IMPACT OF COMMERCIAL THINNING ON ANNUAL RADIAL GROWTH AND WOOD DENSITY IN PLANTATION-GROWN BLACK SPRUCE

*Queju Tong**

Postdoctoral Researcher

Francis Tanguay

Technologist
FPInnovations
Québec City, QC, Canada G1P 4R4

S.Y. Zhang†

Senior Scientist
FPInnovations
Vancouver, BC, Canada V6T 1W5

(Received January 2011)

Abstract. This study examined ring width and density of plantation-grown black spruce 6 yr after commercial thinning (CT). Sample trees were from a 49-yr-old plantation receiving CT at age 43 yr near Kapuskasing, Ontario, Canada. There was a significant and positive effect on annual radial growth for heavy thinning (one of three rows removed) but not for light thinning (one of four rows removed). CT had little effect on wood density. Increased radial growth caused by thinning was mainly from an increase in earlywood width. Latewood proportion was not affected by thinning. With increasing tree diameter from 100-220 mm, ring width increased 0.93-2.19 mm, whereas ring density decreased slightly 523-487 kg/m^3. Ring width decreased from 1.31 mm at stump height to 1.13 mm at 2.5-m height and then increased to 1.62 mm at 7.5-m height. From stump height to 7.5 m, ring density decreased steadily from 525-491 kg/m^3. The effect of thinning depended on tree diameter and height position. This study suggests CT in black spruce accelerated radial growth but had little effect on wood density. Appropriate thinning intensity may target radial growth increase to trees of certain diameters.

Keywords: Commercial thinning, black spruce, plantation, annual growth, wood density.

INTRODUCTION

Black spruce (*Picea mariana* [Mill.] B.S.P.) is one of the most important commercial and reforestation species in eastern Canada. Because sizable sawlogs are becoming scarce, stand density management has become common practice to stimulate tree growth and shorten rotation age for some species growing in eastern Canada. Although thinning black spruce is not yet recommended practice in some provinces (OMNR 1997) because of lack of information (McKinnon et al 2005), it is receiving increasing attention and has become an increasingly important practice. For example, commercial thinning (CT) has become a regular silvicultural practice for J.D. Irving, Ltd., and several entries have been applied to its black spruce plantations to produce large-size and high-value sawlogs (Pelletier 2001). It is commonly accepted that thinning in general leads to an increase in tree growth, crown size, and branch diameter and thus a decrease in wood and stem quality. Consequently, concerns have arisen about negative effects of thinning on wood and lumber quality.

The effect of precommercial thinning on tree growth, mortality, and stand yield has been intensively studied for many species including jack pine (Tong and Zhang 2005; Tong et al 2005; Zhang et al 2006), loblolly pine (Moschler

* Corresponding author: Tessie.Tong@fpinnovations.ca
† SWST member

et al 1989; Tasissa and Burkhart 1997), balsam fir (Lavigne and Donnelly 1989; Zhang et al 1998), Norway spruce (Jaakkola et al 2005), Douglas-fir (Megraw and Nearn 1972), and black spruce (Shepard and Shottafer 1990; Hillman and Takyi 1998; Pelletier 2001; Fleming et al 2005; Tremblay 2005; Tong et al 2009). These studies confirmed the positive impact of thinning on tree radial growth. According to Schneider (2007), a jack pine tree of 150-mm diameter at breast height (DBH) will have a 33% increase in annual ring width following a moderate thinning and a 65% increase following a heavy thinning. A recent study in jack pine (Duchesne and Swift 2008) showed a 37% increase in DBH 31 yr after a heavy thinning. CT increases growth in large trees more than in small trees (Mayor and Rodà 1993) and leads to a radial growth increment on the lower part of the stem (Vincent et al 2009). Growth response diminishes 9-12 yr after CT in holm oak (Mayor and Rodà 1993), whereas in balsam fir, the effect of thinning on ring width lasts for 5 yr (Koga et al 2002) to 12 yr (Tasissa and Burkhart 1997). Barbour et al (1994) reported that the effect of thinning in jack pine lasts longer on density decrease than on ring width increase.

Neither earlywood density nor latewood density is affected by thinning in balsam fir (Koga et al 2002) and Norway spruce (Jaakkola et al 2005). However, thinning shows different effects on ring density for different species and thinning intensities. Ring density decreased following moderate thinning in balsam fir (Koga et al 2002) and increased by 5% following light thinning but not following heavy thinning in Scots pine (Peltola et al 2007). With respect to black spruce, most studies focus on the effect of precommercial thinning and spacing (Burns et al 1996; Northwest Science & Technology 1998). To the authors' knowledge, only a few studies (Hillman and Takyi 1998; Pelletier 2001; Tremblay 2005; Lussier 2007; Vincent et al 2009) on CT in black spruce have been conducted. This is partly because thinning in black spruce is not yet a recommended practice in some provinces in Canada. In addition, specifications for black spruce CT have not been available in Ontario until recently (Kayahara et al 2007). These studies focused on growth response and mortality following CT. Information on the effect of CT on annual ring growth and density is still lacking.

Based on CT trials of the (Ontario) Provincial Growth Plot Network, this study intends to evaluate early response of wood properties and lumber quality to CT in black spruce plantations. Specifically, this study examined the effect of CT on earlywood width, latewood width, ring width, latewood proportion, earlywood density, latewood density, and ring density. A better understanding of the impact of CT along the wood value chain will help define the optimal thinning strategy to produce quality wood and wood products while maximizing economic value.

MATERIALS AND METHODS

Sampling Plots Selection

This study is based on permanent black spruce CT trials established in 2000 in Owens Township (Site 1, 49°25′14″ N, 82°38′52″ W) and Eilber/Devitt Township (Site 2, 49°36′20″ N, 83°16′47″ W) near Kapuskasing, Ontario, Canada. Both sites were classified as ES6f for ecosystem type and V4 for vegetation type. Soil type in Site 1 was categorized as S15 and that in Site 2 as S13. Managed by the Forest Cooperative out of Thunder Bay, Ontario, these trials were planted in 1958 with 2 + 2 bare-root black spruce seedlings at about 1.8 × 3.6-m spacing. These trials are part of the Provincial Growth Plot Network that extends across Ontario and some parts of Northern Quebec. In 2000, when the stands were 42 yr old, a number of permanent plots were established on these sites. At establishment, merchantable stand density was 2300 (C1) and 2100 trees/ha (C2) with average tree height of 12.8 and 12.5 m in Sites 1 and 2, respectively. In 2001, CT was carried out in both sites. Stands of about 2.5 ha with one row removed from every three rows in Site 1 (T1) and one row removed from every four rows in Site 2 (T2) were selected for this study. Thinned

Table 1. Description statistics for sample trees and disks used in this study.

