RELATIONSHIPS BETWEEN WOOD DENSITY AND ANNUAL GROWTH RATE COMPONENTS IN BALSAM FIR (*ABIES BALSAMEA*)

Shinya Koga[1]
Visiting Scientist

and

S. Y. Zhang†
Research Scientist and Group Leader
Resource Assessment and Utilization Group
Forintek Canada Corp.
319 rue Franguet
Sainte-Foy, Quebec
Canada G1P 4R4

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ABSTRACT

This study examined relationships of wood density components with annual growth rate components (or annual ring width components) in juvenile wood and mature wood of balsam fir [*Abies balsamea* (L.) Mill.]. The relationships were studied at two different levels: 1) inter-tree level (between trees), and 2) intra-tree level (within a tree). In addition, juvenile-mature wood correlations for these characteristics were investigated. Wood density and annual ring width components of individual growth rings were measured by X-ray densitometry. Based on tree averages (at the inter-tree level), wood density is significantly correlated with its components (earlywood density, latewood density) and latewood percentage in both juvenile wood and mature wood; and earlywood density and latewood percentage are the two most important parameters in determining the overall wood density of the tree. Wood density, however, is not significantly correlated with annual growth rate (ring width) in either juvenile wood or mature wood, although a weakly negative correlation tends to strengthen in mature wood. This suggests that the relationship between wood density and annual growth rate in this species may vary with cambial age. Intra-ring wood density variation (IDV) shows a positive correlation with wood density traits, latewood width, and latewood percentage in both juvenile wood and mature wood, whereas a weakly negative correlation of IDV with ring width and earlywood width exists in balsam fir. Latewood traits are the most important parameters in determining the intra-ring wood density uniformity. At the intra-tree level (based on ring averages within a tree), relationships between wood density components and ring width components are similar to those found between the trees, although some relationships, to some extent, vary with tree. For each wood density trait, the juvenile-mature wood correlation is significant but moderate. For this species, earlywood density in juvenile wood seems to be the best parameter for predicting mature wood density.

Keywords: Balsam fir, wood density, ring width, earlywood, latewood, juvenile wood, mature wood, variation, correlation.

INTRODUCTION

Balsam fir [Abies balsamea (L.) Mill.] is one of the most important commercial species in eastern Canada and northeastern United States. The wood of this species is used mainly for lumber production. Balsam fir lumber in Northern America is marketed with spruces and pines as Spruce-Pine-Fir lumber (Mullins and McKnight 1981). Among the S-P-F group, balsam fir has the lowest wood density and strength properties. Wood density in balsam fir is 17.5% and 21.4% lower than in black spruce and jack pine, respectively; and mod-

[1] Present Address: Department of Forest and Forest Products Sciences, Graduate School of Agriculture, Kyushu University, Tsubakuro 394, Sasaguri, Kasuya, Fukuoka, JAPAN 811-2415.
† Member of SWST.

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ulus of rupture (MOR) in this species is 25.5% and 15.8% lower than in black spruce and jack pine, respectively (Jessome 2000).

As the forest industry in eastern Canada moves toward intensive silviculture, balsam fir has become a preferred species for precommercial thinning. Over the past decade, hectares of balsam fir stands thinned precommercially have increased dramatically in eastern Canada. This silvicultural treatment applied to young and dense balsam fir stands is intended primarily to accelerate the diameter growth of individual trees and shorten rotation age (Zarnovican and Laberge 1996). With large spacing and accelerated growth rate, wood quality of thinned balsam fir stands has become a concern in recent years. Since balsam fir wood is remarkably weaker than other species in the S-P-F group, any significant decrease in wood quality in this species may make this species too different from the others in the group. In 1995, a multidisciplinary project was initiated by Forintek to examine the impact of precommercial thinning on tree and wood characteristics, product quality, and value recovery in balsam fir (Zhang et al. 1998).

