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ORIGINAL PAPER

Variation in black spruce (*Picea mariana* (Mill.) BSP) wood quality after thinning

Manon Vincent · Cornelia Krause · Ahmed Koubaa

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Abstract

- ***Introduction*** Commercial thinning (CT) could contribute to increase short-term tree growth and be beneficial in a cold climate, as in boreal regions. Thus, growth rate, ring density and flexural modulus of elasticity (MOE) of trees may change after CT. Moreover, mechanical wood properties vary with position in the tree, and there is a need to develop optimal log allocation strategies in order to allocate logs to their best use.
- ***Objectives*** The objectives of the study were to evaluate the impact of commercial thinning on the lumber quality of nine thinned stands compared with unthinned stands and to determine whether this impact varies longitudinally along the first 4 m of the stem.
- ***Results*** Despite a significant increase in ring width following thinning ($p = 0.0003$), annual variations in ring density were subtle. No significant variation in average ring density due to CT was observed ($p = 0.5122$) after thinning, which may be explained by between-stand variability. Thinning showed no significant effect on flexural MOE over a 10-year period. Moreover, variability in average ring density along the stem with tree height was greater than that induced by thinning. A significant decrease in ring density was observed up the stem (from 490 to 463 kg m^{-3} up to the fourth metre, $p < 0.0001$).
- ***Conclusion*** Because it induced increased growth without negative effects on wood mechanical properties, thinning is advisable for slow growth naturally regenerated black spruce stands in the northern boreal region.

Keywords Black spruce · Modulus of elasticity · Ring density · Wood quality · Commercial thinning

1 Introduction

The boreal forest biome covers much of the landmass of the northern hemisphere and contains most of the global carbon stock (Melillo et al. 1993; Dixon et al. 1994). Black spruce (*Picea mariana* (Mill.) BSP.) is one of the most widespread boreal tree species in Canada (Parent and Fortin 2008; Zhang and Koubaa 2009). Its excellent wood and fibre quality makes it highly valued for pulpwood and lumber production (Zhang and Koubaa 2009). However, black spruce stems are relatively small in diameter, especially in northern areas, resulting in very low lumber volume recovery per stem volume (Pnevmaticos et al. 1979). Increased light penetration to the forest floor after commercial thinning can raise the temperature of surface soil layers, thereby accelerating nitrogen mineralization (Thibodeau et al. 2000) and increasing the available light to individual trees. This can contribute to increase short-

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term tree growth and can be particularly beneficial in a cold climate, as in boreal regions (Pothier 2002). Partial cutting through thinning could therefore be a sound choice for sustainable development within global market constraints whilst achieving maximum economic value (Zhang et al. 2006).

Many studies have reported that commercial thinning (CT) regularized forest size and growth, increased sawn timber availability, decreased rotation age and management costs, and enhanced stand value and quality (Prégent 1998; Cameron 2002; Petrás 2002). However, forest product properties also depend strongly on wood characteristics such as ring density, basic density, modulus of elasticity (MOE) and microfibril angle (Downes et al. 2002; Zhang et al. 2005). More specifically, wood density has a major impact on the yield, quality and value of wood-based composites and solid wood products (Shi et al. 2007). Both microfibril angle and intra-ring wood density variation determine a wood's suitability for specific end uses (Echols 1972; Koubaa et al. 2002). Numerous studies have investigated the relationship between growth rate and wood quality in many commercial species, with somewhat inconsistent results (Kellogg and Warren 1984; Castéra et al. 1996; Zhang et al. 2002). Moreover, whereas many studies have evaluated the impact of initial spacing on the wood value recovery chain (Koga and Zhang 2002; Zhang et al. 2002; Alteyrac et al. 2005), to our knowledge, none have addressed variations in wood mechanical properties after commercial thinning in natural black spruce stands. Nevertheless, black spruce is one of the main species used in machine stress-rated (MSR) lumber production, and MOE is one of the most important lumber bending properties used to determine end uses and MSR grade yield.

Because mechanical wood properties vary with position in the tree (Larson et al. 2004; Alteyrac et al. 2005), there is an increasing need to develop optimal log allocation strategies in order to allocate logs to their best use, maximize the value of the resource and ensure end-product quality (Shi et al. 2007). According to some authors, however, research on the effect of silvicultural practices on the value recovery chain has lagged behind research on growth and yield. The result is a disconnection across the value-added chain as the forest industry still lacks some basic information linking tree growth to product value (Briggs and Fight 1992; Kang et al. 2004).

This study tested the hypothesis that thinning treatments are followed by changes in the flexural MOE and density of black spruce wood. The objectives were to evaluate the impact of commercial thinning on the lumber quality of nine thinned stands compared with unthinned strands and to determine whether this impact varies longitudinally along the first 4 m of the stem.

