Variation of the Physical and Mechanical Properties of Hybrid Poplar Clones

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The physical and mechanical properties of poplar clones largely determine their suitability for various end-uses, especially for high value-added applications. The main objective of this study was to determine the clonal variation of selected physical and mechanical properties of seven hybrid poplar clones grown at three sites in southern Quebec, Canada. Five trees per clone were randomly sampled from each site for wood properties measurement. Site had a significant effect on all measured properties except radial shrinkage. All properties of hybrid poplar wood showed significant interclonal variation, indicating the possibility of identifying clones with superior wood properties, especially for density, flexural modulus of rupture, and ultimate crushing strength. High heritability values for the studied properties indicated that these properties are under moderate to high genetic control. The genetic gain for these wood properties ranged from 2.0% to 13.5%.

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INTRODUCTION

Hybrid poplar has received considerable attention for its high productivity compared to other Canadian hardwood and softwood species. It has been widely planted throughout North America due to its fast growth rate and easy hybridization. Hybrid poplar yield reaches up to 15 m³/ha·yr, much higher than the 1.7 m³/ha·yr current average yield in Canadian natural forests (Arseneau and Chui 2003). Perinet (1999) reported yields ranging from 8 to 12 m³/ha·yr in Quebec. The maximum yield observed is 40 m³/ha·year in Southern Quebec, with 2222 stems/ha (Fortier *et al*. 2010). Mean annual increment in hybrid poplar plantations at age 7 to 15 years has also been reported to be over 2.6 times higher than that of unmanaged natural stands at age 55 years in southern Ontario (Zsuffa 1973).

Hybrid poplars are hybridizations of two or more species within the genus *Populus*, which, as one of the fastest growing temperate trees, has considerable commercial value (Zsuffa *et al*. 1996). Hybrid poplars have been genetically improved through selection and crossbreeding to improve growth rate, trunk form, adaptability, and disease resistance (Hernández *et al*. 1998; Riemenschneider *et al*. 2001; Zhang *et al*. 2003; Pliura *et al*. 2007).

For many years the selection criteria were mainly good tree and growth characteristics, resistance to pest and disease, adaptability, and low levels of growth stress. Despite the need to include wood properties in breeding programs, basic wood properties were not seriously considered so far. Since timber is the final objective of genetic tree improvement program, studies on wood properties of clones appear to be of far greater interest (Nocetti 2008). This increase has revealed a need for the selection and improvement of planting materials, to be used in the production of high quality timber. Thus, wood properties of hybrid poplar clones and their end-use potential have been taken into account in breeding programs (Zhang *et al*. 2003).

The fast growth of hybrid poplar is generally associated with quite low wood properties, especially wood density and mechanical properties (Beaudoin *et al*. 1992; Hernández *et al*. 1998). Wood basic density of hybrid poplar in North America ranges from 300 to 390 kg/m^3, and standing trees have high moisture content, typically almost 100%, with only minor differences between sapwood and heartwood (Balatinecz *et al*. 2001). Currently, poplar wood is used primarily to supply fiber for pulp and paper production and engineered wood products such as oriented strand board (OSB), laminated veneer lumber (LVL), and structural composite lumber (Balatinecz *et al*. 2001). Hybrid poplar wood is particularly well suited for these uses (Mansfield 2007).

Mechanical properties are controlled by physical and anatomical characteristics such as wood density, grain angle, fiber length, and microfibril angle of the S2 layer in the cell wall (Tokumoto *et al*. 1997). Wood density is a commonly used quality indicator that is related to other wood properties such as mechanical strength and shrinkage as well as pulp yield and properties (Panshin and de Zeeuw 1980). Wood density is influenced mainly by genotype (Zhang 1998). Flexural stiffness and strength are strongly influenced by wood density (Huang *et al*. 2003; De Boever *et al*. 2007; Innes 2007) and cellular structure.

A number of studies have been conducted on inter- and intra-clonal variation of wood density and shrinkage in poplar species (Nepveu *et al*. 1978; Olson *et al*. 1985; Ivkovich 1996; Koubaa *et al*. 1998a; Pliura *et al*. 2007). Only few investigations concerning variations in fiber characteristics, density, and mechanical properties of different poplar clones can be found in the literature (Hernández *et al*. 1998; Koubaa *et al*. 1998b; Pliura *et al*. 2007, Huda *et al*. 2011, 2012). However, little is known about the clonal variation influencing physical and mechanical properties of hybrid poplar clones. Besides, little information is available on the genetic parameters of the physical and mechanical properties of poplar clones, such as heritability and genetic gain, except for a few studies on density and shrinkage (Hernández *et al*. 1998; Koubaa *et al*. 1998a; Zhang *et al*. 2003). Therefore, the main objective of this study was to investigate the clonal variation in the physical and mechanical properties of selected hybrid poplar clones grown at three sites in southern Quebec, Canada. The heritability and genetic gain in selected properties of these clones were also studied.

