of the cessation of juvenile (and transition) wood formation. The alternative of using set thresholds was deemed inappropriate given that in the plot of the ring SG data at BH, the threshold of 0.5 was crossed near ring number one. It should be noted that the juvenile-to-mature wood transition is commonly reported to occur at a cambial age of 10 at BH in loblolly pine (Clark et al 2006), and herein, we recognize the possibility of some mature wood being within ring number 20 and below; however, the objective was to ensure that wood designated as mature wood was indeed only mature wood. Also, in a prior study (So et al

Table 3. Paired *t*-test for effect of direction on wood property and ring width data, including mean values, standard deviations (in parentheses), and probabilities (*p*) of rejecting the null hypothesis for the juvenile-transition (rings ≤20) core section.

Relative height	Direction	Ring SG	Latewood SG	Earlywood SG	Percent latewood	Ring width (mm)
BH	North	0.572 (0.038)	0.777 (0.041)	0.354 (0.021)	51.4 (6.8)	4.15 (1.21)
	South	0.571 (0.042)	0.765 (0.045)	0.358 (0.019)	52.1 (7.4)	4.15 (1.21)
	Difference	0.001 (0.043)	0.013 (0.036)	0.004 (0.020)	0.7 (10.0)	0.00 (0.58)
	p	0.950	0.291	0.539	0.825	0.995
1Q	North	0.514 (0.033)	0.749 (0.041)	0.331 (0.016)	43.1 (4.9)	3.91 (1.01)
	South	0.514 (0.036)	0.755 (0.048)	0.331 (0.015)	42.6 (3.7)	4.14 (1.23)
	Difference	0.000 (0.029)	0.006 (0.047)	0.000 (0.011)	0.5 (3.8)	0.23 (0.45)
	p	0.973	0.713	0.907	0.693	0.143
MID	North	0.497 (0.015)	0.732 (0.027)	0.329 (0.019)	41.3 (2.9)	3.50 (0.86)
	South	0.494 (0.030)	0.730 (0.020)	0.330 (0.021)	40.9 (4.8)	3.52 (0.80)
	Difference	0.003 (0.026)	0.002 (0.028)	0.001 (0.009)	0.4 (4.4)	0.02 (0.32)
	p	0.688	0.826	0.648	0.788	0.827
3Q	North	0.509 (0.043)	0.694 (0.033)	0.349 (0.028)	46.8 (11.3)	2.67 (0.88)
	South	0.498 (0.042)	0.683 (0.038)	0.345 (0.030)	45.9 (11.2)	2.49 (0.78)
	Difference	0.011 (0.042)	0.011 (0.053)	0.004 (0.032)	0.9 (13.9)	0.18 (0.40)
	p	0.482	0.559	0.728	0.853	0.219

Significance ($p < 0.05$) is in boldface. SG, specific gravity; BH, breast height; 1Q, one-quarter height; MID, midheight; 3Q, three-quarter height.

2018), juvenile and mature wood zones were already divided along ring number 20 to localize differences in the northern and southern directions for ring SG in the mature wood, and latewood SG in the juvenile wood, when using whole-tree data.

Figures 1-4 show the mean ring width and selected wood property means (ring SG, percent latewood, and latewood SG) plotted against ring number. A vertical line on each plot delineates data points attributed to approximated juvenile and mature wood zones. Consistent with ring widths being essentially the same between northern and southern directions at each of the four heights (Table 2), Fig 1 shows the north and south smoothed lines follow nearly identical traces, with ring width declining when moving from pith to bark for all four heights; this is consistent with the finding of a lack of significant

Table 4. Paired *t*-test for effect of direction on wood property and ring width data, including mean values, standard deviations (in parentheses), and probabilities (*p*) of rejecting the null hypothesis for the mature (>20 rings) core section.

