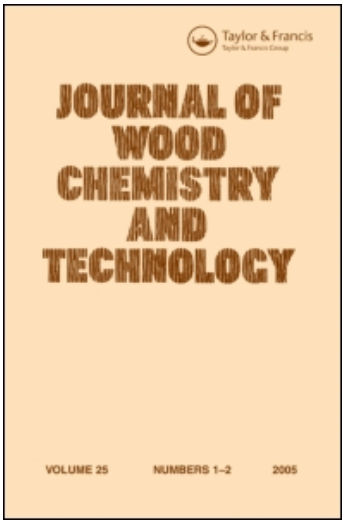

Journal of Wood Chemistry and Technology
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597282

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Online publication date: 04 December 2010

To cite this Article Mansfield, Shawn D. and Weineisen, Henrik(2007) 'Wood Fiber Quality and Kraft Pulping Efficiencies of Trembling Aspen (*Populus tremuloides* Michx) Clones', Journal of Wood Chemistry and Technology, 27: 3, 135 — 151
To link to this Article: DOI: 10.1080/02773810701700786
URL: http://dx.doi.org/10.1080/02773810701700786

Journal of Wood Chemistry and Technology, 27: 135–151, 2007

ISSN 0277-3813 print/1532-2319 online
DOI: 10.1080/02773810701700786

Wood Fiber Quality and Kraft Pulping Efficiencies of Trembling Aspen (*Populus tremuloides* Michx) Clones

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Abstract: The natural variation in wood and pulp fiber quality of 15 aspen (*Populus tremuloides* Michx) clones, represented by 47 trees, was assessed from 4 different sites in British Columbia, Canada. Kraft pulping trials revealed substantial variation in the pulping efficiencies, illustrated by differences of 6% in total pulp yield, ~30% differences in H-factor required to attain a target kappa of 21, and differences of up to 2 ISO brightness units in bleachability of kappa 21 pulp. Clearly, enormous variation exists in the natural stands of aspen, and presents some exciting opportunities for selecting clonal aspen for targeted end-product applications. A comprehensive characterization of wood chemical composition, wood density, and fiber properties indicated that pulp yield is directly related to syringyl lignin monomer composition, and not inherent wood density, regardless of geographic locations, whereas pulp bleachability and viscosity appear to be associated with the inherent cell wall thickness of the starting wood resources (fiber coarseness). These findings suggest that geographic location imparts influences on wood fiber coarseness traits, while substantial genetic variability exists on all sites.

Keywords: Aspen, *Populus tremuloides*, kraft pulping, kappa, fiber properties, syringyl lignin, pulp yield

The authors thank Dr. Paul Watson of PAPRICAN (Vancouver Lab) for his aid in the procurement and selection of clonal variants, as well as contributing to the costs of harvesting trees.

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INTRODUCTION

Globally, forest management is rapidly evolving from timber foraging to a system of agricultural cropping.[1] Although global harvest from industrial plantations was negligible as late as the 1950s, by 2000 it had risen to an estimated 34%, with 10% of this harvest comprised of exotic tree species.[2] It is anticipated that the share of fiber from industrial plantations will rise to between 50 and 75% by the year 2030.[3] In 2001, the total production of pulp in the world was 186 million metric tons, from which 23% was derived from plantations. It is estimated that to meet the growing global demand this number will have to rise to more than 40% by 2030.[3]

In Canada, the boreal and temperate forests cover 417 million hectares, approximately half of the landmass, and form the foundation of the Canadian forest products industry. *Populus spp.* (including aspen) represent Canada's most widespread and fastest growing tree species.[4] They typically have a substantial breadth of distribution inhabiting several geographical and climatic ecoregions, and are notable for their vigorous growth. *Populus spp.* are estimated to represent over 50% of all hardwoods, and approximately 11% of the entire Canadian timber resource.[5] They possess a unique asexual reproductive mechanism that generates several genetically identical stems, known as ramets, that originate from a common root system. This pattern promotes the occurrence of natural genetic clones in highly concentrated geographic stands.

Hybrid poplar (cottonwoods) and aspen are becoming increasingly important, particularly as short rotation fiber species, and concurrently as a mitigation strategy for climate change. In recent years, there has been an increasing commitment to establish high-yield short-rotation forest plantations of hybrid poplar and aspen that display averages of 9 to 30 $m^3\ ha^{-1}\ yr^{-1}$ and 5 to 7 $m^3\ ha^{-1}\ yr^{-1}$, respectively, which is substantially greater than the overall average yield of 1.7 $m^3\ ha^{-1}\ yr^{-1}$ for Canadian forests.[6] Thus, fast-growing high-yield fiber farms offer enormous potential to provide a productive new resource for the pulp and fiber manufacturing sector, with suggested rotation times of 6 to 10 years.[7] The importance of this species is best illustrated by activities in China that have established significant hybrid poplar plantations (10 million hectares in 2002) throughout the country, and have evaluated both the native and exogenous genotypes (53 species) for almost all applications in both primary and secondary manufacturing, ranging from pulp to plywood and furniture manufacture.[8]

In contrast to the cottonwood poplars, with extremely fast growing and lower wood density,[9,10] the aspens are slower growing and have denser wood than the cottonwoods. Aspen inherently has fibers of small diameter and thin walls, which are ideal for producing high-density paper sheets with very good optical properties. Furthermore, both the cottonwoods and aspen are low in lignin and high in carbohydrate, which makes them amenable to a variety of pulping regimes.[11,12] Clearly, *Populus spp.*, including aspen, represents a phenomenal, untapped resource with rich genetic diversity. The

aim of this project was to investigate the utilization of aspen (*Populus tremuloides* Michx) as a fiber source for Kraft pulping and identify clones with desired properties, particularly for ease of chemical pulping and fiber variation.

