JUVENILE/MATURE WOOD TRANSITION IN LOBLOLLY PINE AS DEFINED BY ANNUAL RING SPECIFIC GRAVITY, PROPORTION OF LATEWOOD, AND MICROFIBRIL ANGLE

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ABSTRACT

The length of juvenility or number of years a tree produces juvenile wood at a fixed height can be defined by the age of the wood at which properties change from juvenile to mature wood. This paper estimates the age of transition from juvenile to mature wood based on ring specific gravity (SG), proportion of annual ring in latewood, and ring average microfibril angle (MFA). The threshold method and the segmented modeling approach were used to estimate the age of transition. Twenty loblolly pine (*Pinus taeda* L.) plantations, 20–27 years old, were sampled across five physiographic regions in the southern United States. Increment cores were collected at 1.3 meters from 15 trees in each stand to determine ring specific gravity and proportion of latewood by X-ray densitometry and annual ring MFA by X-ray diffraction. Precisely determining the transition age between juvenile and mature wood was difficult because transition is gradual, not abrupt. The age of transition was found to differ by wood property because these properties mature at different rates due to genetic and environmental factors. Both the threshold and the segmented model approach showed that transition age varied among regions. Both approaches showed that length of juvenility based on ring SG was shorter in the South Atlantic and North Atlantic Coastal Plains (ranging from 5.5 to 7.9 years) compared to that in the Hilly Coastal Plain that ranged from 10.4 to 13.6 years. Using MFA to estimate the age of demarcation, both approaches showed the South Atlantic, Gulf Coastal, and Hilly Coastal Plains had shorter lengths of juvenility (ranging from 8.4 to 10.4 years) than the Piedmont and North Atlantic Coastal Plain (ranging from 10.5 to over 20 years).

Keywords: Juvenile/mature transition, *Pinus taeda* L., specific gravity, percent latewood, MFA.

INTRODUCTION

The South currently produces 60% of the wood harvested in the United States and 15% of the wood harvested in the world (Wear and Greis 2002). In order to meet the growing demand for wood, it is estimated that by the year 2040, 67% of the softwood production in the South will come from intensively managed loblolly pine (*Pinus taeda* L.) plantations. The high proportion of juvenile wood in intensively managed plantations makes plantation wood differ-

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ent from that of pines harvested from older, slow-growing natural stands. Juvenile wood is produced by the young cambium in the live active crown and forms a cylinder of wood surrounding the pith that extends the length of the tree. The faster a tree grows during the first few years of a rotation, the larger the diameter of the juvenile core in the lower bole.

Juvenile wood is low in stiffness and strength, and thus wood from fast-growing young trees is less desirable for solid wood products (Senft et al. 1985). It is important that the forest industry understand the impact of silvicultural practices on wood properties, and the volume of juvenile wood produced. However, to evaluate the impact of management practices on juvenile wood properties a thorough understanding of the age of transition between juvenile and mature wood is needed. Juvenile wood has a high proportion of earlywood-type tracheids and thus lower specific gravity (SG), thinner cell walls, wider microfibril angle (MFA), and less latewood than mature wood (Thomas 1984). Because of its tracheid characteristics, juvenile wood has significantly lower strength and stiffness, more longitudinal shrinkage, and less radial and tangential shrinkage than mature wood (Pearson and Gilmon 1971; Bendtsen 1978; Bendtsen and Senft 1986).

It is important that the forest industry understand the impact of silvicultural practices on wood properties and the volume of juvenile wood produced. However, to evaluate the impact of management practices on juvenile wood properties, a thorough understanding of the age of transition between juvenile and mature wood is needed. To define the age of demarcation between juvenile and mature wood, researchers examine the rate of change of a given property in juvenile wood until the property reaches that of mature wood. Plots of annual ring SG at 1.3 m above ground over ring number from pith are significantly different in loblolly pine compared to Douglas-fir or western hemlock. In loblolly pine, ring SG is lowest for the first 2 – 4 rings next to the pith in the crown-formed wood zone and then increases rapidly for the next 5 – 8 rings in the transition zone until it reaches the SG of mature wood (Clark and Saucier 1989). In Douglas-fir and western hemlock, ring SG is highest in the first 1 to 5 rings from the pith, then declines to a low point between rings 10 and 20, at which point it increases until leveling off in mature wood (Krahmer 1966; Megraw 1986; Jozsa 1998). In loblolly pine, MFA at 1.3 m is largest for 2 – 3 rings near the pith and then decreases in rings 4 – 12 and then levels off in mature wood.

