ESTIMATING THE AGE OF DEMARCATION OF JUVENILE AND MATURE WOOD IN DOUGLAS-FIR[1]

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ABSTRACT

In order to characterize trends and to estimate the age of transition from juvenile to mature wood in Douglas-fir, piecewise linear regression analysis was applied to the radial pattern of intra-ring characteristics found in increment cores of Douglas-fir trees sampled at breast height. The data were collected with X-ray densitometry. Average ring density of all trees along the radius showed an initial decline within the first ten rings from the pith, a rapid increase to about ring thirty, and a continued increase at a lower rate thereafter. Three main wood-density profiles were found among trees. Piecewise regression models were used successfully to characterize radial development of wood density and to determine the demarcation of juvenile and mature wood.

Keywords: Wood density, juvenile wood, mature wood, demarcation, Douglas-fir.

INTRODUCTION

The most studied within-tree variability is the trend in wood properties from pith to bark, a radial pattern frequently described in terms of juvenile and mature wood zones. Juvenile wood, the portion of the tree stem surrounding the pith, is characterized by a progressive change in cell features and wood properties (Panshin and deZeeuw 1980). The radial pattern appears along the entire stem and has been explained in terms of changes in tracheid dimensions and, ultimately, in terms of needle development and hormone production (Larson 1973). Characteristics of juvenile wood have been summarized by Thomas (1984) and Krahmer (1986), and their impact on wood utilization has been well documented (Kellogg 1982; Senft and Bendtsen 1984; Maloney 1986; Megraw 1986). Although juvenile wood is not necessarily substandard, e.g., for newsprint and quality printing paper (Zobel 1984), it is well substantiated that its properties can adversely affect some properties of solid wood, pulp and paper, and composition board. There is considerable interest in its properties because its volumetric proportion in products from both thinnings and final harvest is increasing as a result of intensive forest management.

If the extent and quality of juvenile wood are to be better understood, the demarcation between it and mature wood must first be defined, a complicated task because the change from juvenile to typical mature wood occurs gradually over years (Bendtsen 1978). Several methods of varying complexity and objectivity have been used to identify the demarcation. They range from identifying the dull appearance of juvenile wood by visual examination

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of stem cross sections of slash pine (Zobel et al. 1958) to applying nonlinear regression techniques in quaking aspen (Roos et al. 1990). The most frequently used method is visual examination of graphic plots of wood properties over rings from the pith (e.g., Bendtsen and Senft 1986; Clark and Saucier 1989).

Shiokura (1982) used a logarithmic formula to describe the radial variation in tracheid length with ring number (pith = 0) and then calculated the percentage of annual increment of tracheid length. The point at which the annual increment of the length decreased to 1% was considered to be the boundary between juvenile and mature wood. Loo et al. (1985), investigating specific gravity and tracheid length in loblolly pine, used an iterative procedure involving two linear regressions of individual tree data, one for juvenile and the other for mature wood, noting their intersection. Each iteration was made with the two subsets created by the previous one, and the intersection point from the last iteration was regarded as the boundary between juvenile and mature wood. Where the procedure produced negative slopes in the juvenile wood group, Loo et al. (1985) visually determined the boundary. Yang et al. (1986), studying tracheid length in larch, used a slightly different iterative procedure, defining the preliminary boundary for the first iteration visually from the density of growth rings.

Bendtsen and Senft (1986) have discussed the difficulties of estimating the demarcation of juvenile and mature wood in loblolly pine and cottonwood with segmented regression, discriminate analysis, and slope analysis of both individual-tree and average values for mechanical and anatomical properties, noting that "because of the large variability in values from tree to tree or year to year, none of the three methods produced demarcation points that appeared to be consistent juvenile-mature wood boundaries."

The objectives of this study were: 1) to describe the average trend in wood density of Douglas-fir over time and the various configurations of density in individual trees, and 2) to characterize the trends and estimate the age of transition from juvenile to mature wood by applying piecewise linear regression (Neter et al. 1989), where the regression of density on age follows one linear relation in the juvenile-wood range, but another in the mature-wood range.