Relative height	Direction	Ring SG	Latewood SG	Earlywood SG	Percent latewood	Ring width (mm)
BH	North	0.585 (0.038)	0.772 (0.031)	0.342 (0.021)	56.7 (5.8)	1.99 (0.44)
	South	0.581 (0.044)	0.770 (0.035)	0.343 (0.018)	55.7 (7.6)	1.82 (0.42)
	Difference	0.004 (0.023)	0.002 (0.034)	0.001 (0.014)	1.0 (3.6)	0.17 (0.27)
	p	0.577	0.887	0.803	0.426	0.084
1Q	North	0.544 (0.027)	0.748 (0.048)	0.329 (0.017)	51.4 (5.2)	1.72 (0.36)
	South	0.519 (0.030)	0.731 (0.056)	0.328 (0.014)	46.9 (5.2)	1.64 (0.65)
	Difference	0.025 (0.017)	0.017 (0.051)	0.001 (0.015)	4.5 (3.2)	0.08 (0.37)
	p	**0.001**	0.349	0.806	**0.002**	0.504
MID	North	0.524 (0.038)	0.743 (0.052)	0.327 (0.023)	47.0 (7.0)	1.53 (0.51)
	South	0.508 (0.018)	0.705 (0.046)	0.335 (0.030)	47.0 (7.4)	1.61 (0.50)
	Difference	0.016 (0.041)	0.038 (0.066)	0.008 (0.022)	0.0 (5.8)	0.08 (0.29)
	p	0.233	0.102	0.317	0.994	0.397
3Q	North	0.485 (0.069)	0.709 (0.024)	0.335 (0.037)	39.9 (15.8)	1.63 (0.54)
	South	0.471 (0.058)	0.698 (0.030)	0.320 (0.028)	40.1 (16.8)	1.70 (0.77)
	Difference	0.014 (0.032)	0.011 (0.043)	0.015 (0.031)	0.2 (7.7)	0.07 (0.42)
	p	0.211	0.508	0.171	0.929	0.603

Significance ($p < 0.05$) is in boldface. SG, specific gravity; BH, breast height; 1Q, one-quarter height; MID, midheight; 3Q, three-quarter height.

