Relationships between acoustic variables and different measures of stiffness in standing *Pinus taeda* trees

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Abstract: Acoustic tools are increasingly used to estimate standing-tree (dynamic) stiffness; however, such techniques overestimate static stiffness, the standard measurement for determining modulus of elasticity (MOE) of wood. This study aimed to identify correction methods for standing-tree estimates making dynamic and static stiffness comparable. Sixty *Pinus taeda* L. trees, ranging from 14 to 19 years old, obtained from genetic tests established in the southeastern United States, were analyzed. Standing-tree acoustic velocities were measured using the TreeSonic tool. Acoustic velocities were also recorded in butt logs cut from the same trees using the Director HM200. A strong but biased relationship between tree and log velocities was observed, with tree velocities 32% higher (on average) than the corresponding log velocities. Two correction methods, one for calibrating tree velocities and one for accounting for differences in wood moisture content, were used to determine an adjusted MOE. After correction, adjusted MOE estimates were in good agreement with static longitudinal MOE values measured on clearwood specimens obtained from the trees, and no systematic bias was observed. The results of this study show that acoustic estimates of MOE on standing trees largely depend on how the data are processed and the reference method used.

Résumé : Des outils acoustiques sont de plus en plus utilisés pour estimer la rigidité (dynamique) des arbres debout. Cependant, de telles mesures surestiment la rigidité statique, la technique standard pour déterminer le module d'élasticité (MOE) du bois. Cette étude visait à identifier les méthodes de correction des estimations sur les arbres debout pour rendre les valeurs de rigidité dynamique et statique comparables. Soixante tiges de *Pinus taeda* L. ont été analysées. Elles étaient âgées de 14 à 19 ans et provenaient de tests génétiques établis dans le sud-est des États-Unis. La vitesse sonique dans les arbres debout a été mesurée avec l'appareil TreeSonic. La vitesse sonique a aussi été mesurée dans la bille de pied coupée chez les mêmes arbres avec le Director HM200. Une relation étroite mais biaisée a été observée entre la vitesse sonique dans les arbres debout et les billes. La vitesse sonique était en moyenne 32 % plus élevée dans les arbres que dans les billes. Deux méthodes de correction ont été utilisées pour déterminer un MOE ajusté : une méthode pour calibrer la vitesse sonique dans les arbres et une autre pour tenir compte de la différence d'humidité dans le bois. Après avoir effectué la correction, les estimations du MOE ajusté correspondaient bien aux valeurs du MOE longitudinal statique mesuré sur des échantillons de bois sain provenant des arbres et aucun biais systématique n'a été observé. Les résultats de cette étude montrent que les estimations acoustiques du MOE chez les arbres debout dépendent largement de la façon dont les données sont traitées et de la méthode de référence utilisée.

[Traduit par la Rédaction]

Introduction

Mechanical properties are the most important wood characteristics for structural applications. Particularly important is the modulus of elasticity (MOE) or stiffness, which provides a measure of a wood member's resistance to deformation. MOE is often determined by a static bending test in which a wood section of fixed dimensions and moisture content is subjected to a known load. The procedure involves the use of the load–deflection relationship of a supported beam to determine static longitudinal MOE (E_S) (Pellerin and Ross 2002). Despite its simplicity, this technique is costly, as it requires destructive sampling of trees to provide samples for testing (Raymond et al. 2007). As a conse-

