WOOD AND LUMBER PROPERTIES FROM UNTHINNED AND PRECOMMERCIALLY THINNED BLACK SPRUCE PLANTATIONS

Que-Ju Tong

Postdoctoral Researcher
FPInnovations–Forintek Division
Quebec City, Quebec
Canada G1P 4R4

Robert L. Fleming

Forest Ecologist
Great Lakes Forestry Centre
Canadian Forest Service
Sault Ste. Marie, Ontario
Canada P6A 2E5

Francis Tanguay

Technologist
FPInnovations–Forintek Division
Quebec City, Quebec
Canada G1P 4R4

S.Y. Zhang†

Research Scientist
FPInnovations–Forintek Division
Vancouver, BC
Canada V6T 1W5

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Abstract. This study examined wood and lumber bending properties of 44-yr-old plantation black spruce subjected to precommercial thinning (PCT) at age 23. PCT and tree diameter at breast height (DBH) had little effect on heartwood content and the No. 2 & Better lumber grade yield. With increasing DBH of 10 – 18 cm, basic wood density (Db), lumber bending modulus of elasticity (MOE), and modulus of rupture (MOR) decreased by 8.1, 15.8 and 19.0%, respectively. The Db, MOE, MOR, and machine stress-rated (MSR) lumber yield from the stand with 35% basal area removal (T35) were lower than those of the control (T0) and the stand with 20% basal area removal (T20). The T20 had no significant effect on the Db, MOE, MOR, and MSR lumber yield. Juvenile wood content had a negative effect on lumber bending properties. The percentage of lumber pieces complying with the design values decreased with increasing thinning intensity. On average, MOE from T0, T20, and T35 were 10.9, 12.1, and 19.5% lower, respectively, than that from mature natural black spruce stands and 19.6, 18.0, and 10.8% higher, respectively, than that from wider-spaced black spruce plantations. MOE from T0 was also 14.5% higher than that from 50 – 60-yr-old natural jack pine stands. This study indicates that it is possible to produce high-quality lumber from dense black spruce plantations with appropriate thinning.

Keywords: Precommercial thinning, thinning intensity, black spruce, plantation, wood properties, lumber bending properties, visual grading, MSR lumber.

INTRODUCTION

Black spruce [*Picea mariana* (Mill.) B.S.P.] is one of the most important commercial and reforestation species in Canada. Stand density

* Corresponding author: Tony.zhang@fpinnovations.ca
† SWST member

management [eg initial spacing, precommercial thinning (PCT), and commercial thinning] has significant effects on tree growth and stand yield of black spruce (McClain et al 1994; Wells 1994; Burns et al 1996; Prégent et al 1996; Fleming et al 2005). Stem and wood characteristics (eg knots, taper, stem form, and wood quality) are also affected by stand density management (McClain et al 1994; Zhang and Chauret 2000). Although most emphasis in intensifying boreal forest management has been placed on increasing wood volume, maximizing economic value also depends on the production of high-value materials. Thus, there is a strong imperative to understand the impact of stand density management on black spruce wood and product quality and on economic value.

Although spacing plays an important role in determining wood properties, its effects are species-specific. Studies with jack pine (*Pinus banksiana* Lamb.) showed that wood density was affected by initial spacing, PCT, and commercial thinning (eg Barbour et al 1994; Kang et al 2004; Zhang et al 2006). Koga et al (2002) observed that PCT had little effect on earlywood and latewood density in balsam fir [*Abies balsamea* (L.) Mill.] but a negative effect on average ring density. Regarding spruce species, Pape (1999) observed a moderate decrease in basic wood density associated with increasing thinning intensity in Norway spruce [*Picea abies* (L.) Karst.]. Juvenile wood and tracheid length in white spruce [*Picea glauca* (Moench) Voss] (Yang 1994, 2002) and sapwood basal area in black spruce (Yang and Hazenberg 1992) increase with increasing spacing, whereas relative density and tracheid length in black spruce decrease with increased spacing (Yang 1994). Alteyrac et al (2005) reported that stand density had more influence on ring width than on ring density in naturally regenerated black spruce.

