IMPACT OF INITIAL SPACING ON PLANTATION BLACK SPRUCE LUMBER GRADE YIELD, BENDING PROPERTIES, AND MSR YIELD

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ABSTRACT

For decades, initial spacing of 2 m × 2 m has been used for black spruce (*Picea mariana*) reforestation in eastern Canada. In recent years, however, wider spacings for black spruce are being advocated to reduce establishment costs and accelerate tree growth. Wider spacings will affect not only return on investment but also the quality of products from the plantations, both of which are critical to the success of reforestation programs. As part of a multidisciplinary project, this study evaluated and quantified the impact of initial spacing on lumber grade yield, bending properties, and MSR yield in this species. Furthermore, visual grades of the plantation-grown lumber were compared for their bending properties and their compliance to the current grade requirements for bending stiffness. A total of 139 sample trees were collected from 4 different spacings (3,086, 2,500, 2,066, 1,372 trees/ha) in a 48-year-old initial spacing trial, and 849 pieces of 2-in.-thick lumber from the 4 spacings were graded visually and tested for bending strength and stiffness.

With decreasing initial stand density from 3,086 to 2,066 trees/ha, branch diameter showed a steady increase. However, the 3 higher stand densities (3,086, 2,500, and 2,066 trees/ha) had a comparable Select Structural (SS) grade yield thanks to the relatively small branches in this species. Lumber strength and stiffness in those 3 spacings were also quite comparable. When the initial stand density was further reduced to 1,372 tree/ha, however, a remarkable decrease in the SS grade yield due to knots occurred, and lumber strength and stiffness also decreased significantly. The real concern occurred when the plantation-grown lumber was compared to that from natural stands currently being processed in eastern Canada. On average, the plantation-grown black spruce lumber stiffness was 28.9% lower than that of lumber from the natural stands. As a result, a high percentage of the plantation-grown lumber did not meet the bending design values. However, the percentage of the compliance to the design values tended to increase with increasing initial stand density. This article discusses the possible causes for the significantly lower bending properties of the plantation-grown lumber, and potential solutions for increasing lumber properties and the percentage of the compliance.

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This study also found that although visual grading was effective in characterizing knottiness, wood density and other wood characteristics that affect lumber strength and stiffness could not be taken into consideration in visual grading. As a result, visual grades of the plantation-grown black spruce lumber can not effectively reflect the differences in lumber strength and stiffness. This raises the need for machine grading this resource.

Keywords: Black spruce, initial spacing, visual grading, bending properties, MSR lumber, design values, wood characteristics.

INTRODUCTION

Wood supply is emerging as a constraint to the growth and prosperity of the forest industry in eastern Canada. To sustain the long-term wood supply and to preserve the environment, it has become critical to invest in reforestation programs. Black spruce (*Picea mariana* [Mill.] B.S.P.) is the most important reforestation species in eastern Canada. Over 100,000 hectares of black spruce plantations are established each year (CCFM 1996). This species is also the most important commercial species, highly valued for both pulpwood and lumber production (Mullins and McKnight 1981).

For decades, initial spacing of 2 m × 2 m (2,500 trees/ha) has been adopted for black spruce reforestation in eastern Canada (McClain et al. 1994). This spacing is based on intensive studies on the relationships of initial spacing with tree growth and yield that were carried out during the 1940s to the 1970s (Sjolte-Jorgenstern 1967; Evert 1971). In recent years, however, wider spacings for black spruce are being advocated by some to reduce establishment costs and accelerate diameter growth of individual trees (McClain et al. 1994). In fact, initial spacing for black spruce in some regions of eastern Canada has already been reduced to 2,000 trees/ha or even lower.

Initial spacing has a decisive effect on the initial establishment costs, tree growth, and stand yield. It also affects crown structure, branch size, and the characteristics of the wood produced (Evert 1971; Daniel et al. 1979). Therefore, decisions on initial spacing will affect not only the stand value and return on investment but also the quality of products yielded from the plantations (Evert 1971; Ballard and Long 1988; Bell et al. 1990). It has been widely recognized that the aim of reforestation programs is not to produce the greatest wood volume, but to produce materials that yield quality products demanded by the market, and at the same time, the best return (Evert 1971). Therefore, an optimal initial spacing required to yield quality products and the best return on the investment is critical to the success of the reforestation programs.

While wider spacings for black spruce are an effective way to reduce initial establishment costs, returns from wider spacings remain to be evaluated. Wider spacings may accelerate diameter growth of individual trees, but at the same time they may have a negative effect on wood characteristics and lumber quality. A significant decrease in lumber quality may jeopardize the competitive edge that the Canadian lumber industry has enjoyed on the global markets over the past decades for its high-quality products. To ensure that the reforestation programs are cost-effective and black spruce plantations will yield quality products, it is important to understand the relationship of product quality and value recovery with initial spacing in this species.

The relationships of growth and yield with stand density in natural black spruce stands have been studied intensively. In recent years, several studies (Yang and Hazenberg 1992, 1994; Yang 1994) have also evaluated the effect of initial spacing on wood characteristics in black spruce. No single study, however, has yet examined the impact of initial spacing on product quality and value recovery in this species. In 1998, Forintek initiated a multidisciplinary project on the initial spacing of black spruce in collaboration with the Ontario Ministry of Natural Resources (OMNR). The overall objective of this project is to quantify the impact of initial spacing on product quality and return on investment so as to determine an optimal initial spacing for black spruce. The present paper, as part of this multidisciplinary project, reports on the impact of initial spacing on lumber grade yield, bending properties, and MSR yield. Impact of initial spacing on dimensional stability will be reported in a separate paper.

MATERIALS AND METHODS

Materials

This study was based on the oldest initial spacing trial established in 1950 by the OMNR. One site located in Stanley (48 22′N, 89 23′W), 10 km north of Thunder Bay, provided the materials for this study. The trial area was classified by Rowe (1972) as Superior (B.9) of the Boreal Forest Region. Soil texture was fine sandy loams over sandy clay loam (McClain et al. 1994). The estimated site index (mean dominant height at age 50) for black spruce was 18 m (Thrower 1986).

