JUVENILE-MATURE WOOD DEMARCATION IN LOBLOLLY PINE TREES

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ABSTRACT

Specific gravity data from loblolly pine (*Pinus taeda* L.) trees in a region-wide thinning study in southeastern United States were used to determine the age of demarcation between juvenile and mature wood. Segmented modeling, iterative solution, and constrained solution approaches were used to estimate the demarcation age. The results indicated that the age of demarcation between juvenile and mature wood occurs at approximately 11 years of physiological or cambial age (i.e., number of rings from the pith). Constraining the slope of the mature wood equation to a non-negative value lowered the demarcation age typically to less than 10 years. Within-tree variation in the age of demarcation was minor, suggesting that the use of the demarcation age estimate at breast height is adequate when quantifying the proportion of juvenile wood in a tree. Variations in the age of demarcation along the stem due to thinning effects and physiographic region did not show consistent trends. Trees in the Coastal Plain, however, tended to have lower ages of demarcation than trees from other areas.

Keywords: Segmented model, demarcation age, specific gravity, iterative solution, *Pinus taeda*.

INTRODUCTION

Juvenile wood, wood formed earlier in tree life and in the live crown of trees, has been defined in various ways based on position, stage of maturity, tree development, and phases of vegetative growth (Yang et al. 1986). As it has properties markedly different from those of mature wood, juvenile wood causes problems of processing and quality in certain end uses (Senft and Bendtsen 1984). Juvenile wood has low specific gravity and hence is structurally weak, tends to yield pulp and paper products of inferior quality, and is characterized by considerable changes with physiological age in anatomical, chemical, and physical properties (Thomas 1984). The large fibril angles and the preponderance of reaction wood in juvenile material cause excessive longitudinal shrinkage and instability in service (Bendtsen 1978; Bendtsen and Senft 1986; Yang et al. 1986; Roos et al. 1990). Nonetheless, paper properties such as burst strength, tensile strength, fold endurance, uniformity of formation, and print uniformity typically increase with increasing content of juvenile fibers (Semke 1984).

Because of the accelerated diameter growth achieved in intensively managed plantations, a given diameter is achieved much sooner than in natural stands and rotation ages are typically shorter. Consequently, the wood produced in these plantations tends to have a large proportion of juvenile wood. Forest managers are therefore increasingly interested in information on the proportion of juvenile wood produced in a given harvest. A prelude to an accurate determination of the proportion of juvenile wood in a tree is knowing the boundary between juvenile and mature wood.

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Many studies have been conducted to determine the point of demarcation between the juvenile and mature wood in various species [Loo et al. (1985) loblolly pine; Bendtsen and Senft (1986) loblolly pine and cottonwood (*Populus deltoides* Bartr.); Yang et al. (1986) larch (*Larix laricina* (Du Roi) K. Koch); Clark and Saucier (1989) loblolly pine and slash pine (*Pinus elliottii* Englm.); Roos et al. (1990) quaking aspen (*Populus tremuloides* Michx.); and Abdel-Gadir and Krahmer (1993) Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco)].

Researchers have used various methods to determine the age of demarcation between mature and juvenile wood. Loo et al. (1985) determined the age of demarcation as the point of intersection of two linear regressions of specific gravity. Where the slope of the mature wood equation was less than zero, they subjectively identified the demarcation age. Bendtsen and Senft (1986) used segmented regression analysis, discriminant analysis, analysis of slope, and subjective visual analysis of specific gravity to determine the age of demarcation. Clark and Saucier (1989) used visual inspection of specific gravity graphs; Yang et al. (1986) used changes in ring width and tracheid length; and Abdel-Gadir and Krahmer (1993) applied piece-wise linear regression of specific gravity values to determine the demarcation point between juvenile and mature wood.

Investigators reported difficulty in precisely and consistently determining the age of demarcation between juvenile and mature wood, and often relied on combinations of techniques including subjective means. Determining the age of demarcation between mature and juvenile wood can be difficult because the transition from juvenile to mature wood is not abrupt but gradual (Thomas 1984; Yang et al. 1986; Roos et al. 1990), and varies among species (Bendtsen and Senft 1986), genetic families (Abdel-Gadir and Krahmer 1993), and geographic location (Clark and Saucier 1989). Also, within-tree variation in the demarcation point is not usually addressed and may have contributed to the inability to consistently establish the point of demarcation (Yang et al. 1986).