Researchers have found it difficult to define the age of demarcation between juvenile and mature wood because the change in wood properties is gradual and not abrupt, since wood properties do not mature at the same rate. The number of years the cambium of loblolly pine produces juvenile wood at a given height based on ring SG has been reported to range from 5 to 15 years (Zobel and McElwee 1958; Pearson and Gilmore 1980; Clark and Saucier 1989; Tasissa and Burkhart 1998; Mora et al. 2005). Researchers have reported that the length of juvenility in loblolly pine varies by geographic region (Clark and Saucier 1989; Tasissa and Burkhart 1998). Clark and Saucier (1989) found the length of juvenility averages 5 to 8 years in the Atlantic Coastal Plain and 9 to 11 years in the Piedmont.

Various methods have been used to determine the age of transition from juvenile to mature wood. The simplest method is the so-called threshold or graphic method where a value is selected from graphs to define when a property has reached that of mature wood (Clark and Saucier 1989; Jozsa 1998; Clark and Edwards 1999; Clark et al 2005). Plots of a property over ring number from pith are visually evaluated to locate a ring number or age based on the property curve when the property reaches the threshold value for mature wood. A second method is to use linear segmented regression models (Loo et al 1985; Szymanski and Tauer 1991; Sauter et al. 1999) or nonlinear regression models (Hodge and Purnell 1993; Tassisa and Burkhart 1998; Mora et al. 2005) to estimate the age of demarcation. An advantage of the threshold method is that mature wood can be defined as having properties of a minimum specified value that can relate to the wood properties of a final product, whereas the segmented approach defines mature wood based on the rate of change of a property.

This paper compares the threshold method and segmented modeling approach for estimating the transition age between juvenile and mature wood for loblolly pine based on annual ring SG, annual ring percent latewood, and annual ring MFA.

MATERIAL AND METHODS

Field and laboratory

Twenty loblolly pine plantations, 20 – 27 years old, were sampled across five physiographic regions in the southern United States to determine annual ring SG and MFA (Fig. 1). The plantations sampled were planted at 1480 to 1980 trees per hectare (TPH) with nursery run seedlings. The stands sampled were thinned to 300 to 1200 TPH after age 15. No competition control or fertilization was applied at planting or during the rotation. Two increment cores, 12 mm in diameter, were collected at breast height (1.3 m) from 15 trees in each plantation. The sample trees were selected in proportion to the diameter distribution in each stand. One increment core from each tree was dried at 50°C for 24 h, glued to core holders, and sawn into 1.6-mm-thick strips. Specific gravity of earlywood and latewood for each annual ring and radial growth of each ring were determined at 0.06-mm intervals using an X-ray densitometer (Quintek Measurement Systems™) with a resolution of 0.00001. A specific gravity value of 0.48 was used to distinguish earlywood from latewood. The densitometer was calibrated to express specific gravity on green volume and oven-dry weight basis. The second increment core was dried and shipped to Silviscan™ in Australia for MFA determination. MFA was measured at 1-mm intervals from the pith to the