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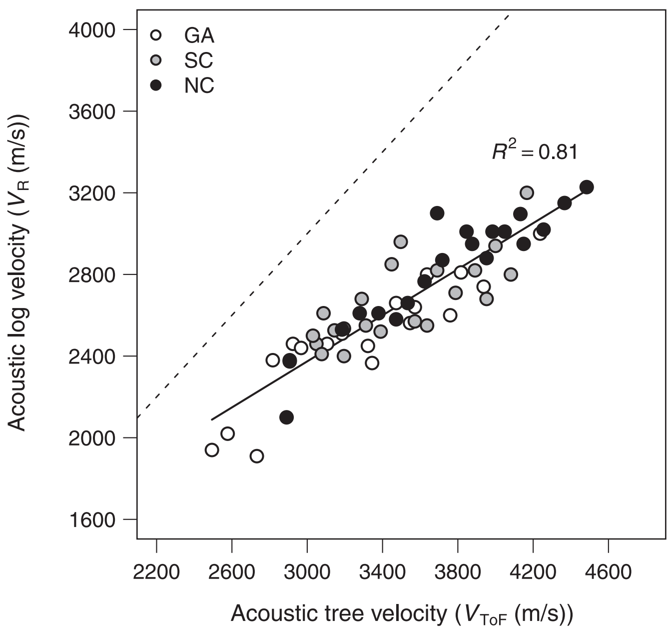
Table 1. Individual-tree mean characteristics on each test site.

Test	Location	Physiographic region	Age (years)	*n*	DBH (cm)	HT (m)
1	GA	Piedmont	15	10	18.8 (0.6)	13.8 (0.2)
2	GA	Piedmont	16	10	19.0 (0.5)	15.7 (0.1)
3	SC	Coastal plain	14	10	22.7 (0.7)	20.1 (0.4)
4	SC	Coastal plain	15	10	23.9 (0.5)	20.2 (0.5)
5	NC	Coastal plain	18	10	23.9 (1.2)	19.0 (0.4)
6	NC	Coastal plain	19	10	22.2 (1.4)	19.7 (0.6)

Note: DBH, diameter at breast height (1.4 m); HT, total height. GA, central Georgia; SC, southwestern South Carolina; NC, North Carolina Atlantic coast. Standard errors are given in parentheses.

Fig. 1. Comparison between acoustic velocity on standing trees (V_{ToF}) and in butt logs cut from the same trees (V_R) obtained from three genetic field tests (central Georgia (GA), southwestern South Carolina (SC), and North Carolina (NC) Atlantic coast). The segmented line represents the line of equivalence.



quence, research has been undertaken to develop nondestructive evaluation techniques capable of predicting wood stiffness in a rapid and cost-efficient way (Wang et al. 2007*a*). Acoustics, near infrared spectroscopy, and SilviScan have been found to be good alternatives to traditional bending tests (e.g., Schimleck and Evans 2002; Wang and Ross 2002; Schimleck et al. 2005; Evans 2006). The development of robust, inexpensive, field-based acoustic tools (Chauhan et al. 2006) has made the acoustic technique the best option of the three for assessing stiffness in a large number of standing trees.

Standing-tree acoustic measurements are obtained by hammering two sensor probes (transmitting and receiving probes) at a prespecified distance apart into the stem, usually around breast height (1.4 m from the ground). A stress wave is induced by striking the transmitting probe with a steel hammer, and the time-of-flight (ToF) is recorded (Wang et al. 2000). The ToF approach, pioneered by Fakopp Enterprise (Chauhan et al. 2006), provides a nondestructive measurement of dynamic MOE (E_D) in a column of outerwood 2–3 cm thick and approximately 1 m long (Auty and Achim 2008), calculated on the basis of a constant greenwood density (Grabianowski et al. 2006; Toulmin and Raymond 2007). Variations to this approach exist, for example, in terms of the acoustic tool used and how the probes are positioned in the stem (e.g., Lasserre et al. 2004; Mahon et al. 2009; Raymond et al. 2008).

