INFLUENCE OF STAND DENSITY ON RING WIDTH AND WOOD DENSITY AT DIFFERENT SAMPLING HEIGHTS IN BLACK SPRUCE (*PICEA MARIANA* (MILL.) B.S.P.)

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ABSTRACT

Thirty-six black spruce sample trees were collected from an 80-year-old stand to examine the influence of stand density on selected wood quality attributes and their variation with sampling height. The stand, naturally regenerated from fire in 1906, was located in Chibougamau, 400 km north of Québec. Each tree was assigned a local stand density ranging from 1390 to 3590 stems/ha, calculated from the number of neighboring trees. The trees were grouped into three stand density categories (1790, 2700, and 3400 stems/ha). Each sample tree was analyzed by X-ray densitometry, and various ring features including ring width and wood density were measured for each ring from pith to bark, at three heights (2.4, 5.1, and 7.8m) and ring area and earlywood proportion were computed. For all features studied, the variation due to sampling height was larger than that due to stand density. The longitudinal variations for ring density and earlywood density depend largely upon the wood type (juvenile wood or mature wood). A variation of ring density with sampling height in the stem from 425 to 458 kg/m^3 was observed in juvenile wood, but variations with stand density in all the growth ring features studied were small. Notably, it was observed that stand density had more influence on ring width features than on ring density features.

Keywords: Black spruce, stand density, sampling height, ring width, ring density, variation.

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INTRODUCTION

Stand density management is becoming an important forest management strategy in Eastern Canada. It is intended primarily to accelerate the growth of individual trees and shorten rotation age. However, as a result of this increase in tree growth rate, wood quality may be affected. The impact of growth rate on wood quality has been a subject of great interest for decades, and numerous studies have investigated the relationship between growth rate and wood density in several commercial species (Barbour 1991; Kellison et al. 1983; Cregg et al. 1988; Ackermann 1995; Zhang et al. 1997).

Black spruce (*Picea mariana* (Mill.) B.S.P.) is one of the most important commercial and reforestation species in Eastern Canada. This species is valued for both lumber and pulpwood production. In black spruce stands, growth conditions affect crown development (Raulier et al. 1996). Therefore, stand density management (e.g., thinning) affects not only tree growth but also wood quality. For example, it has been reported that precommercial thinning (Chui et al. 1997), growth rate (Barbour 1987), and initial spacing (Zhang and Chauret 2001) can all affect wood quality in black spruce. Moreover, other studies have reported considerable stand density effects on various wood properties in diverse conifers (Alazard 1994; Biblis et al. 1995; Biblis et al. 1997; Bues 1985; Cregg et al. 1988; Huuri et al. 1987; Panshin and de Zeeuw 1980). Even some anatomical properties (Kromhout 1968) and end product values (Middleton et al. 1995) are affected by stand density in some conifer species.

Wood density is one of the most important characteristics of wood quality and a major factor in paper processing (Law and Valade 1997). Variations in wood characteristic with height and radial position motivate us to study within-tree variation. It was shown that the correlations between wood features (ring density and ring width) vary from juvenile wood to mature wood (Koubaa et al. 2000; Koga and Zhang 2002). In addition, this species has also been studied for its wood physical and mechanical properties (Barbour et al. 1989), for its wood density in relation to cambial age (Zhang 1998), for tree growth and genetics (Zhang and Morgenstern 1995), and for its lumber properties in relation to growth (Zhang and Chauret 2001).

As part of a multidisciplinary project, this study was intended to provide a better understanding of the relationships between stand density, sampling height, and selected wood quality features (ring density, earlywood density, latewood density, maximum ring density, ring width, ring area and earlywood proportion) in black spruce.

MATERIALS AND METHODS

Materials

The sample trees came from a stand located in the Chibougamau area, 400 km north of Quebec City, 49°21′N and 75°05′W, at an altitude of 400 m. The average stand density was 1967 trees/ha and the average basal area was 41.3 m^2/ha, with an average tree height of 13.8 m at age 79 (Horvath 2002). It was a natural stand regenerated from fire. No silvicultural treatment was applied to the stand. Therefore, all the trees had comparable ages and heights, but were randomly spaced. In contrast to many previous studies where trees were collected from different stands, the sample trees were selected from the same stand to study the variability due to local stand density only. The Schütz index was used to determine the competition level for each sample tree (Ung et al. 1997). A total of 56 trees were randomly selected and studied to determine a local stand density that was calculated based on the number of surrounding trees in a 4-m ray circular sample plot. Small trees (less than 8 cm at DBH) and dead trees were not considered in the calculation because they would have had limited effects on the sample trees. Next, 36 trees were selected and were categorized into three stand density groups of the same span, namely: 1790 (1390–2190), 2700 (2390–2990), and 3400 (3190–3590) stems/ha, or low, medium and high stand densities, respectively. The 36 trees were felled and measured for diameter at breast height (DBH), total tree height, live crown width and length.