Since the establishment of the trial, no management other than protection has been applied to alter growth and development. Before the sample trees were harvested in the fall of 1998, the trial had been measured a number of times. OMNR keeps the historic records on the development of the black spruce initial spacing trial. With the assistance of the OMNR staff, all trees with 4 spacings (viz. 1,372, 2,066, 2,500, and 3,086 trees/ha) were marked and measured for DBH in the fall of 1998. This measurement provides the DBH class frequency distribution for each of the 4 spacings. Sample trees from each spacing were selected based on its DBH class distribution. From each spacing, 6 trees per DBH class were randomly selected from each merchantable 2-cm DBH class (e.g., 10, 12, 14, ...). There were a few exceptions where an insufficient number of trees were available from either the smallest or largest DBH classes. From the initial spacing of 1,372 trees/ha, 30 sample trees were selected to cover 6 DBH classes (viz. 16–24 cm); 33 trees from the spacing of 2,066 trees/ha to cover 7 DBH classes (viz. 10–22); 40 trees from the spacing 2,500 trees/ha to cover 7 DBH classes (viz. 10–22 cm); and 36 trees from the spacing of 3,086 trees/ha to cover 6 DBH classes (10–20 cm). In total, 139 trees were selected and felled for this study.

For each sample tree selected, various tree characteristics were measured: 1) total tree height and tree height to a 5-cm diameter top, 2) DBH and diameter of stem at an interval of 1-m from the stump height to the 5-cm diameter top, and 3) live crown width and length. The five biggest branches in each sample tree were measured to serve as a branch diameter index as described by DeBell et al. (1994). Based on the measurements of stem diameters at different heights of the tree, stem volume (to a 5-cm diameter top) was calculated. Stem taper was determined based on the stem length from 1 m high to the 5-cm diameter top. For further information on the trial and sampling, refer to Zhang and Chauret (2001).

Methods

Each sample tree was bucked into 8-ft-long logs. From the top of each log, a 3-cm-thick disk was removed for the evaluation of various wood characteristics. Log position in the tree (e.g., butt log, . . . top log) was identified by different letters (e.g., A, B, C, . . .). For each log, log diameters at two ends were measured and average bark thickness was also measured. Any defect (e.g., sweep, crook, rot) was recorded for each log.

To facilitate the primary breakdown of the logs and to identify the origin of each piece of lumber, ends of the logs from each of the 4 spacings were painted with unique color. Special arrangements were made with a cooperating sawmill to reduce the processing speed in order to mark each piece of lumber produced. All the logs from this study were processed in the same manner from the debarking to the sawing. Logs from the 4 spacings were processed separately to collect chip samples. After debarking, logs were sorted into 4 size groups (viz., 3, 4, 6, and 8 in.) before they were sawn into 2-in.-thick lumber. Each piece of lumber was identified by tree number and sawlog position in the tree.

All lumber samples were brought to the Forintek laboratory in Quebec City, where moisture content was measured for each piece of lumber in the green condition. The lumber was graded before drying according to the NLGA rules (NLGA 1996) by a qualified grader from the Quebec Lumber Manufacturers' Association (QLMA), and reasons for downgrade were recorded. For the Canadian softwood structural lumber, there are 5 visual grades defined by the NLGA: Select Structural, No. 1, No. 2, No. 3, and Economy. Since initial spacing has a direct effect on branch size and knot diameter, which are of importance to visual grading, each piece of lumber was also graded based on knots only, without considering other defects. After kiln-drying, all the lumber was dressed in a commercial planer mill. Each piece of dried and dressed lumber was graded again and reasons for downgrade were recorded.

Before the bending tests, the lumber was stored in a conditioning chamber until it reached an approximately 12% moisture content for bending tests. Modulus of elasticity (MOE) and modulus of rupture (MOR) in static bending were determined for each piece of lumber. In total, 849 pieces of lumber were tested, which included 231 pieces of 2 by 3, 499 pieces of 2 by 4, and 119 pieces of 2 by 6. Due to the trimming, a small percentage of lumber was shorter than 8-ft long. All the lumber pieces were tested edgewise with third-point loading in general agreement with ASTM D-4761-96 (ASTM 1997). Just before the bending test, average moisture content was determined by moisture meter for each piece of lumber. Following the ASTM D-2915-94 (ASTM 1997), MOE and MOR were adjusted to 12% MC, and MOE was standardized to the span-to-depth ratio of 21 to 1. In addition, bending width effect on MOR was adjusted for both 3- and 6-in.-width lumber to 4-in.-width using the method described by Barrett and Lau (1994). Following the NLGA SPS 2-97 (NLGA 1997), lumber pieces visually graded as No. 2 and Better were further graded for MSR yield.

Once the bending tests were completed, the types of failure were recorded. Any grain deviation and other defects were measured and recorded. For each piece of lumber, the number of knots larger than 1 cm in diameter was counted and the diameter of the knots was measured. In addition, a small block (c. 15 cm longitudinally × lumber width × lumber thickness) of clear wood sample was removed from each piece of tested lumber to evaluate selected wood characteristics. Wood characteristics determined for each piece include: 1) basic wood density (oven-dry weight/green volume), 2) cambial age (or number of rings from the pith), 3) average ring width, and 4) the distance (of the center of the lumber cross section) to the pith.

In this study, the impact of initial spacing was examined at two levels. At the diameter class level, we compared trees of the same DBH class from the 4 spacings. Based on the average values of the lumber quality parameters determined for each DBH class and the DBH class frequency distribution in each spacing, the average values were calculated for each spacing at the stand level, which allows comparing the 4 spacings at the stand level.

RESULTS AND DISCUSSION

Stem quality characteristics

Table 1 gives average tree DBH, stem taper, and crown characteristics for the 4 spacings at the stand level. As expected, with increasing spacing or decreasing stand density from 3,086 to 1,372 trees/ha, both crown size and average diameter of the 5 biggest branches in the tree show a steady increase. Stem taper also tends to increase steadily with decreasing stand density. A larger crown length and larger branch diameter associated with wider spacings potentially have negative implications for lumber quality. On the other hand, the lowest

TABLE 1. *Selected tree characteristics for the 4 initial spacings (at the stand level).*

Characteristic	Initial stand density (trees/ha)			
	1,372	2,066	2,500	3,086
Average DBH (cm)	20.5	15.9	15.7	15.6
Average stem taper (cm/m)	1.15	0.90	0.91	0.87
Average live crown length (m)	7.8	6.3	6.1	5.6
Average proportion of live crown to total tree height (%)	47.1	44.2	42.3	37.8
Average live crown width (m)	2.8	2.3	2.0	1.8
Average diameter of the 5 biggest branches in the tree (mm)	23.8	18.3	18.4	16.4

stand density of 1,372 trees/ha has a significantly larger average DBH (20.5 cm) than the other 3 densities. However, stand densities of 2,066 and 2,500 trees/ha have only a slightly larger average DBH (15.9 cm and 15.7 cm, respectively) than the highest stand density (15.6 cm).