METHODS AND MATERIALS

Sample Procurement

In 2001, 3 aspen (*Populus tremuloides* Michx), clones (represented by 3 trees) procured from 3 sites (Del Rio, Farrell Creek and Kobes Creek) in the Fort St. John region [121°50′ W and 56°30′ N] in the northeastern parts of British Columbia Canada, while in February 2002, 6 aspen clones (represented by 2 trees each) were selected from 1 site near Fort Nelson [122°35′ W 58°50′ N], northern British Columbia. The clones where chosen and distinguished based on bark color and markings, branch angle, leaf shape, and the time of bud flush. The lower 2 meter butt logs were manually debarked and chipped on a C.M. & Norman chipper (36 inch, 10 knife disc chipper), pooled, air-dried, and screened to collect the 2–6 mm thickness fraction. Samples were stored frozen until use for all analysis.

Wood Chemistry

All samples were first ground in a Wiley mill to pass through a 0.4 mm (40-mesh) screen. The ground wood was then soxhlet extracted with acetone for 8 h to quantify extractable components gravimetrically by rotary-evaporation, and expressed as a percentage of the original weight of the wood sample. The extracted lignocellulosic material was then air-dried and analyzed in quintuplet for sugar and lignin composition as follows.

A 0.2 g sample of extracted wood was transferred to a 15 mL reaction vial in an ice bath. A 3 mL aliquot of 72% (w/w) H_2SO_4 (Fisher Scientific, Nepean Ont.) was added to the sample and thoroughly mixed for 1 min. The test tube was immediately transferred to a water bath maintained at 20°C, and was subsequently mixed for 1 min every 10 min. After 2 h, the contents of each test tube were transferred to a 125 mL serum bottle, using 112 mL nanopure H_2O to rinse all residue and acid from the reaction vial. The serum bottles were then sealed with septa and autoclaved at 121°C for 60 min. Samples were allowed to cool and the hydrolyzates were vacuum-filtered through pre-weighed medium coarseness sintered-glass crucibles. The samples were then washed with 200 mL warm (~50°C) nanopure H_2O to remove residual acid and sugars, and then dried overnight at 105°C. The dry crucibles were re-weighed to determine Klason (acid-insoluble lignin) lignin gravimetrically. The filtrate was then analyzed for acid-soluble lignin by absorbance at 205 nm according to TAPPI Useful Method UM250.[13]

The concentration of sugars in the filtrate was determined using High Performance Anion Exchange Liquid Chromatography. The HPLC system (Dionex DX-500, Dionex, CA, USA) was equipped with an ion-exchange PA1 (Dionex) column, a pulsed amperometric detector with a gold electrode, and a Spectra AS3500 autoinjector (Spectra-Physics, CA, USA). Prior to injection, samples were filtered through 0.45 μm HV filters (Millipore, MA, USA) and a 20 μL volume of sample was loaded, containing fucose as an internal standard. The column was equilibrated with 250 mM NaOH (Fisher Scientific, Nepean Ont.) and eluted with de-ionized water at a flow rate of 1.0 mL/min.

Monolignol Quantification

Accurately weighed dry extractive free wood (~200 mg) or lignin (~50 mg) was weighted into a Pyrex test tube to which 7 mL of 2 M NaOH and 0.4 mL nitrobenzene (Sigma-Aldrich, St. Louis, MO) were added. The tube was then placed into a 170°C oil bath for 2.5 h and shaken regularly. The reaction was terminated by placing the test tubes in an ice water bath for 5 min. An internal standard, 3-ethoxy-4-methoxy-benzaldehyde (200 μL of 14.09 mg/mL in 2 M NaOH; Sigma-Aldrich, St. Louis, MO) was then added to each sample and shaken vigorously. The contents were then transferred to a separatory funnel, to which chloroform (3 × 25 mL; Fisher Scientific, Nepean Ont.) was added and used to remove any nitrobenzene reduction products. The aqueous layer was acidified with concentrated HCl (Fisher Scientific, Nepean Ont.) to a pH of 2 and transferred to a liquid-liquid extractor for extracted with chloroform (Fisher Scientific, Nepean Ont.) for 48 h. The solvent was then reduced to dryness by rotary evaporation. The sample was then re-dissolved in 5 mL methylene chloride (CH_2Cl_2; Fisher Scientific, Nepean Ont.) and made up to exactly 10 mL in a volumetric flask.

Gas chromatography analysis was performed after filtration through a 0.45 μm filter. The oven temperature profile for GC analysis consisted of 1 min at 60°C, a 10°C min^{-1} ramp from 60 to 250°C and held for 10 min at 255°C. The injector port was set to 200°C and the FID set at 270°C. One microliter injections were separated on a 30 m (0.25 μm ID) DB-5 column (J&W Scientific) using helium as a carrier gas at 1 mL/min.