Sample preparation

From each sample tree, 30-cm bolts were collected at 2.4, 5.1, and 7.8-m heights, from which 2-cm-thick disks were removed in order to carry out wood density profile measurements. A radial segment from pith to bark (2.0-cm longitudinal × 1.0-cm tangential × disk radius) was removed from each disk in the southernmost direction. The segments were trimmed into 1.57-mm-thick (longitudinal) strips with a specially designed pneumatic-carriage twin-blade saw. The sawn strips were extracted with a cyclohexane/ethanol (2:1) solution for 24 h and then with hot water for another 24 h to remove extractive compounds. After extraction, the strips were air-dried under restraint to prevent warping, and scanned with an X-ray densitometer available at Forintek Canada Corp. in Quebec City, Canada.

Sample analysis

To determine earlywood and latewood characteristics separately, it is necessary to define the position of the earlywood-latewood transition within the growth ring. Since the transition from earlywood to latewood occurs gradually in black spruce, this boundary was defined as the inflexion point of the intra-ring density profile (Koubaa et al. 2002). The following variables were determined and studied: ring width (RW), ring density (RD), maximum ring density (MD), earlywood proportion (EP), earlywood density (ED), latewood density (LD), and ring area (RA). The latter, was calculated from RW data assuming that the rings are circular (Gartner et al. 2002).

Based on the radial patterns of ring area and maximum ring density, the transition from juvenile wood (JW) to mature wood (MW) was determined visually (Clark and Saucier 1989). Then, according to the results, the wood produced from the pith to age 20 was considered to be JW, and the remaining MW. ANOVA and Duncan tests were carried out with SAS software, sometimes separately for JW and MW when the patterns suggested that the analysis should be divided in two parts.

RESULTS AND DISCUSSION

Patterns of radial variation for growth and density features

Ring width is a feature most frequently used to characterize growth rate. As expected, average RW (Fig. 1) decreases from pith to bark, with the exception of the first 4–5 rings where it tends to increase slightly, as found for Douglas-fir by

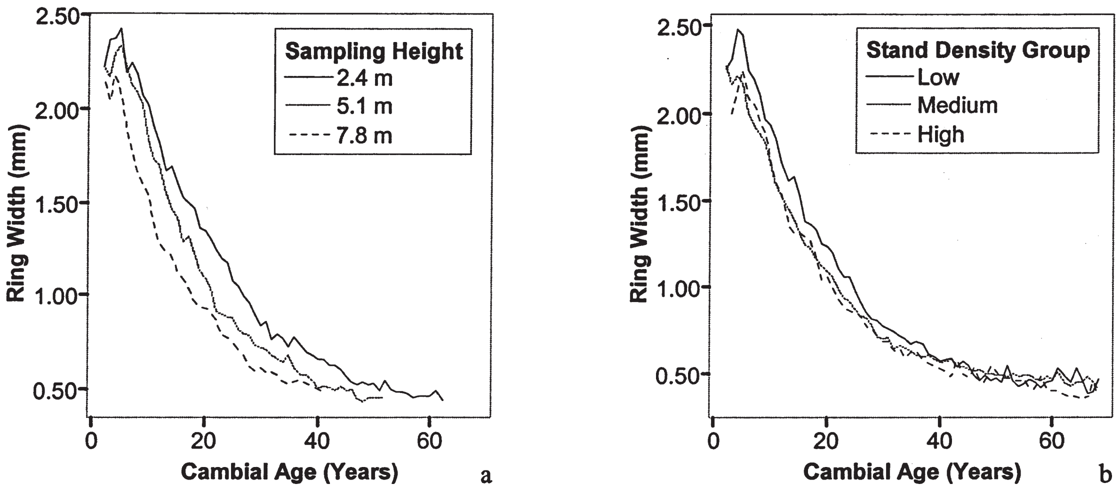

FIG. 1. Average ring width for all 36 trees in relation to cambial age, (a) at three sampling heights, and (b) in three stand density groups (data at 2.4-m high only).

Abdel-Gadir and Krahmer (1993). Figure 1 outlines a steady decrease in RW after the 4th ring.