		Site 1		Site 2	
		Control (C1)	Thinned (T1)	Control (C2)	Thinned (T2)
	Number of trees	20	20	25	30
DBH (cm)	Average	12.9	13.5	12.0	13.5
	Maximum	16.5	16.4	13.6	16.2
	Minimum	10.8	10.9	9.8	11.1
	Standard deviation	1.6	1.4	1.2	1.4
Total height (m)	Average	14.5	17.5	14.0	16.9
	Maximum	20.5	21.7	18.8	22.8
	Minimum	10.6	12.5	9.1	11.6
	Standard deviation	3.4	3.3	2.9	3.5
Number of disks	Total	84	87	92	126
	Average per tree	4.2	4.4	3.7	4.2
	Maximum per tree	5	6	4	5
	Minimum per tree	3	3	3	3
	Standard deviation	0.62	0.75	0.48	0.66
Disk diameter (cm)	Average	12.0	14.4	11.7	13.8
	Maximum	15.7	18.1	14.8	18.8
	Minimum	8.9	10.8	7.7	9.5
	Standard deviation	2.3	2.3	2.2	2.7

DBH, diameter at breast height.

stands (Tx) were adjacent to corresponding control stands (Cx). To avoid destructive sampling in permanent plots, three temporary circular plots of 400 m^2 (11.28 m in radius) were established next to the permanent plots in each stand. In the temporary plots, each tree was measured for DBH to obtain DBH class distribution. The temporary plots had a similar DBH class distribution to the corresponding permanent plots with the average stand density ranging 1700-2000 trees/ha for the controls (C1 and C2), 1100 to 1200 trees/ha for T1, and 1300 to 1400 trees/ha for T2. The temporary plots were considered representative of the permanent plots. Sample trees were collected from the temporary plots in Fall 2007.

Selection and Measurements of Sample Trees

Whenever possible, one to two trees in each merchantable DBH class (eg 10, 12, 14, etc) were randomly selected from each temporary plot, totaling five trees per DBH class per stand. In total, 30 trees each were cut from C1, T1, and T2, respectively, to cover six DBH classes (100-200 mm for C1 and 120-220 mm for T1 and T2) and 25 trees from C2 to cover five DBH classes

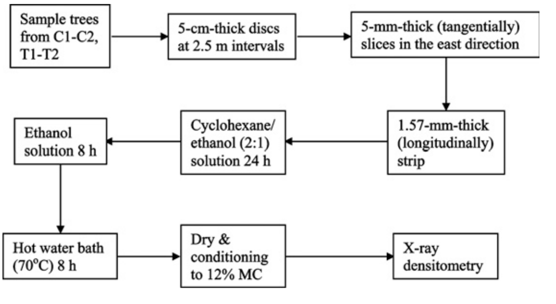

Figure 1. Schematic of X-ray densitometry sample preparation.

(100-180 mm). The full-length stems were transported to FPInnovations facility in Québec City for further analysis. Two trees from each DBH class from both C1 and T1 were randomly selected and set aside for log quality analysis. Log quality will be reported in a separate article. A summary description of sample trees is presented in Table 1. X-ray densitometry sample preparation is schematized in Fig 1.

Evaluation of Wood Properties

Fifty-mm-thick disks were cut at the butt of each stem and at 2.5-m intervals along the stem, totaling 389 disks (Table 1). From each disk, a 5-mm-thick (tangentially) piece was sliced along the grain from bark to pith in the east direction (or as close to east as possible). The piece was then trimmed into a 1.57-mm-thick (longitudinally) strip with a specially designed pneumatic-carriage twin-blade circular saw (Jozsa and Myronuk 1986). The trimmed strips were extracted with cyclohexane/ethanol (2:1) solution for 24 h, followed by ethanol solution for 8 h, and then with a hot water bath (75°C) for another 8 h to remove extraneous compounds. Then the strips were air-dried to 12% MC under restraint to prevent warping in a conditioning chamber. With a direct reading X-ray densitometer (DRXRD Mark II), the air-dried strips were scanned to estimate basic wood density (ovendry weight/green volume) for each ring from pith to bark. Based on intraring microdensitometric profile, density and width were determined for each ring (Jozsa et al 1987). Intraring wood density variation (IDV) was estimated using Eq 1, a transformation of the equation by Vargas-Hernandez and Adams (1991), assuming that within-ring variation is primarily caused by average differences in earlywood density (ED) and latewood density (LD):

$$IDV = (LD - ED)\sqrt{\frac{1}{4} - \left(LP - \frac{1}{2}\right)^2} \qquad (1)$$

where LP is latewood proportion in a ring.

Statistical Analysis

The last ring (formed in 2007) was excluded because of incompleteness. The experimental design lent itself to a two-factor (treatment and DBH class) factorial experiment with a split-plot factor (height position). Analysis of covariance (ANCOVA) was performed to detect effect of thinning treatment, DBH class, and height position on ring characteristics. The average of 31 rings formed between 1970 and 2000 (excluding the first five rings near the pith because they were often too narrow or too irregular for the densitometer to take proper readings) served as a covariate to account for the pre-existing difference before thinning. Latewood proportion was root-squared and then arcsine-transformed before analysis.

Because of the unbalanced nature of the experimental design, ie different coverage of DBH classes in different treatments and different number of disks from trees of different total heights, ANCOVA was performed in two steps. First, we eliminated the 100-, 200-, and 220-mm DBH classes and 10.0-m height position to obtain relatively balanced data. Second, we ran ANCOVA for each treatment separately to account for those DBH classes and height positions that were not included in the first step.

Six individual rings formed after thinning (2001-2006) as well as the average of these six rings were examined at the 0.05 significance level. Bonferroni's multiple comparison was used to locate the source of difference in each independent variable, and level of significance was adjusted for the number of comparisons. Comparisons of treatments were made between the two controls (for site difference) and between Cx and Tx in each site (for thinning effect). Treatment effects in annual growth and density were displayed graphically when interactions were significant. SAS software (SAS 1999) was used for all statistic analyses.

RESULTS AND DISCUSSION

Variations of Ring Width with Year

Figure 2 shows variations of ring width and its components at 2.5-m height with years. Prior to thinning, earlywood width and ring width were significantly larger ($p < 0.05$) in T1 than in C1 for individual rings formed during 1981-2000 and larger in T2 than in C2 for those formed during 1974-2000. Extreme differences between Tx and Cx occurred during 1977-1988 with a larger difference for Site 2 than for Site 1. Analysis of variance results suggest that average annual growth before thinning was also significantly greater ($p < 0.001$) in Tx than in Cx for both sites, except earlywood width in T1 ($p = 0.089$)