Syringyl:guaiacyl ratio was also determined by thioacidolysis[14] using 10 mg samples of extractive-free wood. Tetracosane (Sigma-Aldrich, St. Louis, MO: 2 mL of 0.25 mg/mL in CH_2Cl_2) was used as the internal standard. The silylation reaction proceeded for a minimum of 1.5 h. Gas chromatography analyses were performed on a HP 5890 Series II fit with a 30 m × 0.25 mm DB-5 column (J&W Scientific) and FID detector. The GC method used a 2.0 μL injection volume, an initial injector temperature of 250°C, and a detector temperature of 270°C. The initial oven temperature was set to 130°C (held for 3 min) and thereafter ramped at a rate of 3°C min^{-1} to 260°C and held for 5 min.

Wood Density Analysis

Wood density was measured on two radii on each cookie taken from the butt section of each log from all clones employed in this study. The samples (1 cm × 1 cm) were first soxhlet extracted overnight with acetone, and then precision cut to 1.68 mm thickness with a twin blade pneumatic saw, and allowed to acclimate to 7% moisture before density analysis. All samples were scanned by X-ray densitometer from pith to bark with a resolution of 0.0254 mm.

Fiber Properties

Fiber length and coarseness were analyzed in triplicate from each tree. The samples were macerated in Franklin solution (1:1, 30% hydrogen peroxide: glacial acetic acid; Fisher Scientific, Nepean Ont.) for 48 h at 70°C. The solution was decanted and the remaining fibrous material was washed under vacuum with de-ionized water until a neutral pH was achieved. The samples were dried overnight at 50°C, and the moisture content measured to determine fiber mass for coarseness measurements. Accurately weighed sub-samples were then re-suspended in 10 mL of de-ionized distilled water and fiber properties determined on a Fibre Quality Analyzer (OpTest Equipment Inc., Canada).

Pulping

Small-scale pulping (50 g oven dry weight) was conducted in 500 mL reaction bombs at 170°C at 25% sulfidity, 13% effective alkali, and a 4.5:1 liquor to wood ratio. The reaction bombs were placed into an oil bath and the temperature was ramped from room temperature (23°C) to 170°C over 60 min. The vessels were maintained at 170°C for set times to achieve the target H-factors of 600, 1,100, and 1,500. The reaction bombs were removed from the oil bath and immediately placed in an ice bath to terminate the pulping reaction. The cooked wood chips were then thoroughly washed with warm tap water, separated in a standard British disintegrator for 15 min (25,000 revolutions), and then filtered and collected with a Büchner funnel. The pulp was washed until the filtrate was colorless, screened for rejects, and dried for 2 days at 50°C for yield determination, expressed as a percent of dry weight. Four replicate pulps for each sample (clone) were produced.

Pulp Analysis

Kappa numbers (residual lignin) and pulp viscosity were determined in triplicate using TAPPI standard method T236 cm-85[15] and T230 om-94,[16] respectively.

Pulp Bleaching

Ten gram pulp samples were bleached at 10% consistency, according to a standard DED sequence (where D = ClO_2 and E = NaOH). Chlorine dioxide was produced by reacting 80% stabilized sodium chlorite (Acros) with 1.5 equivalents of potassium persulfate (Sigma-Aldrich, St. Louis, MO) in distilled water at room temperature. The resulting solution was stripped with UHP-nitrogen. The nitrogen gas containing stripped chlorine dioxide was passed through a column of sodium chlorite and then scrubbed in cold de-ionized water, pH adjusted to 4 with 0.1 wt.% aqueous sulphuric acid. The resulting chlorine dioxide was checked for purity by iodometric titration and used for all bleaching experiments. Following bleaching, 4 g brightness pads were made and maintained at a controlled temperature (23°C) and humidity (50%). Brightness measurements (%ISO) were made on a Technobrite Micro TB-1C.

The conditions at the different bleaching stages were as follows:

D_0: 1.5% ClO_2 and 0.05% NaOH at 80°C for 78 min.
E: 1.3% NaOH at 78°C for 42 min.
D_1: 0.5% ClO_2 at 70°C for 194 min.

RESULTS AND DISCUSSION

Wood supply is emerging as one of the primary constraints to the growth and prosperity of the forest sector.[10,17] Effective management of impending reductions to supply is strategically vital to both forest companies and wood suppliers. Furthermore, it is crucial that the processing of wood (pulping) and wood fiber (bleaching) be undertaken in an environmentally benign and energy-efficient manner.[18] It is anticipated that in the future, a large percentage of wood, more specifically hardwood-derived pulpwood, will come from intensively managed, fast-rotation plantation forests. Aspen is an ideal species in North America and Europe, as it exhibits good fiber properties,[19] is amenable to reforestation and genetic selection. Aspen is a substantial, genetically diverse resource from which we can select superior clonal material within our natural forest.

