STUDY OF GEOGRAPHICAL VARIATION IN KILN-DRYING BEHAVIOR OF PLANTATION-GROWN WHITE SPRUCE

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ABSTRACT

White spruce (*Picea glauca* [Moench] Voss) is one of the most important tree species for reforestation in Canada. Over the past 30 years, hundreds of thousands of hectares were planted. Plantation-grown wood will become an important source of supply for the lumber industry in the near future. Plantation wood is generally known to have a greater proportion of juvenile wood than that from natural stands. For this reason, quality attributes of lumber from plantations might be considerably reduced, especially after kiln-drying. However, these quality attributes might be influenced by the origin of the seed sources used for the reforestation program. The main purpose of this study was to investigate the genetic variation in the effect of kiln-drying under restraint on shrinkage and warp of dimension lumber processed from 26 provenances originating from the Great Lakes and St. Lawrence Region. Two drying treatments were applied, i.e. conventional and high-temperature drying. Analyses of variance showed no significant differences among provenances for any type of shrinkage (longitudinal shrinkage, shrinkage in thickness, shrinkage in width) or warp (bow, crook, twist) measurements. For the effect of the drying treatment, it was significant only in the case of shrinkage in width.

Keywords: Kiln-drying, restraint, shrinkage, warp, plantation.

INTRODUCTION

The interaction of environmental factors with genetic systems leads to the development of patterns of geographical variation and presumably to the genetic differentiation of populations within a species (Morgenstern 1996). The existence of such a variation is well known and so far has been reported for many tree species (Kriebel 1957; Mergen 1963; Nienstaedt 1969; Morgenstern 1978; Fowler and Park 1988). Wood characteristics often vary as greatly within the range of a species as do growth and adaptability (Zobel and van Buijtenen 1989). Numerous studies have confirmed this fact for traits such as wood density and tracheid length, among others (Zobel et al. 1960; Einspahr and Benson 1967; Taylor et al. 1982; Yanchuk et al. 1984; Corriveau et al. 1987). While wood density provides an indirect means of predicting end-use characteristics of wood such as strength, stiffness, and hardness (Jozsa and Middleton 1994), more

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direct data on the variation of wood processing behavior and mechanical properties are needed, especially when trees are grown in plantations. Indeed, with the worldwide move to fast-growing species and shorter rotation stocks and use of genetically improved material, the proportion of juvenile wood in harvested logs is expected to increase. Juvenile wood is known to cause warping problems that originate from an excessive longitudinal shrinkage and/or spiral grain (Zobel and Sprague 1998). The eventual occurrence of geographical variation in the number and the importance of drying defects would make it possible to improve the quality of kiln-dried products by choosing provenances with the most desirable properties.

The main objective of this study was to investigate the genetic variation in shrinkage and warp in the kiln-drying of 26 white spruce provenances originating from the Great Lakes and St. Lawrence Region. The effect of the drying technique on these quality traits was also investigated.

MATERIALS AND METHODS

Materials

In the spring of 1964, 4-year-old seedlings raised at the Petawawa National Forestry Institute (lat. 45°59′N, long. 77°24′W) were used to establish a provenance trial at the Harrington Forest Farm, now owned by Bowater Incorporated (lat. 45°48′N, long. 74°38′W). The seedlings were from 25 provenances sampled in the Great Lakes and St. Lawrence Region (Table 1). Spacing was 1.8 m × 1.8 m. The experimental design was a randomized complete block design, with each provenance represented by a 6 × 6 square plot. Twenty-one years after planting, trees were pruned up to 2 m in height. Twelve years later, i.e. in the fall of 1996, the provenance trial was thinned with a feller/delimber. Six trees from each provenance, having a diameter of at least 17 cm at a height of 5 m, were retained for the current study. Whenever possible, the six trees were taken from the first block. For a few provenances, trees coming from the second block were used to complete the test material. The average diameter below bark at stump level was about 25 cm with values ranging from 20.5 to 36.5 cm.

Each tree was first cross-cut into 2.5-m-long logs. Only the two first logs were kept for this study. These were processed directly on site into three rough-sawn 2 × 4 studs (50 mm × 100 mm) using a portable band sawmill. The log was first squared on three faces and then ripsawn so that the middle piece was boxed-pith, and the two other pieces contained mostly sapwood. Each board was labelled with an aluminum tag identifying the provenance, the tree, and the position of the log (butt or top) in the stem. The lumber was solidly piled, wrapped in plastic film, and transported to Université Laval (Sainte-Foy, Quebec) to be stored at -20°C until further processing. Six more trees were harvested in a natural stand at the Valcartier Forest Experiment Station near Quebec City (lat. 46°56′N, long. 71°28′W). These were processed into 2 × 4s in the same way as for the trees from the provenance trial and were used as the forest-grown standard for data analysis.