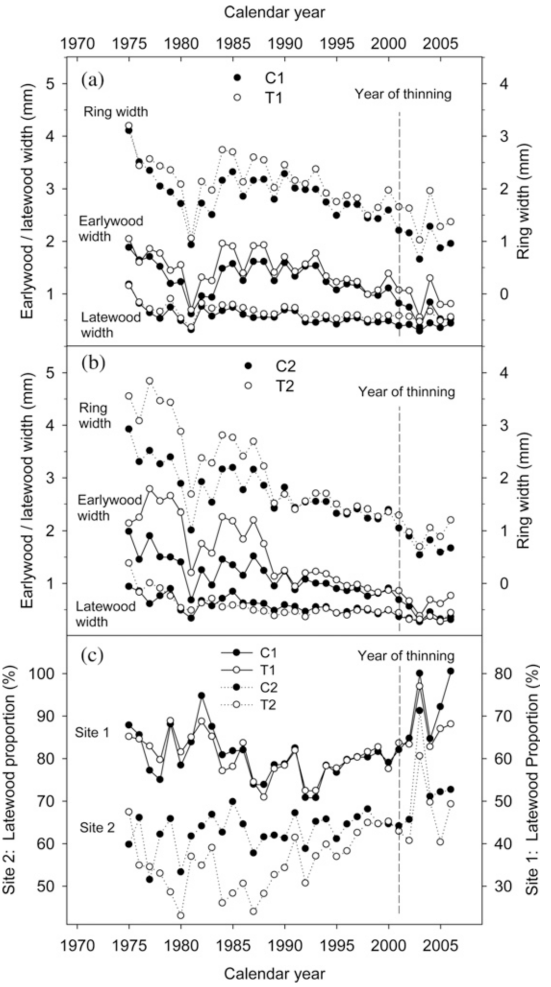

Figure 2. Variation of ring width and its components at 2.5-m stem height in relation to calendar year: (a) Site 1; (b) Site 2; and (c) variation of latewood proportion.

(Table 2). Differences in radial growth between Tx and Cx might have resulted from differences in growing conditions between two adjacent areas where Tx and Cx were located. These differences were accounted for with ANCOVA.

With increasing age, annual radial growth in black spruce tended to slow down despite some variations (Fig 2a-b). This agrees with observations for balsam fir (Koga et al 2002). The rapid slow-down of growth since 1975 and the extremely slow growth in the early 1980s (Figs 2 and 3) reflect the effect of spruce budworm outbreak with onset in the mid-1970s (LaChance et al 1991). Latewood width appeared to have less variation throughout the growth years, averaging 0.57 mm, compared with earlywood width and ring width. Annual radial growth slowed down rapidly during the first 2 yr after thinning, especially in year 2003 (Figs 2 and 3). This might result from thinning shock, an immediate negative physiological response to thinning treatment (Harrington and Reukema 1983). However, thinning shock in this plantation was not evident, or this plantation did not respond to thinning, either negatively or positively, during the first 3 yr after thinning, because growth in the control stands slowed down at a similar rate. The low growth rate postthinning was more likely caused by the drought that occurred during the growing seasons of 2002, 2003, 2005, and 2006. Ring width depends mainly on rate of periclinical cell division and the enlargement phase in the cambial region, which occurs in spring and early summer (Larson 1994) and is controlled mainly by precipitation (Wimmer and Grabner 1997). According to the historic data available in the National Climate Data and Information Archive (www.climate.weatheroffice.ec.gc.ca), total precipitation from December to August in the study area (Station Kapuskasing CDA, Ontario, Canada) was 421, 428, 332, and 424 mm in 2002, 2003, 2005, and 2006, respectively, which was 25-42% lower than the normal of 572 mm (1960-2000). This does not agree with Simonin et al (2006) that heavy thinning can produce thinning shock during extreme drought in ponderosa pine.

Effect of Thinning and Diameter at Breast Height Class on Annual Growth

As shown in Tables 3 and 4, thinning led to a significant increase in average earlywood width and ring width in T1 but not in T2. Latewood width was not affected by thinning in either site. As a result, latewood proportion was higher ($p = 0.034$) (Table 4) in C1 (43.1%) than in T1 (34.2%) (Table 3); however, there was no difference between C2 and T2. Individually, all six rings formed after thinning (2001-2006) had significantly wider earlywood width and ring width

Table 2. Ring width and its components and ring density and its components, before and after thinning, in each stand.

	Before/after thinning	Site 1			Site 2		
		Control (C1)	Thinned (T1)	*p* value[d]	Control (C2)	Thinned (T2)	*p* value
Earlywood width (mm)	Before[a]	1.40 (0.46)[c]	1.65 (0.45)	0.089	1.26 (0.33)	1.74 (0.41)	< 0.0001
	After[b]	0.82 (0.31)	1.30 (0.28)	< 0.0001	0.55 (0.17)	0.98 (0.44)	< 0.0001
Latewood width (mm)	Before	0.65 (0.16)	0.73 (0.14)	0.122	0.72 (0.15)	0.69 (0.15)	0.020
	After	0.50 (0.13)	0.60 (0.13)	0.440	0.39 (0.07)	0.46 (0.14)	0.023
Ring width (mm)	Before	2.06 (0.49)	2.38 (0.51)	0.045	2.03 (0.41)	2.45 (0.47)	< 0.0001
	After	1.33 (0.34)	1.90 (0.35)	0.001	0.94 (0.19)	1.44 (0.55)	< 0.0001
Latewood proportion (%)	Before	33.5 (9.4)	32.2 (7.3)	0.661	37.6 (9.1)	30.0 (7.6)	0.007
	After	42.2 (12.9)	33.0 (6.3)	0.001	45.3 (11.9)	36.3 (10.9)	0.005
Earlywood density (kg/m^3)	Before	411.5 (23.4)	413.7 (18.6)	0.748	420.2 (16.7)	406.1 (17.8)	0.661
	After	418.4 (20.6)	421.1 (18.6)	0.004	430.4 (21.2)	413.4 (22.7)	0.007
Latewood density (kg/m^3)	Before	640.5 (26.3)	641.8 (18.4)	0.849	639.9 (19.5)	626.6 (19.6)	0.073
	After	644.4 (20.2)	656.9 (22.6)	0.016	611.2 (45.7)	626.5 (44.2)	0.218
Ring density (kg/m^3)	Before	488.8 (38.5)	487.6 (27.7)	0.912	506.8 (30.2)	474.3 (25.8)	0.098
	After	515.1 (39.9)	497.4 (24.3)	< 0.0001	520.1 (29.5)	495.0 (33.7)	0.006

[a] Average of 31 rings (1970-2000) before thinning, eliminating first five rings close to pith.
[b] Average of six rings (2001-2006) after thinning.
[c] Standard deviation.
[d] Significance level of difference in mean of each variable between control stands and thinned stands in each site.

Figure 3. Two X-ray densitometry strips from C2 and T2, respectively, showing narrow rings formed in 1981 and 2003.

in T1 than in C1, whereas only rings formed in 2001, 2005, and 2006 were wider in T2 than in C2. Again, thinning had little effect on latewood width of individual rings.

No statistical differences in earlywood or latewood width were found among DBH classes 120-180 mm ($p > 0.1$) for either the average of the six rings or individual rings. Despite a small p value (0.035) for DBH class effect (Table 4), post hoc tests could not find significant differences in ring width among DBH classes. However, ring width showed a clear trend of increase from 0.93-2.19 mm with DBH from 100-220 mm ($R^2 = 0.52$) (Fig 4).