2 Materials and methods

2.1 Study area

Wood from nine thinned stands and six control stands in the boreal forest of Quebec, Canada, were investigated. Stands had to be accessible by truck and located close to trails so that field material and samples could be transported by foot. Stands were selected according to two main criteria: thinning treatment was performed 10–12 years before sampling and thinning was performed in naturally regenerated unmanaged natural black spruce stands (Table 1). Whenever possible, a nearby unthinned natural black spruce stand with similar characteristics was selected as a control (Table 1). Control stands were selected mainly for stand age and location close to a thinned stand. In two instances where all stands had the same environmental characteristics, the same control stand was used for comparison with more than one nearby thinned stand. To identify the stands, initial letters refer to the stand location followed by a number representing the thinning year or the letter C for control (Table 1). See also Vincent et al. (2009a, b) for further information.

Latitude ranged from 47.9° N to 49° N, longitude from 70.5° W to 72.7° W and altitude from 210 to 671 m (Table 1). The boreal forest is characterized by cold winter temperatures and short vegetation periods. Over the last 30 years, the average annual minimum temperature for this region was −18.4°C and average annual maximum temperature was 19.3°C. Average annual precipitation varied from 920 to 1,187 mm in the studied stands (Environment Canada 2008). Average age of the studied stands at time of thinning varied from 47 to 82 years. Other than CT, no silvicultural treatment had been applied. Basal area at thinning year ranged between 17 and 50 m^2/ha (Table 1). The herbaceous and moss layers were composed of mainly *Pleurozium schreberi* (Brid.) Mitt., *Polytrichum* sp., *Ptilium crista-castrensis* (Hedw.) De Not., *Ledum groenlandicum* Oeder, *Vaccinium angustifolium* Ait. and *Kalmia angustifolia* L.

2.2 Sampling

A 20×20-m quadrat comprising at least 35 black spruce trees (diameter at breast height >9 cm) was randomly selected in each stand. Total tree height (*H*), diameter at breast height (Dbh), diameter at the stump (Dsh) and stem height at the lowest living branch were measured for each tree in the quadrat. Site quality was estimated using dominant tree height and production tables (Pothier and Savard 1998; Table 1). Six black spruce trees in each thinned stand and three in each control stand were randomly selected and felled, for a total of 72 trees harvested for stem analysis (one

Table 1 Stand characteristics

Block	Site	Location	Annual precipitation (mm)	Temperature (average min/ average max, °C)	TY	Stand age at TY	Dbh at TY (cm)	G at TY (RES + THI m²/ha)	Merchantable thinning intensity (%)	$\mathrm{Dbh}_{\mathrm{RES}}$ at TY/ $\mathrm{Dbh}_{\mathrm{THI}}$ at TY	Site index at 50 years
1	HEB95	N47.887W71.464	992.9	−12.1/17.9	1995	48.4 ± 10	13.0	29.2	19.6	1.4	12–15
	HEB96-1	N48.315W71.679	992.9	−12.1/17.9	1996	58.7 ± 9	15.4	23.8	9.7	1.0	15–18
	HEB96-2	N48.279W71.683	992.9	−12.1/17.9	1996	53.2 ± 8	16.6	41	31.8	1.0	15–18
	HEBC	*N48.145W71.589*	*992.9*	*−12.1/17.9*		*51.3 ± 9*	*15.8*	*48.3*			*15–18*
2	LB95	N48.033W72.33	1,012.7	−16.8/17.3	1995	81.9 ± 27	14.7	33.1	13.1	1.4	15–18
	LBC	*N48.032W72.334*	*1,012.7*	*−16.8/17.3*		*67.1 ± 23*	*14.6*	*17.2*			*15–18*
3	LC96	N48.143W71.879	1,036.7	−11.7/19.3	1996	56.3 ± 6	15.1	44.8	39.6	1.3	18–21
	LCC	*N48.143W71.878*	*1,036.7*	*−11.7/19.3*		*54.9 ± 13*	*20.7*	*35.2*			*18–21*
4	LJ96	N48.983W72.738	919.8	−18.4/17.6	1996	46.8 ± 6	13.6	42.3	52.5	0.8	15–18
	LJC	*N48.983W72.741*	*919.8*	*−18.4/17.6*		*53.1 ± 7*	*12.3*	*48.9*			*12–15*
5	MV95	N48.794W70.544	1,187.3	−16.1/17.5	1995	60.9 ± 11	14.1	40	39.7	1.3	12–15
	MV96	N48.76W70.551	1,187.3	−16.1/17.5	1996	59.5 ± 8	12.9	33	30.8	1.3	12–15
	MVC	*N48.764W70.55*	*1,187.3*	*−16.1/17.5*		*52.8 ± 12*	*14.6*	*49.8*			*15–18*
6	SL97	N48.874W71.747	1,061.4	−11.7/18.2	1997	57.1 ± 7	17.1	40	37.4	1.3	18–21
	SLC	*N48.874W71.475*	*1,061.4*	*−11.7/18.2*		*50.2 ± 7*	*15.5*	*34*			*18–21*
	Mean for CT stand				58	14.7	38.5	30.5	1.2		
	Mean for C stands				*55*	*15.6*	*38.9*				

