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Original article

Defining the transition from earlywood to latewood in black spruce based on intra-ring wood density profiles from X-ray densitometry

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Abstract – Defining the transition from earlywood to latewood in annual rings is an important task since the accuracy of measuring wood density and ring width components depends on the definition. Mork's index has long been used as an anatomical definition of the transition from earlywood to latewood. This definition is arbitrary and extremely difficult to apply to X-ray densitometry. For X-ray densitometry, a threshold density of between 0.40 to 0.55 g cm^{-3}, depending on species, has been chosen to differentiate between earlywood and latewood density, but this method has shortfall. Therefore, new methods need to be developed and integrated into the computational programs used to generate X-ray densitometry data. In this study, we presented a mathematical method. We modelled the intra-ring wood density profiles in 100 plantation-grown black spruce (*Picea mariana* (Mill.) B.S.P.) trees using high order polynomials. The correlation between the predicted and the measured densities is very high and highly significant. Based on this model, we define the transition from earlywood to latewood as the inflexion point. Results indicate that wood density at the earlywood-latewood transition point varies from juvenile to mature wood. This method could be easily integrated into any X-ray densitometry program and allows to compare individual rings in a consistent manner.

transition / earlywood / latewood / X-ray densitometry / wood density / black spruce / modelling

Résumé – Définition de la transition du bois initial au bois final chez l'épinette noire à partir des profiles de densité intra cernes obtenus par densimétrie aux rayons X. La précision de l'estimation des densités et des largeurs du bois initial et du bois final dans un cerne annuel dépend de la définition de la transition du bois initial au bois final. L'indice de Mork a longuement servi pour donner une définition anatomique à cette transition. Cette définition est arbitraire et difficile à appliquer en densimétrie aux rayons X. En général, un seuil de densité variant entre 0,40 à 0,55, dépendamment de l'essence, sert à différencier le bois initial du bois final. Cette méthode a certaines limites et d'autres méthodes doivent être développées et intégrées aux programmes de densimétrie aux rayons X. Nous avons utilisé une approche mathématique pour modéliser les profiles de densité intra cernes dans 100 arbres d'épinette noire (*Picea mariana* (Mill.) B.S.P.). Le point d'inflexion de polynômes aux degrés élevés a servi pour définir la transition du bois initial au bois final. Les corrélations entre les densités mesurées et prédites sont élevées et significatifs. La transition du bois initial au bois final varie entre le bois juvénile et le bois adulte. Cette méthode est facile à intégrer dans les programmes de densimétrie aux rayons X et permet d'obtenir des comparaisons consistantes entre cernes annuels.

transition / bois initial / bois final / densimétrie aux rayons X / densité du bois / épinette noire / modélisation

1. INTRODUCTION

Wood density is considered by many as the most important wood quality attribute. It is related to many wood properties including strength, stiffness and dimensional stability. It also affects wood processing properties. Wood density is highly variable. The variation in wood density may be due to genetic, environmental, physiological or silvicultural treatments [15, 20–22]. Physiological variation of wood density is related to cambial activity and varies with age, season, climate and environmental conditions [15, 22]. Physiological variation is the main cause of within-a-tree variations which include axial, radial, and within-a-ring (intra-ring) variations [15, 22]. Intra-ring variation is mainly due to differences between cell structure, and formations between earlywood and latewood. Based on the samples of black spruce (*Picea*

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mariana (Mill.) B.S.P.) examined in this study, wood density within a growth ring ranged from 0.23 to 0.83 g cm^{-3}. Intra-ring wood density variation is also indicative to wood uniformity [4–6, 9, 10]. Woods with large differences between earlywood and latewood densities (e.g., larches) are not uniform, whereas woods with small differences between earlywood and latewood densities (e.g., poplars, birches) are uniform. Intra-ring wood density variation also determines the suitability of a wood for specific end-uses [4–6]. Uniform woods, for example, are preferred for veneer and panelboard manufacturing, whereas non-uniform woods are preferred for appearance products mainly because of the contrast between earlywood and latewood.

