SELECTED MECHANICAL PROPERTIES OF FAST-GROWING POPLAR HYBRID CLONES

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ABSTRACT

Twenty-eight nine-year-old trees from ten clones of the hybrid *Populus* × *euramericana* from one site in Quebec were sampled to study the variation of selected mechanical properties within trees, within clones, and among clones. Four small and clear ASTM wood samples were taken from each tree at breast height, as well as a 10-mm diameter increment core. The parallel-to-grain compliance coefficient and ultimate crushing strength were evaluated on the ASTM samples for air-dry and green conditions. The dynamic compliance coefficient was measured on increment cores using an ultrasonic wave propagation method. Differences in all mechanical properties among clones were highly significant, while variation among trees was generally not significant. The dynamic compliance coefficient tended to be lowest near the pith, increased to a maximum at one third of the tree diameter, and then decreased outward towards the bark. There was also a highly significant correlation between mechanical properties of ASTM samples and dynamic compliance coefficients of increment cores. Mechanical properties were only moderately correlated to wood density. Finally, there was a significant but weak correlation showing that wood density and mechanical properties decreased with increasing growth rate.

Keywords: Populus × *euramericana*, intraclonal variation, interclonal variation, wood density, compliance coefficient, ultimate crushing strength, nondestructive evaluation.

INTRODUCTION AND BACKGROUND

Forest managers increasingly rely on genetically improved material and intensive forest management practices to make timber production economical and to cope with increasing demand for wood and fiber products. Although programs in forest genetics research and tree improvement have resulted in numerous advances, especially for *Populus* species (Bendtsen 1978), certain areas, including wood utilization, require further investigation (Bendtsen et al. 1981). Most improvement programs have emphasized improved growth, form, adaptability, and disease resistance.

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Wood density and fiber characteristics are important to the pulp and paper industry and have been addressed by some poplar tree improvement program researchers (Walters and Bruckmann 1965; Posey et al. 1969; Zobel 1976; Nepveu et al. 1978, 1985; Murphey et al. 1979; Yanchuk et al. 1983, 1984; Beaudoin et al. 1992; Koubaa et al. 1998). However, genetic selection for the suitability of trees for solid wood end-use products has received little attention (Zobel and Jett 1995). It is possible that wood from hybrids with superior growth rates, improved form, adaptability, and good fiber characteristics for paper may be less suitable for solid wood products compared to woods from the parent or native trees. This means that to diversify wood utilization, hybrids should be selected for a variety of wood properties—particularly strength, density, and dimensional stability—as well as fiber properties.

The objective of this study was to provide information on selected mechanical property variations within trees, within clones, and among clones of *Populus* × *euramericana* hybrid trees coming from one site in south-central Quebec. We also evaluated a nondestructive method for estimating wood mechanical properties by comparing standard specimen wood densities, compliance coefficients, and ultimate crushing strengths to increment core wood densities and dynamic compliance coefficients.

MATERIALS AND METHODS

The sample site was approximately 50 kilometers south of Sorel, south-central Quebec (45° 50′ north latitude, 73° 13′ west longitude). This site is part of the Champlain marine deposit with rich silty-clay soil (40% clay). A total of twenty-eight trees from ten adjacent clones of *P.* × *euramericana* (*P. deltoides* × *P. nigra*) were chosen from a clonal plantation on the site. Trees were randomly selected after taking into account stem straightness and absence of obvious decay. Two to four trees per clone were used; all trees were nine years old. Two 10-mm diameter increment cores were extracted from bark to bark through the pith at breast height (1.3 m above ground). Each core was labeled, wrapped in plastic to avoid dehydration and breakage, and held in cold storage until measurements were made. Only knot-free cores were used. Four clear standard specimens were sampled from each tree immediately above and below breast height to evaluate mechanical properties. Final dimensions of these specimens were as specified by ASTM D143 (1986) that is, 100 mm long with a cross section of 25 mm × 25 mm. These samples were wrapped, stored, and frozen until measurements were made.

Two of the four standard specimens from each tree were kept 80 days in a conditioning room at 20°C and 65% relative humidity (RH) to reach 14% equilibrium moisture content (EMC). The conditioned samples were weighed to the nearest 0.001 g. Dimensions were taken with a digital micrometer to the nearest 0.001 mm. The remaining two standard specimens were soaked in distilled water for 72 hours to ensure a moisture content above the fiber saturation point. The saturated weight of the sample was taken to the nearest 0.001 g. The saturated volume of each sample was evaluated by water displacement (also measured to the nearest 0.001 g). Excess surface water was removed with a cloth. Prior to testing, specimen dimensions were measured to the nearest 0.001 mm.