Lumber strength properties are also affected by stand density management practices in many species, eg loblolly pine (*Pinus taeda* L.) (Clark et al 1994; Biblis et al 1995), *Eucalyptus urophylla* (Huang et al 2000), Scots pine (*Pinus sylvestris* L.) (Minin and Moskaleva 1986; Malinauskas 1999), slash pine (*Pinus elliotti* Engelm. var. elliottii) (McAlister et al 1997), lodgepole pine (*Pinus contorta* Dougl. Ex Loud. var. *latifolia* Engelm.) (Middleton et al 1995), and red spruce (Wolcott et al 1987). In eastern Canada, Zhang et al (2002) evaluated the impact of initial spacing on lumber grade recovery and bending properties in black spruce plantations, and Zhang et al (2006) assessed the influence of PCT on lumber properties in jack pine.

We are examining the impact of PCT on the forest-wood value chain in boreal black spruce. The specific objectives of this article are to quantify wood density, heartwood content, lumber grade yield, and bending properties from plots subjected to different thinning intensities. A better understanding of thinning impacts along the wood value chain will help define the optimal thinning strategy required to produce quality wood and wood products and maximize economic value.

MATERIALS AND METHODS

Experimental Design

This study was located in one of the oldest black spruce PCT trials in eastern Canada, located about 15 km north of Beardmore, Ontario (long. 49 E, 37′ N, lat. 88 E, 15′ W). The trial was established by the Canadian Forest Service (CFS) in 1985 in a dense 210-ha black spruce plantation planted on burned-over land in 1962 – 1963 under the supervision of George Marek of the then Ontario Department of Lands and Forests. Initially spring-planted in 1962 at 1.8 × 1.8 m spacing, insect defoliation that summer led to complete replanting the next spring between the existing rows. Subsequently, high survival of both plantings resulted in densities comparable to fully stocked Site Class 1a natural spruce stands.

In Fall 1985, a series of 25 × 25 m plots were established, cleaned to remove all trembling aspen and white birch (averaging about 25% of the total basal area), and then thinned to various intensities using a combination of geometric and low thinning (Fleming et al 2005). This particular stand was selected because the high density of planted spruce permitted examination of stand growth and yield across an exceptionally wide range of stocking levels. We focus on plots with thinning levels of 0 (T0), 20% (T20), and 35% (T35) of the existing black spruce basal area. Immediately after treatment in 1985, mean stand densities were 5674, 3689, and 3400 trees/ha for the T0, T20, and T35 stands, respectively. More details on site description, stand history, and silvicultural treatments are given in Fleming et al (2005).

Since establishment of the trial, no management other than maintenance and periodic measurements has been applied that would alter growth and development. In Winter 2005 – 2006, snow damage resulted in some plots being dropped from the long-term experiment. This presented an opportunity to examine thinning effects on wood quality using sample trees selected from undamaged portions of these plots.

Selection and Measurements of Sample Trees

In Fall 2006, we measured the diameter at 1.3 m above ground [diameter at breast height (DBH)] of all trees (greater than 9 cm DBH) and the height of every fifth tree in all study plots. Immediately afterward, we selected sample trees from partially damaged plots for wood quality determination for each of the three thinning treatments. Within each treatment, five trees were chosen to represent each of four nominal merchantable 2-cm DBH classes (ie 10, 12, 14, and 16 cm) spanning the common range of diameters. A few larger trees were also selected where present to expand the inference space. In total, 22 trees were collected from T0, 20 from T20, and 21 from T35. For each tree, crown width and DBH were first measured; then immediately after felling, total tree height, length below live crown, and diameters of the five largest branches were recorded. The full-length stems were then transported to FPInnovations–Forintek Division in Quebec City for further analysis. The sample trees had an average DBH of 14.3, 13.8, and 14.1 cm for T0, T20, and T35, respectively, with an average total height of 14.0, 13.5, and 13.7 m; stem taper of 7.9, 7.9, and 8.0 mm/m; and sweep of 7.6, 8.5, and 7.5 mm/m, respectively.

Evaluation of Wood Properties

Each stem was scanned using Forintek's mobile scanner (C1-Scan&Snap-Scan; COMACT Optimization) to acquire 3D geometric information. After scanning, each stem was bucked into 2.5-m long logs, and log defects (eg sweep, crook, rot) were recorded. A 50-mm thick disc was then removed from the tree butt and the top of each log for the evaluation of selected wood properties. These discs were placed in a plastic bag immediately on removal from the logs and kept in a freezer (–35°C).

The heartwood–sapwood boundary was first identified on each frozen disc. Under these conditions, the heartwood–sapwood boundary was clearly defined by the difference in MC. Then, four radii at 90° intervals from the pith to this boundary and the cambium were measured to obtain heartwood and sapwood thickness. Heartwood content was determined as the ratio of heartwood to disc area. One-fourth of each disc (90° arc) was then removed and the volume determined by water displacement. The quarters were then oven-dried and weighed to determine the average basic wood density and MC of each disc. All discs had greater than 60% MC.