Methods

The lumber was dried to a final moisture content (FMC) of 10% in an experimental kiln of 2.5 m^3 capacity at Université Laval. Two treatments were applied, i.e. conventional drying and high-temperature drying. Each treatment was replicated three times (Fig. 1). The drying schedules were based on commercially developed schedules for white spruce dimension stock (Cech and Pfaff 1978) and adapted to the drying of value-added products (target FMC of 10%). A complete description of treatments is provided in Girard et al. (submitted).

In order to constitute the six drying loads, the lumber was first divided into six groups, the six boards from the same tree belonging to the same group. Because of the loss of identification for some material in the logging-

TABLE 1. *Geographic origin of white spruce seed lots used in the study.**

Place Name	Latitude (° ′ N)	Longitude (° ′ W)	Elevation (m)	Traits[1]								
				Shrinkage (%)						Warp (mm)		
				In thickness		In width		Longitudinal				
				Conv.[2]	High[3]	Conv.	High	Conv.	High	Δ bow	Δ crook	Δ twist
Peterborough, ON	44 33	78 15	250	3.13	4.01	2.99	2.44	0.16	0.18	2.4	0.3	6.3
Winchester, ON	45 06	75 21	75	3.49	4.42	3.56	3.05	0.19	0.16	3.9	0.7	3.9
Cushing, QC	45 36	74 28	60	2.84	3.64	2.96	2.37	0.21	0.16	3.1	0.6	5.4
Beloeil, QC	45 34	73 12	30	3.08	3.80	3.22	2.70	0.23	0.18	3.9	0.6	6.0
Grandes Piles, QC	46 41	72 44	150	3.20	4.29	3.05	2.76	0.19	0.15	2.8	0.5	5.0
St-Raymond, QC	46 54	71 50	120	2.66	4.60	3.32	2.70	0.19	0.16	3.6	1.2	4.8
Casey, QC	47 53	74 11	425	2.74	4.14	2.99	2.73	0.20	0.15	3.6	0.4	5.1
Lac Mattawin, QC	46 49	74 18	490	3.20	4.54	3.20	2.65	0.16	0.12	3.0	0.2	5.8
Canton Franchère, QC	46 51	75 02	425	2.91	4.34	2.94	2.46	0.17	0.16	2.6	0.8	5.9
Réservoir Baskatong, QC	46 48	75 50	305	3.27	3.84	3.28	2.38	0.15	0.23	1.8	0.8	7.1
Lac Dumoine, QC	46 54	77 54	365	3.27	3.20	3.54	2.27	0.16	0.14	2.6	1.2	5.2
Notre-Dame-du-Laus, QC	46 05	75 37	245	2.65	3.69	2.98	2.44	0.17	0.15	3.5	0.6	3.6
Chalk River, ON	46 01	77 27	150	3.18	3.63	2.89	2.61	0.24	0.15	3.8	0.8	4.7
Miller Lake, ON	46 15	81 00	215	3.38	4.07	3.13	2.52	0.14	0.15	3.5	0.1	5.9
Monk, QC	47 06	69 59	365	3.45	3.82	3.31	2.60	0.19	0.17	2.7	1.8	4.9
Price, QC	48 36	68 07	60	2.73	4.16	2.93	2.76	0.20	0.16	2.7	0.5	4.0
Edmundston, NB	47 23	68 20	245	2.71	4.30	3.09	2.69	0.19	0.16	4.3	0.5	3.5
Kakabeka, ON	48 24	89 37	300	3.30	4.24	3.21	3.05	0.15	0.15	2.2	0.8	4.4
Lac Mitchinamecus, QC	47 21	75 07	425	3.34	4.00	2.87	2.55	0.14	0.13	2.8	0.2	5.3
Lac Simard, QC	47 37	78 41	245	3.85	3.06	3.62	2.47	0.14	0.16	3.6	0.4	5.7
Swastika, ON	48 06	80 06	365	2.85	3.89	3.06	2.60	0.15	0.21	3.2	0.3	4.7
Valcartier, QC	46 56	71 28	180	2.93	3.74	2.99	2.36	0.22	0.17	3.4	0.2	3.0
Grand Rapids, MN	47 14	93 31	410	2.50	3.80	3.04	2.51	0.17	0.16	2.7	0.8	4.7
Luce, MI	46 30	85 30	215	2.95	3.78	3.04	2.47	0.19	0.16	2.6	0.6	4.6
Marquette, MI	46 33	87 23	440	3.45	3.95	3.11	2.78	0.16	0.17	3.7	0.1	6.2
Second-growth forest	46 52	71 32	150	2.97	3.55	3.35	2.43	0.14	0.14	3.9	1.4	2.9
Overall mean				3.08	3.94	3.14	2.59	0.18	0.16	3.1	0.6	4.9

