MATHEMATICAL APPROACH FOR DEFINING JUVENILE-MATURE WOOD TRANSITION ZONE IN BLACK LOCUST AND CHESTNUT

*Stergios Adamopoulos**

Assistant Professor

Anthony Karageorgos

Lecturer

Technological Educational Institute of Larissa

Department of Forestry and Management of Natural Environment

431 00 Karditsa, Greece

Costas Passialis

Professor

Marina Chavenetidou

PhD Research Scientist

Aristotle University of Thessaloniki

School of Forestry and Natural Environment

Laboratory of Forest Utilization

541 24 Thessaloniki, Greece

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Abstract. This article defines age of transition from juvenile to mature wood in two ring-porous species, black locust (*Robinia pseudoacacia* L.) and chestnut (*Castanea sativa* Mill.). A logistic function was proposed using fiber length and ring width data of three black locust trees, aged 35-37 yr, and five chestnut coppice trees, aged 25-27 yr, from Sithonia Peninsula, Chalkidiki, Greece. The approach proved to be practical and objective in delineating maturity zones, and it was based on rate of change of yearly fiber length. The juvenile wood zone spread to the sixth growth ring from the pith in both species, whereas the demarcation of juvenile and mature wood was at age 12 and 14 yr in chestnut and black locust, respectively. Transition zone width comprised rings 7-12 in chestnut and rings 7-14 in black locust.

Keywords: Juvenile wood, transition zone, logistic function, fiber length, black locust, chestnut.

INTRODUCTION

As stated by Zobel and van Buijtenen (1989), "The wood first laid down by the cambium near the centre of the tree has characteristics that differ from the wood formed at a greater number of rings from the pith, or tree center. This first-formed wood is called juvenile wood." Juvenile wood roughly forms a cylinder up the tree and according to predominant view, it is directly related to cambium age (Pearson et al 1980).

Much research has been done on juvenile wood structure and properties and differences between juvenile and mature wood, especially in conifers. Juvenile wood is characterized by faster growth rate, smaller cells with thinner walls, larger microfibril angles, lower percentage of latewood, lower density, higher longitudinal shrinkage, higher lignin and hemicellulose content, lower alpha cellulose, and lower stiffness and strength than mature wood (Larson 1960; Boutelje 1968; Bendtsen 1978; Zobel 1980; Thomas 1984; Senft et al 1985; Wheeler 1987; Zobel and van Buijtenen 1989; Zobel and Sprague 1998; Larson et al 2001).

* Corresponding author: adamopoulos@teilar.gr

Furthermore, many studies have been devoted to determining cambial age of growth rings in which juvenile wood formation stops and mature wood formation begins. There is no abrupt shift from juvenile to mature wood within 1 yr. Instead, the change takes several years and gradually grades from one into the other (Zobel 1980). Nearly all wood properties are highly variable from ring to ring within the juvenile zone and relatively constant within the mature zone (Saranpää 2003). The zone in between is often referred to as the transition zone, and it has been found to vary greatly among different species and properties. To define the boundary between juvenile and mature wood, researchers have used various methods. The simplest is the threshold or graphic method in which property curves are visually evaluated to locate a ring number or age when the property reaches the threshold value for mature wood (Clark and Saucier 1989; Heliñska-Raczkowska 1994; Clark and Edwards 1999; Heliñska-Raczkowska and Fabisiak 1999; Adamopoulos and Voulgaridis 2002; Passialis and Kiriazakos 2004; Clark et al 2006). Visual differentiation between juvenile and mature wood is rather arbitrary, lacks sufficient scientific reliability, and can only be treated as an estimation. Conversely, it has the advantage that mature wood can be defined as having properties of a minimum specified value, which might be a prerequisite for a specified final product. Another method is the linear segmented modeling approach, which defines mature wood based on rate of change of a property (Loo et al 1985; Cook and Barbour 1989; Di Lucca 1989; Szymanski and Tauer 1991; Abdel-Gadir and Krahmer 1993; Danborg 1994; Sauter et al 1999; Zhu et al 2000). That method was developed to provide more reliable scientific results, but a statistical problem arises when segmented regression models are used without consideration of the time series nature of a given property from a pith-to-bark profile, interdependencies in property data from adjacent annual rings, and statistical distributions in a population. To overcome these limitations, nonlinear regression or polynomial models have been discussed (Hodge and Purnell 1993; Tasissa and Burkhart 1998; Mutz et al 2004; Koubbaa et al 2005).

