Relationships of density, microfibril angle, and sound velocity with stiffness and strength in mature wood of Douglas-fir

B. Lachenbruch, G.R. Johnson, G.M. Downes, and R. Evans

Abstract: The relative importance of density, acoustic velocity, and microfibril angle (MFA) for the prediction of stiffness (MOE) and strength (MOR) has not been well established for Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco). MOE and MOR of small clear specimens of mature wood were better predicted by density and velocity than by either variable alone (183 trees >20 years old, six specimens per tree, 1087 specimens total). Specimens sampled around the stem circumference had similar density (intraclass correlation coefficient t = 0.74) but not MOE (t = 0.40) or acoustic velocity (t = 0.32), indicating benefits from sampling several circumferential positions. For MOE, the path coefficients (β) were moderate for density and velocity. For MOR, β was only high for density. End-matched samples of one specimen per tree were analyzed with SilviScan. Simple correlations with MOE were highest for density (r = 0.67) and then acoustic velocity^2 (0.53), MFA (–0.50), earlywood MFA (–0.45), and latewood proportion (0.40). Most correlations were weaker for MOR. Density had a higher β than did MFA for either MOE or MOR. In more complex path models, latewood proportion and latewood density were the most important contributors to MOE and MOR, and MFA was relatively unimportant. The path analyses showed what simple correlation did not: that latewood proportion has strong predictive value for Douglas-fir mature wood quality.

Résumé : L'importance relative de la densité, de la vitesse sonique et de l'angle des microfibrilles (AMF) pour prédire la rigidité (MOE) et la résistance mécanique (MOR) n'a pas été clairement établie pour le Douglas vert (*Pseudotsuga menziesii* (Mirb.) Franco). Le MOE et le MOR de petites éprouvettes de bois mature sans défauts ont été mieux prédits par une combinaison de la densité et de la vitesse sonique que par seulement l'une ou l'autre de ces variables (183 arbres >20 ans, six éprouvettes par arbre, 1 087 éprouvettes au total). Les éprouvettes prélevées autour de la circonférence de la tige avaient une densité similaire (coefficient de corrélation intra-catégorie t = 0,74), mais ce n'était pas le cas pour le MOE (t = 0,40) ou la vitesse sonique (t = 0,32). Ce résultat indique qu'il serait bénéfique d'échantillonner plusieurs positions circonférentielles. Dans le cas du MOE, les coefficients de pistes (β) étaient modérés avec la densité et la vitesse sonique. Dans le cas du MOR, β était élevé seulement avec la densité. Des échantillons bouvetés à une des éprouvettes de chaque arbre ont été analysés au moyen de SilviScan. Les corrélations simples les plus élevées avec le MOE provenaient de la densité (r = 0,67), suivie de la vitesse sonique^2 (0,53), de l'AMF (–0,50), de l'AMF du bois initial (–0,45) et de la proportion de bois final (0,40). La plupart des corrélations avec le MOR étaient plus faibles. Le β de la densité était plus élevé que celui de l'AMF, que ce soit avec le MOE ou le MOR. Dans des analyses de pistes plus complexes, ce sont la proportion de bois final et la densité du bois final qui apportaient la plus importante contribution au MOE et au MOR, alors que celle de l'AMF était relativement peu importante. Les analyses de pistes ont montré ce que les corrélations simples ne montraient pas : soit que la proportion de bois final a une valeur prédictive élevée pour la qualité du bois mature de douglas vert.

[Traduit par la Rédaction]

Introduction

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) logs and lumber are of economic importance for forest products industries in western North America, New Zealand, parts of Europe, and other locations where acceptable growth rates can be achieved. Its primary uses are building and construction, and it is used in such products as dimension lumber, piles, and plywood (Alden 1997; Forest Products Laboratory 1999) as well as laminated veneer lumber and many other products. Douglas-fir has maintained a strong market presence because of its superior stiffness (modulus of elasticity, MOE) and strength (modulus of rupture, MOR) (Barbour and Kellogg 1990). This research was designed to better understand the relationships between MOE, MOR, and two factors often used for their estimation, wood density and

Received 11 March 2009. Accepted 14 October 2009. Published on the NRC Research Press Web site at cjfr.nrc.ca on 20 January 2010.

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 doi:10.1139/X09-174

acoustic velocity, and to learn how microfibril angle (MFA) and density affect strength properties independently and in combination. The research was undertaken using small clear specimens of mature wood.

MOE is often estimated rather than measured directly to minimize complexity and cost and (or) to avoid destructive sampling. One common technique for such estimation is to use the velocity of acoustic waves through wood, with or without the additional factor of wood density. Theory shows that MOE = wood density × acoustic velocity^2 (Knowles et al. 2004; Bucur 2006). Experimentally, acoustic velocity measurements are easier to make than mechanical measurements and can be undertaken on sawn specimens, entire logs, and standing trees. Moreover, the acoustic data are simple to manipulate and interpret. Here, we model MOE and MOR using density, MFA, acoustic velocity, and acoustic velocity^2 to learn which factors best explain variation in our sample set.

