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ORIGINAL ARTICLE

Prediction of transverse shrinkages of young-growth Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*) with ultrasonic measurements

TURKER DUNDAR[1], XIPING WANG[2] & ROBERT J. ROSS[2]

[1]*Faculty of Forestry, Istanbul University, Istanbul, Turkey and* [2]*US Forest Service, Forest Products Laboratory, Madison, WI, USA*

Abstract

The objective of this study was to examine the potential of acoustic measurement as a rapid and nondestructive method to predict the dimensional stability of young-growth Sitka spruce and western hemlock. Ultrasonic velocity, peak energy, specific gravity, and radial and tangential shrinkages were measured on twenty-four 25- × 102- × y 25-mm specimens obtained from a 58-year-old stand in Southeast Alaska. We found that specific gravity and peak energy of ultrasonic signals were not good predictors of transverse shrinkage, as indicated by poor correlations. Ultrasonic velocity, on the other hand, was found to be a significant predictor of transverse shrinkage and therefore has good potential to be used as a field method to evaluate dimensional stability. The single-parameter prediction model explained 86% of transverse shrinkages in western hemlock and 71% of transverse shrinkages in Sitka spruce. Further study is needed to test the capability and feasibility of using acoustic velocity to predict both longitudinal and transverse shrinkages of wood in standing trees.

Keywords: *Peak energy, radial shrinkage, tangential shrinkage, ultrasonic velocity, young-growth wood.*

Introduction

With the move to intensive forest management to meet wood demand and to preserve the environment, Southeast Alaska is experiencing a period of significant changes in terms of wood characteristics and wood quality. Understanding the product value and economic potential of young-growth timber from the region was identified as a high-priority information need.

Previous lumber studies in Southeast Alaska on old-growth Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*) have become outdated because of resource and technology changes (Sullivan and Shields 1958, Lane *et al*. 1972, Woodfin and Snellgrove 1976, Fahey 1983, Fahey and Cahill 1983, Ernst *et al*. 1986). Veneer recovery and defect studies were reported for Pacific Northwest for western hemlock (Fahey 1978, Fahey and Woodfin 1982). Recent wood quality studies examined lumber recovery, grade yield, and some mechanical properties for commercially thinned and unthinned young-growth Sitka spruce and western hemlock (Christensen *et al*. 2002). However, no studies have been reported that examine dimensional stability of young-growth Sitka spruce and western hemlock and relate their shrinkage information to individual tree characteristics and thinning treatment.

Dimensional stability of a product during use affects the efficient utilization of wood and is, therefore, of huge economic value to the forest industry. Dimensional changes of wood caused by water adsorption are anisotropic and dependent on anatomical direction in the wood (Timell and Skaar 1988). Wood shrinkage also depends on microstructural and molecular features of the cell wall. These include microfibril angle (the angle at which the cellulose fibrils wind in the tracheid cell walls) and physical properties of the surrounding matrix. Longitudinal shrinkage of wood is generally quite small (0.1–0.2% of the green condition when oven-dried). This small change is often neglected in the manufacture and

Correspondence: X. Wang, Forest Products Laboratory, US Forest Service, Madison, WI 53726-2398, USA. Tel: 1-608-231-9461. Fax: 1-608-231-9303. E-mail: xwang@fs.fed.us

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subsequent use of wood products. However, transverse shrinkages in tangential and radial directions are of major importance. Tangentially, wood shrinks from 5% to 9% of the green dimension when dried from green to the oven-dry condition for softwood (FPL 2010); in the radial direction, the corresponding shrinkage is roughly half the tangential shrinkage for a given wood specimen. One theoretical explanation is that tangential shrinkage is largely controlled by changes in latewood, which is strong enough to force earlywood to comply with it, whereas, radial shrinkage is a summation of the weighted contribution of earlywood and latewood (Pentoney 1953). This differential of radial- tangential shrinkage is one of the primary factors causing shape distortion during the seasoning of lumber and during ultimate use.