Lumber Conversion and Grading

Each log was converted into nominal 2 × 4 or 2 × 3 lumber using a portable sawmill (Wood-Mizer LT40). In all, 287 pieces of lumber, including 158 2 × 4 and 129 2 × 3, were produced from the 63 sample trees. After kiln-drying, each piece was dressed, and any defects that could affect lumber grade and mechanical properties were recorded. Each piece was then visually graded according to the National

Lumber Grades Authority (NLGA) grading rules by an inspector from the Québec Forest Industry Council, and the causes for downgrades were recorded. Each piece was graded as stud or economy stud for 2.5-m long lumber and also as "Structural Light Framing" (NLGA article 124) to detect smaller differences in lumber quality. The NLGA defines five visual grades for Structural Light Framing: Select Structural (SS), No. 1, No. 2, No. 3, and Economy. Following current grading practice, the SS and No. 1 grades were combined as No. 1 grade. About 17% of the lumber was trimmed to 2.2 or 1.9 m lengths to improve grade yield, and trimming reasons were recorded.

Lumber Bending Strength and Stiffness

Before bending tests, lumber was stored in a conditioning chamber until it reached approximately 15% MC. Immediately before the bending test, average MC was measured for each piece with a moisture meter at a depth of 9 mm in the center of the lumber surface. Lumber was tested edgewise with third-point loading in accordance with ASTM D-4761-02a (ASTM 2003) to determine modulus of elasticity (MOE) and modulus of rupture (MOR). Following the ASTM D-1900-00 (2002) (ASTM 2003), MOE and MOR were normalized to 15% MC. In addition, the MOR values of 76-mm wide lumber were normalized to 102-mm wide lumber using the method described by Barrett and Lau (1994), and the MOE was standardized to the span-to-depth ratio of 21:1 following the procedures described in the NLGA SPS 2-2003 (NLGA 2003). Following the NLGA SPS 2-2003 (NLGA 2003), lumber pieces were further graded for machine stress-rated (MSR) lumber yield.

Once the bending test was completed, the types of failure were recorded for each piece. Two small blocks (about 50 mm longitudinally $\times$ lumber width $\times$ lumber thickness) of clear wood samples were then removed from each piece, one from each side of the failure (as close to the failure as possible), to evaluate: 1) basic wood density; 2) average ring width; and 3) presence or absence of pith.

Statistical Analysis

Tree-level basic wood density was determined using disc area at each height level as the weighting parameter. Tree-level lumber bending properties were calculated as mean values for all lumber pieces from a given tree. At the DBH-class level, we compared trees of the same DBH class from the two thinning intensities and the control for heartwood content, basic wood density, and lumber bending stiffness and strength. Based on the mean value of each property examined for each DBH class, and the merchantable DBH class frequency distribution in each treatment, an overall mean value was determined for each treatment at the stand level. SAS software (SAS Institute Inc 1999) was used in all statistical analyses.

RESULTS AND DISCUSSION

Heartwood Content

No consistent patterns in heartwood content were found between trees of the same DBH class from the different thinning intensities or among DBH classes for a given intensity. Heartwood content was not affected by tree diameter ($r = -0.13$, $p = 0.323$) (Table 1). Because heartwood thickness (radius from pith to the heartwood–sapwood boundary) increases with tree diameter (Gominho and Pereira 2005), it is not surprising that heartwood content (the ratio of heartwood area to disc area) did not show a significant correlation with tree diameter. As expected, heartwood content decreased steadily with increasing height level ($r = -0.79$, $p < 0.0001$) (Table 1; Fig 1).

Wood Density

Basic wood density decreased slightly with increasing tree diameter at all height levels ($r \leq -0.26$, $p < 0.043$) except at the 10 m height ($r = 0.05$, $p = 0.905$). As a result, tree-level

Table 1. *Pearson correlation matrix (r values) for heartwood content and basic wood density in relation to DBH and height position by treatment.*[a]

	T0		T20		T35		Combined	
	DBH (n = 22)	Height level (n = 85)	DBH (n = 20)	Height level (n = 72)	DBH (n = 21)	Height level (n = 78)	DBH (n = 63)	Height level (n = 235)
Heartwood content	−0.05 (0.828)	−0.83 (<0.0001)	−0.36 (0.123)	−0.72 (<0.0001)	−0.05 (0.820)	−0.81 (<0.0001)	−0.13 (0.323)	−0.79 (<0.0001)
Basic wood density	−0.26 (0.235)	0.15 (0.185)	−0.30 (0.199)	0.03 (0.824)	−0.44 (0.048)	−0.11 (0.339)	−0.30 (0.016)	0.05 (0.406)

[a] *P* values of the correlation coefficients are shown in parentheses.
DBH, diameter at breast height.