Wood Chemistry

Chemical analyses (Table 1) of the fifteen naturally occurring Aspen clones showed that, despite differences in macro-geographic origin, there were few differences in the carbohydrate composition of the different clones. It appears that the Aspen clones harvested from the Fort Nelson region have

Table 1. Average chemical composition of *Populus tremuloides* clones

	Carbohydrates (mg/100 mg)[a]					Lignin (mg/100 mg)[a]			
Clone	Arabinose	Galactose	Glucose	Xylose	Mannose	Acid-soluble	Acid-insoluble	Total lignin	Extractives (mg/100 mg)
D1	0.43 (0.05)	0.55 (0.04)	50.9 (0.41)	18.6 (0.51)	2.3 (0.33)	3.4 (0.56)	18.8 (0.72)	22.2 (0.26)	2.12 (0.10)
D2	0.35 (0.01)	0.41 (0.003)	49.9 (0.32)	18.2 (0.32)	3.0 (0.18)	3.2 (0.16)	19.4 (0.17)	22.7 (0.32)	1.61 (0.18)
D4	0.41 (0.004)	0.55 (0.01)	51.2 (0.18)	19.0 (0.18)	1.2 (0.09)	2.7 (0.11)	18.2 (0.05)	20.9 (0.15)	1.67 (0.16)
F3	0.38 (0.01)	0.47 (0.005)	51.0 (0.17)	17.6 (0.17)	2.0 (0.12)	2.9 (0.21)	18.0 (0.24)	20.9 (0.42)	2.27 (0.29)
F6	0.58 (0.01)	0.65 (0.01)	48.5 (0.25)	19.9 (0.25)	2.8 (0.06)	4.5 (0.26)	18.2 (1.44)	22.8 (1.43)	2.75 (0.21)
F7	0.51 (0.01)	0.60 (0.01)	51.7 (0.44)	19.9 (0.44)	2.8 (0.10)	4.6 (0.13)	17.4 (0.20)	22.0 (0.29)	2.03 (0.31)
K1	0.48 (0.02)	0.68 (0.01)	51.3 (0.46)	19.7 (0.46)	2.1 (0.09)	2.8 (0.16)	16.7 (0.14)	19.5 (0.13)	1.59 (0.17)
K2	0.47 (0.05)	0.60 (0.05)	52.6 (0.54)	18.6 (0.54)	2.4 (0.29)	4.0 (0.22)	17.0 (0.60)	21.0 (0.59)	2.71 (0.22)
K7	0.42 (0.01)	0.54 (0.01)	50.5 (0.28)	19.3 (0.28)	2.7 (0.04)	3.4 (0.17)	18.1 (0.24)	21.4 (0.13)	2.08 (0.23)
FN10	0.34 (0.01)	0.49 (0.05)	52.7 (0.38)	19.7 (0.38)	1.9 (0.19)	2.4 (0.22)	17.7 (0.31)	20.2 (0.50)	2.23 (0.34)
FN16	0.37 (0.02)	0.62 (0.02)	54.9 (1.51)	17.4 (1.51)	1.0 (0.47)	2.7 (0.28)	16.2 (0.39)	19.0 (0.30)	1.82 (0.18)
FN18	0.37 (0.08)	0.49 (0.04)	54.6 (0.69)	17.7 (0.69)	1.9 (0.34)	2.9 (0.25)	16.7 (0.35)	19.6 (0.32)	1.89 (0.11)
FN19	0.41 (0.01)	0.62 (0.01)	52.4 (0.20)	18.2 (0.20)	1.8 (0.25)	3.1 (0.16)	17.5 (1.49)	20.6 (1.42)	1.53 (0.09)
FN21	0.37 (0.01)	0.52 (0.08)	52.2 (0.35)	18.0 (0.35)	2.6 (0.22)	2.9 (0.12)	16.3 (1.60)	19.2 (1.54)	1.55 (0.32)
FN26	0.36 (0.01)	0.59 (0.02)	51.1 (0.13)	19.0 (0.13)	2.3 (0.15)	3.6 (0.18)	16.1 (0.56)	19.7 (0.57)	1.37 (0.22)

[a]Average of six replicates (standard deviation in brackets).

slightly higher glucan content, when compared to the clones procured from the Fort St. John region. Similarly, the trees from Fort Nelson exhibited lower total extractive and total lignin contents. A closer inspection of the lignin shows that the reduced lignin in the Fort Nelson clones is directly related to the acid insoluble moieties, whereas the acid-soluble composition appears to be similar to the clones harvested in the more southerly region (Table 1). It is apparent that the elevated glucan content, by weight, is related to a direct reduction in both lignin and extractives.

Wood and Fiber Properties

Although there were distinct differences in wood density of the Aspen clones evaluated, a clear difference between geographic locations was not apparent (Figure 1). The wood density values ranged from 313 kg/m^3 to 409 kg/m^3, which concurs with previously published values for aspen[20,21] and cottonwoods,[10,22] and the average density for all clones, regardless of site, was determined to be 364 kg/m^3.