Increase in ring width caused by thinning was mainly from increase in earlywood width, leading to a decreased latewood proportion in thinned plots (Fig 2c). No significant difference in latewood proportion, however, was observed in either site ($p > 0.1$). This agrees with earlier reports by Koga et al (1996) in Karamatsu, Moschler et al (1989) in loblolly pine, and Guller (2007) in Turkish red pine, which all showed that radial growth increased but latewood proportion

Table 3. Least squares means for ring width and its components and ring density and its components after thinning (2001-2006).

	Thinning treatment				DBH class (cm)				Height position (m)			
	C1	T1	C2	T2	12	14	16	18	0.0	2.5	5.0	7.5
Earlywood width (mm)	0.77 (0.05)[a]	1.21 (0.05)	0.63 (0.04)	0.77 (0.04)	0.79 (0.05)	0.77 (0.05)	0.86 (0.04)	0.97 (0.05)	0.78 (0.03)	0.72 (0.03)	0.8 (0.02)	1.09 (0.04)
Latewood width (mm)	0.51 (0.02)	0.58 (0.02)	0.4 (0.02)	0.42 (0.02)	0.48 (0.02)	0.47 (0.02)	0.47 (0.02)	0.49 (0.02)	0.54 (0.01)	0.44 (0.01)	0.43 (0.01)	0.49 (0.02)
Ring width (mm)	1.29 (0.05)	1.8 (0.06)	1.02 (0.04)	1.19 (0.04)	1.25 (0.06)	1.23 (0.05)	1.33 (0.05)	1.48 (0.06)	1.31 (0.03)	1.13 (0.03)	1.23 (0.03)	1.62 (0.05)
Latewood proportion (%)	43.1 (0.05)	34.2 (0.06)	41.8 (0.03)	40.1 (0.04)	43.8 (0.05)	39.3 (0.04)	38.6 (0.04)	37.4 (0.04)	46.5 (0.02)	41.1 (0.02)	38.7 (0.02)	32.9 (0.03)
Earlywood density (kg/m^3)	426.4 (5.0)	421.8 (5.4)	428.2 (4.6)	414.1 (4.6)	422.0 (5.2)	425.0 (4.8)	424.2 (4.5)	419.4 (4.7)	423.4 (4.4)	422.7 (4.2)	419.8 (4.2)	424.7 (5.3)
Latewood density (kg/m^3)	628.7 (9.4)	646.9 (9.7)	610.5 (6.8)	630.4 (8.1)	628.4 (8.7)	614.3 (7.6)	636.3 (7.6)	637.5 (7.8)	636.4 (6.5)	622.2 (5.3)	629.4 (5.5)	628.6 (6.5)
Ring density (kg/m^3)	520.7 (4.8)	499.3 (5.1)	508.4 (4.1)	507.3 (4.6)	519.5 (4.9)	506.3 (4.7)	507.5 (4.2)	502.4 (4.6)	525.5 (2.4)	514.7 (2.4)	504.6 (2.3)	491.0 (2.8)
Intraring density variation (kg/m^3)	87.9 (3.0)	102.1 (3.2)	82.5 (2.4)	93 (2.4)	86.8 (2.9)	87.7 (2.5)	93.7 (2.5)	97.4 (2.6)	89.6 (2.3)	88.8 (2.2)	90.8 (2.1)	96.4 (2.4)

[a] Standard error.
DBH, diameter at breast height.

Table 4. Analysis of covariance tables for ring width and its components and ring density and its components for average of six rings formed during 2001-2006.

	Degree of freedom	Sum of squares	F value	*p* value	Post hoc	Sum of squares	F value	*p* value	Post hoc
		Earlywood width				Latewood width			
T	3	7.85	25.3	< **0.0001**	**T1 > C1**	1.07	15.9	< **0.0001**	**C1 > C2**
D	3	0.68	2.19	0.101		0.02	0.35	0.787	
T × D	9	1.97	2.12	0.046		0.17	0.83	0.591	
Tree (T × D)	48	4.97				1.08			
H	3	1.52	18.0	< **0.0001**	**0.0–5.0 < 7.5**	0.48	18.7	< **0.0001**	**0.0 > 2.5, 5.0; 5.0 < 7.5**
T × H	9	1.09	4.33	< 0.0001		0.23	3.01	0.003	
D × H	9	0.25	0.99	0.453		0.04	0.47	0.893	
T × D × H	27	0.94	1.24	0.215		0.31	1.35	0.135	
Error	134	3.76				1.14			
		Earlywood density				Latewood density			
T	3	0.005	1.5	0.227		0.036	3.51	0.022	
D	3	0.001	0.24	0.871		0.020	1.96	0.133	
T × D	9	0.010	0.89	0.538		0.056	1.83	0.086	
Tree (T × D)	48	0.057				0.163			
H	3	0.001	0.21	0.887		0.004	0.91	0.440	
T × H	9	0.005	0.57	0.821		0.019	1.37	0.206	
D × H	9	0.002	0.25	0.986		0.017	1.18	0.311	
T × D × H	27	0.024	0.85	0.683		0.050	1.18	0.261	
Error	134	0.142				0.209			
		Ring width				Latewood proportion			
T	3	14.41	35.9	< **0.0001**	**C1 > C2; T1 > C1**	0.21	3.12	**0.034**	**C1 > T1**
D	3	1.25	3.11	0.035		0.12	1.77	0.165	
T × D	9	2.54	2.11	0.047		0.20	0.99	0.461	
Tree (T × D)	48	6.42				1.09			
H	3	2.83	24.6	< **0.0001**	**0 > 2.5; 0.0–5.0 < 7.5**	0.46	13.6	< **0.0001**	**0.0 > 5.0, 7.5; 2.5 > 7. 5**
T × H	9	1.23	3.57	0.001		0.23	2.22	0.025	
D × H	9	0.36	1.04	0.416		0.05	0.49	0.882	
T × D × H	27	1.75	1.69	0.028		0.12	0.4	0.997	
Error	134	5.14				1.52			
		Ring density				Intraring density variation			
T	3	0.010	3.19	**0.032**	**C1 > T1**	10038.6	9.18	< **0.0001**	**C1 < T1; C2 < T2**
D	3	0.008	2.52	0.069		4132.3	3.78	0.016	
T × D	9	0.013	1.34	0.241		6734.7	2.05	0.053	
Tree (T × D)	48	0.052				17495.9			
H	3	0.033	33.37	<**.0001**	**0 > 2.5 > 5.0 > 7.5**	1665.4	2.28	0.082	
T × H	9	0.015	4.96	<.0001		4538.8	2.07	0.036	
D × H	9	0.002	0.69	0.718		1779.4	0.81	0.605	
T × D × H	27	0.005	0.61	0.935		7579.5	1.15	0.291	
Error	134	0.044				32602.3			

T, thinning treatment; D, diameter at breast height class (12-18 cm); H, height position (0.0-7.5 m). In absence of interaction effects, significant differences are shown in bold for p value < 0.05.

was not affected significantly by thinning treatment. However, this is inconsistent with results reported by Koga et al (2002) that moderate thinning had a negative impact on latewood proportion in balsam fir.