Intra-ring wood density variation also provides information on wood formation and physiological processes [16, 22]. The X-ray densitometry profile of a single growth ring provides considerable information on how the ring was formed and how physiological processes changed during the growing season. In addition, the anatomy of successive annual rings provides a remarkable record of past environmental conditions over the years [1, 21, 22].

Intra-ring wood density profiles by X-ray densitometry are also used to determine annual ring width and wood density components. Earlywood and latewood widths and wood density components along with minimum and maximum densities within a growth ring are determined from the profiles. The earlywood and latewood densities and widths depend on the earlywood-latewood (E/L) transition point. The latter is difficult to determine and several methods have been reported in literature. Mork's index [14] has long been used to determine this E/L transition point. There are at least two different interpretations of Mork's index [3]. According to the first interpretation, the E/L transition is obtained when double wall thickness become greater or equal to the width of its lumen. From the second interpretation, the E/L transition is obtained when the double cell wall thickness multiplied by 2 becomes greater or equal to lumen width. Although this index, from both interpretations, is arbitrary and very time consuming to measure, it allows to measure earlywood and latewood features in a consistent manner.

Since Mork's index method is based on double wall thickness and lumen diameter, it is necessary to measure these wood anatomical features of individual growth rings on microscopic slides or use indirect microscopic procedures [7]. In addition, this method is difficult to be integrated into X-ray computational programs.

The result of a previous study [1] showed a good agreement between earlywood and latewood features as determined by three methods: Mork's definition; threshold density; and maximum derivative method. However, Mork's index and maximum derivative methods showed better estimates for physiological variations than threshold method. The three methods gave good evidence for environmental influence.

Most laboratories equipped with X-ray facility use the threshold density to differentiate between earlywood and latewood [11, 13, 16, 17]. Depending on species, a wood density of between 0.40 and 0.55 g cm^{-3} is usually chosen for this differentiation. This method has the advantage of allowing automatic determination of the earlywood and latewood transition point and thus can be easily integrated into X-ray densitometry computational programs. This method assumes that the transition points for all samples have the same wood density. In a preliminary and unpublished study [8], some very detailed measurements of annual rings were made. The E/L transition point was established for 84 annual rings by Mork's index. Basic wood density measurements were made at these transition points and were found to vary greatly. Hence, the validity of establishing a fixed cut-off point comes into question [11].

Other laboratories use the minimum and maximum density methods to define the earlywood-latewood transition [2, 19]. This method determines the E/L transition from the minimum and maximum density of the densitometry profiles of individual growth rings. Few formulas were used previously to define this transition point [2, 19]. Although this method is rapid, consistent and easy to be integrated into X-ray densitometry computational programs, it is based on two single values and thus does not consider the variation in the whole intra-ring wood density profiles. A few other mathematical and numerical approaches have been reported in previous studies [1, 18] to define the earlywood latewood transition. These methods are commonly known as maximum derivative methods where the transition point is generally defined as the maximum of the derivative function that describes the intra-ring wood density variation. This approach is promising and further research should be focused on developing similar methods that could be consistent in estimating earlywood and latewood features. These approaches should also consider the intra-ring wood density profiles and its variation. Modelling these profiles using various techniques such as polynomial functions or smoothing techniques would consider both the profile and intra-ring density variation in estimating earlywood-latewood transition. The objectives of this work are: (1) to model the intra-ring wood density profile in black spruce using polynomial functions; (2) to determine the E/L transition using a mathematical definition; and (3) to study the variation in the E/L transition from juvenile to mature wood.

2. MATERIALS AND METHODS

One hundred trees from a 50-year-old black spruce plantation located in Victoriaville, Québec (lat. 46° 01' N, long. 72° 33' W, elev. 90 m) were sampled randomly. Initial spacing in this plantation was 2 m × 2 m. Average annual precipitation in the plantation site is 1000 mm and average annual temperature is 4.5 °C. The length of the growing season varies from 180 to 190 days. From a constant compass direction, an increment core of 6 mm in diameter was taken at breast height from each sample tree. Each increment core was wrapped in a plastic bag and kept frozen until the X-ray densitometry was started.

