VARIATION IN WOOD PROPERTIES OF HYBRID POPLAR LUMBER BY RADIAL AND VERTICAL POSITION IN STEM: A CASE STUDY FROM BOARDMAN, OREGON[1]

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Abstract. Understanding of wood quality of hybrid poplar is critically important for manufacturers who want to know the suitability of the wood for specific products. To this end, lumber was milled from the merchantable stem of four hybrid poplar clones ages 10-11 yr, grown at a single site near Boardman, OR. The vertical and radial position in the stem were recorded for each board and the boards were kiln dried, surfaced, and samples from each board tested to determine specific gravity (SG), dimensional stability, hardness, screw withdrawal, and bending strength and stiffness (modulus of rupture [MOR] and modulus of elasticity [MOE], respectively) from small clear specimens. Results show differences in wood properties relative to vertical and radial position in the stem. SG, hardness, screw withdrawal, and bending properties of lumber samples generally increased with height in tree. Tangential hardness, SG, and MOR varied significantly between different sides of the trees corresponding to predominant wind in the area. Boards milled from the center of the stem had lower MOE and MOR than boards milled from nearer the bark. The results of this study may be used to target specific stem locations for different end uses.

Keywords: Hybrid poplar, wood quality, lumber quality, wood specific gravity, MOE, MOR.

INTRODUCTION

Human-controlled intraspecific hybridization of species in the genus *Populus* has been practiced for more than a century (Stanton and Villar 1996), the resulting trees are commonly called hybrid poplar. Due to rapid growth rates relative to other temperate species (up to 35 $m^3 \cdot ha^{-1} \cdot yr^{-1}$) hybrid poplar was considered for large-scale commercial cultivation as a biomass crop during the petroleum crisis of the 1970s (Stanton et al 2002). At the same time, considerable research on poplar

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genetics and silviculture demonstrated the potential for genetic improvements in growth and wood properties (Carlson 1998). As oil prices and support for biofuels fell in the 1980s, interest in hybrid poplar shifted from the energy sector to the pulp and paper industry (Stanton et al 2002). In the Pacific Northwest USA, tens of thousands of hectares of hybrid poplar were planted in the 1980s and 1990s by pulp and paper companies anticipating regional shortages in hardwood pulp. Small landowners were also encouraged to plant the trees as a sustainable, short rotation woody crop to help meet the looming shortfalls. The projected lack of hardwood pulp did not materialize as expected and shifts in the paper market led to a reduced demand for hybrid poplar chips.

Hybrid poplar has many commercially attractive qualities, which have led to new utilizations and the establishment of plantations for solid wood and veneer-based products as the demand from the pulp and paper industry has waned. It is the fastest growing tree species in much of the temperate zone (Carlson 1998). It is easily bred, cloned, propagated, and established resulting in high potential for relatively rapid and targeted genetic improvement in growth and wood characteristics (Farmer and Wilcox 1968; Bradshaw et al 2000). Hybrid poplar also shares similar properties with pure *Populus* species like aspen and cottonwood, which are used in oriented strand board (OSB) production and for core veneer (Balatinecz and Kretschmann 2001). The commercial potential for hybrid poplar lumber utilization for furniture, paneling, trim, picture frame materials, light structural applications, and decorative box stock has also been recognized in research and on an operational scale (Carlson 1998; Kretschmann et al 1999). Moreover, hybrid poplar lumber has potential value in next-generation engineered wood products like cross laminated timber (CLT) that could serve as a pathway for hybrid poplar lumber into larger structural building material markets (Kramer et al 2014). There has also been a resurgent interest in hybrid poplar as a feedstock for biofuels production (Simmons et al 2008; Sannigrahi et al 2010; Stanton et al 2021).

Despite the potential commercial value of hybrid poplar for solid wood products, wood quality has been understudied. Past research was largely focused on genetic variability in lumber properties that could be selected upon in tree improvement programs (Balatinecz and Kretschmann 2001). The wood quality trait of hybrid poplar considered most frequently in the literature is specific gravity (SG). Possible reasons that SG is often investigated include hybrid poplar's origins in bioenergy, pulp, and paper; the widely held belief that SG is the most significant wood property for utilization; research that shows SG can be influenced by both genetic and silvicultural manipulation; or the fact that SG is correlated to other important wood quality variables in many species (Matyas and Peszlen 1997; Kretschmann 2010). Multiple studies have found significant clonal effect on SG and moderate to high heritability of the trait (Mutibaric 1971; Bao et al 2001; Peters et al 2002; Zhang et al 2003; Pliura et al 2005; Hernandez et al 2011; Porth et al 2013), and environmental conditions associated with site do not consistently affect SG (Farmer and Wilcox 1968; Peszlen 1998; Huda et al 2014).

Few studies have looked at the variability of other solid wood properties that are important for commercial applications. Hernandez et al (1998) found significant differences in the strength characteristics of standard clear samples from different *Populus* × *euramericana* clones with clones accounting for 34-66% of the total variation in mechanical tests while variation between trees of the same clone was generally not significant. Besides clonal differences, Hernandez et al (1998) also found wood density and strength increased with radial distance from the pith, which was substantiated by observations that modulus of elasticity (MOE) and modulus of rupture (MOR) tend to be greater in mature wood than in juvenile wood of *Populus* spp. (Bendtsen and Senft 1986; Roos et al 1990). Similarly, Peszlen (1998) found mechanical properties tended to increase from the pith to the bark and De Boever et al (2007) observed changes in MOE, MOR, and density with tree height in hybrid poplar that they attributed to changes in the ratio of heartwood to tension wood. Koubaa et al (1998b) found that tangential and volumetric shrinkage tended to increase from pith to bark in hybrid poplar and that clones varied significantly in wood shrinkage properties but variation between trees of the same clone, while statistically significant, accounted for less than 5% of the variation in shrinkage. Shrinkage results reported by Pliura et al (2005) were similar; clonal variation was significant but only tangential shrinkage showed clear intertree changes with cambial age. Although each clone had a different pattern, in general, tangential shrinkage increased from pith to middiameter then decreased outward. A suite of wood properties have found to be under moderate to high genetic control with little evidence for site by clone interactions in most properties relevant to wood products (Huda et al 2014, 2018).

The purpose of this study was to determine the SG, swelling, hardness, screw withdrawal, MOR, and MOE of lumber milled from four hybrid poplar clones and quantify the variability between different positions of the stem. In particular, we were interested in the impact of vertical position in the stem and persistent winds from the southwest might have on wood properties. With this information we hoped to guide future optimal merchandizing strategies for plantation-grown hybrid poplar at the the Collins Company's Upper Columbia Mill near Boardman, OR. Multiple studies have previously investigated wood properties in hybrid poplar, but no single study has looked at this broad of a suite of traits commonly used in the marketing of lumber. Moreover, boards were milled to intentionally imitate industrial conditions, providing valuable real-world connections between science and industry.