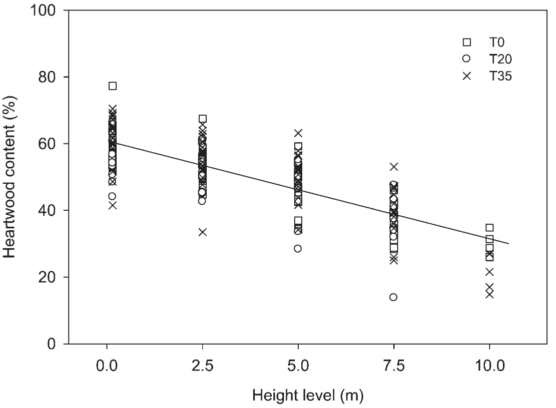

Figure 1. Heartwood content (%) in relation to height level. The solid line is a regression line with $p < 0.0001$ for both the intercept and slope coefficient.

wood density decreased from 419 to 382 kg/m^3 with increasing tree diameter of 12 – 18 cm for all treatments combined (r = –0.30, p = 0.016) (Table 1). Among individual thinning treatments, however, the correlation was significant only for T35. This likely resulted from the large differences (p = 0.047) in wood density between the 10 cm class and the other DBH classes in T0 and T20. When trees of the 10 cm DBH class were excluded, the correlations between wood density and DBH were significant in all treatments (r = –0.45 to –0.66, p = 0.046–0.004). Larger trees usually grow faster and have wider growth rings than smaller trees at a given tree age and thus have lower wood density. On the other hand, there were no consistent differences in wood density among height levels for the same DBH class (p = 0.827) or between wood density and height level for all treatments and DBH classes combined (r = 0.05, p = 0.406) (Table 1).

Previous studies have shown that thinning effects on wood density vary with species. For example, thinning had a negative effect on wood density for radiata pine (Cown 1973), Douglas-fir (Erickson and Harison 1974), jack pine (Barbour et al 1994), and loblolly pine (Smith 1968); a positive effect for slash pine (MacPeak et al 1990); and little effect for balsam fir (Koga et al 2002) and *Pinus brutia* Ten. (Guller 2007). In this study, average wood density at the stand level (ie weighted by the DBH frequency distribution) was 412, 407, and 396 kg/m^3 for T0, T20, and T35, respectively. Although the difference in average stand-level wood density between the control and the two thinning intensities was not significant (p = 0.292), a slight decrease in wood density with increasing thinning intensity was found. This is similar to the results reported by Shepard and Shottafer (1990) that the specific gravity of black spruce from a PCT stand was smaller than that from an unthinned older stand.

Lumber Visual Grade Yield

In eastern Canada, lumber grades SS, No. 1, and No. 2 are usually combined and sold together as No. 2 & Better in the same price category. Nearly 85% of the total sawn lumber volume fell into grades No. 2 & Better, and only 10 and 6% was graded as No. 3 and Economy, respectively. No consistent differences in No. 2 & Better grade–yield between trees of the same DBH class from the two thinning intensities and control were found. The variation in the 10 and 12 cm DBH classes was greater than that in the other DBH classes. Pearson χ^2 tests showed that neither tree diameter nor thinning intensity had a significant effect on lumber visual grade yield. Lumber visual grade yield had a significant negative relationship with log position in T0 (r = –0.30, $p = 0.002$), but not in the thinned stands ($|r| < 0.10$, $p > 0.287$). Branches on lower logs (logs closer to the bottom of the stem) are generally smaller than those from logs higher up (logs closer to the top of the stem). Therefore, higher logs often produce lumber with larger knots, reducing "better grade" yield. Because knots accounted for a smaller percentage of the downgrades to No. 2 (Table 2) in T20 and T35 than in T0, the visual grade yield in relation to log position was weaker in T20 and T35 than in T0.

Of the major defects causing lumber downgrades, wane was responsible for 59.0 – 68.9% of the lumber downgrades to No. 3 and Economy, whereas various stages of wood decay (unsound wood) caused an additional 17.5 – 23.0% of the downgrades (Table 2). In T35, other defects (eg shake and lumber deformation, including twist, crook, and warp) accounted for 18% of the total downgrade compared with 8.1% in T0 and 9.8% in T20. This suggests that the 35% basal area removal treatment (T35) might have altered the growth of residual trees.

