VARIATION IN TREE GROWTH, WOOD DENSITY, AND PULP FIBER PROPERTIES OF 35 WHITE SPRUCE (*PICEA GLAUCA* (MOENCH) VOSS) FAMILIES GROWN IN QUEBEC

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ABSTRACT

Thirty-five fast-growing white spruce families planted at two sites were compared for their growth, wood and fiber properties. The analysis was made at family level, and each family comprised four individual trees. There was a significant difference in growth rate (expressed as mean annual ring width) between the two sites, and trees grew faster at Lac St-Ignace site compared to Valcartier site. The faster tree growth rates recorded at Lac St-Ignace site resulted in significantly shorter fibers for 33 of the 35 families analyzed in comparison to Valcartier, but had no significant effect on basic wood density and fiber coarseness. The pulping properties varied between the three families analyzed at two sites. Overall, the handsheet tear index properties were low but the tensile indices were high. The fastest-growing families at Lac St-Ignace site tended to have lower tear index and pulp yields but slightly higher handsheet densities than the same families grown at Valcartier site. Thus, the white spruce pulps appear more appropriate for better bonded paper grades where surface smoothness and good printability are required rather than for paper grades where high sheet strength is required.

Keywords: White spruce (*Picea glauca* (Moench) Voss), plantation, growth ring width, basic wood density, fiber length, fiber coarseness, kraft pulping properties, genetic variation.

INTRODUCTION

The increased demand for Canadian wood products over the last decades has put high pressure to produce more wood. Also, the current trend of allocating more forests for conservation, eco-tourism, or non-harvesting activities will reduce forest areas available for wood production. To sustain wood supply, efficient forest management strategies must be applied on a larger scale to increase the extremely low forest productivity in Canada. The efforts should result in more fiber production over a shorter rotation time. Several countries including New Zealand, Sweden, United States, and China have established large areas of fast-growing plantations comprised of selected "elite" trees (i.e., genetically improved trees), and they practice various silvicultural treatments (e.g., thinnings, fertilization etc.). The strategic advantage of breeding elite trees is that the genetic gain through selection can be transferred from one generation to the next generation. For example, the Swedish forest inventory showed that standing wood volumes increased by over 30% between 1953 and 1992 (Elfving and Tegnhammar 1995). This is attributed, in part, to the use of genetically improved fast-growing stocking and intensive silviculture. Through tree selection, Atwood et al. (2002) reported a genetic gain of 20.5% in stem volume

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for 17-year old loblolly pine. It is thus important to understand how much genetic gain in volume could be achieved. It is also important to understand how wood and fiber quality will be affected by faster growth rates (volume growth) and shorter rotations, and what kinds of products could be made out of the genetically improved fast-growing and shorter-rotation materials (Zobel and van Buijtenen 1989; Zhang and Morgenstern 1995). Several studies (Beaulieu and Corriveau 1985; Zhang 1996) indicate a decrease in wood density with increasing growth rate However, Taylor et al. (1982) reported a negative but not significant correlation between wood density and growth rate of white spruce for four different stands, with longer tracheids occurring in mature wood from northern stands. For Norway spruce, Danborg (1994) reported a negative correlation between ring width and basic density. Bergqvist et al. (2000) reported that length-weighted mean fiber length was significantly affected by growth rate for Norway spruce grown under birch shelterwood. The study reported that trees showing a low growth rate had fibers 6–13% shorter than other (faster) growth rate classes. Zhang and Morgenstern (1995) found that selection for diameter growth in black spruce could lead to a considerable reduction in wood density, as there was a negative genetic correlation between growth rate and wood density. However, the correlation between wood density and growth rate in this species was found to vary from family to family (Zhang et al. 1996). Moreover, the genetic correlation (Zhang et al. 1996) and the phenotypic correlation between wood density and growth rate in black spruce were reported to vary with cambial age as well. Corriveau et al. (1987) found that the adverse effect of rapid growth on the wood mechanical properties of white spruce could be partly or entirely avoided by selection and breeding of populations and individuals that produce high-density wood. Beaulieu and Corriveau (1985) reported that the variance in white spruce wood density could be partitioned into three sources: 11% was attributed to provenance differences, 8% to provenance and repetition interactions, and 81% to differences among trees of the same provenance and to experimental error. Beyond wood density, several other characteristics (e.g., fiber or tracheid dimension, spiral grain, microfibril angle, wood chemical composition, wood ultrastructure, etc.) need to be assessed in relation to growth conditions and genetics in order to increase our understanding and control of the properties of fiber-based end-products.