Visual lumber grade yield

Table 2 gives average yields of grades No. 2 and Better at both the diameter class level and stand level. Trees from the lowest stand density appear to have a lower Select Structural (SS) grade yield than trees of the same DBH class from the other 3 densities. This applies to the DBH classes 16, 18, and 20 cm, but the reverse holds true for the 22-cm DBH class. However, no consistent patterns can be recognized between trees of the same diameter class from the other 3 densities. On the other hand, SS grade yield does not show a consistent pattern of variation with DBH class. For example, SS grade yield in the 2,066 trees/ha stand tends to decrease with increasing DBH class, whereas the opposite trend appears to be true in the stand density of 3,086 trees/ha.

At the stand level, the lowest stand density of 1,372 trees/ha has the lowest SS grade yield (61.3%), approximately 7% lower than the other 3 densities. The lower SS grade yield in this stand density most likely results from downgrades due to a considerably larger branch size (Table 1). Although the stand densities of 2,066 and 2,500 trees/ha have a larger knot diameter than the stand density of 3,086 trees/ha, SS grade yields in these two densities are still comparable to that in the highest stand density. As shown in Table 1, even the diameters of the biggest 5 branches from the stand densities of 2,066 and 2,500 trees/ha are smaller than the allowable knot size required by NLGA (1996) for the Select Structural grade of 2 by 4 and 2 by 6 (Table 3). This suggests that knots in these two densities might not be large enough to cause major downgrades for 2 by 4 and 2 by 6 lumber. In

TABLE 2. *Lumber grade yield in relation to DBH class and initial spacing.*

DBH class (cm)	Select structural grade				No. 1 grade (%)				No. 2 grade (%)				No. 2 and better grades (%)			
	Initial stand density (trees/ha)				Initial stand density (trees/ha)				Initial stand density (trees/ha)				Initial stand density (trees/ha)			
	1,372	2,066	2,500	3,086	1,372	2,066	2,500	3,086	1,372	2,066	2,500	3,086	1,372	2,066	2,500	3,086
10		71.4	37.5	56.1		0.0	0.0	8.8		0.0	25.0	11.7		71.4	62.5	76.7
12		73.8	49.7	57.5		14.3	0.0	0.0		11.9	40.7	21.9		100	90.4	79.4
14		65.9	67.2	77.8		0.0	0.0	0.0		30.7	19.6	12.8		96.6	86.8	90.6
16	54.3	66.5	75.3	65.6	0.0	2.1	0.0	0.0	30.4	20.1	19.7	34.4	84.7	88.7	95.0	100.0
18	62.0	69.9	71.8	73.9	4.7	5.3	1.8	2.7	22.8	18.7	14.9	18.6	89.5	93.9	88.5	95.2
20	67.3	69.3	81.2	76.5	1.6	3.9	2.3	2.4	21.1	16.4	4.7	18.9	90.0	89.6	88.2	97.8
22	64.4	55.9	43.9		0.0	0.0	2.5		28.0	29.0	42.5		92.4	84.9	88.9	
24	58.7				0.0				31.5				90.2			
Stand level	61.3	68.4	66.7	68.8	0.7	4.0	0.7	1.4	27.6	19.6	20.5	23.3	89.6	92.0	87.9	93.5

TABLE 3. *Knot size restriction required by NLGA (1996) for the select structural grade of different nominal lumber widths.*

Nominal lumber width (inch)	Allowable knot size			
	Knots at edge		Knots at centerline	
	(in inch)	(in mm)	(in inch)	(in mm)
3	½	12.7	½	12.7
4	¾	19.1	⅞	22.2
6	1⅛	28.6	1⅞	47.6

fact, only 9.6% of the total downgrades in the black spruce lumber is due to knots (Table 4) thanks to its relatively small branches, whereas 70% of the downgrades is due to wane. This is in a contrast to Douglas-fir, where 29.1% and 28.6% of the downgrades were due to knots and wane, respectively (Middleton and Munro 1989). This indicates that lumber grade yield in black spruce, to a large extent, is dictated by wane, a processing defect rather than a resource defect. This fact probably explains the conflicting patterns of variation in SS grade yield with DBH class (Table 2).

Table 2 also shows that No. 1 grade lumber accounts for a fractional percentage of the total lumber volume production. Obviously, most of the downgrades go to No. 2 grade. As a result, the lowest stand density of 1,372 trees/ha has the highest No. 2 grade yield (27.6%), followed by the highest stand density of 3,086 trees/ha (23.3%), whereas the stand densities of 2,066 and 2,500 trees/ha have a comparable No. 2 grade yield.

In eastern Canada, lumber grades Select Structural, No. 1, and No. 2 are usually sold together as No. 2 and Better. As shown in Table 2, the differences in the yield of combined No. 2 and Better grades among the 4 spacings are quite small. Therefore, under the present marketing practice, a lower SS grade yield in the lowest stand density of 1,372 trees/ha does not necessarily have a significantly negative impact on lumber value. However, it does not imply that larger knots associated with the lowest stand density have no negative effect on lumber grade yield. In fact, knots in the lowest stand density cause more than 13% of the lumber downgraded to No. 3 and Economy, whereas knots in the highest stand density do not cause any downgrade to No. 3 and Economy (Table 4). It is also interesting to note that the percentage of lumber downgraded to No. 3 and Economy due to compression wood (8.3%) is considerably higher in the lowest stand density than in the other 3 densities. On the other hand, the downgrades due to wane show a steady decrease with decreasing stand density. For example, in the highest stand density 94.3% of the downgrades to No. 3 and Economy is due to wane, whereas the downgrades due to wane in the lowest stand density account for only 62.2% of the total downgrades. A lower percentage of the downgrades in lower stand density is probably due to the fact that lumber from larger trees is less likely to have wane.

