COMPARISON BETWEEN GENETIC AND ENVIRONMENTAL INFLUENCES ON LUMBER BENDING PROPERTIES IN YOUNG WHITE SPRUCE

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ABSTRACT

This study investigated variation in lumber bending properties of white spruce (*Picea glauca* [Moench] Voss) and its correlation with tree growth, wood density, and knot size and number. A total of 242 sample trees from 39 open-pollinated families harvested from 36-year-old provenance-progeny trials at two sites in Quebec, Canada through a thinning operation were processed. The results indicate that mechanical properties of lumber from young white spruce plantation-grown trees are low. It appears that low wood density, the occurrence of numerous knots, and a high proportion of juvenile wood are the main factors contributing to the low lumber stiffness and strength properties. The narrow-sense heritability for lumber stiffness was low to moderate, whereas that of strength was hardly different from zero. Thus environmental growing conditions highly influence white spruce wood mechanical properties. The results also revealed a strong negative correlation between stem volume and lumber stiffness and strength at the family means, which suggests that selection for volume would have an indirect negative effect on lumber quality. However, the absence of such significant correlation at the phenotypic level also suggests that mass selection with vegetative propagation would be a promising avenue for improving white spruce wood properties without having to give up gains in volume.

Keywords: Modulus of elasticity, modulus of rupture, *Picea glauca*, studs, wood density, knots.

INTRODUCTION

Sustained overall demand for wood products over the last century has stimulated industrial use of old-growth forest resources in most parts of the world. With major natural disturbance events, heavy harvesting has already seriously depleted available lumber resources from natural forests. To sustain the long-term wood supply, most countries have now had to resort to refor-

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estation programs and intensively managed plantations. For instance, the radiata pine (*Pinus radiata* D. Don) plantation area totals about 2.2 million hectares in New Zealand and Australia (Jayawickrama and Carson 2000). Over the next few years, the annual harvest of this species in New Zealand will increase to about 30 million m³ (Sorensson et al. 1997). In 1998, 1.1 million hectares of loblolly pine were planted in the United States (Moulton and Hernández 2000), 83% of which were located in the southeast (McKeand et al. 2003) and accounted for about 17% of the actual southern timberland (Stanturf et al. 2003). In Canada, about 425 000 hectares are planted yearly (CCFM 2003), mostly with spruces. With more and more plantations reaching rotation age, plantation-grown wood will rapidly become a major source of supply for the forest industry.

Intensive plantation forestry has made it possible to markedly increase production using limited territory areas. This success was achieved thanks to science-based developments in research fields such as nursery practices, soil-site classification, vegetation and pest management and tree breeding. With the use of genetically improved stock and intensive plantation silviculture, rotation age can also be reduced because trees reach marketable size more quickly. However, wood product quality is known to be highly influenced by shorter rotations because of the strong effect of juvenile wood on many wood properties (Bendtsen 1978; Zhou and Smith 1991; Kretschmann and Bendtsen 1992). While wood characteristics such as bending strength and stiffness can be partially predicted indirectly through wood density (Harris et al. 1976; Jozsa and Middleton 1994), more direct data are needed on mechanical properties of plantation-grown wood because juvenile wood is known to cause warping problems and to negatively affect bending properties due to the presence of spiral grain and wide microfibril angle with cell axis (Cave and Walker 1994; Zobel and Sprague 1998; Cown et al. 1999). Moreover, bending strength and stiffness properties of plantation-grown and second-growth lumber might be sufficiently different from the

properties of current lumber production to eventually affect design code properties (MacPeak et al. 1990; Barrett and Kellogg 1991). Bending properties of plantation-grown lumber have been studied for many species, including loblolly pine (*Pinus taeda* L.; Biblis et al. 1995), radiata pine (Bier 1986), slash pine (*Pinus elliottii* Engelm.; Biblis 1990), black spruce (*Picea mariana* (Mill.) B.S.P.; Zhang et al. 2002), and white spruce (*Picea glauca* [Moench] Voss; Zhou and Smith 1991). Geographical variation in these properties has also been examined for some species (see Burdon et al. (2001) for radiata pine, and Chui (1995) for Norway spruce (*Picea abies* (L.) Karst.), for instance), but genetic variation in these traits has been studied for only a very few species (e.g. McAlister and Powers 1994 (loblolly pine), Matheson et al. 1997a (radiata pine)) and not for white spruce.

White spruce is highly valued for lumber and is extremely versatile. Its dimensional stability (Beaulieu et al. 2003) and superior gluing properties make it popular in the prefabrication industry (Forintek Canada Corp. 1995). It is used in the manufacture of modular houses, trusses, and other structural components. Dimension lumber from white spruce of various sizes and grades is manufactured by many mills in eastern Canada and is used for a variety of products including building construction (framing, sheathing, roofing, sub-flooring), general millwork, and a variety of other products including furniture, edge joists, interior finishing, boxes and packing cases. The main objectives of this study were to explore the potential of achieving genetic gains in white spruce lumber properties. To do so, we (1) determined the extent of genetic variation in static bending lumber characteristics (MOE and MOR), and (2) examined the relationships between these traits and growth and knot characteristics at both the individual and family levels.