MATERIALS AND METHODS

Site Description

Trees were all harvested at the GreenWood Resources' Boardman Tree Farm (BTF), Boardman, OR (45°44′54″ N by 119°33′37″; elevation 192 m). Boardman is in a xeric climate east of the Cascade Mountains in Oregon, receiving only 230 mm annual precipitation and growing season daily high temperature regularly exceeds 37°C. Soils are well-drained loamy sands and sandy loams originated from eolian sands and tend to have very slightly acidic to basic pH. Natural vegetation for the area is sagebrush steppe. There is a predominant wind from the southwest that causes some varieties of trees to form distinct sweeps in the lower stem. The BTF was approximately 10,000 ha of drip-irrigated hybrid poplar plantation grown in large (>15 ha) monoclonal uniform blocks originally converted from circle pivot agricultural fields and receiving water from the Columbia River. Trees were planted with 46 cm dormant hardwood cuttings at 716 tree·ha^{-1} and pruned to a height of 7.3 m with multiple entries during the first 5 yr of a 10- to 15-yr rotation. A total of eight trees were sampled consisting of four clones (1-3 trees per clone). All trees were sampled between September and December following their 11th or 12th growing season and were selected to avoid major stem defects. All trees of a given clone were sampled from the same monoclonal stand on the BTF. Sampled trees were, at least, 30 m from any stand boundaries to avoid edge effects and stems with major defects were avoided.

Tree Sampling and Milling

The four cardinal directions (N, S, E, and W) were marked at breast height on each selected tree, diameter at breast height (DBH) was measured, and then trees were felled with a chainsaw leaving as short a stump as possible. Stump height ranged from 13 to 55 cm from the ground. The range in DBH of trees sampled was 23.8-39.2 cm. A measuring tape was stretched down the length of the stem and 2.4-m segments were marked for bucking until the diameter of the stem tapered below 15 cm (log segments of clone BC 78 were inadvertently cut at 2.6 m in length). Prior to bucking, the cardinal directions were transposed to every segment up the tree and each segment was labeled consecutively starting with the butt. Segments were then bucked, and the segment number and cardinal directions were transposed to the cut ends. The segments were debarked by hand and milled into variable width boards 32 mm thick using a model HM126 Woodland Mill portable sawmill. All milling was completed within 2 wk of harvesting the trees and stem segments were stored inside between harvesting and milling. Guidelines described by Malcolm

(1965) for milling grade lumber from hardwood logs were followed, ie where boards are cut longitudinally from the bark toward the pith on four sides of a log when possible resulting in random widths greater than 10 cm (Fig 1). As each board was milled, the face nearest the bark was labeled with the tree number, log number, the cardinal direction of the cut face (N, NE, E, SE, S, SW, W, NW), and the board number cut from that longitudinal face. As boards were milled closer to the center of the tree segments, determining the predominant cut face became problematic. For example, a board milled from the exact center of a segment with only two cutting faces could have one side corresponding to the N side of the tree, whereas the other side corresponds to the S side of the tree and wood at the edges of the board are more representative of the E and W face of the tree. To better isolate any effects related to the cardinal direction, we labeled boards with more than half of both sides consisting of darker colored heartwood, which was present in all trees, as "core" rather than coming from the N, NE, E, SE, S, SW, W, or NW side of the tree (Fig 1). Boards consisting of predominantly discolored heartwood were also reported to have different drying and strength properties by lumber graders working at the Collins Company's Upper Columbia Mill. Designating these boards as "core" was only to distinguish them from boards milled near the surface of logs that could be clearly associated with different longitudinal faces of the tree and not meant to differentiate them as juvenile wood or to suggest that surface boards were mature wood. All boards milled from these trees were assumed to be juvenile wood based on previous studies. For example, Bendtsen and Senft (1986) found mature wood didn't develop in *Populus deltoides* until age 17 or 18, and Peszlen (1994) found that complete maturation of wood anatomical properties, like fiber length and vessel lumen area, of *Populus* clones occurred between ages 9 and 13. Koubaa et al (1998b) and DeBell et al (2002) also suggest that most, if not all wood, in *Populus* clones at age 9, was juvenile wood. The "core" was typically around half the diameter of the logs in the study. Boards with excessive wane were edged, and if necessary, trimmed to minimum length of 1.8 m. The labels were transcribed to board edges and the boards were stacked, stickered, and kiln dried to 8% moisture content (MC) and surfaced on two sides to 26-mm thickness by an abrasive planer at the Collins Company's Upper Columbia Mill in accordance with the mill's operating standards. The kiln-dried and surfaced boards were then sent in clonal batches to the Oregon Wood Innovation Center at Oregon State University, where boards were then cut into test specimens as follows (Fig 1):

- Section A: 150 mm long by the width of the board specimens were cut from one end of each board and used for measuring dimensional stability as described below; following the tests of dimensional stability, 15 mm cubes (A1) were cut from the specimens and used for measuring specific gravity.
- Section B: From the opposite end of each board, 150 mm long by width of the board specimens were cut for measuring hardness and screw withdrawal as described below.
- Section C: A 610-mm long section was cut from the remaining material and a 50-mm wide piece (C1) was then ripped from this and used in the tests of bending properties.

Dimensional Stability and Specific Gravity

Swelling was determined rather than the more conventional approach of shrinkage given that the samples were already kiln dried. Swelling also provides a real-world connection between science and industry as most customers purchase dried lumber and are concerned about its dimensional stability while it is in service. A 150-mm long section was cut from one end of each board and labeled with the original board number. Samples were marked to indicate the location for width and thickness measurements and noted as to whether the measurement was in the radial or tangential direction relative to the growth rings. Samples were placed in an oven at 103°C for 24 h. Each sample was weighed, and dimensions recorded in the oven-dry condition. The samples were then immersed in distilled water in a sealed vacuum chamber under pressure for at least 24