MATERIAL AND METHODS

Sample Collection and Preparation

Seven hybrid clones from three sites (Saint-Ours, Pointe-Platon, and Windsor) in southern Quebec, Canada were selected for this study (Fig. 1, Table 1). Trees for hybrid clones trials grown at Saint-Ours and Windsor were planted in 1993. Trees for the trials

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at Pointe-Platon site were planted in 1991. For the clone DNxM-915508 at Pointe-Platon site, trees were obtained from a 1995 trial (Table 2). The Saint-Ours site is located in the Champlain marine deposit, where the soil consists of a silty clay deposit with 40% clay (Table 2). The two other sites consist of sandy loam soil (Pliura *et al*. 2007). The Windsor site is located in a slightly more elevated geographical area with cooler climatic conditions. All tree plantation trial sites had a randomized block design with ten blocks each. One systematic thinning was carried out in 1995 at the Platon site and in 1996 at the Windsor and Saint-Ours sites. Early in 2006, a thinning operation was carried out, removing two-thirds of the trees from these plantation sites.
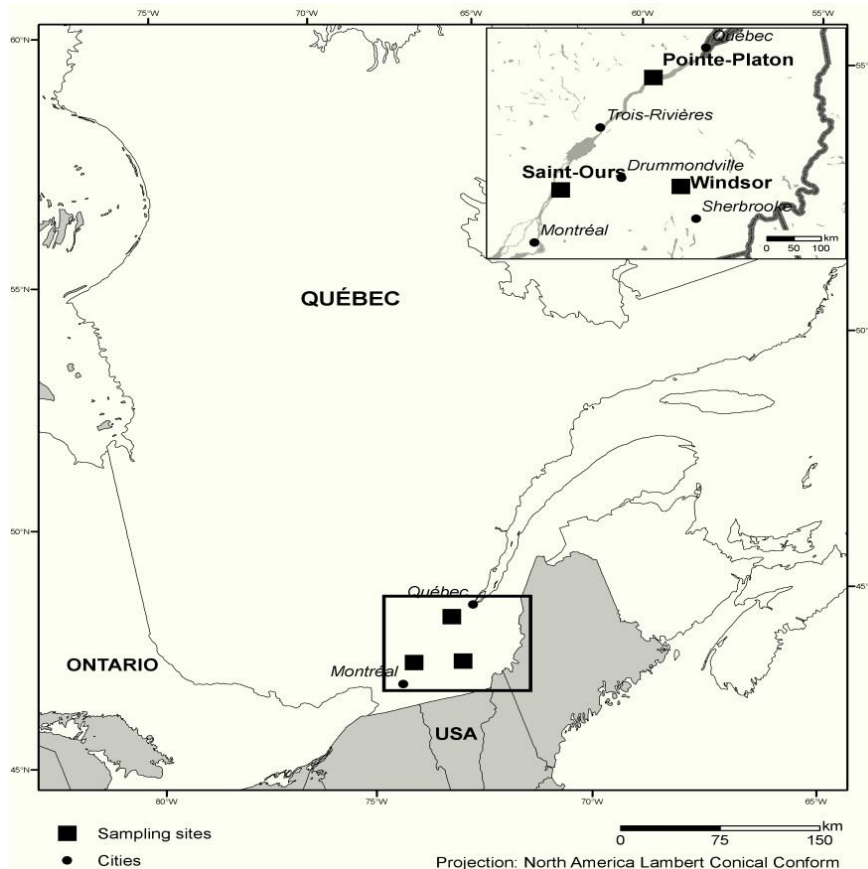
Fig. 1. Map of sampling sites located in the south of the Province of Quebec, Canada

Five trees of each clone were randomly sampled at each site, for a total of 105 trees. Samples were collected in July, August, and early September 2007. A disc of 800 mm in length with its base at a height of 0.5 m above the ground was collected for physical and mechanical property measurements from each tree stem after felling. Disc edges were coated with wax to maintain wood moisture content and to prevent decay and other environmental alterations. Samples were then transported to the Wood Research Centre (Centre de recherche sur le bois, Université Laval, Quebec, Canada), and were kept frozen until the test samples preparation. A 2.5 cm-wide slab was cut along the diameter of each disc (bark to bark passing through the pith) and then conditioned at 20 °C and 60% relative humidity for several weeks until an equilibrium moisture content of 12% was reached.