The effect of thinning on the age of demarcation between juvenile and mature wood is an important management issue since one of the long-standing concerns regarding thinning effects on wood quality can be partly addressed by answering this question. Regional variation in the specific gravity of loblolly pine has been documented (Zobel and McElwee 1958; Zobel et al. 1972; Talbert and Jett 1981; Clark and Saucier 1989; Tasissa and Burkhart 1998). A question of interest to foresters is whether there is a corresponding regional variation in the age of demarcation between juvenile and mature wood.

The purpose of this study was to investigate the age of demarcation between juvenile and mature wood in loblolly pine using ring specific gravity. The specific objectives of the study were to evaluate within-tree variation in demarcation age, to investigate the effects of thinning on the age of demarcation, and to identify any regional variation in the age of demarcation.

MATERIALS AND METHODS

Data

The data used in this study were obtained from stem analysis conducted on trees removed in a second thinning from a region-wide loblolly pine thinning study (Burkhart et al. 1985) maintained by the Loblolly Pine Growth and Yield Research Cooperative at Virginia Polytechnic Institute and State University (USA). The thinning study was established during the 1980–1982 dormant seasons in 186 plantations throughout the native range of loblolly pine, and consisted of two thinning treatments and a control. To be included in the thinning study, the plantations had to be on cutover, site-prepared sites, and of genetically unimproved stock. The plantations included in the study varied in age (8 to 25 years), number of trees per hectare at thinning (679 to 2,347 trees), site index[1] (14 to 27 meters), and seed source.

The thinning study plots were distributed over 12 states and four broad physiographic regions: Atlantic-Coastal Plain, Gulf-Coastal Plain, Piedmont, and Highlands in southeastern United States (within approximately 30°N to 37°N and 76°W to 97°W). The thinning treatment levels were light thin (approximately 30% of the basal area removed) and heavy thin (approximately 50% of the basal area removed). The plots were monitored over time by taking basic mensurational data such as dbh (diameter at breast height), total tree height, crown height, and subjective measures of stem quality at plot establishment and every 3 years thereafter.

A second thinning was conducted in roughly half of the plots during the 1992–1994 dormant seasons. Prior to thinning, two trees were randomly selected from each plot for stem analysis. In the light thin and heavy thin plots, the actual trees selected were used; whereas in the control plots, trees characteristically (in dbh, total height, stem form, etc.) similar to those selected were taken from trees in the buffer zone surrounding the plots. The selected trees were felled and sectioned at approximately 1.2-m intervals starting at stump height to a top diameter of approximately 5 cm. A disk approximately 2.5 cm thick was cut from the top of each section and sent to the USDA Forest Service laboratory in Athens, Georgia. At the laboratory, 5-mm-square radial cores were prepared. The cores for heights at stump, dbh, 2.6 m, 5.0 m and approximately every 5.0 m thereafter were selected and sent to the Weyerhaeuser Technology Center in Tacoma, Washington, to obtain ring-by-ring specific gravity and other measurements using the X-ray densitometry technique.

In order to prepare each core for X-ray scanning, the sample was sawn in the grain direction to about 2-mm (±0.025-mm) thickness throughout the length and was then treated with alcohol/benzene solution to extract the pitch and phenolic colorings and conditioned to a uniform moisture content (75 degrees, 50% relative humidity). The scanning was conducted with a system using a customized scanning stage with a standard commercial X-ray diffractometer.

The sample was scanned past a 50-μm by 40-μm collimated X-ray beam, where the X-ray conditions were chosen to achieve maximum discrimination between the highest and lowest density to be encountered. A reference standard (calibrated step wedge) was X-rayed along with every sample. Each X-ray intensity value transmitted from the sample was converted to a specific gravity value by relating it to a regression fit between the step wedge intensity values and the calibrated wood specific gravity values assigned to the steps. The samples were continuously scanned, typically about 10 sample points per mm. A 0.500 specific gravity value was used to signal the end of one ring and the beginning of another. The specific gravity values were expressed on an oven-dry weight, green-volume basis. A total of 256 trees with 27,571 ring specific gravity observations were used (Table 1). Tasissa and Burkhart (1998) used the data to model ring specific gravity in an earlier study.

