WOOD PROPERTY MAPS SHOWING WOOD VARIABILITY IN MATURE LONGLEAF PINE: DOES GETTING OLD CHANGE JUVENILE TENDENCIES?[1]

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Abstract. Established illustrations of juvenile wood in pines depict a central core of wood, varying little by diameter or cambial age, to be nested within mature wood tapering to the upper portion of the stem; alternative illustrations show greater complexity in attributing variability within this central core of wood to its proximity to the crown and/or the maturity of the tree when the wood was formed. The present study addresses the degree to which different representations of juvenile wood are applicable to a sampling of 70-yr-old longleaf pine (*Pinus palustris* Mill.) trees. Wood property maps were derived from X-ray densitometry data gathered from tree disks taken at every 61 cm along each tree bole. Unique to the wood property maps herein is that the two cardinal directions of the data (north and south) were preserved, thus providing true full-stem profiles. Compared with maps reported for younger southern pines, the central core of low-density wood extending the length of the tree boles was noticeably wider at the midheight than at the lower and higher relative heights. Another difference was that the higher ring specific gravity (SG) values, particularly at the lower heights, did not extend all the way to the wood closest to the bark. Narrower ring width and higher ring SG values above the 3Q height, normally being wood features associated with higher wood quality, can be attributed to the maturity of the study trees. Altogether, the wood property maps and data comparisons were consistent with an alternative juvenile wood illustration proposing that all the wood at the base of the tree, comprised of juvenile corewood and juvenile outerwood, as being different from the majority of the tree wood, upward from a one-quarter relative height.

Keywords: Corewood, juvenile wood, wood property maps, wood quality.

INTRODUCTION

The topic of juvenile wood, particularly for the southern pines, has been widely studied, given its increased contribution to the wood resource, coinciding with high forest productivity that allows for the harvesting of usable timber at short

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rotation ages. Herein, the term "juvenile wood" is used synonymously with "corewood," and although it is an "unfortunate misnomer" (Larson et al 2001), juvenile wood is still the most commonly used term in the scientific literature. Reviews of juvenile wood in the literature provide insight into its physiological origin, anatomical features, and its chemical, physical, and mechanical properties; discussions also extend to how juvenile wood properties impact the utility of solid wood or reconstituted wood products in which they are present (Zobel and van Buijtenen 1989; Zobel and Sprague 1998; Larson et al 2001; Lachenbruch et al 2011; Moore and Cown 2017). With such a wealth of information, there is the risk of becoming complacent in understanding the dynamic nature wood formation and the changes to the wood that occur as a tree matures, an example of the latter being heartwood formation. Indeed, because most of the consternation over juvenile wood is because of its relatively high presence in young timber, the bulk of the data in the literature is based on young timber. In the present study, we address the representations of juvenile wood and the degree to which they are applicable to the variability of the wood in a mature southern pine, specifically, longleaf pine (*Pinus palustris* Mill.).

Established illustrations depicting juvenile wood show a central core of wood, varying little (or not at all) by diameter or cambial age, to be nested within mature wood tapering to the upper portion of the stem (Zobel and van Buijtenen 1989; Zobel and Sprague 1998). Taking into account that wood juvenility may be attributed to the proximity to the tree crown, the so-called crown-formed wood, Lachenbruch et al (2011) provides an illustration showing a central core, with a constant diameter, but comprised of nested individual growth rings shown as being juvenile when formed near the crown, but mature as they extend outward and down the bole of the tree, adding to the mature wood zone. Again with a constant diameter in a central core, other illustrations put forth by Kibblewhite (1999) and Burdon et al (2004) show even greater complexity in attributing the variability of this central core of wood with its proximity to the crown and/or the maturity of the tree when the wood was formed; thus, juvenile wood terminology being reserved by Kibblewhite (1999) for that wood formed when the tree itself was of a juvenile age.

Complementary to the aforementioned illustrations of juvenile wood and mature wood zones in trees, wood property data gathered at different heights and radial positions have been used to generate tree maps showing profiles of tree physical and mechanical properties (Mora and Schimleck 2009; Auty et al 2014; Longuetaud et al 2016; Dahlen et al 2018; Schimleck et al 2018a, 2018b). Maps of specific gravity (SG) generally show a central core of wood that is lower in SG from the base of the tree to the top, and at specific heights, increasing in SG from the center of the tree (pith) and outward (wood near bark). Smoothing of the data, as performed in most cases, provides maps with gradual transitions in wood properties (Mora and Schimleck 2009; Auty et al 2014; Longuetaud et al 2016; Dahlen et al 2018; Schimleck et al 2018a, 2018b); however, maps of fiber characteristics, showing the data for discrete increments, have also been published (Ohshima et al 2005). A common character of most tree maps, particularly those cited earlier, is that they report data in a single radial direction (or without regard to cardinal direction); thus, maps are shown as a bisection (one half) of a tree stem. To provide a full profile, analogous to illustrations of juvenile wood in tree stems, the mirror image has been included to provide a full-stem profile (Groom et al 2002a, 2002b; Mott et al 2002; So et al 2002; Downes et al 2009).

It is noteworthy that very early tree maps generated by Fernow (1896) and Trendelenburg (1935) provided full-stem profiles, although in the former case it may be presumed that the wood SG data were not measured in opposing radial directions. An interesting feature of the tree map provided by Trendelenburg (1935) is that the data are presented in the northern and southern cardinal directions, and although the SG data are largely presented as being symmetrical between the two directions, there is a zone of higher density mature wood in the northern cardinal direction. This difference in wood SG with cardinal direction cannot be dismissed outright as an anomaly for measurements conducted on a single tree, given that statistically significant differences in wood SG with cardinal direction have been reported (Olesen 1973; Zeidler and Šedivka 2015; Eberhardt et al 2018). Trendelenburg (1935) noted that the analysis of an individual tree can give a clear picture of within-tree variability; details of how this map was generated were not reported, save for the fact that it is a representation of data collected from 200 specimens and constructed according to the position of each wood specimen within the tree. In all cases, the tree maps depicting variability in the central core with respect to tree height for individual trees (Trendelenburg 1935; Fernow 1896; Downes et al 2009) are from trees ranging from 124 to *ca.* 200 yr in age. Heartwood formation, and the contribution of extractives to wood density (Eberhardt and Samuelson 2015), is undoubtedly represented in those maps.