Knots did not cause downgrades to No. 3 and Economy regardless of PCT treatment level. The average diameters (less than 2.47 cm) of the five largest branches in all DBH classes from the two thinning treatments and the control were smaller than the allowable knot sizes (25 and 38 mm dia) required by the NLGA (2003) for No. 1 grade 2 × 4 and 2 × 6 lumber.

Of the total downgrades to No. 2 and lower grades, only 1.6% were from knots, whereas 40.2% were from wane (Table 2). Surprisingly, a large proportion (35.4%) of the total downgrades were the result of skip dress, a machining defect resulting from uneven thickness or width in a piece of lumber. Therefore, lumber visual grade yield in this plantation-grown black spruce is dictated to a large extent by wane and skip dress, which are processing rather than resource defects.

Lumber Bending Properties

As shown in Table 3, lumber bending MOE and MOR had a negative correlation with tree diameter (r = –0.32 to –0.35, $p < 0.0001$). For all DBH classes except the 10 cm class, lumber from T35 had a lower MOE than that from T0 and T20, whereas MOR for T35 was consistently lower than that of T0 (Table 3). This suggests that moderate thinning (20% basal

Table 2. *Visual lumber downgrades caused by different defects.*

Defect	T0	T20	T35	Average
	Percentage of lumber downgrades to No. 3 and Economy (%)			
	Thinning intensity			
Knots	0.0	0.0	0.0	0.0
Skip	10.8	0.0	0.0	3.6
Unsound wood	17.5	21.3	23.0	20.7
Wane	63.6	68.9	59.0	63.2
Other	8.1	9.8	18.0	12.5
Total	100.0	100.0	100.0	100.0
	Percentage of total lumber downgrades (to No. 2, No. 3, and Economy) (%)			
Knots	2.7	0.0	1.7	1.6
Skip	36.8	39.2	31.5	35.4
Unsound wood	17.6	10.8	22.9	17.7
Wane	40.9	43.0	37.5	40.2
Other	2.0	7.0	6.3	5.1
Total	100.0	100.0	100.0	100.0

Table 3. *Lumber stiffness (MOE) and strength (MOR) in relation to DBH class in three thinning intensities.*[a]

	MOE (GPa)				MOR (MPa)			
DBH class	T0	T20	T35	Combined	T0	T20	T35	Combined
10	^{A} 9.95 ^{ab}	^{A} 10.86 ^{ab}	^{A} 10.86 ^{ab}	10.56 ^{abc}	^{A} 49.35 ^{ab}	^{A} 46.79 ^{ab}	^{A} 46.85 ^{ab}	47.66 ^{a}
	(0.700)	(0.523)	(0.698)	(0.415)	(3.964)	(3.296)	(4.251)	(2.298)
12	^{A} 11.83 ^{a}	^{AB} 11.18 ^{a}	^{B} 9.68 ^{ab}	11.17 ^{a}	^{A} 52.48 ^{a}	^{A} 49.77 ^{a}	^{B} 40.2 ^{ab}	49.06 ^{a}
	(0.271)	(0.261)	(0.329)	(0.186)	(1.535)	(1.648)	(2.004)	(1.028)
14	^{A} 11.73 ^{a}	^{AB} 11.14 ^{a}	^{B} 10.39 ^{a}	11.09 ^{a}	^{A} 49.76 ^{ab}	^{AB} 46.88 ^{ab}	^{B} 44.96 ^{a}	47.20 ^{a}
	(0.218)	(0.188)	(0.177)	(0.129)	(1.233)	(1.184)	(1.08)	(0.715)
16	^{A} 10.67 ^{ab}	^{A} 10.65 ^{ab}	^{B} 9.82 ^{a}	10.38 ^{b}	^{A} 45.51 ^{ab}	^{AB} 43.81 ^{ab}	^{B} 40.73 ^{ab}	42.87 ^{b}
	(0.294)	(0.209)	(0.174)	(0.145)	(1.665)	(1.318)	(1.063)	(0.801)
18	^{A} 10.90 ^{ab}	^{AB} 9.17 ^{b}	^{B} 8.71 ^{b}	9.59 ^{c}	^{A} 43.77 ^{b}	^{AB} 38.2 ^{b}	^{A} 38.11 ^{b}	39.75 ^{b}
	(0.336)	(0.427)	(0.193)	(0.186)	(1.904)	(2.691)	(1.179)	(1.028)
20	10.41 ^{b}			10.41 ^{abc}	43.94 ^{b}			43.94 ^{ab}
	(0.264)			(0.271)	(1.498)			(1.504)
Pearson	−0.33	−0.32	−0.41	−0.32	−0.41	−0.40	−0.29	−0.35
correlation	(0.001)	(0.003)	(<0.0001)	(<0.0001)	(<0.0001)	(<0.001)	(0.004)	(<0.0001)
Average	^{A} 11.16	^{A} 11.01	^{B} 10.08	10.95	^{A} 50.08	^{AB} 47.27	^{B} 42.95	47.05