* Location of the provenance trial: Lat. 45° 48′N, Long: 74° 38′W, Elev. 150 m.
[1] Δ bow, differential bow (bow after kiln-drying − bow before kiln-drying), Δ crook, differential crook, Δ twist, differential twist.
[2] Conventional temperature drying.
[3] High-temperature drying.

sawing process, only 24 of the 26 provenances (including the forest-grown standard) were present in five of the six drying loads, the sixth one containing 25 provenances. Wherever necessary, green dummy specimens were used to complete the stack made of 15 rows of 10 boards each. Three groups among the six available were randomly selected and used as replicates for conventional drying while the three others were submitted to high-temperature drying. Because of the variation in lumber thickness due to the use of a portable sawmill, the lumber was presurfaced on both wide faces to a thickness of 41.5 mm just prior to drying. A top-load restraint of 7.2 kg/m^2 (150 lb/ft^2) was applied in each drying run.

Evaluation of drying quality

Before drying, weight and dimension measurements were performed on each of the 144 to 150 pieces of the kiln load. Initial warp (bow, crook, and twist) was also assessed to the nearest 1 mm on a plane steel I-beam. The same data were repeated immediately after drying. In addition, the average FMC of each stud was obtained using a resistance-type moisture meter. Residual drying stresses were determined by two techniques. For the perpendicular-to-grain stresses, a 25-mm-long section was cut at two different locations (at the center and 15 cm from one of the ends) of stud No. 3 from both logs. Only four prov-

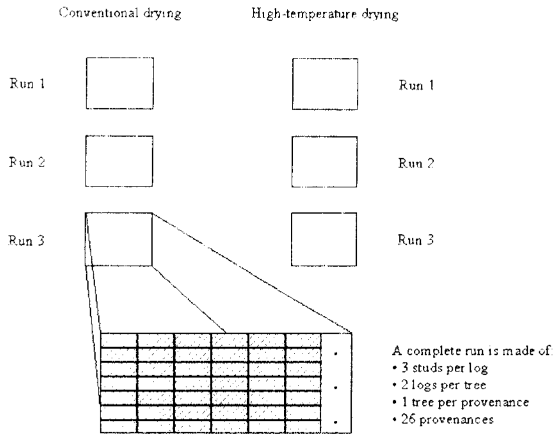

FIG. 1. Schematic representation of the experimental design used in this study.

enances were considered for this test because it was time-consuming and material had to be put aside for machining (Hernández et al. 2001) and mechanical tests. Each section was resawn into seven slices parallel to the wide face of the board (McMillen 1955). The length of each slice was measured before and after cutting using a LVDT sensor, and the recovery strain served as an indication of the perpendicular-to-grain stress present in the board. Final moisture content profiles across the thickness of the board were also determined from the same slices through oven-drying. For longitudinal stresses, stud No. 3 of 13 other provenances was resawn lengthwise across the thickness to produce two 2 × 2s. This led to the relief of longitudinal stresses and the resulting warp. Bow, crook, and twist were then recorded to the nearest 1 mm. In order to estimate the real effect of each treatment, statistical analyses on warp were performed on differential values, which were obtained from warp measurements before and after drying.

Data analysis

For the data collected on 2 × 4 studs before and after kiln-drying, the analysis of variance was based on the following mixed model:

$$Y_{ijklm} = \mu + \tau_i + r_{ij} + \rho_k + (\tau\rho)_{ik} + s_{ijk} + \lambda_l + (\tau\lambda)_{il} + t_{ijl} + (\rho\lambda)_{kl} + (\tau\rho\lambda)_{ikl} + u_{ijkl} + e_{ijklm}, \quad (1)$$

where:

Y_{ijklm} is the trait measured on the mth stud from the log in position l in the tree representing provenance k submitted to treatment i in run j;

μ is an overall effect;

τ_i is the effect of ith treatment (conventional or high-temperature kiln-drying) (i = 1,2);

r_{ij} is the random effect of the jth run within the ith drying technique; it is assumed that r_{ij} is an observation from a normal distribution with mean zero and variance σ^2_r (j = 1, 2, 3);

ρ_k is the effect of the kth provenance (k = 1, . . . , 26);

$(\tau\rho)_{ik}$ is the effect of the interaction between the ith drying technique and the kth provenance;

s_{ijk} is the random tree effect; it is assumed that $s_{ijk} \sim N(0, \sigma^2_s)$;

λ_l is the effect of the lth log position (first or second log of the stem, l = 1, 2);

$(\tau\lambda)_{il}$ is the effect of the interaction between the ith drying technique and the lth log position;

t_{ijl} is the random effect of the group of logs in the lth position for all provenances in the jth run within the ith drying technique; it is assumed that $t_{ijl} \sim N(0, \sigma^2_t)$;

$(\rho\lambda)_{kl}$ is the effect of the interaction between the kth provenance and the lth log position;

$(\tau\rho\lambda)_{ikl}$ is the effect of the interaction between the ith drying technique, the kth provenance and the lth log position;

u_{ijkl} is the random effect of the log in the lth position from the kth provenance in the jth run within the ith drying technique; it is assumed that $_{uijkl} \sim N(0, \sigma^2_u)$; and

e_{ijklm} is a random error term associated with the mth stud from the log in the lth position of the trees of the kth provenance, in the jth run within the ith drying technique; it is assumed that $e_{ijklm} \sim N(0, \sigma^2_e)$.