Compression tests parallel-to-grain were carried out on a Riehle testing machine according to ASTM D143 specifications for small clear specimens. Strain in the axial direction was measured over a 50-mm span in the central part of the specimen, using a two-side clip gauge with a linear variable differential transformer. The cross-head speed was set to 0.07 mm/min. These tests permitted the establishment of the compliance coefficient in the longitudinal direction (s_{11}), which is the reciprocal of the modulus of elasticity (MOE). Ultimate crushing strength in the longitudinal direction (σ_L) was obtained from maximum load at failure and the cross-sectional area. In all cases, calculations were made using the cross-sectional area measured at the time of testing.

Finally, all standard specimens were progressively oven-dried from 20 to 103 ± 2°C over 5 days. Specimens were then cooled down to room temperature, and oven-dry weight was taken to the nearest 0.001 g. Green and air-dry moisture contents were expressed on an oven-dry weight basis. The basic density is reported on an oven-dry weight to green volume ratio. The air-dry density was estimated on an air-dry weight to air-dry volume ratio.

As published elsewhere (Beaudoin et al. 1992), one increment core from each tree was used to measure the basic density. The second increment core was conditioned at 20°C and 65% RH, to provide a nominal EMC of 14%. Once equilibrium was reached, the dynamic compliance coefficient s_{11} was measured as described by Bucur (1981, 1983) and Herzig (1991). The core was placed between two ultrasonic sensors (transmitter and receiver), and a 1-MHz pulse was propagated in the axial direction through the core. A reading was taken every 15 mm along the core from the pith outwards. The time for the wave to pass through the segment was measured to the nearest 10^{-8} of a second. Since wood density at the time of testing is required, the core was divided into 15-mm segments, and the volume of these segments was determined by a mercury-displacement method. Each segment was weighed to the nearest 0.001 g. The dynamic compliance coefficient in the axial direction, s_{11}, was obtained using the following equation:

$$s_{11} = (D_H v^2)^{-1} \quad (1)$$

D_H = air-dry density at time of testing (nominal EMC)

v = velocity of wave propagation

The velocity of wave propagation into wood was corrected using a 10-mm diameter Plexiglas cylinder reference block. This correction compensates for time errors caused by the presence of coupling agents and by transport of electrical waves within the measuring circuit. More details of this correction can be found in Herzig (1991). It should be noted that the effect of Poisson's ratio on the segments was not considered and no corrections were applied. Therefore, compliance coefficients should be considered apparent as proposed by Bucur (1981).

Finally, all segments were oven-dried for 24 hours at 103 ± 2°C to a nearly constant weight. Once segments were cooled down to room temperature, their oven-dry weights were measured to the nearest 0.001 g. The air-dry moisture content was expressed on an oven-dry weight basis.

Analyses of variance (ANOVA) were conducted on the data with significance given to 95% and 99% probability levels using GLM and VARCOMP procedures. The homogeneity of the variance was verified using Bartlett's test (SAS 1988a), and the normality of the data was verified using Shapiro-Wilk's test (SAS 1988b). Correlation and regression analyses on physical and mechanical properties were performed with CORR and REG SAS procedures.

RESULTS AND DISCUSSION

The average basic density of *P.* × *euramericana* clones was 348 kg/m³ for increment cores and 335 kg/m³ for standard specimens (Table 1); the difference was statistically significant. The lower value of standard specimens could be due, in part, to differences in the position within the original tree, as discussed below. The average wood density for increment cores was similar to the average for the merchantable portion of the stem from the same material (349 kg/m³) previously reported (Beaudoin et al. 1992). The dynamic s_{11} was 19% lower than the static s_{11} (Table 1). Similar behavior has previously been reported (Bodig and Jayne 1982; Bucur 1981, 1982, 1983; Herzig 1991).