We know in a general way that the microscopic structure of wood is very important to the stiffness and strength of clear samples (defined as samples that have a minimum of "defects" such as knots, compression wood, slope of grain, and microfractures). However, we have limited understanding of the microscopic properties that best account for the variations in stiffness and strength in Douglas-fir mature wood. The stiffness of lumber can be estimated by analyzing its component materials at several different scales. On the larger scale, one can ask whether MOE is better predicted by density or MFA. Bulk density is an isotropic measure of the amount of material (often assumed to have uniform specific stiffness) available to accommodate stresses. MFA is a major determinant of the anisotropic properties of wood and a measure of the effectiveness of that material to accommodate stresses (Cave 1968; Cave and Walker 1994). The effect of density on MOE has been studied extensively because of its relative ease of measurement (e.g., Cown et al. 1999, 2004; Rozenberg et al. 1999) and because it is correlated with many wood quality traits. MFA effects are being increasingly studied (Evans 1997; Yang and Evans 2003; Barnett and Bonham 2004) as measurement methods become more accessible (Evans 1997; Evans and Ilic 2001). The variation in MOE of clear straight-grained wood can be better explained by using both density and MFA in combination rather than using either single measure (Megraw 1986; Evans and Ilic 2001; Downes et al. 2002; Knowles et al. 2003; Vikram 2008).

On the smaller scale, one can ask whether MOE can be predicted by the proportion of latewood (LW) in a sample because LW is denser and has a lower MFA than earlywood (EW) and therefore contributes a larger proportion to the sample's stiffness. Composite theory shows that the MOE of wood should be the simple volume-weighted average of the MOE of the EW and the MOE of the LW (Bodig and Jayne 1982). Therefore, we could find that LW proportion, a factor that is quite simple to characterize in Douglas-fir, is a strong driver of MOE because it combines information on both LW and EW MOEs. On an even smaller scale, one can ask whether MOE can be predicted from detailed EW or LW characteristics alone and the extent to which each of these characteristics contributes to local MOE.

The relationships between MOR and either density or MFA are typically weaker than the corresponding relationships for MOE (Downes et al. 2002; Yang and Evans 2003). Materials science shows that MOR should be determined less by a simple relationship with density and (or) MFA than by the weakest component within the sample. Such weak components can result from stress risers at all scales, such as at the molecular level in the polymer structure, and at pits, rays, resin canals, compression wood, internal checks, microfractures, slope of grain, and knots (Bohannan 1966; reviewed in Kollmann and Côté 1968, Chap. 7). Therefore, knowledge of the average material properties will not necessarily give good predictions of MOR. Nonetheless, correlations and regressions are commonly tabulated, studied, and refined for MOR and MFA (e.g., Dinwoodie 2000; Yang and Evans 2003) or MOR and density (e.g., Zhang 1995; Forest Products Laboratory 1999; Downes et al. 2002; Kumar 2004; Liu et al. 2007). These relationships are of value, even though theory does not support that they are entirely causal.

The first objective of this study was to determine the predictive power of density and acoustic velocity for estimating MOE and MOR in small clear specimens of Douglas-fir. This information will be helpful in interpretation of acoustic velocity data for samples of various sizes for both research and operations. The second objective was to better understand the relationships between Douglas-fir's mature wood MFA and its MOE and MOR with and without considering wood density. This information will be useful for silviculturists as they manipulate tree growth through practices affecting anatomy, for tree breeders as they make selections that include wood quality, and for tree growers and log buyers as they estimate the value and quality of trees and logs.

Materials and methods

Wood material

Wood samples came from 17 Douglas-fir stands. We selected stands that were >20 years old at breast height, included a range of site indices ensuring a range of radial growth rates, had no fertilization or precommercial thinning in the previous seven years, and had needle retention values indicating that Swiss needle cast disease was not impacting growth: all stands had more than three annual cohorts of needles at the fifth whorl from the top (see Maguire et al. 2002). The stands were located in the Coast Range and the western Cascades in northwestern Oregon (between latitudes 44.2 and 45.6° and between longitudes –122.0 and –123.7°) at intermediate elevations (from 220 to 1012 m). Stands averaged 22–41 years old at breast height and site indices (King 1966) ranged from 35.0 to 45.3 m at age 50. Ring width was estimated for each tree as the average of the six specimens per tree from the outer 10 mm of the breast height bolts (see below). Of the 183 trees, radial growth rate varied by a factor of 6 from 1.1 to 6.2 mm/year (0.04–0.24 in./year).

From each stand, 7–12 dominant or codominant trees were sampled to include a range of diameters in each stand for a total of 183 trees. We selected trees such that when they were removed, the remaining stand spacing was consistent with a thinning, not a patch cut. To avoid complications of compression wood, trees were rejected if their lower stem was leaning at breast height.

After trees were felled, a 30 cm tall bolt was cut from directly above breast height (1.4 m) and then a thin disk was cut from above that bolt. While the wood was still green, six vertical-grained specimens 1 × 1 × 30 cm (radial × tangential × longitudinal) were cut from the outer xylem of each bolt. Depending on the radial growth rate of the tree, a specimen contained from 1.5 to 9 annual rings. The specimens were air-dried to constant mass at 12% moisture content and weighed and then measured in all three dimensions for calculation of wood density (dry mass per volume at 12% moisture content) defined as $density_d$ (directly measured density). This value is distinct from the density value from SilviScan, $density_{ss}$, described below.

We randomly chose one specimen from each tree (n = 183) and then marked its end-matched location on the disk while the disk was still fresh. A short strip 2 cm wide (tangential direction) and about 2 cm long (radial direction) was removed from that location, extracted in ethanol, and air-dried following SilviScan requirements (Downes et al. 1997).

Bending tests

The specimens were subjected to static bending tests on an Instron universal testing machine with a 4200 N load cell that had a standard error of 4 N. We followed ASTM standard D 143-94 (ASTM 1999) with the load applied to the tangential–longitudinal face closest to the pith but with specimen supports set 15 cm apart for a 15:1 span to depth ratio. The load was applied continuously at a rate of 5 mm/min. MOE_d (stiffness) and MOR_d (the maximum force withstood before breaking) were then calculated according to the formulas specified in Markwardt and Wilson (1935); MOE_d was the slope of the linear portion of the stress–strain curve and MOR_d was the stress applied at specimen failure. Note that the MOE_d and MOR_d data used in all analyses came from direct measurements and not from SilviScan. Values are designated with subscript "d" if they were determined directly on entire small clear specimens and with subscript "ss" if they derived from the SilviScan estimates of the end-matched strip.