Values in italics are for the control stand

TY thinning year, *Dbh* diameter at breast high, *G* basal area, *RES* residual stem, *THI* thinned stem, *CT* commercial thinning, *C* control (unthinned stand) tree was excluded due to handling errors in the laboratory). Stems were cut at every metre, starting at ground level and moving up to the fourth metre, to collect 50-cm-long bolts for mechanical analysis and disks for density analysis.

Disks for density analysis were cut to yield 1.57-mm-thick (longitudinal)×5-mm (tangential) samples in a north–south direction along the pith using a specially designed pneumatic twin-blade saw (FPInnovations, Forintek Division). 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 extractives. After extraction, strips were air-dried under restraint to prevent warping.

From the sampled bolts, 10-mm (radial)×10-mm (tangential)×150-mm (longitudinal) specimens from bark to pith were processed along both northern and southern radial directions. Specimen dimensions were defined so that the outermost samples contained mainly tree rings formed after CTand inner samples had tree rings formed before CT. Defect-free specimens were then dried under restraint from green to 12% moisture content in a conditioning room (20°C, 65% HR) and selected for bending tests (see Alteyrac et al. 2006 for a detailed description). These samples were used to test MOE before and after CT.

2.3 Sample analyses

Strips were scanned by X-ray densitometry in air-dry conditions. To accommodate a logistic change, densitometry tests were conducted at FPInnovations, Forintek Division., Quebec City, and at UQAT, Rouyn-Noranda, Canada. The same conditions (sample size, preparation and relative humidity) were imposed. However, because X-ray densitometry is a relative measure, density values may vary with the measuring instrument. Reference samples were tested with both densitometers to evaluate the method and verify the compatibility of the results. Moreover, samples from controls and associated thinned sites were measured with the same instrument. X-ray densitometry provided the radial patterns of several properties, including ring width (RW), early-wood width (EWW), late-wood width (LWW), ring density (RD), maximum ring density (MaxRD), minimum ring density (MinRD), early-wood density (EWD) and late-wood density (LWD). Mean annual RD was calculated for 10 years before and after thinning. To determine early-wood and latewood characteristics separately, it is necessary to define the position of the early-wood/latewood transition within the growth ring. Since the transition from early-wood 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 correlation between measured and modelled values by this method exceeded 0.99 for all analysed rings, indicating the power of the model to predict all estimated parameters (Koubaa et al. 2002).

Bending tests were performed at UQAC, Chicoutimi, Canada, according to ASTM D-143 standard test methods for small clear specimens (ASTM 2007). Specimens were placed with growth rings horizontal and with a span of 110 mm. The MOE (stiffness) was evaluated using an MTS-Alliance RT/100 material testing system.

2.4 Statistical analyses

Ring characteristics (RW, EWW, LWW and RD), average RD and MOE variations following CT were examined. In order to reduce environmental and thinning characteristics effects on response variation, we defined a randomized block design (Thysell and Carey 2001; Mäkinen and Isomäki 2004). Each thinning site (9) was matched with a control site (with similar characteristics) to form a block. In two instances, however, the same control stand was used for comparison with more than one nearby thinned stand. Data were compiled by multifactor analysis of variance (ANOVA) using restricted maximum likelihood estimation, the method of variance component estimation suggested for multifactor unbalanced designs (Searle 1992; Quinn and Keough 2002). Block designs included factorial experiment and combination between factors: thinning (two levels: thinned (CT) and unthinned (C)) and time (20 levels: years; and two levels: before and after) in the first part of the paper and height (four levels), thinning and time in the last part. Block was a random effect factor, whereas thinning, time and height were fixed effects. All statistical tests were performed using JMP software (SAS Institute Inc., Cary, NC) at the 95% confidence level.

3 Results

At thinning year, thinned stands had a mean age of 58 years and unthinned 55 years (Table 1). Based on the initial basal area, merchantable thinning intensity varied from 9.7% to 52.5% across stands, classified as light to heavy thinning. Moreover, based on the Dbh ratio of residual and thinned stems at thinning year ($\mathrm{Dbh_{RES}}$ at TY/$\mathrm{Dbh_{THI}}$ at TY), different CT types can be identified. When this ratio is <1, dominant trees are released to accelerate residual tree growth, which is classed as CT from above. When the ratio is >1, suppressed trees are released to stimulate the dominant storey, which is classed as CT from below (Table 1).