TRENDS IN AVERAGE INTRA-RING PROPERTIES ACROSS THE RADIUS

Density-profile data from two 12-mm increment cores were extracted at breast height from each of 360 Douglas-fir trees in progeny trials in the Wind River National Forest and Mount Hood National Forest (Abdel-Gadir et al., 1993). Intra-ring characteristics at 9% moisture content were obtained by X-ray densitometry with procedures and equipment described by Hoag and McKimmy (1988) and Hoag and Krahmer (1991).

Data were averaged across all trees to produce an average profile for each intra-ring characteristic (Fig. 1). The higher density in rings 1 to 5 than in rings 6 to 10 is attributable to a higher proportion of latewood and higher density of earlywood in the first five rings (Fig. 1A, B, C). These profiles for Douglas-fir are essentially in agreement with the findings of other investigators (Kennedy and Warren 1969; Megraw 1986; Senft et al. 1986). However, they differ from the general pattern summarized by Bendtsen (1978), which consisted of a juvenile zone with wood-property values rapidly increasing or decreasing directly from the pith, a mature zone with little or no change, and an undefined transition zone between. Megraw (1986) noted that the zone of juvenile wood in Douglas-fir is more complex and not as well defined as in loblolly pine. Only latewood density showed a distinct juvenile-mature boundary in our study (Fig. 1D), with a rapid increase during the first 12 years followed by a definite change to a constant or a decreasing trend.

The radial patterns of the other characteristics indicate two developmental phases during juvenile wood formation. Ring density, the percentage of latewood, and earlywood density