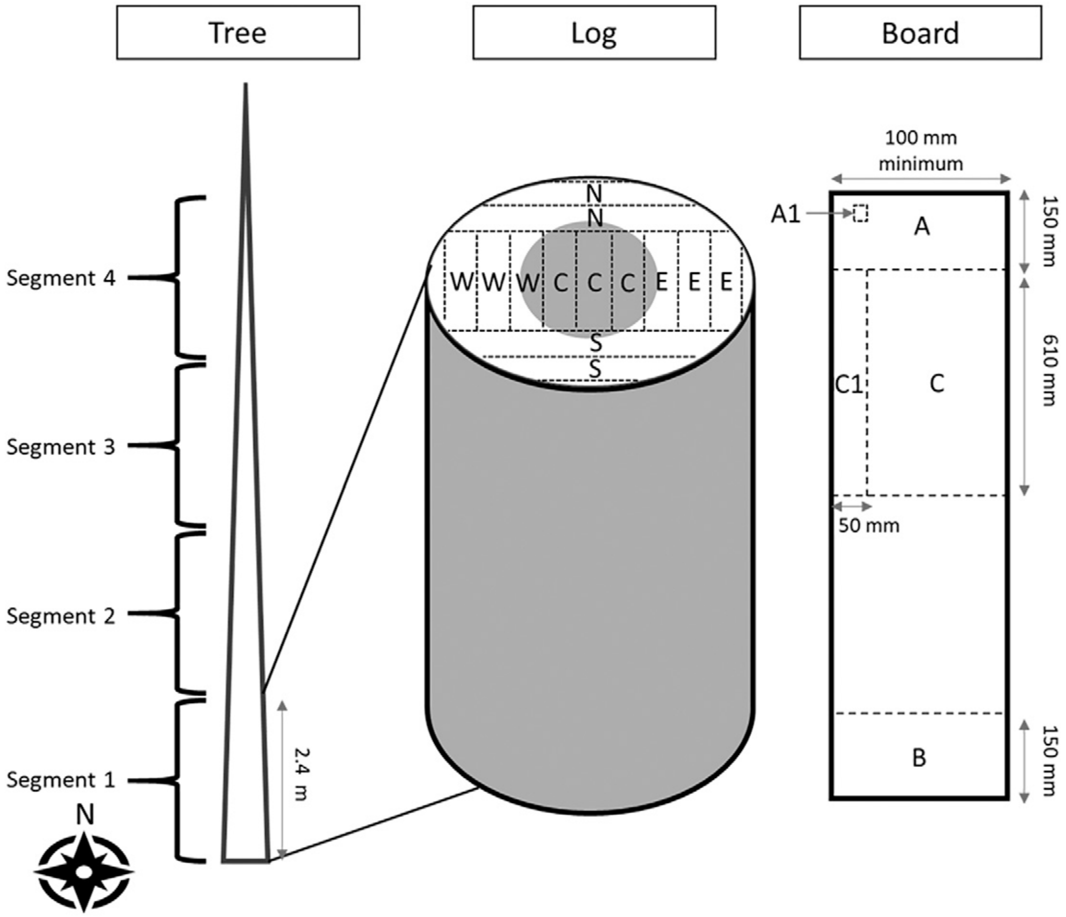

Figure 1. Schematic of sampling procedures showing how trees were segmented, milled into boards, and boards were further broken down into test specimens. Diameter at breast height of trees ranged from 23.8 to 39.2 cm. Each segment was 2.4-2.6 m long. Stump height was 13-55 cm from the ground. N, W, E, S correspond to north facing, west facing, east facing, and south facing, respectively, while C stands for core, which was determined by dark discoloration in the center of the stem that was apparent in all trees. Samples of section A from each board were used for dimensional stability, A1 for specific gravity, B for hardness, and screw withdrawal and sections cut from C (eg C1) were used for testing bending properties.

h to achieve an MC in the wood at or above the fiber saturation point (FSP). Wet samples were removed, weighed, measured, and MC and percentage swelling from the oven-dry condition were calculated. The MC for all samples was determined to be at least 40% with an average of 110% ensuring that FSP had been exceeded (Simpson and TenWolde 1999).

Small cubes (~15 cm^3) were cut from each of the green swelling specimen to determine SG. Cubes were first weighed in the saturated state then the water displacement method (ASTM D2395-02 2002) was used to determine volume by completely submerging samples in a beaker of water on a digital scale and the difference in grams is equivalent to 1 cm^3 volume. Each block was then dried in an oven at 103°C for at least 24 h and weighed. SG was calculated as oven-dry mass divided by the mass of an equal volume of water to the saturated specimen and expressed as a unitless relative measure.

Hardness and Screw Withdrawal

The B sections (Fig 1) were placed in the environmental chamber (20°C and 65% relative humidity (RH); equilibrates wood to 12% MC) and periodically weighed until the sample weight stabilized, indicating equilibrium. Further, spot checks with a moisture meter were conducted and verified specimens were at 11-12% MC and several SG specimens were weighed after conditioning and had an average MC of 11.6% with a standard deviation of 0.65%. Janka hardness was measured in two locations per specimen in the radial section and two locations per specimen in the tangential section using a universal testing machine and following American Society for Testing and Materials (ASTM) procedures (ASTM D143-14 2014).

Following hardness testing, #10, 50-mm wood screws were inserted into each board to a depth of approximately 25 mm or through the full thickness of the board as appropriate. Screws were inserted in the specimens in both the tangential and radial faces. Screws were pulled using a universal testing machine and the peak load of force required to withdraw the screws was recorded.

Bending

The C sections (Fig 1) were placed in an environmental chamber at constant conditions of 20°C and 65% RH (equilibrates wood to 12% MC) and periodically weighed until the sample weight stabilized, indicating equilibrium. Small batches of boards were moved from the conditioning chamber and tested immediately so that all testing could be completed within 30 min of removing samples from the conditioning chamber. Boards were then ripped to 50-mm wide sections (C1, Fig 1) and three-point bending tests were conducted on a 360-mm span using a universal testing machine following the methods described in ASTM D143-14 (2014), and adapted for the smaller specimen dimensions. The standard requires square specimens be used in bending tests which would have required ripping to 26 mm instead of 50 mm. However, there should be no differences in results from testing on rectangular specimens compared with square specimens based on previously published studies (Way et al 2020), and ripping the specimens wider increased ease of handling. Peak stress (MOR) at failure was recorded as was bending modulus (MOE).

Statistics

The effect of vertical position in the stem represented by log segment and radial position in the stem relative to cardinal direction on average dimensional stability, SG, hardness, screw withdrawal, and bending properties of boards was tested using a linear mixed model. Clone and tree nested within clone were included as random effects to account for clone and tree variability and log segment and radial position were evaluated as fixed effects. Analysis was carried out in R version 4.2 (R Core Team 2020) using the lme4 package (Bates et al 2015). Likelihood ratio tests were used to identify important predictor variables as well as test for interactions. Models were fit using log-likelihood optimized estimates for fixed-effect variable selection and final models were scaled using random effects maximum likelihood. Center sawn samples labeled as "core" were not considered in the analysis of aspect and log segment but post hoc pairwise comparisons were evaluated by comparing estimated marginal means of boards milled from the center of logs and all other boards pooled together using the emmeans package (Lenth 2021). Impact of position within or outside the center of the stem was evaluated using analysis of variance for each property. There was a total of 186 boards used in analysis of aspect and log and 65 core boards. Data from three samples of radial hardness, two samples of MOE and one sample of tangential hardness were lost because the test results were not saved, or the sample specimen was unusable for the specific test. Model assumptions were assessed visually using residual plots and model fit was evaluated using the Akaike Information Criterion (Akaike 1974). No inferences about varietal performance were made because there were too few replicates of trees within clone and each clone was harvested in a different stand potentially confounding genetic and environmental effects. However, previous studies have shown clone consistently accounts for the largest portion of variation in many hybrid poplar wood properties (Hernandez et al 1998; Koubaa et al 1998a, 1998b; Peszlen 1998; Peters et al 2002; De Boever et al 2007) and it is common in the literature to report on clonal differences in hybrid poplar wood properties even when a small number of trees are sampled and wood samples are not collected from properly replicated and randomized common garden studies typically used to infer differences arising from genetics. Further, as these varieties are commercially available and this is the first reported data on some of them, wood property characteristics by clone are likely to be of interest to producers and manufacturers. For all these reasons, we have included summary statistics for each clone.

RESULTS AND DISCUSSION

Results

The radial position of boards relative to cardinal direction of the stem face significantly affected SG, tangential hardness, and MOR. The log segment from which the board was cut, which represents the vertical position in the stem, also significantly affected SG, tangential and radial hardness, MOR, MOE, and screw withdrawal. Bending properties were significantly different for boards milled from near the center of the stem compared with boards originating nearer the bark. Model results are shown in Table 1.