Effect of faster growth on wood quality has been a subject of great interest, and numerous studies have investigated the relationship between growth rate and wood density in many commercial species. However, very limited studies have investigated the effect of faster growth rate on wood quality in balsam fir. Zobel and van Buijtenen (1989) concluded that a negative relationship between growth rate and wood density was common for some genera including *Abies*, although this generalization has many exceptions. Kennedy (1995) noted that there seemed to be a negative relationship for *Abies* species in the Pacific Northwest. Zhang (1995) reported a negative correlation of growth rate with wood density and selected mechanical properties in two *Abies* species. Although previous studies suggest that there may exist a negative correlation between ring width and wood density in balsam fir, the intrinsic relationship between annual growth rate and wood quality is not well understood in this important commercial species. It is well known that the relationship between growth rate and wood quality within a species may vary with provenance (Dorn 1969), family (Abdel-Gadir et al. 1993; Zhang et al. 1996; Zhang 1998), cultivars (Koga et al. 1997), cambial age (Keith 1961; Zobel and van Buijtenen 1989; Zhang 1998; Koubaa et al. 2000), location (Hall 1984; Zhang 1998; Abdel-Gadir et al. 1993), silvicultural manipulations (Zobel and van Buijtenen 1989; Koga et al. 1996), and wood quality attributes (Zobel and van Buijtenen 1989; Zhang 1995).

As part of that multidisciplinary project, this study was intended to better understand the relationship between annual growth rate and wood density, one of the most important wood quality attributes in this species. To this end, this research thoroughly studied the intrinsic relationships of wood density components with annual ring width components (annual growth rate components). The relationships were examined at two different levels: 1) inter-tree level (between trees), and 2) intra-tree level (within a tree). In this study, juvenile wood and mature wood were investigated separately to see whether there is any difference in the relationships between juvenile wood and mature wood. In addition, juvenile-mature wood correlations were analyzed for each characteristic to evaluate the possibility for early selection. In another paper (Koga et al. 2001), effects of precommercial thinning on both annual growth and wood density in balsam fir were investigated.

MATERIALS AND METHODS

Materials used for this study came from a precommercial thinning trial located in the Bas Saint-Laurent Region of Québec. The trial was naturally regenerated from a clearcutting in 1955. At the end of the growing season in 1969, plots of heavy thinning, moderate thinning, and control were established. In the heavy thinning plots, all trees within a distance of 7 feet around each residual tree were removed; in the moderate thinning plots, all trees within a distance of 5 feet around each residual tree were removed. The control plots had a stand density of approximately 20,000 trees/ha in 1969. At the beginning of the growing season in 1993, 18 sample trees (6 trees/plot) were collected from each thinning intensity as well as the control plots. In total, 54 sample trees ranging from 10 to 18 cm at the diameter of breast height were collected for this study. From each sample tree, a 4-cm-thick disk was collected at breast height for X-ray densitometry study. For further information on the trial and sample trees collected, refer to Schneider (2001).

A radial segment from pith to bark (1 cm longitudinally × 1 cm tangentially × radius) was removed from each disk at the north direction. The segments were trimmed to about 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 h and then with hot water for another 24 h to remove extraneous compounds. After the extraction, the strips were air-dried under restraint to prevent warping. Using a direct reading X-ray densitometer, the air-dried strips were scanned to determine the basic wood density (oven-dry weight/green volume) for each ring from the pith to bark. The first few rings near the pith were excluded because they were so narrow that densitometry analysis could not be performed for these rings. Based on the densitometric profiles, earlywood and latewood boundary in each ring was defined by a predetermined fixed basic wood density (540 kg/m^3) as explained by Jozsa et al. (1987). Various ring width parameters (ring width, earlywood width, latewood width, latewood percentage) and ring density parameters (e.g., earlywood density, latewood density, and average wood density of individual growth rings) were obtained for each ring scanned.

The boundaries of juvenile wood (until the 15th ring from the pith) and mature wood (from the 21st ring to the outermost ring) in this species were determined, based on the radial pattern of variation in wood density. Based on ring width and wood density data on individual growth rings from the pith to bark in each tree, weighted averages of wood density, earlywood density, and latewood density were computed for juvenile wood, mature wood, and whole tree as described by Barbour et al. (1992). Latewood percentage for each strip (tree) was calculated based on the total latewood width of the growth rings divided by the total width of the rings. In addition, intra-ring wood density variation was estimated using the equation given by Vargas-Hernandez and Adams (1991).

In total, eight characteristics were measured: ring width (RW) and its components including earlywood width (EW) and latewood width (LW), latewood percentage (LWP), wood density (WD) and its components including earlywood density (ED) and latewood density (LD), and the intra-ring wood density variation (IDV). For correlations between each pair of these characteristics at the inter-tree level (between trees), analyses were based on the tree average data for these characteristics in the 54 sample trees. Ring average data for these characteristics within a tree were used to calculate correlations at the intra-tree level (within a tree). All statistical analyses were performed using the Statistical Analysis System procedures (SAS Institute 1988).