SilviScan analyses

SilviScan was used to estimate microfibril angle (MFA_{ss}) and density traits (Evans and Ilic 2001) on the xylem that was end-matched to the one specimen per tree (n = 183 trees). $Density_{ss}$ and MFA_{ss} were estimated in the radial direction at 0.05 and 0.2 mm intervals, respectively. For each sample, SilviScan provided ring-by-ring values for ring $width_{ss}$, EW $width_{ss}$, LW $width_{ss}$, LW $proportion_{ss}$, ring $density_{ss}$, EW $density_{ss}$, LW $density_{ss}$, ring MFA_{ss}, EW MFA_{ss}, and LW MFA_{ss}. We counted one growth ring in from the cambium and then used the data from entire growth rings that were totally or partially in the next 1 cm of the strip. Note that the actual beam, while roughly coming from this same location, did not necessarily include entire growth rings. We weighted values by the EW and LW ring widths for those selected growth rings to estimate the average specimen value for $density_{ss}$, EW $density_{ss}$, LW $density_{ss}$, MFA_{ss}, EW MFA_{ss}, LW MFA_{ss}, and LW proportion.

Acoustic velocity

After specimens had been tested mechanically, a 15 cm or longer unbroken piece was sent to CSIRO (Clayton, Australia). Acoustic velocity of each segment was measured at 12% moisture content (Ilic 2001).

Data analysis

We described the data by determining the mean and variance values for the dependent variables MOE_d and MOR_d and the independent variables $density_d$, acoustic $velocity_d$, $density_{ss}$, MFA_{ss}, EW $density_{ss}$, EW MFA_{ss}, LW $density_{ss}$, LW MFA_{ss}, and LW $proportion_{ss}$. For the dependent variables and the first two independent variables, there were data for 1087 specimens. For the remaining variables, there was one sample for each of the 183 trees.

The intraclass correlation coefficient (t) was used to quantify the relative repeatability of within-tree estimates. The stronger the correlation, the more the individual estimates within a tree are alike compared with estimates from other trees. The intraclass correlation coefficient was estimated as

$$t = \sigma^2_{\text{among trees}}/(\sigma^2_{\text{among trees}} + \sigma^2_{\text{within trees}})$$

Variance components were estimated with the SAS varcomp procedure with the REML option using the model Variable = Tree.

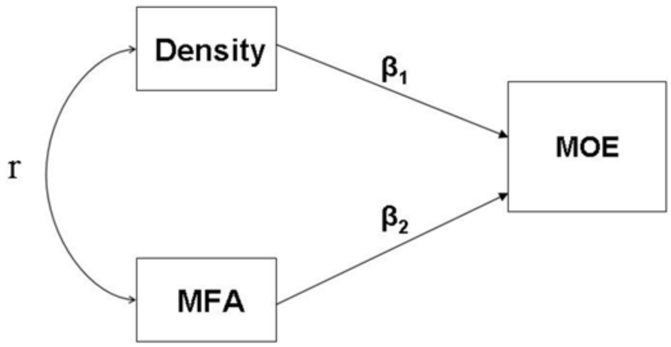
We used simple correlations to determine the association of the dependent variables (MOE_d and MOR_d) with the independent variables ($density_d$, $velocity_d$, $velocity_d^2$, $density_{ss}$, MFA_{ss}, $1/MFA_{ss}$, MFA_{ss}^2, EW $density_{ss}$, EW MFA_{ss}, LW $density_{ss}$, LW MFA_{ss}, LW $proportion_{ss}$, and $density_d/MFA_{ss}$). These correlations were run for three data sets: specimen-level data using the 183 samples for which there were associated data from SilviScan, specimen-level data using all 1087 specimens, and tree-level data using the tree means from the six specimens per tree. The specimen-level analyses treated each specimen as an independent sample.

We had examined the variable $density_d/MFA_{ss}$ because in *Eucalyptus*, it was more strongly correlated with MOE than was either MFA or density alone (Yang and Evans 2003). In the current study, the correlation of MOE with $density_d/MFA_{ss}$ (r = 0.611) was intermediate between the correlation of MOE_d with $density_d$ (r = 0.672) and MOE_d with MFA_{ss} (r = –0.498). The results were similar for MOR_d: the correlation of MOR with $density_d/MFA_{ss}$ (r = 0.426) fell between those with $density_d$ (r = 0.626) and with MFA_{ss} (–0.283) alone. Because it did not improve predictions over those from the best variable alone ($density_d$), no further analyses were done with $density_d/MFA_{ss}$.

Regressions were also performed with the REG procedure in SAS (SAS 1999) to estimate either MOE_d or MOR_d using all combinations of one, two, or three of the following variables associated with the short clear specimens: $density_d$, $velocity_d$, and $velocity_d^2$.

Lastly, we performed path analyses to better understand the independent effects (the direct paths) in several associations of dependent and independent variables. Figure 1 shows a simple path diagram for the relationships among density, MFA, and MOE. The direct path between density and MOE (labeled β_1) indicates the correlation if the other independent variables (here, just MFA) are held constant. The simple cor-

Fig. 1. Simple path diagram showing the path coefficients (β_1 and β_2) relating density and microfibril angle (MFA) to modulus of elasticity (MOE).



relation between density and MOE ($r_{\text{density–MOE}}$) is the sum of the direct path (β_1) and the indirect path ($r_{\text{density–MFA}}\beta_2$). A more thorough explanation of path analysis can be found in Sokal and Rohlf (1995).