To better understand the impact of initial spacing on branch size and its practical implications for lumber grade yield, lumber from the 4 spacings was also graded based on knots

TABLE 4. *Lumber downgrades caused by different defects.*

Defect	Percentage of lumber downgraded to No. 3 and Economy (%)					Percentage of any lumber downgrade (%)				
	Initial stand density (trees/ha)					Initial stand density (trees/ha)				
	1,372	2,066	2,500	3,086	Average	1,372	2,066	2,500	3,086	Average
Knots	13.4	13.9	3.3	0.0	7.7	9.7	14.1	6.6	7.8	9.6
Compression wood	8.3	0.0	5.7	5.7	4.9	2.2	0	1.9	1.2	1.5
Wane	62.2	54.2	84.2	94.3	73.7	65.8	60.4	78.2	78.6	70.0
Shake	4.2	17.4	4.4	0.0	6.5	16.5	18.3	12.4	10.9	14.9
Others	12.0	14.5	2.5	0.0	7.3	5.7	7.21	0.8	1.6	4.1
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 5. *Lumber grade (grading based on knots only) yield in relation to DBH class and spacing.*

DBH class (cm)	Select structural grade				No. 1 grade (%)				No. 2 grade (%)				No. 2 and better grades (%)			
	Initial stand density (trees/ha)				Initial stand density (trees/ha)				Initial stand density (trees/ha)				Initial stand density (trees/ha)			
	1,372	2,066	2,500	3,086	1,372	2,066	2,500	3,086	1,372	2,066	2,500	3,086	1,372	2,066	2,500	3,086
10		71.4	89.3	79.5		28.6	10.7	20.5		0.0	0.0	0.0		100.0	100.0	100.0
12		73.8	73.7	71.2		26.2	18.4	23.3		0.0	8.0	5.5		100.0	100.0	100.0
14		93.2	91.6	86.2		3.4	5.3	11.5		3.4	0.0	2.3		100.0	96.9	100.0
16	58.2	86.4	90.8	88.8	25.2	8.6	9.2	8.8	12.7	1.8	0.0	2.4	96.1	96.8	100.0	100.0
18	70.5	84.1	79.7	87.1	20.5	11.5	13.7	11.1	6.2	4.4	6.7	1.8	97.2	100.0	100.0	100.0
20	90.3	87.4	88.5	91.7	8.1	6.0	9.8	8.3	1.6	1.1	1.6	0.0	100.0	94.5	100.0	100.0
22	86.2	74.2	88.8		9.2	18.6	8.7		3.7	3.9	2.5		99.1	96.7	100.0	100.0
24	82.4				8.2				7.9				98.5			100.0
Stand level	79.1	84.6	86.5	86.1	12.9	11.5	10.3	11.8	6.4	2.5	2.5	2.1	98.4	98.4	99.3	100.0

only (Table 5). At the diameter class level, trees from the lowest stand density have a lower SS grade yield than those of the same DBH class from the other 3 densities. With increasing DBH class from the 10-cm class, SS grade yield appears initially to increase until a peak is reached and then decreases again. At the stand level, the lowest stand density also has an approximately 7% lower SS grade yield than the other 3 densities. This confirms that the 7% lower SS grade yield in the lowest stand density (Table 2) is indeed due to the downgrades caused by knots. Although black spruce trees have relatively small branches, between 13.5 and 20.9% of lumber pieces could still be downgraded due to knots alone (Table 5). However, this downgrade is considerably lower than in balsam fir, where up to 48.3% of lumber could be downgraded by knots (Zhang et al. 1998). As with balsam fir, most downgrades in the black spruce end up in grades No. 1 and No. 2. Therefore, combined yields of No. 2 and Better grades for the 4 spacings are still comparable.

Lumber strength and stiffness, MSR yield, and lumber compliance to the grade requirements for the bending stiffness

Table 6 gives average lumber modulus of rupture (MOR) and modulus of elasticity (MOE) for trees of each DBH class in each spacing. Trees from the lowest stand density tend to have a lower lumber strength and stiffness than trees of the same DBH class from the other 3 densities, but the differences among those 3 densities are not appreciable. On the other hand, lumber strength and stiffness, unlike SS grade yield, tend to decrease with increasing DBH class. As a result of the

TABLE 6. *Lumber bending strength and stiffness in relation to DBH class and spacing.*

DBH class (cm)	MOR (MPa)				MOE (MPa)			
	Initial stand density (trees/ha)				Initial stand density (trees/ha)			
	1,372	2,066	2,500	3,086	1,372	2,066	2,500	3,086
10		53.63	46.79	52.74		12,282	9,491	10,181
12		50.41	48.27	51.42		9,556	9,213	10,040
14		50.81	50.59	52.14		10,763	10,585	10,616
16	37.91	47.07	49.20	44.05	8,355	9,868	10,071	9,525
18	39.25	39.92	41.81	42.85	8,766	8,447	9,022	9,613
20	38.75	42.94	37.32	41.04	8,255	9,173	8,740	9,048
22	36.04	39.15	38.67		8,140	9,175	8,334	
24	36.07				7,824			
Stand level	37.24	46.01	46.22	46.39	8,178	9,679	9,661	9,791

TABLE 7. *Stiffness of the lumber from the 48-year-old black spruce plantations in comparison to that from natural stands of black spruce as well as jack pine and balsam fir (S-P-F species).*

			Lumber MOE (MPa)	
Species	Material	Source	Average	In comparison to the natural stands of black spruce (%)
Black spruce	Natural stands	Forintek's data bank	13,118	100.0
Black spruce	Plantation (1372 tree/ha)	This study	8,178	62.3
Black spruce	Plantations (average of the 4 spacings)	This study	9,327	71.1
Jack pine (*Pinus banksiana* Lamb.)	Natural stands	Forintek's data bank	10,726	81.8
Balsam fir (*Abies balsamea* (L.) Mill.)	Natural stands	Forintek's data bank	10,074	76.8

decreasing strength and stiffness with DBH class, lumber from the lowest stand density at the stand level has a significantly lower MOR (37.24 MPa) and MOE (8,178 MPa) than the other 3 densities. As shown in Table 6, the lowest stand density has almost 20% lower lumber strength and about 15% lower lumber stiffness. However, lumber strength and stiffness in the other 3 densities are quite comparable. This study suggests that lumber strength and stiffness in black spruce plantations do not decrease significantly as long as the initial spacing is at least 2,066 trees/ha, but a significant decrease in both lumber strength and stiffness may be expected when initial stand density is further reduced to 1,372 trees/ha.