Table 1. Clones of Hybrid Poplar Selected for the Study

Clone	Hybrid	Female parent	Male parent	Note
DxN-131	*Populus deltoides × P. nigra*	*P. deltoides*	*P. nigra* 'Italica' as the putative father	A natural hybrid selected from the Montreal area, Québec
TxD-3230	*P. trichocarpa × P. deltoides* Syn.: *P.×generosa* 'Boelare'	*P. trichocarpa* 'Fritzi Pauley' (from Washington)	*P. deltoides* S.1-173 (from a cross between *P. deltoides* V.5 from Iowa and V.9 from Missouri)	Clone S.910-8 from Belgium. Cultivar 'Boelare'
DxN-3565	*P. deltoides × P. nigra* Syn.: *P.×canadensis*	*P. deltoides* S.513-60 (from a cross between *P. deltoides* V.5 from Iowa and V.12 from Illinois)	*P. nigra* S.157-3 (from a cross between *P. nigra* V.220 from Italy and V.450 from Belgium)	Family/tree from Belgium: 78.017/164
DxN-3570	*P. deltoides × P. nigra*	*P. deltoides* S.513-60	*P. nigra* S.157-4 (from a cross between *P. nigra* V.220 from Italy and V.450 from Belgium)	Family/tree from Belgium: 78.018/204
DxN-3586	*P. deltoides × P. nigra*	*P. deltoides* S.513-60	*P. nigra* S.132-4 (from a cross between *P. nigra* V.441 from Italy and V.450 from Belgium)	Family/tree from Belgium: 78.016/156
DxN-4813	*P. deltoides × P. nigra*	*P. deltoides* 226 (from Trois-Rivieres, Quebec)	*P. nigra* 'Italica'	A controlled cross selected from Quebec
DNxM-915508	(*P. deltoides × P. nigra*) *× P. maximowiczii*	*P. deltoides × P. nigra* (from Quebec City)	*P. maximowiczii* (from Japan)	A controlled cross selected from Quebec

For physical and mechanical properties, specimens were cut into 20 mm (T) x 20 mm (R) x 100 mm (L) pieces for density, shrinkage, and compression tests, and 20 mm (T) x 20 mm (R) x 330 mm (L) pieces for bending tests. Sample preparation and measurement of physical and mechanical properties were conducted according to ASTM D143, except for dimension of samples. Physical properties measured were basic density (oven-dry mass to green volume ratio), total volumetric, longitudinal, tangential, and radial shrinkage. Mechanical properties measured were modulus of elasticity (MOE) and modulus of rupture (MOR) in static bending, and the ultimate crushing strength (CS) parallel to the grain in compression. Basic density was calculated as the oven-dry mass to green volume ratio just after the sample preparation. The specimens were weighed in an analytical balance and a digital micrometer was used to determine their T, R, and L dimensions. Longitudinal, radial, and tangential shrinkages were calculated as the ratio of the dimensional variation in each direction between saturated and oven-dry states on the dimension in the saturated state. Volumetric shrinkages were calculated from direct volume measurement. Three-point static bending tests were carried out using a universal testing machine (Zwick/Roell Z020) with a span length of 300 mm and maximum load of 20 kN. Compression parallel to the grain tests were performed on a universal testing machine (Zwick/Roell Z100) with a maximum load of 100 kN.

Table 2. Site Characteristics of Hybrid Poplar Clonal Trials

	Site		
Characteristics	Pointe-Platon	Saint-Ours	Windsor
Trial number	PLA01791	STO10893	WIN10593
Establishment year	1991	1993	1993
Geographic coordinates	$46^0$40'N, $71^0$51'W	$45^0$54'N, $73^0$09'W	$45^0$42'N, $71^0$57'W
Elevation (m)	60	15	260
Ecological sub-region–bioclimatic domain	2bT[*] Sugar maple – basswood domain	2aT[*] Sugar maple – bitternut hickory domain	2cT[*] Sugar maple – basswood domain
Surface deposit	Sandy loam soil	Champlain marine deposit with silty clay soil.	Sandy loam soil
Initial spacing	1 m x 3 m	1.2 m x 3.5 m	1.5 m x 3.5 m

[*] Quebec is divided into three vegetation zone. The studied sites are located in the Hardwood forest subzone of Northern Temperate Zone (Zone II). Sites Pointe-Platon and Windsor located in Sugar maple-basswood domain, and Saint-Ours located in Sugar maple-bitternut hickory domain. Here, 2 represents Zone II, a, b, and c represents alphabetic order and T represent Temperate zone.