The model was reduced to its most straightforward form by testing successively for the significance of each variance component, starting with σ^2_u and ending with σ^2_r. If, based on a likelihood ratio statistic test, a given random effect was not significant at 0.30, it was excluded from the model as recommended by Milliken and Johnson (1984). On the contrary, it was not excluded from the model, and the reduction process was carried on with other random effects not yet tested.

For data collected on resawn studs (i.e. on 2×2s), model (1) was modified to take into account the effects of the two pieces of wood coming from the same stud:

$$Y_{ijklm} = \mu + \tau_j + r_{ij} + \rho_k + (\tau\rho)_{ik} + s_{ijk} + \lambda_l + (\tau\lambda)_{il} + t_{ijl} + (\rho\lambda)_{kl} + (\tau\rho\lambda)_{ikl} + e_{ijklm}, \quad (2)$$

where symbols are defined as in model (1) up to $(\tau\rho\lambda)_{ikl}$. The term u_{ijkl} was removed because there was only one stud considered by log position. For the term e_{ijklm}, it is a random error term associated with the m^{th} part of the stud from the log in the l^{th} position of the trees of the k^{th} provenance in the j^{th} run within the i^{th} drying technique; it is assumed that $e_{ijklm} \sim N(0, \sigma^2_e)$.

The perpendicular-to-grain stress measurements as well as the FMC across the thickness of the studs, obtained from the wood slices, were analyzed with repeated measures mixed models of analysis of variance developed on rules similar to those for models (1) and (2). Due to lack of space, these models are not presented here but can be obtained from the author upon request. The random error term was assumed to be $\sim N(\mathbf{O}, \Sigma)$, with $\mathbf{O}$ being a 7×1 vector of zeros, and Σ being a 7×7 symmetric positive definite matrix with variances on its main diagonal and covariances elsewhere. The models were reduced to their most straightforward form in investigating the structure of Σ through a hierarchical series of variance-covariance structures. Each structure in the hierarchy was compared with the previous one through a likelihood-ratio test. For perpendicular-to-grain stresses, the final structure of Σ was one of compound symmetry. The compound symmetry covariance structure is such that the errors on any pair of slices are constant and the variances on the diagonal are also constant but distinct from the covariances out of the diagonal. For FMC, a Toeplitz structure with seven parameters (Littell et al. 1996) was finally selected. The Toeplitz covariance structure is such that the covariance between the errors on adjacent slices is constant, the covariance between the errors for two slices situated two locations apart is also constant, but distinct from that for adjacent pairs, and so on. This means that the covariances in Σ are constant along any diagonal or subdiagonal, distinct from one diagonal or subdiagonal to another, and not constrained to be larger for adjacent slices than for more remote ones.

Model (2) as well as the models developed for perpendicular-to-grain stresses and FMC across the thickness were also reduced to their most straightforward form following the same procedure as for model (1). The MIXED procedure of SAS was used to perform all the analyses of variance (Littell et al. 1996; SAS Institute Inc. 1997). Correlation analysis (Proc CORR, SAS Institute Inc. 1997) was performed among all the wood traits including the nominal relative density in order to show the relationships existing among warp and shrinkage and the effect of wood density on them.

RESULTS AND DISCUSSION

Shrinkage and warp mean values for each provenance after kiln-drying are presented in Table 1. Shrinkage in thickness for conventional drying varied from 2.50% to 3.85% with an overall mean of 3.08%, and for high-temperature drying, it varied from 3.06% to 4.60% with an overall mean of 3.94%. The corresponding overall mean values for shrinkage in width were 3.14% and 2.59%, respectively. As expected, the high-temperature drying treatment increased shrinkage in thickness and decreased shrinkage in width in compar-

TABLE 2. *Observed significance ($P > F^1$) associated with the analysis of variance of shrinkage variables.*