3.1 Growth variation

During the 20-year period studied (including the thinning year), RW varied from 0.03 to 2.6 mm, with a mean of 0.58 mm, for wood from control stands and from 0.03 to 2.6 mm, with a mean of 0.6 mm, for wood from thinned stands (Fig. 1a).

RW varied from 0.57 mm before thinning to 0.62 mm after thinning for thinned stands and from 0.6 mm before the thinning year to 0.57 mm after thinning for the control stands (Fig. 1a). A 12% increase in RW was observed for thinned stands, whereas a 2% decrease in RW was observed for control stands (Table 2). Statistical analysis revealed a significant influence of thinning on RW variation over time ($p=0.0003$ for interaction time × thinning, Table 3).

EWW for thinned stands varied from 0.39 mm before thinning to 0.43 mm after thinning (Fig. 1b), or a 5% increase in EW proportion (Table 2). For control stands, EWW varied from 0.41 mm before thinning year to 0.38 mm after, or a 4% decrease in EW proportion (Fig. 1b and Table 2). EWW followed the same pattern as RW over time (Fig. 1b), and a significant influence of interaction time × thinning on EWW was noted ($p=0.0019$ for interaction time × thinning, Table 3). In contrast, LWW varied from an average of 0.21 mm before thinning to 0.22 mm after thinning for thinned stands, or a slight 1% increase in LW proportion (Table 2). LWW in control stands varied from 0.21 mm before thinning year to 0.23 mm after thinning year, or a 15% increase in LW proportion. Despite the very small difference between thinned and control stands (Fig. 1c), thinning significantly influenced LWW (Table 3).

3.2 Ring density variation

Before thinning, RD of thinned stands was about 504 kg/m^3, decreasing thereafter by about 2% to approximately 493 kg/m^3. RD for control stands varied from 472 to 471 kg/m^3 (Fig. 2a and Table 2). Before thinning, RD for thinned stands was higher than the annual RD for control stands and decreased after thinning year (time=0, Fig. 2a). The third year after thinning, RD for thinned stands was lower than RD for controls and continued decreasing thereafter. However, no significant difference was found over time due to thinning ($p=0.2749$ for interaction time × thinning, Table 3). Despite a decrease in average RD after thinning for thinned stands (Fig. 2b), no significant variation due to thinning was noted ($p=0.5122$ for interaction time × thinning, Table 3).

3.3 MOE variation with thinning

MOE for wood from thinned stands varied from 9.16 to 12.14 GPa, with a mean of 10.53 GPa, and MOE for wood from control stands varied from 10.53 to 11.16 GPa, with a mean of 9.63 GPa (Fig. 3). Figure 3 shows increased MOE for both thinned and control stands after thinning year. No significant variation due to thinning over time ($p=0.2235$ for interaction time × thinning, Table 3) was seen.

3.4 Stem height influence on MOE and average RD

Figure 4 shows a decrease in average RD with increasing stem height for both thinned and control stands ($p>0.0001$ for height, Table 4). Average RD varied from 490 kg/m^3 at the bottom of the log to 463 kg/m^3 in the upper part of the log (Fig. 4a, b). However, thinning did not influence average RD up the stem ($p=0.94122$ for the interaction thinning × height × time). On the contrary, a slight increase in MOE with increasing tree height for both thinned and control stands is seen in Fig. 4c, d. MOE varied from 9.81 GPa at the bottom of the log to 10.33 GPa in the upper part of the log, and Table 4 shows significant differences in MOE between thinned and control stands.

4 Discussion

4.1 Variation in wood characteristics due to thinning

CT significantly increased RW, EWW and LWW (Table 3). Moreover, EW proportion increased at the expense of LW proportion (Table 2) after CT in thinned stands. Because silvicultural treatments such as thinning are used mainly to increase growth rate, many studies have addressed the impact of silvicultural treatments on tree growth (Yang et al. 1988; Yang and Hazenberg 1994; Tong and Zhang 2005) and the influence of growth rate on wood anatomical features. A recent study demonstrated that CT led to increased radial growth at the stem base in naturally regenerated black spruce stands (Vincent et al. 2009b). Koga et al. (2002) showed that in balsam fir stands, the annual radial growth response to precommercial thinning (PCT) was limited to EWW, whereas LWW showed little response. According to these authors, lightly thinned and control plots had comparable EWW and latewood percentage. In our case, CT influenced both EWW and LWW, with a more pronounced increase in EWW.