The aim of the present study—as part of a larger project that aims at evaluating the wood and end-product quality of a white spruce provenance/progeny trial in eastern Canada (Zhang et al. 2003)—was to (1) evaluate and compare the impact of rapid growth on basic wood density and selected fiber properties, and (2) determine the pulping properties and evaluate the suitability of the genetically improved white spruce for pulp and paper manufacturing.

MATERIALS AND METHODS

Genetic materials

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 on two sites in Quebec. These sites were located at the Valcartier Forest Experiment Station (Lat. 46° 50′ N; Long. 71° 30′ W; Elev. 150 m) and at the Lac St-Ignace Arboretum (Lat. 49° 00′ N; Long. 66° 20′ W; Elev. 500 m), see Fig. 1. Both sites were abandoned farmlands.

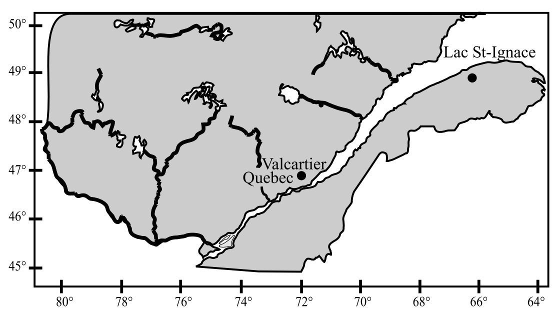

FIG. 1. Location of 35 white spruce families planted at two sites.

The surface deposit at Valcartier is a well-drained sand along the Jacques-Cartier River, while at Lac St-Ignace, it is a shaly till containing boulders. The seedlings came from 40 open-pollinated families representing 8 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-x 1.8-m spacing. Cultural treatment of both trials consisted of stem–pruning to a 2-m height in 1986.

In the fall of 2001 when the trees were 36 years old, the provenance progeny plots were thinned and, whenever available, one tree per family per block for a total of 4 trees per family were sampled to carry out a research project on the genetics of wood and end-product quality in white spruce (Zhang et al. 2003). In addition, genetic variation in wood decay resistance was also examined (Yu et al. 2004). A total of 270 trees from 35 families were harvested, i.e., 140 trees at Valcartier, and 130 at Lac St-Ignace. Each sample tree was bucked into two 2.5-m-long logs and transported to Forintek Canada Corp. facility in Quebec City, Canada.

Evaluation of wood and fiber properties

A 5-cm-thick disc was collected from the bottom of the second log (e.g., 2.5 m from ground) of each tree for this study. The discs were used to estimate average growth ring width, wood basic density, pulping and fiber properties. For fiber analyses, a pie-shaped sample was collected from each disc, and these samples were grouped into families (4 trees per family) for fiber maceration. Thus, only an average fiber length was obtained for each family at each site. Macerations were performed by heating wood sticks in equal volume of glacial acetic acid and hydrogen peroxide 30%. Fiber length and coarseness were determined using the Fiber Quality Analyzer (FQA).