	Shrinkage in thickness			Shrinkage in width			Longitudinal shrinkage		
	df[2]			df			df		
	dfn	dfd	(P > F)	dfn	dfd	(P > F)	dfn	dfd	(P > F)
Fixed effects[3]									
Treatment (τ)	1	4.1	0.0190	1	4.1	0.0048	1	4.1	0.2258
Provenance (ρ)	25	89.1	0.6823	25	762	0.5132	25	89.3	0.4025
Treatment × provenance ($\tau\rho$)	25	89.1	0.5350	25	762	0.8221	25	89.3	0.4297
Log position (λ)	1	672	0.8573	1	761	0.6046	1	672	0.0001
Treatment × log position ($\tau\lambda$)	1	672	0.3391	1	761	0.3081	1	672	0.4081
Provenance × log position ($\rho\lambda$)	25	672	0.1640	25	761	0.9998	25	672	0.2986
Treatment × provenance × log position ($\tau\rho\lambda$)	25	672	0.9974	25	761	0.9997	25	672	0.5355

[1] Significant at $\alpha = 0.05$ after Bonferroni correction when $P < 0.0083$ (0.05/6).
[2] df, degrees of freedom; dfn, degrees of freedom of the numerator; dfd, degrees of freedom of the denominator.
[3] Random effects are not shown because they are not of interest in the current study.

ison with the conventional drying treatment (Cech and Huffman 1974). Longitudinal shrinkage was similar for both drying treatments. Average differential bow varied from 1.8 mm to 4.3 mm, while differential crook varied from almost nothing for Miller Lake, Ontario, to 1.8 mm for Monk, Quebec. Under the same conditions, differential twist was more important than the two other warp defects with an overall mean of 4.9 mm and a maximum of 7.1 mm for Réservoir Baskatong, Quebec.

The ANOVA showed that the type of kiln-drying treatment significantly affected shrinkage in width (Table 2). For shrinkage in thickness, differences between both drying treatments were almost significant at the 0.05 level (after Bonferroni correction). This confirms the importance of creep during presteaming and high-temperature drying (Wu and Milota 1995), making shrinkage in width smaller and shrinkage in thickness greater. For the four other traits measured, it was not possible to reject the hypothesis that both drying treatments produced similar results (Tables 2 and 3), despite the fact that there was on average 10% less grade fall down with high-temperature drying. Moreover, an analysis of variance carried out on stud grading values based on NLGA standards did not make it possible to detect any significant differences between treatments (Girard et al. submitted). High-temperature drying under restraint, as was carried out in the present study, is known to produce

TABLE 3. *Observed significance ($P > F^1$) associated with the analysis of variance of warp variables collected on 2 × 4 studs.*

	Δ bow[2]			Δ crook			Δ twist		
	df[3]			df			df		
	dfn	dfd	(P > F)	dfn	dfd	(P > F)	dfn	dfd	(P > F)
Fixed effects[4]									
Treatment (τ)	1	4.2	0.3599	1	4.1	0.8340	1	4.3	0.2781
Provenance (ρ)	25	89.5	0.9304	25	89.4	0.2223	25	89.6	0.1741
Treatment × provenance ($\tau\rho$)	25	89.5	0.8687	25	89.4	0.0223	25	89.6	0.9522
Log position (λ)	1	672	0.0009	1	93.1	0.0008	1	672	0.0001
Treatment × log position ($\tau\lambda$)	1	672	0.6534	1	93.1	0.8368	1	672	0.2603
Provenance × log position ($\rho\lambda$)	25	672	0.6381	25	93.1	0.9508	25	672	0.9993
Treatment × provenance × log position ($\tau\rho\lambda$)	25	672	0.6084	25	93.1	0.8485	25	672	0.9815

[1] Significant at $\alpha = 0.05$ after Bonferroni correction when $P < 0.0083$ (0.05/6).
[2] See Table 1 for definitions.
[3] df, degrees of freedom; dfn, degrees of freedom of the numerator; dfd, degrees of freedom of the denominator.
[4] Random effects are not shown because they are not of interest in the current study.

lumber with higher quality in an overall shorter drying time (Price and Koch 1980). Wood is known to develop more creep and mechano-sorptive deformation under stress at higher temperatures (Wu and Milota 1995). The redistribution and relaxation of internal drying stresses would thus allow us to obtain lumber with fewer defects.

Neither differences among the provenances tested nor the interaction between provenances and drying treatments were significant for any of the shrinkage and warping traits. Furthermore, there was no significant difference between the plantation and the second-growth stand studs for any of the traits. The absence of significant differences among provenances is somewhat surprising because variation among provenances exists in white spruce for several traits including growth traits as well as wood density (Nienstaedt and Teich 1972; Beaulieu and Corriveau 1985; Li et al. 1997). The use of top load restraint for both drying treatments probably contributed to the uniformity of drying quality among provenances.

The absence of differences at the population level means that the end-use quality traits considered in this study cannot be improved in selecting superior provenances. However, that does not preclude the presence of differences among families and genotypes within families. Indeed, for most of the forest tree species, the vast majority of the variation is within provenances or populations, and this is the major source of variation the geneticists use in selection and breeding programs (Zobel and Talbert 1984).