MATERIALS AND METHODS

Wood material

In the spring of 1969, 4-year-old seedlings raised at the Petawawa Research Forest, Ontario,

Canada (Lat. 45° 59′ N; Long. 77° 24′ W; Elev. 168 m) were used to establish a provenance-progeny test replicated at two sites in Québec. The two sites were located at the Valcartier Forest Experiment Station (Lat. 46° 50′ N; Long. 71° 30′ W; Elev. 150 m) and the Lac St. Ignace Arboretum (Lat. 49° 00′ N; Long. 66° 20′ W; Elev. 500 m). Both sites were abandoned farmlands. The surface deposit at Valcartier is a well-drained sand along the Jacques-Cartier River, while at Lac St. Ignace, it is a shaley till with the presence of boulders. The seedlings came from 39 open-pollinated families representing eight natural populations from the Ottawa River Valley in Ontario. The experimental layout was a randomized complete block design with four blocks. Each row plot contained 13 trees at 1.8-× 1.8-m spacing. Silvicultural treatment of both trials consisted of mechanical cleaning to prevent overgrowing by grass in the first three years and stem–pruning to a height of 2 m in 1986. At Valcartier, fertilizers were also applied three times to supply soil mineral nutrients due to a deficiency noted by foliage discoloration. Survival was much higher at Valcartier and a 40% thinning was performed in 1993 to stimulate growth of residual trees. After this thinning operation, survival was 57% and 35% at Valcartier and Lac St. Ignace, respectively.

In the fall of 2001, the provenance-progeny test plot was thinned and, whenever available, one tree per plot was retained for this study. A total of 286 trees from 39 families (four trees from each family) were harvested, with 156 trees successfully harvested from Valcartier but only 130 from Lac St. Ignace. This discrepancy was due to the fact that only 35 families could be sampled in Lac St. Ignace and that 10 of these families provided only three trees each. Tree heights were measured in the field before the trees were felled. Each sample tree was further cross-cut into two 8-ft (2.45 m)-long logs and transported to the Eastern Laboratory of Forintek Canada Corp. in Quebec City, Canada. The diameter at breast height (dbh) was then measured and tree volume estimated using a two-entry volume table (Bolghari and Bertrand 1984). The butt logs were processed with a por-table sawmill and converted to lumber for the evaluation of lumber properties. Depending on its diameter, the log was sawn to dimensions of 2 by 3 (50.8 mm × 76.2 mm), 2 by 4 (50.8 mm × 101.6 mm) or 2 by 6 (50.8 mm × 152.5 mm) inches. The number of boards obtained per log varied from 1 to 7, but was generally 3. Then, the lumber was kiln-dried to moisture content (MC) of 12% ± 3% with a drying schedule common in the eastern Canada lumber manufacturing industry. Due to the presence of white-rot decay in some of the logs, we had to reject them. Thus, the final number of sampled trees for this study was 242.

Measurement of lumber quality attributes

The lumber was first visually graded by a professional grader using the structural light framing classification system. All reasons for downgrading boards were noted. When a better grade could be given to the board by shortening it, this was done. Hence, about 15% of the studs were cut to 5-, 6- or 7-foot (1.52-, 1.83-, or 2.13-m)-long pieces. Lumber stiffness was estimated using the modulus of elasticity (MOE) whereas lumber strength was obtained via the modulus of rupture (MOR). Both were determined by bending tests using the "3rd–point-loading method" according to ASTM D4761-02a/D198-02e1 (ASTM 2002a). The bending tests were carried out using a Metriguard testing machine with a maximum load of 10,000 lbs (4536 kg). Both MOE and MOR values were adjusted to a 12% MC following the ASTM D-2915-03 procedure (ASTM 2003) and Practice D-1990-00 (ASTM 2002b). For the lumber less than 2.45 m long, MOE was adjusted to a uniform span-to-depth ratio of 17:1 following ASTM 2915-03 procedure (ASTM 2003). MOR for both 3-in. (7.6-cm) and 6-in. (15.2-cm) lumber was adjusted for size effect to a uniform width of 4 in. (10.2 cm) according to the method of Barrett and Lau (1994). The type of fracture of each board was recorded. The fracture patterns were classified as simple tension, brash tension, cross-grain tension, shear tension, and compression, as well as combinations of the first four individual fracture patterns and their appearance at a knot. The

number of knots per stud with a diameter greater than 10 mm was also counted. The diameters of the five biggest knots were measured and their average was calculated. Once all the measurements were carried out, a clear 15-cm-long sample was cut as close to the location of the fracture as possible. Using these clear wood samples, both growth rate and basic wood density, i.e., oven-dry weight on green volume, were determined. Data of every trait were averaged for each tree and then submitted to statistical analysis.

Statistical analyses

Data were submitted to analysis of variance using the following mixed model:

$$y_{ijkl} = \mu + \lambda_i + b_{ij} + \rho_k + \pi_{ik} + f_{kl} + s_{ij} + e_{ijkl},$$

where:

y_{ijkl} is the value of the dependent variable obtained from the tree sampled in the lth family ($l = 1, \ldots, 6$) from the kth provenance ($k = 1, \ldots, 8$) and located in the jth block ($j = 1, \ldots, 4$) in the ith site ($i = 1, 2$);

μ is an overall effect;

λ_i is the fixed effect of site i;

b_{ij} is the random effect of the jth block in the ith site; it is assumed that b_i is an observation from a normal distribution with mean zero and variance σ^2_b ($j = 1, \ldots, 4$);

ρ_k is the fixed effect of provenance k;

π_{ik} is the fixed effect of the interaction between the site i and the provenance k;

f_{kl} is the random effect of the lth family from the kth provenance; it is assumed that $f_{kl} \sim N(0, \sigma^2_f)$;

s_{il} is the random effect of family l under the growing conditions of site i; it is assumed that $s_{il} \sim N(0, \sigma^2_s)$; and,

e_{ijkl} is the random error term associated with a tree sampled in the plot (i,j) for the lth family of the kth provenance; it is assumed that $e_{ijkl} \sim N(0, \sigma^2_e)$.