The path analyses were undertaken for two dependent variables (MOE_d and MOR_d) and four combinations of independent variables: $density_d$ and $velocity_d{}^2$ (Models 1a and 1b), $density_d$ and MFA_{ss} (Model 2), $density_{ss}$ and MFA_{ss} (Model 3), and EW $density_{ss}$, EW MFA_{ss}, LW $density_{ss}$, LW MFA_{ss}, and LW $proportion_{ss}$ (Model 4). The last model is more complex than the three-variable model in Fig. 1, but the same principles apply. Instead of one indirect path for each independent variable, four independent paths exist for each correlation between each independent variable and the dependent variable.

Direct paths were determined by first standardizing all of the traits to have a mean of 0 and a standard deviation of 1 and then by running a regression with MOE_d or MOR_d as the dependent variable and the combinations listed above as the independent variables. The regression coefficients represent the path coefficients (β). Even though there was a slight improvement in the models using MFA_{ss}^2 over MFA_{ss}, we used MFA_{ss} in the path analyses because the improvement in fit was negligible and there is no physical justification for the use of MFA_{ss}^2. The variance explained by MFA or transformations of it (i.e., MFA^2, 1/MFA) was 28% or less, and with such high residual variance, there is insufficient statistical support for using variations of MFA in multiple regression analysis of these data. Analyses were performed on both the individual specimen data and tree averages using the SAS REG procedure (SAS 1999).

Results

Data description

The dependent variables MOE_d and MOR_d had more variation associated with them than did the density and $velocity_d$ measurements, as shown by their higher coefficients of variation (Table 1). The MFA_{ss} measurements had the largest coefficients of variation of all values reported.

Wood $density_d$ had the highest intraclass correlation coefficient (t) of the four variables examined (Table 1): 74% of the variance in $density_d$ among and between trees was explained by variance among trees. In other words, the six specimens taken from around the circumference had values that were relatively similar. In contrast, MOE_d and acoustic $velocity_d$ had relatively small t values (0.40 and 0.32, respectively) and MOR_d had a moderate t value (0.57). These values demonstrate considerable within-tree variation for MOE_d, acoustic $velocity_d$, and MOR_d (Table 1).

Predicting MOE_d and MOR_d with $density_d$ and acoustic $velocity_d$

Here, we report on the relationships of MOE_d and MOR_d with variables that were measured directly on 1087 specimens. Among-tree correlations (Table 2*c*) were generally higher than were among-specimen correlations (Tables 2*a* and 2*b*) as a result of the more stable estimates with the tree means. The strongest correlation of MOE_d with direct-measured values was with MOR_d followed by $density_d$, then $velocity_d^2$, and then $velocity_d$ (Table 2). MOR_d had a similar correlation with density as did MOE_d but much lower correlations with $velocity_d$ or $velocity_d^2$. The correlations of $velocity_d^2$ with MOE_d and MOR_d were only slightly stronger than those with $velocity_d$. Among the ring MFA variables, MFA_{ss}^2 had slightly higher correlations with MOE_d and MOR_d than did MFA_{ss} or $1/MFA_{ss}$, but all values were of very similar magnitude.

Table 3 shows the regression models predicting MOE_d and MOR_d with various combinations of $density_d$, acoustic $velocity_d$, and acoustic $velocity_d^2$. All of the models had adjusted R^2 values >0.3 for MOE_d. Unlike MOE_d, MOR_d was predicted poorly by $velocity_d$, $velocity_d^2$, or their combination; adjusted R^2 values ranged from 0.08 to 0.25. When $density_d$ was included in the models for MOR_d, the adjusted R^2 values increased, although they were substantially lower than the values for the same model for MOE_d.

The single-variable regression models indicated that $velocity_d^2$ was a slightly better predictor than was $velocity_d$ of MOE_d or MOR_d (Table 3). Two-variable models using $density_d$ and $velocity_d$ essentially explained the same amount of variation as the two-variable models using $density_d$ and $velocity_d^2$. The three-variable models offered no real improvement over the two-variable models: only one of the three-variable models was significantly better than its two-variable counterpart (MOE_d for small clear specimens), but it explained <1% more of the variation as R^2 increased from 0.547 to 0.551.

The regression models for the tree averages explained more variation than did the corresponding models using the specimens (Table 3) because of the greater stability of the tree averages. Likewise, in the path model analyses, the model with tree-level data (Model 1a, Table 4) explained more of the variation than did the models including only specimen-level data (remaining models in Table 4).

For MOE_d, the path coefficients (β) for both $density_d$ and $velocity_d^2$ were relatively high (0.44–0.57) (Models 1a and 1b, Table 4). For MOR_d, however, the β value for $density_d$ (0.58–0.61) was much higher than that for $velocity_d^2$ (0.17–0.20).

Most of the correlations involving MOE_d (r, Table 2*b*) lay on the direct paths (β, Model 1b, Table 4): for MOE_d and $density_d$, r = 0.59 and β = 0.49 and for MOE_d and $velocity_d^2$, r = 0.57 and β = 0.45. The same pattern held for MOR_d and $density_d$ (r = 0.62 and β = 0.58), but most of the correlation between MOR_d and $velocity_d^2$ derived from the indirect path

Table 1. Description of means and variance of specimen-level data.