Wood from plantations is known to have a higher proportion of juvenile wood (Zobel and Sprague 1998), which has properties such as the presence of spiral grain and/or high longitudinal shrinkage that tend to increase warp during the drying process (Haslett et al. 1999). In the current study, no significant differences were found for any defects between the plantation-grown wood and that from the second-growth forest. This is probably due to the fact that second-growth white spruce wood has characteristics similar to those of plantation-grown wood. On the other hand, recent studies seem to indicate that little of the warp in graded softwood lumber grown in a naturally regenerated forest is attributable to measurable growth characteristics in the lumber (Milota 1992; Beard et al. 1993; Wu and Smith 1998).

While the log position in the tree stem did not significantly affect shrinkage in thickness or shrinkage in width, it had a significant effect on longitudinal shrinkage and warp defects due to kiln-drying (Table 3). Longitudinal shrinkage as well as bow and crook differential defects were significantly higher in studs coming from the butt log. Differential twist was, however, higher in the second log. Average longitudinal shrinkage was 0.18% and 0.15% for the butt and second log, respectively, with a standard error of 0.0046%. For the same positions, the average defects were, for differential bow, 3.57 mm and 2.74 mm with a standard error of 0.251 mm, for differential crook, 0.92 mm and 0.46 mm with a standard error of 0.134 mm, and for differential twist, 4.43 mm and 5.40 mm with a standard error of 0.031 mm. This log position effect is likely related to differences in wood characteristics such as proportion of juvenile wood and growth ring curvature.

The ANOVA on nominal relative density (oven-dry weight/volume at FMC) of studs showed the presence of significant differences between the drying treatments (Table 4). On average, the high-temperature drying treatment caused a higher volumetric shrinkage than the conventional process (Table 1). Nonetheless, the average nominal relative density of studs dried at high temperatures was smaller, i.e. 0.332, as compared with 0.340 for the studs dried at conventional temperatures, the standard error being 0.0032. This apparent discrepancy could be explained by the fact that high-temperature drying leads to some hydrolysis of hemicelluloses (Goring 1963), and thus to a weight decrease.

Overall nominal relative density for studs coming from plantation material varied from 0.319 for Cushing, Quebec, to 0.357 for Winchester, Ontario; and on average a significant

TABLE 4. *Observed significance (P > F) associated with the analysis of variance of nominal relative density of 2 × 4 studs.*

	df			
	dfn	dfd	F	(P > F)
Fixed effects[1]				
Treatment (τ)	1	89.4	6.68	0.0114
Provenance (ρ)	25	92.8	3.11	0.0001
Treatment × provenance ($\tau\rho$)	25	92.8	0.48	0.9808
Log position (λ)	1	4.41	0.16	0.7043
Treatment × log position ($\tau\lambda$)	1	4.41	0.06	0.8141
Provenance × log position ($\rho\lambda$)	25	669	1.28	0.1673
Treatment × provenance × log position ($\tau\rho\lambda$)	25	669	0.94	0.5533

[1] Random effects are not shown because they are not of interest in the current study.

difference among the plantation-grown provenances was disclosed. These results confirm those observed by Corriveau et al. (1990) using 24-year-old material collected from the same set of provenances in another replication of the provenance trial. The nominal relative density of studs representing the second-growth forest was also significantly different from those of the provenance test with an average of 0.384, compared with 0.334.

Results of the ANOVA on longitudinal drying stresses, i.e. the warp measurements conducted on resawn studs, showed that only the interaction between the provenance and the log position in the tree (Table 5) was hardly significant. All other effects were not significant at an α level of 0.05. Here again, the application of a top-load restraint has likely contributed to the decrease in variability between provenances.

Results of the ANOVA on perpendicular-to-grain drying stresses and on FMC profiles obtained from the slicing technique are presented in Table 6. For perpendicular-to-grain stress, significant differences were found among provenances as well as between slices. A significant interaction between treatment and log position in the stem was also disclosed. Differences among provenances are due mainly to the Winchester, Ontario, provenance that was significantly different from the three others originating either from Quebec or Michigan. The stress profiles across the thickness of the studs are presented for both treatments in Fig. 2A. Stresses follow a quadratic pattern ($p \leq 0.0001$) from surface to core. Although the

TABLE 5. *Observed significance (P > F*[1]*) associated with the analysis of variance of warp variables collected on resawn studs.*