Departure from the normal distribution and homogeneity of variance was tested for the residuals using statistics provided by Proc UNIVARIATE (SAS Institute Inc. 2001). The number of knots per stud had to be transformed using the square root transformation, whereas the average diameter of the five biggest knots and tree volume had to be transformed using logarithmic transformation to meet the assumptions. All analyses of variance were conducted to partition total genetic variation into the various components according to the model presented above. They were carried out with the GLM procedure of SAS (SAS Institute Inc. 2001), and the sums of squares were computed with the Type III function. Variance components were estimated using the VARCOMP procedure of SAS (SAS Institute Inc. 2001) with the REML method.

For the estimation of covariance of each pair of characteristics, the GLM procedure of SAS (SAS Institute Inc. 2001) was used with the MANOVA statement. The covariance components were estimated in equating each of the expected mean squares to the mean squares actually obtained and in solving the resulting equations for the individual components.

Families were considered as half-sibs, and additive genetic variance was then estimated as four times the family variance component (Falconer 1981). To determine the degree of genetic control of traits, heritabilities were obtained using the following equations:

$$h^2_i = 4\sigma^2_f/(\sigma^2_f + \sigma^2_s + \sigma^2_e), \text{ and}$$

$$h^2_f = \sigma^2_f/(\sigma^2_f + \sigma^2_s/s + \sigma^2_e/k_1),$$

where h^2_i and h^2_f are individual-tree and family-mean heritability, respectively, s is the number of blocks, and k_1 is the number of trees per family (Becker 1985, p. 51). Standard errors of the individual-tree heritability and heritability of family means were estimated according to Dickerson's method (Dieters et al. 1995).

Phenotypic correlations between traits for both individual trees and family means were estimated using the CORR procedure (SAS Institute Inc. 2001). The latter was used as a surrogate for estimating genetic correlation, recogniz-

ing the limitations of this method (see Lynch and Walsh 1998, pp. 636–637).

RESULTS

Means, mean ranges, and coefficients of variation of each trait measured either on white spruce trees or on lumber pieces obtained from these trees are presented in Table 1. On average, tree dbh and volume were higher at Lac St. Ignace than at Valcartier, whereas the contrary was observed for height with 12% superiority at Valcartier. Both lumber MOE and MOR were also higher at Valcartier than at Lac St. Ignace. The coefficients of variation of both lumber mechanical properties were of similar magnitude at both sites except for MOR, which was about 35% higher at Valcartier than at Lac St. Ignace (Table 1). Average wood densities measured on studs near the location of fracture after static bending tests were similar at both sites. Among all the wood traits and properties studied, the average number of knots per stud was the one having the largest coefficient of variation. Both the average number of knots per stud and its coefficient of variation were smaller at Lac St. Ignace than at Valcartier.

Results of the analyses of variance are presented in Table 2. There were significant differences between sites for most of the tree and lumber characteristics at $\alpha = 0.05$. Variance due to families within provenance was significantly different from zero ($p < 0.05$) for wood density only. Even though variance due to families was not significantly different from zero at the usual $\alpha = 0.05$ level for characteristics such as MOE, MOR, and knot frequency, it was not considered equal to zero. This decision is based on the Milliken and Johnson (1984, p. 262) recommendation to assume a variance component as zero when the p value is higher than 0.30. In doing so, we recognize however that the heritability estimates for these traits are very low and imprecise. Variance due to individual trees within a family (residual) accounted for most of the variation in all traits (Table 3). Wood density appeared to be under medium to strong genetic control whereas lumber MOE seemed to be un-

TABLE 1. *Least square means, ranges of family means and coefficients of variation for growth and dimension lumber characteristics of 39 open-pollinated families tested on two sites.*

Characteristics	Valcartier			Lac St. Ignace			Overall		
	Mean	Mean range	Coefficient of variation	Mean	Mean range	Coefficient of variation	Mean	Mean range	Coefficient of variation
Height (m)	14.9	13.5–16.1	4.2	13.3	11.1–15.4	7.8	14.2	12.3–15.7	4.5
Dbh (cm)	19.3	16.5–23.8	8.6	21.4	17.0–25.6	9.9	20.3	18.4–23.0	6.2
Volume (dm³)	0.188	0.131–0.311	20.3	0.205	0.137–0.285	20.5	0.200	0.157–0.275	14.4
MOE (MPa)	6956	5003–10036	14.9	5428	4019–7140	14.3	6214	4942–7680	10.3
MOR (MPa)	33.88	22.82–52.60	17.9	28.26	19.69–36.36	13.3	30.84	23.24–40.39	11.0
Wood density	0.312	0.285–0.341	3.5	0.319	0.293–0.344	4.1	0.317	0.296–0.336	2.9
Growth rate (mm)	4.88	3.29–5.75	10.6	5.35	4.50–6.30	7.4	5.10	4.32–5.79	6.5
Number of knots	40.7	24.9–70.0	27.9	36.3	21.4–54.4	23.0	37.9	23.2–49.9	16.2
Knot size (mm)	15.85	12.4–20.0	10.6	18.38	15.7–21.6	6.9	17.09	14.9–20.2	6.5

TABLE 2. *Type III analysis of variance for growth and dimension lumber characteristics of 39 open-pollinated families tested at both Valcartier and Lac St. Ignace sites.*

		Height	Dbh	Volume	MOE	MOR	Wood density	Growth rate	Knot frequency	Knot size
Source of variation	df*	$P > F$	$P > F$	$P > F$	$P > F$	$P > F$	$P > F$	$P > F$	$P > F$	$P > F$
Fixed effects										
Site	1	0.0095	0.0022	0.1971	0.0004	0.0131	0.3340	0.0379	0.1018	0.0007
Provenance	7	0.1626	0.4705	0.3445	0.2315	0.1430	0.5859	0.0150	0.1563	0.1882
Site*provenance	7	0.1455	0.0758	0.0250	0.1259	0.0085	0.8082	0.4212	0.0132	0.4146
Random effects										
Block(S)	6	<.0001	0.0936	0.0560	0.0644	0.0229	0.0002	0.0049	0.0989	0.1014
Family(P)	31	0.3805	0.3480	0.2696	0.0922	0.1951	0.0144	0.5955	0.1445	0.4639
Site*Famiy(P)	27	0.0862	0.0411	0.1770	0.3187	0.6308	0.3895	0.4831	0.0342	0.3283
Residuals	206									

* The degrees of freedom for the residuals of lumber characteristics is 163.