Given the decrease in LW proportion after CT, a decrease in RD would be expected. However, despite a slight decrease in RD after the thinning year (Fig. 2), this variation was not statistically significant (Table 3). No clear relationship between wood density and growth rate was found. Zhang et al. (1996) and Zobel and Van Buijtenen (1989) observed that although a negative relationship generally exists between wood density and growth rate in conifer species, there were many exceptions, and a non-significant or even a weak positive relationship between wood density and growth rate can be found in some families. Koubaa et al. (2000) reported a significant negative relationship between wood density and growth rate in juvenile black spruce only. In mature wood, this relationship was no longer significant. In jack pine (*Pinus banksiana*

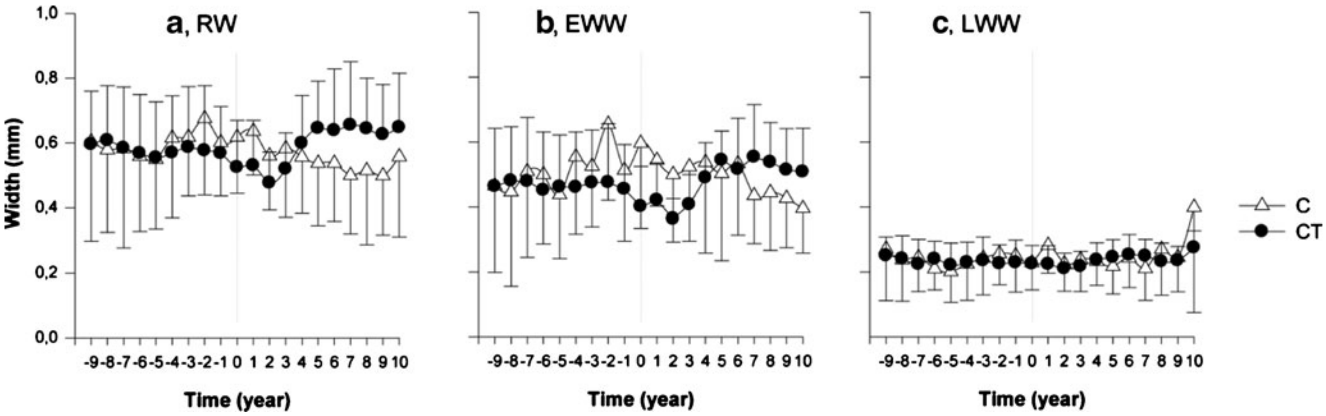

Fig. 1 Change before and after thinning year (time=0) in ring width (*RW,* millimetres) (**a**), early-wood width (*EWW,* millimetres) (**b**) and latewood width (*LWW,* millimetres) (**c**) for both thinned (*CT, black circle*) and control (*C*, *white triangle*) stands

Lamb.) and balsam fir (*Abies balsamea* L.), Barbour et al. (1994) and Kang et al. (2004) observed a reduction in wood density after thinning and with increasing initial spacing. Bendtsen (1978) found negligible effects of accelerated growth on wood properties compared with differences in the properties of mature and juvenile wood. The same result was obtained recently in black spruce stands by Tong et al. (2009) who found no significant variation in average ring density between control and two PCT intensities. Therefore, thinning intensity may have varying influence on growth ring features. Indeed, in terms of wood anatomy, ring growth increment may be insufficient to lead to decreased RD. This implies that increased growth rate is not necessarily linked to decreased wood mechanical properties. Moreover, external factors may also explain the variable results on mechanical properties. For example, St-Germain and Krause (2008) demonstrated that wood growth features such as RW, EWW and LWW decreased with latitude. The age of the studied trees and the length of the studied period also contributed to explain the variation in measured RD. Koubaa et al. (2000) demonstrated a decreasing correlation between RW and RD with increasing age.

Table 2 Ring characteristics and MOE variation by stand

Site	RW variation (%)	Variation in EWW proportion (%)	Variation in LWW proportion (%)	RD variation (%)	MOE variation (%)
HEB95	97.6	101.9	95.6	98.6	115.8
HEB96-1	113.0	90.0	112.0	94.6	107.1
HEB96-2	105.7	99.8	96.0	102.3	106.3
HEBC	96.8	96.7	105.2	101.6	103.8
LB95	109.0	101.4	90.6	95.2	110.8
LBC	91.4	94.1	115.3	96.5	94.9
LC96	96.9	94.9	107.8	97.3	101.7
LCC	123.1	94.4	95.4	97.7	108.2
LJ96	110.3	99.4	103.0	100.1	116.2
LJC	86.7	93.3	115.7	98.0	108.0
MV95	99.5	199.2	125.8	97.0	112.6
MV96	175.6	54.2	62.3	98.2	113.6
MVC	79.3	110.6	114.8	102.4	94.0
SL97	97.8	105.4	101.2	95.0	118.7
SLC	107.4	86.6	148.5	100.6	107.7
Mean for CT stand	111.7	105.1	99.3	97.6	111.4
Mean for C stands	97.5	95.9	115.8	99.5	102.8