RESULTS AND DISCUSSION

Variations between trees

Table 1 shows means and variations of eight characteristics for juvenile wood, mature wood, and whole tree in the 54 balsam fir trees. The mean basic wood density for the whole tree (351 kg/m^3) is slightly higher than that (335 kg/m^3) reported previously for this species (Jessome 2000). Ring width and earlywood width in juvenile wood are significantly larger than those in mature wood, but latewood percentage in juvenile wood is significantly lower than that in mature wood, although there are no differences in latewood

TABLE 1. *Mean, standard deviation, and coefficient of variation of the eight characteristics in the 54 balsam fir sample trees.*

Characteristic[1]	Juvenile wood			Mature wood			Whole tree		
	Mean	SD[2]	CV[3]	Mean	SD	CV	Mean	SD	CV
RW (mm)	2.58	0.54	20.7	1.47	0.40	26.9	2.06	0.36	17.5
EW (mm)	2.34	0.52	22.4	1.22	0.35	28.6	1.82	0.34	18.5
LW (mm)	0.24	0.07	27.3	0.24	0.07	29.1	0.24	0.06	24.1
LWP (%)	9.5	2.7	28.9	16.8	3.8	22.4	11.8	2.5	21.4
WD (kg/m^3)	335	23	6.8	359	38	10.5	351	21	5.9
ED (kg/m^3)	316	17	5.3	318	17	5.2	317	14	4.5
LD (kg/m^3)	552	23	4.2	574	26	4.5	564	22	3.9
IDV (kg/m^3)	70	11	16.1	99	12	12.6	79	10	12.4

[1] RW: ring width; EW: earlywood width; LW: latewood width; LWP: latewood percentage; WD: wood density; ED: earlywood density; LD: latewood density; IDV: intraring wood density variation.
[2] SD: standard deviation.
[3] CV: coefficient of variation (%).

width between juvenile and mature wood. On the other hand, earlywood densities in juvenile wood and mature wood are quite comparable, although latewood density and wood density in mature wood are slightly higher than those in juvenile wood. This agrees with reports by Zobel and van Buijtenen (1989) and Kennedy (1995) that genus *Abies* generally has a radial pattern of very limited change in wood density from the pith to bark. Intra-ring wood density variation in the whole tree (79 kg/m^3) is a little bit higher in balsam fir than in black spruce (58 kg/m^3) (Zhang 1998), but considerably lower than in Douglas-fir (198 kg/m^3) (Vargas-Hernandez and Adams 1991). This means that balsam fir shows a slightly larger variation in wood density within a growth ring than black spruce, but a smaller variation than Douglas-fir. As a result of a higher latewood density in mature wood, the intra-ring wood density variation in mature wood is significantly larger than that in juvenile wood (Table 1).

Variations in wood density and its components (ED, LD) among the 54 trees are quite comparable between juvenile and mature wood (Table 1). The coefficient of variation for wood density of the whole tree is almost equal to that reported by Jessome (2000). Compared to ring width and its components (EW, LW), wood density traits show a considerably smaller variation; the coefficients of variation for wood density traits are less than 11%, whereas the coefficients for ring width and its component range from 21 to 29%. The same case was reported for other species (Jourdain and Olson 1984; Magnussen and Keith 1990; Park et al. 1989; Zhang et al. 1996; Zhang and Jiang 1998). Of the eight characteristics studied, latewood percentage and intra-ring wood density variation show an intermediate variation.

Correlations between trees

The present study examined only phenotypic correlations because the trial where the sample trees were collected has no genetic structure. Table 2 shows the correlation coefficients between all pairs of the eight characteristics in juvenile wood (upper triangle) and mature wood (lower triangle). In juvenile wood, ring width is positively correlated with both earlywood width and latewood width. But, its correlation with earlywood width ($r = 0.99$) is much stronger than with latewood width ($r = 0.29$). This suggests that in the juvenile wood of balsam fir, earlywood width is critically important in determining the ring width. In fact, earlywood width alone explains 98% (r^2) of the variation in ring width. Table 2 also shows that in juvenile wood, earlywood width is not significantly correlated with latewood width. As a result, a significantly negative correlation between ring width and latewood percentage ($r = -0.49$) was found. The above correlations between ring width and its components