Several studies have examined the relationships between acoustic measurements on standing trees and E_S of wood with mixed results. Wang et al. (2001) found that acoustic E_D determined on 38- to 70-year-old western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and Sitka spruce (*Picea sitchensis* (Bong) Carrière) trees was moderately correlated with E_S of short clearwood specimens obtained from the same trees (r = 0.66). Lindström et al. (2004) reported a strong correlation (r = 0.89), at a clonal mean level, between acoustic E_D and E_S measured by axial compression loading on wood billets cut from 3-year-old Monterey pine (*Pinus radiata* D. Don.) trees. Recently, Eckard (2007) reported only a moderate phenotypic correlation (r = 0.67) between stress wave velocity (squared) and E_S of short clearwood specimens in 8-year-old loblolly pine (*Pinus taeda* L.) clones; while Auty and Achim (2008) found a coefficient of determination of R^2 = 0.53 (r = 0.73) between E_S and stress wave velocity in 45- to 72-year-old Scots pine (*Pinus sylvestris* L.) trees. Similarly, Raymond et al. (2008), working with 28- to 43-year-old *P. radiata* trees, reported a correlation of 0.79 between short clear E_S and E_D measured in standing trees.

Conversely, Matheson et al. (2002) reported relationships between stress wave velocity and lumber stiffness for *P. radiata* (approximately 30 years old) that ranged from r = 0.01 (no correlation) to r = 0.33 (weakly correlated). Kumar et al. (2002) found a weak phenotypic correlation (r = –0.47) between the transit time measured in 12-year-old *P. radiata* trees and stiffness measured on small clearwood samples cut from the trees, and Cherry et al. (2008), comparing E_S with acoustic E_D in 25-year-old Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) trees, also found a weak phenotypic correlation (r = 0.45) between both traits.

Wood mechanical properties are affected by silvicultural practices, especially thinning (Wang and Ross 2002), and acoustics have had an important role in assessing the impact of initial stocking or thinning practices on wood stiffness. For example, Wang et al. (2001) found that trees from unthinned stands had higher acoustic velocities and stiffness than trees from medium and heavily thinned stands. Lasserre et al. (2005) reported that planting density (ranging from 833 to 2500 trees/ha) significantly influenced stiffness in

Table 2. Estimated Poisson ratios (ν) and measured wood properties for each test site.

Test	V_{ToF}/V_R	ν	ρ_{DBH} (kg/m^3)	ρ_L (kg/m^3)	MC_{DBH} %	MC_L %	ρ* (kg/m^3)
1	1.29 (0.03)	0.358	965.8 (8.6)	952.2 (9.5)	124.1 (5.6)	130.7 (4.2)	803.6
2	1.35 (0.03)	0.374	962.0 (9.2)	943.5 (8.6)	121.2 (4.9)	127.0 (4.0)	803.3
3	1.30 (0.02)	0.360	966.2 (11.1)	963.5 (11.1)	123.7 (5.0)	128.3 (4.7)	804.3
4	1.33 (0.03)	0.369	990.0 (9.9)	986.1 (10.3)	117.7 (5.5)	126.3 (5.4)	830.5
5	1.29 (0.01)	0.358	1007.0 (7.8)	998.0 (5.1)	110.4 (3.2)	120.7 (3.7)	853.1
6	1.35 (0.02)	0.376	1018.2 (5.5)	1002.8 (5.8)	103.0 (2.0)	111.3 (2.7)	871.7

Note: Standard errors are given in parentheses. The subscripts DBH and L indicate properties measured at breast height and in logs, respectively. V_{ToF}, tree velocity (m/s); V_R, log velocity (m/s); ρ, green density; MC, moisture content (dry basis); ρ*, effective density at breast height.

11-year-old *P. radiata* trees, with values in the high-density plots exceeding those observed for low-density plots by 34%. Similarly, Roth et al. (2007) reported an increase of 31% in stress wave velocity (squared) measured in 6-year-old *Pinus taeda* trees when planting density increased from 1334 to 2990 trees/ha, while Waghorn et al. (2007) found an increase of 37% in acoustic E_D when stocking increased from 275 to 2551 trees/ha in 17-year-old *P. radiata* trees.