Analysis

In order to determine the age of demarcation between juvenile and mature wood, alternative approaches were considered. Specific gravity in loblolly pine is a function of ring physiological age, as shown by the average ring specific gravity profile depicted in Fig. 1. As seen in Fig. 1, average specific gravity increases sharply until about age 10 and then increases gradually, leveling off at about age 15. Past that, it stabilizes showing little change with increasing age. The age of demarcation is considered to be the age at which the transition from juvenile to mature wood is completed, leading to a stable specific gravity reading.

Three interrelated approaches—iterative so-

[1] Site index for base age 25.

TABLE 1. *Summary statistics for tree and ring data used in the study; combined and by thinning treatment.*

Variable	n	Mean	Coefficient of variation	Minimum	Maximum
Combined					
dbh (cm)	256	21.7	23.1	10.9	35.6
Height (m)	256	18.2	14.5	10.3	26.8
Age (yr)	256	26.0	15.4	20.0	36.0
Specific gravity	27,571	0.453	17.1	0.252	0.762
Control					
dbh (cm)	64	20.6	25.6	10.9	34.3
Height (m)	64	18.0	15.5	10.3	24.5
Age (yr)	64	26.0	16.2	20.0	36.0
Specific gravity	6,750	0.450	17.5	0.264	0.760
Light thin					
dbh (cm)	95	21.9	20.6	12.4	35.3
Height (m)	95	18.1	15.3	12.6	25.9
Age (yr)	95	26.0	15.6	20.0	36.0
Specific gravity	10,386	0.452	16.9	0.269	0.748
Heavy thin					
dbh (cm)	97	23.5	18.6	13.7	35.1
Height (m)	97	18.4	13.6	12.6	26.8
Age (yr)	97	26.0	14.8	20.0	36.0
Specific gravity	10,435	0.451	17.0	0.275	0.763

lution, segmented model, and constrained solution—were used to determine the age of demarcation at breast height and at different heights along the stem. The effects of thinning were evaluated by estimating average demarcation age by thinning treatment at specific heights. Similarly, regional variation was evaluated by determining average demarcation age by physiographic region at specific heights along the stem.

Iterative solution

An iterative solution approach has been used in the past to determine the age of demarcation between juvenile and mature wood (Loo et al. 1985; Abdel-Gadir and Krahmer 1993). Two linear models, one for the juvenile and another for the mature portion, are specified and the age of demarcation is determined as the age which "minimizes" the mean-squared error. In this approach, the data are divided into two parts using one of the ages as a demarcation point, a linear regression is fitted, and the mean-squared error is noted. Several linear regression runs are conducted and the age with minimum mean-squared error is taken to be the age of demarcation. Let:

$$Y_i = \beta_0 + \beta_1 X_i + \beta_2 (X_i - \alpha) I + \epsilon_i \quad (1)$$

where

- Y_i is ring specific gravity
- X_i is ring physiological age
- α is the physiological age at which wood changes from juvenile to mature
- I is an indicator variable where

$$I = \begin{cases} 1 & \text{if } X_i - \alpha \geq 0, \\ 0 & \text{otherwise} \end{cases}$$

- β_i's are regression coefficients, and
- ϵ_i's are errors.

If α was known, Eq. (1) is a linear regression, and its parameters (β_i's) may be estimated using piece-wise linear regression (Neter et al. 1989). Thus for $X_i \leq \alpha$ (the juvenile wood),

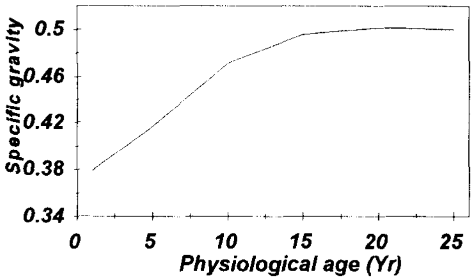

FIG. 1. Average specific gravity (oven-dry weight, green volume) by physiological age.

$$E(Y_i) = \beta_0 + \beta_1 X_i \quad (2)$$

And for $X_i > \alpha$ (the mature wood)

$$E(Y_i) = \beta_0 + \beta_1 X_i + \beta_2(X_i - \alpha)$$

$$= (\beta_0 - \beta_2\alpha) + (\beta_1 + \beta_2)X_i$$

$$= \gamma_0 + \gamma_1 X_i \quad (3)$$

In this formulation, the two regression lines are continuous at the join point (α). Consequently, at the boundary Eq. (2) yields $Y_i = \beta_0 + \beta_1\alpha$, and Eq. (3) becomes $Y_i = (\beta_0 - \beta_2\alpha) + (\beta_1 + \beta_2)\alpha = \beta_0 + \beta_1\alpha$. The case where there is a jump, rather than a continuous transition, at the join point may be accommodated by a second dummy variable (Neter et al. 1989; Abdel-Gadir and Krahmer 1993).