Although RA is seldom used, it can also be considered as a growth variable because it refers to wood production in both radial and tangential directions, which is linked to periclinal and anticlinal divisions of cambial cells (Lei et al. 1997). It has been noticed that RA provides contrasted information and is better than RW for calculating the radial growth index, although both RW and RA yield the same qualitative results (Lei et al. 1997). The RA radial profile (Fig. 2) shows a different radial pattern than does the RW profile (Fig. 1). While RW decreases over the whole life of the tree, RA increases until about the 20th ring. Therefore, the RW and RA variables lead to different interpretations of growth rate. The results suggest that RA increases until the 20th ring and explain the rapid increase in cross-section observed during the juvenile period, which is possibly linked to live crown activity. Since the disks were collected only at heights of 2.4, 5.1, and 7.8 m, it was difficult to estimate the total stem volume, although the best indicator of growth rate is wood volume (Chui et al. 1997).

Earlywood proportion presents a radial pattern (Fig. 3) similar to RA. It increases until the 10th ring and then decreases to the bark. A transition in EP appears to occur at the 10th ring. Also, the EP decreases with height in the tree. Although RW (Fig. 1) is maximized at the 4th ring, RA (Fig. 2) reaches a maximum at the 20th ring, which seems to correspond to the JW/MW transition. The results show that growth trait patterns determined by RA, RW, and EP differ from one another.

The radial pattern of RD (Fig. 4) is of type II as described by Panshin and de Zeeuw (1980). The high densities of the first rings are due to both high ED (Fig. 6) and low EP (Fig. 3). Then, the decrease in RD from about 470 kg/m^3 to 410 kg/m^3 could be due to the decrease of ED and increase of EP. Ring density decreases until about the 10th ring and then increases slowly towards the bark. It corresponds to the reciprocal of the EP pattern (Fig. 3) and shows the importance of EP in determining RD. The radial pattern of ED (Fig. 6) decreases until age 11 then increases slightly, and also presents a similar pattern to RD, implying that it is as important as EP in determining RD.

In contrast, latewood density shows a completely different radial pattern (Fig 7), which increases until age 20 then is maintained at a constant value of 600 kg/m^3. The MD profile (Fig. 5) follows a pattern similar to the LD profile pre-

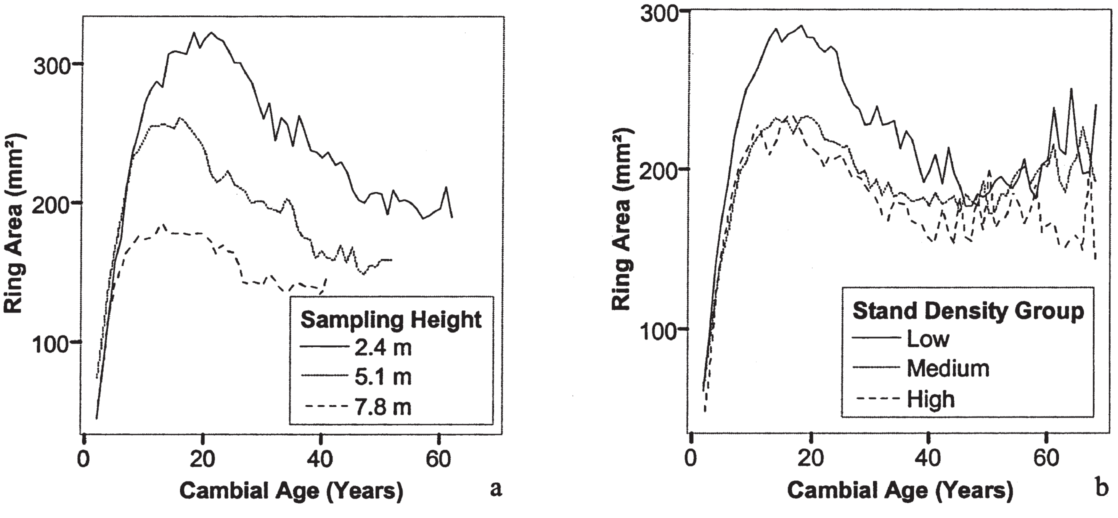

FIG. 2. Average ring area for all 36 trees in relation to cambial age, (a) at three sampling heights, and (b) in three stand density groups (data at 2.4-m high only).