Analysis of kraft pulps

Since tear and tensile tests are costly and time-consuming, only three white spruce families that show the largest phenotypic variation in fiber properties were selected for further evaluation of kraft pulping properties. The three families were selected based on the average length-weighted fiber length measured in Valcartier: family No 5309 (27) had long fibers, No. 5221 (21) medium-length fibers, and No. 5210 (13) short fibers (Table 2). This arbitrary choice was necessary because of the variation within families between sites. Thus, a specific family that showed long fibers in Valcartier could have short fibers in Lac St-Ignace. The effect of location on pulping properties within families was evaluated by preparing 6 kraft pulps from the 3 families described above. Wood chips (ca. 700 g oven-dry weight) were pulped in autoclaves submerged in a glycol bath with a liquid to wood ratio of 4.5:1. The temperature was increased from 70° to 170°C with 1°C/min and then kept constant at 170°C. The effective alkali concentration of the white liquor was 16%, and its sulfidity ranged between 25.4 and 26.4%. All pulps were cooked to an H-factor of 1450. (An H-factor of 960 is reached after one hour at 170ºC.) Each pulp was characterized by its kappa number according to Tappi test standard methods T236.

Statistical analysis

Curve fitting and T-tests for comparison of the means between the two plantations were carried out using Statgraphics Plus 5.0.

RESULTS AND DISCUSSION

Wood and fiber properties

The basic wood density, mean annual ring width (MARW), fiber length, and fiber coarseness measured for the 35 white spruce families are shown in Table 1. The mean tree diameters at the height where the discs were taken (2.5 m) were 16.4 cm (s.d. 1.3) for Valcartier (V) and 17.7 cm (s.d. 1.9) for Lac St-Ignace (L). The average cambial age at the sampling height was 18.9 years for Valcartier and 16.5 years for Lac St-Ignace. There was no significant difference in mean basic wood density between the two sites (0.330 g/cm^3 for V and 0.325 g/cm^3 for L). Although the 35 families had the same genetic makeup (same parent trees), a significant difference in growth (MARW) (p-level = 0.0001, 95% confidence intervals) was observed between the two sites (Table 1; Fig. 2a), with all 35 families showing faster growth at Lac St-Ignace. This indicates a strong genotype-environment interaction for tree growth. For the two 36-year-old plantations analyzed, there was a negative correlation between fiber length and MARW (Fig. 3a). No correlation was found between fiber coarseness and MARW (Fig. 3b). The 35 families, which contain a high proportion of juvenile wood, had the same low fiber coarseness values (0.113–0.114 mg/m) regardless of the location (Table 1). As a result, the handsheets pro-

TABLE 1. *Wood and fiber properties of 35 fast-growing white spruce families grown in two plantation sites—Valcartier (V) and Lac St-Ignace (L)—in the province of Quebec. The three families in bold were further assessed for their pulping properties (Table 2).*