Mean unweighted SG of the samples by clone ranged from 0.35 to 0.40 on a green volumetric basis (Table 2). Vertical position in the stem and cardinal direction affected SG. Boards cut from west-facing aspects were higher in SG compared with boards cut from south sides (Fig 2; $p < 0.05$). SG tended to be higher in the first segment than the second segment and increase from the second segment to the top of the tree (Fig 3; $p < 0.05$). SG was moderately correlated with tangential hardness, MOR, and screw withdrawal (Pearson's $r > 0.4$; $p < 0.05$). Position within or outside of center "core" of the stem had no effect on SG.

The ratio of tangential to radial stability (T/R ratio) is an important metric for kiln drying lumber as it is an indicator of the amount and severity of warp and surface checking that is likely to develop during seasoning (Longwood 1961). The mean T/R ratio by clone ranged from 1.38 to 1.79 (Table 2). Log position in the stem and aspect had no effect on swelling in the tangential or radial directions or the T/R ratio (Table 2; Figs 2 and 3). Swelling in both directions was generally uncorrelated with other properties measured except for weak relationships with SG (Fig 4). Position within or outside of stem center had no significant effect on swelling properties.

In general, the tangential face of the boards was consistently harder than the radial face. Boards cut from southwest and west aspects were harder in the tangential direction than boards milled from the south and northeast facing sides of trees. Radial hardness was unaffected by aspect (Fig 2). Both tangential and radial hardness increased with stem height except for the first log which was slightly higher than the log above. Tangential and radial hardness were moderately correlated (Pearson's R = 0.47). Both tangential and radial hardness were correlated with screw withdrawal (Pearson's R = 0.47 and 0.3, respectively). Radial hardness was also slightly correlated with MOR (Pearson's R = 0.32). Boards milled from the core of the stem are related to lower hardness in the tangential direction. Radial hardness was unaffected by central position.

Aspect had no effect on screw withdrawal (Fig 2). Screw withdrawal increased with increasing height in the stem (Fig 3). Screw withdrawal was moderately correlated with MOR, tangential hardness, and SG (Fig 4). Screw withdrawal was unaffected by the central position in the stem.

Mean clonal values for MOR ranged from 57 to 68 $N{\cdot}mm^{-2}$ and MOE ranged from 6236 to 7481 $N{\cdot}mm^{-2}$. MOR was lower in boards cut from east aspects compared with boards cut from southwest and west aspects (Fig 2). MOE was unaffected by aspect. Both MOR and MOE increased with stem height. MOR and MOE were highly correlated (Pearson's R = 0.72). MOR was correlated with both metrics of hardness and SG (Pearson's R > 0.32; Fig 4). Both MOE and MOR were lower

Table 1. Statistical results and coefficients. Log segment 2-6 represent vertical position in the stem and correspond to the 2.4-2.6 m log segments cut from the stem with lower number being closer to the stump. AspectNE, aspectE, aspectSE, aspectS, aspectSW, and aspectNW represent the boards milled from the face of the tree facing the corresponding cardinal direction. Log segment 1 and north (N) aspect are represented by the constants.

	Dependent variable					
	Radial hardness (1)	Modulus of elasticity (2)	Screw withdrawal (3)	Specific gravity (green) (4)	Tangential hardness (6)	Modulus of rupture (7)
Log segment 2	−28.007	33,454.800[a]	−163.505[a]	−0.004	−140.958[a]	53.403
	(48.348)	(13,384.960)	(63.764)	(0.006)	(55.866)	(122.929)
Log segment 3	−25.245	48,160.050[b]	−146.311[a]	0.002	−96.092	86.042
	(49.104)	(13,791.050)	(64.997)	(0.006)	(55.780)	(123.240)
Log segment 4	27.692	56,137.350[b]	−13.097	0.021[c]	23.523	274.706
	(56.474)	(15,661.650)	(74.370)	(0.008)	(65.985)	(146.217)
Log segment 5	174.308[c]	95,507.060[b]	97.073	0.033[b]	29.945	650.674[b]
	(63.007)	(17,494.760)	(82.868)	(0.008)	(72.759)	(161.000)
Log segment 6	211.946[a]	24,744.270	77.913	0.041[b]	160.410	478.036[a]
	(93.711)	(24,711.340)	(117.496)	(0.012)	(101.267)	(224.187)
aspectNE				0.00005	−60.874	−294.091
				(0.010)	(88.939)	(197.739)
aspectE				−0.008	−3.375	−333.319*
				(0.008)	(66.126)	(146.297)
aspectSE				−0.0004	52.462	−157.212
				(0.010)	(88.287)	(196.074)
aspectS				−0.012	−39.654	−147.667
				(0.008)	(68.892)	(152.227)
aspectSW				0.017	250.826[c]	276.987
				(0.010)	(89.595)	(199.408)
aspectW				0.012	79.341	106.699
				(0.008)	(66.435)	(146.091)
aspectNW				−0.010	15.876	−92.191
				(0.010)	(85.566)	(190.568)
Constant	1112.544[b]	50,4498.800[b]	1708.473[b]	0.333[b]	1249.295[b]	4534.910[b]
	(44.010)	(24,670.450)	(143.135)	(0.012)	(77.520)	(209.560)
sd(clone:tree)	79.770	15,556.416		0.017	75.490	225.914
sd(clone)	0.016	43,994.052	271.463	0.015	83.372	280.718
residual	228.176	63,823.190	305.226	0.030	261.366	577.343
Observations	183	184	186	186	185	186
Akaike Inf. Crit.	2471.101	4493.972	2616.554	−638.192	2483.177	2775.169
Bayesian Inf. Crit.	2499.986	4522.906	2642.360	−586.580	2534.703	2826.781

[a] $p < 0.05$; [b] $p < 0.001$; [c] $p < 0.01$.

when originating from the stem center compared with the outer part of the stem ($p < 0.05$). The average MOE and MOR for "core" boards was 6061 $N{\cdot}mm^{-2}$ and 51 $N{\cdot}mm^{-2}$, respectively. The average MOE and MOR for all other boards were 7565 $N{\cdot}mm^{-2}$ and 63 $N{\cdot}mm^{-2}$, respectively.

Discussion

In this study, we demonstrate that vertical position in the stem and the cardinal direction in which the board was sawn within the stem both affect the variation in properties associated with density, strength, and bending but the magnitude of the affect depends on the property. We also demonstrate that boards sawn from central positions in the stem can have a substantially lower MOE, MOR, and tangential hardness.

Both the range and variability of SG found in this study are comparable to what has been previously

Table 2. Mean Wood Property Values with SD in parenthesis. BC78, BC79, BC81, and PC1 are the different clonal varieties. N, NE, E, SE, S, SW, W, and NW represent cardinal directions of the stem face that boards were milled from. "Core" boards are all bored milled from the center part of the tree and not associated with a cardinal direction. Face boards are all not milled from the core (eg all N, NE, E, SE, S, SW, W, and NW board grouped). Numbers 1-6 represent log segments with 1 being the log segment closest to the stump. The range in stump height was 13-55 cm and the range in diameter at breast height of trees sampled was 23.8-39.2 cm. Each log segment was 2.4-2.6 m long. SG is the specific gravity and is a unitless measure. T/R is the ratio of tangential to radial swelling, MOR is the modulus of rupture, and MOE is the modulus of elasticity.