Among the southern pines in the southeastern United States, loblolly pine (*Pinus taeda* L.) is the most abundant, with its range widely expanded through fire suppression, natural seeding on abandoned agricultural lands, and extensive planting (McKeand et al 2003; Fox et al 2007; South and Harper 2016). The only other southern pine species that increased in its acreage between 1992 and 2012 was longleaf pine, as a product of tree planting incentives (Landers et al 1995; South and Harper 2016); given that the total acreage longleaf pine dominated forests has stagnated since 2010, efforts are underway to make progress toward the goal of 8 million acres of longleaf pine by 2025 (McIntyre et al 2018). With the potential to generate sufficient timber for utilization (Landers et al 1995), studies on its growth, yield, and wood properties specific to longleaf pine are warranted. Herein, the objective was to expand on an investigation of wood properties in a sampling of mature longleaf pine trees (Eberhardt et al 2018; So et al 2018), capturing the variability throughout the stem and in the context of illustrations of juvenile and mature wood zones. Unique to the wood property maps generated in the present study is that the data for two cardinal directions (north and south) were preserved for each tree disk, thus providing a true full-stem profile, not a bisected profile with a mirror image merely for the purpose of illustration.

MATERIALS AND METHODS

Study Trees, Harvesting, and Disk Collection

A scheduled thinning at the study site (Palustris Experimental Forest, Alexandria, LA (N31.176°, W92.677°) provided the opportunity to sample ten 70-yr-old longleaf pine trees, covering a range of diameters at breast height (DBH) (14.5-49.8 cm) and total heights (17.6-27.5 m). Tree-specific data are shown in Table 1. All study trees were marked so as to retain the northern and southern cardinal directions on 5-cm-thick disks cut at stump height (15 cm), followed by 77 cm above the ground level, then every 61 cm along the tree bole. Disks taken at breast height (BH, 1.37 m), and closest to one-quarter (1Q) height, midheight (MID), and three-quarter (3Q) height were used for comparisons. The 3Q height was

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

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 stem quality defects. The generation of tree maps used all disks from which defect-free bark-to-pith specimens could be prepared. A total of 339 disks gave 678 opposing wood cores, of which 21 cores were discarded because they were unusable (eg knots); in the worst case, for a single tree, 4 of 72 cores were discarded.

Specimen Processing and X-Ray Densitometry

A bark-to-bark wood strip (1 cm × 1 cm), encompassing the pith, was cut along a north-to-south line of each disk. Air-dried wood strips were solvent extracted before preparation of specimens suitable for X-ray densitometry (Eberhardt et al 2018; So et al 2018). Densitometry was performed using a Quintek Measurement Systems X-ray densitometer (Knoxville, TN) to measure SG values at 0.06 mm intervals, using a SG of 0.480 to differentiate between earlywood and latewood zones (Koubaa et al 2002; Clark et al 2006; Antony et al 2012). Data were excluded for bark-to-pith specimens where there were significant defects (eg knots) that prevented the generation of usable ring counts. Bark-to-pith data were automatically processed to provide wood properties (ring SG, earlywood SG, latewood SG, and percent latewood) and width for each growth ring. Densitometer calibration was on a green volume and oven-dry mass basis.

Statistical Analysis and Curve Fitting

Wood properties (eg ring SG and latewood SG) at BH, and each of the three relative heights (1Q, MID, and 3Q), were averaged at each ring number between the two cardinal directions; the resultant data for the 10 tree disks at each relative height, using three proxy disks for the 3Q height, were averaged and plotted using PROC GPLOT (SAS/STAT 9.3, Cary, NC). 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 in the semicircle in each cardinal direction. Mean basal area-weighted whole-core values for each tree disk were then averaged for the 10 trees at BH and each of the three relative heights. This was also repeated for various wood zones: the first growth rings from the center of the tree ($\leq$5 rings), those rings typically attributed to juvenile wood core in the southern pines ($\leq$10 rings), and those rings extending beyond the transition wood and into the mature wood ($\leq$20 rings). The selection of these zones was based on the juvenile–mature wood transition commonly reported as being around a cambial age of *ca.* 10 at BH in loblolly pine (Clark et al 2006) and inflection points for ring SG and percent latewood previously noted for the study trees (see Eberhardt et al 2018). Duncan's multiple range tests were conducted using PROC GLM (SAS/STAT 9.3) to assess measured property differences between BH and each of the three relative heights. A determination of significance was made with $p < 0.05$.

Generation of Wood Property Maps

To create the wood property maps, the actual position for each data point was converted to a relative position in each tree, retaining the appropriate cardinal direction (north and south). The relative height was determined by dividing each actual disk height by the maximum tree height. The relative core position was determined by dividing each actual radial position from the pith by the corresponding maximum radial distance, either north or south for each disk. These positions were then rounded to the nearest 0.05 increment. A mean parameter value was then calculated for each point across all of the sample trees. Because this would leave gaps in the map, the data were smoothed using a bivariate spline (Harder and Desmarais 1972; Meinguet 1979) through PROC G3GRID in SAS (SAS Institute Inc 1990), allowing for 500 data points in each of the vertical and horizontal directions. To maintain a shape which resembles a tree profile, polynomial regression lines were fit to the relative profile of all of the sample trees (both north and south) and the data truncated to remove points falling outside of these lines. PROC GCONTOUR (SAS Institute Inc 1990) was used to draw the wood property maps.

RESULTS AND DISCUSSION

Wood property and ring width data were normalized to relative height and relative core position to pool the data from several trees and generate wood property maps. This approach is an extension of comparing wood property data at targeted relative heights (Lukášek et al 2012; Zeidler and Šedivka 2015; Eberhardt et al 2018) which normalizes the data pooled for trees of different heights. Prior comparisons showed differences in wood property data between the northern and southern cardinal directions at 1Q height (Eberhardt et al 2018). In the present study, the objective was to generate maps showing the radial variation, coupled with the vertical variation (ie vs height) over a 2-dimensional profile space, retaining the capacity to compare the northern and southern cardinal directions.

For nine of the trees, where the range of heights was 22.9-27.5 m, normalization would correct for the relatively minor deviations in total height. The number of disks from these trees ranged from 37 to 44, generally coinciding with the tree heights. The highly suppressed tree was of initial concern, being roughly 70% the average height of the other nine trees; however, maps generated with all of the study trees were essentially the same as those that excluded the suppressed tree. Thus, the tree maps presented here include all 10 study trees. Baldwin et al (2000) showed different silvicultural practices (spacing and thinning) resulted in only minor shifts in mean profiles of relative diameter to relative height for loblolly pine. Thus, for the limited number of trees used in the present study, differences in tree taper were presumed to be subtle and of little consequence. The objective herein was not to provide stem taper for longleaf pine trees of a general age class, but to instead provide whole-tree maps demonstrating the variability in wood properties for the study trees.