In contrast, a clear difference in fiber coarseness was observed between the clones from the two different sampling regions (Figure 2). Clones from the Fort Nelson area exhibited significantly lower average coarseness values (0.11 mg/m) than the corresponding clone, from the three sites in the Fort St. John region (0.16 mg/m). Fiber length evaluation indicated that a similar clear differentiation in length was not apparent in the two different geographic regions, where fiber length ranged from 0.86 to 1.07 mm on

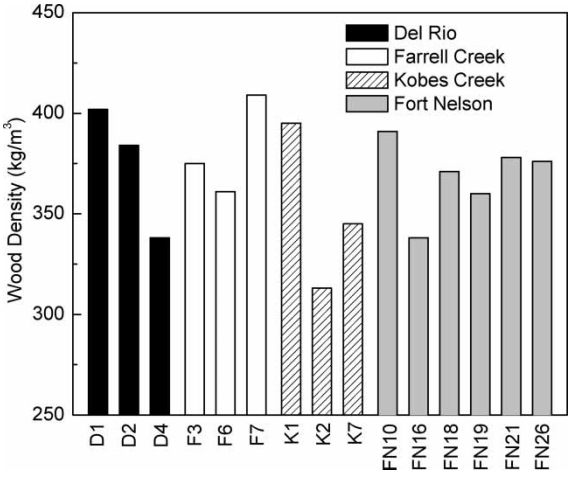

Figure 1. Wood density of *Populus tremuloides* clones.

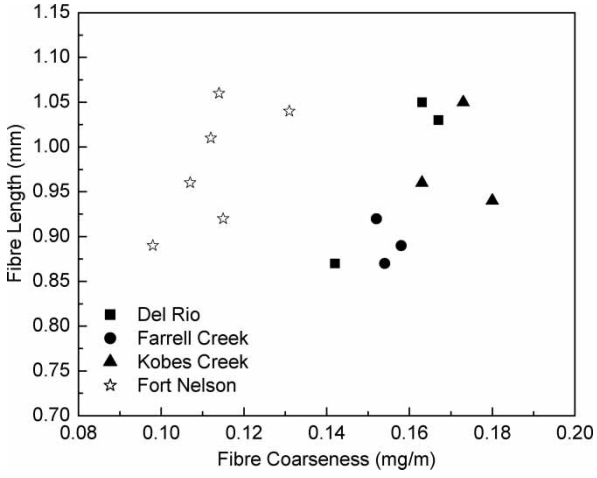

Figure 2. Fiber length and coarseness of *Populus tremuloides* clones.

both sites. It is, however, possible that fiber properties (primarily coarseness) may be used to distinguish clones from different growing regions in British Columbia. Fiber properties are undoubtedly related to differences in environmental and climatic extremes between the two sampling sites. The more northern growing environment has a shorter growing period, is slightly colder, has a slightly elevated topography, but has similar average daylight hours. There is also a possibility that the difference, at least to some extent, is due to genetic differences; however, this is more so reflected in the fiber length measurements, which show similar distributions on both sites.

It is well recognized that paper properties are highly correlated to inherent fiber morphology, such as fiber length, fiber diameter, and wall thickness (coarseness),[23–25] with fiber length contributing the greatest influence.[26,27] Hardwood fibers generally impart good optical properties and act as filler for a small percentage of softwood-derived carrier or reinforcing fibers, in the manufacture of fine paper. It has been shown that paper strength is generally enhanced by longer fibers, and the importance of long fibers is vital in sheets with low bonding strength, such as sheets made of only slightly beaten pulp or wet sheets. On the other hand, fiber coarseness is affected by cell wall thickness, fiber width and cell wall density, and can be seen as a summary measurement of these basic fiber properties.

The significant genetic diversity is illustrated by the broad span of fiber properties found within the clones from each sampling area, and suggests that there is a profound possibility to select clones suitable for specific end-use applications. Furthermore, the review of the physical properties indicated that there is no correlation between wood density and fiber length, or wood density and fiber coarseness.

Kraft Pulping Characteristics

Previous results[9–12,18,19,21] indicated that there is a huge amount of variability in the processibility (efficiency of pulping) of aspen or poplar clones in the native forests. All 15 aspen clones were pulped, in duplicate, at H-factors of 600, 1,100, and 1,550. The residual lignin content following pulping, expressed as kappa numbers, displayed a typical pulping curve (Figure 3A). The difference in kappa at an H-factor of 600 ranged from 30 to 50, whereas variations of 15–27 and 9–20 were observed at H-factors corresponding to 1,100 and 1,550, respectively. As expected, the more extensive the cook, the lower the variation in range of residual kappa among the trees pulped. The results demonstrated that the H-factor required to attain a target kappa of 21 differs widely between the clones, independent of location of harvest. However, it is also apparent that the clones obtained from the Fort Nelson region generally pulp more easily than the clones from the Fort St. John area, at a given H-factor.

The pulp yields at the three different H-factors were also determined and are expressed as a function of residual kappa numbers (Figure 3B). Pulp yield determinations demonstrate that there is significant variation in yield of the fibrous material following Kraft pulping, ranging from screened pulp yields of 58.5–63.5, 56–61, and 55–60.5 at H-factors of 600, 1,100, and 1,550, respectively. As expected, the more severe the cooking conditions, the lower the overall yield, and a reduction the number of rejects observed in the ensuing pulps (data not shown). Interestingly, the deviation in pulp yield does not narrow with increasing pulping severity, as is observed in residual kappa. Furthermore, striking differences exist between clones. For example, at H-factor of 1,550, comparing FN16 and F6, which represent two extremes in the study, resulted in pulp that had a kappa number of 10.2 and a yield of 59.7%, and 16.7 and a yield of 55%, respectively (Figure 3C). The results conclusively illustrate that there are opportunities[19] for clonal selection within the individual locations, and that identifying desirable clones with the inherent propensity to give low kappa number and high yields at a relatively low H-factor is possible. Such clones could offer significant advantages in breeding trials or propagations effort for reforestation and afforestation endeavors in a plantation forestry context.