	Number of trees	Number of boards	Average green SG	Radial swelling (%)	Tangential swelling (%)	T/R ratio	Radial hardness (N)	Tangential hardness (N)	MOR (N/mm^2)	MOE (N/mm^2)	Screw withdrawal (N)
BC78	3	92	0.34 (0.04)	3.91 (1.36)	5.41 (1.46)	1.54 (0.69)	1791 (624)	1932 (526)	57 (10)	7285 (1060)	2559 (463)
BC79	2	64	0.36 (0.04)	4.01 (1.39)	6.49 (1.46)	1.79 (0.67)	1979 (397)	2157 (473)	68 (12)	7482 (1461)	3375 (654)
BC81	2	68	0.32 (0.02)	4.44 (1.31)	5.59 (1.67)	1.38 (0.60)	1647 (380)	1756 (380)	58 (9)	7101 (1306)	2550 (493)
PC1	1	27	0.33 (0.02)	4.38 (1.48)	5.88 (1.31)	1.53 (0.75)	1813 (329)	1903 (410)	57 (8)	6236 (822)	2273 (208)
N	na	30	0.34 (0.04)	3.64 (1.13)	5.74 (1.07)	1.75 (0.81)	1854 (410)	2008 (443)	64 (11)	7631 (1282)	2653 (577)
NE	na	14	0.34 (0.02)	3.77 (1.44)	5.35 (1.72)	1.62 (0.76)	1744 (348)	1862 (267)	62 (11)	7725 (953)	2832 (499)
E	na	35	0.33 (0.03)	4.17 (1.23)	5.75 (1.32)	1.48 (0.49)	1734 (422)	1949 (506)	59 (8)	7354 (1062)	2555 (508)
SE	na	14	0.35 (0.03)	4.76 (2.18)	6.12 (1.13)	1.50 (0.61)	1925 (339)	2083 (506)	66 (10)	7692 (910)	2986 (459)
S	na	28	0.33 (0.03)	3.92 (1.35	5.38 (1.14)	1.49 (0.49)	1785 (401)	1934 (408)	62 (9)	7472 (1081)	2714 (673)
SW	na	14	0.35 (0.06)	4.27 (0.83)	5.33 (1.11)	1.33 (0.53)	1890 (464)	2317 (665)	68 (10)	7762 (1163)	3119 (1052)
W	na	35	0.35 (0.05)	3.93 (1.33)	5.31 (1.48)	1.51 (0.73)	1882 (439)	2086 (513)	65 (8)	7474 (944)	2674 (659)
NW	na	16	0.33 (0.03)	4.28 (1.23)	5.95 (1.05)	1.57 (0.73)	1938 (327)	1948 (369)	65 (9)	7864 (643)	2863 (511)
"Core" boards	na	65	0.33 (0.04)	4.42 (1.46)	6.33 (2.08)	1.61 (0.77)	1711 (688)	1723 (442)	51 (10)	6061 (1191)	2718 (642)
Face boards	na	186	0.34 (0.04)	4.03 (1.35)	5.59 (1.28)	1.54 (0.65)	1834 (405)	2013 (477)	63 (10)	7565 (1039)	2739 (635)
1	na	68	0.33 (0.04)	4.22 (1.58)	6.35 (1.93)	1.70 (0.78)	1844 (612)	1954 (486)	57 (11)	6539 (1372)	2816 (560)
2	na	58	0.32 (0.03)	4.25 (1.46)	5.29 (1.26)	1.36 (0.48)	1669 (389)	1788 (400)	59 (9)	7065 (1109)	2561 (543)
3	na	55	0.34 (0.04)	4.00 (1.17)	5.56 (1.39)	1.53 (0.62)	1725 (437)	1907 (425)	59 (12)	7370 (1082)	2592 (553)

(*continued*)

Table 2. Mean Wood Property Values with SD in parenthesis. BC78, BC79, BC81, and PC1 are the different clonal varieties. N, NE, E, SE, S, SW, W, and NW represent cardinal directions of the stem face that boards were milled from. "Core" boards are all bored milled from the center part of the tree and not associated with a cardinal direction. Face boards are all not milled from the core (eg all N, NE, E, SE, S, SW, W, and NW board grouped). Numbers 1-6 represent log segments with 1 being the log segment closest to the stump. The range in stump height was 13-55 cm and the range in diameter at breast height of trees sampled was 23.8-39.2 cm. Each log segment was 2.4-2.6 m long. SG is the specific gravity and is a unitless measure. T/R is the ratio of tangential to radial swelling, MOR is the modulus of rupture, and MOE is the modulus of elasticity. (cont.)

	Number of trees	Number of boards	Average green SG	Radial swelling (%)	Tangential swelling (%)	T/R ratio	Radial hardness (N)	Tangential hardness (N)	MOR (N/mm^2)	MOE (N/mm^2)	Screw withdrawal (N)
4	na	33	0.35 (0.04)	3.90 (1.40)	5.62 (1.50)	1.63 (0.81)	1815 (389)	2016 (525)	64 (9)	7661 (1041)	2808 (587)
5	na	27	0.36 (0.04)	4.40 (1.10)	5.88 (1.21)	1.45 (0.55)	1976 (513)	2048 (601)	67 (13)	7942 (1174)	2966 (894)
6	na	10	0.38 (0.03)	3.58 (1.16)	6.31 (0.94)	1.99 (0.83)	2263 (409)	2297 (511)	69 (7)	7367 (1286)	3084 (980)
All Samples	8	251	0.34 (0.04)	4.13 (0.01)	5.78 (0.02)	1.40 (0.68)	1802 (495)	1939 (484)	60 (11)	7172 (1265)	2734 (635)

reported for *Populus* hybrids (Shupe et al 1995; Kopitovic et al 1996; Peters et al 2002; Zhang et al 2003; Pliura et al 2005; De Boever et al 2007; Hernandez et al 2011). Patterns of within-stem variation in hybrid poplar of similar age have been previously described and exist in both the vertical direction and radial plane. SG first decreases slightly then increases from the pith toward the bark and from the base to the top of the merchantable stem (Bendtsen and Senft 1986; Beaudoin et al 1992). In this study, we did observe an initial decrease in SG from the base of the tree to the top but there were no significant differences between samples taken near the pith (core) and boards milled nearer the bark. The lack of difference in SG between "core" boards and outer boards is likely due to the young age of the trees. Bendtsen and Senft (1986) suggested the increase in SG in wood toward the bark was attributable to the transition between juvenile and mature wood that occurred around age 17-18 in *Populus deltoides*. The younger age of the trees in this study suggest they had not yet developed mature wood. The radial and vertical variation in SG are possibly the result of differences in the percentage and size of vessels and fibers in response to crown development as described in *P. deltoides* by Isebrands (1972); although tension wood and other fiber anatomical properties may also play a part (Bendtsen and Senft 1986; Beaudoin et al 1992; Badia et al 2006; Huda et al 2012). The significant and moderately strong positive correlations we observed between SG and MOR, hardness and screw withdrawal indicate that SG may be a reasonable proxy clonal selection criterion for multiple wood quality traits (Huda et al 2018). SG has previously been shown to be under strong genetic control (Beaudoin et al 1992; Peszlen 1998).