The increment cores were sawn into 1.57 mm thick (longitudinal) strips with a specially designed pneumatic-carriage twin-bladed saw. The sawn strips were extracted with cyclohexane/ethanol (2:1) solution for 24 hours and then with hot water for another 24 hours to remove extraneous compounds. After the extraction, the strips were air dried under restraint to prevent warping. Using a direct reading X-ray densitometer at Forintek Canada Corp., the air-dried strips were scanned to estimate the basic wood density (ovendry weight/green volume) for each ring from the pith to bark. Ring density (RD) and ring width (RW) of each ring were determined based on the intra-ring microdensitometric profiles [11]. Incomplete rings false rings and rings with compression wood or branch tracers were eliminated from the analysis.

Matlab® software was used to model the intra-ring wood density profiles to determine the E/L transition point. This point was used to calculate earlywood density, latewood density and latewood proportion. High order polynomial models (Eq. (1)) were used to describe the intra-ring wood density profile, 4th to 6th order polynomial were tested.

The E/L transition was defined as the inflexion point. The latter is obtained by equalling the second derivative of the polynomial function to zero (Eq. (2)). For a 6th order polynomial function, the second derivative gives 4 solutions; only one solution is of interest (*figure 1*). Few restrictions were specified in the Matlab program to obtain this unique solution. These restrictions specify that the solution should be included in a positive slope and in the range of 40 to 90% of ring width proportion. If more than one solution is obtained, the highest value among solutions is chosen.

$$D = a_o+a_1RW+a_2RW^2+a_3RW^3+ a_4RW^4+....+a_nRW^n \quad (1)$$

$$d^2D/dRW^2 = 2a_2+6a_3RW+12a_4RW^2+....+n(n-1)a_nRW^{n-2} \quad (2)$$

where D is ring density; RW is ring width in proportion and a_i are parameters to be estimated.

3. RESULTS AND DISCUSSION

3.1. Modelling intra-ring wood density profiles

To develop a mathematical definition of the E/L transition, we need to model the intra-ring wood density profiles. Previous researchers [1] used smoothing techniques and a maximum derivative method to determine the earlywood-latewood transition point. They used a modified spline function technique to smooth the intra-ring wood density profiles. The E/L transition point was defined as the maximum of the derivative of the spline function. Theoretically, the maximum represents an inflexion point in the intra-ring wood density profile and could be determined mathematically. Another study [18] also used a numerical derivative method to define the E/L transition point.

Table I indicates that high order polynomials fit the intra-ring wood density profiles in black spruce well. The higher polynomial is, the better fitness is. In general, the 6th order polynomials are good enough to describe the intra-ring wood density profiles. *Figure 2* illustrates the fitness of the 6th order and 4th order polynomials for the average profiles for ring 20 from 100 trees. The coefficients of determination for the 4th order polynomial were high, in most cases they were well above 0.80 (results not shown). However, the 6th order polynomials have much better fitness and higher coefficient of determination compared to the 4th order polynomials. In fact, the coefficients of correlation between the measured and the predicted data from the 6th order polynomial models were well over 0.90 (*table I*). In most cases, they were close to 0.99. This indicates that these models are able

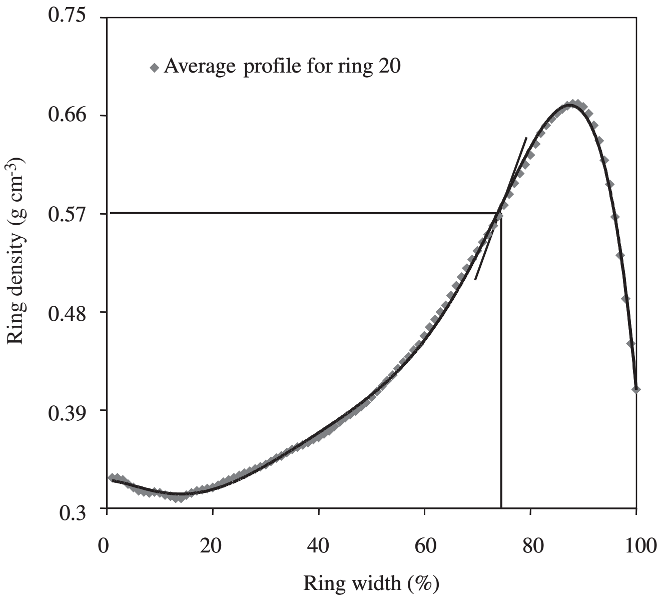

Figure 1. Average within-ring density profile (from 100 trees) for the twentieth ring from pith showing the E/L transition point as determined by the inflexion point method.