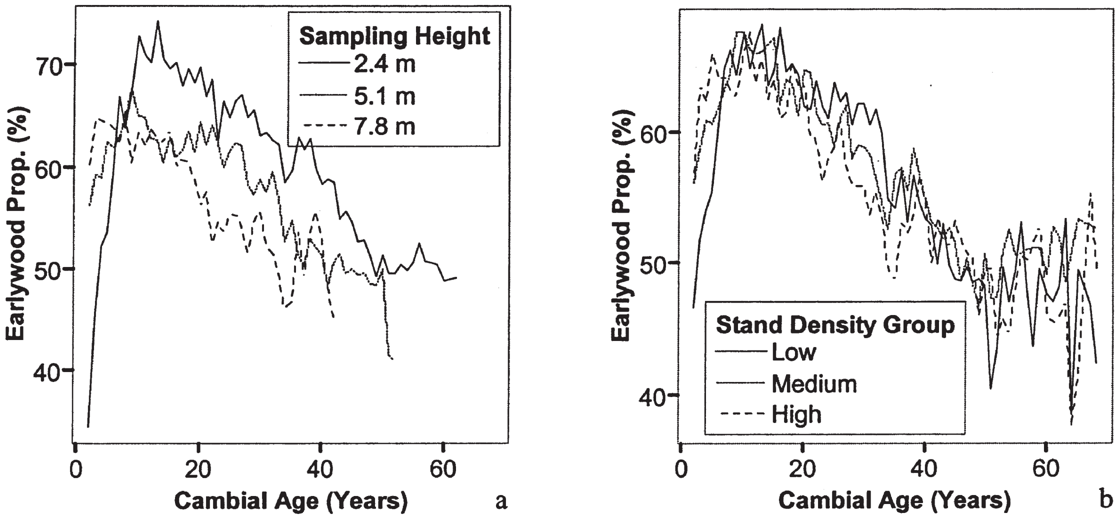

FIG. 3. Average earlywood proportion for all 36 trees in relation to cambial age, (a) at three sampling heights, and (b) in three stand density groups (data at 2.4-m high only).

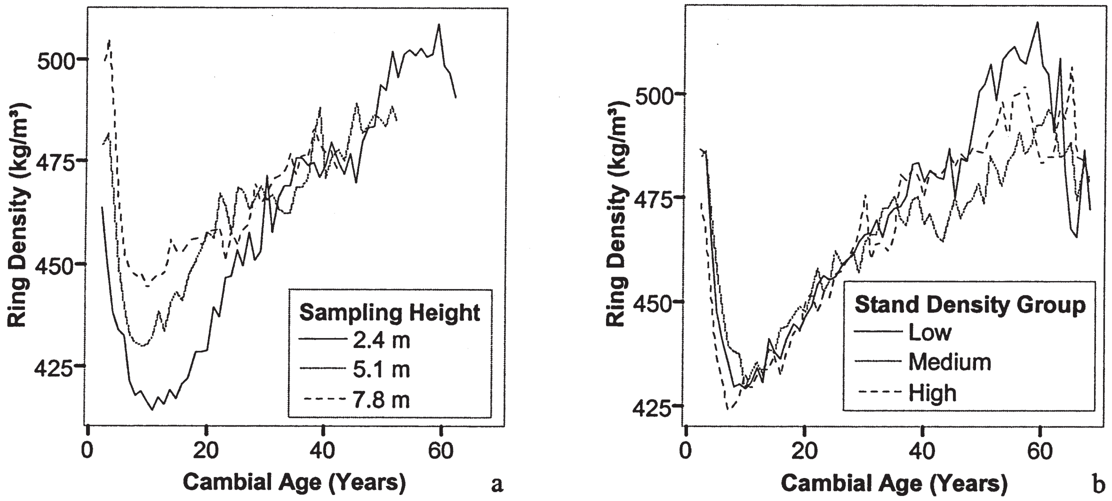

FIG. 4. Average ring density for all 36 trees in relation to cambial age, (a) at three sampling heights, and (b) in three stand density groups (data at 2.4-m high only).

sented by Sauter et al. (1999) for Scots pine. Maximum ring density is, by definition, higher than LD, and shows a strong correlation with it. Moreover, in contrast to LD or ED, MD does not depend on the determination of the earlywood/latewood boundary. For these reasons, MD was preferred to visually estimate the JW/MW boundary. During the first 20 years, the MD increases, and then decreases slowly towards the bark. It was noticed that MD presents a radial pattern similar to that observed for RA (Fig. 2).

Juvenile wood-mature wood transition

The determination of the transition age from JW to MW has been studied extensively because