Statistical Analysis

SAS[®] version 9.3 (SAS Institute Inc. 2010) was used for all statistical analyses. Residuals were tested for normality and homogeneity of variance using statistics provided by the UNIVARIATE procedure. Data transformations were not necessary to satisfy the assumptions of analysis of variance and other analyses. Analyses of variance were performed with the GLM procedure using Type III (partial sums of squares) estimation to assess the relative magnitude of each variation source. The tree effect was confounded with the error term since it was not statistically significant for all studied properties. The mixed linear model was used for the univariate analysis,

$$X_{ijk} = \mu + S_{i\,+} C_j + (S \times C)_{ij} + \varepsilon_{ijk} \qquad (1)$$

where X_{ijk} is an observation on the the *jth* clone from the *ith* site; μ is the overall mean; S_i is the fixed effect due to the *ith* site; C_j is the fixed effect due to the *jth* clone; $(S \times C)_{ij}$ is the interaction between site and clone and ε_{ijk} is the random error. Some *F*-ratios involved more than one means square in the denominator and were tested with approximate degrees of freedom.

Tukey's Studentized range (HSD) was used to test the statistical significance (at $p<0.05$) of differences among means of clones for each site (PROC GLM, SAS). The variance components were estimated in the model using VARCOMP with the restricted maximum likelihood method (REML) and expressed as a percentage (VAR). The individual broad-sense heritability (H^2) was calculated from the variance estimates, as follows (Eq. 2) (Becker 1984; Falconer and Mackay1996),

$$H^2 = \sigma_G^2 / \sigma_P^2 \tag{2}$$

where σ_G^2, and σ_P^2 are the genotypic and phenotypic variance, respectively. Phenotypic variance (σ_P^2) was calculated as shown in Eq. (3),

$$\sigma_P^2 = \sigma_s^2 + \sigma_c^2 + \sigma_e^2 \tag{3}$$

where σ_s^2, σ_c^2, and σ_e^2 are the variance of site, clone, and environmental effects, respectively. The genotypic coefficient of variation (CV_G) and the phenotypic coefficient of variation (CV_P) were calculated from Eqs. 4 and 5, respectively (Burton 1952; Henderson 1953).

$$CV_G = (\sqrt{\sigma_G^2 / \text{mean}}) \times 100 \tag{4}$$

$$CV_P = (\sqrt{\sigma_P^2 / \text{mean}}) \times 100 \tag{5}$$

The mathematical expression for the genetic gain (G) is expressed in Eq. 6. The potential genetic gain from individual tree selection is computed by selection differential (Eq. 7) and 10% selection intensity,

$$G = h^2 * S \tag{6}$$

$$S = i * \sigma_P \tag{7}$$

where h^2 is the heritability, S is the selection differential, i is the selection intensity (10%), and σ_P is the phenotypic standard deviation. The estimated selection differential was based on a 10% selection intensity which corresponds to 1.73 for a sample of 100 (here $n = 105$) as suggested by Falconer and Mackay (1996).

RESULTS AND DISCUSSION

Site Variation

In this study, the physical and mechanical properties of selected hybrid poplar clones wood in three sites were determined. Site had a significant effect on all studied properties except for radial shrinkage (Table 3). This exception was probably due to edaphic effects and climatic conditions such as variation in drainage, elevations of the sites, temperature, and precipitation amounts. The site effect accounted for 2.3% to 15.9% of the total variation, depending on the examined property (Table 3). These results are in good agreement with Pliura *et al*. (2005; 2007) and Zhang *et al*. (2003), who reported significant site effects on wood physical and mechanical properties of hybrid poplar clones.

The effect of site on density was statistically significant. Significant site effects for wood density have been reported by Zhang *et al*. (2003) and Pliura *et al*. (2005). By contrast, Peszlen (1998) did not find any density difference among the three clones of *Populus* planted in two sites in Hungary.