[a] *P* values for Pearson correlation coefficients for a given column are shown in brackets. Mean values in a given column followed by the same lower case letter, or in a given row preceded by the same capital letter, are not significantly different at 0.05 using one-way ANOVA followed by Student-Newmann-Keuls multiple comparison test. Standard errors are shown in parentheses.

DBH, diameter at breast height.

area removal) did not have a significant effect on lumber stiffness and strength, but lumber bending strength and stiffness tended to be reduced significantly with increased thinning intensity.

The MOE from T0, T20, and T35 was 10.9, 12.1, and 19.5% lower, respectively, than the average from mature natural stands of black spruce (12.5 GPa) (FPInnovations–Forintek Division's data bank). However, this involves comparing lumber from relatively small and young (44-yr-old) trees with that of 100-yr-old or older trees. MOE values for the initially dense (5674 trees/ha) black spruce plantation in this study were 19.6, 18.0, and 10.8% higher, respectively, for T0, T20, and T35 than overall mean MOE for similarly-aged black spruce stands planted at wider initial spacings (2066 – 3086 trees/ha) (Zhang et al 2002). This suggests that it is possible to produce high-quality products from dense black spruce plantations with appropriate thinning levels. The unthinned 44-yr-old black spruce plantation (T0) in this study also had a 14.5% higher MOE than the 50- to 60-yr-old natural jack pine stands reported by Zhang et al (2006) and Duchesne (2006).

Machine Stress-Rated Lumber Grade Yield

Black spruce has been the primary species for MSR lumber production in eastern Canada. Several contract studies by FPInnovations–Forintek Division as well as a PhD study (Lemieux et al 2002) showed that before visual quality level (VQL) inspection (for qualification for MSR grading), over 80% of the No. 2 and Better grades from natural stands of black spruce qualified for MSR grades of 1650f-1.5E or better. In this study, 74.9% of the No. 2 and Better grades qualified for the same MSR grades. Moreover, of the pieces that did not qualify for MSR grades by VQL inspection, 54.5% fell into MSR grades of 1650f-1.5E or better. When MSR grade 1450f-1.3E was included, the total MSR lumber yield averaged 90.4% (Table 4). This was almost twice as great as the MSR yield (46.7%) from the 48-yr-old black spruce plantations studied by Zhang et al (2002).

Table 4 also lists the observed and required values of the lower 5th percentile MOR for each MSR grade as well as the required value for the same E grade with higher strength requirements. The lower 5th percentile MOR of each MSR grade clearly exceeded both the bending strength required for that MSR grade and for the higher strength class of the same E grade. For example, for the 1.8E grade, the lower 5th percentile MOR (47.0 MPa) was higher than the required strength levels for 2100f-1.8E (30.4 MPa) and for 2400f-1.8E (34.7 MPa).

T0 had a notably higher yield of grades 2400f-2.0E and 2100f-1.8E than T20 and T35 (Table 4). In fact, no lumber from the thinned stands qualified as grade 2400f-2.0E, and very few pieces from T35 qualified as grade 2100f-1.8E. A Pearson χ^2 test showed that thinning intensity had a significant impact on MSR grade yield ($p < 0.0001$), and Pearson correlation analysis ($r = -0.46$, $p < 0.0001$) further indicated that MSR grade yield was negatively correlated to thinning intensity (Table 4).

Overall, 77.4% of the lumber pieces met the required bending property design values (Table 5). It appeared that the percentage of lumber complying with the required bending stiffness design values decreased with increasing thinning intensity for each visual grade ($p < 0.013$) (Table 5). This further confirmed that thinning had a negative impact on lumber bending properties.