Segmented model

When the join point in Eq. (1) is unknown, the problem becomes nonlinear (Gallant and Fuller 1973) and the join point has to be estimated along with the regression parameters. The join point is usually estimated using segmented regression procedures. A solution may be directly obtained by using nonlinear least squares procedures available in statistical packages with the demarcation age being the physiological age which minimizes the mean-squared error. Since the demarcation age is unknown, its identification is the main objective of this study. The nonlinear least squares procedure in SAS (SAS Inc. 1985) was used in this study to obtain estimates of the regression parameters and the age of demarcation (join point).

Constrained solution

An analysis of Eq. (3), both using nonlinear least squares and estimating the demarcation age iteratively, showed that the minimum mean-squared error is usually achieved with $\gamma_1 < 0$ (i.e., with a negative slope for the mature wood portion of the curve). Average ring specific gravity of the mature wood, however, is expected to show a slight increase with increasing age, or at least remain constant (i.e., $\gamma_1 \geq 0$). While the main purpose of this study was not to predict specific gravity but to identify the age of demarcation between mature and juvenile wood, a negative slope in Eq. (3) is undesirable as it gives the impression that mature wood specific gravity decreases with increasing age. To alleviate this phenomenon, the age of demarcation was estimated by constraining the slope parameter in the mature wood equation to a non-negative value.

RESULTS

Before presenting the results, a brief examination of the relationships among the methods used to estimate the demarcation age is appropriate. The difference between the iterative solution and segmented model methods was that the segmented model solution yielded demarcation ages with "true" minimum mean-squared error, whereas in the iterative solution integer demarcation age values were obtained. When the demarcation age estimates from the segmented model were rounded to the nearest integer, the methods provided very similar results.

Constraining the solution almost always led to a demarcation age much younger than indicated by minimum mean-squared error (Fig. 2). While the constrained solution gave positive slope for the mature wood component, if the results are to be used for estimating the proportion of mature wood in a tree, the demarcation ages obtained from the unconstrained solutions provide more realistic estimates. Consequently, the segmented model was used in evaluating thinning effects on the age of demarcation and regional variation in

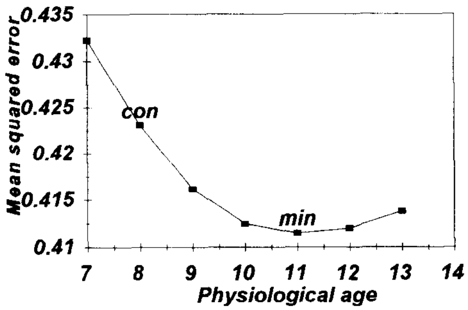

FIG. 2. A comparison of constrained and minimum sum of squares solution for identifying demarcation age at breast height (con = constrained, min = minimum mean-squared error).

the age of demarcation. The results reported herein focus on the age of demarcation up to 5 meters because the decreased sample size from higher points along the stem tended to yield rather erratic demarcation age estimates.

Within-tree variation in demarcation age

An understanding of the demarcation age variation along the stem helps in deciding whether a single sample point is adequate to determine the age of demarcation. As shown in Table 2, for the portion of the tree bole up to 5 m in height, there is only a minor within-tree variation in the age of demarcation, particularly for the iterative and segmented model solutions. This result agrees with conclusions drawn earlier based on visual demarcation of juvenile and mature wood (Zobel and McElwee 1958; Zobel et al. 1959). Though based on samples concentrated in the lower bole, the results indicate that there is roughly a cylindrical (implicitly, with cone-shaped top) core of juvenile wood in loblolly pine trees making it easy to estimate the proportion of juvenile wood in a tree.