Table 3. Results of the Analysis of Variance of Wood Physical and Mechanical Properties of Hybrid Poplar Clones (basic density (BD), volumetric shrinkage (VSH), longitudinal shrinkage (LSH), radial shrinkage (RSH), and tangential shrinkage (TSH))

		BD (kg/m^3)		VSH (%)		LSH (%)		RSH (%)		TSH (%)	
	DF[b]	P>F-value	VAR[a]	P>F-value	VAR	P>F-value	VAR	P>F-value	VAR	P>F-value	VAR
Site	2	6.8**	8.4	6.2**	4.8	8.9**	15.9	2.6ns	2.3	3.7*	2.5
Clones	3	13.4**	42.3	4.0**	2.7	4.3**	15.6	2.4*	4	4.6**	10
Site x Clones	12	0.8ns	-	3.4**	29.0	0.9ns	-	1.7ns	11.1	2.4**	19.7
Error	83		49.4		62.5		68.5		82.6		67.8

		Mechanical Properties					
		Flexural MOE (MPa)		Flexural MOR (MPa)		Ultimate crushing strength ‖ to grain (MPa)	
	DF[b]	P>F-value	VAR[a]	P>F-value	VAR	P>F-value	VAR
Site	2	10.5**	11.3	6.3**	6.6	9.9**	14.8
Clones	3	4.5**	4.5	18.6**	50.4	11.5**	38.4
Site x Clones	12	2.5**	20.7	1.0ns	0.2	0.4ns	-
Error	83		68.0		42.8		46.8

*Significant at $P < 0.05$ probability level
**Significant at $P < 0.01$ probability level
[ns] Non-significant at $P < 0.05$ probability level
[a] Variance component as a percentage of the total variance
[b] Degrees of freedom

　　　　Based on multiple comparisons, Windsor differed significantly in average density from other sites at the 0.05 level. Trees from the Saint-Ours site showed the highest density values, and trees from Windsor showed the lowest. These results differ from the findings of Pliura *et al*. (2005), who reported higher wood density at the Windsor site than at the Saint-Ours site. However, the clones they used were younger than those of the present study.

　　　　Based on multiple comparisons, trees from the Pointe-Platon site differed significantly in volumetric and tangential shrinkage from other sites at the 0.05 level. The shrinkage values appeared to be lower in Pointe-Platon site compared to Saint-Ours and Windsor sites (Table 4). Therefore, dimensional stability of trees coming from this site should be better. Trees from Windsor and Saint-Ours showed similar values of volumetric, tangential, and radial shrinkages. These results concur with the previous study on hybrid poplar clones collected from Saint-Ours and Windsor sites by Pliura *et al*. (2005). Nepveu *et al*. (1985) have reported significant site effect for tangential shrinkage of poplar clones. The Windsor site showed significant difference with other sites for longitudinal shrinkage (Table 4). However, no significant difference was found for radial shrinkage among the sites.

　　　　Differences among sites were also significant for wood mechanical properties, as shown in Table 3. The variance component analysis indicates that the site effect varied among the studied mechanical properties ranging from 6.6% to 14.8%. Based on multiple comparisons, the overall mechanical properties were more homogenous between the

Pointe-Platon and Saint-Ours sites (Table 4). A similar observation was reported for mechanical properties of 10 years old hybrid poplar clones for these two sites by Yu *et al.* (2008). Mátyás and Peszlen (1997) also reported that site did not affect MOE and MOR of three *euramericana* poplar hybrid clones. They concluded that the lack of difference was probably due to narrow range of density in their study. However, the Windsor site differed significantly from the two other sites at the 0.05 level, having lower strength properties. This site has a very high elevation compared to the other two sites that might explain the lower mechanical properties of wood grown in this site. Cown *et al.* (2006) observed strong and negative effects between structural wood properties of radiata pine and elevation. Saint Saint-Ours trees showed the highest average flexural MOE and crushing strength parallel to grain. Pointe-Platon trees showed the highest flexural MOR.

Table 4. Least Squares Means of Clones and Multiple Comparison Tests of Hybrid Poplar Clones (basic density (BD), volumetric shrinkage (VSH), longitudinal shrinkage (LSH), radial shrinkage (RSH), tangential shrinkage (TSH), flexural modulus of elasticity (MOEF), flexural modulus of rupture (MORF), and ultimate crushing strength parallel to the grain (CS))