Dimensional stability is not widely reported for hybrid poplar, and when it is, it is determined by the percent volume shrinkage from fresh green condition to dry. In this study, wood properties, including dimensional stability, were tested on kiln-dried finished lumber, so the percent volume increase from dry to fiber saturation (all values were measured as $>40\%$ MC) was measured. Studies that do report dimensional

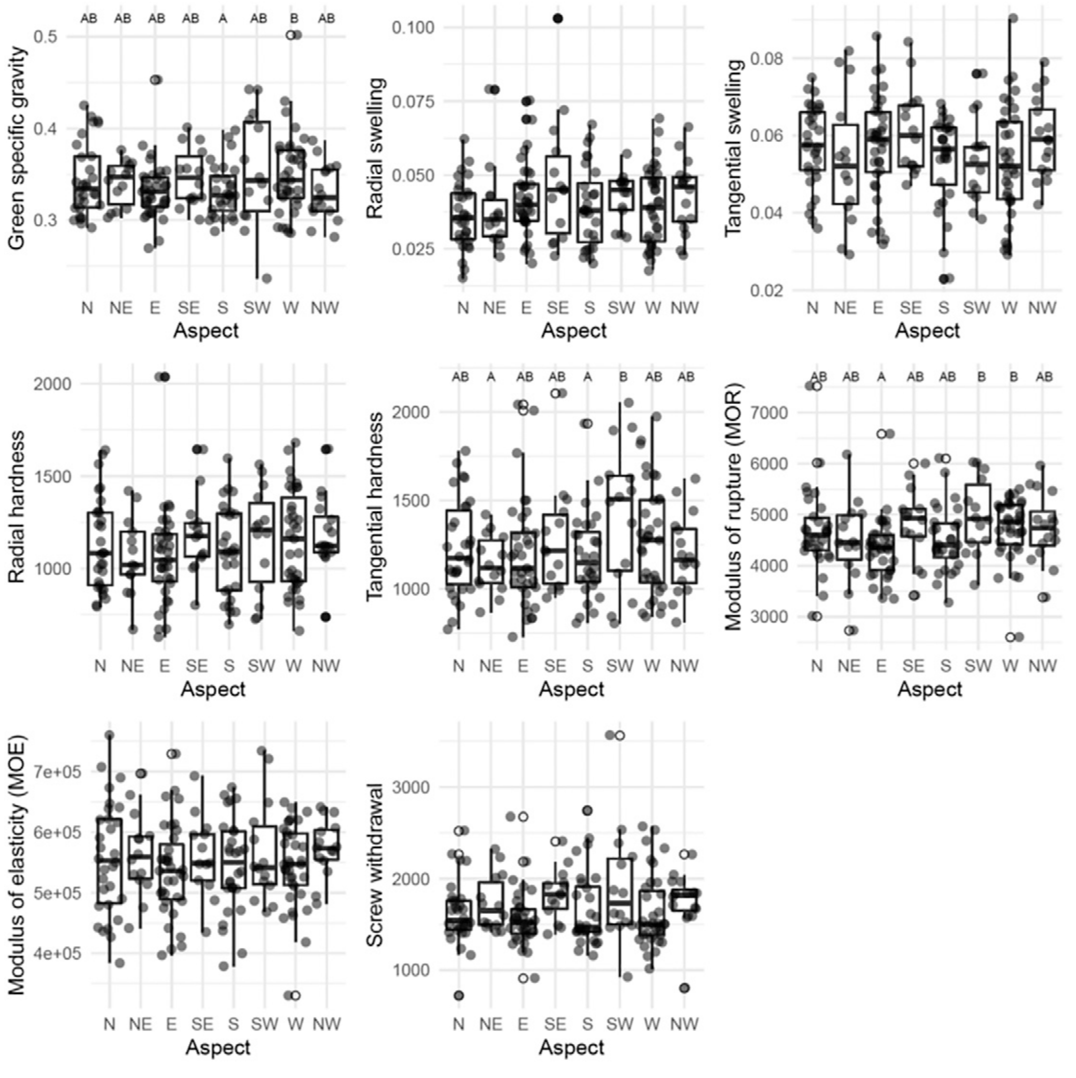

Figure 2. Results for specific gravity (SG), swelling, hardness, modulus of elasticity (MOE), modulus of rupture (MOR), and screw withdrawal by cardinal direction of the standing tree face that boards were milled from. Differences in wood properties between cardinal direction of the stem face were statistically significant ($p < 0.05$) for SG, tangential hardness, and MOR.

stability in terms of shrinkage report much higher values (lower stability) in the tangential plane than found in this study. Balatinecz and Kretschmann (2001) found that hybrid poplar has a high tangential shrinkage to radial shrinkage ratio, which is typically between 1.5 and 2.0 for many species while the clonal averages based on swelling from our study ranged from 1.21 to 1.62. Koubaa et al (1998b) found an average tangential shrinkage of 9.5% for ten *P.* × *euramericana* clones and Peters et al (2002) reported tangential shrinkage that ranged from 6.64% to 9.91% for hybrid poplar clones, whereas the clonal average tangential swelling in this study was between 5.41% and 6.49%. Huda et al (2018) report a similarly low range for tangential dimensional stability with 3.95-6.12% across seven clones and three sites. The range of radial swelling in this study was almost identical to the range reported for radial