Wood density, MOE, and ultimate crushing strength in *P.* × *euramericana* clones were compared to those of native poplars at 12%

TABLE 1. *Selected mechanical properties of 10* Populus × euramericana *clones.*

		Increment core		Standard specimen (ASTM D143)				
					Air-dried		Saturated	
Clone	Number of trees	Basic density (kg/m³)	Dynamic s_{11}[1] (TPa⁻¹)	Basic density (kg/m³)	Static s_{11} (TPa⁻¹)	σ_L[2] (MPa)	Static s_{11} (TPa⁻¹)	σ_L (MPa)
37	2	362 BC[3]	—	350 AB	152 ABCD	280 B	163 B	164 ABC
131	2	321 D	126 A	308 E	147 ABCD	275 BC	166 B	148 BC
136	2	303 D	145 AB	283 F	169 AB	249 CD	262 A	111 D
205	3	404 A	102 D	345 BC	129 CD	290 B	158 B	167 AB
1102	4	357 BC	108 D	339 C	136 BCD	296 AB	149 B	188 A
1132	2	349 C	112 D	345 BC	132 CD	301 AB	159 B	164 ABC
3005	3	380 AB	108 D	361 A	151 ABCD	296 AB	157 B	166 ABC
3301	2	363 BC	110 D	348 BC	120 D	322 A	144 B	169 AB
3307	4	360 BC	133 BC	343 BC	163 ABCD	278 B	217 A	134 CD
3308	4	319 D	147 A	326 D	182 A	243 D	236 A	117 D
Average		348	124	335	151	280	181	153
SD[4]		*25*	*16*	*23*	*6*	*45*	*14*	*48*

[1] s_{11} Compliance coefficient in the longitudinal direction.
[2] σ_L Ultimate crushing strength in the longitudinal direction.
[3] Means with the same letter within a column are not statistically different at the 5 percent probability level (Duncan test).
[4] Standard deviation.

MC reported by Jessome (1977). The relationships proposed by Bodig and Jayne (1982) were used to adjust mechanical values for euramericana poplar clones to this MC. The overall average basic density of the ten euramericana clones (335 kg/m³) was lower than that of *P. deltoides* (352 kg/m³) and *P. tremuloides* Michx. (374 kg/m³). The radial position of the standard samples and the fast-growing behavior of the euramericana clones may have influenced the density results. Many studies have suggested that a rapid growth rate may decrease density (Kennedy and Smith 1959; Cech et al. 1960; Farmer and Wilcox 1966, 1968; Farmer 1970; Yanchuk et al. 1984; Beaudoin et al. 1992).

The overall average MOE (7,540 MPa) of the clones studied was lower than *Populus tremuloides* Michx. (12,700 MPa) and only slightly lower than *P. deltoides* (8,140 MPa). However, these samples of *P. × euramericana* clones came from juvenile wood and, at maturity, they could develop higher MOE as discussed later.

Although the modulus of elasticity and wood density of the euramericana poplar clones were lower than the average values of other commercial poplar species, the average ultimate crushing strength of these clones (31.4 MPa) was higher than that of *P. deltoides* (26.5 MPa) and only moderately lower than that of *P. tremuloides* (36.3 MPa). Since the ultimate crushing strength for the euramericana clones was higher than for the native *P. deltoides,* tree form characteristics (bole straightness and size, branch frequency, size distribution, etc.) which normally contribute to lumber grade and quality could determine the suitability of these hybrids for solid wood products.

Finally, we note that the wood properties of this hybrid could be improved by clonal selection. In fact, the extent of wood property variation among clones appears to be under genetic control and should be investigated.

Interclonal, intraclonal, and within-tree variation of the mechanical properties

The ANOVA carried out on arithmetic average of two standard clear specimens by tree showed significant differences among the ten *P. × euramericana* clones for the compliance coefficient s_{11} and ultimate crushing strength under both air-dried and saturated conditions (Table 2). However, intraclonal variation was

TABLE 2. *Analysis of variance and broad-sense heritabilities of selected mechanical properties of* P. × euramericana *clones.*

Source of variation and property	Degree of freedom	Mean square	Variance component	Broad-sense heritability
Compliance coefficient (s_{11}), on air-dried standard specimens				
Interclone	9	2.2×10^{-9}**	3.48×10^{-10}	0.34
Intraclone	15	0.7×10^{-9} n.s.	1.08×10^{-10}	
Error	25	0.4×10^{-9}	5.69×10^{-10}	
Compliance coefficient (s_{11}), on saturated standard specimens				
Interclone	9	7.8×10^{-9}**	1.44×10^{-9}	0.50
Intraclone	18	1.1×10^{-9} n.s.	0	
Error	26	1.5×10^{-9}	1.44×10^{-9}	
Ultimate crushing strength (σ_L), on air-dried standard specimens				
Interclone	9	31.4**	5.09	0.47
Intraclone	16	8.5 n.s.	0.69	
Error	25	4.5	5.06	
Ultimate crushing strength (σ_L), on saturated standard specimens				
Interclone	9	33.9**	7.29	0.61
Intraclone	18	5.3 n.s.	0	
Error	26	4.8	4.71	
Compliance coefficient (s_{11}), on air-dried increment cores				
Interclone	8	2.5×10^{-9}**	3.5×10^{-10}	0.66
Intraclone	15	0.4×10^{-9}*	0.5×10^{-10}	
Error	51	0.2×10^{-9}	1.3×10^{-10}	