Table 7 compares the 48-year-old black spruce plantation-grown lumber stiffness with that of lumber from Spruce-Pine-Fir natural stands. Lumber stiffness data presented for the natural stands came from Forintek in-grade tests of thousands of lumber pieces from several regions across eastern Canada. As shown in Table 7, the stiffness of the lumber from the plantations with the lowest stand density (1,372 trees/ha) is 37.7% lower than from the natural stands. On average, lumber from the black spruce plantations of the 4 spacings are still 28.9% lower in bending stiffness. It may appear unethical to compare the lumber from the 48-year-old plantations to that from natural stands currently being harvested in eastern Canada, which are usually about 100-years-old or even older. As shown in Table 1, however, the 48-year-old plantations had reached a tree size that is close to that of the natural stands being harvested in northern Quebec and Ontario. This means that in terms of tree size the plantation-grown black spruce could be harvested for lumber production in a much shorter rotation age. Therefore, practically speaking, sawlogs from plantations would be much younger than those from natural stands. In fact, shortening long rotation age for sawlog production is one of the most important objectives of intensive forest management in eastern Canada. Table 7 also shows that the plantation-grown black spruce lumber has an

TABLE 8. *MSR grade yield (%) from the 4 initial spacings.*

	Initial stand density (trees/ha)						
MSR grade	1372	2066	2500	3086	Grand total (%)	Average MOE for each MSR grade (10^6 psi)	The 5th percentile of MOE for each MSR grade (10^6 psi)
2100f-1.8E	0.0	2.1	1.2	5.4	2.2	1.82	1.74
1650f-1.5E	11.0	29.6	24.9	25.7	22.3	1.51	1.40
1450f-1.3E	12.5	19.4	28.6	32.5	22.2	1.32	1.25
Total	23.5	51.1	54.7	63.6	46.7		

TABLE 9. *Percentage of lumber pieces which meet the current grade requirements for bending stiffness design values.*

Visual grade	Design values used in comparison with the black spruce lumber in this study[1] Mean MOE (MPa)	Percentage of lumber pieces which meet the bending stiffness design values (%) Initial stand density (trees/ha) 1372	2066	2500	3086	4 densities combined
Select structural	10865	2.7	18.5	17.6	25.0	15.5
No. 1/2	10044	13.5	38.1	24.8	26.6	24.7
No. 3	9296	8.3	14.3	40.0	66.7	25.0
Grand total		6.2	22.9	20.4	26.7	18.4

[1] Design values based on Barrett and Lau (1994), and adjusted to 12% moisture content.

even lower bending stiffness than that from natural stands of both jack pine and balsam fir. Overall, this study suggests that the plantation-grown black spruce lumber will be considerably weaker than the lumber presently being produced in eastern Canadian sawmills using high-quality natural resource.

Lower strength and stiffness of plantation-grown lumber have been reported in pines (Biblis 1990; MacPeak et al. 1990; Kretschmann and Bendtsen 1992; Biblis et al. 1993; Cave and Walker 1994). A significantly higher juvenile wood content in the plantation-grown black spruce of a much shorter rotation age may explain much of the decrease in the plantation-grown lumber bending properties. It is well documented that juvenile wood in softwoods has significantly lower mechanical properties than the mature wood (Kennedy 1995; Zobel and Sprague 1998; Bao et al. 2001). For example, Bendtsen et al. (1988) reported that the parallel-to-grain tensile strength of the 2 × 4 juvenile wood lumber was only 59% of the mature wood strength, while the juvenile wood MOE was 72% of the mature wood stiffness. Lower mechanical properties in juvenile wood also apply to those species where wood density is higher near the pith. These include black spruce (Fig. 2), Scots pine (*Pinus sylvestris*) (Mattsson et al. 2002), and Amabilis fir (*Abies amanbilis*) (Kennedy 1995). It has been recognized that lower strength and stiffness of juvenile wood can not be explained simply by wood density (Kennedy 1995; Zhang 1996; Butterfield 1997). As a matter of fact, in western hemlock (Kennedy 1995) and Scots pine (Mattsson et al. 2002), both wood strength and stiffness show a steady increase from the pith to the juvenile-mature wood boundary, while wood density decreases considerably. Other studies (Kennedy and Warren 1969; Zhang and Zhong 1992) have reported an increasing specific strength (strength/wood density) from the pith to the juvenile-mature wood boundary. These results clearly suggest that there are other parameters that affect wood strength and stiffness. It is well known that both physical and mechanical properties of wood depend on its anatomical structure and ultrastruc-

TABLE 10. *The 5th percentile of MOR, mean MOR and mean MOE in relation to visual grade and spacing.*

Visual grade	Initial stand density (trees/ha) 1,372 Sample size	Mean MOR (MPa)	5th percentile MOR (MPa)	Mean MOE (MPa)	2,066 Sample size	Mean MOR (MPa)	5th percentile MOR (MPa)	Mean MOE (MPa)
Select structural	148	37.37	24.32	8,290	119	44.45	28.25	9,509
No. 1	2	43.28	37.92	9,947	4	36.85	23.49	8,190
No. 2	67	37.23	18.39	8,115	46	44.52	24.29	9,470
No. 3	12	34.61	20.31	7,579	7	33.07	16.02	8,300
Economy	16	39.52	21.47	8,179	12	41.86	19.35	8,968
Grand total	245	37.37	24.47	8,215	188	43.77	22.28	9,398