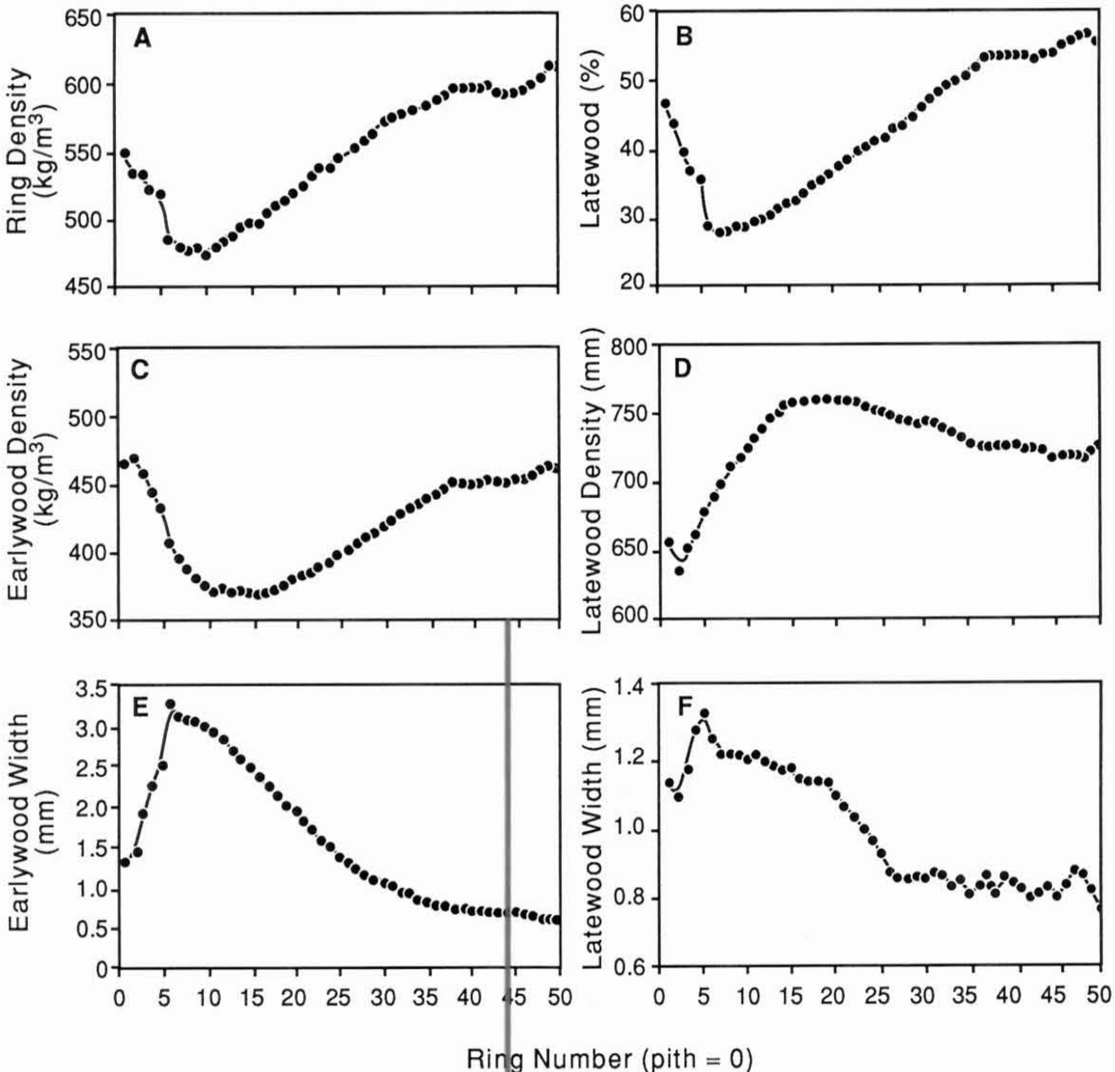

FIG. 1. Average trends for six intra-ring characteristics across the radius of the stem (n = 360).

(Fig. 1A, B, C) first decreased rapidly from the pith until a minimum value was reached, and thereafter increased rapidly for a time before values leveled out in the mature wood zone. An initial increase within the first 6 rings, followed by a fast decline that continued for more than 20 years, was shown by earlywood width (Fig. 1E), latewood width (Fig. 1F), and ring width (not shown; similar to earlywood width). Clark and Saucier (1989) also showed that the wood formed during the juvenile period in southern pine trees can be divided into two segments (crown-formed and transition wood) according to the rate of change in wood properties. The average trends shown in Fig. 1 in our study suggest that, at least at breast height, biological maturity begins somewhere between rings 27 and 37 from the pith, depending upon the property under consideration.

TRENDS OF WOOD DENSITY IN INDIVIDUAL TREES

Density-profile data for this analysis were from increment cores selected randomly from samples originally collected from Douglas-fir trees for previous studies. Sixty cores were from 30 trees in the Wind River and Mount Hood National Forests (Abdel-Gadir et al. 1993), and fifteen (one per tree) were from trees sampled for a growth and yield study in the 1980s in the Siuslaw National Forest (R. L. Krahmer unpublished data). Ring-density data from individual trees were plotted for graphic analysis of profile variations and were used for the regression analysis.

The density data showed considerable fluctuation with age, making it unclear as to where a demarcation line between juvenile and mature wood could be drawn. However, visual examination of individual plots suggested three general patterns, typified by the data for selected trees shown in Fig. 2. Each of these patterns has additional variations that increase the number of profile patterns to twelve. In the juvenile zone, after wood density rapidly increases in succeeding rings, it may either level off gradually in a transition zone leading into mature wood, or shift abruptly from one zone to the other; in mature wood, density may either remain constant or continue to increase at a lower rate than in juvenile wood.