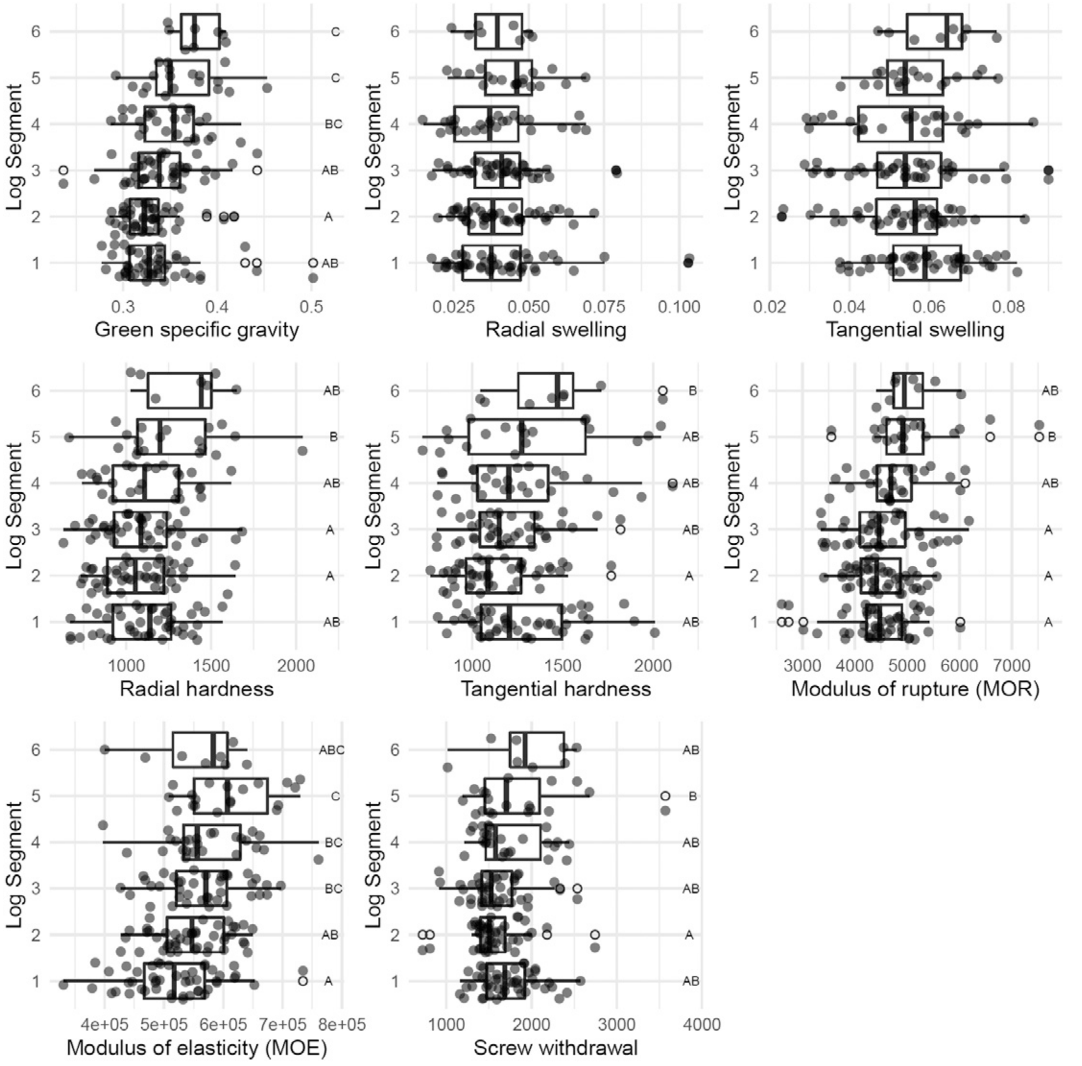

Figure 3. Results for specific gravity (SG), swelling, hardness, modulus of elasticity (MOE), modulus of rupture (MOR), and screw withdrawal by log segment for all trees combined. (1 = closest to the stump and 6 = closest to the treetop). Stump height was 0.3 m and log segments were 2.4-2.6 m in length. Differences in wood properties between log segments of the stem were statistically significant ($p < 0.05$) for SG, tangential and radial hardness, MOR, MOE, and screw withdrawal.

shrinkage by Koubaa et al (1998b) and Peters et al (2002) but nearly two percentage points higher than Huda et al (2018). The tangential shrinkage found in this study was closer to the values reported for *Populus tremuloides* than for hybrids (Jessome 1977). The higher dimensional stability we found may be an artifact of measuring swelling instead of shrinkage; in the course of kiln drying some cell collapse could have occurred and some of the collapsed cells may not recover and thus will not swell like intact cells when rehydrated (Ananías et al 2014; Yang and Liu 2018). Cell collapse was not specifically investigated in the samples from this study, but internal checking anecdotally attributed to cell collapse has been reported by lumber graders at the Collins Company's Upper Columbia Mill in some of the varieties

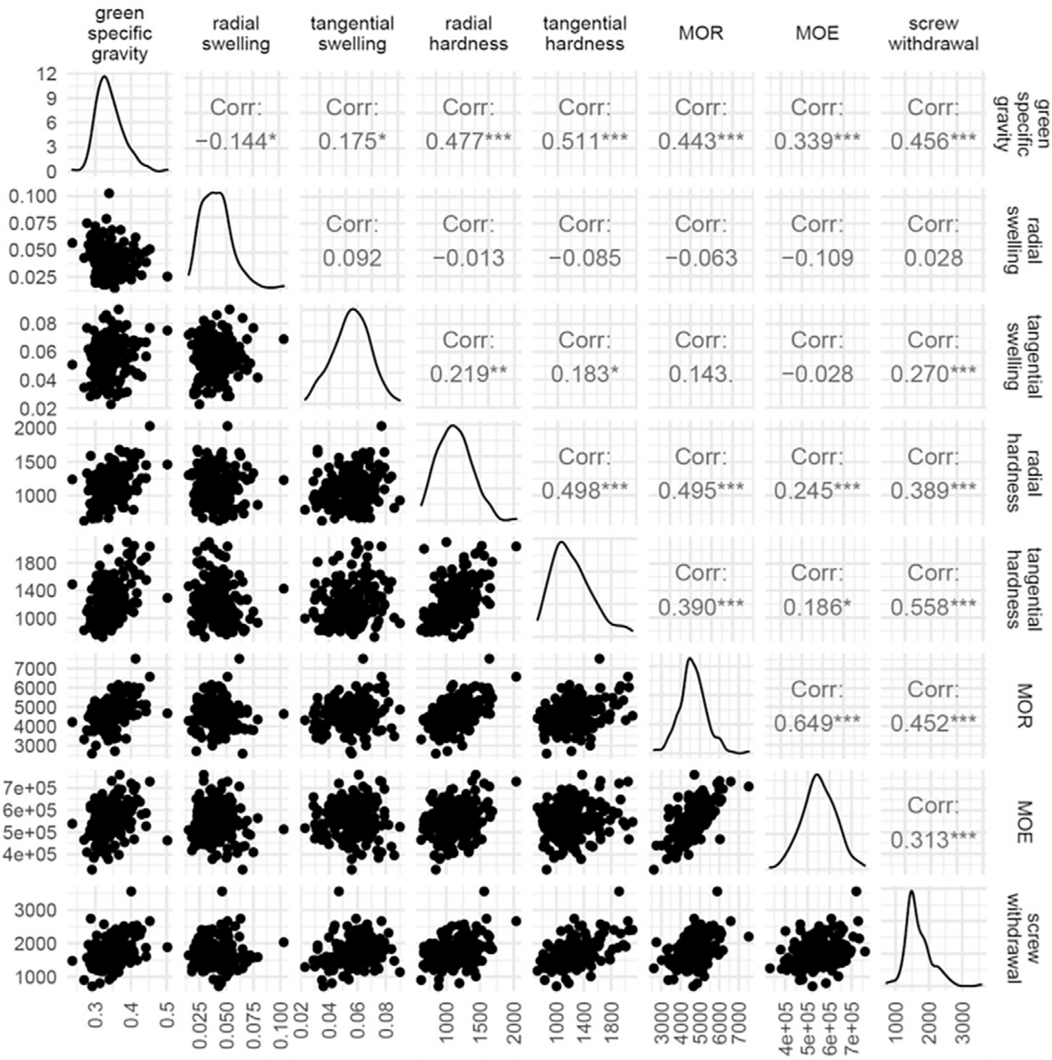

Figure 4. Correlations between measured wood properties. The correlation coefficients are Pearson's R and statistical significance is indicated by $*p < 0.05$, $**p < 0.01$, $***p < 0.001$.

tested. We did inspect samples from the mill that were not part of this study with a scanning electron microscope and the images were consistent with cell collapse described elsewhere (Yan and Liu 2018).