		Dependent variables		Independent variables								
	Age (years)	MOE_d (MPa)	MOR_d (MPa)	$Density_d$ (g/cm^3)	$Velocity_d$ (m/s)	$Density_{ss}$ (g/cm^3)	MFA_{ss} (°)	EW $density_{ss}$ (g/cm^3)	EW MFA_{ss} (°)	LW $density_{ss}$ (g/cm^3)	LW MFA_{ss} (°)	LW $proportion_{ss}$
Mean	28.8	11533	107.2	0.553	5443	0.526	14.6	0.298	16.3	0.860	11.8	0.413
SD	5.4	1992	18.8	0.052	367	0.054	3.0	0.028	3.9	0.084	2.1	0.06
CV	0.19	0.17	0.18	0.09	0.07	0.10	0.21	0.09	0.24	0.10	0.18	0.16
Minimum	17	2630	45.4	0.372	3757	0.319	9.4	0.215	9.5	0.536	8.7	0.18
Maximum	49	17820	167.7	0.783	6254	0.651	24.2	0.459	26.7	1.101	21.2	0.56
n	183	1087	1087	1087	1087	183	183	183	183	183	183	183
t		0.40	0.57	0.74	0.32							

Note: Subscript "d" denotes that the value was derived from a direct measurement; subscript "ss" denotes that the value was derived from SilviScan. CV, coefficient of variation (SD/mean); *n*, sample size: direct information for 1087 specimens and SilviScan information from 183 specimens; *t*, intraclass correlation (see text).

Table 2. Simple correlations (*r*) for characteristics measured among trees and among specimens.

	Direct measures				SilviScan measures								
Variable	MOR_d	$Density_d$	$Velocity_d$	$Velocity_d^2$	$Density_{ss}$	MFA_{ss}	$1/MFA_{ss}$	MFA_{ss}^2	EW $density_{ss}$	EW MFA_{ss}	LW $density_{ss}$	LW MFA_{ss}	LW $proportion_{ss}$
(*a*) Specimens, SilviScan subsample													
MOE_d	0.731	0.672	0.524	0.528	0.584	–0.498	0.471	–0.503	0.221	–0.447	0.343	–0.343	0.398
MOR_d		0.626	0.311	0.320	0.412	–0.283	0.258	–0.291	0.131	–0.257	0.220	–0.164	0.395
$Density_d$			0.330	0.339	0.739	–0.395	0.383	–0.395	0.226	–0.337	0.482	–0.270	0.568
Velocity				0.999	0.364	–0.694	0.658	–0.697	0.067	–0.664	0.295	–0.537	0.175
$Velocity^2$					0.373	–0.698	0.667	–0.699	0.069	–0.670	0.298	–0.535	0.182
(*b*) All specimens													
MOE_d	0.731	0.594	0.564	0.569									
MOR_d		0.622	0.295	0.308									
$Density_d$			0.222	0.241									
Velocity				0.998									
(*c*) Trees													
MOE_d	0.729	0.762	0.680	0.687									
MOR_d		0.693	0.454	0.465									
$Density_d$			0.424	0.438									
Velocity				0.999									

Note: (*a*) Sample subset that was analyzed with SilviScan, *n* = 183 specimens (one specimen per tree); (*b*) full data set of all direct measurements, *n* = 1087 specimens; (*c*) tree-mean data set, *n* = 183 tree values (each value is the mean for six specimens).

Table 3. Regression models for predicting modulus of elasticity (MOE_d) and modulus of rupture (MOR_d) with $density_d$, acoustic $velocity_d$, and acoustic $velocity_d^2$.

Intercept	Coefficient: $Density_d$ (g/cm^3)	$Velocity_d$ (m/s)	$Velocity_d^2$	Adjusted R^2
MOE_d, specimens				
–999	22723			0.352
–5201		3.0778		0.317
2727			0.00001304	0.324
20991		–7.0002	0.000963	0.329
–12368	18863	2.4803		0.548
–5703	18546		0.0002356	0.545
–27513	19695	8.1596	–0.0005453	0.551
MOE_d, trees				
–1320	23294			0.578
–9976		3.9551		0.460
449			0.000373	0.470
41814		–15.51	0.00182	0.483
–11986	17645	2.5334		0.733
–5147	17431		0.000238	0.732
–18774	17887	5.0515 ns	–0.0002375 ns	0.732
MOR_d, specimens				
–16.939	224.71			0.387
24.522		0.01519		0.086
62.161			0.00000151	0.094
541.3		–0.18366	0.000019	0.138
–55.841	211.51	0.00849		0.412
–33.364	210.13		0.000000823	0.413
32.317	206.67	–0.0245 ns	0.00000317 ns	0.413
MOR_d, trees				
–17.62	225.99			0.477
–46.08		0.2817		0.202
27.12			0.00000269	0.212
759.31		–0.27454	0.0000283	0.253
–68.75	198.91	0.01214		0.506
–36.26	197.44		0.00000116	0.507
106.78	192.65	–0.5306 ns	0.00000614	0.505

Note: Reported are the intercept, regression coefficients, and adjusted R^2 for the model. All independent variables were significant at p = 0.02, except for the ones marked "ns" (nonsignificant). For MOE_d and MOR_d, specimens, used full data set of all direct measurements, n = 1087 specimens; for MOE_d and MOR_d, trees, used tree-mean data set, n = 183 tree values where each value is the mean of six specimens.

(r = 0.31 and β = 0.17). Therefore, looking solely at the correlations could lead one to assume incorrectly an elevated importance of acoustic $velocity_d$ for MOR_d.