The observed differences in alkaline pulping efficacy of the different clonal aspen could be related to several putative phenotypic chemical differences within the trees, including: (i) phenolic hydroxyl groups content—implying more rapid/complete degradation, (ii) degree or number of β-O-4 inter-unit linkages, and (iii) ratio of syringyl to guaiacyl lignin—implying less condensed 5-5/β-5 type linkages and perhaps more β-O-4 linkages. Similarly, pulping efficacy may be related to structural and/or morphological characteristics inherent to the wood or wood ultrastructure. For example, it has been suggested that lignin diffusion from cell walls is the rate-limiting step in pulping, which is influenced by low wood density.[28] Thus, clonal variation

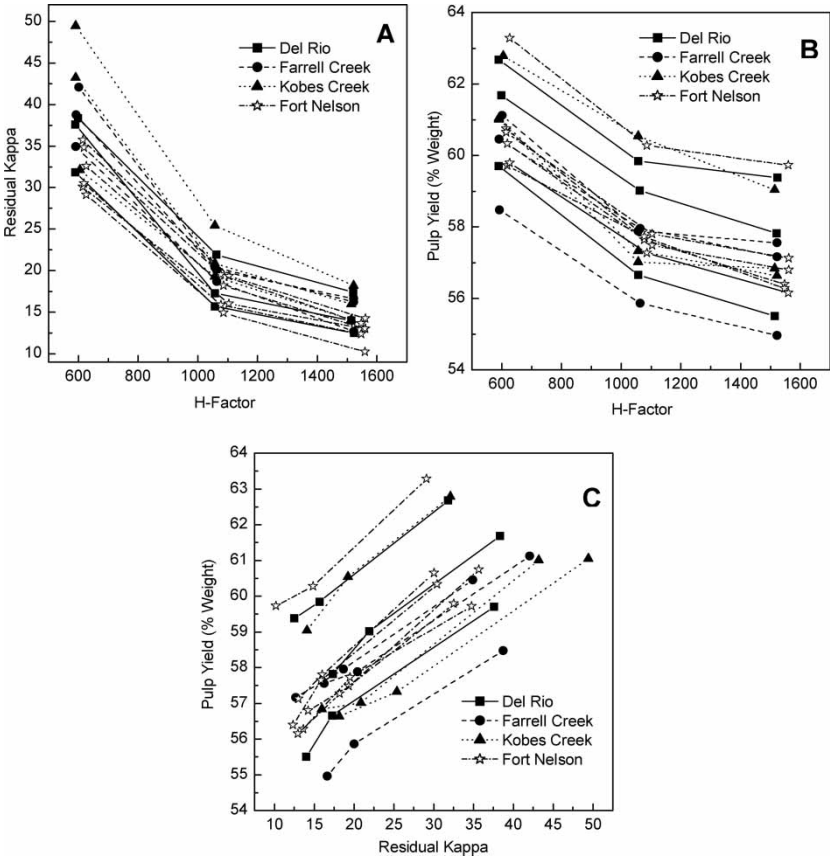

Figure 3. Residual pulp kappa (A) and kraft pulp yield (B) at different pulping H-factors, and pulp yield versus residual kappa (C) of *Populus tremuloides* clones.

may inherently exhibit different structural or morphological differences, such as: (i) ratio of vessel elements to fibers, (ii) differences in lignin location, middle lamella versus primary wall versus secondary wall, and/or (iii) lower average molecular weight lignin.[18]

A comparison of basic wood density and pulp yield (Figure 4) clearly shows that wood densities are not an effective predictor of pulp yield and, consequently, ease of pulping. In contrast, an evaluation of syringyl to guaiacyl (S:G) ratio, as determined by thioacidolysis, shows that the clones that inherently exhibited a slightly higher lignin S:G ratio might account for improved ease of pulping (Figure 5; Table 2). When comparing all aspen clones collectively, regardless of site, a very strong relationship ($r^2 = 0.85$) exists between the inherent S:G ratio of the wood and pulp yield at kappa 21. It appears that the lower overall yield is related to the fact that the trees with higher mol%

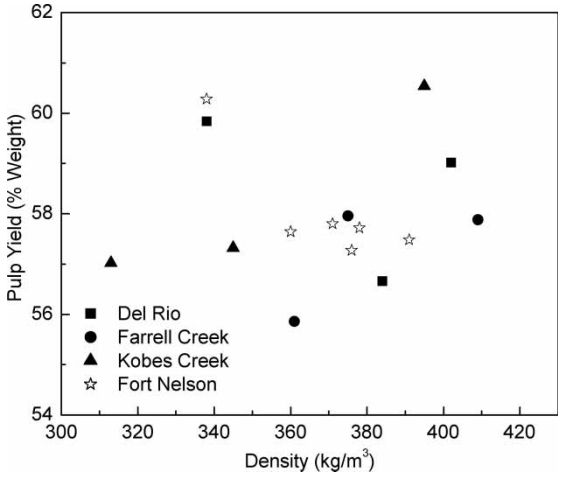

Figure 4. Pulp yield, at kappa 21, versus wood density of the various *Populus tremuloides* clones.