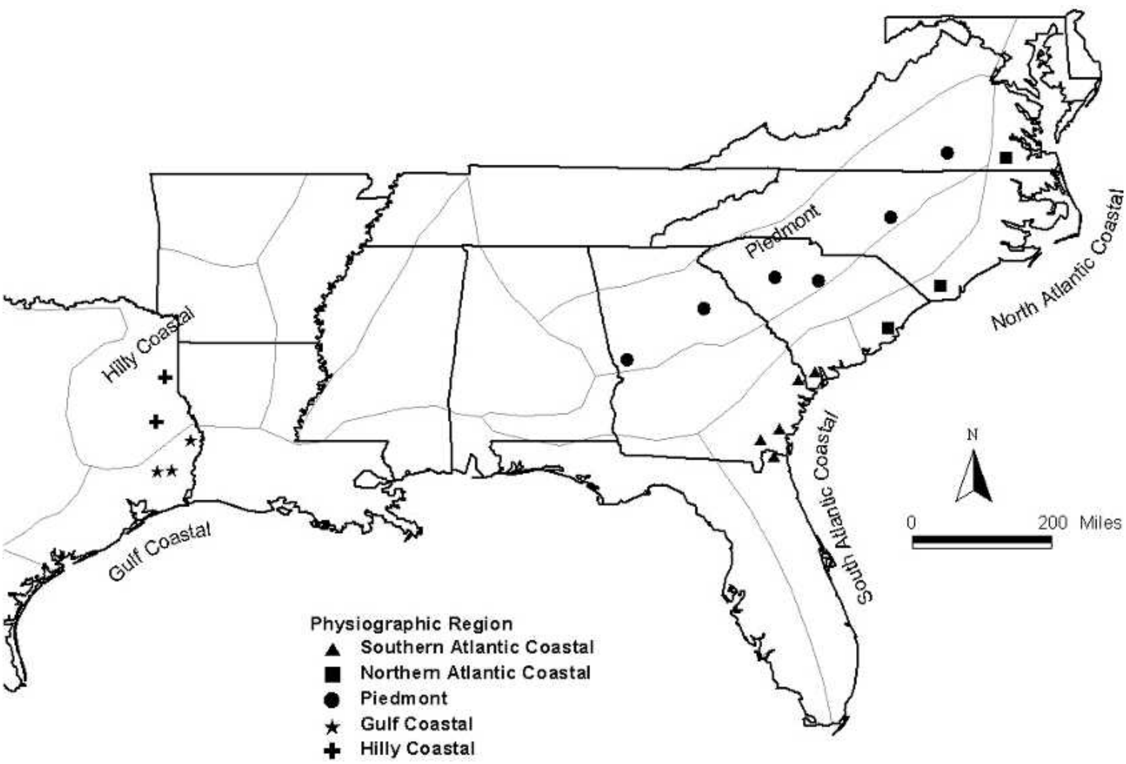

FIG. 1. Location of loblolly pine plantations sampled by physiographic region.

bark using X-ray diffraction on the radial surface. The MFA data were assigned to an annual ring based on the radial measurements collected on the densitometer and during X-ray diffraction. Annual ring SG and MFA were calculated as the arithmetic average of each observation in a ring.

Analysis

The age of demarcation between juvenile and mature wood was determined using the threshold method and the segmented modeling approach. Under the threshold approach, we defined the demarcation between juvenile and mature wood as the age in which ring SG was ≥0.50. When examining percent latewood to estimate the transition age, we defined the transition age as where percent latewood was ≥50% for two consecutive annual rings. When using MFA as the indicator property, we defined the start of mature wood as the age in which MFA <20 degrees. These average threshold values were selected based on visual examination of plots of annual ring SG, percent latewood, and MFA over cambial age from several loblolly pine studies (Clark and Saucier 1989; Clark and Edwards 1999; Clark et al 2005).

The nonlinear least squares procedure in SAS (SAS Institute 2001) was used to obtain estimates of the regression parameters and the age of demarcation or joint point. An analysis was run on all trees combined and by physiographic region. The following nonlinear segmented model developed by Tasissa and Burkhart (1998) was used to estimate the age of demarcation between juvenile and mature wood across all regions and by physiographic region:

$$y_i = \beta_0 + \beta_1 x_i + \beta_2 (x_i - \alpha) I + \varepsilon_i. \tag{1}$$

where,

y_i is ring SG, percent latewood or MFA,

x_i is ring cambial age,

α is the estimated cambial age at which wood changes from juvenile to mature,

I is an indicator variable where

$I = 1$ if $x_i - \alpha \geq 0$

0 otherwise,

β_i are regression coefficients, and

ε_i are normally distributed random errors.

Trees with compression wood were deleted from the analysis.

RESULTS

The trees sampled to determine the age of transition from juvenile to mature wood at breast height based on annual ring SG, percent latewood, and average MFA averaged 22 years old (Table 1), 23.0-cm in dbh and 19.2 m in total height (Table 2). Figure 2 shows average observed annual ring SG, percent latewood, and MFA at 1.3 m above ground plotted over cambial age for all trees sampled. Figure 2 also shows the transition age estimated using the threshold definition and a plot of the segmented equation predicted curve and estimated transition age. The plot of SG and percent latewood over cambial age showed the same curve form as reported for loblolly pine by other researchers (Wareing 1958; Zahner 1963; Thomas 1984; Clark and Saucier 1989). Low SG and percent latewood in rings 1–3 in the crown-formed wood zone were followed by a rapid increase in the next 2 to 9 rings in the transition zone, then a leveling off in mature wood. The plot of MFA

TABLE 1. *Mean, standard deviation, and range of stand characteristics for stands sampled by physiographic region.*