Clone	Physical properties					Mechanical properties		
	BD (kg/m^3)	VSH (%)	LSH (%)	RSH (%)	TSH (%)	MOEF (MPa)	MORF (MPa)	CS (MPa)
Site Average								
Pointe-Platon	350^A	7.53^B	0.41^B	2.71^A	4.64^B	7330^A	77.2^A	44.4^{AB}
Saint-Ours	353^A	8.11^A	0.40^B	2.61^A	5.13^A	7500^A	75.8^A	45.6^A
Windsor	340^B	8.19^A	0.48^A	2.45^A	5.19^A	6560^B	73.2^B	42.9^B
Clonal Average								
DxN-131	341^B	8.33^{AB}	0.37^{BC}	2.75^{AB}	4.85^{BC}	7010^{AB}	72.4^B	41.9^{CD}
TxD-3230	339^B	8.30^{AB}	0.46^{AB}	2.41^{AB}	5.53^{AB}	7020^{AB}	73.1^B	42.5^{CD}
DxN-3565	369^A	7.93^{BC}	0.45^{AB}	2.87^A	5.22^{BC}	7480^A	82.2^A	46.8^B
DxN-3570	343^B	7.37^C	0.35^C	2.33^B	4.54^C	6970^{AB}	74.7^B	43.0^{CD}
DxN-3586	327^B	7.56^{BC}	0.40^{BC}	2.62^{AB}	4.56^C	6600^B	69.9^B	40.8^D
DxN-4813	380^A	8.92^A	0.54^A	2.85^A	5.80^A	7520^A	84.9^A	49.9^A
DNxM-915508	334^B	7.25^C	0.44^{BC}	2.27^B	4.45^C	7290^{AB}	70.3^B	44.6^{BC}
Overall Average ± SE	348 ± 25	7.95 ± 1.12	0.43 ± 0.09	2.59 ± 0.65	4.99 ± 1.06	7130 ± 804	75.4 ± 7.16	44.3 ± 4.03
*Means within a column followed by the same letter are not statistically different at *p* = 0.05 for each site separately.								

It is generally believed that rapid growth rate results in low density and low mechanical properties. Variations in wood quality with tree growth are strongly related to physical and chemical characteristics of soil. Sites with favorable soil properties for stand growth may produce low density wood (Grekin and Verkasalo 2010). Numerous authors have shown the importance of environmental effects on wood properties (Zobel and Van Buijtenen 1989). One of the most difficult environmental factors to relate to wood quality is the overall effect of soil and climate, known as site quality (Zobel and Jett 1995). Also, the success of timber production is primarily governed by genotype, site quality, and

silvicultural practices (Malan 1995). According to our results, the variations in the mechanical properties in clones could be based on different factors, such as site and growth conditions. In particular, altitude, soil, climatic conditions, spacing, and elevation can affect the physical and mechanical properties, as reported by Macdonald and Hubert (2002). The difference observed among sites for these wood properties emphasize the importance of proper site selection.

Clonal Variation

The analysis of variance (Table 3) indicated significant clonal variation in the physical and mechanical properties of hybrid poplar clones wood. The significant differences observed among clones for the studied properties are an indication of a clonal effect on wood properties. As indicated by the variance component results, the clone is either low or medium, ranging from 2.7% to 50.4%, depending on the examined property (Table 3).

With respect to physical properties, clonal variation accounted for 42.3% of the total variance in wood density (Table 3). The high clonal variation in wood density is in good agreement with previous works (Yanchuk *et al*. 1983; Beaudoin *et al*. 1992; Zhang *et al*. 2003; Pliura *et al*. 2005; 2007). Clone DxN-4813 showed the highest wood density (380 kg/m^3), whereas clone DxN-3586 showed the lowest (327 kg/m^3). Similar results were obtained with samples taken at greater heights within the same trees in a wood machining experiment (Hernández *et al*. 2011).

On the other hand, the clonal variation accounted for only 2.7% of the total variance in volumetric shrinkage. This result is in good agreement with previous reports (Nepveu *et al*. 1978; Koubaa *et al*. 1998a; Pliura *et al*. 2005). Clone DxN-4813 showed the highest volumetric shrinkage (Table 4). The clonal variation accounted for 16%, 4%, and 10% of the total variance in longitudinal, radial, and tangential shrinkages, respectively. Overall means for longitudinal, radial, and tangential shrinkages were 0.43%, 2.6%, and 5%, respectively (Table 4). These values are slightly lower than those reported in previous studies (Alden 1995; Koubaa *et al*. 1998a; Pliura *et al*. 2005). These lower shrinkage values indicate higher dimensional stability of these clones.

The difference in the physical properties may be attributed to factors such as age, origin, and juvenile wood proportion of the trees. The range of clonal means for density and shrinkage suggests that there was sufficient variation among clones to justify clonal selection to improve wood physical properties.