** Significant at the 99% probability level.
* Significant at the 95% probability level.
n.s. Not significant at 95% probability level.

not significant. The ANOVA testing differences in dynamic compliance coefficients, carried out on the arithmetic average of 3 to 5 segments of a 10-mm increment core by tree, also indicated that significant differences existed among the nine euramericana clones examined. Intraclonal variation was in this case, however, moderately significant. This could be attributed to the radial variation (s_{11} was measured on 15-mm sections from pith to bark), which is included in the intraclonal variation for nondestructive testing. The non-significant or low intraclonal variation (Table 2) may be due, in part, to the small number of replicates used, all coming from a single site, hence limiting the environmental variation within clones. It is also possible that the genotype of a single clone reacted in the same way in all trees. Further studies with higher numbers of replicates and more than one site are needed to make stronger conclusions.

The estimated variance components due to different clones accounted for 34 to 66% of the total variation, depending on the mechanical property involved (Table 2). This ratio of variance components, referred to as broad-sense heritability, was calculated based on individual trees. Heritability values were moderate to high, possibly due to the fact that all clones came from the same site and the low number of replicates, thus reducing the environmental variation. Variance ratios for mechanical properties of euramericana poplar hybrid appeared to be under moderate to relatively strong genetic control. However, due to the small number of replicates in this clonal trial, the heritability values are only indicative of the genetic control of the properties reported.

Since there were such significance differences among clones, Duncan's multiple-range test was applied to determine which clones

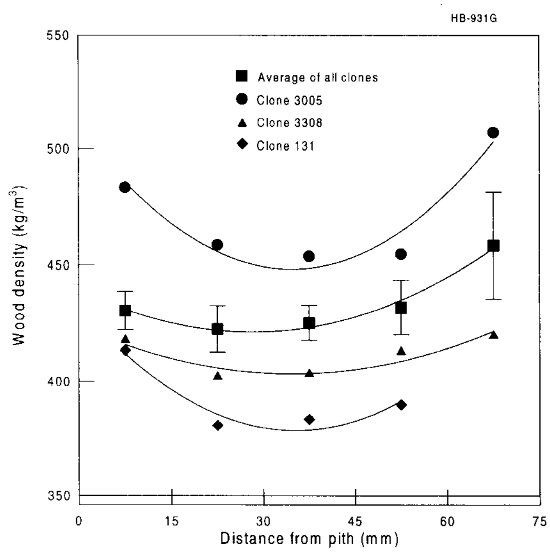

FIG. 1. Radial variation in wood density of *Populus* × *euramericana* clones. Bars indicate standard errors.

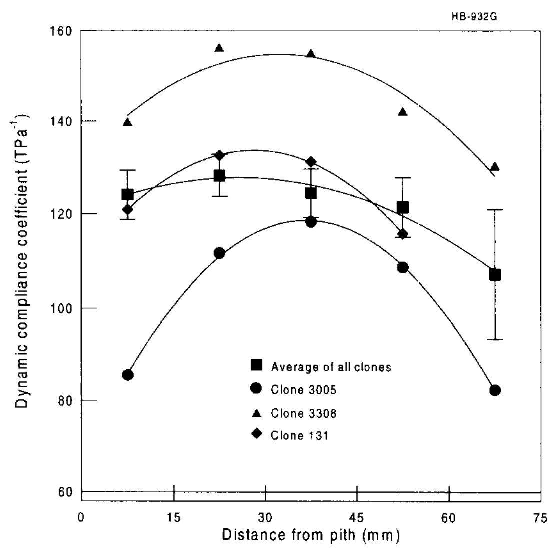

FIG. 2. Radial variation in the dynamic compliance coefficient of *Populus* × *euramericana* clones. Bars indicate standard errors.

might differ at the 95% probability level (Table 1). The practical implication for foresters is that, if a range of clones is available, it should be possible to select those with the best mechanical properties. Saturated and air-dried measurement conditions used here indicated superior mechanical properties and a preference for clones 3301, 1132, 3005, 1102, and 205 compared to clones 3308, 131, and 136. If we use only the preferred clones for calculating mechanical property averages, the euramericana hybrid compared more favorably to the characteristics of other poplar woods mentioned earlier. However, additional work with a larger number of replicates and different sites is needed before making generalizations for poplar hybrids.