TABLE 3. *Estimates of genetic parameters for growth and dimension lumber characteristics of 39 open-pollinated families tested at both sites.*

Characteristics	σ^2_{pheno}	σ^2_f	$\sigma^2_{residual}$	h^2_i	h^2_f
Height	1.9208	0.1184	1.8023	—	—
Dbh	7.8268	0.0785	6.8036	—	—
Volume	0.0906	0.0024	0.0840	0.107 ± 0.281	0.139 ± 0.365
MOE	1.6158	0.1127	1.4169	0.279 ± 0.320	0.301 ± 0.346
MOR	57.2979	0.2249	57.0730	0.016 ± 0.174	0.025 ± 0.277
Wood density	3.827 10^{-4}	0.4280 10^{-4}	3.399 10^{-4}	0.447 ± 0.261	0.450 ± 0.263
Growth rate	0.5397	—	0.5397	—	—
Knot frequency	0.9801	0.0500	0.7563	0.204 ± 0.399	0.197 ± 0.387
Knot size	0.0194	—	0.0192	—	—

der low to medium genetic control. Other growth and wood characteristics seemed to be highly influenced by the environment, the genetic control over them being low to very low, as expected from the ANOVA results.

Lumber MOE and MOR showed moderate positive and significant phenotypic correlations with tree height, but they were not significant at the family mean level (Table 4). MOE showed also low to moderate negative phenotypic correlation with dbh whereas at the family mean level, it was moderately negatively correlated with both dbh and volume. Lumber MOR correlated with dbh and volume only at the family mean level and these correlations were negative (Table 4). It was also highly positively correlated to lumber MOE at the phenotypic and family mean levels (Table 4). MOE and MOR were also negatively correlated at both the phenotypic and family mean levels with knot frequency and knot size.

DISCUSSION

The nonsignificant variation among families at $\alpha = 0.05$ for height and dbh was unexpected. Indeed, these traits are known to be under low to moderate genetic control, and significant family variation has already been reported in the literature (Dhir 1976; Kiss and Yeh 1988; Li et al. 1993; Xie and Yanchuk 2002). This situation is likely due to the way the material was assembled for the study. Trees were obtained from a low thinning of the genetic tests. This thinning was the second to be carried out in these tests and consequently, little variation was observed in dbh and height. With random selection of trees, higher total and among family variation than in the present study would have likely been observed as in previous studies.

The mechanical performance of wood is described by both MOE (stiffness) and MOR (strength). Lumber MOE is seen as the most

TABLE 4. *Estimated individual-tree phenotypic* (above diagonal) and family means† (below diagonal) correlations between growth and dimension lumber characteristics of 39 open-pollinated families tested at both sites. P-values are between parentheses.*

Characteristics	Height	Dbh	Volume	MOE	MOR	Wood density	Growth rate	Knot frequency	Knot size
Height	1.000	0.055 (0.3936)	0.430 (<0.0001)	0.434 (<0.0001)	0.317 (<0.0001)	−0.193 (0.0026)	−0.111 (0.0835)	−0.076 (0.2381)	−0.187 (0.0034)
Dbh	0.114 (0.4898)	1.000	0.921 (<0.0001)	−0.204 (0.0014)	−0.072 (0.2634)	−0.098 (0.1265)	0.552 (<0.0001)	−0.193 (0.0026)	0.525 (<0.0001)
Volume	0.411 (0.0094)	0.948 (<0.0001)	1.000	−0.016 (0.8007)	0.059 (0.3562)	−0.172 (0.0073)	0.458 (<0.0001)	−0.201 (0.0016)	0.405 (<0.0001)
MOE	0.064 (0.6966)	−0.447 (0.0043)	−0.428 (0.0066)	1.000	0.714 (<0.0001)	0.109 (0.0898)	−0.415 (<0.0001)	−0.207 (0.0012)	−0.404 (<0.0001)
MOR	0.101 (0.5420)	−0.357 (0.0258)	−0.335 (0.0372)	0.821 (0.0001)	1.000	0.115 (0.0725)	−0.220 (0.0001)	−0.252 (<0.0001)	−0.357 (<0.0001)
Wood density	−0.145 (0.3788)	0.285 (0.0782)	0.245 (0.1328)	−0.095 (0.5642)	−0.097 (0.5579)	1.000	−0.209 (0.0011)	−0.003 (0.9635)	−0.047 (0.4657)
Growth rate	0.159 (0.3327)	0.649 (<0.0001)	0.648 (<0.0001)	−0.453 (0.0038)	−0.302 (0.0620)	0.029 (0.8607)	1.000	−0.097 (0.1306)	0.482 (<0.0001)
Knot frequency	−0.020 (0.9041)	−0.160 (0.3300)	−0.114 (0.4896)	−0.355 (0.0267)	−0.257 (0.1137)	−0.021 (0.8974)	0.079 (0.6342)	1.000	0.191 (0.0028)
Knot size	0.093 (0.5716)	0.483 (0.0019)	0.507 (0.0010)	−0.625 (<0.0001)	−0.678 (<0.0001)	0.079 (0.6326)	0.454 (0.0037)	0.344 (0.0319)	1.000

* n = 243
† n = 39

important attribute among lumber quality traits. Indeed, wood stiffness is generally more significant than wood strength for mechanical performance (Kliger 2000). In this study, overall lumber MOE and MOR were very low. Mean lumber MOE was 37% lower than that of lumber from white spruce grown in natural forests (Jessome 1977), and 41% lower than lumber from SPF (Spruce-Pine-Fir group) in Canada by the standard CAN/CSA-086.1-M89 (CWC 2001).