Ring SG

The tree map for ring SG (Fig 1) is unique among those presented to date in that it provides a high level of resolution illustrating the radial and vertical variability for data from a group of southern pine trees of the same age. At the risk of being redundant, using relative values may be likened to overlaying transparencies of individual maps, each enlarged or reduced in size to achieve a common scale, thus sharing a similar outline. This is unlike maps where absolute radial distances and absolute heights are used, with the corresponding data averaged or modeled to generate a map of the property of interest (Mora and Schimleck 2009; Auty et al 2014; Longuetaud et al 2016; Schimleck et al 2018a, 2018b). These alternatives also provide very useful property maps for trees of similar dimensions. Maps can also be generated using cambial age, where there is some normalization of the data for trees of different dimensions, but of similar age (So et al 2002; Schimleck et al 2018a). Although maps of single trees may show unique patterns of property variability at different tree heights (Groom et al 2002a, 2002b; Mott et al 2002; Downes et al 2009), it is open to discussion on how far to extend the applicability of a map from the single tree to a sample or population of trees.

Similar to other maps of the southern pines, either based on single trees, averaged tree data, or models representative of even larger groups of trees, the map in Fig 1 shows a central core of low-density wood (SG < 0.450) running the length of the tree bole. This low-density wood is attributed to juvenile wood (corewood) and follows established illustrations (Zobel and van Buijtenen 1989; Zobel and Sprague 1998), whereby a central core of wood, varying little by radial distance or cambial age, is nested within mature wood tapering to the upper regions of the stem. Again, in the present study, the term juvenile wood is used synonymously with corewood, recognizing that preferences for the latter term are becoming more prevalent (Kibblewhite 1999; Amarasekara and Denne 2002; Burdon et al 2004). An interesting feature of the ring SG tree map shown in Fig 1 is that the zone of low

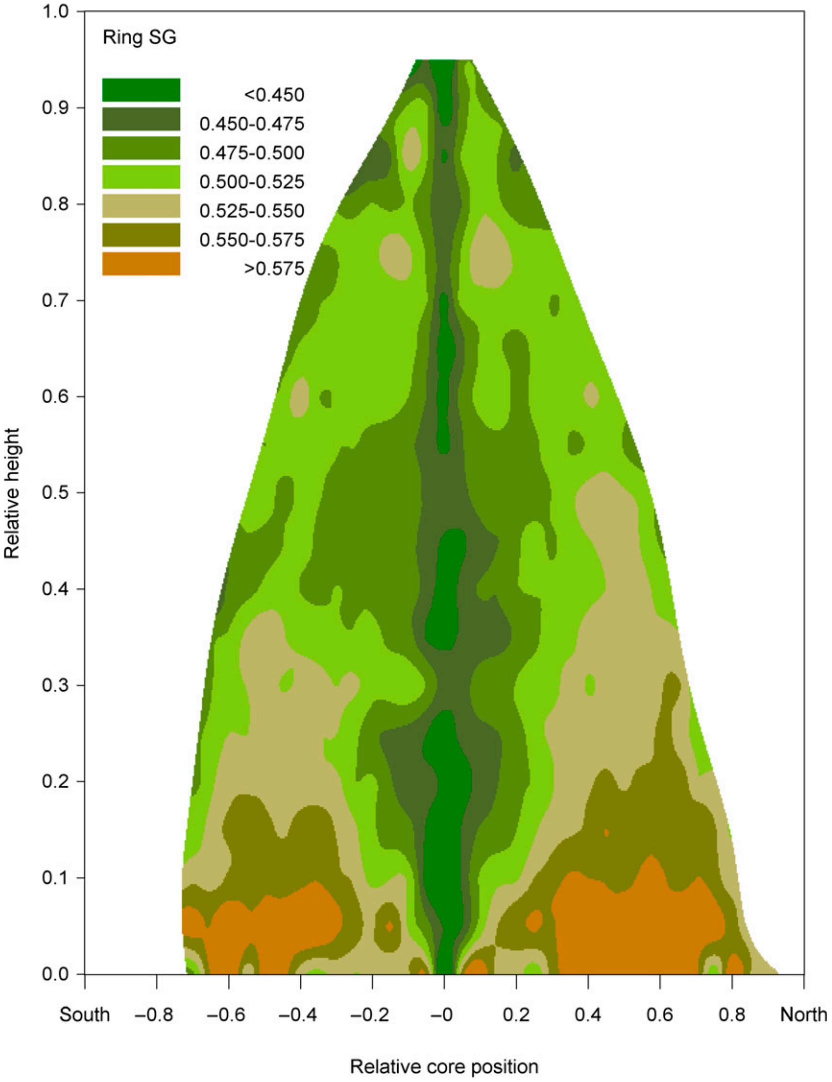

Figure 1. Wood property map for ring specific gravity (SG) in mature longleaf pine. Relative height is the height of the measurement divided by the tree height and relative core position is the radial distance to the measurement position divided by the maximum radius at that height; south is defined in a negative direction for graphical purposes only.

ring SG wood in the center of the tree is wider at MID than at the lower and higher relative heights. This observation is not restricted to mature longleaf pine, with a zone of low SG wood near the MID being wider for loblolly pine at relatively young ages of 13 and 22 yr (Schimleck et al 2018b).

Typical of other tree maps, there is higher ring SG wood toward the base of the tree; however, unlike most tree SG maps, this does not extend all the way to the wood closest to the bark. Indeed, this pattern is more consistent with density traces taken at BH where ring SG increases through juvenile wood formation, plateaus in the mature wood zone, and declines in the wood close to the bark (Spurr and Hsiung 1954; Jordan et al 2008; Eberhardt and Samuelson 2015). Also of interest is the fairly symmetrical regions of high ring SG above the 3Q height. This observation is seemingly supportive of Kibblewhite's (1999) schematic, showing the wood in the crown (the so-called top corewood) to be different from the juvenile wood zone at the base of the tree.