	Δ bow[2]			Δ crook			Δ twist		
	df[3]			df			df		
	dfn	dfd	(P > F)	dfn	dfd	(P > F)	dfn	dfd	(P > F)
Fixed effects[4]									
Treatment (τ)	1	8.9	0.1707	1	9.13	0.3748	1	52	0.2840
Provenance (ρ)	12	49	0.6019	12	49.8	0.3879	12	51.5	0.1295
Treatment × provenance ($\tau\rho$)	12	49	0.3246	12	49.8	0.4036	12	51.5	0.8236
Log position (λ)	1	6.95	0.9630	1	7.44	0.3063	1	49.8	0.0218
Treatment × log position ($\tau\lambda$)	1	6.95	0.8171	1	7.44	0.5093	1	49.8	0.8944
Provenance × log position ($\rho\lambda$)	12	203	0.0139	12	45.8	0.6006	12	49.2	0.4883
Treatment × provenance × log position ($\tau\rho\lambda$)	12	203	0.1904	12	45.8	0.4586	12	49.2	0.2661

[1] Significant at $\alpha = 0.05$ after Bonferroni correction when $P < 0.0167$ (0.05/3).
[2] See Table 1 for definitions.
[3] df, degrees of freedom; dfn, degrees of freedom of the numerator; dfd, degrees of freedom of the denominator.
[4] Random effects are not shown because they are not of interest in the current study.

TABLE 6. *Observed significance (P > F[1]) associated with the analysis of variance of perpendicular-to-grain stresses and FMC profiles obtained from slices of wood cut at two locations on 2 × 4 studs.*

	Perpendicular-to-grain stresses			FMC		
	df[2]			df[2]		
	dfn	dfd	(P > F)	dfn	dfd	(P > F)
Fixed effects[3]						
Treatment (τ)	1	4	0.0389	1	3.91	0.0245
Provenance (ρ)	3	60.5	0.0064	3	17.6	0.0293
Treatment × provenance ($\tau\rho$)	3	60.5	0.6664	3	17.6	0.2555
Log position (λ)	1	60.5	0.3900	1	24.3	0.8093
Treatment × log position ($\tau\lambda$)	1	60.5	0.0024	1	24.3	0.2961
Provenance × log position ($\rho\lambda$)	3	60.5	0.5511	3	24.3	0.6667
Treatment × provenance × log position ($\tau\rho\lambda$)	3	60.5	0.6224	3	24.3	0.3486
Location (β)	1	60.5	0.9944	1	54.7	0.0804
Treatment × location ($\tau\beta$)	1	60.5	0.3435	1	54.7	0.2742
Provenance × location ($\rho\beta$)	3	60.5	0.0449	3	54.7	0.4485
Treatment × provenance × location ($\tau\rho\beta$)	3	60.5	0.5877	3	54.7	0.8777
Log position × location ($\lambda\beta$)	1	60.5	0.5973	1	54.7	0.5634
Treatment × log position × location ($\tau\lambda\beta$)	1	60.5	0.4331	1	54.7	0.2093
Treatment × provenance × log position × location ($\tau\rho\lambda\beta$)	3	60.5	0.5239	3	54.7	0.8034
Slice (δ)	6	382	0.0001	6	93.2	0.0001
$Slice_{lin.}$	1	382	0.2731	1	93.2	0.1650
$Slice_{qua.}$	1	382	0.0001	1	93.2	0.0001
Lack of fit	4	382	0.7859	1	93.2	0.0001
Treatment × slice ($\tau\delta$)	6	382	0.4330	6	93.2	0.0752
Provenance × slice ($\rho\delta$)	18	382	0.1749	18	93.2	0.6563
Treatment × provenance × slice ($\tau\rho\delta$)	18	382	0.2401	18	93.2	0.9666
Log position × slice ($\lambda\delta$)	6	382	0.8754	6	93.2	0.6852
Treatment × log position × slice ($\tau\lambda\delta$)	6	382	0.5398	6	93.2	0.8218
Provenance × log position × slice ($\rho\beta\delta$)	18	382	0.9238	18	93.2	0.9259
Treatment × provenance × log position × slice ($\tau\rho\lambda\delta$)	18	382	0.9574	18	93.2	0.9488
Location × slice ($\beta\delta$)	6	382	0.9229	6	93.2	0.9786
Treatment × location × slice ($\tau\beta\delta$)	6	382	0.8345	6	93.2	0.3425
Provenance × location × slice ($\rho\beta\delta$)	18	382	0.9341	18	93.2	0.6628
Treatment × provenance × location × slice ($\tau\rho\beta\delta$)	18	382	0.9775	18	93.2	0.8541
Log position × location × slice ($\lambda\beta\delta$)	6	382	0.6729	6	93.2	0.8984
Treatment × log position × location × slice ($\tau\lambda\beta\delta$)	6	382	0.1113	6	93.2	0.8534
Provenance × log position × location × slice ($\rho\lambda\beta\delta$)	18	382	0.9210	18	93.2	0.9393
Treatment × provenance × location × slice ($\tau\rho\beta\delta$)	18	382	0.6679	18	93.2	0.9354