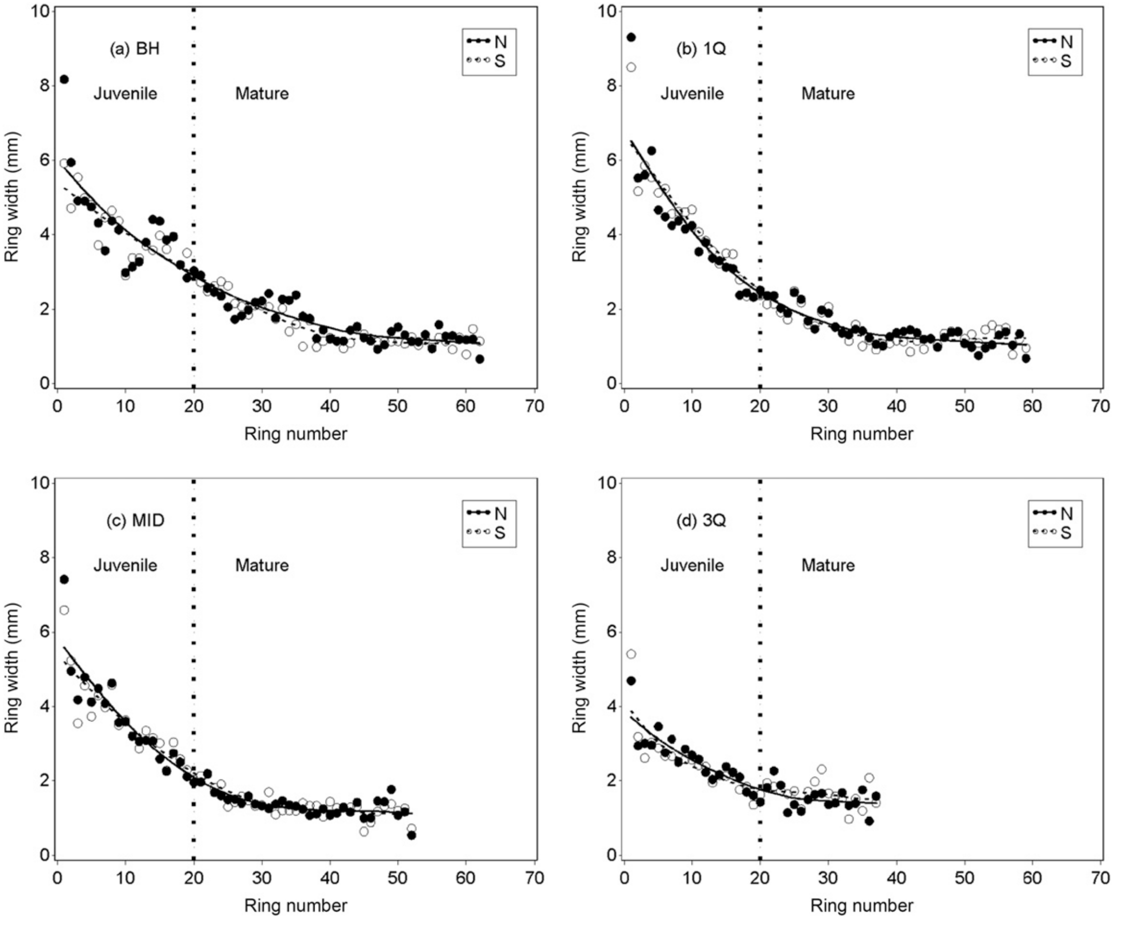

Figure 1. Plot of mean ring width as a function of ring number for (a) breast height (BH), (b) one-quarter height (1Q), (c) midheight (MID), and (d) three-quarter height (3Q) disks. Ring numbers ≤20 are predominantly, but not exclusively, juvenile wood.

differences between the northern and southern directions. The ring number at which ring width leveled off to a near constant value decreased with increased height from ring number ca. 45 for the BH disks (Fig 1[a]), to ring number ca. 25 for the 3Q disks (Fig 1[d]).

Ring SG values at BH for the northern and southern directions gave very similar traces (smoothed lines in Fig 2[a]). It is noticeable that the scatter for both sets of data points increases beyond the juvenile wood zone toward the bark and becomes more evident higher up the tree (Fig 2[b-d]). At each of the four heights, the total number of rings was not the same for all trees. Thus, for the highest ring numbers, the data points represented means of less than 10 values. Because single values for the highest ring numbers were discarded, each data point represents a mean value based on data for at least two trees. It should be noted that the outermost rings (adjacent to the cambium) contained earlywood only, thus affording low ring SG values for the outermost data points. In very mature pine trees, a decline in tree vigor has been suggested to lead to a plateau in ring SG followed by a decline toward the outermost growth rings (Xiang et al 2014). It is not known if this pattern is due to age or position in the tree (Spurr and Hsiung 1954); however, this pattern was demonstrated during