Physiographic Region	Stands Sampled (No.)	Age (years)		Site Index		Trees per Hectare (No)		Basal Area (m^2/h)	
		Mean (Std)	Range	Mean (Std)	Range	Mean (Std)	Range	Mean (Std)	Range
South Atlantic	5	22 (1.3)	21–24	25 (1.8)	22–27	680 (267)	371–995	30 (10.2)	13–39
North Atlantic	3	23 (1.5)	21–24	21 (3.1)	19–25	731 (396)	469–1186	32 (3.4)	30–36
Piedmont	6	23 (1.6)	21–25	20 (1.3)	18–22	547 (147)	329–766	25 (2.9)	21–29
Gulf Coastal	3	22 (4.0)	20–27	17 (1.6)	16–19	591 (215)	420–833	18 (6.8)	12–25
Hilly Coastal	3	20 (0)	20–20	22 (3.2)	18–24	778 (39)	733–808	25 (4.3)	21–28
All stands	20	22 (2.1)	20–27	21 (3.1)	16–27	649 (224)	329–1186	27 (7.3)	12–39

TABLE 2. *Mean, standard deviation, and range of tree characteristics for trees sampled by physiographic region.*

Physiographic Region	Stands Sampled (No.)	Trees Sampled (No.)	D.b.h. (cm)		Total Height (m)		Ring Specific Gravity		Ring Proportion Latewood (%)		Ring MFA (degrees)	
			Mean (Std)	Range	Mean (Std)	Range	Mean (Std)	Range	Mean (Std)	Range	Mean (Std)	Range
South Atlantic	5	71	24.0 (5.1)	14.5–38.1	22.2 (2.3)	16.4–26.7	0.528 (0.095)	.302–.794	47 (18.2)	3–87	23 (8.0)	8–46
North Atlantic	3	45	24.5 (5.7)	13.4–34.8	19.4 (3.0)	14.9–25.0	0.495 (0.085)	.330–.713	44 (18.2)	2–86	28 (7.7)	9–53
Piedmont	6	89	24.8 (4.7)	15.7–36.6	18.5 (1.8)	15.1–23.5	0.479 (0.085)	.293–.738	40 (17.5)	0–96	27 (7.4)	9–51
Gulf Coastal	3	42	18.8 (3.3)	13.2–24.9	15.8 (2.5)	11.9–19.8	0.485 (0.077)	.246–.695	39 (16.3)	0–80	24 (7.3)	8–41
Hilly Coastal	3	45	19.9 (4.2)	12.7–29.2	18.7 (3.0)	13.4–23.2	0.467 (0.087)	.212–.710	36 (15.7)	0–81	24 (7.2)	9–45
All stands	20	293	23.0 (5.3)	12.7–38.1	19.2 (3.1)	11.9–26.7	0.492 (0.089)	.212–.794	42 (17.8)	0–96	25 (7.8)	8–53

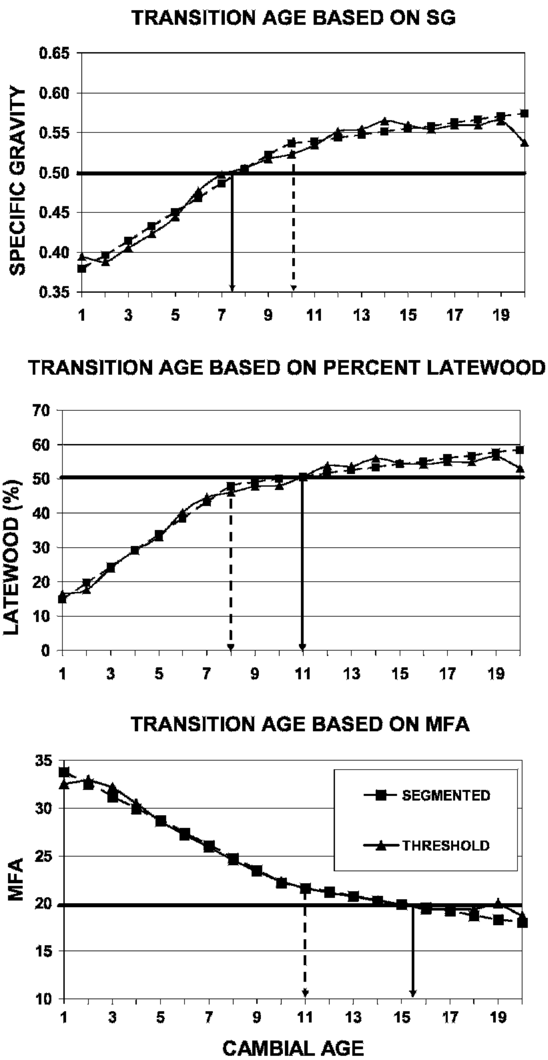

FIG. 2. Average age of transition from juvenile to mature wood for loblolly pine based on annual ring SG, percent latewood, and MFA as estimated using the threshold and segmented approach applied to all trees sampled.