The interclonal variation in mechanical strength (flexural MOE, flexural MOR, and ultimate crushing strength parallel to the grain) was significant (Table 3). Clones with denser wood generally showed higher mechanical properties (Table 4). This result is in good agreement with previous reports (Bendtsen *et al*. 1981; Hernández *et al*. 1998; Kretschmann *et al*. 1999; De Boever *et al*. 2007). In contrast, Mátyás and Peszlen (1997) did not detect significant clonal effects for strength properties of poplar clones. Based on multiple comparisons, differences among clones were found for mechanical properties at the 0.05 percent level, which helps to select clones with high yield mechanical properties.

The interclonal variation accounted for 4.5% and 50.4% of the variance in flexural MOE and flexural MOR, respectively (Table 3). The overall MOE of the clones studied was comparable to or higher than previous results (Mátyás and Peszlen 1997; Kretschmann *et al*. 1999; De Boever *et al*. 2007). On the other hand, the overall MOR of clones was higher than previous results (Kretschmann *et al*. 1999; De Boever *et al*.

2007). Based on multiple comparisons, clone-4813 and clone-3565 showed higher flexural strength properties among all studied clones (Table 4).

The interclonal variation accounted for 38% of the variance in ultimate crushing strength parallel to the grain (Table 3). The overall ultimate crushing strength parallel to the grain for the clones was 44.3 MPa, with large standard errors (Table 4). Ultimate crushing strength parallel to the grain of clones in our study was compared with those from previous studies. The results showed higher values than those reported by Bendtsen *et al.* (1981) and Mátyás and Peszlen (1997) and lower than the results of Hernández *et al.* (1998). The lower values obtained in the current study could be explained by several factors including the fact that the material of this study is still juvenile (Table 2). The radial variation of the anatomical properties of the same material also confirmed that the wood of the studied clones is juvenile (Huda *et al.* 2012)

The higher values obtained for mechanical properties of hybrid poplar compared to other poplar species might indicate that wood strength properties of these clones could be improved by clonal selection. The level of variation among clones appeared to indicate the genetic control of these properties.

Direct comparison to data from similar investigations could not be made for the mechanical properties measurement due to the different test conditions, such as moisture condition during testing, portion of tree for sampling, sample dimensions, and sampling methods. The age and site effect could also explain the higher values. Hernández *et al.* (1998) stated that samples from juvenile wood showed lower mechanical strength, but could develop higher properties at maturity.

The site x clone interaction of all variables was not significant (Table 3), except for wood volumetric shrinkage, tangential shrinkage, and flexural MOE properties. The non-significant site x clone interaction for wood density and strength properties indicates that, for these properties, the studied clones behaved similarly in the three sites.

Genetic Parameters of Wood Properties

For many wood quality traits, there is little or no information available about the degree of genetic variation or the heritability of the properties. Most data are available for properties that are easier to measure, such as basic density. In this study, the clonal and environmental variations were used to estimate various genetic parameters, including heritability and genetic gain for physical and mechanical properties of selected hybrid poplar clones. The overall mean values of genetic variation for wood properties are presented in Table 5.

The genetic and phenotypic coefficients of variation values for wood density in the present study were lower than the values reported by Pliura *et al.* (2007). However, our study showed lower difference between the genotypic (5.36) and phenotypic (7.41) coefficients of variation.

This low difference indicates that the environmental influence on wood density of the studied clones was low. The heritability for wood density was 0.72, which is comparable to or higher than previous results. Heritability for wood density of *Populus* clones was reported at 0.51 by Peszlen (1998), and at 0.35 by Yanchuk *et al.* (1983) for *Populus tremuloides*, and at 0.69 by Farmer and Wilcox (1968) and Beaudoin *et al.* (1992) for *P. euramericana* clones, and at 0.22 to 0.52 by Pliura *et al.* (2007) for hybrid poplar clones.

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Table 5. Estimates of Genetic Parameters of Wood Properties for 7 Hybrid Poplar Clones

Traits*	Broad-sense heritability	Genotypic coefficient of variation	Phenotypic coefficient of variation	Genetic gain
BD (kg/m^3)	0.72	5.36	7.41	6.65
VSH (%)	0.39	5.61	14.36	4.77
LSH (%)	0.53	13.62	25.74	13.53
RSH (%)	0.19	4.74	25.44	2.02
TSH (%)	0.40	8.73	21.73	6.52
MOEF (MPa)	0.37	4.58	12.26	2.07
MORF (MPa)	0.76	7.54	9.97	9.52
CS (MPa)	0.74	7.12	9.59	9.43