Family Code		MARW (mm)		Basic density (g/cm3)		Fiber length* (mm)		Coarseness (mg/m)	
Site	No.	V	L	V	L	V	L	V	L
5193	1	4.7	5.7	0.294	0.302	2.44	2.22	0.105	0.108
5194	2	4.5	5.1	0.319	0.313	2.39	2.08	0.110	0.127
5195	3	4.1	5.0	0.326	0.316	2.43	2.13	0.111	0.132
5196	4	4.6	5.6	0.310	0.319	2.36	2.09	0.107	0.121
5199	5	4.0	5.7	0.368	0.335	2.23	2.00	0.119	0.121
5201	6	5.0	5.9	0.317	0.323	2.27	1.88	0.113	0.102
5202	7	4.4	4.8	0.332	0.318	2.35	2.14	0.122	0.128
5203	8	4.4	5.3	0.296	0.325	2.50	2.03	0.112	0.124
5204	9	4.1	4.8	0.328	0.344	2.46	1.98	0.137	0.133
5205	10	4.9	5.7	0.318	0.364	2.33	2.08	0.118	0.115
5206	11	4.6	5.1	0.340	0.340	2.42	1.95	0.119	0.101
5209	12	4.5	5.0	0.334	0.344	2.26	2.04	0.102	0.131
5210	13	4.2	5.9	0.359	0.336	2.19	2.25	0.102	0.117
5211	14	4.4	5.5	0.328	0.315	1.92	1.99	0.111	0.114
5213	15	3.9	5.2	0.312	0.343	2.17	2.07	0.105	0.093
5214	16	3.8	5.3	0.322	0.307	2.18	1.94	0.112	0.107
5216	17	3.9	4.7	0.335	0.326	2.21	1.94	0.093	0.096
5218	18	4.4	5.0	0.368	0.317	2.26	2.06	0.113	0.091
5219	19	4.2	5.4	0.350	0.300	2.38	2.06	0.115	0.112
5220	20	3.9	6.3	0.329	0.297	2.24	2.04	0.103	0.104
5221	21	4.3	5.5	0.348	0.326	2.30	2.05	0.113	0.105
5222	22	5.1	5.5	0.332	0.306	2.31	2.12	0.119	0.111
5223	23	4.7	6.6	0.334	0.331	2.36	2.00	0.121	0.115
5224	24	5.2	5.5	0.329	0.308	2.29	2.19	0.116	0.113
5225	25	4.2	5.4	0.369	0.352	2.31	2.00	0.118	0.127
5226	26	4.7	6.1	0.303	0.339	2.33	2.19	0.118	0.108
5309	27	4.8	5.2	0.342	0.329	2.48	1.90	0.127	0.106
5310	28	4.3	5.1	0.341	0.310	2.45	2.20	0.104	0.121
5312	29	4.2	6.0	0.335	0.327	2.29	2.16	0.106	0.131
5324	30	3.9	4.8	0.334	0.316	2.34	2.11	0.105	0.098
5332	31	4.1	6.4	0.340	0.326	2.47	2.17	0.126	0.116
5333	32	4.2	5.2	0.317	0.337	2.29	2.02	0.110	0.108
5334	33	4.6	6.0	0.308	0.341	2.23	2.23	0.103	0.124
5338	34	4.3	6.0	0.335	0.336	2.10	1.87	0.113	0.101
5339	35	4.5	5.7	0.312	0.303	2.41	2.01	0.114	0.113
Mean value		4.4	5.5	0.330	0.325	2.31	2.06	0.113	0.114
Std dev.		0.4	0.5	0.019	0.016	0.12	0.10	0.009	0.012