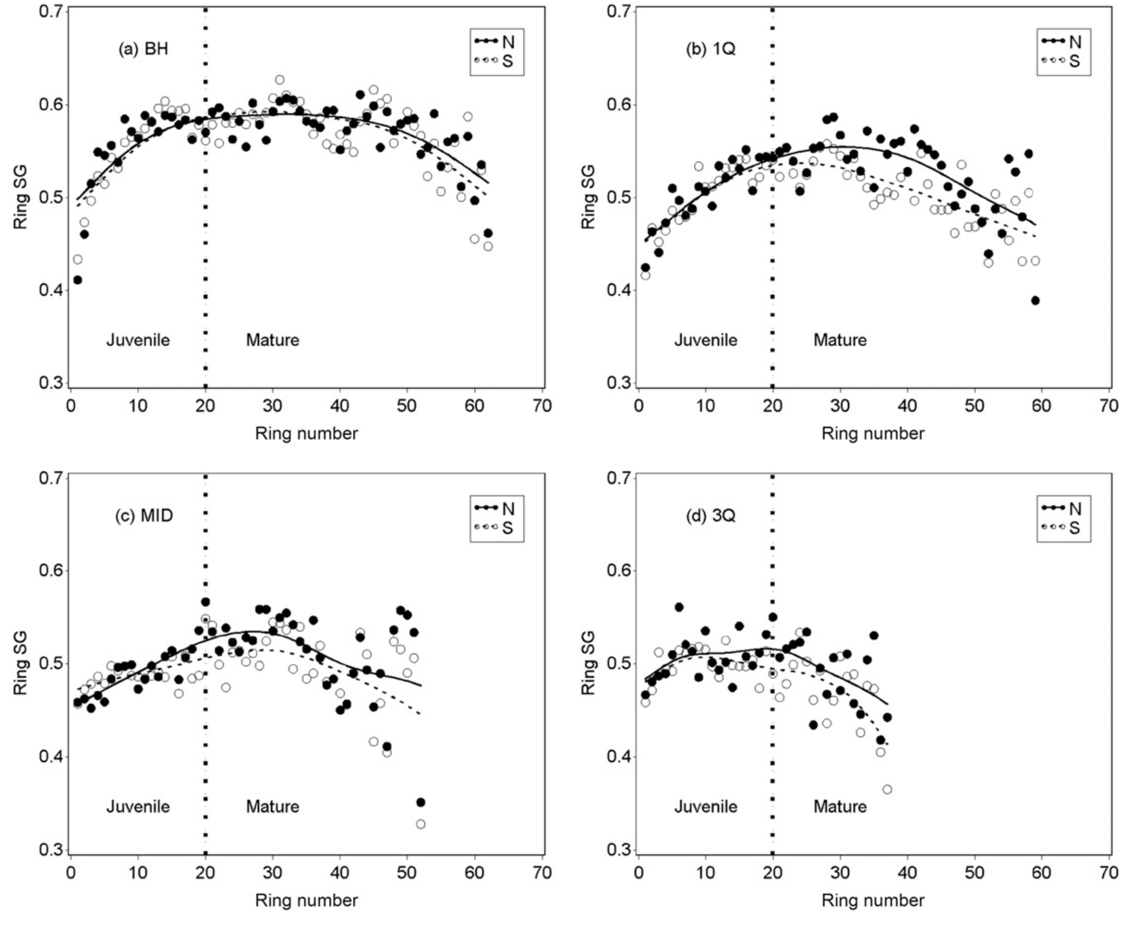

Figure 2. Plot of mean ring specific gravity (SG) as a function of ring number for: (a) breast height (BH), (b) one-quarter height (1Q), (c) midheight (MID), and (d) three-quarter height (3Q) disks. Ring numbers ≤20 are predominantly, but not exclusively, juvenile wood.

the earliest wood quality studies on the southern pines (Fernow 1896).

In the plots at 1Q, MID, and 3Q heights, the smoothed lines for the northern direction generally tracks higher than that for the southern direction beyond the juvenile wood zone. This is consistent with the ring SG data listed in the tables, in which the north–south difference is minimal in juvenile wood zone (Table 3), whereas higher ring SG values are obtained from the northern direction in the mature wood zone (Table 4). Although, the probabilities shown in Table 3 were notably higher than those in Table 4, those for the mature wood zone were generally not significant ($p > 0.05$). Indeed, a significant difference ($p = 0.001$) was only observed for ring SG (Table 4) with the mature wood zone for the 1Q disks. In the earlier study by So et al (2018) using the whole-tree data (up to 44 disks per tree), the northern direction provided significantly higher ring SG values in the mature wood zone ($p = 0.012$) as compared with the juvenile wood zone ($p = 0.511$), thus showing any differences in ring SG occurs in the mature and not the juvenile wood zone.