The percentage corresponds to the ratio of mean values by stand of ring characteristics and MOE for the 10 years preceding thinning year on the mean values by stand of ring characteristics and MOE ring characteristics for the 10 years following thinning year

RW ring width, *EWW* early-wood width, *LWW* late-wood width, *RD* ring density, *MOE* modulus of elasticity, *CT* commercial thinning, *C* controls

Table 3 ANOVA for thinning and temporal effects on RW, EWW, LWW, RD, average RD and MOE

Test	Source	*DF*	DFDen	*F* ratio	Prob. > *F*
Ln(RW)	Thinning	1	4.997	0.0196	0.8942
	Time	19	180.2	1.1424	0.3128
	Time × thinning	19	180.2	2.6921	0.0003[a]
Ln(EWW)	Thinning	1	4.983	0.0187	0.8967
	Time	19	292	0.7551	0.7593
	Time × thinning	19	292	2.2898	0.0019[a]
Ln(LWW)	Thinning	1	4.96	0.0050	0.9466
	Time	19	232.2	3.1414	<.0001[a]
	Time × thinning	19	232.2	2.0862	0.0061[a]
Ln(RD)	Thinning	1	4.963	2.9606	0.1464
	Time	19	324.6	3.0524	<0.0001[a]
	Time × thinning	19	324.6	1.1771	0.2749
Ln(Average RD)	Thinning	1	4.649	3.1472	0.1407
	Time	1	40.51	1.5646	0.2182
	Time × thinning	1	40.51	0.4372	0.5122
MOE	Thinning	1	4.736	18.5509	0.0087[a]
	Time	1	7.029	16.7981	0.0045[a]
	Time × thinning	1	7.029	1.7824	0.2235

Data are transformed when necessary

[a] Significant at the 95% confidence level

Table 1 presents between- and within-block differences in terms of thinning influence. Specifically, block LB is questionable because LBC had a G_{TY} nearly half that of LB95 (Table 1). It is therefore arguable that these two stands were not comparable. However, a previous study on the same material demonstrated that both LBC and LB95 were affected by outbreaks of spruce budworm (*Choristoneura fumiferana* (Clemens)) in the late 1970s (Morin et al. 2000; Vincent et al. 2009b). Comparing radial growth over time, these outbreaks appear to have affected LBC longer (by about 2 years) than LB95 (data not shown). Moreover, radial growth for LBC after the outbreaks resumed faster and was greater than for LB95 (Vincent et al. 2009b). These variations in tree growth may influence changes in RD and affect the results. In fact, most studies in this area show a predominance of between-stand, inter-tree and intra-tree variability in silvicultural impacts on mechanical wood properties. Dutilleul et al. (1998) noted that the correlation between RW, RD and mean tracheid length may be affected by heavy thinning, which would partly explain the contradictory results reported in the literature.

No significant variation in MOE due to thinning was observed in this study (Table 3). MOE differed between thinned and control stands and increased after thinning year in both thinned and control stands. However, average RD tended to decrease after thinning, with a slight increase in MOE after thinning. Although variations in MOE due to different initial spacings were observed, the influence of CT on MOE was more ambiguous. Zhang et al. (2002) studied lumber strength variation following three different initial spacings of black spruce plantations.

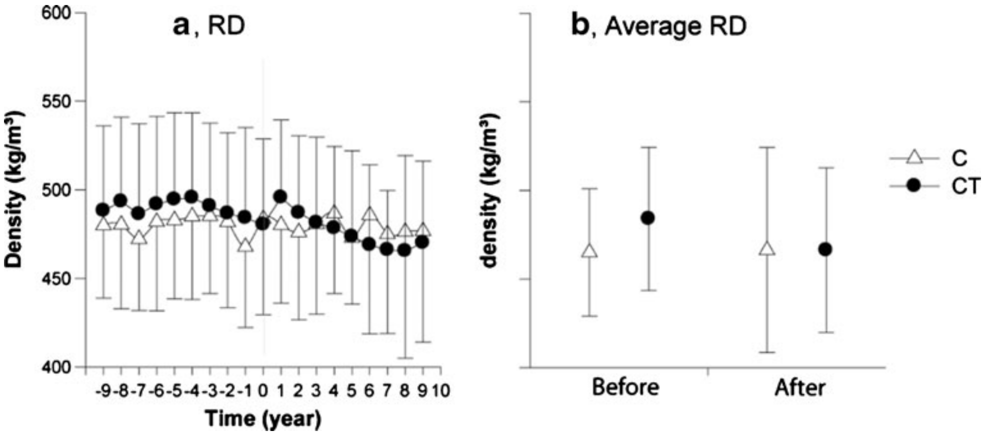

Fig. 2 Change before and after thinning year (time=0) in ring density (*RD*, kilograms per cubic metre) (**a**) and average ring density (*Average RD*, kilograms per cubic metre) (**b**) for both thinned (*CT*, *black circle*) and control (*C*, *white triangle*) stands