*length-weighted

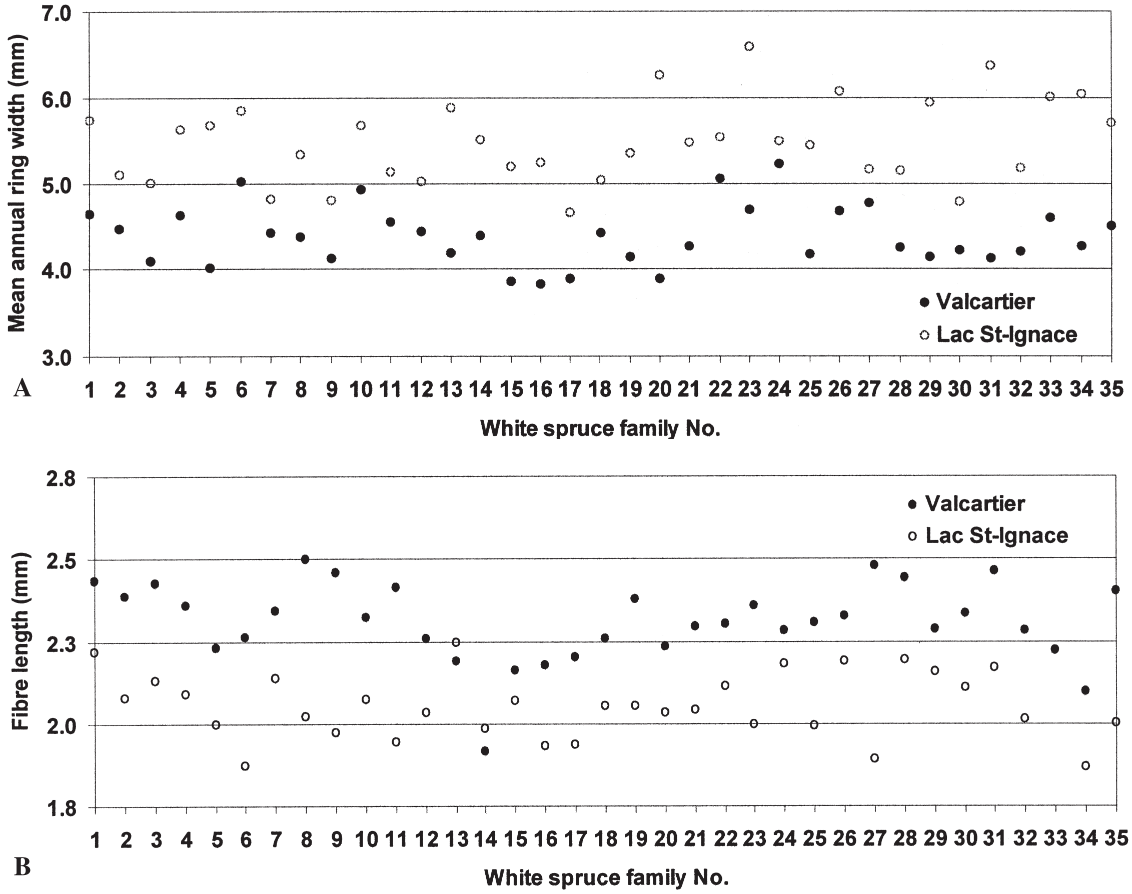

FIG. 2a, b. Relationship between fiber length (a) and mean annual ring width (b) for 35 white spruce families grown in Lac St-Ignace and Valcartier.

duced show a relatively high unbeaten sheet density (0.52–0.63 g/cm³), which is typical for juvenile wood as compared to mature wood (Hatton 1997). This indicates that the white spruce pulp fibers were thin-walled and conformable, which is known to increase interfiber bonding and tensile strength. Such low variability in fiber coarseness between families may be an advantage for raw material entering the pulp mill as it provides homogeneous conditions for pulping.

The tree families grown in Lac St-Ignace produced significantly shorter fibers (range of 1.87–2.25 mm, p-level = 0.003) than those grown in Valcartier (1.92–2.50 mm). The mean length-weighted fiber length was 2.06 mm for Lac St-Ignace and 2.31 mm for Valcartier (Table 1). Figures 2a and b show that a higher growth rate usually resulted in a lower fiber length. In fact, 33 out of the 35 families evaluated produced shorter fibers in Lac St-Ignace (Fig. 2b) than in Valcartier, because of faster growth rate and environmental conditions. This negative relationship between fiber length and circumferential growth rate has been reported for white spruce and other Canadian coniferous species from natural stands (Fujiwara and Yang 2000; Zhang and Morgenstern 1995; Koubaa et al. 2000). Although a significant difference in fiber length was found between families, the mean wood basic density was not statistically different between the two sites (Table 1). Since wood density did not reveal intrinsic differ-