As to be expected, the plots for percent latewood (Fig 3) followed a similar pattern to those for ring SG. The percent latewood values in the mature

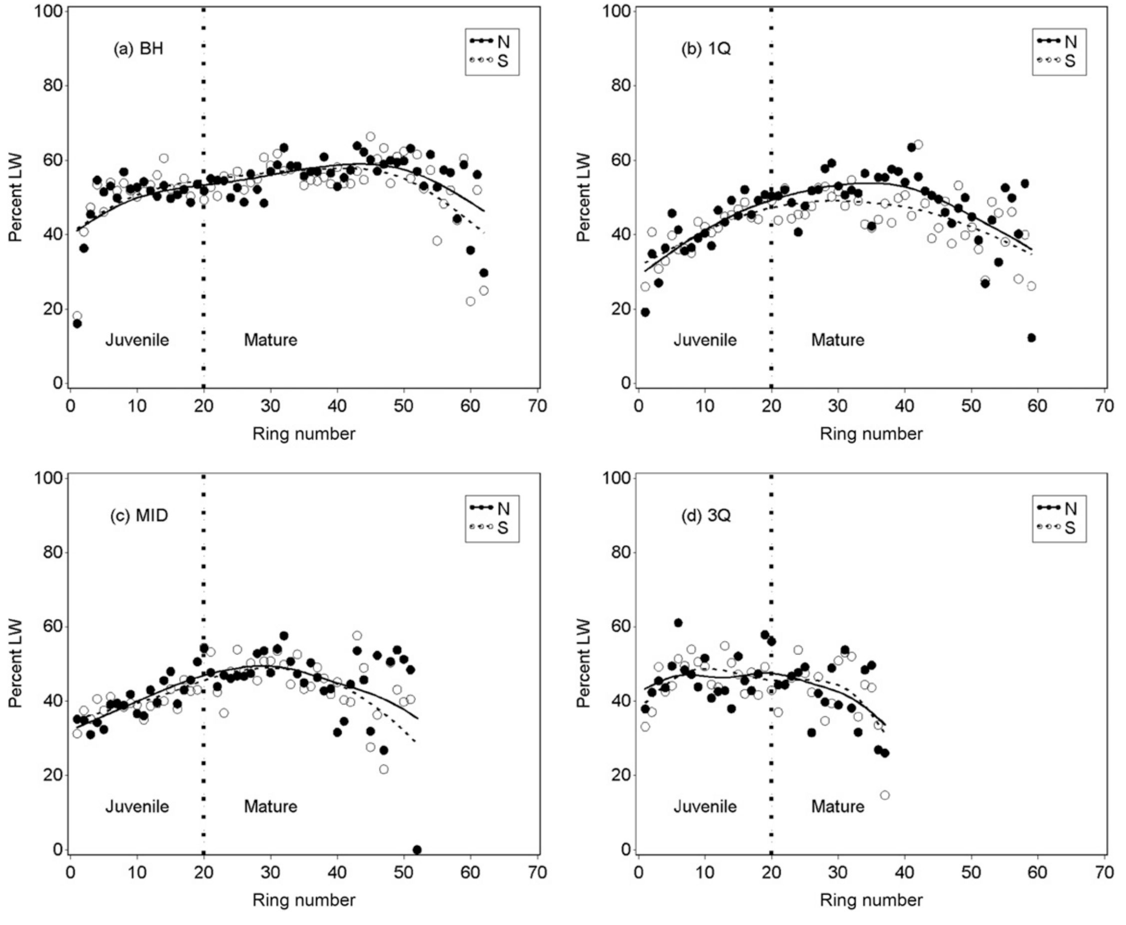

Figure 3. Plot of percent latewood (LW) as a function of ring number for: (a) breast height (BH), (b) one-quarter height (1Q), (c) midheight (MID), and (d) three-quarter height (3Q) disks. Ring numbers ≤20 are predominantly, but not exclusively, juvenile wood.

wood zone are seen to decrease with increasing height (Table 4) and the same is observed in the juvenile wood zone except at 3Q height, near the crown (Table 3). Parallel to the results for ring SG, percent latewood showed a significant difference ($p = 0.002$) in the mature wood zone of the 1Q disks (Table 4), but not in the juvenile wood zone (Table 3).