shows the angle to be largest in the crown-formed wood zone in rings 2 – 3 near the pith, then a decrease gradually in the next 4 to 12 rings in the transition zone, followed by a leveling off in mature wood.

The threshold approach based on using 0.5 SG for the start of mature wood showed that for all trees combined the transition age was 7.3 years compared to 9.7 years for the segmented equation method (R^2 = .46) (Fig. 2). The transition age for all trees combined based on annual ring percent latewood was 10.5 years using a threshold of 50% latewood compared to 8.1 years for the segmented approach (R^2 = .55). The age of transition for all trees combined based on a threshold of a MFA of <20 degrees for the start of mature wood was 15.0 years compared to 10.3 years for the segmented method (R^2 = .38).

Plots of average annual ring SG, percent latewood, and MFA over cambial age by physicgraphic region (Figs. 3, 4, and 5) show regional differences in the properties plotted. The plots of average annual ring SG show, that on average, ring SG is higher in the South Atlantic, North Atlantic, and Gulf Coastal Plains compared to that of the Piedmont or Hilly Coastal Plain. These regional differences in ring SG are significantly correlated (r = .92) with the amount of high SG latewood in the ring. The length of the growing season is longer and the amount of late summer precipitation higher along the Atlantic and Gulf Coast compared to that inland; thus the trees produce more high SG latewood. The plot of average annual MFA shows MFA to be smaller in the South Atlantic, Hilly and Gulf Coastal Plains compared to the North Atlantic Coastal Plain and Piedmont. These regional differences in MFA are likely genetically related to seed provenance.

The age of transition from juvenile to mature wood based on ring SG using the threshold approach was shortest in the South Atlantic Coastal Plain (5.5 years) and longest in the Hilly Costal Plain (10.4 years) (Table 3). The segmented method, based on ring SG, also estimated the length of juvenility to be shortest in the South Atlantic Coastal Plain (7.9 years) and longest in the Hilly Coastal Plain (13.6 years). Using plots of annual ring percent latewood, the threshold method estimated the length of transition to be shortest in the South Atlantic Coastal Plain (6.5 years) and longest in the Piedmont (13.1 years). The segmented approach based on percent latewood also estimated the length of transition to be shortest in the South Atlantic

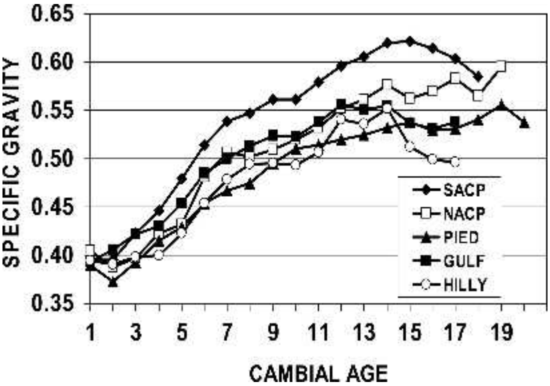

FIG. 3. Average annual ring wood SG over cambial age for loblolly pine sample in the South Atlantic (SACP), North Atlantic (NACP), Gulf (GCP), and Hilly Coastal Plain (HCP), and Piedmont (PIED).

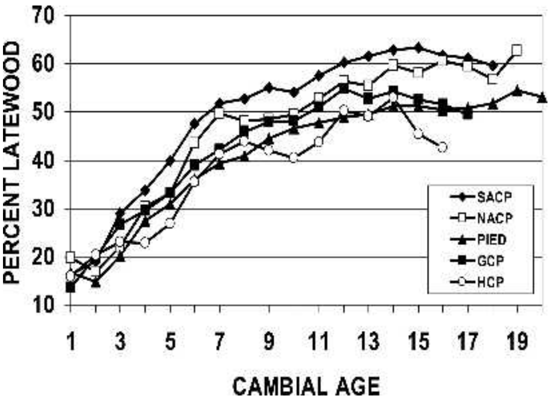

FIG. 4. Average annual ring percent latewood over cambial age for loblolly pine sample in the South Atlantic (SACP), North Atlantic (NACP), Gulf (GCP), and Hilly Coastal Plain (HCP), and Piedmont (PIED).