Thinning effects on the age of demarcation

In order to evaluate thinning effects on the age of demarcation, the data were grouped by thinning treatment, and the age of demarcation was evaluated at several heights along the stem. A plot of the demarcation age by height

TABLE 2. *Demarcation age at different heights using alternative methods.*

	Demarcation age		
Height (m)	Iterative	Segmented	Constrained
0.2	12	12.1519	9
1.4	11	11.3641	8
2.6	11	11.4093	9
5.0	12	12.5329	11

and thinning treatment did not show a consistent trend (Fig. 3) and firm conclusions could not be drawn. Inspection of Fig. 3 shows that only the control plot has significantly higher demarcation age at breast height than the thinned plots. Further tests[2] performed by grouping the data into thinned and control showed that the control plots had a lower age of demarcation at stump height and at 5.0 m, while showing higher demarcation age at breast height and at 2.6 m. Thus, there is not a consistent pattern by height in the stem, and one may conclude that thinning effects on the age of demarcation are not significant.

Regional variation in the age of demarcation

To evaluate regional variation in the age of demarcation, the data were grouped into the four broad physiographic regions, the age of demarcation was evaluated separately for each physiographic region, and the age of demarcation was plotted by height for each physiographic region (Fig. 4). While the graph does not show a consistent overall pattern, the ages of demarcation occurred earlier in the Gulf Coastal Plain than in the Atlantic Coastal Plain, Piedmont, and the Highlands.

The ages of demarcation were also determined by combining the Coastal Plain data, and the data from the other areas (Piedmont and the Highlands). The results showed that the ages of demarcation for the trees from the Coastal Plain sites are consistently lower than those of the other areas. The trends observed are similar to those of Zobel and McElwee (1958), and Clark and Saucier (1989), who

[2] All tests in this study were conducted at $\alpha = 0.05$.

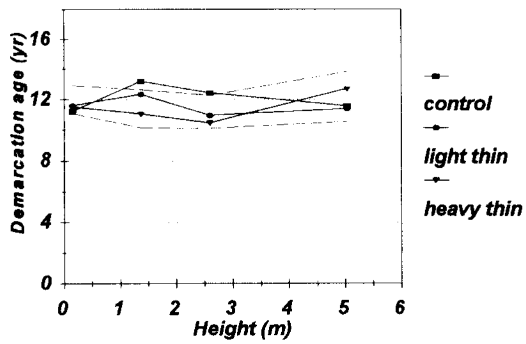

FIG. 3. Thinning effects on the age of demarcation between juvenile and mature wood. The dashed lines show the 95% confidence band for the mean demarcation age.

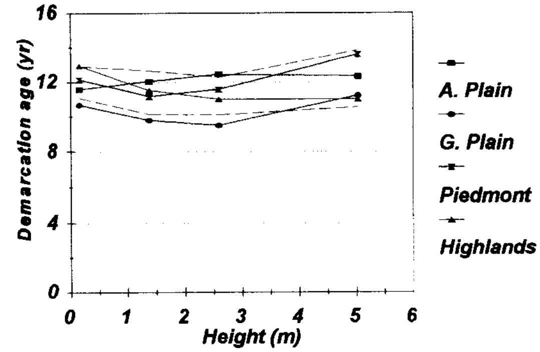

FIG. 4. Regional variation in the age of demarcation between juvenile and mature wood (A. Plain = Atlantic Coastal Plain, G. Plain = Gulf Coastal Plain). The dashed lines show the 95% confidence band for the mean demarcation age.

evaluated regional variation in the age of demarcation between juvenile and mature wood of loblolly pine using samples from breast height.

DISCUSSION AND CONCLUSIONS

The average demarcation age found in this study compares closely with those reported for loblolly pine by Loo et al. (1985), and Bendtsen and Senft (1986). Many past studies examining the age of demarcation between juvenile and mature wood in loblolly pine (Loo et al. 1985; Bendtsen and Senft 1986; Clark and Saucier 1989) used data at one point along the stem (generally breast height) and usually trees from one geographic area. The level of detail and the geographic extent of the data used in this study enabled us to evaluate vertical variation (up to 5 m) in the age of demarcation, thinning effects on the age of demarcation, and regional variation in the age of demarcation. As observed in an earlier detailed analysis of the age of demarcation (Zobel et al. 1959), the results of this study indicate that the vertical variation in the age of demarcation is slight. The practical significance of the outcome is that one can obtain an estimate of the proportion of juvenile wood in a standing tree without costly upper stem sampling.