According to Andrews (2002), ToF tools used on standing trees are considered less accurate than resonance tools, now commonly used for sorting logs (Carter et al. 2006). A biased relationship between tree and log acoustic measurements evidently exists (Chauhan and Walker 2006; Wang et al. 2007*b*); thus acoustic velocity derived from ToF readings must be interpreted differently when assessing wood stiffness in standing trees (Wang et al. 2007*a*). In addition, because of the systematic bias in the relationship between ToF and resonance, Andrews (2003) concluded that squaring the ToF speed will seriously overestimate wood stiffness in standing trees. Experimental results have also shown that E_D calculated from stress wave velocity and green-wood density increases with an increase in moisture content (Gerhards 1975; Wang and Chuang 2000); this finding disagrees with the data observed from static tests, making it necessary to account for differences in wood moisture content when acoustic E_D is calculated. Similarly, the assumption of a constant green-wood density and its impact on predicted MOE values need to be evaluated (e.g., Wielinga et al. 2009). Furthermore, in most studies involving the evaluation of standing trees the inherent differences between static and dynamic estimates of wood stiffness have been overlooked, thereby producing a bias in the relationship between predicted and observed MOE values, as noted by Ilic (2001) and Raymond et al. (2007).

Despite these apparent unresolved issues, standing-tree acoustic tools are of great value for tree breeding, as the wood properties of potential parents for future generations can be nondestructively and rapidly measured (Kumar et al. 2002). The main objective of this study was to examine the relationships between acoustic variables and wood stiffness measured in *P. taeda* trees obtained from three genetic field tests established in the southeastern United States. The specific objectives were (*i*) to analyze the relationship between ToF measured on trees and resonance measured on merchantable logs cut from the trees, and (*ii*) to study their relationships with the different techniques used to measure MOE (static bending and SilviScan).

Materials and methods

Pinus taeda trees

Trees were obtained from progeny tests established by members of the North Carolina State University Cooperative Tree Improvement Program between 1987 and 1992. The field tests were located in three main regions (central Georgia (GA), southwestern South Carolina (SC), and North Carolina (NC) Atlantic coast). A six-tree disconnected diallel mating design was used to produce progeny of 12 parents, and a randomized complete block design was used on each test location. Thirty full-sib families plus one check lot were available for sampling at each test site. A total of 20 trees representing different full-sib families were destructively sampled in each test (Table 1). Trees that were suppressed, atypical in form, or infected by fusiform rust (caused by *Cronartium quercuum* f.sp. *fusiforme*) were excluded from sampling.

Acoustic measurements on standing trees

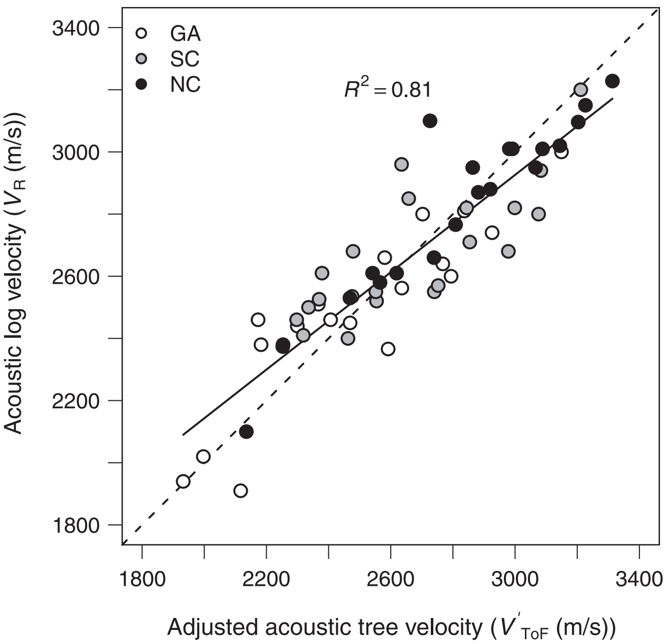
Tree acoustic velocity (V_{ToF}), measured in metres per second, was calculated as the average of three consecutive ToF readouts (µs/m) obtained on each tree with the Fakopp TreeSonic microsecond timer (Fakopp Enterprise, Ágfalva, Hungary). The probes were positioned on the same side of the stem, 1 m apart, at approximately 45° with respect to the main axis of the trunk, centered around breast height (1.4 m) and always on the same aspect to minimize environmental variation. Stress waves were induced by striking the transmitting probe with a steel hammer.