Plots for earlywood SG were generated and showed no obvious trend differences for cardinal direction (plots not shown); negligible north–south differences were observed in the earlywood SG values in both juvenile (Table 3) and mature (Table 4) wood zones. The plot of latewood SG provided curves that also showed minimal north–south differences at BH (Fig 4[a]). For the remaining higher disks (1Q, MID, and 3Q), the scatter of data points again increases into the mature wood, and although the differences appear minor in the juvenile wood, the latewood SG appears higher for the northern direction in portions of the mature wood zone (Fig 4[b-d]), although not to any significance (Tables 3 and 4) given how the data were partitioned. Although it is concluded that the higher ring SG for the northern direction results from a greater proportion of latewood alone, the latewood SG plots raise the possibility of temporal differences between the northern and southern direction.

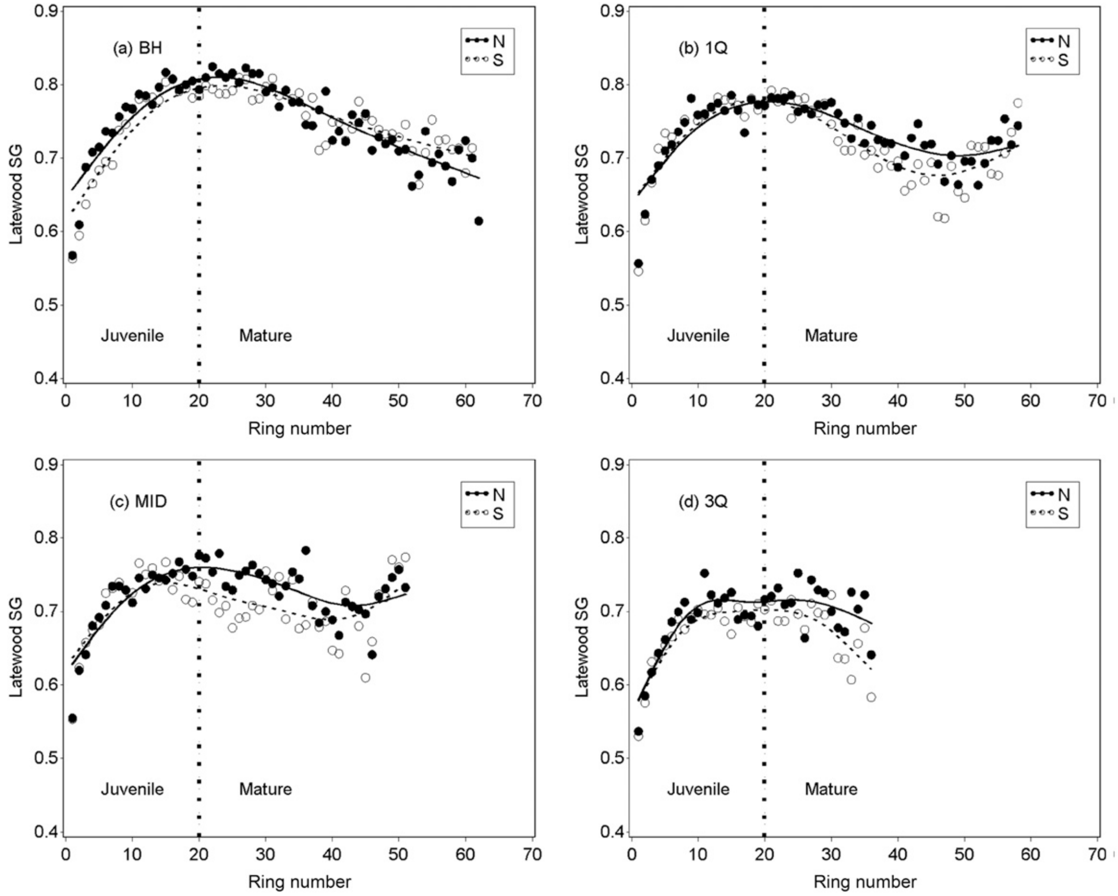

Figure 4. Plot of mean latewood specific gravity (SG) as a function of ring number for: (a) breast height (BH), (b) one-quarter height (1Q), (c) midheight (MID), and (d) three-quarter height (3Q) disks. Ring numbers ≤20 are predominantly, but not exclusively, juvenile wood.