Shrinkage has been correlated traditionally with density (Suchsland 2004). This correlation is not particularly strong and represents a general trend for sound wood of different species (Suchsland 2004, Leonardon *et al.* 2010). X-ray lumber density scanning is successful in grading structural lumber based on the prediction of stiffness and strength, but no shrinkage prediction capability was established (Schajer 2000). Some studies investigated the potential of near-infrared (NIR) spectroscopy as a tool for shrinkage prediction. It was reported that for five-year-old *Eucalyptus urophylla* × *E. Grandis* hybrids, tangential shrinkage could be modeled with 82% accuracy by NIR (Bailleres *et al.* 2002), whereas weak correlations with RS (0.45) and longitudinal shrinkage (0.35) precluded similar predictions. For mahogany (*Swietenia macrophylla*), 63% of the variation in volumetric shrinkage could be predicted by NIR (Taylor *et al.* 2008).

A number of studies suggest that acoustic wave techniques may be used to assess the dimensional stability of structural lumber. Wang and Simpson (2006) evaluated the potential of acoustic analyses as presorting criteria to identify warp-prone boards before kiln-drying. Dimension lumber (38 × 89 × 2440 mm) sawn from open-grown, small-diameter ponderosa pine trees was acoustically tested lengthwise at green condition. They found that the amount of warp in the form of crook and bow that developed during drying decreased as green board measurements of acoustic speed and acoustic modulus of elasticity (MOE) increased and rate of wave attenuation decreased. Results also showed a statistically significant correlation between acoustic properties of the boards and grade loss because of exceeding warp limits. Ivkovic *et al.* (2009) investigated a range of wood properties that can be measured with relative ease and low cost for their ability to predict wood stiffness, strength, and shrinkage in juvenile wood of radiata pine. With respect to shrinkage prediction, they found that density and MOE had a weak relationship with radial and tangential shrinkages ($r^2 = 0.13$–0.16), whereas acoustic velocity and MOE had strong negative nonlinear relationships with longitudinal shrinkage of the inner ring samples ($r^2 = 0.78$ and 0.58, respectively). Based on their findings, they recommended that acoustic velocity combined with increment core density be used as practical measurement parameters for predicting stability in young trees.

The objective of this study was to assess the potential of ultrasonic measurement as a rapid and nondestructive method to predict the dimensional stability of young-growth Sitka spruce and western hemlock. The specific objectives were to (1) determine radial and tangential shrinkages of young-growth Sitka spruce and western hemlock; (2) examine the relationships between transverse shrinkages and specific gravity, ultrasonic velocity, and peak energy of ultrasonic signals; and (3) determine the best nondestructive parameters for predicting transverse shrinkages of young-growth Sitka spruce and western hemlock.

Materials and methods

Specimen preparation

Materials used in this study were obtained from young-growth Sitka spruce and western hemlock trees of a 58-year-old stand in Prince of Wales Island, Southeast Alaska. This stand was originally selected for a field wood quality study and included thinned and unthinned plots. The wood specimens for shrinkage measurements were prepared from kiln-dried dimension lumber following the wood quality study. The sizes of the specimens were nominal 25 × 102 × 25 mm, with the 102-mm dimension along the grain. Twenty-four specimens were obtained, including 12 Sitka spruce, and 12 western hemlock. The specimens of each species included samples from both thinned and unthinned stands.

Experimental procedure

All specimens were first subjected to a reconditioning process in a closed container with 99.9% relative humidity (RH) at 20°C to bring the moisture content (MC) up to a higher level. At the end of the conditioning process, the specimens reached an average 20% equilibrium moisture content (EMC) for Sitka spruce and 17% EMC for western hemlock. Then the initial weight and dimensions of all specimens under this condition were immediately measured and recorded. The weight was measured to the nearest 0.01 g, and the dimension was measured to the nearest 0.01 mm.

A Sylvatest Duo (CBS-CBT, Les Ecorces, France) device operating at a frequency of 22 kHz was used to measure the ultrasonic velocity and peak energy of the received signal in each specimen. The transmitter probe and the receiver probe were positioned at the opposite faces of a specimen with a constant pressure (69 kPa) applied to the probes to improve coupling between the probes and wood. Figure 1 illustrates the ultrasonic measurement patterns on each specimen – three measurements in radial direction (Figure 1a) and one in tangential direction (Figure 1b). For each measurement, the transmitter probe emitted five consecutive pulses through the specimen. An average ultrasound propagation time (UPT) and an average peak energy of the received signal were recorded after each measurement. The ultrasonic velocity (V) of the specimen was calculated based on the average UPT value and the distance between two probes (L):

$$V = \frac{L}{\mathrm{UPT}}(m/s) \quad (1)$$

The peak energy recorded was peak voltage (mV) of the ultrasound signals detected by the receiver probe and represents relative energy loss (attenuation) or propagation efficiency of the ultrasonic waves traveling through the specimen.