The tree property map for ring SG (Fig 1) is unique in that it illustrates property differences both vertically and radially for the two cardinal directions (north and south). The only other tree map found in the literature that shows two opposing cardinal directions is that presented by Trendelenburg (1935) for a single tree. In that map, the SG data are largely presented as being symmetrical between the two directions; however, there is a zone of higher density mature wood in the northern cardinal direction near the tree base. For the study trees in the present study, a statistically significant difference was observed for ring SG at the 1Q height, with the higher value being in the northern cardinal direction (Eberhardt et al 2018). The tree map for ring SG (Fig 1) illustrates that finding vertically, showing a zone at relative heights between 0.1 and 0.3, encompassing the 1Q height, as having higher ring SG in the northern cardinal direction. Partitioning the ring SG data at the 1Q height gave a significant difference that could be attributed to the mature wood (Eberhardt et al 2018). This finding is validated by the tree map in Fig 1 where the radial asymmetry in ring SG is prevalent at relative core positions lower than −0.4 (south) and greater than 0.4 (north). Although such variability in ring SG may be of little consequence for timber utilization, it raises the question of how localized environmental factors (eg angle of sunlight on tree and localized temperature gradients on the stem) may have a measurable impact on tree growth and wood properties.

Percent Latewood

Because percent latewood and ring SG have been shown to trend together (Clark and Saucier 1989; Tasissa and Burkhart 1998; Eberhardt and Samuelson 2015), with a higher proportion of latewood contributing to higher ring SG, it is not surprising that the map for percent latewood (Fig 2) is similar to that for ring SG. A proportion of latewood of 50% has been used in prior studies to demark the transition from juvenile wood to mature wood in loblolly pine (Clark et al 2006). This metric is generally applied to radial strips of wood (eg cores) taken at BH. Adhering to this demarcation, and progressing upwards in tree height, it might be concluded that the transition from juvenile wood to mature wood occurs at wider dimensions at midrange tree heights, before tapering down to relative distances similar to those at BH, or even narrower. Perhaps, even more intriguing is the high proportion of latewood in zones above the 3Q height. If adhering to the 50% threshold for the proportion of latewood as an indicator of mature wood formation (Clark et al 2006), then by extension, one might conclude that in mature southern pines used in the present study, much of the wood in the crown would be classified as being mature. This would be in agreement with those models of juvenile wood formation that proposed the wood at the top of pine trees be identified as top corewood (Kibblewhite 1999) or mature corewood (Burdon et al 2004) as opposed to juvenile wood.

Relative Height and Radial Zone Comparisons

Tree maps developed using absolute values for height may use absolute values for radial distance, or alternatively, ring number (cambial age), with the latter allowing one to draw reference to the juvenile wood boundary generally accepted to occur at a cambial ages ranging from 7 to 11 yr in loblolly pine (Clark et al 2006). Worth noting, the boundary between juvenile and mature wood has been observed to be at higher cambial ages (14-19 yr) for loblolly pine growing outside its native range (Tanabe et al 2016). Illustrations of wood maturity proposed by Burdon et al (2004) and Kibblewhite (1999) use cambial age, not radial distance. Complementary to the tree map for percent latewood, and the data in Table 2, percent latewood values at the four sampling heights were plotted against ring number (Fig 3). The plot at BH is typical to that observed in other studies for the southern pines where a curve fitted to the data points crosses the

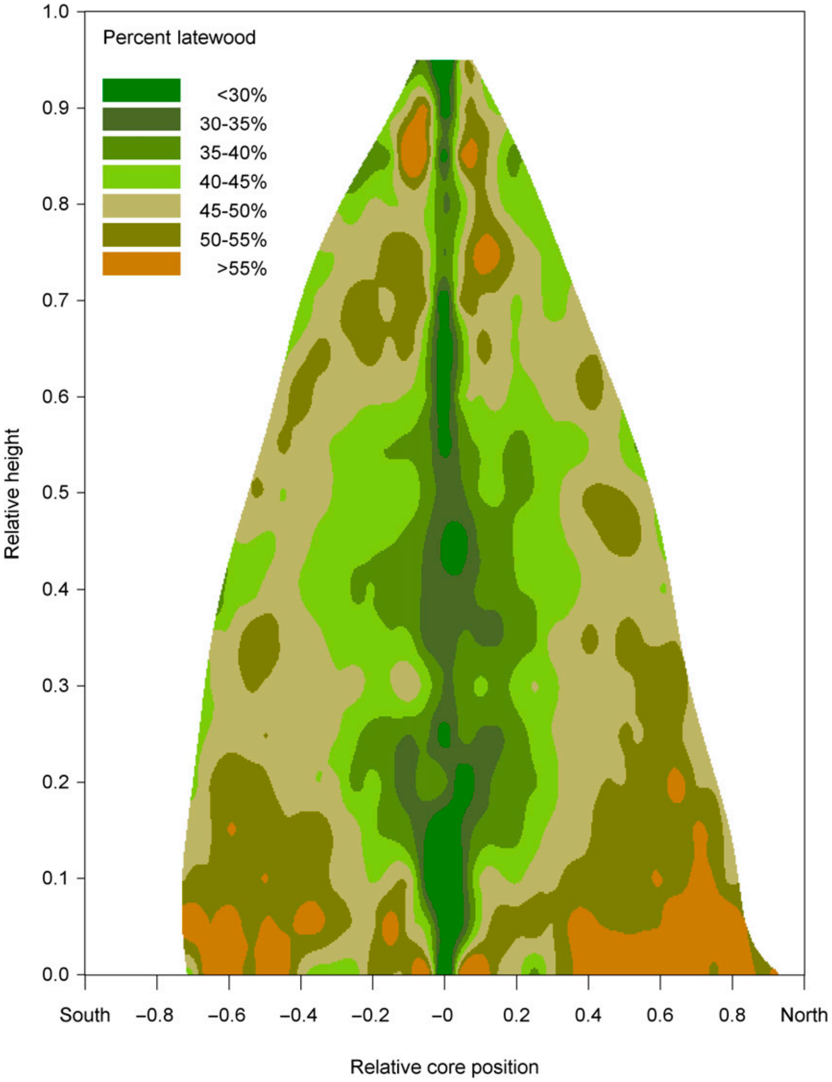

Figure 2. Wood property map for percent latewood in mature longleaf pine. Relative height is the height of the measurement divided by the tree height and relative core position is the radial distance to the measurement position divided by the maximum radius at that height; south is defined in a negative direction for graphical purposes only.

threshold for the proportion of latewood of 50% used as a demarcation of the juvenile wood zone within. Observation of the plots moving up the tree shows this threshold to be crossed at ring numbers of *ca*. 20 and *ca*. 30 for the 1Q and MID heights, respectively. It is beyond the scope of this study to dispute the longstanding boundaries set for juvenile wood in the southern pines (eg $\leq$10 rings); however, as clearly illustrated by Lachenbruch et al (2011), the juvenile/mature wood transition may be a function of tree diameter, thus not related to the growth rate or number of growth rings.