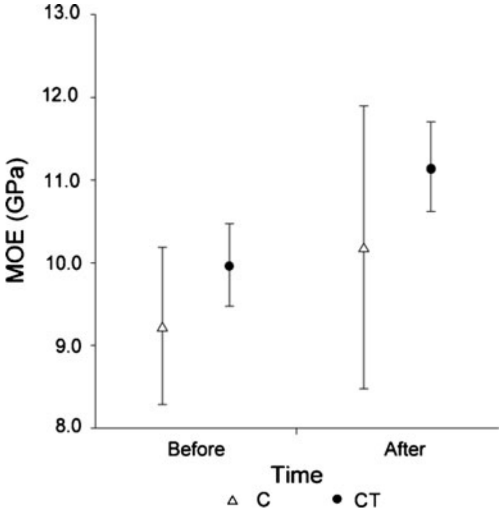

Fig. 3 Variation in modulus of elasticity (*MOE*, gigapascals) for both thinned (*CT*, *black circle*) and control (*C*, *white triangle*) stands

Compared with natural stand lumber currently processed in eastern Canada, the stiffness of plantation-grown black spruce lumber was 28.9% lower on average. As a result, a high percentage of the plantation-grown lumber did not meet the bending design values (Zhang et al. 2002). In contrast, CT in plantations increased radial growth and did not lead to decreased MOE. From a wood supply standpoint, bigger logs from thinned natural stands would not be expected to have the lower mechanical properties associated with plantation logs of similar dimensions.

The larger variation of MOE from the unthinned control stands compared with thinned stands may be of interest for further studies to discuss because it may disclose a more heterogeneous wood material in the unthinned stand. Alteyrac et al. (2006) demonstrated that ring density had lower contribution in predicting MOE than the modulus of rupture and that it was negatively correlated to microfibril angle. According to these authors, this relation between MOE and microfibril angle is not dependant on radial growth rate. However, Herman et al. (1999) demonstrated that intra- and inter-ring trajectories of microfibril angle in Norway spruce were affected by growth rate. This relation between MOE and microfibril angle may be the cause of the variations observed between material from thinned and unthinned stands, but it requires further study in order to better explain these observations.