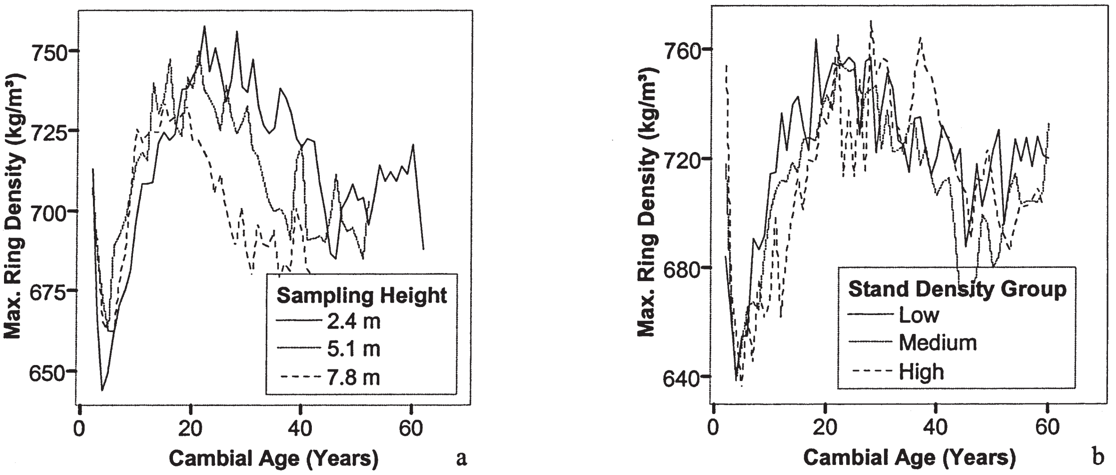

FIG. 5. Average maximum ring density for all 36 trees in relation to cambial age, (a) at three sampling heights, and (b) in three stand density groups (data at 2.4-m high only).

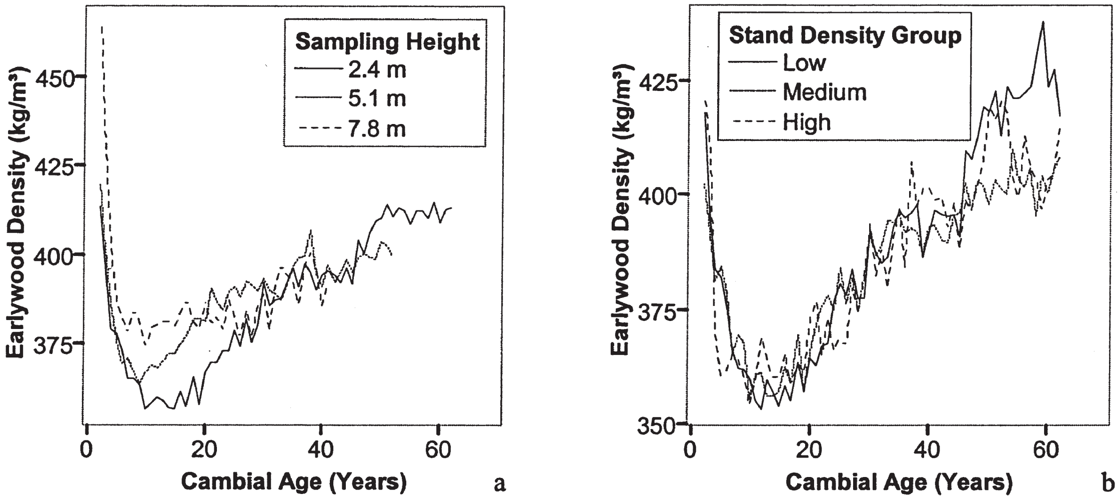

FIG. 6. Average earlywood density for all 36 trees in relation to cambial age, (a) at three sampling heights, and (b) in three stand density groups (data at 2.4-m high only).

of its impact on wood quality. Usually, the JW to MW boundary can be determined by microfibril angle or longitudinal shrinkage measurements. It has been shown that the transition age varies among species and among wood traits (Abdel-Gadir and Krahmer 1993), occurs over years (Yang et al. 1986) and can be determined visually (Clark and Saucier 1989). Sauter et al. (1999) found that LD was a good indicator of the boundary. Although the RW and RD profiles (Figs. 1 and 4) show sharp transitions at the 4th and 10th rings, respectively, they do not allow a clear determination of the JW/MW transition. Furthermore, based on the radial patterns observed in the current study for RD, RA, RW, and EP, the boundary can be progressive (over several years) or abrupt (over one or a few years). Ring width and EP (Figs. 1 and 3) show sharp transitions, whereas RA and RD (Figs. 2 and 4) show more progressive transitions over the