Different thinning effects in two sites were probably caused by a difference in thinning intensity. Thinning intensity was heavier in T1 (one of three rows removed) than in T2 (one of four rows removed), and this led to more accelerated growth in T1. Generally, heavier thinning is more effective on annual growth (Guller 2007), mainly because of the increased amount of carbohydrate produced by a tree from increased growing space for roots and crowns of residual trees (Smith et al 1996). In addition, difference in soil condition/quality between two sites, which explains the difference in annual growth between C1 and C2 (Table 4), might also contribute to differences in thinning effect.

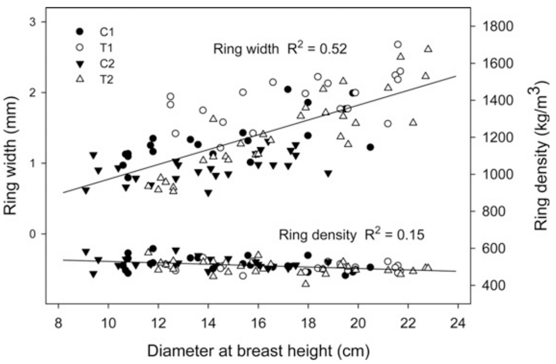

Figure 4. Ring width and ring density in relation to tree diameter and thinning. Solid lines are regression lines with $p < 0.02$ for intercepts and slopes.

Variations of Wood Density with Year

Despite the year-to-year variations, ring density and its components at the 2.5-m height did not appear to have a clear trend with cambium age in both sites (Fig 5). No consistent and appreciable differences in ring density from pith to bark were observed between C1 and T1, whereas C2 appeared to have a consistently higher density than did T2 for rings formed before 1999. Since 1999, the difference in ring density and earlywood density became smaller between C2 and T2. This pattern of variation partly reflects the pattern of variation in ring width and its components at the same height level as shown in Fig 2. Statistically, however, differences in earlywood density, latewood density, and ring density prior to thinning were not statistically significant at 0.05 between Cx and Tx (Table 2).

Effect of Thinning and Diameter at Breast Height Class on Wood Density

Thinning had little effect on earlywood density ($p = 0.227$) (Table 4). Despite a low probability

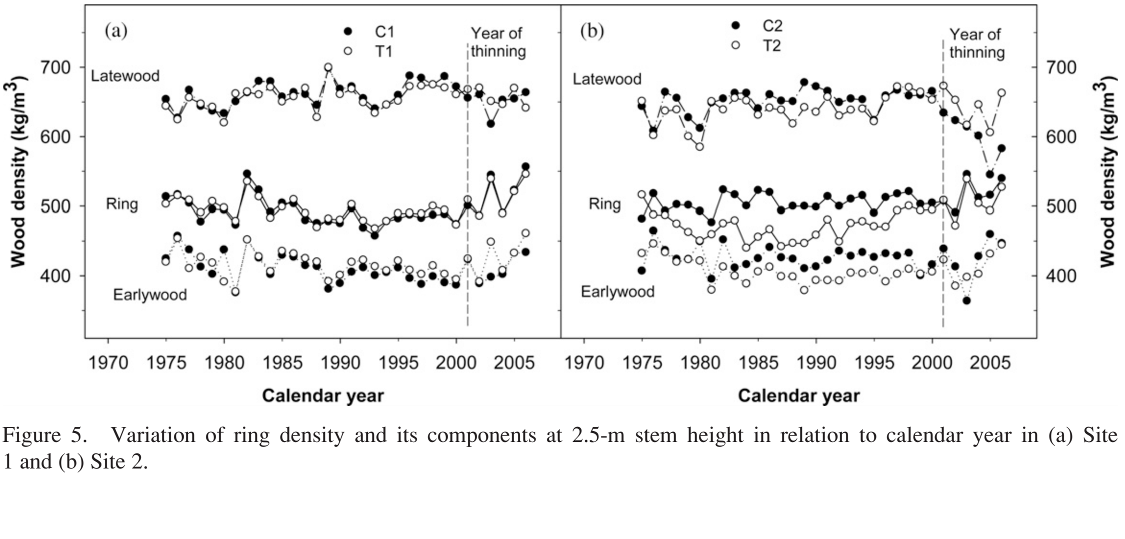

Figure 5. Variation of ring density and its components at 2.5-m stem height in relation to calendar year in (a) Site 1 and (b) Site 2.

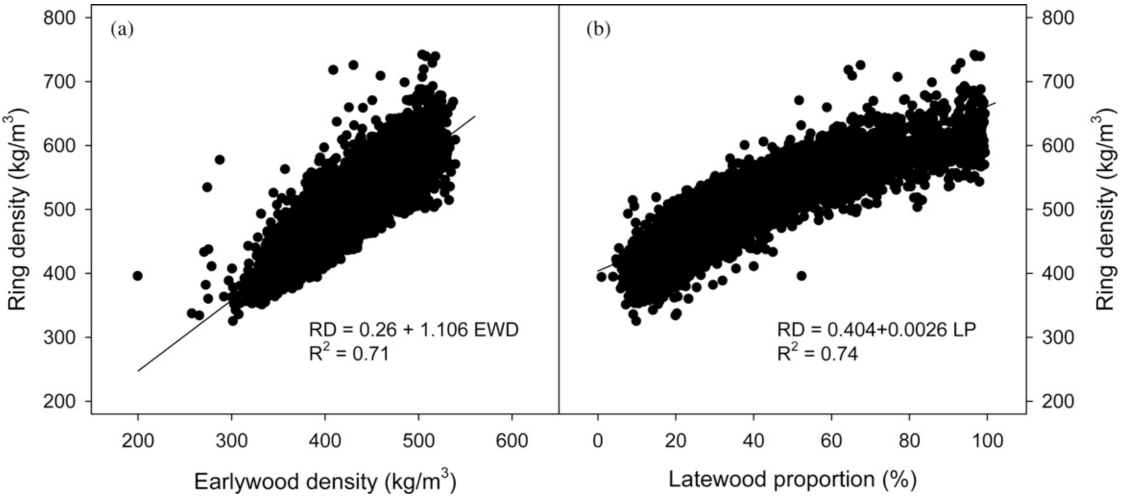

Figure 6. Ring density in relation to (a) earlywood density and (b) latewood proportion. Solid lines are regression lines with $p < 0.0001$ for intercepts and slopes.

($p = 0.022$), Bonferroni's multiple comparison could not detect any significant difference in latewood density between Cx and Tx. In contrast, ANCOVA suggested a significantly higher ring density (520.7 kg/m^3) in C1 than in T1 (499.3 kg/m^3) ($p = 0.032$) (Tables 3 and 4). This was expected because ring density increased with increasing latewood proportion ($R^2 = 0.74$) (Fig 6b) and latewood proportion was larger in C1 than in T1 ($p = 0.034$) (Tables 3 and 4).