The fiber length–age relationship is of great importance with respect to indicating the juvenile growth period in forest trees (Panshin and de Zeeuw 1980; Zobel and van Buijtenen 1989). Trends in fiber length are much more uniform and consistent than trends in ring width and wood density, and they are therefore used by researchers to delineate juvenile and mature wood zones in hardwoods (Taylor 1979; Evans et al 2000). However, transition from juvenile to mature wood based on pith-to-bark profiles of fiber length is of a nonrigorous character and therefore arbitrarily defined. Because duration of juvenile wood production influences quality of most wood products, our objective was to define more precisely the transition age from juvenile to mature wood in two ring-porous hardwoods, black locust and chestnut. In this context, a mathematical approach was used to analyze radial patterns of fiber length for defining the juvenile-mature wood transition zone in these species.

MATERIALS AND METHODS

Sampling and Laboratory Measurements

The material was the same as in a previous article on relationships between wood density and fiber length with cambium age and ring width in black locust and coppice-grown chestnut (Adamopoulos et al 2010). Three black locust trees aged 35-37 yr and five chestnut coppice trees aged 25-27 yr from Sithonia Peninsula, Chalkidiki, Greece, were used. The trees were straight with uniform crowns, and they were free from lean and visible defects. Black locust trees were 181-277 mm diameter at ground level, whereas chestnut trees were 191-240 mm diameter.

From each tree, a 20-mm-thick disk was cut at the base (0.30 m above ground level) and conditioned at 20°C and 55% RH. Trees were sampled at the base to include all annual rings in the analysis. A pith-to-bark strip about 20 mm tangentially and 15 mm longitudinally was prepared along an average radius from each disk. This strip was subsequently divided into two strips. One strip (about 10 mm wide and 15 mm thick) was used to assess ring width, and the other was used to measure fiber length. For measuring growth rate (annual ring width) from pith to bark, the radial wood strips were smoothed with sandpaper on their transverse surfaces. Annual ring width measurement was performed with a digital position meter to the nearest 0.01 mm. Strips for measuring fiber length were split into individual rings, from which matchstick-sized subsamples were cut with a razor blade. Subsamples were macerated by warming in glacial acetic acid and 30% hydrogen peroxide (v:v) at 60°C for 24 h. After being washed with water several times, macerated elements were transferred to a clean slide. Subsequently, lengths of 80 randomly selected unbroken fibers per annual ring were measured with a light microscope equipped with an image analysis system.

Analysis and Approach

Models of fiber length (FL) in relation to cambium age (CA) and ring width (RW) developed previously on the same material by Adamopoulos et al (2010) were used. The following general models could significantly model fiber length variations with cambium age and ring width in black locust (FLBL, F = 213.029, $p < 0.0001$, 108 observations) and chestnut (FLC, F = 72.433, $p < 0.0001$, 130 observations):

$$\begin{aligned} \mathrm{FLBL} = {} & 0.5170 + 0.1480\,\mathrm{Ln}(\mathrm{CA}) \\ & + 0.0283\,\mathrm{RW} - 0.0091\,\mathrm{Ln}(\mathrm{CA})\cdot\mathrm{RW} \end{aligned} \tag{1}$$

$$\begin{aligned} \mathrm{FLC} = {} & 0.8160 + 0.0865\,\mathrm{Ln}(\mathrm{CA}) \\ & - 0.0066\,\mathrm{RW} + 0.0110\,\mathrm{Ln}(\mathrm{CA})\cdot\mathrm{RW} \end{aligned} \tag{2}$$

The combined model approach incorporating cambium age and ring width has been a very good predictor of fiber length and further improved the fiber length–age relationship in the two species. The combination of cambium age and ring width could describe 86% and approximately 63% of total fiber length variation in black locust and chestnut, respectively (Adamopoulos et al 2010).

Using Eqs 1 and 2 as a starting point, we performed mathematical analyses using Statistica 8.0 software (StatSoft, Inc, Tulsa, OK) to systematically define the juvenile-mature wood transition zone in the stem cross-sections of black locust and chestnut. Specifically, we fitted a logistic function to yearly fiber length data obtained by Eqs 1 and 2, and subsequently, we defined the transition zone based on rate of change of the fitted function considering that transition to maturity initiates when rate of change falls below a selected threshold.