Anatomical drivers of MOE_d and MOR_d

Here, we investigated the relationships of MOE_d and MOR_d with the SilviScan-estimated values from the 183 end-matched samples (Table 2*a*). The strongest correlation of MOE_d was with $density_{ss}$ (r = 0.58) followed by the MFA_{ss} estimates (all around –0.50) and then EW MFA_{ss} (–0.45). The correlations between these characteristics and MOR_d were all weaker than for MOE_d, with the exception of LW proportion, which was of similar strength. Of the SilviScan-estimated characteristics, $density_{ss}$ (r = 0.41) and LW $proportion_{ss}$ (r = 0.40) correlated most strongly with MOR_d.

Plots of MOE_d and MOR_d versus three of the strongest drivers ($density_d$, MFA_{ss}, and LW $proportion_{ss}$) are presented to allow inspection of the data for the 183 specimens that had SilviScan data (Fig. 2). We plotted the direct-measured $density_d$ rather than the SilviScan-estimated $density_{ss}$ because $density_d$ is a better estimate of the sample from which MOE_d and MOR_d were measured. The correlation of $density_d$ with $density_{ss}$ was only 0.74 (Table 2), and mean $density_d$ was higher than mean $density_{ss}$ (Table 1). The fact that the correlation was not stronger may have resulted from three separate issues. First, unlike the direct-measured specimens, the SilviScan samples had been in ethanol, removing some of the mass. Second, $density_d$ integrates the entire specimen, whereas $density_{ss}$ was estimated from a transect across an end-matched strip adjacent to the specimen (corresponding to only 0.5% of the volume of the short clear sample). Third, growth rings may have been incomplete in the direct-measured specimens, which were sawed to measure 10 mm in the radial direction, but complete growth rings were used for the SilviScan samples. This difference in growth rings is potentially of much importance in a species

Table 4. Path coefficients (β) for the models representing the relationships between predictive variables and modulus of elasticity (MOE_d) and modulus of rupture (MOR_d).

	MOE_d				MOR_d			
Variable	β	SE	p	Model R^2	β	SE	p	Adjusted R^2
Model 1a (183 trees)				0.732				0.507
$Density_d$	0.570	0.043	<0.001		0.605	0.058	<0.001	
$Velocity_d^2$	0.438	0.043	<0.001		0.200	0.058	<0.001	
Model 1b (1087 specimens)				0.545				0.413
$Density_d$	0.485	0.021	<0.001		0.582	0.024	<0.001	
$Velocity_d^2$	0.452	0.021	<0.001		0.167	0.024	<0.001	
Model 2 (183 specimens)				0.510				0.387
$Density_d$	0.563	0.056	<0.001		0.609	0.063	<0.001	
MFA_{ss}	–0.276	0.056	<0.001		–0.043	0.063	0.500	
Model 3 (183 specimens)				0.391				0.168
$Density_{ss}$	0.447	0.067	<0.001		0.361	0.078	<0.001	
MFA_{ss}	–0.274	0.067	<0.001		–0.102	0.078	0.192	
Model 4 (183 specimens)				0.394				0.211
EW $density_{ss}$	0.199	0.060	<0.001		0.091	0.069	0.188	
EW MFA_{ss}	–0.249	0.069	<0.001		–0.124	0.079	0.116	
LW $density_{ss}$	0.281	0.065	<0.001		0.210	0.074	0.005	
LW MFA_{ss}	–0.099	0.071	0.164		–0.007	0.081	0.928	
LW $proportion_{ss}$	0.314	0.060	<0.001		0.358	0.069	<0.001	

such as *Pseudotsuga menziesii* that has such large differences between EW and LW values of density and MFA.

As with the correlation analyses (Table 2), regression analyses showed that higher R^2 values were obtained with models with $density_d$ than models with $density_{ss}$ (Table 5). This result may have been in part due to the fact that the SilviScan strips did not truly represent the adjacent short clear samples. MFA_{ss} was not statistically significant in predicting MOR_d when density was already included in the model.

The path coefficients for the simple models examining the impact of density (as either $density_d$ or $density_{ss}$) and MFA_{ss} on MOE_d and MOR_d are shown as Models 2 and 3 in Table 4. $Density_d$ was more strongly associated with MOE_d and MOR_d than was $density_{ss}$, and either value of density was more strongly associated with MOE_d and MOR_d than was MFA_{ss}. For predicting MOE_d, MFA_{ss} gave β values only half the magnitude of those obtained using either $density_d$ or $density_{ss}$. MFA_{ss} was not a significant predictor of MOR_d when density was in the model (Models 2 and 3, Table 4).

It is interesting to note that MFA_{ss} behaved similarly to acoustic $velocity_d$ (and acoustic $velocity_d^2$) in the previous section in that both were less predictive of MOE than was $density_d$. Likewise, acoustic $velocity_d$ was correlated more strongly with MFA_{ss} (r = –0.69) than with $density_d$ (r = 0.33) or $density_{ss}$ (r = 0.36) (Table 2*a*). These results support the theoretical expectation that velocity is much more strongly determined by MFA than by density. In fact, when path analysis was used to estimate the dependence of $velocity_d$ on $density_d$ and MFA_{ss}, the direct path for MFA_{ss} was statistically significant (β = –0.667, p < 0.001), but the direct path for $density_d$ was not (β = –0.067, p = 0.255).