For individual rings, only those formed in 2002 and 2003 had significantly higher ring density in C1 than in T1. However, this significant difference cannot be attributed to the effect of thinning. As shown in Figs 2 and 3, the ring formed in 2003 was extremely narrow because of drought, especially in the earlywood portion. This extremely narrow ring made it difficult for the X-ray densitometer to precisely identify the boundary between two rings and the transition point from earlywood to latewood, even with manual override. Also, because of extremely slow growth of this ring during the growing season, earlywood could be as dense as latewood, making it even harder to detect the transition point. This may explain the unusual earlywood and latewood density for the 2003 ring (Fig 5). If these two rings were not included in the analysis, the difference in average ring density was not significant ($p = 0.106$) between C1 and T1.

Conflicting results have been reported for thinning effect on wood density in the literature. For example, Pape (1999) observed a moderate decrease in basic wood density associated with increasing thinning intensity in Norway spruce, whereas Jaakkola et al (2005) found that thinning had little effect on ring density and its components in the same species. In balsam fir, thinning and thinning intensity had little or no effect on earlywood and latewood density, however, ring density decreased following moderate thinning (Koga et al 2002). In Scots pine, Peltola et al (2007) noticed an increase in wood density by light thinning, whereas Mörling (1999) observed no thinning effect on wood density. Barbour et al (1994) concluded that thinning resulted in lower relative density in jack pine. Other studies stated little or no thinning effect on wood density in Turkish red pine (Guller 2007), Karamatsu (Koga et al 1996), loblolly pine (Moschler et al 1989), and Douglas-fir (Parker et al 1976). This suggests that effect of thinning on wood density is species-specific and site-specific.

A strong correlation was observed between ring density and earlywood width ($r = -0.51$, $p < 0.0001$) and between ring density and latewood proportion ($r = 0.85$, $p < 0.0001$) (Fig 6b), implying that effect of thinning on wood density, although not significant, is attributed to increased earlywood growth and decreased latewood proportion. About 71% of the variations in ring density could be explained by earlywood density alone (Fig 6a) and only 6.4% by latewood density alone. This agrees with Schweingruber (1988) that ring density is mainly determined by earlywood density because earlywood usually has a wider ring than does latewood in black spruce, thus contributing more to average ring density.

No significant differences in earlywood or latewood density ($p > 0.133$) were detected among DBH classes (Table 4). However, a slight decrease in ring density with increasing DBH ($R^2 = 0.15$) was observed (Fig 4). This trend agrees with observations in other studies (Tong et al 2009). When individual treatments were considered separately, a difference in ring density was significant only between the smallest and largest DBH classes in C1 (542.0 vs 510.9 kg/m^3) ($p = 0.001$) and in T2 (523.3 vs 487.2 kg/m^3) ($p < 0.0001$).

Despite a low p value (0.016) (Table 4), no significant difference was found in IDV among DBH classes using Bonferroni's multiple comparison test. Thinning increased IDV significantly ($p < 0.0001$) in both sites. This suggests that thinning results in higher density variation within a ring. Most rings formed since the thinning year were generally narrow (Figs 2a-b and 3) because of the drought with latewood proportion greater than 50% (Fig 3c). However, faster annual growth stimulated by thinning is mainly from faster growth in earlywood, resulting in a decreased latewood proportion. According to Eq 1, IDV was parabolically related to latewood proportion. For the rings with latewood proportion less than 50%, IDV increased with increasing latewood proportion, whereas for those with latewood proportion greater than 50%, the trend was reversed.

Annual Growth and Wood Density at Different Heights in Stem

Earlywood width was significantly larger at the 7.5-m height (1.09 mm) than at the lower heights ($\leq$0.8 mm) (Tables 3 and 4). In contrast, latewood width was larger at the stump and 7.5-m heights than at the other heights. Consequently, latewood proportion was larger at lower heights than at higher heights (Table 4), and ring width decreased first from 1.31 mm at the stump height to 1.13 mm at the 2.5-m height and then increased to 1.62 mm with further increasing height position to 7.5 m (Table 3). This implies that these spruce trees may have a large taper in butt logs but a small taper in other logs. The variations in ring width along the stem are in conflict with the results reported by Alteyrac et al (2005) that ring width decreases with increasing height position in naturally generated black spruce. Also, at higher tree heights, the wood is more likely to be juvenile. The wider rings at 7.5-m height than at the lower heights suggest that wood formed in the same year contains a high proportion of juvenile wood, implying that this spruce plantation may have a high juvenile wood content.

No significant difference in earlywood density and latewood density was found among different height positions ($p > 0.133$) (Table 4). With increasing height position from the stump to 7.5 m, however, ring density decreased from 525.5-491.0 kg/m^3 ($p < 0.0001$) (Tables 3 and 4). This decreasing trend is the result of the combination of trends of increasing earlywood width and decreasing latewood proportion with height position. This trend is consistent with that reported by Alteyrac et al (2005) in naturally generated black spruce but opposite to results in Norway spruce (Petty et al 1990; Saranpää 2003; Molteberg and Høibø 2006; Jyske et al 2008).

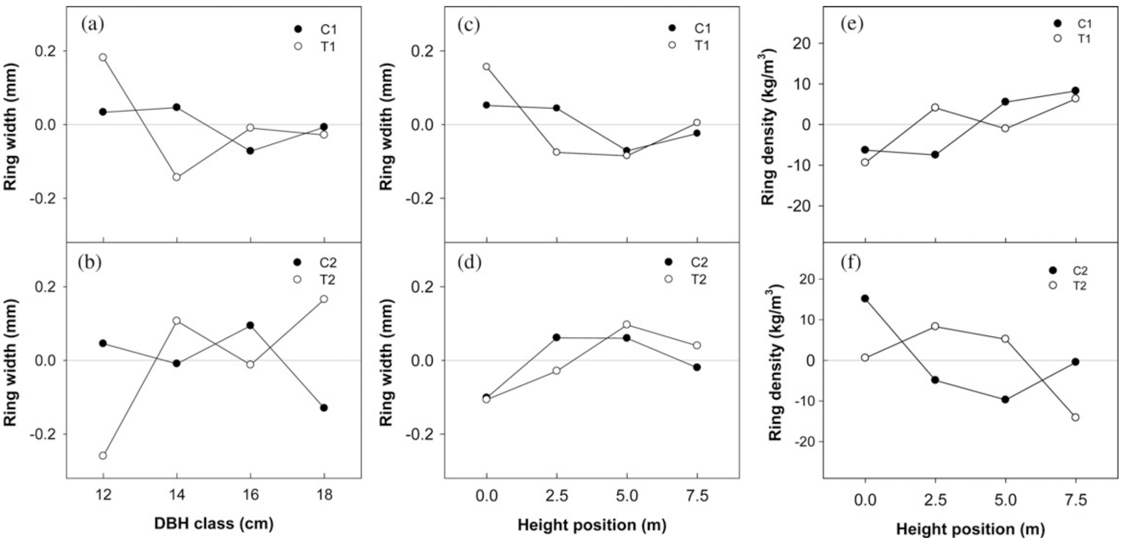

Figure 7. Interaction effects of thinning and diameter at breast height (DBH) class on ring width (main effect of each variable has been removed) in (a) Site 1 and (b) Site 2 and of thinning and height position on ring width in (c) Site 1 and (d) Site 2 and ring density in (e) Site 1 and (f) Site 2.