syringyl monomers also appear to have higher total lignin contents (Figure 6). Thus, when pulping to a target kappa (residual lignin content), despite ease of cooking, results in trees with a slightly lower yield as more lignin is solublized during the chemical pulping reaction. It has previously been shown that trees

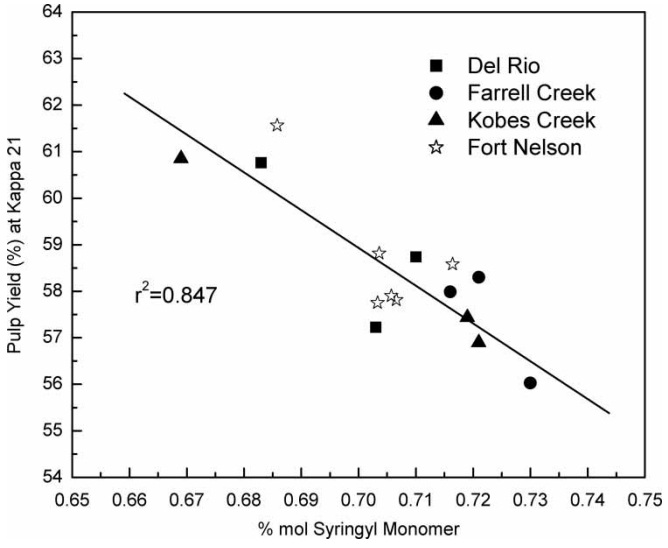

Figure 5. Pulp yield, at kappa 21, versus %mol syringyl lignin monomer composition of the various *Populus tremuloides* clones.

Table 2. Thioacidolysis monomer yield and syringyl to guaiacyl ratio (S:G) of *Populus tremuloides* clones

Clone	$Guaiacyl_t$ (μmol/g lignin)	$Guaiacyl_e$ (μmol/g lignin)	$Syringyl_t$ (μmol/g lignin)	$Syringyl_e$ (μmol/g lignin)	Total yield (μmol/g lignin)	S:G	%S
D1	176.73	187.20	433.68	462.24	1259.85	2.46	0.71
D2	189.19	195.86	451.25	460.51	1296.82	2.37	0.70
D4	182.19	190.05	395.81	406.85	1174.91	2.16	0.68
F3	170.93	177.94	445.08	455.39	1249.35	2.58	0.72
F6	180.04	185.26	446.76	447.15	1259.21	2.45	0.71
F7	187.06	190.49	469.79	482.14	1329.49	2.52	0.72
K1	193.81	202.54	393.34	406.38	1196.07	2.02	0.67
K2	175.70	180.24	450.49	461.76	1268.19	2.56	0.72
K7	206.92	212.94	404.22	413.58	1237.67	1.95	0.66
FN10	149.08	154.36	371.13	359.61	1034.19	2.41	0.71
FN16	197.12	186.00	444.43	394.39	1221.94	2.19	0.69
FN18	169.92	160.06	401.02	382.73	1113.73	2.38	0.70
FN19	155.33	148.92	398.83	369.92	1072.99	2.53	0.72
FN21	172.26	166.14	425.53	389.01	1152.93	2.41	0.71
FN26	175.51	169.25	437.79	378.42	1160.97	2.37	0.70

with lignin composed of a greater percentage of syringyl-based monomers facilitate a greater ease of chemical pulping.[29] Furthermore, transgenic hybrid poplar trees with elevated syringyl lignin monomer content were also shown to pulp to a substantially lower kappa number at the same

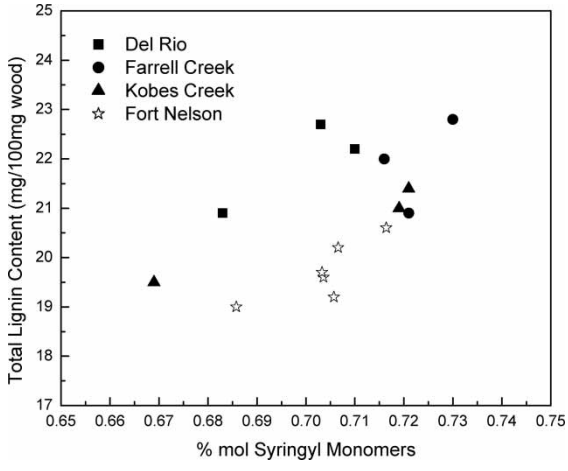

Figure 6. Relationship between total wood lignin content and %mol syringyl lignin monomer composition of the various *Populus tremuloides* clones.

H-factor when compared to the corresponding control trees.[30] These findings confirm that syringyl-rich syringyl-guaiacyl wood, with a higher propensity to form β-o-4 linkages, is more labile and prone to degradation during the Kraft pulping process, as proposed by Chang and Sarkanen.[29]

It is plausible that percentage cell wall lignin, by weight, may be a contributing factor influencing pulping efficacy. However, a closer inspection of pulp yield data at kappa 21 clearly indicates that several aspen clones had much lower pulp yields than those harvested from the Fort Nelson region, which demonstrated a trend toward lower lignin content. If total wood lignin content was a major influential factor, one might anticipate that the Fort Nelson aspen clones would be clearly distinct from the corresponding aspen clones harvested from the three different sites in the Fort St. John region. However, this is not the case.