To assess whether the juvenile wood properties varied with height, for a specific number of growth rings, comparisons were made at BH and three relative heights using data from the 5, 10, and 20 innermost growth rings. Although the 10 innermost growth rings could include some transition wood, it

Table 2. Wood property analysis of variance for effect of disk height, including mean values, standard deviations (in parentheses), and probabilities of a type 1 error (*p*) for whole and partial wood cores.

Wood Core	Disk Height	Ring SG	Latewood SG	Earlywood SG	Percent latewood	Ring width (mm)
Whole (all rings)	BH	0.580 (0.035)^a	0.773 (0.030)^a	0.346 (0.017)	54.9 (5.4)^a	2.60 (0.63)
	1Q	0.525 (0.025)^b	0.745 (0.040)^b	0.329 (0.013)	46.7 (3.6)^b	2.73 (0.71)
	MID	0.501 (0.013)^b	0.721 (0.026)^b	0.333 (0.019)	43.0 (4.1)^b	2.86 (0.52)
	3Q	0.502 (0.030)^b	0.679 (0.019)^c	0.350 (0.025)	46.1 (7.5)^b	2.55 (0.63)
	p	**<0.0001**	**<0.0001**	0.0711	**0.0001**	0.6994
Partial ($\leq$20 rings)	BH	0.577 (0.033)^a	0.780 (0.041)^a	0.354 (0.015)^a	52.4 (4.6)^a	4.02 (1.18)
	1Q	0.514 (0.032)^b	0.752 (0.037)^a	0.331 (0.015)^b	42.8 (3.9)^b	4.05 (1.12)
	MID	0.491 (0.019)^b	0.717 (0.021)^b	0.337 (0.020)^b	39.9 (3.1)^b	3.84 (0.77)
	3Q	0.500 (0.037)^b	0.671 (0.020)^c	0.357 (0.023)^a	45.3 (9.9)^b	2.89 (0.85)
	p	**<0.0001**	**<0.0001**	**0.0080**	**0.0002**	0.0566
Partial ($\leq$10 rings)	BH	0.554 (0.048)^a	0.730 (0.031)^a	0.369 (0.025)^a	52.3 (11.6)^a	4.48 (1.53)^{ab}
	1Q	0.487 (0.039)^b	0.724 (0.033)^a	0.344 (0.020)^b	37.3 (6.0)^b	5.25 (1.49)^a
	MID	0.479 (0.024)^b	0.687 (0.026)^b	0.357 (0.022)^{ab}	36.6 (3.7)^b	4.77 (0.93)^a
	3Q	0.497 (0.047)^b	0.644 (0.023)^c	0.374 (0.023)^a	44.8 (14.9)^{ab}	3.40 (1.06)^b
	p	**0.0009**	**<0.0001**	**0.0292**	**0.0034**	**0.0255**
Partial ($\leq$5 rings)	BH	0.535 (0.081)^a	0.688 (0.052)^a	0.372 (0.026)^b	51.7 (19.1)^a	4.96 (1.42)^{ab}
	1Q	0.465 (0.030)^b	0.678 (0.026)^a	0.355 (0.022)^b	34.0 (5.6)^b	6.15 (1.66)^a
	MID	0.464 (0.022)^b	0.635 (0.035)^b	0.378 (0.023)^{ab}	33.7 (5.4)^b	5.41 (1.01)^a
	3Q	0.484 (0.050)^b	0.601 (0.027)^c	0.397 (0.022)^a	41.9 (19.4)^{ab}	3.92 (1.26)^b
	p	**0.0122**	**<0.0001**	**0.0043**	**0.0210**	**0.0098**

SG, specific gravity; BH, breast height; 1Q, one-quarter height; MID, midheight; 3Q, three-quarter height.
Significance ($p < 0.05$) is in boldface, with letters after the means indicating significant differences by Duncan's multiple range test.

would be highly unlikely that the five innermost growth rings would include anything but juvenile wood. Results in Table 2 show that there are indeed differences in the ring SG values taken at different heights, irrespective of using whole-core data (all rings) or that representing different inner cores of wood along the bole (eg $\leq$5 rings). As expected, the same trend was observed for percent latewood. All the highly significant analysis of variance *p*-values can be attributed to the data at BH being significantly higher than those at the three relative heights. These results appear to support the Burdon et al (2004) illustration, whereby the wood near the base of the tree, the so-called juvenile corewood and juvenile outerwood, possesses different properties from that in the vast majority of the tree, from the 1Q height and higher; note that the Burdon et al (2004) illustration shows mature corewood to occur, starting at 5 m in a 20 m tree, equivalent to a relative height of 1Q used in the present study.

Ring Width

In the preceding section, the results were consistent with the Burdon et al (2004) illustration of corewood maturity with height. The tree map for ring width brings one caveat, albeit intuitive, that ring width does indeed vary with height (Fig 4), and thus, patterns in the maps and illustrations based on cambial age may appear different from those based on absolute radial distances (or relative radial distances), but both being useful in demonstrating wood variability in a 2-dimensional space. In the present study, using relative height and relative radial distance, the ring width tree map suggests nested cones of wood with decreasing ring widths with increasing relative radial distance at any given relative height. At the base of the tree moving upward, the range of ring widths decreases, with the largest ring widths occurring in the lower regions of the stem. Rapid growth that occurs at younger ages for the southern pines is associated with the predominance of juvenile wood, impacting the quality of the wood, resulting in the reduction in design values for southern pine lumber (Butler et al 2016; Dahlen et al 2018).