Interaction Effects of Thinning, Diameter at Breast Height, and Height Position

For the study sites, it appears that the effect of thinning on annual growth was different for trees of different DBH classes (Fig 7a-b). For example, heavier thinning (T1) appeared more beneficial to small trees but had little effect on large trees (Fig 7a). In contrast, lighter thinning (T2) appeared to suppress growth of small trees and accelerate growth of large trees (Fig 7b). Small trees grow slower, partly because of competition for light and nutrition with adjacent trees. Heavier thinning redirects growth to small trees by making more room for them to grow faster, whereas the space created from lighter thinning might not be enough to accelerate small tree growth.

T1 appeared to have wider earlywood width and ring width than did C1 at all heights ($p < 0.0001$), but this was not the case between C2 and T2. Thinning tends to affect annual growth differently at different heights. As shown in Fig 7c-d, thinning appeared to be more beneficial to annual growth at stump height in T1 but tended to suppress growth at the 2.5-m height in both sites. This suggests that trees from Tx had a larger taper in the butt logs and a smaller taper in the logs higher up than those from Cx. A possible explanation might be that CT directs more radial increment on the lower part of the stem, whereas control trees have prevailing radial growth on the top (Vincent et al 2009).

Like ring width, wood density responded to thinning differently at different heights. For example, thinning in T1 increased ring density by 12 kg/m^3 at the 2.5-m height and decreased ring density by 7 kg/m^3 at the 5.0-m height, whereas there was little change at the stump and 7.5-m heights (Fig 7e). T2 resulted in about 14 kg/m^3 increase at the 2.5- and 5.0-m heights and about the same magnitude of decrease at the stump and 7.5-m heights (Fig 7f). Increase in ring density at the 2.5-m height from thinning (Fig 7e-f) was coincident with suppression in ring width at the 2.5-m height (Fig 7c-d).

The pure interaction effects presented in Fig 7, having eliminated the main effects of thinning, DBH class, and height level, imply that effect of thinning may depend on both diameter and height level. This suggests that increased growing space from different thinning intensities might be more beneficial to trees of specified diameters or at specified height. This has implications for stand managers in choosing an optimal thinning intensity and thinning regime (eg thinning from below and from top) to achieve different goals (eg to improve small tree growth and to accelerate large tree growth) for a specific stand.

It is a common belief that CT does not affect black spruce tree growth. Although this study indicated a significant CT effect on radial growth, this study covered only 6 yr. Coincidently, during the 6 yr, it was droughty for 4 yr, and the drought might have interacted with the thinning. Further studies should occur across a longer period to examine the long-term effect of CT on annual growth and wood density. Also, edge effect may have been present in the sample trees. Efforts were made to sample X-ray densitometry strips along the thinning row direction (east–west direction) to minimize the edge effect.

CONCLUSIONS

Based on 6-yr results after a CT on 49-yr-old plantation-grown black spruce trees, the following conclusions could be drawn:

1. Heavy CT had a significant and positive effect on annual radial growth in plantation-grown black spruce. Latewood proportion and wood density were not significantly affected by CT;
2. Increased annual growth caused by thinning was mainly from an increase in earlywood width. The effect of thinning on ring width and density depended on tree diameter and height position;
3. With increasing tree diameter, ring width increased while ring density decreased slightly. Ring width decreased with increasing height position up to 2.5 m and then increased with further increasing height position. Ring density decreased with increasing height position; and
4. Stand managers may choose optimal thinning intensity and a thinning regime to achieve different goals for a specific stand.

ACKNOWLEDGMENTS

This study was part of a multidisciplinary project supported by the Enhanced Forest Productivity Science Program of the Forestry Futures Trust. We sincerely thank the Tembec FRM for the permission of destructive sampling and Mr. Jeff Leach of Tembec FRM, Kapuskasing, Ontario, Canada, for sharing historic information on the study sites. We also thank our colleagues at FPInnovations: Mr. Luc Bedard for his participation in field work and sample tree collection, Mr. Yves Giroux for his work in stem scanning, and Mr. Dave Munro for his assistance in X-ray densitometry.

REFERENCES

Alteyrac J, Zhang SY, Cloutier A, Ruel JC (2005) Influence of stand density on ring width and wood density at different heights in black spruce (*Picea mariana* [Mill.] B.S.P.). Wood Fiber Sci 37(1):83-94.

Barbour RJ, Fayle DCF, Chauret G, Cook J, Karsh MB, Ran SK (1994) Breast-height relative density and radial growth in mature jack pine (*Pinus banksiana* Lamb.) for 38 years after thinning. Can J For Res 24:2439-2447.

Burns J, Puettmann KJ, Perala D (1996) Strip thinning and spacing increases the growth of young black spruce. North J Appl For 13(2):68-72.

Duchesne I, Swift DE (2008) Impact of intensive silviculture on wood product quality and value in a jack pine stand—Long-term impact of late commercial thinning at wide spacing. FPInnovations-Forintek General Revenue Report Project No. 5767.

Fleming RL, Mossa DS, Marek GT (2005) Upland black spruce stand development 17 years after cleaning and precommercial thinning. For Chron 81:31-41.

Guller B (2007) The effects of thinning treatments on density, MOE, MOR and maximum crushing strength of *Pinus brutia* Ten. wood. Ann Sci 64(4):467-475.

Harrington CA, Reukema DL (1983) Initial shock and long-term stand development following thinning in a Douglas-fir plantation. Forest Sci 29(1):33-46.

Hillman GR, Takyi SK (1998) Response of black spruce to thinning and fertilization in a drained swamp. North J Appl For 15(2):98-105.

Jaakkola T, Mäkinen H, Saranpää P (2005) Wood density in Norway spruce: Changes with thinning intensity and tree age. Can J For Res 35:1767-1778.

Jozsa LA, Myronuk RM (1986) Direct reading x-ray densitometer. Canadian Forest Service Report No. 21. Forintek Canada Corp., Vancouver, BC, Canada.

Jozsa LA, Richards JE, Johnson SG (1987) Calibration of Forintek's direct reading X-ray densitometer. Canadian Forest Service Report No. 36a. Forintek Canada Corp., Vancouver, BC, Canada.

Jyske T, Mäkinen H, Saranpää P (2008) Wood density within Norway spruce stems. Silva Fennica 42(3): 439-455.

Kayahara G, McKinnon L, White RG (2007) Commercial thinning specifications and exceptions monitoring protocol for jack pine, white spruce and black spruce in Ontario's boreal forest. Forestry Research Partnership. http://forestresearch.canadianecology.ca/Projects/fibre/CTSpecsPjSwSb.pdf (5 June 2009).