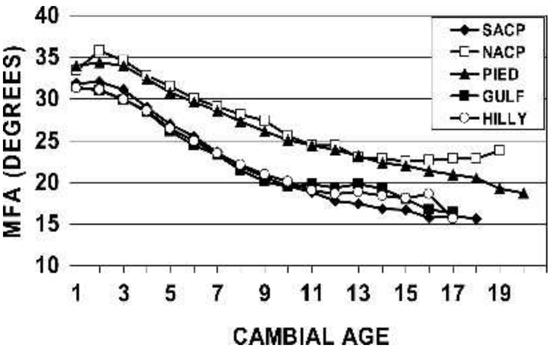

FIG. 5. Average annual ring MFA over cambial age for loblolly pine sample in the South Atlantic (SACP), North Atlantic (NACP), Gulf (GCP), and Hilly Coastal Plain (HCP), and Piedmont (PIED).

TABLE 3. *Estimated age of transition from juvenile to mature wood by physiographic region based on ring SG, percent latewood, and MFA as estimated using the threshold and segmented approach.*

	Transition Age					
	SG		Percent latewood		Mean	
Physiographic Region	Threshold	Segment	Threshold	Segment	Threshold	Segment
			(Years)			
South Atlantic Coastal	5.5	7.9	6.5	6.9	9.5	10.4
North Atlantic Coastal	6.8	7.9	7.1	7.0	20 +	13.4
Gulf Coastal	7.1	10.7	10.6	7.9	9.0	8.9
Piedmont	9.3	10.4	13.1	8.8	18.3	10.5
Hilly Coastal	10.4	13.6	12.0	12.5	10.2	9.8
All regions	7.3	9.7	10.5	8.1	15.0	10.3

Coastal Plain (6.9 years) but longest in the Hilly Coastal Plain (12.5 years). The age of transition from juvenile to mature wood using the threshold approach based on ring MFA was shortest in the Gulf Coastal Plain (9.0 years) and longest in the North Atlantic Coastal Plain (+20 years) (Table 2). The segmented method, based on ring MFA, also estimated the length of juvenility to be shortest in the Gulf Coastal Plain (8.9 years) and longest in the North Atlantic Coastal Plain (13.4 years).

The ages of transition for each physiographic region estimated by the threshold and segmented approach were highly correlated when predicted based on SG ($r = 0.87$), percent latewood ($r = .69$), and MFA ($r = 0.80$) (Table 3). Both methods for estimation showed that transition age varied among physiographic regions. Based on ring SG, both methods showed the length of juvenility was longer in the Hilly Coastal Plain compared to the South Atlantic, North Atlantic, and Gulf Coastal Plains. Both methods showed that when using ring MFA to estimate the age of transition, the length of juvenility was longer in the Piedmont and North Atlantic Coastal Plain compared to the South Atlantic, Gulf and Hilly Coastal Plains (Table 3).

SUMMARY AND CONCLUSIONS

Precisely estimating the age of transition between juvenile and mature wood is difficult because transition in loblolly pine is gradual and not abrupt. Determining the transition age based on different wood properties makes the determination of the age of demarcation even more difficult to define because properties mature at varying rates due to genetic and environmental factors. Both the threshold and segmented methods did a good job estimating the transition age between juvenile and mature wood, since no one answer is correct. An advantage of the threshold method is that mature wood can be defined as having properties of a minimum specified value that can relate to the final product, whereas the segmented approach defines mature wood based on the rate of change of a property. Both the threshold and segmented model approach showed transition age varied among physiographic regions. Based on ring SG, both the threshold and segmented approaches showed the length of juvenility of loblolly pine was shorter in the South Atlantic and North Atlantic Coastal Plains ranging from 5.5 to 7.9 years compared to that in the Hilly Coastal Plain that ranged from 10.4 to 13.6 years. Using MFA to estimate the point of demarcation, both methods showed the South Atlantic, Gulf Coastal, and Hilly Coastal Plains to have lengths of juvenility ranging from 9.0 to 10.4 years and compared to the North Atlantic Coastal Plain and Piedmont that have lengths of juvenility ranging from 10.5 to over 20 years.

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