The more complex path diagram examining the EW and LW components are shown in Model 4 (Table 4). Of all of the associations tested between independent variables and MOE_d or MOR_d in Model 4, LW $proportion_{ss}$ had the strongest association, but the corresponding β values were only 0.31 and 0.36, respectively. To a large extent, the variation in LW proportion incorporates the LW versus EW differences in $density_{ss}$ (0.86 versus 0.30 g/cm^3) (Table 1) and MFA_{ss} (11.8 versus 16.3°) (Table 1). Other anatomical components that were statistically significant drivers of MOE_d were LW $density_{ss}$, EW $density_{ss}$, and EW MFA_{ss} (all of which had β values ≤0.28). Besides LW $proportion_{ss}$, the only other significant anatomical driver of MOR_d was LW $density_{ss}$, with a low β value of 0.21.

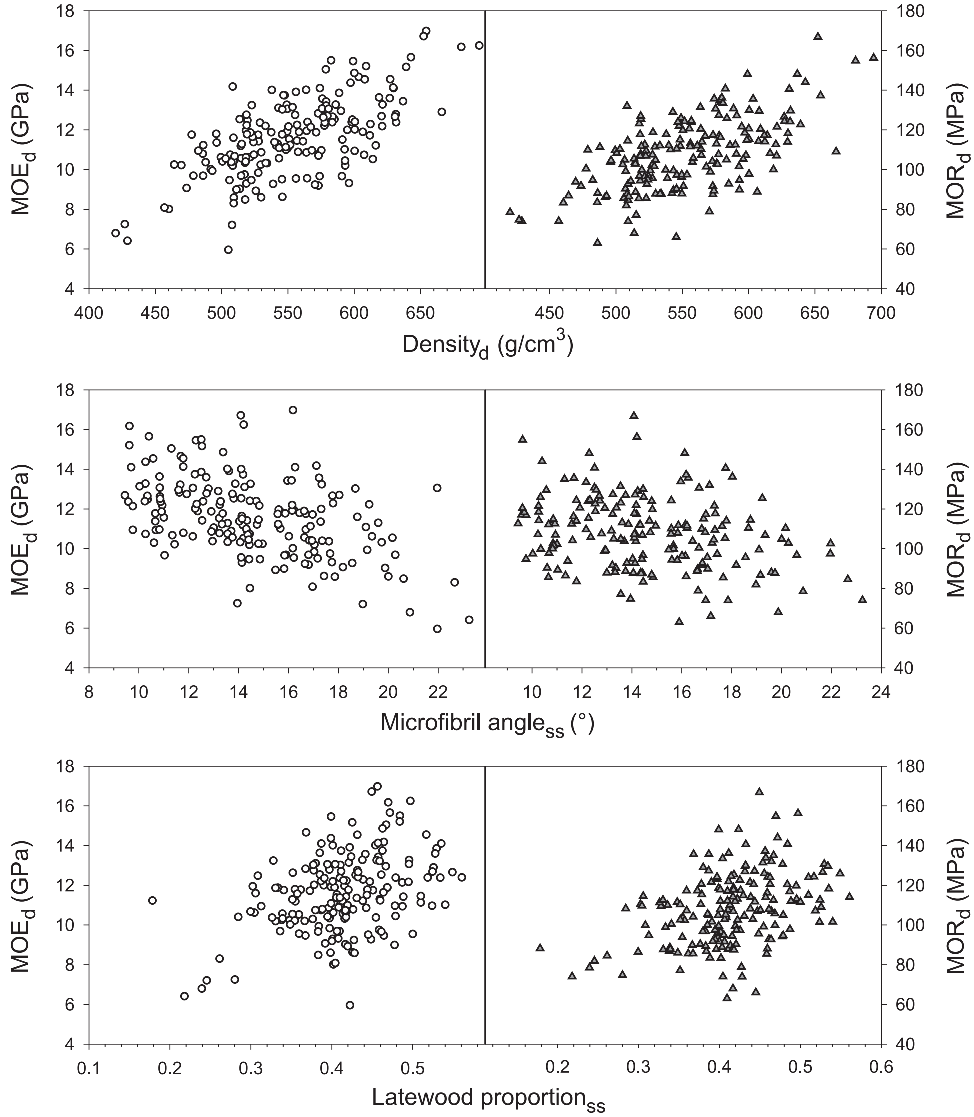
Discussion

Predicting MOE and MOR from density and acoustic velocity

The first objective of this study was to determine the predictive power of density and acoustic velocity for estimating MOE and MOR in small clear specimens of mature wood in Douglas-fir. $Density_d$ was only slightly better than acoustic $velocity_d$ as a means of predicting MOE_d, but both variables together greatly improved the predictive power. For specimens, the adjusted R^2 increased from 0.35 to 0.55 going from the best single-variable to the two-variable model (Table 3), and for trees, the adjusted R^2 increased from 0.55 to 0.73 (Table 3). Because both $density_d$ and $velocity_d$ had fairly strong direct paths (β) for predicting MOE_d, the two variables together gave better predictions than did any single-variable model. Of the two-variable models, it did not make any meaningful difference in the R^2 whether $velocity_d$ or $velocity_d^2$ was used with $density_d$.

In *Pinus radiata* D. Don, Chauhan and Walker (2006) found that the acoustic velocity was tightly correlated with MOE (which had been estimated by SilviScan) for three age classes of trees, despite the fact that the strength of the correlations between density and MOE depended on stand age (either not correlated or correlated very weakly in the

Fig. 2. Specimen modulus of elasticity (MOE_d) (circles) and modulus of rupture (MOR_d) (triangles) versus specimen $density_d$, average microfibril $angle_{ss}$, and latewood $proportion_{ss}$.