After initial measurements, all specimens were sequentially subjected to 75%, 65%, and 55% RH at a constant temperature of 21.1°C in a climatic room in order to reach EMCs of 15%, 12%, and 10%, respectively, followed by oven-drying at 103 ± 2°C for 48 h to reach 0% MC. When each MC level was reached, the weight and dimension of each sample were measured, followed by ultrasonic measurements in both radial and tangential directions using the Sylvatest Duo device.

Data analysis

In this study, tangential and radial shrinkages of the specimens were determined from the moisture condition of initial measurement (20% for Sitka spruce and 17% for western hemlock) to oven-dry condition. To compare measured shrinkages with shrinkage values given in the *Wood Handbook* (FPL 2010) for the species, adjustment was made on measured values based on the reference shrinkage from green to initial MC, which was derived using:

$$S_{\mathrm{MC}_i} = S_0\left(\frac{\mathrm{FSP} - \mathrm{MC}_i}{\mathrm{MC}_i}\right), \quad (2)$$

where $S_{\mathrm{MC}i}$ is shrinkage (%) from green condition to a MC of MC_i, S_0 is total shrinkage given in the *Wood Handbook* (Sitka spruce, 4.3 for radial shrinkage and 7.5 for tangential shrinkage; western hemlock, 4.2 for radial shrinkage and 7.8 for tangential shrinkage), and FSP is fiber saturation point for the species (28.5% for Sitka spruce and 28% for western hemlock) (FPL 2010).

Specific gravity of the specimens was determined based on 12% EMC volume and oven-dry mass (ASTM 2007).

For radial ultrasonic velocity, an average value was obtained from the ultrasonic measurements in three paths of each specimen and used as a representative radial velocity for the specimen.

Single-variable statistical regression analysis was used to determine the following relationships: (1) tangential and radial shrinkages related to wood MC; (2) ultrasonic velocity and peak energy related to wood MC; (3) ultrasonic velocity related to tangential and radial shrinkages; and (4) ultrasonic peak energy related to tangential and radial shrinkages.

Results and discussion

Specific gravity and transverse shrinkages

Table I summarizes the statistics of specific gravity, radial shrinkage, tangential shrinkage, and tangen-

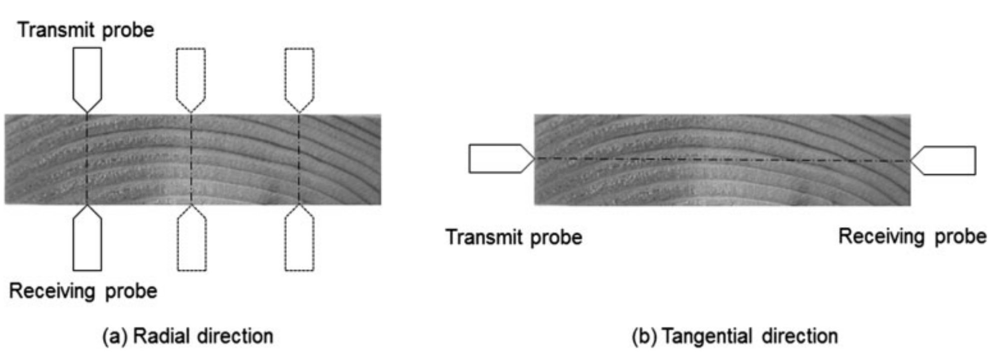

Figure 1. Patterns of ultrasonic measurements conducted on the specimens.

Table I. Specific gravity and transverse shrinkage of Sitka spruce and western hemlock.