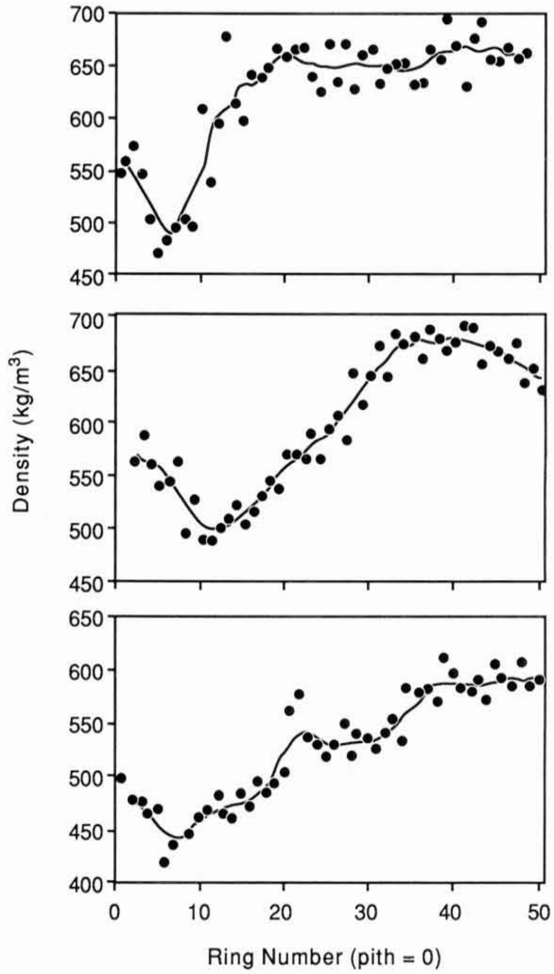

FIG. 2. Three main patterns of variation in wood density with age from the pith as typified by data from three individual trees.

REGRESSION MODELS

A search was made for a statistical model that would adequately characterize the trend of wood density across the radius, and that would be applicable to the patterns of wood density-age profiles, relevant to the concept of juvenile and mature wood—hence spontaneous in defining the boundary, easy to compute, and preferably, applicable to age trends of other properties.

The radial development of ring density is a function of cambial age (ring number from pith). Ring density from the age of the minimum density outward (Figs. 1 and 2) indicates that two regression models are needed to characterize wood-property variation with respect to age: one for juvenile and one for mature wood segments. However, the models can be joined in a single regression model. One method available for fitting this type of model is piecewise linear regression (Neter et al. 1989), a technique in which dummy variables are used to describe data that suggest changes in the coefficients of regression from one range of the independent variable(s) to another. The overall residual sum of squares obtained by such a model is minimized with respect to both the regression coefficients and the change point(s). For the ring-density profiles, the assumption was made that, from the ring with the minimum density in the profile outward, one point will mark the boundary between juvenile and mature wood. The two-piecewise model can then be expressed as follows:

$$Y_i = \beta_0 + \beta_1 X_i + \beta_2(X_i - X_{i*})D_i + \epsilon_i \quad (1.0)$$

where

Y_i = wood density of individual rings,
X_i = ring number starting from the one with lowest wood density to ring 50,
X_{i*} = ring number after which the slope of the first segment changes (last ring in juvenile wood),
D_i = 1 if $X_i > X_{i*}$ (in the mature wood zone), 0 otherwise (in the juvenile wood zone),
β_0 = intercept of the line of juvenile wood,
β_1 = slope of the line of juvenile wood,
β_2 = difference between the slopes of the regression lines for mature and juvenile wood,
ϵ_i = independent, normally distributed random error term.

For rings (cambial ages) before the boundary, $D_i = 0$ so that

$$E(Y_i) = \beta_0 + B_1 X_i. \quad (1.1)$$

After the boundary, $D_i = 1$, so that

$$E(Y_i) = \beta_0 + \beta_1 X_i + \beta_2(X_i - X_{i*}) = (\beta_0 - \beta_2 X_{i*}) + (\beta_1 + \beta_2)X_i. \quad (1.2)$$

The line of the mature wood segment has slope $\beta_1 + \beta_2$ and intercept $\beta_0 - \beta_2 X_{i*}$. The piecewise regression model requires that the regression lines of the two segments meet at the boundary that divides the data (X_{i*}). There is no discontinuity in the relationship since, at the boundary, Eq. (1.1) yields $Y_{i*} = \beta_0 + \beta_1 X_{i*}$, and Eq. (1.2) yields $Y_{i*} = [(\beta_0 - \beta_2 X_{i*}) + (\beta_1 + \beta_2)X_{i*}] = \beta_0 + \beta_1 X_{i*}$.