In softwoods, lumber MOE and MOR values are known to be lower when the proportion of juvenile wood (Pearson and Gilmore 1971; Bendtsen 1978; Barrett and Kellogg 1991; Kretschmann and Bendtsen 1992; Kennedy 1995; Bao et al. 2001) and the microfibril angle (Olson and Poletika 1947; Cave and Walker 1994; Megraw et al. 1999) are higher. The count of year rings near the top end of the logs determined a mean age of 18 years. In plantation-grown white spruce, it is generally assumed that mature wood formation does not start before the 15th ring (Corriveau et al. 1990; Zhou and Smith 1991). Using this criterion, the juvenile wood content was estimated to be 84.8% in the present study. Thus, it is clear that most of the lumber was made of juvenile wood only and that the high proportion of juvenile wood content was likely the main reason for the poor bending properties observed. Unfortunately, microfibril angle was not measured, and it is not possible to directly relate low bending properties to this characteristic. In addition, the high growth rate and low density may have contributed to the low strength and stiffness values observed. Estimates of wood density reported here are slightly lower than those already published (see for instance Jessome 1977; Corriveau et al. 1987; Corriveau et al. 1991). However, differences are likely due to the fact that contrary to the other studies, samples were not all collected at the dbh but at a height varying from tree to tree and corresponding to the point where the lumber fracture happened during the bending test. Estimating wood density from samples close to the fracture zone should help increase the correlation between wood density and mechanical properties. Thus, even if wood density is generally believed to be a good indicator of mechanical properties (Porter 1981), considering the overall low cor-

relation observed in this study (see Table 4), it appears that, at least for the white spruce population assayed, density is not a good predictor of dimension lumber strength from juvenile wood. Other features of juvenile wood, such as the presence of compression wood, are known to dramatically affect wood density without improving lumber strength as would be expected from its high density (Keith and Kellogg 1981). However, when visual grading of the boards was done, only 2.4% were downgraded in one of the test sites due to that reason, whereas in the second test site, no boards were downgraded due to the presence of compression wood. Thus, the presence of compression wood cannot be put forward to explain the low correlation observed. Additionally, relatively few lumber pieces had deviated grains.

Considerable variation was also observed at both sites in growth rate and lumber quality traits (Table 1). Numerous authors have shown the importance of environmental effects on wood properties (see Zobel and van Buijtenen 1989). One of the most difficult environmental factors to relate to wood quality is the overall effect of soil and climate, which is often referred to as site quality (see Zobel and Jett 1995, p. 43). In this study, the environmental factors at the two sites had significant effects on both lumber MOE and MOR (Table 1 and Table 2). MOE and MOR at Valcartier were 28% and 20% higher than at Lac St. Ignace, respectively. While trees were significantly taller at Valcartier than at Lac St. Ignace, their average dbh was smaller (Table 2). Indeed, the radial growth rate at Valcartier was about 10% lower than at Lac St. Ignace (Table 1). Differences in environmental factors between the two sites brought about very contrasting plantation densities, which in turn had a major impact on stem form. In 1993, (i.e., 25 years after planting), survival at Valcartier was three times that at Lac St. Ignace (97% vs 35%). A negative correlation was found between bending traits and dbh as well as with growth rate, especially at the family mean level when data from both sites were combined (Table 4). Lower survival at Lac St. Ignace, which resulted in higher radial growth, is likely the main

factor that negatively affected lumber MOE and MOR on that site. The negative effect of fast radial growth on bending properties has already been reported for other species such as Scots pine (Mattsson 2002), loblolly pine (Pearson and Gilmore 1980; Biblis et al. 1997), radiata pine (Grant et al. 1984), Douglas-fir (Barrett and Kellogg 1991), and Norway and Sitka spruces (Danborg 1996).

The average numbers of knots per full-size lumber were around 41 and 36 at Valcartier and Lac St. Ignace, respectively (Table 1). The average frequency of knots per stud was lower at Lac St. Ignace but the knots were about 16% larger (Table 1). This is likely because survival was lower at Lac St. Ignace and thus average spacing was larger, which allowed trees to develop bigger branches and crowns. Previous studies carried out on different tree species showed that average knot ratio and wood density had significant effects on stress grades of structural timber and plywood from radiata pine (Grant et al. 1984; Okuma et al. 1984; Bier 1985, 1986). In this study, lumber MOE and MOR were negatively correlated with knot frequency and size at both the phenotypic and family means levels. Moreover, the percentage of studs that showed knot-related fractures totaled 68.5% of the tested lumbers. This result is in close agreement with those of Zhou and Smith (1991), who examined lumber properties from 52-year-old plantation-grown white spruce. They found that knots directly contributed to the failure of 46% of the lumber pieces, and that altogether 73% of the failures observed were knot-related when including fractures caused indirectly by knots. A similar percentage had previously been reported for white spruce by Rochester (1938). Growth rate and knot size are two characteristics that are correlated to each other at both the phenotypic and family means levels. This is expected as when spacing is larger, trees develop larger crowns, bigger branches and larger stem diameters.