* BD: Basic density; VSH: volumetric shrinkage, LSH: longitudinal shrinkage, RSH: radial shrinkage, TSH: tangential shrinkage, MOEF: flexural modulus of elasticity, FMOR: flexural modulus of rupture, CS: ultimate crushing strength parallel to the grain

The reasons for high heritability for wood density could be related to a lower contribution for nonadditive genetic variance and substantial genome by environment (G x E) interactions (Saifullah and Rabbani 2009). The site x clone interaction for wood density was non-significant and accounted for less than 1% of the total variation (Table 3). There is also evidence that the properties that are highly responsive to environmental variation are well known to have low heritability (Price and Schluter 1991). The genetic gain for wood density obtained in the present study is comparable to that reported by Zhang *et al*. (2003).

The difference between genotypic and phenotypic coefficients of variation of shrinkage properties were high, indicating high environmental influence on such properties. These properties showed moderate heritability except radial shrinkage. The heritability values of shrinkage were in agreement with those of Koubaa *et al*. (1998a) and Nepveu *et al*. (1978) for *P. x euramericana* hybrid. The genetic gain values for shrinkage properties ranged from 2.0 to 13.5. The highest genetic gain was observed for longitudinal shrinkage (13.5), followed by tangential shrinkage (6.5).

There are even fewer works for genetic parameter of hybrid poplar clones in the literature on mechanical properties. Hernández *et al*. (1998) observed a broad sense heritability of 0.34 for MOE and 0.47 for crushing strength, which are comparable with the values found in the present study. The flexural MOR and crushing strength showed high heritability values of 0.76 and 0.74, respectively. The genetic gain for flexural MOE was low. However, flexural MOR and ultimate crushing strength parallel to the grain showed high genetic gains (Table 5).

Practical Implications

Seven hybrid poplar clones investigated in this study showed significant variation in physical and mechanical properties among sites and clones, indicating good opportunities for selecting the best performing clones both for breeding and for desired end-products. The differences observed among sites and clones for these wood properties emphasize the importance of proper site and genotype selection along with proper silvicultural practices which govern the success of timber production (Malan 1995).

Wood dimensional stability is one of the most significant physical property for the manufacture of solid wood products, where drying and seasoning are mandatory. The

dimensional stability of all the studied poplar clones indicates their potential to be used for manufacturing of solid wood products for indoor applications and building materials.

Several economic studies have shown that wood density has a major impact on wood products industries profits because of its impact on harvesting, transportation, and milling cost (Lowe *et al*. 1999). In addition, wood density has an impact on pulp and paper products; even slight modification of these properties could be of commercial value. Wood from the studied hybrid poplar clones is well suited for particle-, flake-, and strand-based composite boards due to its low density, ease of flaking, low processing cost and availability (Geimer 1986; Semple *et al*. 2007).

Knowledge of the wood mechanical properties is required to define the utilization in applications such as furniture and building material. Despite this requirement, characteristics related to the strength and elasticity of wood are also fundamental, both to the structural stability of trees and safety of manufactured wood products (Lima *et al*. 1999). Clones with higher density and mechanical properties, such as DxN-4813 and DxN-3565, would result in higher fiber yield for the pulp industry and stronger wood for the lumber industry. Such clones also performed the best for most of the wood machining processes studied in a parallel study (Hernández *et al*. 2011). DxN-4813, together with DxN-3570, had the best response to steam bending process (Kuljich *et al*. 2013). Clones DxN-4813 and DxN-3565 could be potential raw material for the pallet industry in the Quebec region, as both have better density and mechanical properties.

The increase of hybrid poplar clones production as a raw material for pulp and paper, and wood industries requires a deeper knowledge of their genetics. Moderate to high heritabilities in these properties suggest that satisfactory genetic gains could be obtained through proper clones selection.

CONCLUSIONS

1. The significant effects of site on the physical and mechanical properties of hybrid poplar clones show that Saint-Ours site is the best site followed by Pointe-Platon and Windsor sites, respectively.

2. The clone effect is highly significant and more important than site effect for most studied properties, indicating the possibility of selecting clones with desirable attributes.

3. With the exception of radial shrinkage, for which broad-sense heritability is low, all other wood properties investigated are under moderate to high genetic control. The heritability, and genetic and phenotypic coefficients of variation observed for physical and mechanical properties, suggests that high genetic control could be expected from independent selection for each of these properties.

4. The clonal variation, heritability, and genetic gain values for the properties investigated in this study should help poplar breeding programs that aim to optimize poplar hybrid clones for solid wood and fiber-based products.

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