Lumber Bending Properties in Relation to Wood Properties

Several studies (Grant et al 1984; Bier 1986; Barrett and Kellogg 1991; Zhou and Smith 1991; Zhang et al 2002) have reported that wood density and juvenile wood content have an effect on lumber stiffness and strength. In this study, lumber bending MOE and MOR increased steadily with increasing wood density for all treatments combined ($r = 0.41$ and 0.54 for MOE and MOR, respectively, $p < 0.0001$) (Fig 2) and for each treatment ($r > 0.34$, $p < 0.001$) except for MOR in T35

Table 4. *MSR grade yield (%) from three thinning intensities and the lower 5th percentile MOE and MOR for each MSR grade.*[a]

MSR grade	Thinning intensity T0	T20	T35	Combined (%)	Average MOE (GPa)	The 5th percentile MOE (GPa) Observed	Required	The 5th percentile MOR (MPa) Observed	Required	The 5th percentile for higher strength class MSR grade	MOR (MPa)
2400f-2.0E	2.9	0.0	0.0	1.0	14.1	13.7	11.3	62.1	34.7	—	—
2100f-1.8E	21.9	9.8	1.0	11.1	12.7	12.0	10.2	47.0	30.4	2400f-1.8E	34.7
1650f-1.5E	61.0	82.9	41.0	60.3	10.8	9.6	8.5	35.8	23.9	1800f-1.5E	30.4
1450f-1.3E	11.4	0.0	39.0	17.8	9.3	8.8	7.4	32.8	21.0	1650f-1.3E	23.9
Total	97.1	92.7	81.0	90.4							
Pearson χ^2	95.32 (<0.0001)										
Pearson correlation	−0.46 (<0.0001)										

[a] Values shown in parentheses are p values for Pearson χ^2 and Pearson correlation coefficient.
MSR, machine stress-rated; MOE, modulus of elasticity; MOR, modulus of rupture.

Table 5. *Percentage of lumber pieces from each visual grade that comply with the current requirements for bending stiffness design values established for S-P-F species for three thinning intensities.*[a]

Visual grade	Average MOE (GPa)	Design value for S-P-F species[b] Mean MOE (GPa)	Percentage of lumber pieces which meet the bending stiffness design values (%) Thinning intensity T0	T20	T35	Combined	Pearson χ^2 test
No. 1	10.5	9.5	87.5	82.2	56.6	75.9	16.49 (<0.001)
No. 2	10.8	9.5	93.3	89.3	60.0	79.6	13.37 (0.001)
No. 3	10.2	8.8	100.0	100.0	42.9	78.9	8.69 (0.013)
Average			90.1	85.9	56.8	77.4	

[a] Values shown in parentheses are p values of Pearson χ^2 tests for each visual grade.
[b] Design values are based on Barrett and Lau (1994).
MOE, modulus of elasticity.

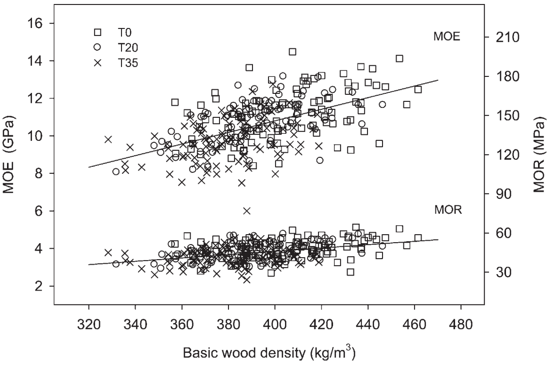

Figure 2. Lumber bending stiffness (MOE) and strength (MOR) in relation to basic wood density and precommercial thinning (PCT) intensity. The solid lines are regression lines for all PCT levels combined ($p < 0.0001$ for both intercepts and slopes).

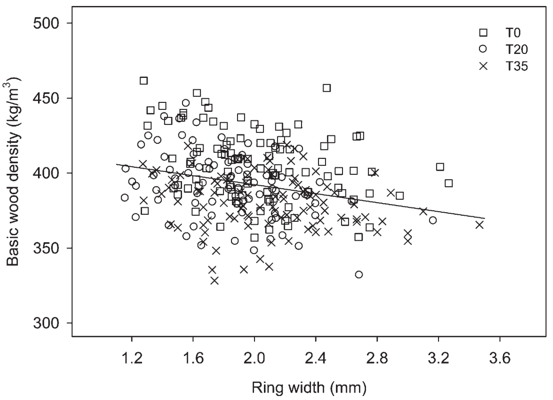

Figure 3. Basic wood density in relation to annual ring width. The solid line is a regression line for all precommercial thinning levels combined ($p < 0.0001$ for both intercept and slope).