Koga S, Tsutsumi J, Oda K, Fujimoto T (1996) Effects of thinning on basic density and tracheid length of karamatsu (*Larix leptolepis* Gord.). Mokuzai Gakkaishi 42:605-611.

Koga S, Zhang SY, Bégin J (2002) Impact of precommercial thinning on annual growth and wood density in balsam fir. Wood Fiber Sci 34(4):625-642.

LaChance D, Thibault J, Monnier C (1991) Forest insects and diseases in the Québec region 1936–1988. Can For Serv Inf Rep LAU-X-97.

Larson PR (1994) The vascular cambium—Development and structure. Springer, Berlin, Germany.

Lavigne MB, Donnelly JG 1989. Early results of a spacing trial in a precommercially thinned balsam fir stand in Western New Foundland. Information Report N-X-269. Forestry Canada, St. John's, Newfoundland, Canada.

Lussier J-M (2007) Overview of commercial thinning in black spruce forest: 40 years later. Branching Out No. 31, 1 p.

Mayor X, Rodà F (1993) Growth response of holm oak (*Quercus ilex* L) to commercial thinning in the Montseny mountains (NE Spain). Ann Sci For 50(3): 247-256.

McKinnon LM, Kayahara GJ, White RG (2005) Biological framework for commercial thinning even-aged single species stands of jack pine, white spruce, and black spruce in Ontario. DRAFT report. OMNR internal document.

Megraw RA, Nearn WT (1972) Detailed DBH density profiles of several trees from Douglas-fir fertilizer/thinning plots. *In* Proc Symp. on the Effect of Growth Acceleration on the Properties of Wood. USDA For Serv Forest Prod Lab, Madison, WI.

Molteberg D, Høibø O (2006) Development and variation of wood density, kraft pulp yield and fibre dimensions in young Norway spruce (*Picea abies*). Wood Sci Technol 40(3):173-189.

Mörling T (1999) Effects of nitrogen fertilization and thinning on growth and clear wood properties in Scots pine (*P. sylvestris*). Doctoral Thesis, Swedish University of Agricultural Sciences, Umea, Sweden.

Moschler WW, Dougal EF, McRae DD (1989) Density and growth ring characteristics of *Pinus taeda* L. fallowing thinning. Wood Fiber Sci 21:313-319.

Northwest Science & Technology (1998) Thinning in black spruce—A demonstration Forest program publication. Ontario Technical Report #11—ISBN 0-7778-5390-6. Northwest Science & Technology, Information Resources Division, Thunder Bay, Ontario, Canada.

OMNR (1997) Pre-commercial thinning in black spruce. Demonstration For Tech Rep 11. Ontario Ministry of Natural Resource, Northwest Sci. and Technol., Thunder Bay, Ontario, Canada. 19 pp.

Pape R (1999) Influence of thinning and tree diameter class on the development of basic density and annual ring width in *Picea abies.* Scand J Fr Res 14:27-37.

Parker ML, Hunt K, Warren WG, Kennedy RW (1976) Effect of thinning and fertilization on intra-ring characteristics and kraft pulp yield of Douglas-fir. Appl Polym Symp 28:1075-1086.

Pelletier G (2001) Commercial thinning in Irving. *In* UQAT/AFAT Precommercial Thinning Workshop, April 25-27, 2001, The Forest Resource Partnership, Amos, Quebec, Canada.

Peltola H, Kilpeläinen A, Sauvala K, Räisänen T, Ikonen V-P (2007) Effects of early thinning regime and tree status on the radial growth and wood density of Scots pine. Silva Fennica 41(3):489-505.

Petty JA, Macmillan DC, Steward CM (1990) Variation of density and growth ring width in stems of Sitka and Norway spruce. Forestry 63(1):39-49.

Saranpää P (2003) Wood density and growth. Pages 87-117 *in* JR Barnett and G Jeronimidis, eds. Wood quality and its biological basis. Blackwell Publishing & CRC Press, Biological Sciences Series, Bodmin, UK.

SAS (1999) SAS user's guide: Statistics. Version 8. SAS Institute, Inc., Cary, NC.

Schneider R (2007) Effect de l'éclaircie commerciale sur la croissance et la qualité du pin gris. PhD Thesis, Université Laval, Québec, Canada.

Schweingruber FH (1988) Tree-rings: Basics and applications of dendrochronology. Kluwer, Dordrecht, The Netherlands.

Shepard RK, Shottafer JE (1990) Effect of early release on specific gravity and wood yield of black spruce. Forest Prod J 40(1):18-20.

Simonin K, Kolb TE, Montes-Helu M, Koch GW (2006) Restoration thinning and influence of tree size and leaf area to sapwood area ration on water relations of Pinus ponderosa. Tree Physiol 26:493-503.

Smith DM, Larson BC, Keltym J, Ashton PMS (1996) The practice of silviculture: Applied forest ecology. Pages 47-68 *in* The response of individual trees to thinning and pruning, 9th Edition. Wiley and Sons Inc., New York, NY.

Tasissa G, Burkhart HE (1997) Modelling thinning effects on ring width distribution in loblolly pine (*Pinus taeda*). Can J For Res 27:1291-1301.

Tong QJ, Fleming RL, Tanguy F, Zhang SY (2009) Wood and lumber properties from unthinned and precommercially thinned black spruce plantations. Wood Fiber Sci 41(2):168-179.

Tong QJ, Zhang SY (2005) Impact of initial spacing and precommercial thinning on jack pine tree growth and stem quality. For Chron 81(3):418-428.

Tong QJ, Zhang SY, Thompson M (2005) Evaluation of growth response, stand value and financial return for pre-commercially thinned jack pine stand in Northwestern Ontario. For Ecol Mgmt 209:225-235.

Tremblay F (2005) Impact of commercial thinning in black spruce. MRNF Report. Ministère des Ressources naturelles et de la Faune, Ste-Foy, Quebec, Canada.

Vargas-Hernandez J, Adams WT (1991) Genetic variation of wood density components in young coastal Douglas-fir: Implication for tree breeding. Can J For Res 21:1801-1807.

Vincent M, Krause C, Zhang SY (2009) How does commercial thinning influence profile shape on *Picea mariana*: A case-study in Québec's boreal forest. *In* XIII World Forestry Congress, October 18-23, 2009, Buenos Aires, Argentina.

Wimmer R, Grabner M (1997) Effect of climate on vertical resin duct density and radial growth of Norway spruce (*Picea abies* [L.] Karst.). Trees (Berl) 11:271-276.

Zhang SY, Chauret G, Swift DW, Duchesne I (2006) Effects of precommercial thinning on tree growth and lumber quality in a jack pine stand in New Brunswick, Canada. Can J For Res 36:945-952.

Zhang SY, Corneau Y, Chauret G (1998) Impact of precommercial thinning on tree and wood characteristics, product quality and value in balsam fir. Canadian Forest Service Report 39. Forintek Canada Corp., Sainte-Foy, Quebec, Canada. 75 pp.