[1] Significant at $\alpha = 0.05$ after Bonferroni correction when $P < 0.025$ (0.05/2).
[2] df, degrees of freedom; dfn, degrees of freedom of the numerator; dfd, degrees of freedom of the denominator.
[3] Random effects are not shown because they are not of interest in the current study.

treatments are not significantly different at 0.05 after a Bonferroni correction, the level of significance is close to 0.05. The observed differences are due mainly to higher tensile stresses in the center of the studs for high-temperature drying. For the FMC profiles, treatments were significantly different as were slice positions. Average FMC values at the surface of the studs were higher for conventional drying than for high-temperature drying. FMCs increased quadratically ($p \leq 0.001$) from surface to core for both treatments (Fig. 2B). The difference in the FMCs between the surface and the center of the studs was slightly higher for the conventional drying treatment (1.10% on average) than for high-temperature drying (0.93% on average).

A correlation analysis showed that shrinkage in width was the only wood defect that was significantly interrelated with nominal rel-

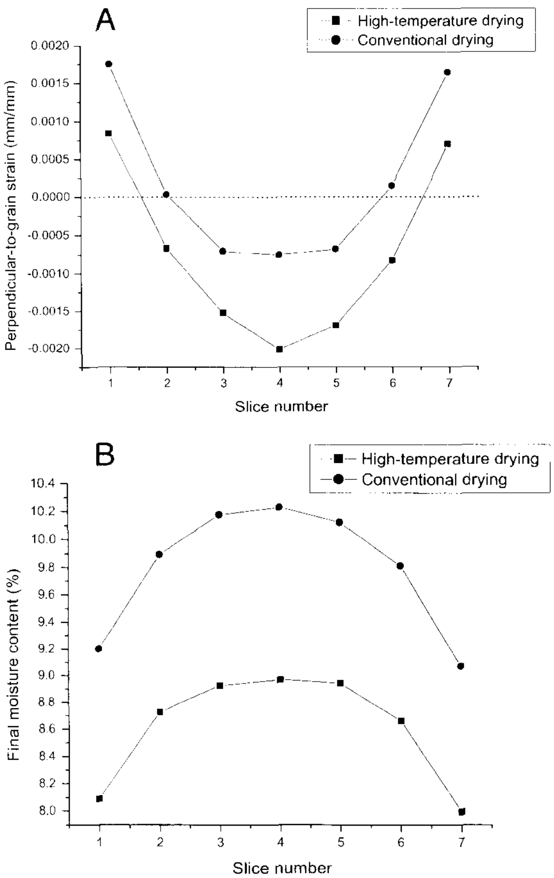

FIG. 2A. Perpendicular-to-grain strain in white spruce studs submitted to conventional and high-temperature drying. Each point on the curves represents an average of 12 slice samples.

FIG. 2B. Final moisture content in white spruce studs submitted to conventional and high-temperature drying. Each point on the curves represents the average of data collected on 12 slices.

ative wood density ($p < 0.0001$), after a Bonferroni correction ($0.05/21 = 0.0023$). The higher the wood density, the higher the shrinkage in width. Longitudinal shrinkage was also closely and negatively related to nominal relative density ($p = 0.0032$). Shrinkage in width was also significantly and negatively related to both shrinkage in thickness and longitudinal shrinkage ($p < 0.0001$). Differential twist was significantly related to shrinkage in the three structural directions ($p < 0.0001$): it was negatively related to shrinkage in width and positively related to the other two. Differential bow was affected by longitudinal shrinkage and, to a lesser extent, by shrinkage in thickness ($p = 0.0032$). Differential crook was negatively related to both shrinkage in width and longitudinal shrinkage ($p < 0.0001$).

Results reported in this study showed that eastern white spruce plantation-grown wood has a similar drying behavior under restraint, whatever the origin of the seed sources. This means that all the provenances responded globally the same way to the drying treatments, and similarly to the second-growth stand. This is a positive result for the wood drying industry because it appears that no special adjustment will be needed for plantation wood based on the origin of the material, provided a proper drying strategy is used. However, tree to tree variation exists, and concerns about plantation wood could be raised again in the future. Indeed, reforestation in eastern white spruce was done mostly with genetically unimproved stock in the past. However, superior genotypes were selected mainly for growth, and seed orchards were set up to produce genetically improved seed to fulfill all the reforestation needs. In the selection process, no attention was paid to wood quality traits. Seed orchards have begun to produce, and the reforestation program is now largely supplied by seed collected in seed orchards. To respond to pressures for conserving a larger percentage of the land for the protection of biodiversity, there is now a new trend toward increasing yield on most fertile sites using clonal forestry for eastern white spruce. If wood quality traits, and especially end-use characteristics of wood, are not taken into account in the selection of the best clones, the lumber industry might be negatively affected in the future.

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