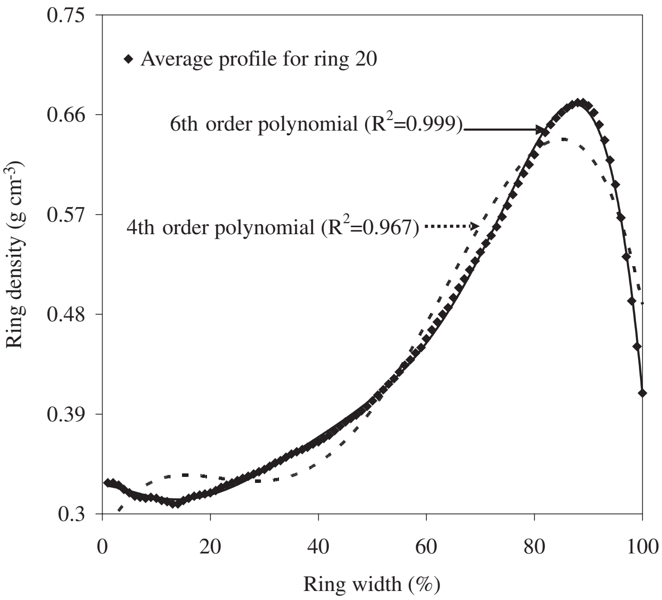

Figure 2. Examples of the fits obtained from the 6th order and the 4th order polynomials for average within-ring density profile for the twentieth ring from pith.

Table I. Average, standard variation and range of Pearson's coefficient of correlation between measured and predicted within-ring density values from the 6th order polynomial models for different rings and for juvenile and mature wood.

	Ring from pith					Juvenile wood (Rings 3 to 10)	Mature wood (Rings 18 to 25)
	5	10	15	20	25		
	Average / range of Pearson's coefficient of correlation						
Average profiles	0.97	0.97	0.98	0.99	0.99	0.99	1.00
Standard deviation	0.02	0.02	0.02	0.01	0.01	0.01	0.00
Range for all profiles	0.92–1.00	0.91–1.00	0.90–1.00	0.94–1.00	0.94–1.00	0.96–1.00	0.98–1.00

Table II. Average, range, standard deviation and coefficient of variation for wood density at earlywood-latewood transition, earlywood proportion, earlywood density and latewood density as defined by the inflexion method for different rings and for juvenile and mature wood.

	Ring from pith					Juvenile wood (Rings 3 to 10)	Mature wood (Rings 18 to 25)
	5	10	15	20	25		
	Density at the earlywood-latewood transition						
Average (g cm^{-3})	0.58	0.58	0.60	0.57	0.58	0.58	0.59
Range (g cm^{-3})	0.36–0.69	0.47–0.77	0.45–0.77	0.44–0.75	0.43–0.75	0.50–0.70	0.46–0.71
Standard deviation (g cm^{-3})	0.05	0.06	0.06	0.06	0.07	0.04	0.05
Coefficient of variation (%)	9.1	9.5	10.4	10.9	11.3	6.6	7.7
	Earlywood proportion (Proportion of ring width at E/L transition)						
Average (%)	78.5	80.6	76.6	73.3	71.8	80.5	72.8
Range (g cm^{-3})	57.0–89.1	63.5–86.7	53.7–84.8	48.8–89.0	42.6–89.5	71.3–85.0	48.0–82.2
Standard deviation	5.6	4.0	6.4	9.21	9.1	2.3	6.5
Coefficient of variation (%)	7.10	9.5	8.4	12.6	12.7	2.8	9.0
	Earlywood density						
Average (g cm^{-3})	0.41	0.38	0.39	0.38	0.38	0.41	0.39
Range (g cm^{-3})	0.32–0.50	0.30–0.57	0.29–0.50	0.26–0.59	0.29–0.55	0.32–0.48	0.31–0.48
Standard deviation (g cm^{-3})	0.04	0.04	0.04	0.05	0.05	0.05	0.04
Coefficient of variation (%)	8.6	9.9	11.0	13.3	12.9	7.3	6.7
	Latewood density						
Average (g cm^{-3})	0.63	0.64	0.64	0.62	0.63	0.61	0.63
Range (g cm^{-3})	0.45–0.72	0.52–0.76	0.42–0.80	0.48–0.80	0.42–0.76	0.55–0.72	0.51–0.74
Standard deviation (g cm^{-3})	0.05	0.05	0.06	0.06	0.07	0.03	0.03
Coefficient of variation (%)	7.5	8.1	9.4	10.2	10.4	7.3	8.7