Knowledge of within-tree pattern variation, especially in young trees with large proportions of juvenile wood (Zobel and van Buijtenen 1989), could be helpful to foresters. We studied within-tree variation on increment cores only. Wood density decreased slightly from the pith to the first third of the diameter, and then increased outwards (Fig. 1). Trembling aspen (*Populus tremuloides* Michx.) wood exhibits a similar pattern of variation (Yanchuk et al. 1983). Accordingly, the dynamic compliance coefficient increased slightly from the pith to the first third of the diameter and then decreased outwards (Fig. 2). These patterns of variation indicated that euramericana poplar clones had a tendency to produce wood with higher density and stronger mechanical properties at maturity. The MOE and modulus of rupture (MOR) of quaking aspen (*Populus tremuloides* Michx.) in static bending were reported to be, respectively, 31% and 18% higher in mature wood than in juvenile wood (Roos et al. 1990). Eastern cottonwood (*Populus deltoides* Bartr.) has also been reported as having, respectively, 38% and 21% higher MOE and MOR in static bending for mature vs. juvenile wood (Bendtsen and Senft 1986).

Nondestructive evaluation of mechanical properties

Evaluating wood quality using small nondestructive specimens would be helpful to the forest geneticist. Data from 10-mm breast height increment cores and clear standard specimens can be evaluated using correlation and regression analysis. The compliance coefficient measured on 10-mm increment cores using ultrasonic wave propagation was compared to the static compliance coefficient measured on air-dried standard wood specimens. There was a linear relationship between the two types of compliance coefficients ($s_{11static} = 20 + 1.054\ s_{11dynamic}$) with a significant coefficient of determination (R^2) of 0.53. The coefficient of variation (12.6%) was lower than 15%; therefore, the model power of prediction is acceptable, which means that the static compliance coefficient can be predicted from the dynamic compliance coefficient. Similar results were reported for beech wood ($R^2 = 0.45$) grown in natural forests by Bucur (1983). Douglas-fir showed a much weaker relationship ($R^2 = 0.09$) between the dynamic and static compliance coefficients (Bucur 1982). For plantation-grown white spruce, a weaker relationship ($R^2 = 0.25$) with a high coefficient of variation (18.5%) was reported (Herzig 1991).

The relationship between dynamic and static s_{11} was relatively moderate; however, the two measurements were taken on samples from different positions within the tree. The dynamic s_{11} represents the average value of the s_{11} for 3 to 5 segments of an increment core taken at breast height, while the static s_{11} represents the average of two clear specimens taken randomly above and below the breast height. This implies important natural variability (radial and vertical) between the two measurements. The effects of shape and size of the specimens could also influence this moderate relationship. These differences could also explain wood density variation between standard specimens and increment cores (Table 1).

Relationships between other mechanical properties, evaluated on standard specimens, and wood density and dynamic compliance coefficient determined from 10-mm increment cores were examined using simple correlation analyses. Results show that mechanical properties from standard specimens were moderately to highly correlated with dynamic s_{11} (Table 3). These correlations were higher than similar ones that used either air-dry or basic increment core density as a factor, which justified using the dynamic compliance coefficient to predict mechanical properties of wood. The 10-mm increment core taken at breast height can be used with reasonable confidence to predict the mechanical properties of the euramericana clones grown at the present study site. There could be wider applications, as the ultrasonic technique has previously been used as a nondestructive method for evaluating natural variation of mechanical properties of Andean alder grown in Colombia (Hernández and Restrepo 1995).

Relationships between mechanical properties and wood density

The logarithmic function $S = \alpha G^{\beta}$ has been established to describe the relationships between mechanical properties (S) and basic density (G) of clear, straight-grained, and defect-free wood (Newlin and Wilson 1919). These relationships were used for commercially important North American softwoods and hardwoods (USDA Forest Service 1987) and were also valid worldwide (Armstrong et al. 1984; Zhang 1994). However, the suitability of this function for juvenile wood and intensively managed trees has not been verified yet.