(r = 0.11, $p = 0.255$). In addition, lumber bending MOE and MOR from T35 were significantly lower than those from T0 and T20 ($p < 0.05$) for lumber of the same wood density.

Figure 3 shows that wood density tended to decrease with increasing ring width (r = –0.27, $p < 0.0001$). This is consistent with the negative relationship between ring width and wood density reported for many softwood species. As lumber bending stiffness and strength increased with increasing wood density (Fig 2), and wood density decreased with increasing ring width (Fig 3), MOE and MOR tended to decrease with increasing ring width (r = –0.39, $p < 0.0001$).

Economy grade had a lower MOE (9.7 GPa) than the other grades ($p = 0.031$). However, wood density was not significantly different among the visual grades ($p = 0.185$). This may be explained by the causes of downgrades. Wane alone was responsible for 63.2% of the downgrades to No. 3 and Economy (Table 2), and it is well documented that lumber strength properties are affected by the reductions in effective cross-section resulting from defects such as knots and wane. Therefore, the low Economy grade MOE more likely reflected the reduced cross-section than differences in wood density.

In this study, we used the presence of pith in a piece of lumber to serve as an indicator of juvenile wood content. Lumber pieces without pith had significantly higher MOE and MOR than those with pith in all three treatments ($p < 0.0001$). This suggests that juvenile wood content had a significant effect on lumber stiffness and strength. Many studies (Barrett and Kellogg 1991; Zhou and Smith 1991; Evans et al 2000) have reported a decrease in lumber stiffness and strength with increasing juvenile wood content. It is well documented that juvenile wood is intrinsically different from mature wood in anatomical structure and ultrastructure, and some studies (Zhang and Zhong 1992; Cave and Walker 1994; Kennedy 1995; Koponen 1997) have found that the S2 microfibril angle of the fiber cell wall is more closely correlated with wood strength and stiffness than with wood density. Therefore, the inferior wood strength and stiffness in the lumber with pith could be explained by the inferior anatomical structure and ultrastructure (eg shorter fibers and larger microfibril angles).

Lumber Bending Properties in Relation to Log Position

Log position (height level) was not significantly correlated with lumber MOE when all log positions were considered (r = –0.11, $p = 0.073$). However, when butt logs (0 – 2.5 m) were excluded, MOE decreased steadily with increasing log height level (r = –0.27, $p < 0.001$). The fact that butt logs did not follow this trend likely reflects the presence of various stages of both unsound and compression wood. Of the total lumber pieces from butt logs, 14.6% contained unsound wood, whereas only 1.5% from other logs did. MOR also decreased steadily from butt to top log (r = –0.31, $p < 0.0001$). Larson et al (2004) reported similar results in a small-roundwood bending study in which log position affected roundwood failure mode, strength, and stiffness. The decrease in lumber bending stiffness and strength with increasing log position (height level) likely resulted from larger and more frequently occurring knots and an increased proportion of juvenile wood at higher log positions from the same tree.

CONCLUSIONS

Based on this study of 21-yr PCT effects on an initially dense 44-yr-old black spruce plantation, the following conclusions could be drawn:

1. Heartwood content and the yield of No. 2 and Better lumber grades were not significantly affected by PCT treatment and tree diameter. Heartwood content decreased steadily with increasing height of log position. Basic wood density and lumber bending stiffness and strength decreased by 8.8, 15.8, and 19.0%, respectively, as tree diameter class increased from 12 to 18 cm.
2. Average wood density, lumber bending properties, and MSR lumber yield from T35 were lower than those from T0 and T20. In contrast, a moderate thinning intensity of 20% basal area removal had much less effect on those properties.
3. Ring width had a negative relationship with wood density and lumber bending stiffness and strength. Juvenile wood content, as indicated by the presence of pith and log position, also had a negative impact on lumber bending stiffness and strength.
4. Lumber bending MOE from the 44-yr-old plantation-grown black spruce was 10.9, 12.1, and 19.5% lower for T0, T20, and T35, respectively, than that from older natural black spruce stands currently being processed in eastern Canada. However, it was 19.6, 18.0, and 10.8% higher for T0, T20, and T35, respectively, than that from similarly-aged wider-spaced black spruce plantations. MOE from T0 was also 14.5% higher than that from 50 – 60-yr-old natural jack pine stands. Therefore, it is possible to produce high-quality lumber from dense black spruce plantations with appropriate thinning.

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