to well describe the intra-ring wood density profiles in black spruce. It is important to note that the fitness is better in mature wood than in juvenile wood. The average coefficients of correlation for mature wood profiles were higher and significantly different from those for juvenile wood at the 1% significance level (results not shown). This is due to the fact that the intra-ring wood density data are noisier in juvenile wood than in mature wood as reported previously [1].

3.2. Earlywood-latewood transition

Wood density at the E/L transition point (E/L transition density) as defined by the inflexion point method showed a large variation (*table II*). For example, the E/L transition density varied from 0.48 to 0.77 g cm^{-3} for the 25th annual ring from the pith. Latewood density defined by this method also showed a large variation. For the 25th ring from the pith, latewood density ranged from 0.43 to 0.77 g cm^{-3}. Similarly, average earlywood density in a ring also varied largely. For the same annual ring, the average earlywood density ranged from 0.29 to 0.55 g cm^{-3}. The average earlywood density in this ring could be even higher than the threshold density (0.54 g cm^{-3}) commonly used to define the E/L transition point.

As shown in *table II*, wood density at the E/L transition point in black spruce is variable. Its radial variation does not seem to follow a particular trend (*figure 3*). In addition, the average wood density at the E/L transition point (0.59 g cm^{-3}) is higher than the threshold wood density used for black spruce (0.54 g cm^{-3}). This result is in accordance with previous findings for Norway spruce [1]. Since the wood density at the E/L transition point defined by the inflexion point method

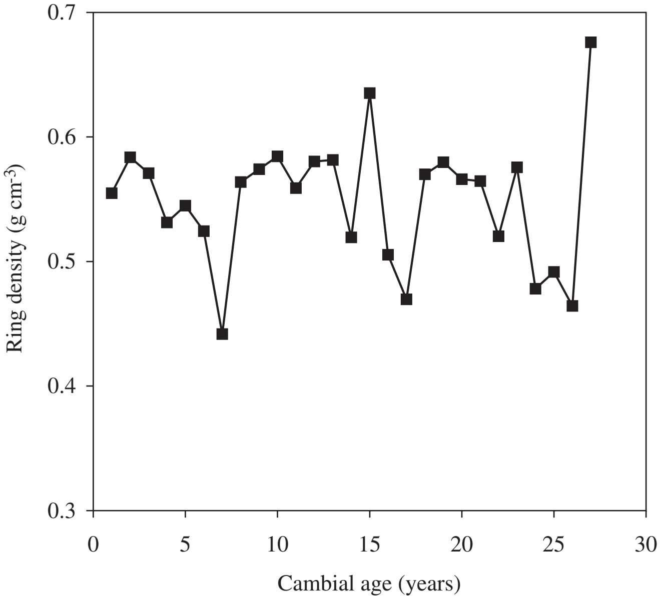

Figure 3. Radial variation of E/L transition density in a single tree.