				Shrinkage from initial MC to 0% MC (%)		
Species	Number of specimens	Initial moisture content (%)	Specific gravity (12% MC)	Radial (RS)	Tangential (TS)	Ratio (TS/RS)
Sitka spruce	12	20	0.39 (0.055)	3.9 (0.88)	5.6 (1.29)	1.44
Western hemlock	12	17	0.44 (0.049)	3.5 (0.61)	4.9 (0.71)	1.40

Note: Numbers in parenthesis are standard deviations.

tial-to-radial shrinkage ratio (TS/RS) for Sitka spruce and western hemlock specimens. Mean specific gravity was found to be 0.39 for Sitka spruce and 0.44 for western hemlock, which is slightly lower than the values given in the *Wood Handbook* (FPL 2010). Shrinkage values presented in this table are from initial MC (20% for Sitka spruce and 17% for western hemlock) to oven-dry condition. Tangential shrinkage was 44% and 40% higher than radial shrinkage for Sitka spruce and western hemlock, respectively. The differences were significant at 0.01 level of probability.

The degree of correlation between shrinkage and specific gravity was evaluated by linear regression analysis. The coefficient of determination was found to be low ($R^2 = 0.001$–0.238), indicating a weak or no relationship between transverse shrinkage and specific gravity.

Figure 2 shows the transverse shrinkage–MC relationship after being adjusted to shrinkage from green to oven-dry MC. The linear lines show the prediction of radial and tangential shrinkages based on *Wood Handbook* data (FPL 2010). It appeared that tangential shrinkages of young-growth Sitka spruce and western hemlock were in a good agreement with *Wood Handbook* predictions. Radial shrinkages, on the other hand, were found to be higher than the *Wood Handbook* predictions. The estimated total radial shrinkage from green to oven-dry was 18.6% higher for Sitka spruce and 21.9% higher for western hemlock than the *Wood Handbook* values.

Ultrasonic velocity and peak energy in relation to MC

Figures 3 and 4 show the relationships between ultrasonic measures (velocity and peak energy) and MC for young-growth western hemlock and Sitka spruce. Ultrasonic velocity in tangential direction was found to increase continuously as MC decreased. This is similar to the influence of MC on MOE (Green and Kretschmann 1994, Kollmann and Cote 1968). A polynomial regression was found to best fit the experimental data ($r^2 = 0.99$ for Sitka spruce and $r^2 = 0.98$ for western hemlock). Ultrasonic velocity in radial direction increased as MC decreased to about 10% MC. When the specimens were oven-dried to 0% MC, radial ultrasonic velocity decreased slightly. This is different from the velocity trend observed in tangential direction, and is also different from that reported in other studies (Mishiro 1996). One explanation could be the development of internal micro checks in the specimens as a result of oven-drying, thus reducing the ultrasonic velocity in the radial direction. A polynomial regression was fit to the experimental data with moderate correlation ($r^2 =$

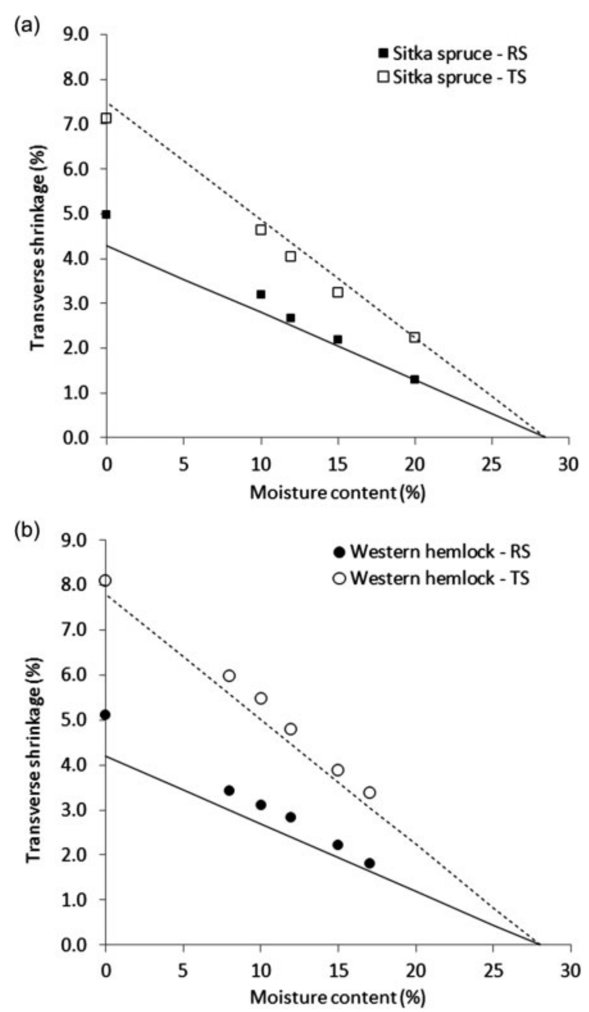

Figure 2. Relationship between transverse shrinkage of young-growth western hemlock and Sitka spruce and EMC. The measured transverse shrinkages of the specimens were adjusted to the shrinkage values from 30% MC to oven-dry condition.