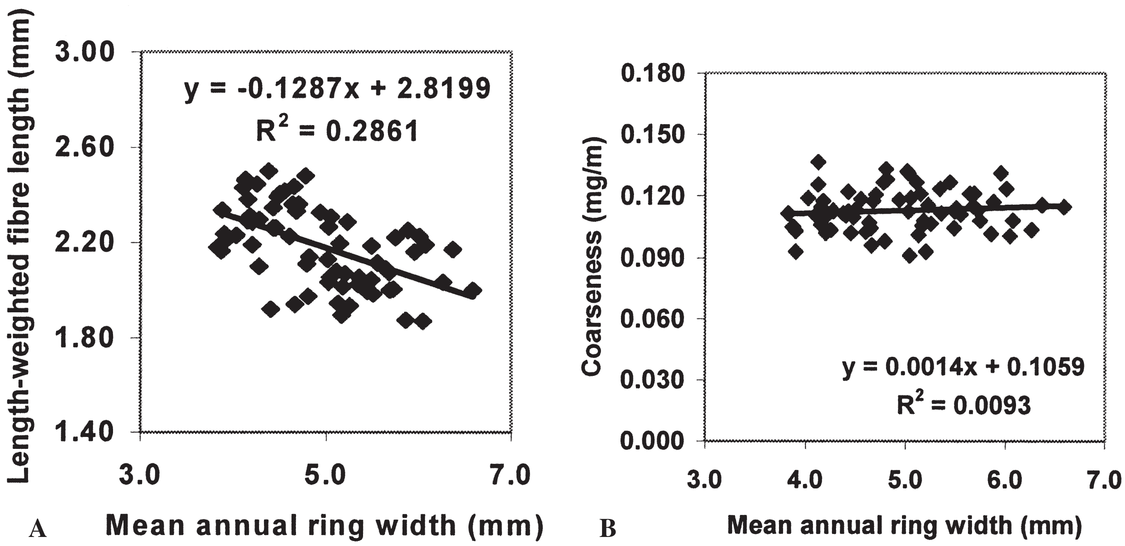

FIG. 3a, b. Relationship between fiber length and mean annual ring width (a), and coarseness and mean annual ring width (b).

ences in fiber characteristics, there is a need for examining end-products quality directly, as suggested in the literature (Zhang et al. 2003, 2004).

In the present study, the mean fiber length (2.06 and 2.31 mm) was shorter than that reported for white spruce in the literature (ca. 3.3 mm) (Panshin and de Zeeuw 1980). This is probably because young trees contain a high proportion of juvenile wood that is known to have shorter fibers than mature wood. In addition, when tree growth is restricted due to increased competition, the proportion of earlywood within an annual ring decreases, while the proportion of latewood stays more or less constant. Within the same annual ring, latewood fibers of Norway spruce have been reported to be longer than earlywood fibers (Frimpong-Mensah 1987). Assuming this is the case in white spruce as well, it would partly explain why trees in Valcartier had longer fibers. Thus, a faster growth rate may have resulted in a larger proportion of short earlywood fibers in the growth rings. In addition, site quality and climate also influence wood formation, although the detailed mechanisms involved are not fully understood. Thus, further research is needed to better understand how wood fiber structure is influenced by environmental and genetic factors.

Pulping properties

As explained above, this study evaluated the pulping properties of only three families grown at the two sites with six kraft cooks (Table 2). There was considerable variation within the same family between the two sites. In fact, the same family could have the longest fibers when growing at Valcartier site and very short fibers at Lac St-Ignace site. Thus, the three families were selected to cover the maximum range of variation in fiber length at Valcartier site. The assumption was made that the families would cover the maximum difference in handsheets properties, since wood fiber morphology is reflected in most handsheet properties (Matolcsy 1975; Macload 1986; Hatton 1997). Valcartier family V27 had the longest fibers; family V21 had medium-length fibers; and family V13 the shortest fibers (Table 2). Handsheets of unbleached kraft pulp were produced and their physical properties tested. The pulp yields after screening were generally low and ranged between 35.8 and 41.8% (Table 2). In general, all

TABLE 2. *Pulping conditions, pulp, and handsheet properties for three fast-growing white spruce families grown on former agricultural land.*