Where the transition from one zone to the other is abrupt or discontinuous, Eq. (1.0) can be extended to Eq. (2.0) by adding another dummy variable, D'_i, to compensate for the shift in the regression line.

$$Y_i = \beta_0 + \beta_1 X_i + \beta_2 (X_i - X_{i*})D_i + \beta_3 D'_i + \epsilon_i \quad (2.0)$$

where Y_i, X_i, X_{i*}, D_i, β_0, β_1, β_2, and ϵ_i are as in (1.0):

D'_i = 1 if $X_i > X_{i*}$ (in the mature wood zone), 0 otherwise (in the juvenile wood zone), and
β_3 = the difference in expected values of wood density (Y_i) for the two regression segments at boundary age (X_{i*}).

For rings (cambial ages) before the boundary (i.e., in the juvenile zone), $D_i = 0$ and $D'_i = 0$, and we obtain

$$E(Y_i) = \beta_0 + \beta_1 X_i. \quad (2.1)$$

In the mature wood zone, $D_i = 1$ and $D'_i = 1$, and the response equation will be

$$E(Y_i) = \beta_0 + \beta_1 X_i + \beta_2(X_i - X_{i*}) + \beta_3 = (\beta_0 - \beta_2 X_{i*} + \beta_3) + (\beta_1 + \beta_2)X_i. \quad (2.2)$$

ANALYSIS AND RESULTS

Density data from rings earlier than the ring with lowest density in the juvenile zone were omitted from all profiles. Because the boundary was not known, models 1.0 and 2.0 in each iteration were fitted to data for each profile with one of the remaining ages as the demarcation (X_{i*}). The results of the regression were considered admissible if the regression coefficients were statistically significant at the 0.05 probability level, if the slope of the mature wood line was positive or zero ($\beta_1 + \beta_2 \geq 0$), and if, in discontinuous models, β_3 was positive. These requirements adapt the general form of piecewise linear regression models to match the concept of juvenile and mature wood. Then the residual sums of squares produced by all admissible regressions were evaluated for each profile to determine the model and switch-point combination best supported by the data, i.e., the one resulting in the smallest error mean square (MSE). All analyses were performed with the Statistical Analysis System package (SAS Institute Inc. 1988).

Approximation of the wood-density profiles by this technique was realistic, and the technique described all existing variants satisfactorily and could be used to estimate the age of shift from juvenile to mature wood. In fact, imposing the three requirements described