Although the tree map may suggest a high proportion of very wide rings (>5 mm) at lower heights, the average ring width is not significantly different ($p = 0.6994$) at BH and the three relative

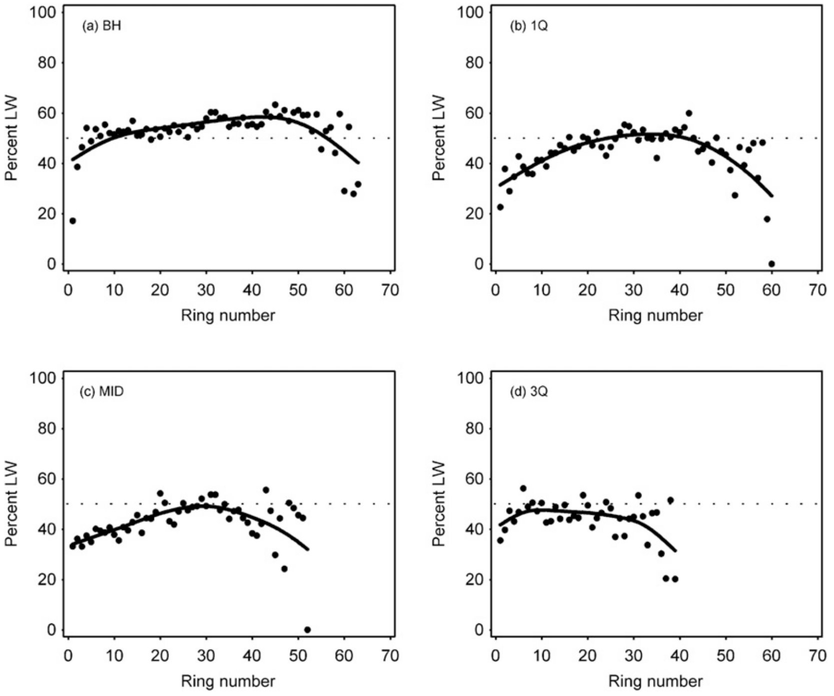

Figure 3. Plot of percent latewood at (a) breast height (BH), (b) one-quarter (1Q) height, (c) midheight (MID), and (d) three-quarter (3Q) height in mature longleaf pine. Dotted line at 50% latewood represents a threshold sometimes used to define the juvenile to mature wood transition.

heights (1Q, MID, and 3Q) with the whole-core data (all rings). Indeed, differences in ring width are only observed when using data for the innermost growth rings (eg ≤10 rings). Consistent with the ring SG and percent latewood maps, the ring width map shows the widest rings at 1Q height, narrowing at lower and higher heights. This trend is better illustrated by the data in Table 2 where the average ring widths are lower at 3Q height than at 1Q and MID heights when comparing ≤10 rings. Seemingly contradictory to what is typical for southern pine wood quality assessments, the wood above the 3Q height had narrow rings and higher ring SG in the tree maps. Such wood features normally are associated with higher wood quality of the mature wood. These observations can be attributed to the maturity of the study trees, approaching the maximum height, and the wide distribution of annual wood growth over a high tree volume, the latter limited by the available crown foliage for a mature southern pine.

Earlywood and Latewood SG

In the present study, and others presenting X-ray densitometry data from the southern pines, the differentiation of earlywood from latewood is based on threshold values for SG (Clark et al 2006; Jordan et al 2008; Antony et al 2012, 2015; Samuelson et al 2013). It is beyond the scope of this article to delve into the different criteria used to determine the point of the earlywood–latewood transition by the analysis of SG data or anatomical features; however, it is sufficient to say that the earlywood–latewood transition is abrupt (Eberhardt and Samuelson 2015), unlike other softwood taxa (eg *Picea*) having gradual earlywood–latewood transitions (Koubaa et al 2002; Franceschini et al 2012, 2013). Both the tree map for earlywood SG (Fig 5), and particularly the data in Table 2, show that the earlywood SG values predominated by juvenile wood (≤20 rings) are significantly higher at the 3Q height than at the 1Q height. Conversely, the data

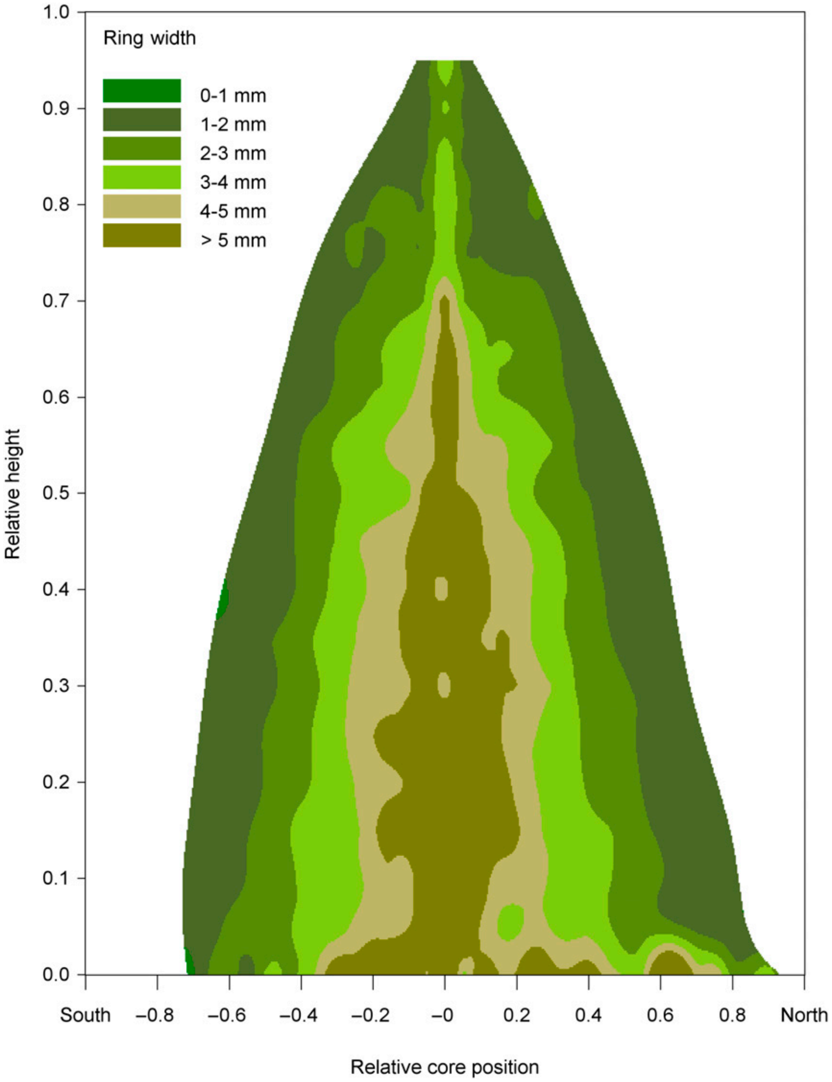

Figure 4. Wood property map for ring width in mature longleaf pine. Relative height is the height of the measurement divided by the tree height and relative core position is the radial distance to the measurement position divided by the maximum radius at that height; south is defined in a negative direction for graphical purposes only.