The results presented here show that any differences in wood properties in relation to cardinal direction appear in the mature wood of these mature 70-yr-old trees. Tree maturity may be a factor, with studies showing differences having ages of 30-40 yr (Zeidler and Šedivka 2015) or 56 yr (Olesen 1973); the tree mapped by Trendelenburg (1935) had an age of 124 yr. The formation of juvenile wood in hardwood and softwood species is well documented (Zobel and Sprague 1998). Specific to the hard pines, juvenile wood is often shown schematically as either a perfect cylinder or ever so slightly wavering cylinder of wood from the base of the tree to the top, tapering into an exclusively juvenile zone in the crown (Zobel and Blair 1976; Clark and Saucier 1991; Zobel and Sprague 1998). This core of juvenile wood is surrounded by mature wood that tapers off until none is present where there is only "crown-formed" wood, essentially at the threshold ring number used to demark the onset of mature wood formation. Alternative descriptions of juvenile wood take into account the vertical maturity (Kibblewhite 1999; Burdon et al 2004) of the wood in addition to radial maturity. It is beyond the scope of the present study to unravel the complexities of juvenile wood formation; however, the point being made is that the variation in wood with respect to relative height could manifest in differences in wood properties and tree growth at different relative heights. This study indicates as much, with differences between the northern and southern cardinal directions, observed specifically for the 1Q disks, and not those at the other heights (BH, MID, and 3Q).

Unlike all of the prior reports regarding different wood properties for pines with respect to cardinal direction, the trees in the present study are not from a temperate climate, but from a humid subtropical climate at a lower latitude. It has been suggested that the observations of wood properties differing by cardinal direction are particular to higher latitudes (Zobel and van Buijtenen 1989). The present study suggests that this may not be entirely true; moreover, herein, at quite a low latitude by comparison, we found higher ring SG to be on the opposite side (ie in the northern direction, as opposed to southern direction as observed in temperate climates). If wood properties do demonstrate a spectrum of variability relative to latitude, results presented here would appear to suggest that differing climate factors (angle of sunlight, moisture, temperature) may have a measurable impact on tree growth and wood properties. Although prevailing winds can cause stem asymmetry through compression wood formation, in the North America, prevailing winds are from the west, not north or south. Furthermore, wind-caused compression wood occurs in coastal areas or high altitudes and is not typical inland, particularly in closed canopy stands (Timell 1986), as in the present study. Because the differences in wood properties in relation to cardinal direction appear to occur in the mature wood, sampling schemes investigating cardinal direction may be reserved to investigations of wood quality in mature pines. Nonetheless, studies are warranted to verify that differences relative to cardinal direction are not present in trees with short rotation ages typical of the southern pines.

CONCLUSIONS

Wood properties and ring width were compared between the northern and southern cardinal directions at different relative heights in mature longleaf pine trees. Data for the 1Q disks showed significant differences in both ring SG and percent latewood between the northern and southern directions. No differences were observed in the earlywood SG or latewood SG, thus indicating that the higher ring SG for the northern direction results from a greater proportion of latewood. Greater ring SG for southern pines is associated with longer growing seasons, but with the likelihood of warmer temperatures along the southern side of the tree, it would be counterintuitive to suggest greater winter metabolic activity on the northern side of the tree bole. Alternatively, moisture provided late in the growing season can afford higher ring SG; however, it would be highly speculative to suggest that possible higher MC in bark on the northern side is an indicator of greater MC of the wood beneath, affording greater latewood formation. Apart from any causal relationships, the present study appears to provide the first demonstration of variation in wood properties with respect to cardinal direction for a pine species growing in a humid subtropical climate.

ACKNOWLEDGMENTS

This material is based on work that is supported by the National Institute of Food and Agriculture, US Department of Agriculture, Hatch project under LAB04545 [CS]. This work would not have been possible without the efforts of Karen Reed, Michael Thompson and Edward Andrews (USDA Forest Service, Southern Research Station).

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