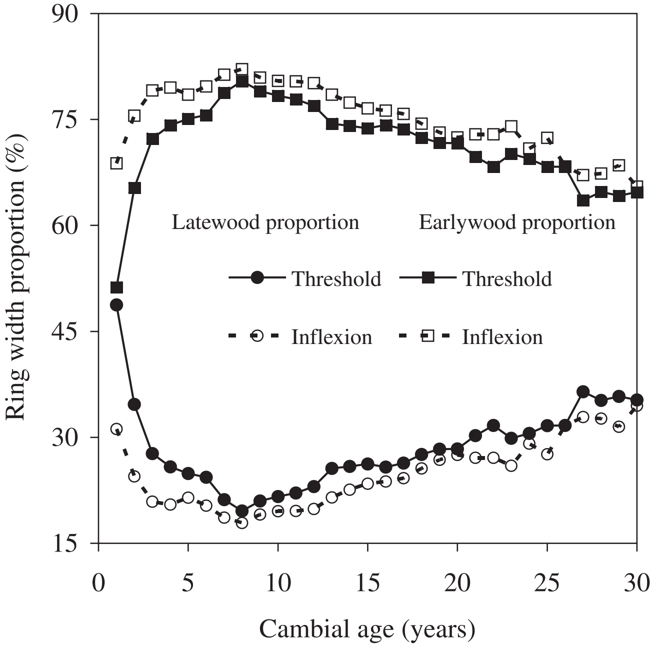

Figure 4. Average radial variation (from 100 trees) of ring density and earlywood density and latewood density as determined by the threshold method (filled symbols) and inflexion point method (open symbols).

is higher than the threshold wood density, the average earlywood and latewood densities defined by the inflexion point method will be higher than those by the threshold wood density method (*figure 4*). Earlywood width defined by the inflexion point method will be larger, whereas latewood width will be smaller (*figure 5*). Consequently, the latewood proportion defined by the inflexion point method will be lower (*figure 6*). In addition, the differences in ring width components defined by the two methods are larger in juvenile wood than in mature wood, especially for latewood width (*figure 5*) and latewood proportion (*figure 6*). For example, for the third annual ring the difference between latewood widths as estimated by the threshold and the inflexion point methods was 0.5 mm or 60%. This difference is statistically significant at the 0.01 level. The difference decreases with increasing number of rings from pith. In mature wood, the difference between latewood widths estimated by the two methods is relatively small (around 15%) but still statistically significant at the 0.01 level (results not shown).

Wood density at the E/L transition point by Mork's definition varied greatly among individual growth rings [8]. This indicates that the use of a predetermined fixed threshold wood density does not reflect the variation in the intra-ring wood density profiles among growth rings in a species. The correlation values between growth traits estimated by the inflexion point and threshold methods are relatively high especially for earlywood traits (*table III*). However, the correlation between density traits is not significant at the 0.05 level. Therefore, the use of a threshold wood density method could lead to errors in estimating earlywood and latewood features, especially latewood proportion for some growth rings (*figure 6*), although earlywood and latewood features defined by the two methods showed a similar pattern of radial variation. The result from this study is in accordance with the conclusions drawn by previous workers [1, 18]. Mathematical approaches like the one presented in this paper could

Table III. Pearson's coefficient of correlation between earlywood and latewood ring width and density estimated from inflexion point method and threshold density methods for different rings (100 trees).

	Ring from pith					All data
	5	10	15	20	25	(All rings from 100 trees)
Earlywood width	0.95**	0.97**	0.97**	0.95**	0.93**	0.95**
Latewood width	0.55**	0.71**	0.54**	0.52**	0.53**	0.54**
Earlywood density	0.14$^{n.s.}$	0.10$^{n.s.}$	0.06$^{n.s.}$	0.11$^{n.s.}$	0.18$^{n.s.}$	0.06**
Latewood density	–0.09$^{n.s.}$	0.14$^{n.s.}$	0.08$^{n.s.}$	–0.03$^{n.s.}$	0.06$^{n.s.}$	0.07$^{n.s.}$
Latewood proportion	–0.06$^{n.s.}$	0.15$^{n.s.}$	–0.03$^{n.s.}$	–0.14$^{n.s.}$	–0.06$^{n.s.}$	0.02$^{n.s.}$