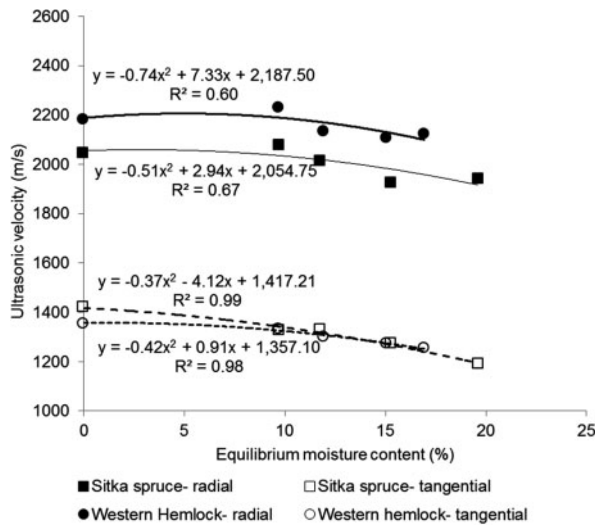

Figure 3. Relationship between ultrasonic velocity and MC.

0.67 for Sitka spruce and $r^2 = 0.60$ for western hemlock).

Peak energy of the received ultrasonic signals for the specimens showed high variability in both radial and tangential directions. This is because the amplitude of ultrasonic signals detected by the receiver probe is very sensitive to coupling between the probe and the specimen. Our experimental data showed a weak correlation between peak energy and MC of the specimens ($r^2 = 0.30$–0.35), except for the measurement of Sitka spruce specimens in tangential direction ($r^2 = 0.95$) (Figure 4).

Relationship between transverse shrinkages and ultrasonic velocity

Figure 5a shows the relationships between transverse shrinkages and ultrasonic velocity for Sitka spruce.

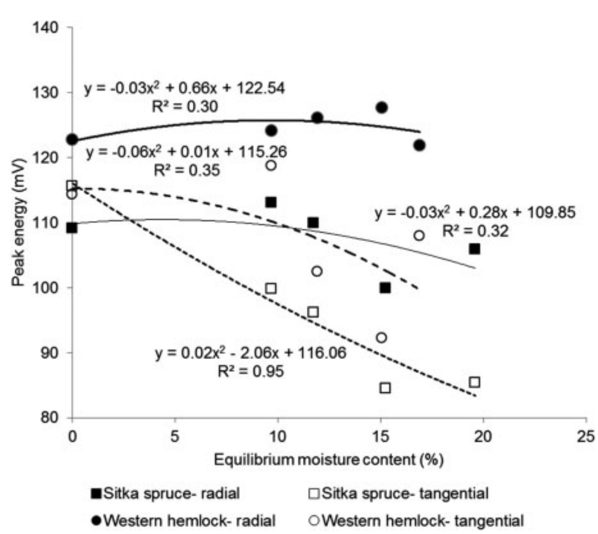

Figure 4. Relationship between peak energy and MC.