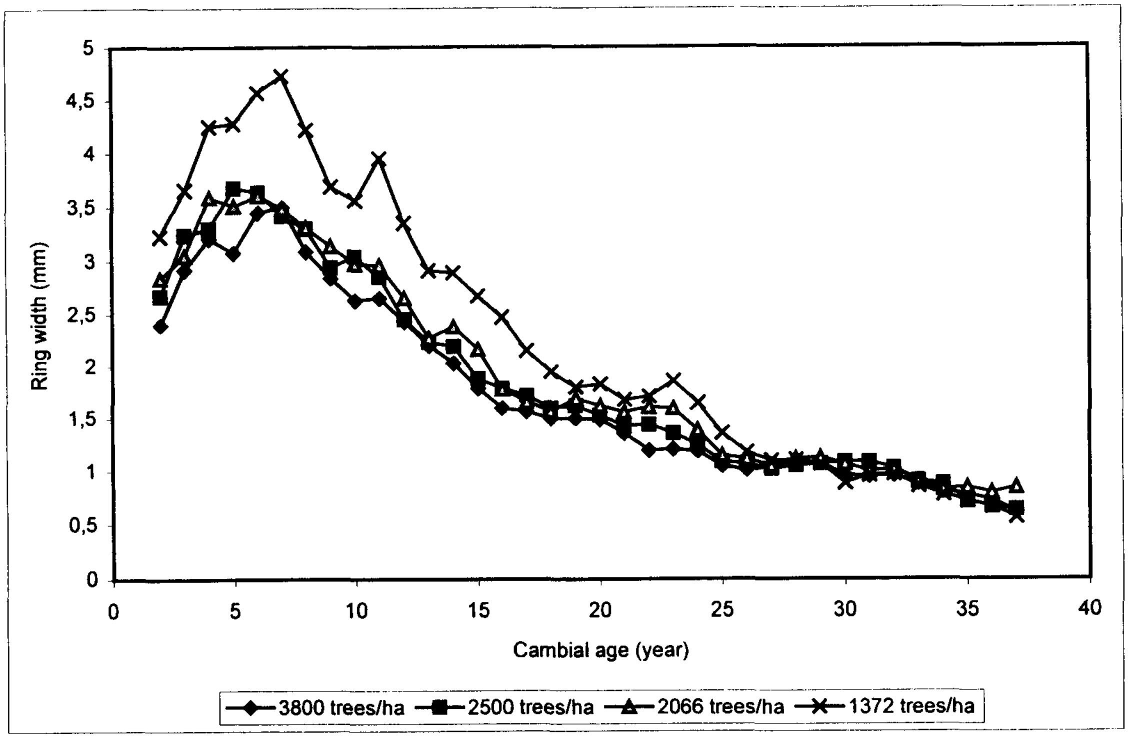

FIG. 1. Ring width (or annual growth rate) in relation to cambial age and spacing (at 8-foot height of the tree).

ture. Intrinsic differences in anatomical structure and ultrastructure between juvenile and mature wood have been well documented (Zobel and Sprague 1998; Bao et al. 2001). It appears that the inferior wood strength and stiffness of juvenile wood can be explained only by its inferior wood anatomical structure and ultrastructure (e.g., shorter fibers, larger microfibril angle). In fact, some studies (Zhang and Zhong 1992; Cave and Walker 1994; Kennedy 1995; Koponen 1997; Tsehaye et al. 1997) have found that the S_2 microfibril angle alone is better correlated with wood strength and stiffness than wood density. Cave and Walker (1994) even reported that the effect of wood density on strength and stiffness might be largely through microfibril angle, because as wood density increases in radiata pine, so does the proportion of highly orientated (small microfibril angle) latewood.

Black spruce has been the primary species

TABLE 10. *Extended.*

Initial stand density (trees/ha)											
2,500				3,086				4 densities combined			
Sample size	Mean MOR (MPa)	5th percentile MOR (MPa)	Mean MOE (MPa)	Sample size	Mean MOR (MPa)	5th percentile MOR (MPa)	Mean MOE (MPa)	Sample size	Mean MOR (MPa)	5th percentile MOR (MPa)	Mean MOE (MPa)
148	44.15	28.23	9,351	132	45.73	30.30	9,773	547	42.72 A[1]	27.78	9,195 A
4	41.66	29.79	9,585	2	40.50	38.94	9,380	12	39.99 A	32.53	9,106 A
49	43.13	25.38	9,134	41	44.50	30.23	9,515	203	41.82 A	24.57	8,961 A
10	38.06	18.23	8,572	3	50.71	43.14	9,844	32	36.99 B	26.92	8,258 B
17	40.89	24.20	9,214	10	46.54	33.17	9,259	55	41.65 A	24.55	8,851 A
228	43.38	25.17	9,261	188	45.54	37.15	9,689	849	42.18	27.27	9,081

[1] Values sharing the same letter are not significantly different at the 0.05 level.

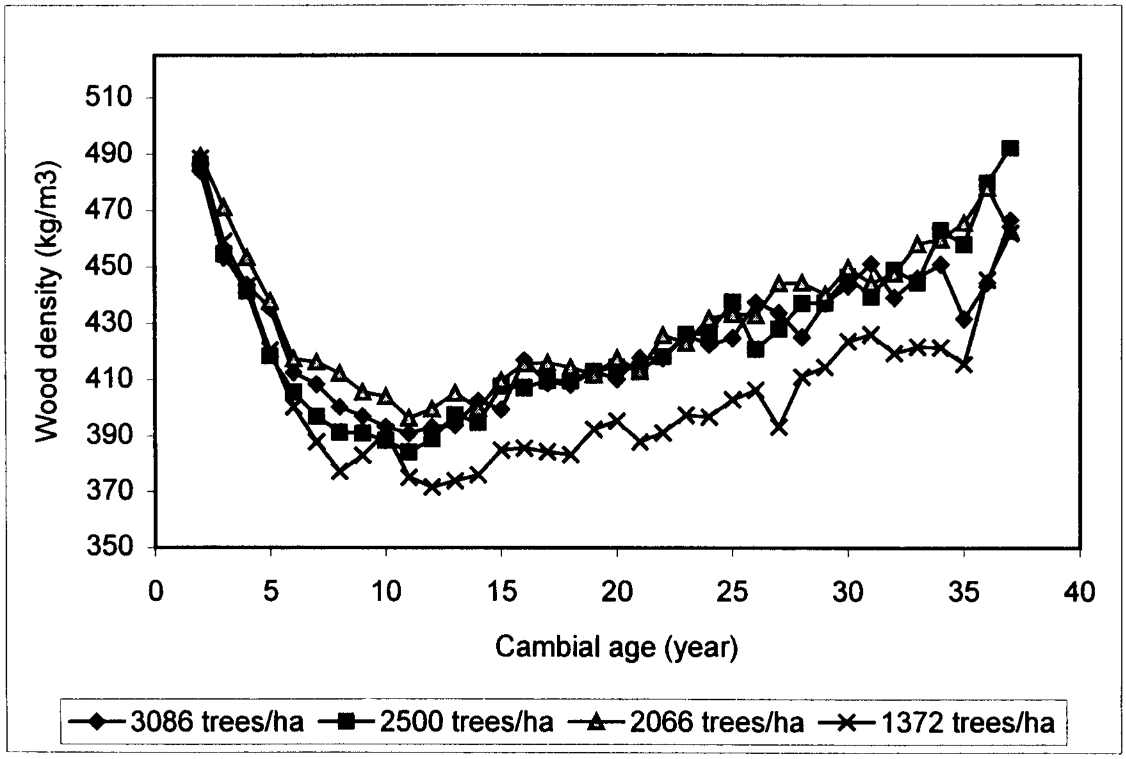

FIG. 2. Wood density in relation to cambial age and spacing (at 8-foot height of the tree).

for MSR lumber production in eastern Canada. Several Forintek studies show that before visual inspection, over 80% of the No. 2 and Better grades from natural stands of black spruce are qualified for MSR grades of 1650f-1.5E or better. However, only 24.5% of the lumber from the 48-year-old black spruce plantations is qualified for the same MSR grades (Table 8). Even when MSR grade 1450f-1.3E is included, the total MSR yield is still quite low (46.7%). Furthermore, the lowest stand density has the lowest MSR yield (23.5%) among the 4 spacings, whereas the highest stand density has the highest MSR yield (63.6%). Overall, MSR yield tends to increase with increasing stand density.