Bao et al (2001) reported clonal mean values for radial hardness ranging from 1820 N to 2550 N, comparable but slightly higher than the range of 1757-2157 found in this study. Value ranges for tangential hardness in hybrid lumber were not found in the literature. The significant effect of aspect on hardness is driven by boards cut from the S and SW side of the tree, which have higher hardness values than boards cut from the NE. The higher hardness values for boards taken from the SW of the tree may be explained by the strong predominant wind that blows from that direction at the BTF. As a result of the wind, tension wood is more likely to form on the side of the tree exposed to the wind in angiosperms like poplar (Gardiner et al 2016), and tension wood has been shown to be associated with increased hardness in other species (Lim 1998). Tangential and radial hardness in response to stem position follow a pattern very similar to SG as discussed earlier, which is not surprising as positive linear relationships between SG and hardness have been reported for wood in other species (Miyajima 1963; Kollman and Cote 1975).

The only study we found that looked at screw withdrawal of hybrid poplar was by Williams (1998), who reported that the average force required to withdraw a screw using the same procedures was 1757 N in the tangential direction, about 64% of the average force required in this study of 2733 N. Similarly, previous testing by the Collins Company on a different clone from the BTF using the same methods at the same lab determined mean screw withdrawal force to be approximately half of the average value from this study. The force required for screw withdrawal in this study is more comparable to higher value hardwoods like red alder, which Williams reported to be 2304 N (1998). There was no obvious explanation for the higher values of screw withdrawal, and it may simply be a lack of sufficient data in the literature to represent the range of variation that exists in hybrid poplar. Log segments 2 and 3 tended to have lower force required for screw withdrawal than other sections of the stem, suggesting that lumber taken from bottom segment and top segments of the stem would be better suited for applications where screw fastening is required.

The range of MOE and MOR in this study was comparable to the range of values reported in other studies using similar methods and materials (Hernandez et al 1998; De Boever et al 2007; Huda et al 2018). The trend of increasing MOE and MOR with tree height was also reported by De Boever et al (2007) and Peszlen (1998) found that both MOE and MOR increased from pith to bark corroborating the lower values found in this study for boards milled from near the core of the tree. Similar to hardness, MOR was markedly higher in boards milled from the wind exposed side of the stem, which was possibly caused by tension wood formed on that side of the tree. The Oregon Wood Innovation Center had previously documented tension wood in lumber samples produced from trees at the site in an unpublished report to the Upper Columbia Saw Mill. However, there were no significant differences in MOE between boards from the windward and leeward sides of the tree, which contrasts with Coutand et al (2004), the only other study we found investigating the relationship of tension wood and bending property in *Populus*, where tension wood caused a three-fold increase in MOE. The discrepancy may be driven by the age difference of the trees tested, Coutland et al's study was on 1-yr-old hybrid poplar, while we examined 11-yr-old trees.

Among all the traits tested, MOE and MOR are the most important for structural applications, which historically have not been suitable for hybrid poplar (Balatinecz and Kretschmann 2001). However, with the growing momentum behind engineered wood products, there may be new utilization opportunities for fast-growing species like hybrid poplar in structural-grade building materials like CLT. Kramer et al (2014) found that CLT made with one variety of hybrid poplar would potentially meet and exceed the shear and bending strength requirements for ANSI/APA PRG-320 CLT Grade E3 but would fail the stiffness (MOE) requirement. Based on the variation in MOE found in this study between clone/site combination, it is not hard to imagine that hybrid poplar varieties could be developed which, with proper silviculture and merchandizing, would consistently yield lumber suitable for low-grade CLT or the interior layers of CLT where strength properties are less important. For example, excluding "core" boards and the two lowest logs, the average MOE of BC 79 exceeds minimum ANSI standards for the lowest CLT Grade, E3 (MOE $>$ 8300 MPa) (ANSI/APA-The Engineered Wood Association 2018). The lower sections of the stem and boards taken from the core can easily be sorted out in most modern mill facilities via log merchandizing (segregate logs from the butt and top of the tree for different end uses) milling process (separate lines for center cants and face slabs) and visual grading (sort boards with minimal heartwood discoloration and no pith for structural purposes). Wood with lower bending properties from the core and lower part of the stem could be utilized for nonstructural products like pallets. The comparison with the ANSI standard is only made to demonstrate how clonal selection, merchandizing, and grading can increase the feasibility of using hybrid poplar in CLT. We make no attempt to establish design parameters for CLT manufactured with hybrid poplar and caution that small clear specimen results may not scale accurately to dimension lumber. Nonetheless, the results, along with evidence of potential genetic gain in MOE and MOR in hybrid poplar from the literature suggest that targeted tree improvement (Huda et al 2014), careful merchandizing of trees and lumber grading can increase the potential applications of hybrid poplar lumber. Other properties of hybrid poplar such as its light weight and rapid growth compared with traditional softwood lumber species may make it a preferable base material for engineered wood products like CLT.

CONCLUSION

SG, MOR, MOE, tangential hardness, and screw withdrawal of lumber samples were significantly affected by the vertical position of boards within the stem, generally showing a pattern of increasing values with tree height. SG, tangential hardness, and MOR were significantly affected by the side of the tree from which samples were milled and corresponding with the direction of the strong predominant wind in the area. MOE and MOR tended to be lower near the pith of the stem, in the "core" boards, relative to boards milled from the parts the stem closer to the bark even though these trees likely had not transitioned to producing mature wood. In fact, previous research on variation between juvenile and mature wood likely has little relevance to hybrid poplar production since trees will almost always be harvested before they begin producing mature wood.

The results of this study highlight opportunities to align log merchandizing, milling techniques, and lumber grading with wood properties to optimize lumber production for specific products. The variation observed in this study could potentially be exploited to uplift the value of otherwise marginal quality hybrid poplar lumber by identifying portions of the stem that produce boards with quality suitable for higher value or higher demand products when isolated from the rest of the tree. While we have cited CLT as one example, other higher value uses like hardwood veneer or lumber for furniture could be similarly optimized through merchandizing and grading based on the variation in wood traits identified in this study. The specific strategies will vary by product and the desired wood characteristics for that product. There are also silvicultural implications from our results. For instances, our data suggests that considering predominant wind direction or other stress factors may be important when establishing plantations for solid wood products. It may be necessary to balance wood quality impacts of tension wood with windthrow risk when orienting planting rows perpendicular or parallel to the direction of strong predominant wind. Future research would benefit from concentrating on clonal effects and multiple sites to identify avenues of further marginal increases in wood quality. Other variables, such as microfibril angle, that may correlate well to wood properties should be explored and high throughput scanning technologies that permit more efficient quantification of wood quality variation could improve efforts to quantify wood properties of hybrid poplar in the future. Next-generation mills that integrate optimization programming and magnetic resonance imaging scans with automated log merchandizing and milling could further facilitate the targeting of the milling of specific products from different parts of the tree.

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