We applied this logarithmic function as well as simple linear regression to the compliance coefficient and ultimate crushing strength at air-dry and green states on the euramericana clones. The above parameters and basic density were measured from the same standard specimens. In all cases, the correlation coefficients (not shown) were lower than those showing the relationship between mechanical properties from standard specimens and basic density measured on an increment core (Table 3). Mechanical properties were more accurately predicted from basic density measured on increment cores than on standard specimens. However, we recommend caution in predicting mechanical properties behavior of these poplar

TABLE 3. *Correlation coefficients between selected properties measured on increment cores and clear wood standard specimens of* P. × euramericana *clones.*

Increment core	ASTM standard specimens						
	Density			Air-dried		Saturated	
	D_b[1]	D_H[2]	D_0[3]	s_{11}[4]	σ_L[5]	s_{11}	σ_L
D_b	0.88**	0.77**	0.65**	−0.44*	0.56**	−0.55**	0.58**
D_H	0.83**	0.85**	0.80**	−0.30 n.s.	0.51*	−0.50*	0.54**
s_{11}	−0.62**	−0.54**	−0.57**	0.72**	−0.74**	0.79**	−0.84**

[1] D_b Basic density.
[2] D_H Air-dry density.
[3] D_0 Oven-dry density.
[4] s_{11} Compliance coefficient in the longitudinal direction.
[5] σ_L Ultimate crushing strength in the longitudinal direction.
** Significant at the 99% probability level.
* Significant at the 95% probability level.
n.s. Not significant at 95% probability level.

hybrids from density data alone. Variation in mechanical properties of juvenile poplar wood must be due to other variables, and determining mechanical properties directly was justified. However, as indicated above, static mechanical properties were better assessed using a nondestructive evaluation of dynamic compliance coefficients.

Relationships between mechanical properties and growth rate

In general, poplar hybrids have a rapid growth rate and it is important to know the influence of growth rate on wood properties. The influence of growth rate on wood density has been studied extensively and it is controversial (Zobel and van Buijtenen 1989). Wood density measured from increment cores and ASTM specimens was adversely correlated to dbh but not to the tree height (Table 4). This means benefits of fast growth on tree volume may be countered by lower wood density. A slight negative correlation between growth rate and wood density for the same clonal trial was reported by Beaudoin et al. (1992). These results are in general agreement with earlier reports for *Populus* (Kennedy and Smith 1959; Cech et al. 1960; Farmer and Wilcox 1966, 1968; Farmer 1970; Yanchuk et al. 1984).

In contrast, there are few data on the relationship between growth rate and mechanical properties. No significant correlation between growth rate and MOE or MOR in static bending were reported for the diffuse porous hard-

TABLE 4. *Simple correlation coefficients for the relationships between wood properties, diameter at breast height (dbh), and tree height for* Populus × euramericana *clones.*

Property	dbh	Tree height
Air-dried standard speciments		
Basic density	−0.38*	−0.18 n.s.
Parallel compliance coefficient (s_{11})	0.22 n.s.	−0.07 n.s.
Ultimate crushing strength (σ_L)	−0.26 n.s.	0.07 n.s.
Saturated standard specimens		
Parallel compliance coefficient (s_{11})	0.30 n.s.	−0.12 n.s.
Ultimate crushing strength (σ_L)	−0.48*	−0.14 n.s.
Air-dried increment core		
Basic density	−0.46*	−0.16 n.s.
Dynamic compliance coefficient (s_{11})	0.42*	−0.06 n.s.

* Significant at the 95% probability levels.
n.s. Not significant at 95% probability level.

woods by Zhang (1995), and for loblolly pine by Pearson and Gilmore (1980). In our study, results for poplar hybrid clones were variable with correlations being both significant and not significant (Table 4). While growth rate of poplar hybrids had a weak negative influence on wood density, the effect of growth rate on mechanical properties was negative but inconsistent. These results were encouraging, given that, within the exceptions to general correlative effects exist correlation breakers which in clonal forestry may be exploited. Thus, it should be possible to simultaneously achieve appreciable gains in both wood properties and growth rate.

CONCLUSIONS

Results from this study led to the following conclusions:

1. The hybrid poplar clones had mechanical properties similar to native cottonwood but slightly lower than those of aspen.
2. Significant differences in mechanical properties existed among the ten clones of *P.* × *euramericana* studied. However, intraclonal variation in mechanical properties was not significant since all trees came from one particular site.
3. The radial variation of the dynamic compliance coefficient indicated that wood of *P.* × *euramericana* clones had a tendency towards better mechanical properties with age.
4. Increment cores taken at breast height were good estimators for mechanical properties.
5. We recommend caution in predicting mechanical properties of wood from density in *P.* × *euramericana* clones at earlier ages.
6. There was a weak but significant negative correlation between growth rate, density, and mechanical properties at breast height.

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