Acoustic measurements on logs and wood samples

After recording the acoustic transit times, trees were measured (diameter and height), felled, delimbed, and destructively sampled. Each tree was cut into merchantable logs (approximately 4.9 m in length), with the number of logs dependent on the tree's length. Only butt logs were considered for the analysis described in this study. Log acoustic velocity (V_R), in metres per second, was calculated as the average of five velocity readouts (to minimize experimental error) obtained on each log using the Director HM200 resonance tool (fibre-gen, Christchurch, New Zealand). The readouts were taken by holding the acoustic tool firmly against the large-end diameter of each log and hitting the end of the log with a steel hammer to induce the stress waves.

From each log, four 4 cm thick wood disks were extracted

Fig. 2. Relationship between acoustic velocity of butt logs (V_R) and adjusted acoustic velocity of standing trees (V'_{ToF}) corrected by using the dilatational theory approach obtained from three genetic field tests (central Georgia (GA), southwestern South Carolina (SC), and North Carolina (NC) Atlantic coast). The segmented line represents the line of equivalence.



at 1.5 m intervals from the base and used for green density, basic density, and moisture content determination according to ASTM Standard D 2395 - 07a (2007). A duplicate disk was obtained at 1.4 m, and a 12.5 mm × 12.5 mm radial section was cut from the center of this disk for SilviScan analysis. In addition, wood billets (0.6 m long) were cut from each log, at a mean (±SE) height of 1.82 m (±0.02 m). The billets were sawn through the center and used to obtain 25 mm × 25 mm × 410 mm wood specimens for static bending testing, starting from the position closest to bark, according to ASTM Standard D 143-94 (2007).

Stiffness determinations

Static bending

Static MOE (E_S) of short clearwood specimens was obtained by a three-point static bending test using a Tinius Olsen 5000 machine (Tinius Olsen Inc., Horsham, Pennsylvania), as described by Schimleck et al. (2005). Wood samples were tested at 12% equilibrium moisture content over a 355.6 mm span with center loading and the pith up until failure. A continuous load was applied at a head speed of 1.78 mm/min. The formulas used to calculate E_S are given in ASTM Standard D 143-94 (2007).

SilviScan

Radial strips, 2 mm tangentially × 7 mm longitudinally, were cut from the 12.5 mm × 12.5 mm radial sections with a twin-blade saw and used for SilviScan-3 analysis (Paprican, Vancouver, British Columbia). The length of the radial strips varied depending on the pith-to-bark length of the wood sections. The strips were not resin extracted. SilviScan MOE estimates were obtained using a combination of X-ray densitometry and X-ray diffractometry data collected at a 5 mm resolution using the expression

$$[1] \qquad E_{D(SS)} = A(I_{CV} \times \mathrm{AD})^B$$

where $E_{D(SS)}$ is the dynamic MOE (GPa); A and B are a scaling and curvature parameters, respectively; AD is the air-dry density (kg/m^3) of the sample, and I_{CV} (dimensionless) is the coefficient of variation of the amplitude of the azimuthal X-ray diffraction intensity profile (Evans 2006). All measurements were made in a controlled environment at 40% relative humidity and a temperature of 20 °C.

Acoustics

Traditionally, acoustic dynamic stiffness (E_D), either in trees ($E_{D(ToF)}$) or logs ($E_{D(R)}$), has been calculated using the one-dimensional equation:

$$[2] \qquad E_D = V^2 \times \rho$$

where E_D is dynamic MOE, V is longitudinal wave velocity (m/s), and ρ is green density (kg/m^3).