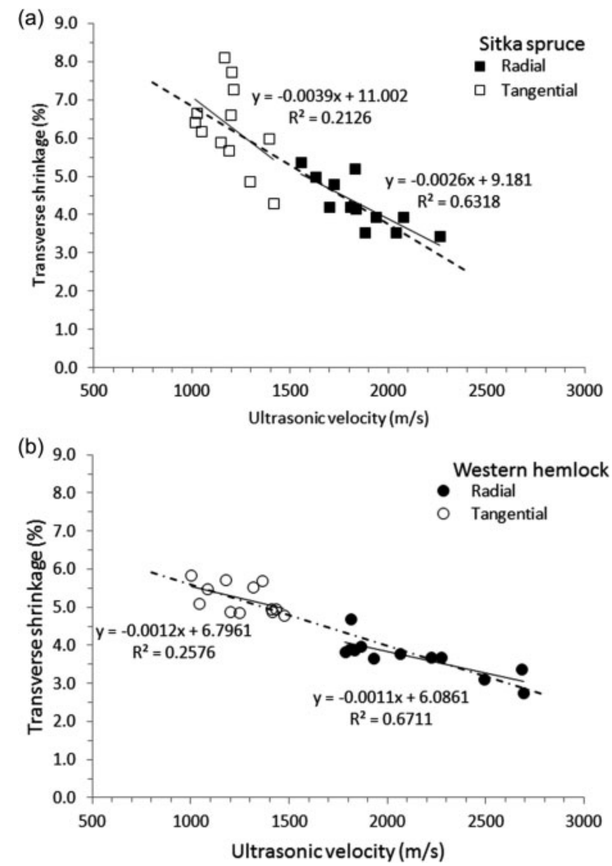

Figure 5. Relationship between transverse shrinkage and ultrasonic velocity.

Both radial and tangential shrinkages decreased linearly with increasing ultrasonic velocity. The correlation was stronger in radial direction ($r^2 = 0.63$) than in tangential direction ($r^2 = 0.21$). A similar relationship was found in western hemlock, with a coefficient of determination $r^2 = 0.67$ in radial direction and $r^2 = 0.26$ in tangential direction (Figure 5b).

The results of linear regression analysis for the transverse shinkage and ultrasonic velocity relations are tabulated in Table II. Note that the shrinkage-velocity data obtained in radial and tangential directions fit the same general trend within each species. Examination of the shrinkage-velocity models indicated that the linear correlation coefficients (b) were close in radial and tangential directions for both Sitka spruce and western hemlock. Considering that radial and tangential shrinkages were measured on the same speciemens in this study, a single linear regression model (dotted line in Figure 5) was proposed to fit the combined shrinkage-velocity data:

$$S_{tr} = a + bV \qquad (3)$$

Table II. Results of linear regression analysis for shrinkage and ultrasonic velocity relationships.

y Shrinkage (%)	*x* Ultrasonic velocity (m/s)	Regression model: $y = a + bx$			
		a	*b*	r^2	*p*
		Sitka spruce			
Tangential (TS)	V_T	11.002	−0.0039	0.21	0.1314
Radial (RS)	V_R	9.181	−0.0026	0.63	0.002
Transverse (TS & RS)	V	9.9503	−0.0031	0.71	<0.001
		Western hemlock			
Tangential (TS)	V_T	6.796	−0.0013	0.26	0.092
Radial (RS)	V_R	6.086	−0.0011	0.67	0.001
Transverse (TS & RS)	V	7.185	−0.0016	0.86	<0.001

where S_{tr} is transverse shrinkage (%), V is ultrasonic velocity (m/s), and a and b are regression coefficients.

The combined model explained 71% of the transverse shrinkage for Sitka spruce and 86% of the transverse shrinkage for western hemlock. This indicated that ultrasonic measurement has good potential to be used as a nondestrutive method for predicting transverse shrinkages.

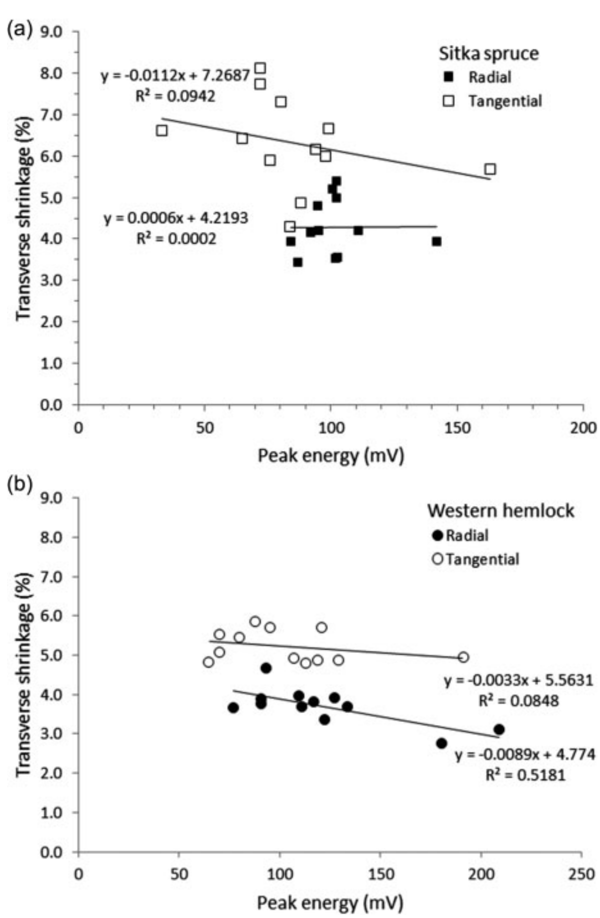

Figure 6. Relationship between transverse shrinkage and peak energy.