A study conducted to determine thinning effects on ring specific gravity using the same data showed no significant treatment effects, though significant regional variation in ring specific gravity was detected (Tasissa and Burkhart 1998). Similar conclusive statements could not be made in this study because demarcation age along the stem by region showed an erratic pattern. The inconsistency may be due to the decreased sample size sustained when grouping the data into physiographic regions and thinning treatment by height, and probably is also due to the extensive tree to tree variation in specific gravity (Zobel and McElwee 1958).

The results of the study showed that there is a tradeoff between obtaining a logical coefficient estimate for estimating demarcation age, having non-negative slope for the mature wood, and finding the age of demarcation with minimum mean-square error. Part of this discrepancy is due to the large variability in within-tree specific gravity. Though average specific gravity shows a distinctive pattern (Fig. 1), specific gravity of individual trees, for instance at breast height, showed considerable variability (Fig. 5). Consequently, while specific gravity in the mature wood is expected to be higher than that in the juvenile part, in several instances, specific gravity values in the mature wood were lower, and hence a negative slope of the mature wood portion of the equation resulted.

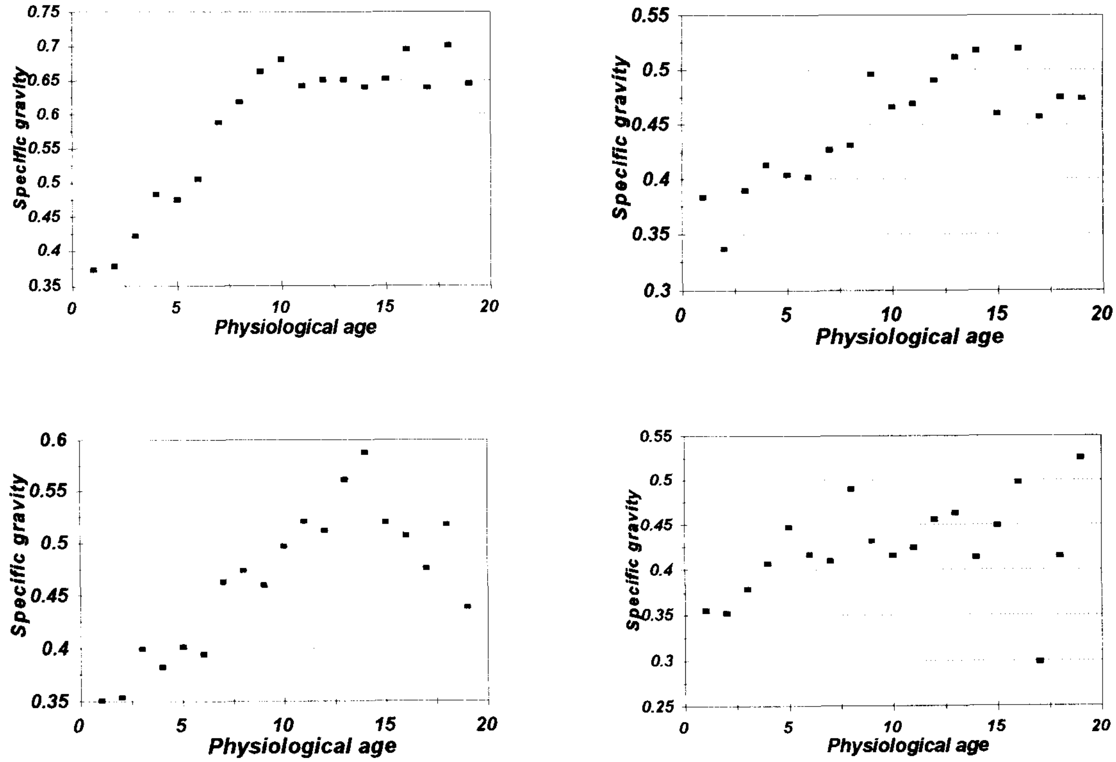

FIG. 5. Specific gravity (oven-dry weight, green volume) by physiological age at breast height for selected trees.

In conclusion, the age of demarcation may be determined by using a constrained solution or by minimizing the mean-squared error. The latter appears to be a more reasonable approach since it agrees well with graphical analysis. Basing demarcation of juvenile and mature wood on physiological age is advantageous because it is independent of the growth rate, and is consistent with the notion that specific gravity and growth rate are poorly correlated in loblolly pine. The lack of consistent trends in variations due to thinning treatments and broad physiographic regions suggests that accounting for these factors is not warranted.

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