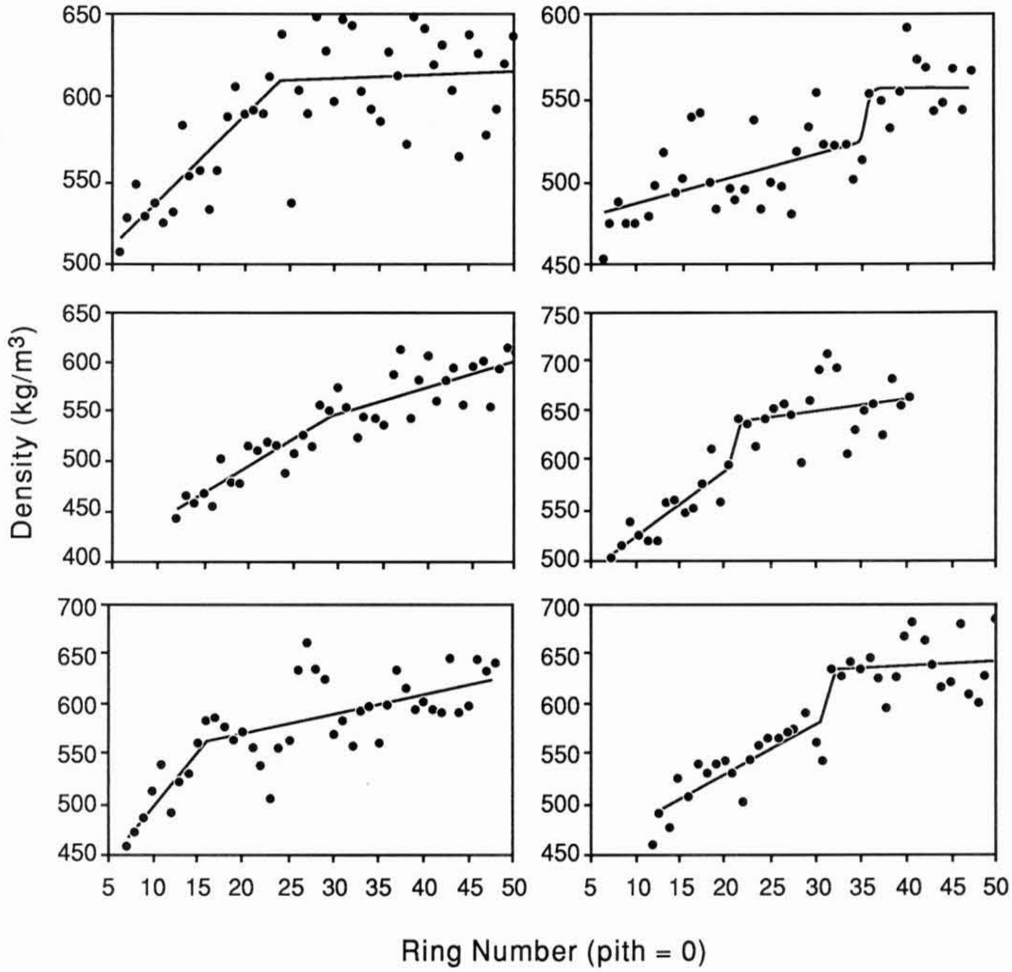

FIG. 3. Examples of fitted piecewise linear regression lines superimposed on wood density data from six trees.

above to results of the regression models reduced the number of profile variants from twelve to four. Wood density in the mature zone showed a constant or an increasing trend with age regardless of whether the mode of onset of mature wood was abrupt or smooth and gradual. The examples in Fig. 3 show lines fitted to data points obtained from individual trees.

Although the radial pattern of wood density in most of the trees could be approximated by a simple regression model, the descriptive power of the model was significantly improved by using piecewise linear regression models to introduce a switch point for the demarcation between juvenile wood and mature wood. Also, in all cases, approximation of the data sets by piecewise regression models was more advantageous (lower MSE) than approximation by a second- or third-order polynomial or by a logarithmic equation. In some trees, error variances calculated from the piecewise regressions were not homogeneous, and the simplifying assumption was made that their heterogeneity would not vitiate the analyses. It must be noted that correcting for nonconstant error variances by transforming the data to a different scale will modify the profile and negate the demarcation analysis.

Analysis of wood density of individual trees revealed that the age at which Douglas-fir wood began to show mature characteristics ranged from 15 to 38, around an average 26 years. Evidence in the literature suggests that the demarcation between juvenile and mature wood varies not only among species but also among wood traits (Bendtsen 1978; Loo et al. 1985; Bendtsen and Senft 1986). Similar results were obtained in this study by fitting piecewise linear regression to average trends of intra-ring characteristics. On average, the shortest juvenile wood period was shown by latewood density (14 years) and the longest period by latewood proportion and earlywood density (37 years). Based on width data from earlywood and latewood, juvenile wood was found to last 30 years and 24 years, respectively. The applicability of piecewise regression to patterns of intra-ring characteristics is obvious, since all patterns follow two straight-line relationships on opposite sides of an undetermined switch point.

Use of this technique requires caution; in some cases, if it is applied to data from young trees, it may detect significant demarcations (indicated by a significant β_2 or β_3) before the actual demarcation point. Only trees containing more than 45 rings from the pith should be used in an analysis to guarantee detection of the true demarcation. (This is made apparent by the fact that, in some of our sample trees, formation of juvenile wood density extended to age 38.)

Defining the age at which juvenile wood merges into mature wood is of great practical importance because of the increasing proportion of juvenile wood in the market. Such information will allow better estimation of average values for juvenile and mature wood properties and hence lead to better technologies for utilizing juvenile wood (Bendtsen and Senft 1986). The technique described here can be used to improve analyses in projects designed to determine the influence of silvicultural, genetic, or other factors on the formation of juvenile wood.

CONCLUSIONS

Piecewise linear regression models were found to be practical and spontaneous in an objective determination of the age of transition from juvenility to maturity in stem wood. Moreover, they were able to provide a full description of the development of a wood property along the radius. The change from juvenile wood to typical mature wood is neither sharp nor the same for all intra-ring characteristics.

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