Wood density near the fracture zone was the trait showing the highest heritability, with values around 0.45 at both the family and individual levels (Table 3). This moderate to high herita-

bility is in accordance with estimates reported in previous studies on white spruce (Corriveau et al. 1991; Yanchuk and Kiss 1993; Ivkovich et al. 2002), even though densities were not measured at the same tree position. The additive genetic variance in lumber MOE accounted for a moderate proportion of the total phenotypic variance, whereas that in MOR was very low and the estimates were rather imprecise (Table 3). Heritability estimates of these two wood properties in radiata pine were reported as being 0.42 for MOE and 0.72 for MOR (see Matheson et al. 1997a, 1997b). Thus, it seems that genetic control of these properties is much lower in white spruce juvenile wood than in radiata pine. However, because of the small number of families used in the present study and the rather limited area of provenance of these families, we believe that additional studies are needed before coming to a definite conclusion about the strength of genetic control of these traits in white spruce. Phenotypic and family mean correlations between wood density and MOE/MOR were not significantly different from zero (Table 4). While wood density can be improved by selection in white spruce (Corriveau et al. 1991), even though this might be slow due to the low coefficient of additive genetic variation (Table 3), progress in wood density would not be followed by progress in bending lumber properties in that species.

Moderate heritability was also found in knot frequency with a high coefficient of variance. Therefore, it seems that breeding for trees with crowns bearing fewer branches is possible in white spruce. Based on the family mean correlation estimates of MOE and MOR with knot frequency, it appears that some progress could be indirectly made in MOE and MOR by selecting and breeding trees with fewer branches. Moreover, as the correlation between knot frequency and knot size is positive and significantly different from zero, selection for trees with fewer branches would also result in a reduction of average knot size, all other environmental variables being the same. Based on the estimates of heritability for volume (Table 3), it appears that some progress could also be made

in tree volume by selecting the best families. However, because the correlation of MOR and MOE family means with volume are negative and significantly different from zero (Table 4), any progress in stem dimension would bring about deterioration in lumber bending properties. Knowledge of correlations between traits studied is essential for tree breeders to understand how selection for a specific trait would indirectly affect other traits.

Finally, compared with the family variance components, the residual variance components of all traits analyzed in this study were much larger, indicating a substantial amount of phenotypic variation among trees within families. This suggests that mass selection followed by vegetative propagation would likely be the fastest method to increase MOE and MOR values in white spruce and obtain end-use-quality products.

CONCLUSIONS

This study indicates that the conversion of fast-growing white spruce thinning at mid-rotation into lumber may present some quality concerns. It appears that low wood density, numerous knots, and a high proportion of juvenile wood are the main factors contributing to the low lumber stiffness and strength. Environmental conditions and planting density may have a strong effect on lumber quality and growth traits. The strong negative correlations between volume and MOE/MOR at the family means level suggest that selection for lumber stiffness and strength in white spruce might lead to a decrease in wood volume production in the next generation and vice versa.

This study was based on a relatively small sample size in two test sites. Results reported here must be considered as preliminary, and additional studies are needed to better evaluate the potential to improve both white spruce volume and wood quality using selection and breeding.

REFERENCES

AMERICAN SOCIETY FOR TESTING MATERIALS (ASTM) D4761-02a/D198-02e1. 2002a. Standard test methods for mechanical properties of lumber and wood-base structural material/Standard test methods of static tests of lumber in structural sizes. ASTM International, West Conshohocken, PA.

———— D1990-00. 2002b. Standard practice for establishing allowable properties for visually-graded dimension lumber from in-grade tests of full-size specimens. ASTM International, West Conshohocken, PA.

———— 2915-03. 2003. Standard practice for evaluating allowable properties for grades of structural lumber. ASTM International, West Conshohocken, PA.

BAO, F. C., Z. H. JIANG, X. M. JIANG, X. X. LU, X. Q. LUO, AND S. Y. ZHANG. 2001. Differences in wood properties between juvenile wood and mature wood in 10 species grown in China. Wood Sci. Technol. 35(4):363–375.

BARRETT, J. D., AND R. M. KELLOGG. 1991. Bending strength and stiffness of second-growth Douglas-fir dimension lumber. Forest Prod. J. 41(10):35–43.

————, AND W. LAU. 1994. Canadian lumber properties. Canadian Wood Council, Ottawa, Canada. 346 pp.

BEAULIEU, J., B. GIRARD, AND Y. FORTIN. 2003. Study of geographical variation in kiln-drying behavior of plantation-grown white spruce. Wood Fiber Sci. 35(1):56–67.

BECKER, W. A. 1985. Manual of quantitative genetics. 4th edition. Academic Enterprises, Pullman, WA. 194 pp.

BENDTSEN, B. A. 1978. Properties of wood from improved and intensively managed trees. Forest Prod. J. 28(10):61–72.

BIBLIS, E. J. 1990. Properties and grade yield of lumber from a 27-year-old slash pine plantation. Forest Prod. J. 40(3):21–24.

————, H. CARINO, R. BRINKER, AND C. W. MCKEE. 1995. Effect of stand density on flexural properties of lumber from two 35-year-old loblolly pine plantations. Wood Fiber Sci. 27(1):25–33.

————, ————, AND ————. 1997. Flexural properties of lumber from two 40-year-old loblolly pine plantations with different stand densities. Wood Fiber Sci. 29(4):375–380.

BIER, H. 1985. Bending properties of structural timber from a 28-year-old stand of New Zealand *Pinus radiata*. N. Z. J. For. Sci. 15(2):233–250.

————. 1986. Log quality and the strength and stiffness of structural timber. N. Z. J. For. Sci. 16(2):176–186.