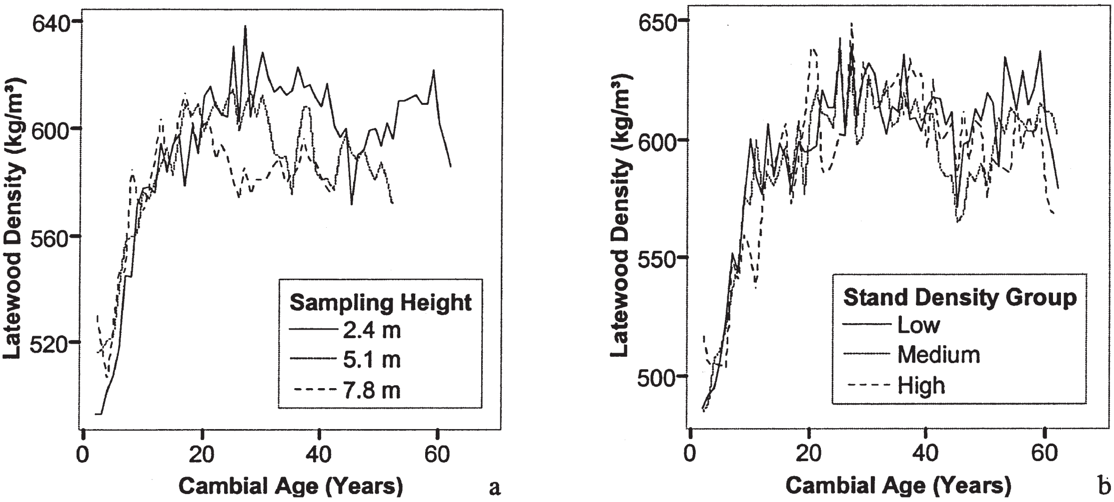

FIG. 7. Average latewood density for all 36 trees in relation to cambial age, (a) at three sampling heights, and (b) in three stand density groups (data at 2.4-m high only).

years. The maximum point of the MD profile, at about 750 kg/m^3, could correspond to the transition from JW to MW; therefore, MD might be used efficiently to determine the JW/MW boundary. From an anatomical point of view, MD corresponds to the density of the last cells of the growth ring which are characterized by a thick cell wall and a small lumen area. The radial pattern of RA (Fig. 2) could also be an indicator of this boundary. In this case also, the maximum occurs at about the 20th ring and is followed by a sharp decrease. The JW/MW transition at a height of 7.8 m appears to be earlier than that at 2.4-m or 5.1-m heights for both RA and MD (Figs. 2a and 5a). Therefore, our results show that the third log produces MW earlier, has a higher RD, and narrower rings (Figs. 1a and 4a). The shorter juvenile wood period at the 7.8-m height could be a consequence of tree aging, cambium aging, decrease of live crown proportion or increasing competition, which are the main characteristics of trees in mature stands.

Variations with sampling height

The growth ring features vary more strongly with height than with stand density (Figs. 1 to 7). Also, the magnitude of the variation depends on the type of wood (JW or MW). This suggests that end product quality should depend more on height and radial position than on stand density.

Ring width (Fig. 1a), RA (Fig. 2a), and EP (Fig. 3a) show large variations with sampling height, demonstrating that growth rate decreases from the base to the top of the stem (Figs. 1 and 2). This means that at the same cambial age, the cambium will produce narrower rings at the 7.8-m stem level than at the 2.4-m stem level. Ring density (Fig. 4a) shows large variations with sampling height, and these variations are larger in JW than in MW. This is consistent with the effect of height on wood density as reported for sessile oak (Degron and Nepveu 1996). The variations of the JW proportion among logs taken at different heights reported by Koga et al. (1995) have also demonstrated the importance of sampling height. Maximum ring density (Fig. 5a) also varies considerably with sampling height.

As explained above, the large variations observed with sampling height may have two origins. First, they could be due to the cambium aging process. Indeed, as cambial age corresponds to the number of rings from the pith at a given stem height, cambium age, is the difference between the year of production of the ring and the first year of the tree. It is also the tree age. Therefore, the last growth ring produced all along the stem has the same cambium age but the cambial age (number of rings from pith to bark) is a function of height. Tree aging could lead to lower cambium activity, inducing a decreasing fiber yield over the years and narrower rings (Went 1942). The second possible origin could be a decreasing live-crown proportion of the tree with aging, which induces a reduction of the growth rate. This is due to the variation in tree competition over the years. Indeed, while the distance between trees remains unchanged during the life of the tree, the diameter of the live crown increases, which increases the inter-tree competition. Thus, as the tree gets older, the live crown proportion decreases as competition increases. The above-mentioned parameters taken individually or in combination can explain the reduction of growth rate during the life of the tree.

As the incremental decrease of average RW with sampling height is low (Table 1), the decrease of average RA is about 45 mm^2 from 2.4 m to 5.1 m and 58 mm^2 from 5.1 m to 7.8 m (Table 2). The decrease in growth rate from the stump to the top is paralleled by an increase in average RD of about 20 kg/m^3 in JW (Table 4 and Fig. 4a). The link between RD and RW observed for sampling height is an interesting result of this study. Usually, the relationships between RD and RW are studied from the radial profile. The radial and height variations presented in this study show that decreases in RW (and especially RA) are proportional to increases in RD. Moreover, it was observed that the JW at the top of the stem seems to have more mature features than JW in the lower part of the stem, which could have major consequences on mechanical properties. Also, the range of variation of RA and RD along the radial profile is lower at 7.8 m than at 2.4 m (Figs. 2a and 4a), indicating more homogeneous wood properties along the radial profile in the top log.