However, as noted by several authors, a biased relationship between stress wave velocities calculated from ToF and velocities measured by resonance is commonly observed, with tree velocities being, in general, higher than log velocities (e.g., Chauhan and Walker 2006; Wang et al. 2007*a*; Mahon et al. 2009). To reduce these differences, Andrews (2003) and Wang et al. (2007*b*) developed a correction method for tree velocities based on dilatational wave theory that makes use of acoustic information collected on both trees and logs.

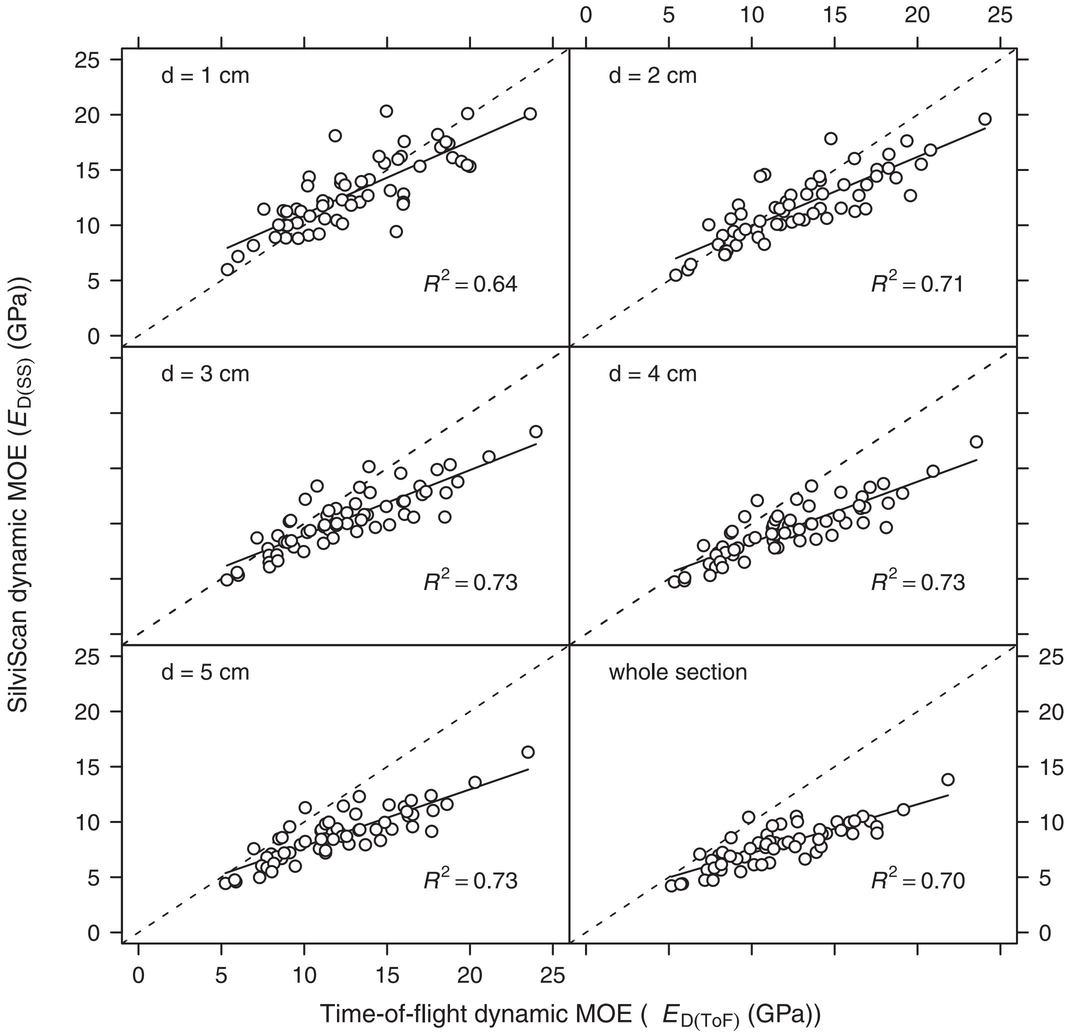
According to Andrews (2003), in an elastic material there are two propagation speeds, the dilatational speed and the shear speed. The speed in a rod can be viewed as the result of multiple interferences and reflections of these two waves, and in equilibrium, the sum is a plane wave moving along the rod at a speed $V = (E_D/\rho)^{0.5}$, which is simply a reexpression of eq. 2. Wang et al. (2007*b*) point out that tree velocities are consistently higher than the corresponding log velocities, which can be interpreted as a good indication that ToF in trees is dominated by dilatational waves rather than one-dimensional plane waves.