Table 9 shows the percentage of lumber pieces from SS, No. 1, No. 2, and No. 3 which meet current bending stiffness design values established for Spruce-Pine-Fir species (Barrett and Lau 1994). As shown in Table 10, mean MOE values obtained for SS grade (9,195 MPa), No. 1 and No. 2 grades (9,106 and 8,961 MPa, respectively), and No. 3 grade (8,258 MPa) are considerably lower than the required mean MOE values given in Table 9. As a result, it is not surprising that only 6.2% of the lumber pieces from the lowest stand density (Table 9) meet the required bending stiffness design values. However, the percentage of lumber pieces that meet the required bending stiffness design values tends to increase with increasing stand density. For example, 26.7% of the lumber from the highest stand density meets the required design values. Overall, only 18.4% of the lumber pieces from the plantation-grown black spruce meet the design requirements for bending stiffness. Of the 4 grades compared, grade SS has the lowest percentage of compliance to the design values. On average, only 15.5% of lumber pieces from this grade meet the bending stiffness design values, where grades No. 1 and No. 2, and grade No. 3 have a considerably higher

TABLE 11. *Average diameter of knots (larger than 1-cm diameter in the lumber) and knot frequency (number of the knots per lumber surface unit) in relation to visual grade and spacing.*

Visual grade	Initial stand density (trees/ha) 1372 Sample size			2066 Sample size			2500 Sample size			3086 Sample size			4 densities combined Sample size		
	Sample size	Average knot diameter (mm)	Knot frequency (#/m²)	Sample size	Average knot diameter (mm)	Knot frequency (#/m²)	Sample size	Average knot diameter (mm)	Knot frequency (#/m²)	Sample size	Average knot diameter (mm)	Knot frequency (#/m²)	Sample size	Average knot diameter (mm)	Knot frequency (#/m²)
Select structural	148	18.5	116	119	17.1	102	148	16.1	110	132	15.6	96	547	16.9 B[1]	106 B
No. 1	2	19.9	101	4	22.4	215	4	231	145	2	22.9	149	12	22.2 A	163 A
No. 2	67	17.9	121	46	16.8	103	49	17.1	101	41	15.8	124	203	17.0 B	113 AB
No. 3	12	19.0	129	7	18.4	93	10	192	169	3	13.7	68	32	18.5 B	128 A
Economy	16	17.7	168	12	17.5	138	17	16.6	128	10	17.3	115	55	17.2 B	139 A
Grand total	245	18.4	121	188	17.2	106	228	16.6	112	188	15.8	103	849	17.1	112

[1] Values sharing the same letter are not significantly different at the 0.05 level.

percentage of compliance (24.7% and 25.0%, respectively). Biblis et al. (1993) also found that a significant percentage of lumber from plantation-grown loblolly pine did not meet the bending design values for the assigned visual grades. Even with second-growth managed Douglas-fir resource, Barrett and Kellogg (1991) reported that lumber in all visual grades containing 90–100% juvenile wood did not meet the current grade requirements.

The design values established for Canadian lumber species (Barrett and Lau 1994) are based on in-grade tests initiated in the late 1970s and at that time the samples collected for the in-grade tests most likely came from high-quality natural stands. As the forest industry in Canada depends increasingly on managed resources for lumber manufacturing (Kellogg 1989), the design values established for major commercial species need to take the changing resource into consideration. From a forest management perspective, one option for ensuring that plantation-grown lumber meets the design values, is to harvest the plantations at a longer rotation age. By so doing, the mature wood content will increase and so will the lumber strength and stiffness. A longer rotation age will also lead to the production of larger sawlogs that yield a higher lumber volume recovery. In addition, it is also important to address the issue using all genetic means. Economically important wood quality traits need to be incorporated into tree breeding programs. In recent years, new forest biotechnologies (e.g., transgenic seedlings, embryogenesis) have also provided promising opportunities to generate future planting stocks with superior fiber quality traits.

Comparisons in bending properties among the visual grades

Table 10 shows the 5th percentile of MOR, mean MOR, and mean MOE for each visual grade in the 4 spacings. Higher lumber grades in the black spruce plantations are not necessarily associated with higher 5th percentile of MOR, mean MOR, and mean MOE. For ex-

TABLE 12. *Average ring width and basic wood density of lumber and its distance to the pith in relation to visual grade and spacing.*

	Initial stand density (trees/ha)							
	1,372				2,066			
Visual grade	Sample size	Ring width (mm)	Basic wood density (kg/m^3)	Distance to pith (cm)	Sample size	Ring width (mm)	Basic wood density (kg/m^3)	Distance to pith (cm)
Select structural	148	1.94	363	1.68	119	1.80	379	1.30
No. 1	2	1.61	374	3.00	4	1.83	386	0.00
No. 2	67	1.86	363	2.31	46	1.73	379	1.61
No. 3	12	2.05	368	1.79	7	1.78	374	2.00
Economy	16	2.38	376	0.80	12	2.28	393	0.73
Grand total	245	1.95	365	1.82	188	1.82	379	1.34

ample, grades SS and No. 2 from the lowest stand density (1,372 trees/ha) have a very comparable mean MOR and mean MOE, although No. 2 grade lumber has a lower 5th percentile of MOR. In fact, No. 1 grade lumber from the same stand density has an even higher 5th percentile of MOR, mean MOR, and mean MOE than the SS grade lumber, but the sample size is too small to take the differences seriously. As expected, No. 2 grade lumber has a higher mean MOR and mean MOE than the No. 3 grade lumber. However, the Economy grade has an even higher 5th percentile of MOR, mean MOR, and mean MOR than the No. 2 grade. These cases do not necessarily apply to the other densities. When the 4 spacings are combined, however, Economy grade still has a significantly higher mean MOR and MOE than the grade No. 3. Even if grade SS has a slightly higher mean MOR and mean MOE, the 4 grades SS, No. 1, No. 2, and Economy, actually show no statistically significant differences in either mean MOR or mean MOE. Only No. 3 grade has a significantly lower MOR and MOE.