Relationship between transverse shrinkages and peak energy

The relationships between transverse shrinkages and peak energy of the received ultrasonic signals were found to be generally weak (Figure 6). Tangential shrinkages of both Sitka spruce and western hemlock decreased linearly with increasing peak energy, but the model explained less than 10% of the variation ($r^2 < 0.10$). Radial shrinkage showed moderate correlation with peak energy for western hemlock ($r^2 = 0.52$), but no correlation existed for Sitka spruce ($r^2 = 0.0002$).

Prediction of transverse shrinkages

Results of this study showed that the specific gravity and peak energy of ultrasonic signals were not good predictors of transverse shrinkage as indicated by poor correlations. Ultrasonic velocity, on the other hand, was found to be a significant predictor of transverse shrinkage and, therefore, has good potential to be used as a field method to evaluate the

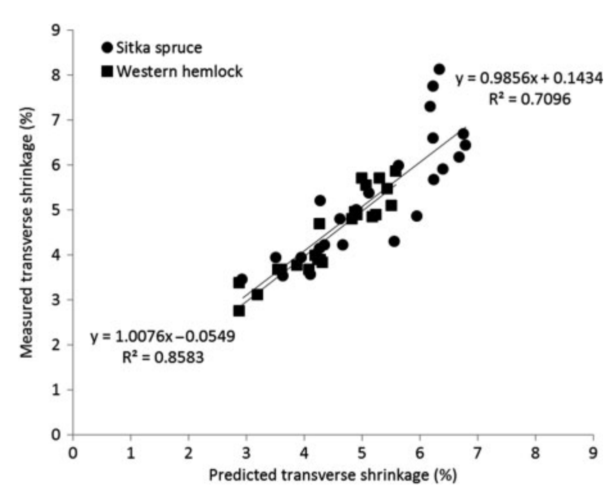

Figure 7. Relationship between predicted transverse shrinkage and measured transverse shrinkage.

dimensional stability of standing trees. Figure 7 shows the plot of predicted transverse shrinkages and measured transverse shrinkage for young-growth Sitka spruce and western hemlock. The single-parameter prediction model explained 86% of transverse shrinkages in western hemlock and 71% of transverse shrinkages in Sitka spruce.

Summary and conclusions

Tangential shrinkages obtained from young-growth Sitka spruce and western hemlock were in good agreement with *Wood Handbook* predictions (FPL 2010). Radial shrinkages, however, were found to be higher than *Wood Handbook* predictions. Estimated total Radial shrinkage from green to oven-dry was 18.6% higher for young-growth Sitka spruce and 21.9% higher for young-growth western hemlock than *Wood Handbook* values.

Ultrasonic velocity in tangential direction was found to increase continuously as MC decreased. Ultrasonic velocity in radial direction increased as MC decreased to about 10% MC, and then decreased slightly as MC reached 0% MC.

Peak energy of received ultrasonic signals showed high variability in both radial and tangential directions. Consequently, the relationship between peak energy and wood MC was generally weak, except for the case of Sitka spruce specimens in tangential direction.

specific gravity and peak energy of ultrasonic signals were found to have weak relationships with transverse shrinkages.

Both radial and tangential shrinkage decreased linearly in a similar trend with increasing ultrasonic velocity. A single linear regression model relating transverse shrinkage to ultrasonic velocity was proposed to predict both radial and tangential shrinkage using ultrasonic velocity. The prediction model explained 71% of the transverse shrinkage for Sitka spruce and 86% of the transverse shrinkage in western hemlock.

Results of this study indicated that ultrasonic velocity was a significant predictor of transverse shrinkages and therefore has good potential to be used as a field method to evaluate dimensional stability of wood. Further study is planned to test the capability and feasibility of using acoustic velocity to predict both longitudinal and transverse shrinkages of wood in standing trees.

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