BOLGHARI, H. A., AND V. BERTRAND. 1984. Tables préliminaires de production des principales essences résineuses plantées dans la partie centrale du sud du Québec. Gouv. Quebec, Min. Energ. Ressour., Serv. Rech., Mem. Rech. For. No 79. 392 pp.

BURDON, R. D., R. A. J. BRITTON, AND G. B. WALFORD. 2001. Wood stiffness and bending strength in relation to density in four native provenances of *Pinus radiata*. N. Z. J. For. Sci. 31(1):130–146.

CANADIAN COUNCIL OF FOREST MINISTERS (CCFM). 2003. National Forestry Database Program. http://nfdp.ccfm.org. (18 October 2004)

CANADIAN WOOD COUNCIL (CWC). 2001. Wood Design Manual 2001. Ottawa, ON. 900 pp.

CAVE, I. D., AND J. C. F. WALKER. 1994. Stiffness of wood in fast-grown plantation softwoods: The influence of microfibril angle. Forest Prod. J. 44(5):43–48.

CHUI, Y. H. 1995. Grade yields and wood properties of Norway spruce (*Picea abies* (L.) Karst.) from the Maritimes. For. Chron. 71(4):473–478.

CORRIVEAU, A., J. BEAULIEU, AND F. MOTHE. 1987. Wood density of natural white spruce populations in Quebec. Can. J. For. Res. 17(7):675–682.

————, ————, ————, J. POLIQUIN, AND J. DOUCET. 1990. Densité et largeur de cernes des populations d'Épinettes blanches de la région forestière des Grands Lacs et du Saint-Laurent. Can. J. For. Res. 20(2):121–129.

————, ————, AND G. DAOUST. 1991. Heritability and genetic correlations of wood characters of Upper Ottawa Valley white spruce populations grown in Quebec. For. Chron. 67(6):698–705.

COWN, D. J., J. HEBERT, AND R. BALL. 1999. Modelling *Pinus radiata* lumber characteristics. Part 1: Mechanical properties of small clears. N. Z. J. For. Sci. 29(2):203–213.

DANBORG, F. 1996. Juvenile wood in Norway and Sitka spruce: Anatomy, density, drying properties, visual grading and strength properties. Forskningsserien no. 18. Danish Forest and Landscape Research Institute, Horsholm, Denmark.

DHIR, N. K. 1976. Stand, family, and site effects in Upper Ottawa Valley white spruce. Pages 88–97 *in* D. W. Einspahr, ed. Twelfth Lake States Forest Tree Improvement Conference. August 28–22, 1975. Petawawa, ON. USDA Forest Service, General Technical Report NC-26. St. Paul, MN

DIETERS, M. J., T. L. WHITE, R. C. LITTELL, AND G. R. HODGE. 1995. Application of approximate variances of variance components and their ratios in genetic tests. Theor. Appl. Genet. 91:15–24.

FALCONER, D. S. 1981. Introduction to quantitative genetics. Longman, London, UK, 340 pp.

FORINTEK CANADA CORP. 1995. Characteristics of Alberta commercial tree species. Properties of white spruce (*Picea glauca* (Moench) Voss). Alberta Department of Economic Development and Tourism. 16 pp.

GRANT, D. J., A. ANTON, AND P. LIND. 1984. Bending strength, stiffness, and stress-grade of structural *Pinus radiata*: effect of knots and timber density. N. Z. J. For. Sci. 14(3):331–348.

HARRIS, J. M., R. N. JAMES, AND M. J. COLLINS. 1976. Case for improving wood density in radiata pine. N. Z. J. For. Sci. 5(3):347–354.

IVKOVICH, M., G. NAMKOONG, AND M. KOSHY. 2002. Genetic variation in wood properties of interior spruce. I. Growth, latewood percentage, and wood density. Can. J. For. Res. 32(12):2116–2127.

JAYAWICKRAMA, K. J. S., AND M. J. CARSON. 2000. A breeding strategy for the New Zealand radiata pine breeding cooperative. Silvae Genet. 49(2):82–90.

JESSOME, A. P. 1977. Strength and related properties of woods grown in Canada. Forestry Tech. Rep. 21. Eastern Forest Products Laboratory. Ottawa, ON.

JOZSA, L. A., AND G. R. MIDDLETON. 1994. A discussion of wood quality attributes and their practical implications. Forintek Canada Corp. Special Publ. No. SP-34. 42 pp.

KEITH, C. T., AND R. M. KELLOGG 1981. The structure of wood. Chapter 3, Pages 41–70 *in* E. J. Mullins and T. S. McKnight, eds. Canadian woods. Their properties and uses. University of Toronto Press, Toronto, ON.

KENNEDY, R. W. 1995. Coniferous wood quality in the future: Concerns and strategies. Wood Sci. Technol. 29: 321–338.

KISS, G., AND F. C. YEH. 1988. Heritability estimates for height for young interior spruce in British Columbia. Can. J. For. Res. 18:158–162.

KLIGER I. R. 2000. Mechanical properties of timber products required by end-users. Proc. World Conference on Timber Engineering, July 31–August 3, 2000, Whistler, BC. 9 pp.

KRETSCHMANN, D. E., AND B. A. BENDTSEN. 1992. Ultimate tensile stress and modulus of elasticity of fast-grown plantation loblolly pine lumber. Wood Fiber Sci. 24(2): 189–203.

LI, P., J. BEAULIEU, A. CORRIVEAU, AND J. BOUSQUET. 1993. Genetic variation in juvenile growth and phenology in a white spruce provenance-progeny test. Silvae Genet. 42(1):52–60.

LYNCH, M., AND B. WALSH. 1998. Genetics and analysis of quantitative traits. Sinauer Associates Inc., Sunderland, MA. 980 pp.