8- and 16-year-old stands and moderately correlated in the 25-year-old stand). Their work suggests that acoustic velocity is a good measure of the nondensity components that determine MOE, presumably MFA. This interpretation is consistent with results reported here, that acoustic $velocity_d$ was more strongly associated with MFA_{ss} (r = –0.69) than with $density_d$ (r = 0.33) or $density_{ss}$ (r = 0.36) (Table 2*a*) and that the direct path for MFA_{ss} with velocity was statistically significant (β = –0.667, p < 0.001) but that the direct path for $density_d$ and velocity was not (β = –0.067, p = 0.255).

Acoustic velocity alone was a very poor predictor of MOR_d, but its inclusion in models with density improved the predictions over density alone, although to a lesser extent than they did for MOE_d (Table 3). This smaller improvement was because of the relatively weak direct path for $velocity_d$ (Table 4), which was nevertheless a reasonable predictor because of its correlation with density and the indirect path with MOE; i.e., the correlation of $velocity_d$ with MOE was not much weaker than the correlation of density with MOE, despite the weak direct path. If one had to choose between $density_d$ and $velocity_d$ for predicting MOR_d, the choice would be $density_d$ unless $density_d$ had a significant cost disadvantage.

The circumferential variability of properties was quantified using intraclass correlation analysis. Much higher uniformity was found for wood $density_d$ (t = 0.74) than for MOR_d (t = 0.57), MOE_d (t = 0.40), or acoustic $velocity_d$ (t = 0.32). Given that the combination of density and MFA explains much of the variability of these dependent variables, this result suggests that MFA varies greatly around the circumference. It would be interesting to study the circumferential variability of MFA and density in many trees to further elucidate their contributions to the variability of MOE; variable growth stresses caused by factors such as prevailing wind directions or branch placement (had the specimens not been clear) could contribute to these differences in interclass correlation among variables. These data

Table 5. Regression models for predicting modulus of elasticity (MOE_d) and modulus of rupture (MOR_d) with $density_d$ and MFA or MFA^2 using 183 specimens.

	Coefficient			
Intercept	$Density_d$ (g/cm^3)	$Density_{ss}$ (g/cm^3)	MFA^2_{ss} ($^{\circ 2}$)	Adjusted R^2
MOE_d				
–3251	26877			0.448
545 ns		21022		0.338
13976			–10.732	0.249
537 ns	22423		–6.005	0.513
4536		15971	–6.035	0.395
MOR_d				
–20.5 ns	232.13			0.388
35.5		137.42		0.165
120.5			–0.0576	0.079
–14.1 ns	224.52		–0.0103 ns	0.387
50.5		118.34	–0.0228 ns	0.171

Note: Reported are the intercept, regression coefficient, and adjusted R^2 for the model. All coefficients significant at α = 0.01, except those marked "ns", which were nonsignificant at α = 0.05.

suggest that sampling for MOE and testing for acoustic velocity should be done at more than one location around the circumference at a given height.

Anatomical drivers of MOE and MOR

The second objective was to better understand the relationship between mature wood MFA, and MOE and MOR. The current research was based on small clear specimens. It will be important to understand the magnitude of the effects on strength values of wood inhomogeneities that raise stress locally (e.g., rays, checks, and knots) and to learn which of these stress risers have the largest effects as the size and volume of the wood sample are increased (e.g., Bohannan 1966). We would expect such information to show that microscopic anatomy is of less importance than was reported here, as other features become increasingly important in larger pieces of wood.

EW MFA was more influential than LW MFA based on the direct paths (β) (Table 4), possibly because EW had a wider range of MFAs than did LW (9.5–26.7° versus 8.7–21.2°, respectively). Path analyses showed that the variable that most impacted MOE_d and MOR_d was LW proportion, a fact not revealed in simple correlations. On average, LW had 2.9 times the $density_d$ and 0.7 times the MFA_{ss} of EW (Table 1). Using the fifth equation in Table 5 and the values of $density_{ss}$ and MFA_{ss} from Table 1, LW is estimated to have 2.3 times the MOE of EW (17 400 versus 7700 MPa), showing the strong potential influence of LW proportion on MOE.

Density had a larger influence than MFA on both MOE and MOR in the current study on *Pseudotsuga menziesii*. This result may have been different had we studied juvenile wood. For example, in studies of juvenile wood of hard pines, MFA had a larger influence than did density on MOE of *Pinus radiata* (Baltunis et al. 2007) and on MOE and MOR of *Pinus resinosa* Ait. (Deresse et al. 2003). In studies that looked at samples of both mature wood and juvenile wood in hard pines, researchers have shown that density is the most important predictor of MOE (and sometimes MOR) in mature wood, but in the juvenile wood, MFA is relatively more important, sometimes more important than density (Cown et al. 2004; Chauhan and Walker 2006; Via et al. 2009). Therefore, further research is needed to learn whether the relationships of anatomy to MOE and MOR differ in juvenile wood from those in mature wood in Douglas-fir. Also, in contrast with the hard pines, *Pseudotsuga menziesii* shows a very high contrast between its EW and LW values of MFA and density, which may greatly magnify the importance of LW proportion on stiffness and strength. Thus, it will be important to look at LW proportion as an explicit factor in research on strength and stiffness of Douglas-fir in juvenile and mature wood, in wood with accelerated growth rate, and in wood resulting from disease or silvicultural practices such as pruning or fertilization that can alter LW proportion. Such proposed research together with the results of this project may be of use to tree breeders, tree growers, and log and lumber processors as they strive to obtain maximum value from their logs and products.

Acknowledgments

We thank Amy Grotta and Matt Peterson for field and laboratory help, John Nairn for discussion, and anonymous reviewers for helpful suggestions. This research was funded by the PNW Agenda 2020 program and a special USDA grant to Oregon State University for wood utilization research.

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