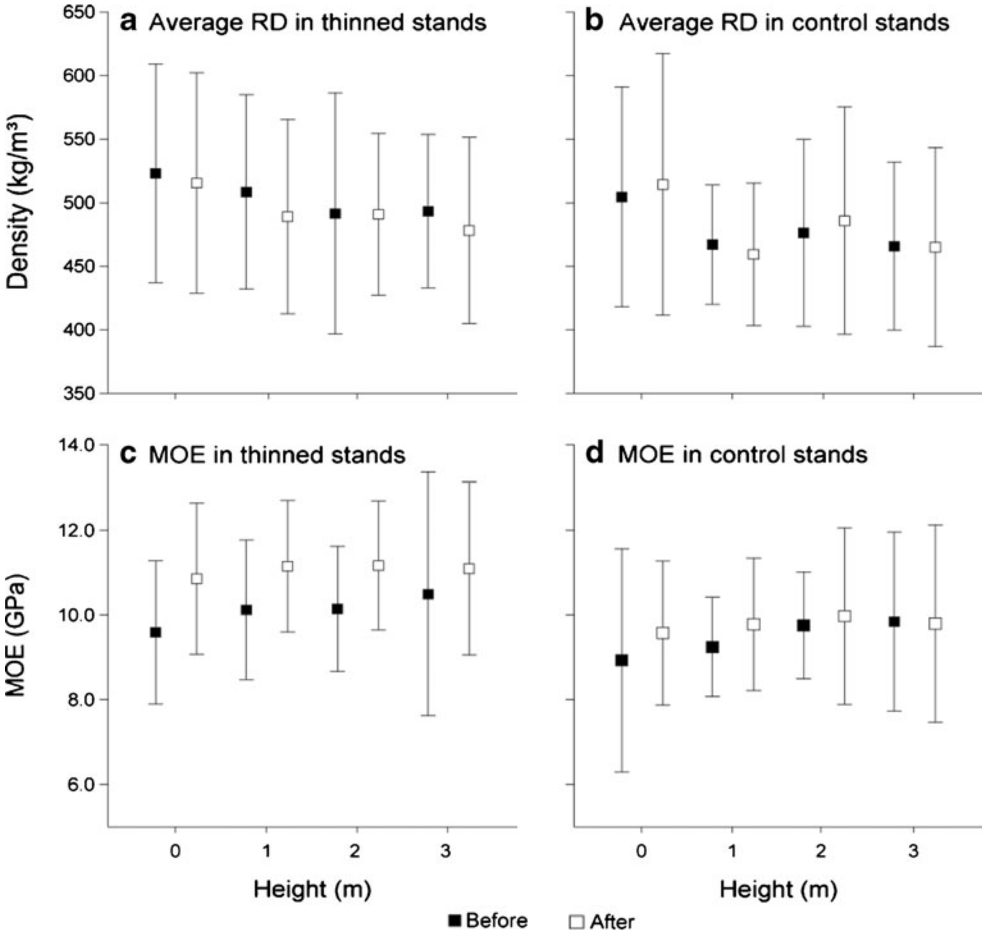

Fig. 4 **a** Change along the first 4 m of stem in average ring density (*Average RD*) for thinned stands. **b** Average RD for control stands. **c**, **d** Modulus of elasticity (*MOE*) for thinned stands and control stands before (*black square*) and after (*white square*) thinning year

Table 4 Effect from ANOVA for average RD and MOE before and after thinning: analysis with tree height

Test	Source	*DF*	DFDen	*F* ratio	Prob. > *F*
Ln(Average RD)	Height	3	25.32	10.7301	<0.0001[a]
	Thinning	1	57.21	3.2067	0.0786
	Thinning × height	3	42.07	0.6460	0.5899
	Time	1	171.4	0.2792	0.5979
	Time × thinning	1	171.4	0.8895	0.3469
	Time × height	3	170.6	0.2030	0.8942
	Time × thinning × height	3	170.6	0.1315	0.9412
MOE	Height	3	21.36	1.0684	0.3834
	Thinning	1	25.39	19.5306	0.0002[a]
	Thinning × height	3	23.48	0.6229	0.6073
	Time	1	38.81	26.7639	<0.0001[a]
	Tiime × height	1	38.81	2.7163	0.1074
	Time × thinning	3	38.72	2.1729	0.1068
	Time × thinning × height	3	38.72	0.7231	0.5443

[a] Significant at the 95% confidence level

4.2 Variation in wood characteristics with tree height

RD and MOE varied significantly with tree height, but no significant effect of thinning with tree height was observed. It was noted previously that logs cut from different positions in the tree had different wood and fibre characteristics (Larson et al. 2004; Tong et al. 2009). Moreover, previous studies have revealed variations in growth rate with log position in the stem after silvicultural treatment (Koga et al. 2002; Vincent et al. 2009a). However, according to Alteyrac et al. (2005), sampling height appeared to have a larger impact on density variation than growth rate on RD. Koga and Zhang (2004) observed a negative correlation between RD and RW in balsam fir, which was significant in the butt log but decreased to insignificance at and above a height of 3 m, and other authors noticed the ring density decreased up to the first 5 m (Evans et al. 2000; Spicer and Gartner 2001). The present study seems in agreement with these authors (Table 4), but more work on data along the entire stem is needed to confirm these findings. Moreover, the rapid decrease in cambial age with tree height may explain changes in ring density up the stem.

Regarding MOE variation with log position, Tong et al. (2009) found no significant correlation between lumber MOE and log position in precommercially thinned black spruce plantations when all log positions were considered. However, when butt logs (0–2.5 m) were excluded, MOE decreased steadily with increasing log height. In the present paper, butt logs were included in the analysis, which may explain the unexpected observations: the differing MOE within butt logs may be attributed to the presence of various stages of compression wood (Larson et al. 2004; Tong et al. 2009). To our knowledge, no study has addressed the role of the root system close to the stump and its influence on wood properties at the stem base. Nevertheless, it is evident that root fibre and stem orientation differ and that the transition between root and stem is not clearly defined. The increasing proportion of less mature wood up to the stem may also explain these results.

5 Conclusion

The main conclusion of this study is that RW significantly increased after CT, but no significant variation in RD due to thinning was observed. Moreover, despite a slight increase observed for thinned stands, MOE did not vary significantly after thinning. These results support the argument for commercial thinning in natural black spruce stands in the boreal forest without concerns about wood quality after thinning. Moreover, the high density associated with lumber stiffness properties of the studied black spruce makes it a good candidate for lumber end uses. However, the large variation in MOE needs to be taken into account.

Finally, this study showed that mechanical wood properties vary up the stem and that this variation is greater than the variation due to thinning. These results are of interest, given the increasing need to develop optimal log allocation strategies. As the forest industry shifts towards value-added end uses, it has become important to allocate logs to the best uses to maximize the value of the resource and ensure end-product quality.

Further studies are needed to enhance our knowledge in this area, notably the influence of different wood mechanical properties on MSR lumber yield, which is usually used for saw log classification.

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