White spruce family No.	5309 (27) Long[1]		5221 (21) Medium		5210 (13) Short	
Stand location[1]	V27	L27	V21	L21	V13	L13
Pulping conditions						
Effective alkali / wood (%)	16	16	16	16	16	16
H-factor	1450	1450	1450	1450	1450	1450
Sulfidity (%)	25.8	25.7	26.4	25.8	25.4	25.8
Temperature (°C)	170	170	170	170	170	170
Liquid to wood ratio	4.5	4.5	4.5	4.5	4.5	4.5
Pulp yield (%)	51.3	50.3	52.1	46.3	51.6	49.0
Yield after screening (0,012″) (%)	39.0	40.1	39.7	35.8	41.8	37.5
Pulp and handsheet properties						
Kappa No.	34.7	30.2	48.5	26.1	30.7	28.1
CSF (ml)	692	671	707	688	685	692
Grammage (g/m^2)	61.0	63.5	62.1	61.2	62.8	61.4
Dryness (%)	92.4	93.8	92.4	93.5	93.3	94.0
Bulk (cm^3/g)	1.74	1.66	1.92	1.78	1.71	1.60
Sheet density (g/cm3)	0.57	0.60	0.52	0.56	0.58	0.63
Tear index ($mN*m^2/g$)	12.2	12.5	14.1	12.0	13.7	11.0
Burst index ($kPa*m^2/g$)	8.3	6.9	6.7	5.7	7.0	6.9
Breaking length (km)	10.8	9.1	9.8	8.6	9.8	10.5
Tensile index (kN*m/kg)	105	89	96	84	96	103
Stretch (%)	2.41	1.65	1.63	1.72	2.50	2.08
Tensile energy absorption (J/m^2)	98	58	60	57	99	85
TEA index (kJ/kg)	1.605	0.909	0.959	0.927	1.574	1.377
Fiber length, arithmetic mean (mm)	1.28	1.10	1.26	1.15	1.26	1.19
Fiber length, length weighted (mm)	2.14	1.87	2.06	1.79	2.10	2.06
Fiber coarseness (mg/m)	0.119	0.104	0.113	0.110	0.103	0.099

[1] Based on the fiber length obtained from the plantation in Valcartier
[2]V = Valcartier, L= Lac St-Ignace

the families at Lac St-Ignace that showed the highest growth rates (high MARW) were more easily delignified compared to those at Valcartier, as shown by their lower kappa numbers after pulping. Family 21 grown at Lac St-Ignace had the lowest pulp yield (Fig. 4c). A 22-unit difference in kappa number was found within family 21 between the two sites. Faster growth rates are often associated with higher proportion of thin-walled earlywood fibers in a growth ring. Moreover, lignin dissolution and diffusion through the fiber wall are normally easier in thin-walled (earlywood) fibers than in thick-walled (latewood) fibers. This might explain the differences observed in the degree of delignification. However, both families 27 and 13 had much less inter-site variation in kappa number.

The tear index was generally low for all the samples analyzed but the "fastest-growing" families at Lac St-Ignace usually showed lower tear index (Fig. 4a,b), and, to some extent, lower tensile index than at Valcartier. This is in agreement with previous studies summarized by Einspahr (1976) where young or short-rotation softwoods with a high juvenile wood content generally produced pulps high in tensile strength and low in tearing strength. The same trend applies for rapid growth compared to normal growth in conifers (Einspahr 1976).

In general, if only tear strength is considered, the pulps from this material, especially the ones from Lac St-Ignace, would probably make low quality kraft pulp grades. All the pulps, however, had a good tensile index (Fig. 4a) probably due to their good fiber collapsibility (low coarseness). This property makes the pulps appropriate for paper grades where high bonding and surface smoothness are required, for example, in top ply of multiply board and in some speciality grades where superior printing quality is needed. The