RESULTS AND DISCUSSION

Mathematical Modeling

To simplify the combined model analyses, cambium age was chosen as the standard variable because its correlation with fiber length was stronger than that of fiber length with ring width (Adamopoulos et al 2010). Ring width in both black locust and chestnut showed a more or less negative correlation with cambium age. The following equations are linear functions for black locust (r = 0.487, F = 32.956, $p < 0.0001$):

$$\mathrm{RW} = 4.1629 - 0.068\,\mathrm{CA} \tag{3}$$

and chestnut (r = 0.796, F = 222.039, $p < 0.0001$):

$$\mathrm{RW} = 5.0147 - 0.1344\,\mathrm{CA} \tag{4}$$

This indicates that fiber length can be sufficiently calculated solely in terms of cambium age. By substituting ring width calculated from Eqs 3 and 4 into the respective Eqs 1 and 2, fiber length values were obtained as a function of cambium age. The relationship between calculated fiber length data and cambium age showed

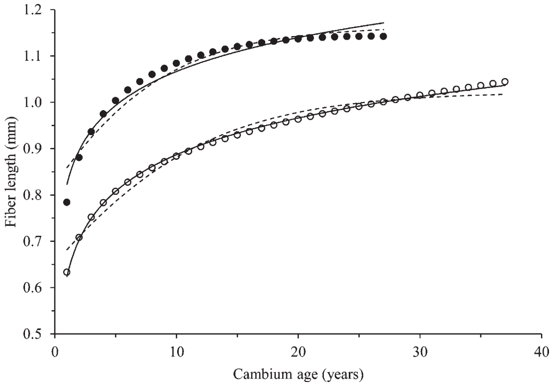

Figure 1. Variation of calculated fiber length in black locust (o) and chestnut (•) when each ring width is substituted. Data are fitted by standard logarithmic function of the form y = a·ln(x) + b (solid curves) and by respective proposed logistic function (dotted curves).

a clear curved behavior (Fig 1) referring to the typical patterns of fiber length increase with age near the pith followed by a more gradual increase until a maximum is reached.

One of the simplest functions satisfying the relationship of Fig 1 is the logarithmic function (Zhu et al 2000). Although we could obtain quite satisfactory logarithmic approximations of fiber length as function of cambium age ($r > 0.98$ in both species), logarithmic functions do not capture the fact that there is an upper limit to fiber length increase. For this reason, we decided to model fiber length as a function of cambium age using a logistic function, and we therefore fitted to both data sets a nonlinear growth function of the following form:

$$f(x) = \frac{L}{1 + E \cdot e^{-kx}} \tag{5}$$

where L, E, and k are coefficients.

Eq 5 has an upper limit of L to which it converges as x grows to infinity. Nonlinear estimation results of fiber length for black locust and chestnut, respectively, were

$$FLBL = \frac{1.022530}{1 + 0.565955 \cdot e^{-0.126327 \cdot CA}} \tag{6}$$

and

$$FLC = \frac{1.163861}{1 + 0.414443 \cdot e^{-0.156066 \cdot CA}} \tag{7}$$

Statistics for Eqs 6 and 7 are given in Table 1. Furthermore, a side-by-side comparison of the logarithmic function and our proposed logistic function is presented in Fig 1.

Juvenile-Mature Wood Transition

Modeled fiber length data and Eqs 6 and 7 were further mathematically analyzed and assessed with respect to juvenile-mature wood transition. Transition from juvenile to mature wood is done when the rate of change of fiber length becomes relatively small. However, transition does not occur instantly but it is a gradual process that takes several years (transition zone). There is an upper limit to fiber length values of Eqs 6 and 7, FL_{max}, which is determined by maximum cambium age CA_{max} of sampled trees. Based on this, it is clear that the rate of fiber length change becomes relatively small when an adequate high fiber length value has been reached. Therefore, for both species, we calculated percentage of FL_{max} reached at each cambium age as well as the respective rates of fiber length change. Rates of fiber length change for black locust and chestnut, respectively, were calculated from derivatives of Eqs 6 and 7:

$$FLBL' = \frac{0.073106 \cdot e^{-0.126327 \cdot CA}}{(1 + 0.565955 \cdot e^{-0.126327 \cdot CA})^2} \tag{8}$$

$$FLC' = \frac{0.075280 \cdot e^{-0.156066 \cdot CA}}{(1 + 0.414443 \cdot e^{-0.156066 \cdot CA})^2} \tag{9}$$

Based on FLBL′ and FLC′ data, maturity of black locust and chestnut was classified in three broad zones: juvenile, transition, and mature. In juvenile wood, the rate of fiber length change was up to approximately 0.02. In the transition zone, it was between approximately 0.02 and 0.01. In mature wood, it was less than approximately 0.01 (Table 2). The resulting maturity zones were quite similar in both species. Juvenile wood covered the first six rings in both

Table 1. Statistics for fiber length logistic model in black locust and chestnut.