** Significant at the 0.01 level; n.s. not significant at the 0.05 level.

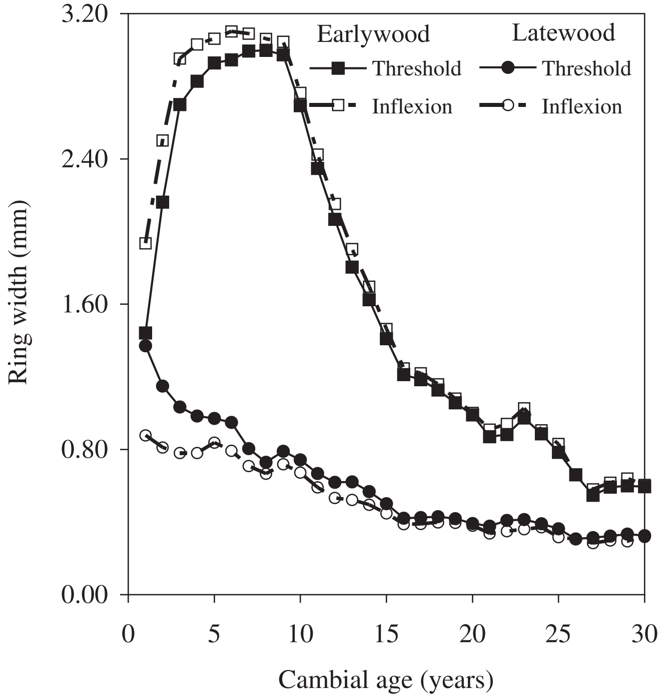

Figure 5. Average radial variation (from 100 trees) of earlywood width and latewood width as determined by threshold method (filled symbols) and inflexion point method (open symbols).

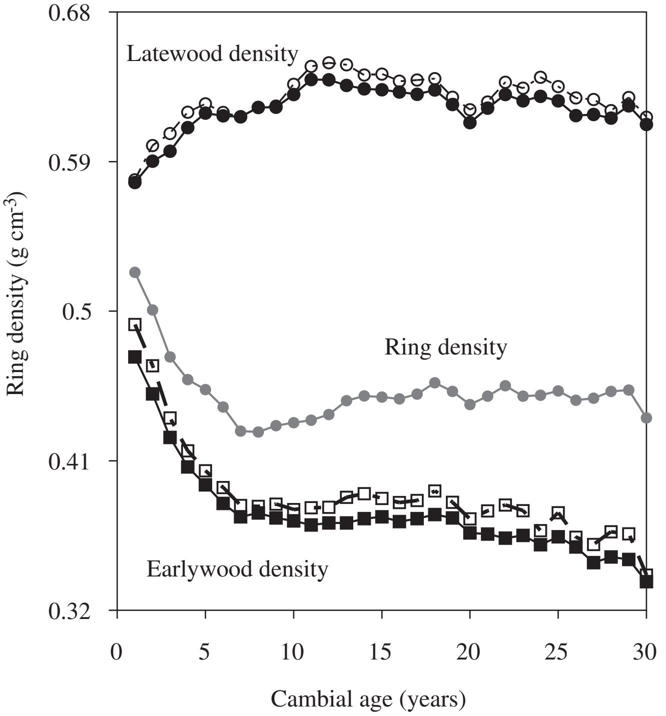

Figure 6. Average radial variation (from 100 trees) of earlywood and latewood proportions as determined by the threshold method (filled symbols) and inflexion point method (open symbols).

consider the ring-to-ring variation in the intra-ring wood density profiles.

Despite the differences in the earlywood and latewood features defined by the two methods, the same trends and peaks are observed (*figures 4–6*). This indicates that each of the two methods has its own merits. Both methods give good evidence especially when we study the variation of wood density with climatic conditions and radial variations of wood density and growth traits [1] and to determine juvenile-mature wood correlations or age-to-age correlations [12]. However, the inflexion point method gives better estimates for earlywood and latewood traits than the threshold wood density methods because it considers ring-to-ring variation in the intra-ring wood density profiles.

The method presented in this work has not been supported by anatomical evidence yet. According to a previous work [1], however, the radial variations of earlywood and latewood features obtained from Mork's index and from maximum derivative method are concordant despite some differences. The correlation between estimates of earlywood and latewood traits from Mork's index and maximum derivative method were high and in most cases higher than the correlation between estimates from Mork's index and threshold method [1].