in Table 2 show that the latewood SG values are lower at the 3Q height than at the 1Q height; however, this difference is not readily apparent in the corresponding tree map for latewood SG (Fig 6). These trends coincide with narrower ring widths at 3Q height and higher. Given the limits of instrument resolution, there is the potential for some latewood to be assigned as earlywood, and vice versa, having a greater impact with ever narrower ring widths. This could be exacerbated by the fact that the threshold value used herein has been largely derived from X-ray densitometry analyses of wood strips/cores taken at BH. Nevertheless, these data are still informative as they further illustrate how a wood physical property, at the earlier cambial ages, varies both with relative radial distance and relative height up the tree. Such within-tree variability, ascribed to earlywood or latewood, has also been observed in

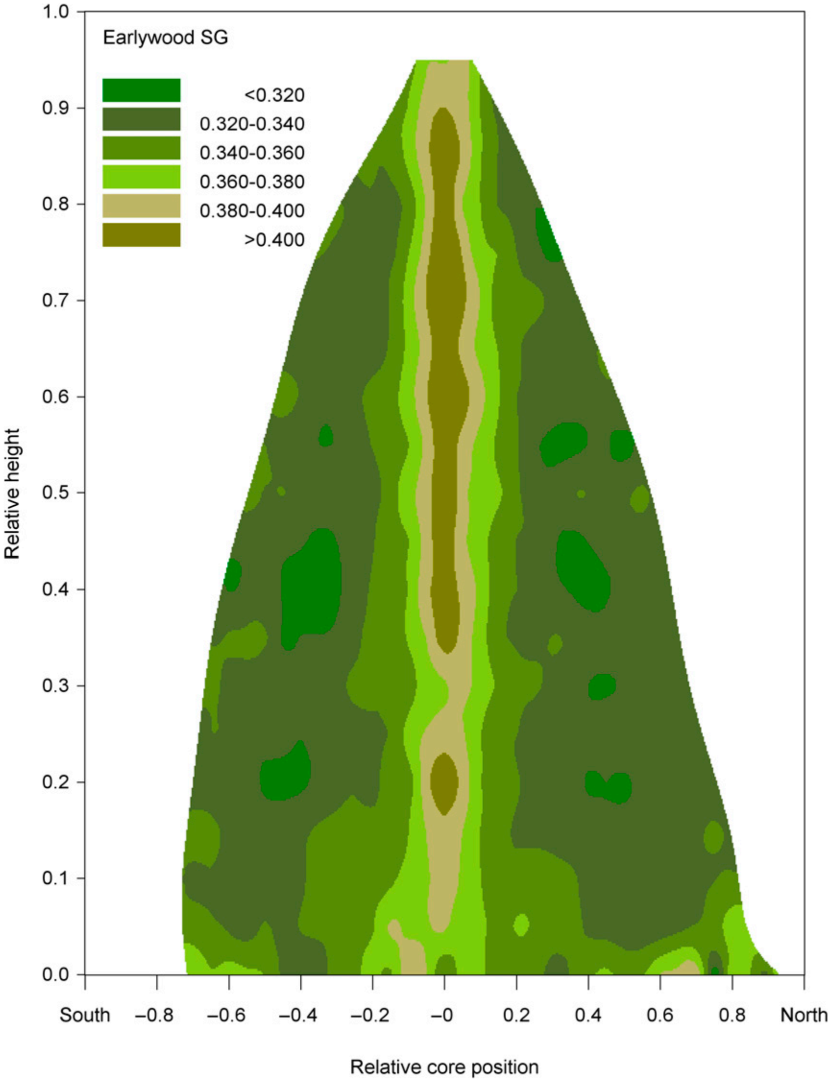

Figure 5. Wood property map for earlywood specific gravity (SG) in mature longleaf pine. Relative height is the height of the measurement divided by the tree height and relative core position is the radial distance to the measurement position divided by the maximum radius at that height; south is defined in a negative direction for graphical purposes only.

tree maps illustrating the mechanical properties of individual wood fibers (Groom et al 2002a, 2002b; Mott et al 2002).

Radial Growth Relative to Cambial Age

As mentioned earlier, the juvenile wood zone has been illustrated both by absolute distance and cambial age. The reader is referred to the detailed synthesis by Lachenbruch et al (2011) for a discussion on the theories of the juvenile wood to mature wood transition as being in response to cambial age or stem diameter; note that maturation may be associated with both growth rate and age (Day et al 2002). In a study by Kojima et al (2009), data from individual large, medium, and small diameter trees were plotted to assess whether wood "maturation" was dependent on diameter in addition to cambial age, and demonstrated that for some species, the maturation occurred in only the