FL = (L)/(1 + E . exp[−k.CA])							
				Confidence limit			
Coefficient	Estimate	Standard error	t	Lower	Upper	F-value	*p*-value
Black locust							
L	1.022530	0.005943	172.04	1.010451	1.034608	45,892	< 0.0001
E	0.565955	0.022595	25.05	0.520036	0.611873		
k	0.126327	0.008103	15.59	0.109860	0.142793		
Chestnut							
L	1.163861	0.006010	193.67	1.151458	1.176264	73,684	< 0.0001
E	0.414443	0.015265	27.15	0.382937	0.445948		
k	0.156066	0.010615	14.70	0.134157	0.177975		

Table 2. Rates of fiber length change and maturity levels in black locust and chestnut.

Rate of FL′ change, × 10^{-2}	Percent FL_{max}	Age, yr	Maturity level
Black locust			
2.87-2.14	66.72-79.04	1-6	Juvenile wood
1.98-1.03	81.05-91.20	7-14	Transition zone
< 0.93	> 92.20	> 14	Mature wood
Chestnut			
3.51-2.18	73.82-86.02	1-6	Juvenile wood
1.95-1.02	87.80-94.01	7-12	Transition zone
< 0.89	> 94.84	> 12	Mature wood

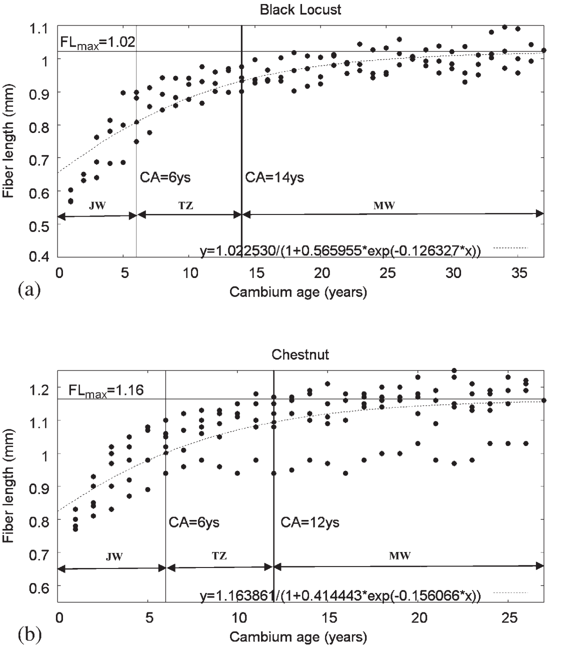

Figure 2. Juvenile-mature wood transition based on variation of modeled fiber length in black locust (a) and chestnut (b). JW, juvenile wood; TZ, transition zone; MW, mature wood. Measured fiber length (•) data from different trees are also plotted.

species, the transition zone covered rings 6-14 in black locust and rings 6-12 in chestnut, and mature wood extended onward from ring 14 in black locust and from ring 12 in chestnut. Rate of yearly fiber length change less than 0.01, as a criterion for wood maturity, is comparable with or even lower than rates of change in wood properties used elsewhere (such as in Tasissa and Burkhart 1998) to mark juvenile-mature transition zones. Furthermore, the estimated maturity points that correspond to cambium ages of 14 yr in black locust and 12 yr in chestnut are quite reasonable as approximately 92 and 95% of FL_{max} has been reached, respectively (Table 2). The juvenile-mature wood transition for black locust and chestnut is graphically depicted in Fig 2.

The logistic function is known to represent increasing values with an upper boundary, and it has been statistically shown to fit sufficiently to the data sets used. However, the results derived here are based on a limited data set at the ground line, meaning that they should be treated with care. For example, it is advisable to calculate new coefficients for the logistic function for fiber length data coming from different stem heights. A future priority would be to test the mathematical logistic approach against new data from populations and clones of black locust and chestnut. Also, the general logistic function could be applied to any wood species and stem height for a particular wood trait (eg cell dimensions, wood density, microfibril angle, chemical constituents) showing typical curved behavior.

CONCLUSIONS

In this study, we proposed a mathematical approach, based on a logistic function, to define age of transition from juvenile to mature wood in two ring-porous species, black locust and chestnut. The approach proved to be practical and objective in defining maturity zones. It involves cambium age as the only independent parameter required to model fiber length, and it is based on criteria defined by rate of change of yearly fiber length. The proposed approach is not restrictive but is extensible to any wood species and stem height for a particular wood property showing typical curved pith-to-bark behavior. Furthermore, the approach can be modified using different maturity points to accommodate different juvenile-mature wood transition zones depending on the purpose that wood maturity classification needs to serve.

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