3.3. Variation in earlywood-latewood transition from juvenile to mature wood

Differences in the intra-ring density profiles were observed between rings of juvenile wood and mature wood

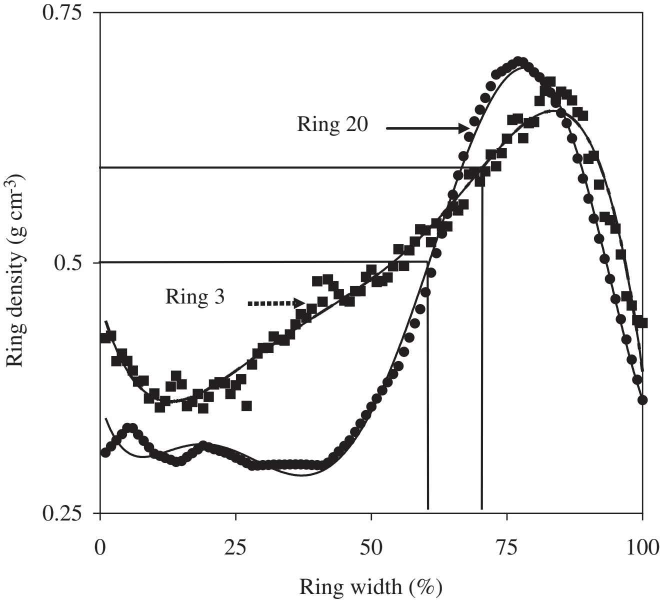

Figure 7. Average within-ring density variation in a juvenile wood ring (Ring 3) and a mature wood ring (Ring 20) from the same tree sample. The E/L transition as estimated by the inflexion point method is shown in both cases.

(*figure 7*). This result is in accordance with the previous work [10]. The intra-ring wood density profiles in juvenile wood are characterized by a higher earlywood density, while the profiles in mature wood are characterized by a higher latewood density and a higher latewood proportion (*table II, figure 7*). Wood density at the E/L transition point did not show any appreciable trend from juvenile to mature wood despite large variation (*table II*). It varied from 0.50 to 0.70 g cm^{-3} in juvenile wood, and from 0.46 to 0.71 g cm^{-3} in mature wood. Earlywood proportion (%), however, showed a particular pattern of variation (*figure 6*). The earlywood proportion is low near the pith, increases steadily to a maximum in the juvenile-mature wood transition zone leading into mature wood where a slow but a steady decrease was observed. The trends defined by the two methods are very comparable. However, earlywood proportion defined by the threshold method is always lower than the one defined by the inflexion point method. This study clearly showed a large variation in wood density at the E/L transition point (*figure 3*), as previously reported [8]. Therefore, the use of a single value to differentiate between earlywood and latewood may lead to errors in estimating earlywood and latewood features for some growth rings.

Differences in the intra-ring wood density profiles between juvenile wood and mature wood explain the radial variation of wood density in black spruce (*figure 4*). Ring density is high near the pith (in juvenile wood zone) and decreases rapidly to a minimum in the juvenile-mature wood transition zone leading into mature wood where a slow but steady increase was observed. The high density near the pith is mainly due to a higher earlywood density (*figures 4* and *7*) and a higher latewood proportion (*figure 6*). The following decrease in ring density is due to a decrease in both earlywood density (*figure 4*) and latewood proportion (*figure 6*). The steady increase in ring density in mature wood is due to an increase in latewood proportion. In mature wood, variation in both earlywood and latewood densities with cambial age (*figure 4*) is much smaller than the variation in latewood proportion (*figure 6*). The average increase in latewood proportion from the transition zone (ages 8 to 12) to mature wood zone (ages 18 to 25) was 41.0% compared to an average increase in earlywood density of 4.5% and an average decrease in latewood density of 2.0%.

4. CONCLUSIONS

Based on this study, the following conclusions can be drawn:

1) Sixth order polynomials are able to well describe the intra-ring wood density profiles in black spruce.
2) The inflexion point method has merits over the traditional threshold density method in terms of defining the earlywood-latewood transition point in black spruce.
3) Differences in the intra-ring wood density profiles were observed between juvenile wood and mature wood. The differences explained the radial pattern of variation in ring density. In addition, variation in the intra-ring wood density profiles with cambial age led to variations in the E/L transition density from juvenile to mature wood.

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