TABLE 2. *Average ring area (mm^2) in relation to sampling height and stand density (data at 2.4-m high only), in juvenile wood (JW) and mature wood (MW). (Numbers with the same letter are not statistically different, read in column).*

Sampling height	Average ring area (mm^2)	Stand density group	Average ring area (mm^2)	
			In JW	In JW
2.4 m	239 C	Low	267 B	260 c
5.1 m	195 B	Medium	239 A	230 b
7.8 m	153 A	High	242 A	214 a

In conclusion, all traits present a strong relationship with sampling height. Specifically, we observed a reduction in growth rate and an increase in wood density at higher sampling positions.

Juvenile and mature wood properties

Ring density, ED, and MD variation with height depend on the wood type (JW or MW). While average RA variation with stand density was more affected in MW (Table 2), average RD variation was not affected by wood type and average MD variation was affected only weakly (Table 5). The radial pattern of RD (Fig. 4a) shows large variations with sampling height especially in JW where the growth rate is higher. This is one of the most important and visible consequences of the interaction between stem position and wood type. The Duncan test carried out in both JW and MW established that large variations of average RD due to sampling height (Table 4) are present in JW, but little influence of sampling height was noticed in MW. Thus, in MW the variation of RW (Fig. 1a) and RA (Fig. 2a) due to sampling height does not induce a var-

TABLE 1. *Average ring width (mm) in relation to sampling height and stand density group. (Numbers with the same letter are not statistically different, read in column).*

Sampling height	Average ring width (mm)	Stand density group	Average ring width (mm) by sampling height		
			2.4 m	5.1 m	7.8 m
2.4 m	1.03 B	Low	1.09 B	1.12 b	1.06 *b*
5.1 m	1.03 B	Medium	1.01 A	1.00 a	0.95 *a*
7.8 m	0.98 A	High	0.98 A	0.98 a	0.94 *a*

TABLE 3. *Average earlywood proportion (%) in relation to sampling height and stand density (data at 2.4-m high only) in juvenile wood (JW) and mature wood (MW). (Numbers with the same letter are not statistically different, read in column.)*

Sampling height	Average early earlywood proportion %		Stand density group	Average earlywood proportion %	
	In JW	In MW		In JW	In MW
2.4 m	65.3 B	57.1 c	Low	64.3 A	58.4 b
5.1 m	62.3 A	53.9 b	Medium	64.4 A	57.4 b
7.8 m	62.1 A	51.3 a	High	68.3 B	54.9 a

TABLE 4. *Average ring density (kg/m^3) in relation to sampling height, in juvenile wood (JW) and mature wood (MW), and in relation to stand density group. (Numbers with the same letter are not statistically different, read in column).*

Sampling height	Average ring density (kg/m^3)		Stand density group	Average ring density (kg/m^3) by samling height		
	In JW	In MW		2.4 m	5.1 m	7.8 m
2.4 m	425.3 A	475.9 b	Low	462.8 A	466.8 b	468.2 *b*
5.1 m	446.1 B	473.1 b	Medium	461.1 A	460.8 a	465.6 *b*
7.8 m	458.7 C	468.6 a	High	462.6 A	464.1 ab	458.1 *a*

TABLE 5. *Average maximum ring density (kg/m^3) in relation to sampling height and stand density (data at 2.4-m high only) in both juvenile wood (JW) and mature wood (JW). (Numbers with the same letter are not statistically different, read in column.)*

Sampling height	Average maximum ring density (kg/m^3)		Stand density group	Average maximum ring density (kg/m^3)	
	In JW	In MW		In JW	In MW
2.4 m	700.3 A	717.8 c	Low	708.8 B	721.7 a
5.1 m	713.0 B	710.8 b	Medium	699.8 B	714.4 a
7.8 m	707.6 B	694.4 a	High	688.3 A	717.5 a

iation of RD (Fig. 4a). It is consistent with a previous finding that a fast growth rate has less negative impact on wood density in MW than in JW (Zhang 1998). The variations of average MD with sampling height are also dependent on the wood type and are more important in MW than in JW (Table 5).

Variation with stand density

Competition between trees is difficult to evaluate since it is a dynamic process depending on time and tree age. Indeed, young trees do not interact the same way as mature trees, even though tree spacing remains unchanged. Unless significant self-thinning occurred, the tree spacing of the stand in 1999 was the same as about 80 years ago, but tree-to-tree competition in 1999 may not represent precisely the competition that existed previously because of mortality and increasing live crown diameter. Consequently, the results should be analyzed with caution considering the estimated local stand density.