The pulps cooked to a target kappa of 21 were subjected to a DED bleaching sequence following pulp (Figure 7). Clones originating from Fort Nelson generally reached the highest brightness. With the exception of one clone from Kobes Creek, the Fort Nelson clones showed on average one ISO brightness unit higher ceiling than the other clones, but as much as two ISO units were attainable. These are significant findings given that all the chips were all pulped to a target kappa. When the pulps were not normalized by kappa and compared at a given H-factor, the Fort Nelson clones clearly display significant improvements over the corresponding aspen clones (data not shown). Similarly, an evaluation of pulp viscosity (Figure 8) at a common target kappa, demonstrates that the clones from the Fort Nelson again differ from the other clones procured from the Fort St. John area. Generally, the Fort Nelson aspen clones had lower viscosities compared to

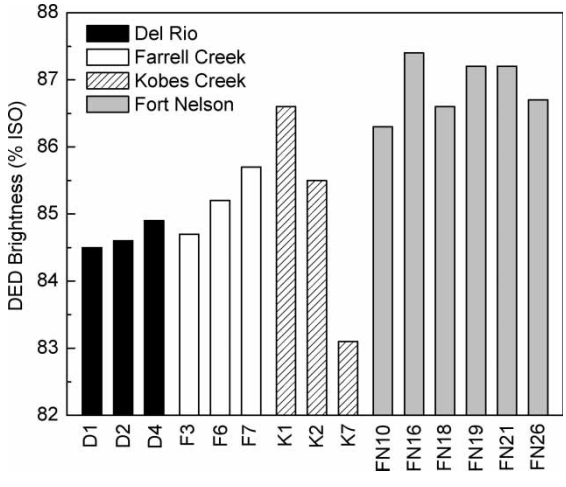

Figure 7. DED brightness, at kappa 21, of the various *Populus tremuloides* clones.

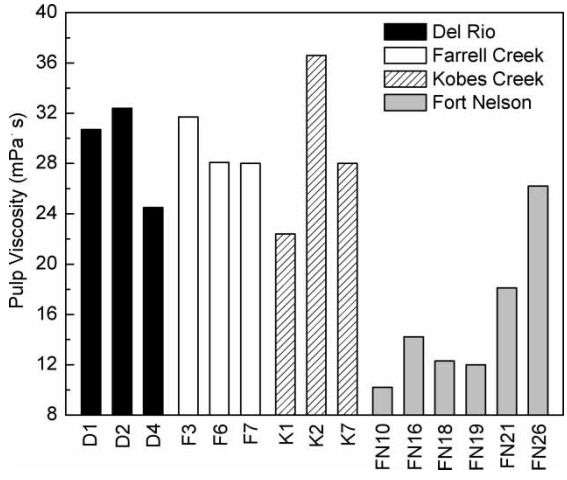

Figure 8. Pulp viscosity, at kappa 21, of the various *Populus tremuloides* clones.

the other clones. These results correlate very well with both the pulping bleaching results. It is plausible that the lower cell wall thickness (fiber coarseness) of the aspen clones from Fort Nelson facilitate an improved environment for accessibility of the bleaching chemical to the residual cell wall lignin, which ultimately manifesting improved pulp brightness values. Similarly, the substantially lower fiber coarseness (cell walls) may alter the extent of reactivity of the cooking chemicals with the carbohydrate moieties of the Fort Nelson aspen, and consequently permit more substantial carbohydrate degradation.

CONCLUSIONS

Wood quality is defined by the intrinsic morphological and chemical components of wood, and as such, plays a critical role in determining the overall economic value of a stem. In addition to growth rate, the rapid and routine measurement of properties such as wood density, fiber length, fiber coarseness, fibril angle, and chemistry can be used to select superior clonal material. Such tools are used to predict end-product quality throughout the forest products value chain and as such represents a critical component in modern plantation development. In this study, we present a comprehensive assessment of aspen clones from the Northeastern region of British Columbia and clearly indicated that the potential exists for selecting superior clonal material. Quantifiable differences were observed that can significantly increase the economic value of the end-product through enhanced processing efficiency, and differentiated products, specific to the pulp and paper industry. Differences in site quality factors and site index were generally shown to be negligible, with the

exception of fiber coarseness. Wood characteristics that affect mill operations such as wood density, which varied from 313–409 kg/m^3 and fiber length, varied from 0.86–1.07 mm. Variations in pulp yield and H-factor required to achieve target residual lignin content prior to bleaching were also significantly different among the clones, confirming that significant chemical and morphological differences exist. Irrespective of geography, it is apparent that wood pulp yield is related to the monomer composition of wood lignin, with higher syringyl monomers facilitating greater ease of delignification. However, the mechanism of improved lignin degradation, whether a higher propensity to form β-o-4 linkages among subunits as proposed by Chang and Sarkanen[29] or a lower overall average molecular weight as proposed by Stewart et al.[18] or a combination thereof warrants future investigations.

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