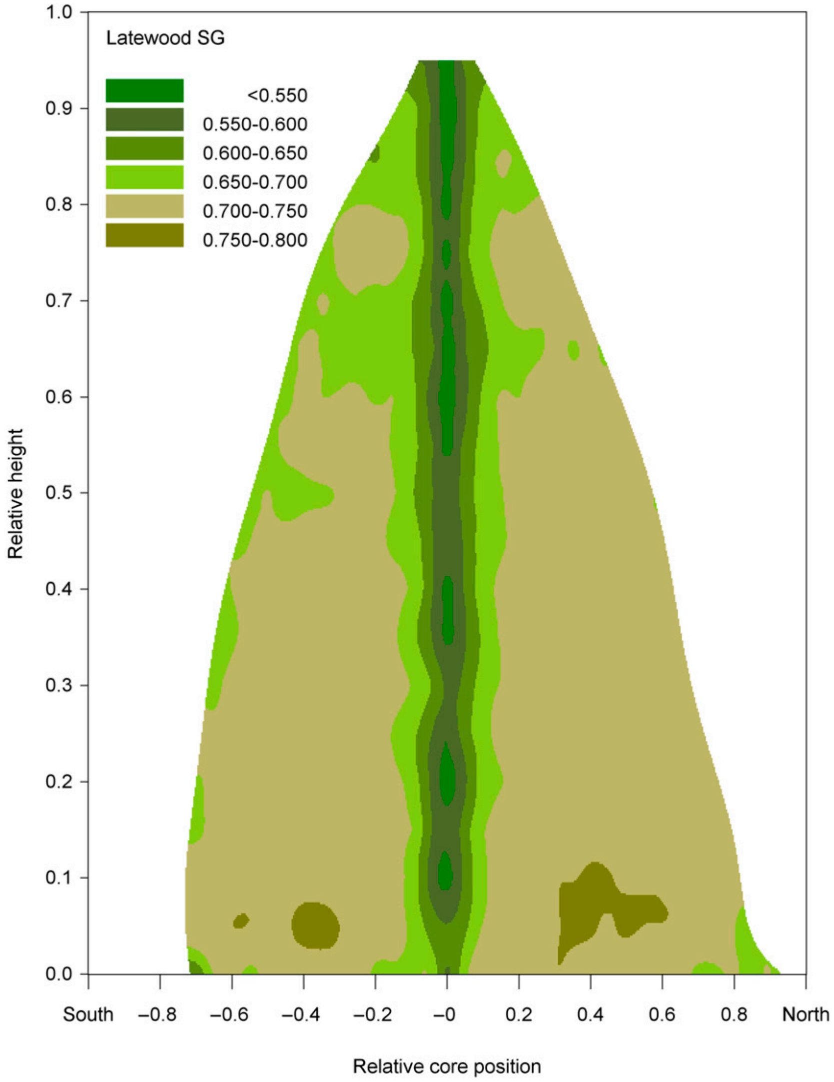

Figure 6. Wood property map for latewood specific gravity (SG) in mature longleaf pine. Relative height is the height of the measurement divided by the tree height and relative core position is the radial distance to the measurement position divided by the maximum radius at that height; south is defined in a negative direction for graphical purposes only.

large diameter trees, whereas in others, it occurred in both large and small diameter trees. An analogous assessment of single trees was conducted in the present study to simply illustrate the relationship between diameter growth and cambial age for the range of growth rates represented by the study trees.

In Fig 7, radial distances are plotted against cambial age for the tree with the largest (DBH) among all trees sampled (Tree 1, 49.8 cm) and the tree with the smallest DBH (Tree 7, 26.2 cm), but still having a similar height (25.5 vs 27.5 m). An intermediate DBH (36.8 cm) tree of similar height (Tree 3) was also selected for comparison. At a cambial age of 10, both the largest tree and intermediate tree have similar radial distances (*ca.* 50 mm). Thus, for seemingly different values

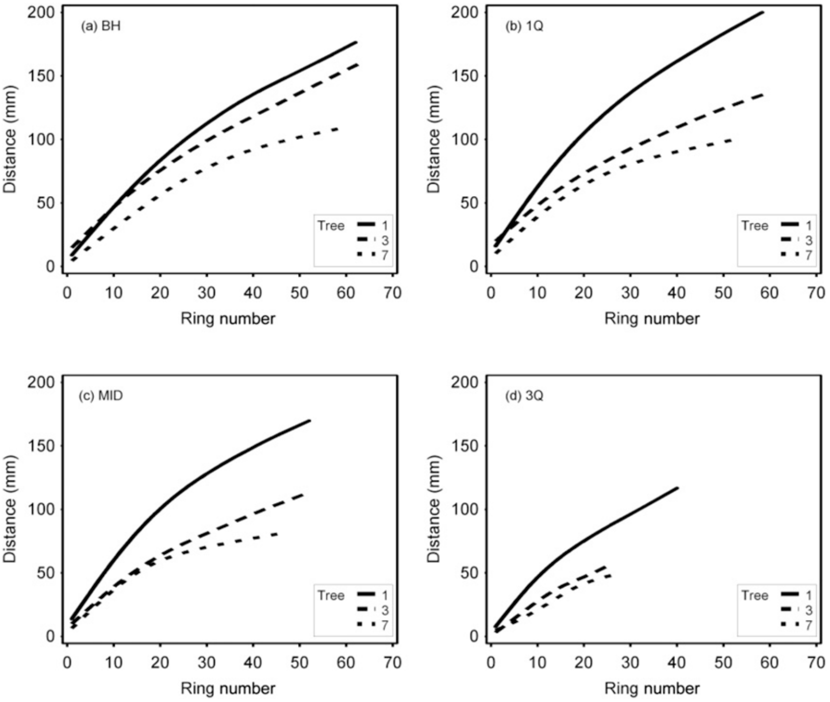

Figure 7. Plots of ring distance from pith for three trees against ring number at (a) breast height (BH), (b) one-quarter (1Q) height, (c) midheight (MID), and (d) three-quarter (3Q) height in mature longleaf pine. Trees 1, 3, and 7 represent fast, intermediate, and slow (suppressed) growth rates, respectively.

for DBH (36.8 vs 49.8 cm), the radial dimensions of the juvenile wood zones would appear to be similar at BH. The smaller radial distance at BH for the smallest tree (same cambial age) is to be expected; however, this illustrates how assigning the juvenile wood zone on the basis of cambial age can give different radial distances for trees of the same age. Further complicating this observation is that the plots for the intermediate and smaller trees show greater similarity at the higher relative heights (Fig 7). Altogether, this illustrates that for trees of the same age but different growth, the zone of wood that may be assigned as juvenile on the basis of cambial age can vary both in absolute radial distance and height.

CONCLUSIONS

Similar to other maps of the southern pines, either based on single trees, averaged tree data, or models representative of even larger groups of trees, the ring SG map shows a central core of low-density wood running the length of the tree bole. Vertical and radial variations in ring SG showed apparent differences between the northern and southern cardinal directions. Dissimilar to most illustrations/maps of juvenile wood (corewood), the zone of low ring SG wood in the center of the tree is wider at MID than at the lower and higher relative heights; also, ring SG increases from the center (pith) but did not extend all the way to the wood closest to the bark, showing that wood radial variability of young trees does not apply directly to mature trees. Seemingly contradictory to what is known about southern pine wood quality, the wood above the 3Q height had narrow rings and higher ring SG, being wood features normally associated with higher wood quality. Altogether, the wood property maps can be interpreted as supportive of an alternative juvenile wood illustration in which the wood near the base of the tree, the so-called juvenile corewood and juvenile outerwood, has different properties from the vast majority of the tree, that being above 1Q relative height.

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