The small impact of stand density on RD (Fig. 4) could be due to the overall high stand density. Zhang and Chauret (2001) found that stand density does not affect wood density significantly over a threshold value of about 1300 trees/ha. Since the lowest estimated local stand density was 1390 trees/ha, the three stand densities considered in this paper were above this threshold value. Moreover, for all traits studied, the variations with stand density are lower than the variations with sampling height. This implies that the within-tree variations in high-density stands are more important than the tree-to-tree variations.

Variations of average RW, RD and ED due to stand density were studied separately at three sampling heights (Tables 1, 4, and 6). On the other hand, variations of average RA, EP, MD, and LD due to stand density were analyzed at the 2.4-m sampling height only, in both JW and MW (Tables 2, 3, 5. and 7). Trees from the lowest stand density show slightly larger rings than those from the two other stand densities regardless of sampling height (Table 1). In the same way, the larger average RA (Table 2) corresponds to the lower stand density in both JW and MW. The average RA in MW increases from the high-density stand to the medium one, by about 15 mm^2/ring, and by about 30 mm^2/ring from the medium-density stand to the lower one. The impact of stand density on average RA was similar for the three sampling heights. The EP gave more contrasted results (Table 3). Indeed, as JW shows a high EP for high stand density, MW shows a low EP for high stand density, indicating a changing trend from JW to MW.

The variations of average RD with stand density are so small that at a 2.4-m sampling height, no significant impact of stand density was found (Table 4). However, at 5.1-m and 7.8-m heights, a very weak trend seems to occur. Nevertheless, and especially at 7.8 m, the results show that the lower stand density gives the higher average RD. The radial profile of RD as a function of sampling height presents distinct effects in JW and MW (Fig. 4a), which is not found in the radial profile with stand density variation (Fig. 4b). Again, this result shows that the intra-tree variation of RD is higher than the inter-tree variation of RD for the stand densities considered in the current study.

At the 2.4-m sampling height and in MW, no significant difference of average MD was found between the stand density groups (Table 5). But in JW, a lower average MD was found for the higher stand densities.

CONCLUSIONS

The objective of this study was to better understand the relationship between growth conditions and selected wood quality features in black spruce. More specifically, this study was designed to investigate the impact of stand density and sampling height in the tree on selected wood quality features for sample trees selected from the same stand. Ring area was used to complement ring width, which is most often used in the wood industry as a growth rate indicator. Wood density was characterized by ring density, maxi-

TABLE 6. *Average earlywood density (kg/m^3) in relation to sampling height, in juvenile wood (JW) and mature wood (MW), and in relation to stand density group. (Numbers with the same letter are not statistically different, read in column.)*

Sampling height	Average earlywood density (kg/m^3)		Stand density group	Average earlywood density (kg/m^3) by sampling height		
	In JW	In MW		2.4 m	5.1 m	7.8 m
2.4 m	366.4 A	396.4 b	Low	389.3 B	393.1 c	392.8 b
5.1 m	377.2 B	394.1 b	Medium	384.9 A	383.8 a	390.7 *b*
7.8 m	390.8 C	387.1 a	High	385.9 A	387.9 b	379.7 *a*

TABLE 7. *Average latewood density (kg/m^3) in relation to sampling height and stand density (data at 2.4-m high only) in both juvenile wood (JW) and mature wood (JW). (Numbers with the same letter are not statistically different, read in column.)*

Sampling height	Average latewood density (kg/m^3)		Stand density group	Average latewood density (kg/m^3)	
	In JW	In MW		In JW	In MW
2.4 m	567.3 A	607.9 c	Low	566.9 A	613.7 b
5.1 m	567.3 A	595.4 b	Medium	567.8 A	604.5 a
7.8 m	567.4 A	586.9 a	High	567.0 A	604.9 a

mum ring density, and latewood density. Based on the present study, the following conclusions can be drawn:

1. Ring width and wood density vary more with sampling height than with stand density over the density range of 1790–3400 stems/ha.
2. The relations between ring density, maximum ring density, and sampling height are dependent on the wood type. Differences in ring density and earlywood density among the three sampling heights are significant in juvenile wood. In mature wood, the variation of ring width and ring area with sampling height does not induce a variation of ring density.
3. The variation of the ring width and ring density profiles with sampling height was significant.
4. Very little variation of wood density was observed with stand density. The variations observed seem to be the result of inter-tree variation. Moreover, the stand density range of the sample trees could be over the limit above which stand density has no significant influence on wood density, as previously concluded by Zhang and Chauret (2001). The interaction between sampling height and stand density was very weak, implying that regardless of the sampling height, the influence of stand density on wood traits remains the same.
5. Growth features rather than density features have the highest variations with stand density.

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