The primary purpose of visual grading for structural lumber is to assign an appropriate allowable stress to each piece of lumber. In general, higher visual grades are associated with higher mean MOR and MOE despite some overlaps between two adjacent grades. This holds true in plantation-grown white spruce lumber (Zhou and Smith 1991) and plantation-grown loblolly pine lumber (Biblis et al. 1993). However, it does not apply to the plantation-grown black spruce lumber in this study, since higher visual grades do not have a significantly higher lumber strength and stiffness. This is not surprising considering the fact that 70% of the downgrades in this study are due to wane, whereas only a small percentage of the downgrades are due to those defects (e.g., knots, compression wood) that may affect lumber strength and stiffness. As shown in Table 11, SS grade lumber on average has the smallest knot diameter (16.9 mm) among the 5 grades. Moreover, lumber in this grade also has the lowest number of knots (larger than 1 cm at diameter) per lumber surface unit (106 knots/m^2), which is significantly lower than the other grades (except for grade No. 2). This suggests that as far as knot characteristics are concerned, visual grading is effective. However, many studies (Grant et al. 1984; Bier 1986; Barrett and Kellogg 1991; Zhou and Smith 1991) have shown that besides knot characteristics, other wood characteristics (e.g., wood density, juvenile wood content), to a varying extent, also have an effect on both lumber strength and stiffness although they are difficult to consider in visual grading. This study also examined wood density and juvenile wood content, while grain deviation was omitted from analysis because very few pieces had grain deviation. In this study, the distance to the pith served as an indicator of juvenile wood content. The closer to the pith a piece of lumber is, the higher

TABLE 12. *Extended.*

Initial stand density (trees/ha)											
2,500				3,086				4 densities combined			
Sample size	Ring width (mm)	Basic wood density (kg/m³)	Distance to pith (cm)	Sample size	Ring width (mm)	Basic wood density (kg/m³)	Distance to pith (cm)	Sample size	Ring width (mm)	Basic wood density (kg/m³)	Distance to pith (cm)
148	1.77	368	1.44	132	1.76	373	1.27	547	1.82 B[1]	370 B	1.43 B
4	2.18	400	1.33	2	2.19	370	0.00	12	1.95 B	383 AB	0.91 B
49	1.82	373	1.35	41	1.83	374	1.70	203	1.81 B	371 B	1.80 A
10	1.84	375	1.35	3	1.63	369	1.33	32	1.89 B	372 B	1.66 AB
17	1.90	390	1.10	10	1.97	382	0.95	55	2.13 A	385 A	0.91 B
228	1.80	371	1.39	188	1.79	373	1.34	849	1.84	372	1.49

[1] Values sharing the same letter are not significantly different at the 0.05 level.

juvenile wood content the piece should contain. As shown in Table 12, on average lumber grades Economy and No. 1 are the closest to the pith (0.91 cm), whereas grades No. 2 and No. 3 are the farthest from the pith. This indicates that grades No. 2 and No. 3 should have the lowest juvenile wood content, followed by SS grade, whereas No. 1 and Economy grades should contain the highest juvenile wood content. Surprisingly, Economy and No. 1 grades still have the highest wood densities (385 and 383 kg/m^3, respectively) despite their higher juvenile wood content and wider ring width, whereas SS grade has the lowest wood density (370 kg/m^3). Statistically, SS grade has a significantly lower wood density than Economy grade. The differences in wood density among the 5 grades help explain why Economy grade has lumber strength and stiffness no different from SS grade with smaller and fewer knots.

Table 12 also shows that the lowest wood density in SS grade is associated with the smallest ring width (1.82 mm/ring), whereas the largest ring width (2.13 mm/ring) in Economy grade is associated with the highest wood density. It is in contrast to a negative relationship between wood density and ring width that exists in many softwood species. However, it is very important to consider the cambial age effect on wood density. In fact, black spruce has a different pattern of radial variation (with cambial age), as shown in Figs. 1 and 2. Unlike many softwood species, wood density in black spruce is very high near the pith, then it decreases remarkably with increasing cambial age to a minimum before increasing again. As shown in Fig. 2, very high wood density in the first 5 rings from the pith coincides with the highest annual growth rate (or ring width) (Fig. 1). This explains why Economy grade lumber that is the closest to the pith still has the highest wood density despite its large ring width. This indicates that using ring width as an indicator of wood density in visual grading systems may not work well in this species.

This study clearly shows that visual grading is not effective in grouping the plantation-grown black spruce into distinctive strength/stiffness categories. This raises the need for machine grading this resource. A similar need was noted for the second-growth managed Douglas-fir resource, which has different wood quality characteristics than the old growth resource (Barrett and Kellogg 1991). Barrett and Kellogg (1991) estimated that loss in value of visually graded lumber due to juvenile wood content in the second-growth Douglas-fir was between 20 and 30%. If the material was machine graded, as much as half of the value loss due to visual grading could be recovered.

CONCLUSIONS

Based on the study on the 48-year-old black spruce initial spacing trial, the following conclusions can be reached:

1. When the initial stand density decreases from 3,086 to 2,066 trees/ha, branch diameter shows a steady increase; but the 3 initial spacings of 3,086, 2,500, and 2,066 trees/ha still have quite comparable Select Structural (SS) grade yields partly due to the relatively small branches in black spruce. When the initial spacing is reduced further to 1,372 tree/ha, however, a significant decrease in SS grade yield due to knots is expected.
2. Visual grading of the plantation-grown black spruce lumber is effective in characterizing knot diameter and frequency. Since wood density and other wood characteristics that may affect lumber strength and stiffness are not taken into consideration in visual grading, visual grades of the plantation-grown black spruce lumber can not effectively reflect their differences in lumber strength and stiffness. In fact, 4 grades SS, No. 1, No. 2, and Economy have no statistically significant difference in lumber strength and stiffness. This raises the need for machine grading this resource.
3. The stand densities of 3,086, 2,500, and 2,066 trees/ha have a comparable lumber strength and stiffness, while stand density of 1,372 trees/ha has a significantly lower strength and stiffness. However, the real concern arises when lumber from the 48-year-old black spruce plantations is compared to that from natural stands currently being processed in eastern Canada. The stiffness of the plantation-grown lumber is over 28.9% lower than that from natural stands. As a result, a high percentage of the plantation-grown lumber does not meet the design requirements for bending stiffness. However, the percentage of the compliance to the design values tends to increases with increasing initial stand density.

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