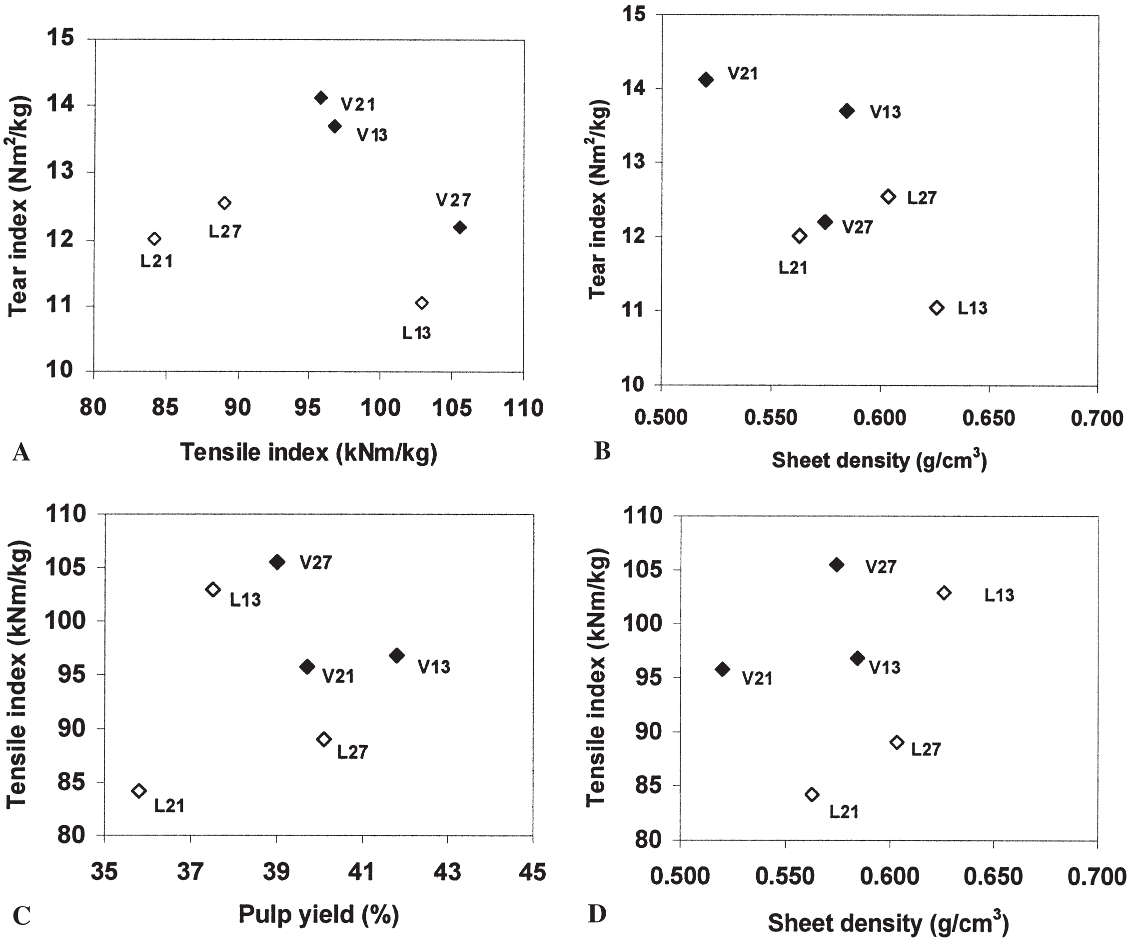

FIG. 4a–d. Handsheet properties of 6 unbleached and unbeaten white spruce pulps (3 families grown at 2 sites). Tear index versus tensile index (a) and sheet density (b); tensile index versus pulp yield (c) and sheet density (d).

three families grown at Lac St-Ignace tended to show a slightly higher sheet density (Table 2, Fig. 4d) than the families at Valcartier, which reflects the ability of the faster-grown fibers to collapse and form denser sheets. Detailed fiber characterization of different raw materials is essential in order to use the right fibers for the right end-product.

CONCLUSIONS

Thirty-five fast-growing white spruce families grown at two sites were studied and compared for their wood and fiber properties. A more rapid growth rate at Lac St-Ignace site resulted in shorter fibers but had no significant effect on fiber coarseness and basic wood density. The pulping properties varied between the three families analyzed at two sites. The fastest-growing family at Lac St-Ignace site had the lowest tear index values, lower than the same families grown at Valcartier site. Overall, the handsheet tear indices were low but the tensile indices were comparable (Law and Koran 1982) or higher than that of other Canadian softwood species (Hatton 1997). The white spruce pulps appear more appropriate for better bonded paper grades where surface smoothness and good printability are required than for paper grades where high tear strength is required.

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