MACPEAK, M. D., L. F. BURKART, AND D. WELDON. 1990. Comparison of grade, yield, and mechanical properties of lumber produced from young fast-grown and older slow-grown planted slash pine. Forest Prod. J. 40(1):11–14.

MATHESON, A. C., J. L. YANG, AND D. L. SPENCER. 1997a. Breeding radiata pine for improvement of sawn product value. Pages IV-19–IV-26 in S. Y. Zhang, R. Gosselin, and G. Chauret, eds. Timber management toward wood quality and end-product value. Proc. CTIA/IUFRO International Wood Quality Workshop, August 18–22, 1997, Quebec City, Canada.

———, D. J. SPENCER, J. G. NYAKUENGAMA, J. YANG, AND R. EVANS. 1997b. Breeding for wood properties in radiata pine. Pages 169–179 *in* R. D. Burdon, and J. M. Moore, eds. IUFRO 97' Genetics of Radiata Pine. Proc. NZFRI-IUFRO Conference. 1–5 December 1997, Rotorura, New Zealand. New Zealand Forest Research Institute Bulletin No. 203.

MATTSSON, S. 2002. Effect of site preparation on stem growth and clear wood properties in boreal *Pinus sylvestris* and *Pinus contorta*. Acta Universitatis Agriculturae Sueciae Silvestria, 240. 139 p.

MCALISTER, R. H., AND H. R. POWERS. 1994. A comparison of some physical and mechanical properties of full-sib and half-sib loblolly pines. Forest Prod. J. 44(2):42–44.

MCKEAND, S., T. MULLIN, T. BYRAM, AND T. WHITE. 2003. Deployment of genetically improved loblolly and slash pines in the South. J. For. 101(3):32–37.

MEGRAW, R., D. BREMER, G. LEAF, AND J. ROERS. 1999. Stiffness in loblolly pine as a function of ring position and height, and its relationship to microfibril angle and specific gravity. Pages 341–349 *in* G. Nepveu, ed. Workshop IUFRO S5.01-04. La Londe-Les-Maures, September 5–12, 1999. INRA, Nancy, France.

MILLIKEN, G. A., AND D. E. JOHNSON. 1984. The analysis of messy data, Vol. 1. Designed experiments. Van Nostrand Reinhold Co., New York, NY.

MOULTON, R. J. AND G. HERNANDEZ. 2000. Tree planting in the United States–1998. Tree Planters' Notes 49(2): 23–26.

OKUMA, M., N. NAKAMURA, AND K. YAMADA. 1984. Manufacture and performance of radiata pine plywood. II. Pruning effect on the properties of plywood. J. Jap. Wood Res. Soc. 30(6):440–447.

OLSON, R. A., AND N. V. POLETIKA. 1947. Strength properties of plantation-grown coniferous woods. Conn. Agric. Exp. Stn. Bull. 511.

PEARSON, R. G., AND R. C. GILMORE. 1971. Characterization of the strength of juvenile wood of loblolly pine (*Pinus taeda* L.). Forest Prod. J. 21(1):23–30.

——— AND ———. 1980. Effect of fast growth rate on mechanical properties of loblolly pine. Forest Prod. J. 30(5):47–54.

PORTER, A. W. 1981. Strength and physical properties of wood. Chapter 4, Pages 71–96 *in* E. J. Mullins and T. S. McKnight, eds. Canadian woods. Their properties and uses. University of Toronto Press, Toronto, ON.

ROCHESTER, G. H. 1938. The strength of eastern Canadian spruce timbers in sizes shipped to the United Kingdom. Canada Forest Service. Circular 54.

SAS INSTITUTE INC. 2001. SAS OnlineDoc®, version 8.02. SAS Institute Inc., Cary, NC.

SORENSSON, C. T., D. J. COWN, B. G. RIDOUTT, AND X. TIAN.

1997. The significance of wood quality in tree breeding: a case study of radiata pine in New Zealand. Pages IV-35–IV-44 in S. Y. Zhang, R. Gosselin, and G. Chauret, eds. Timber Management Toward Wood Quality and End-Product Value. Proc. CTIA/IUFRO International Wood Quality Workshop, August 18–22, 1997, Quebec City, Canada.

STANTURF, J. A., R. C. KELLISON, F. S. BROERMAN, AND S. B. JONES. 2003. Productivity of southern pine plantations. Where are we and how did we get here? J. For. 101(3): 26–31.

XIE, C.-Y., AND A. D. YANCHUK. 2002. Genetic parameters of height and diameter of interior spruce in British Columbia. Forest Genet. 9(1):1–10.

YANCHUK, A. D., AND G. K. KISS. 1993. Genetic variation in growth and wood specific gravity and its utility in the improvement of interior spruce in British Columbia. Silvae Genet. 42(2/3):141–148.

ZHANG, S. Y., G. CHAURET, H. Q. REN, AND R. DESJARDINS. 2002. Impact of initial spacing on plantation Black spruce lumber grade yield, bending properties, and MSR yield. Wood Fiber Sci. 34(3):460–475.

ZHOU, H., AND I. SMITH. 1991. Factors influencing bending properties of white spruce lumber. Wood Fiber Sci. 23(4):483–500.

ZOBEL, B. J., AND J. B. JETT. 1995. Genetics of wood production. Springer-Verlag GmbH & Co. KG, Berlin, Germany.

———, AND J. R. SPRAGUE. 1998. Juvenile wood in forest trees. Springer Series in Wood Science. T. E. Timell, ed. Springer-Verlag, New York, NY.

———, AND J. P. VAN BUIJTENEN. 1989. Wood variation. Its causes and control. Springer-Verlag GmbH & Co. KG, Berlin, Germany.