The theoretical ratio between the dilatational speed (V_{ToF}) and the one-dimensional speed, which according to Andrews (2003) is assumed to be the acoustic velocity measured by resonance (V_R), is related to the Poisson ratio of the material (ν):

$$[3] \qquad \frac{V_{ToF}}{V_R} = \sqrt{\frac{1-\nu}{(1+\nu)(1-2\nu)}}$$

A rod-like specimen subjected to uniaxial tension will exhibit some shrinkage in the lateral direction for most materials. The ratio of lateral strain and axial strain is defined as Poisson's ratio. The Poisson ratio of green wood is not known, but it can be numerically solved from eq. 3 when both V_{ToF} and V_R have been measured on the same trees. Thus, eq. 2 can be rewritten to calculate an adjusted dynamic MOE ($E'_{D(ToF)}$) in standing trees as follows:

Fig. 3. Relationship between dynamic modulus of elasticity (MOE) estimated from time-of-flight (ToF) velocities measured on standing trees ($E_{D(ToF)}$) and weighted dynamic MOE at breast height derived from SilviScan analysis ($E_{D(SS)}$) for different cumulative distances (d) from bark to pith. The segmented line represents the line of equivalence.



$$[4] \qquad E'_{D(ToF)} = \left(\frac{V_{ToF}}{\sqrt{\frac{1-\nu}{(1+\nu)(1-2\nu)}}} \right)^2 \times \rho$$

In addition, eq. 4 can be further modified to take into account the effects of moisture content on $E'_{D(ToF)}$ by replacing ρ by the effective density of the wood (ρ*), defined as follows (Wang and Chuang 2000):

$$[5] \qquad \rho^* = \rho \left\{ 1 - \frac{(1-k)(MC - MC_{FSP})}{100 + MC} \right\}$$

where MC is wood moisture content (%), MC_{FSP} is the moisture content at fiber saturation (assumed to be 30% in this study), and k is the mobility of the free water, defined as the ratio of the mass of free water that vibrates in the same phase with wood cell walls to the total mass of free water (Wang and Chuang 2000). In general, k is determined through simulation, but for this study, k = 0.6 as suggested by Wang and Chuang (2000) for stress wave velocity was adopted. By replacing ρ by ρ* in eq. 4 and including the factor $K = 9.84 \times 10^{-10}$ to incorporate gravitational acceleration and conversion constants to express stiffness in gigapascals, the following is obtained:

$$[6] \qquad E''_{D(ToF)} = K \times \left(\frac{V_{ToF}}{\sqrt{\frac{1-\nu}{(1+\nu)(1-2\nu)}}} \right)^2 \times \rho \left\{ 1 - \frac{0.4(MC - 30)}{100 + MC} \right\}$$

which is simply an adjusted version of eq. 2 that takes into account differences between ToF and resonance stress wave velocities as well as differences in wood moisture content to calculate dynamic MOE from acoustic measurements in standing trees. R version 2.8.1 (R Development Core Team 2008) was used for the analyses.

Results and discussion

Tree versus log acoustic velocities

A strong relationship between tree and log acoustic veloc-

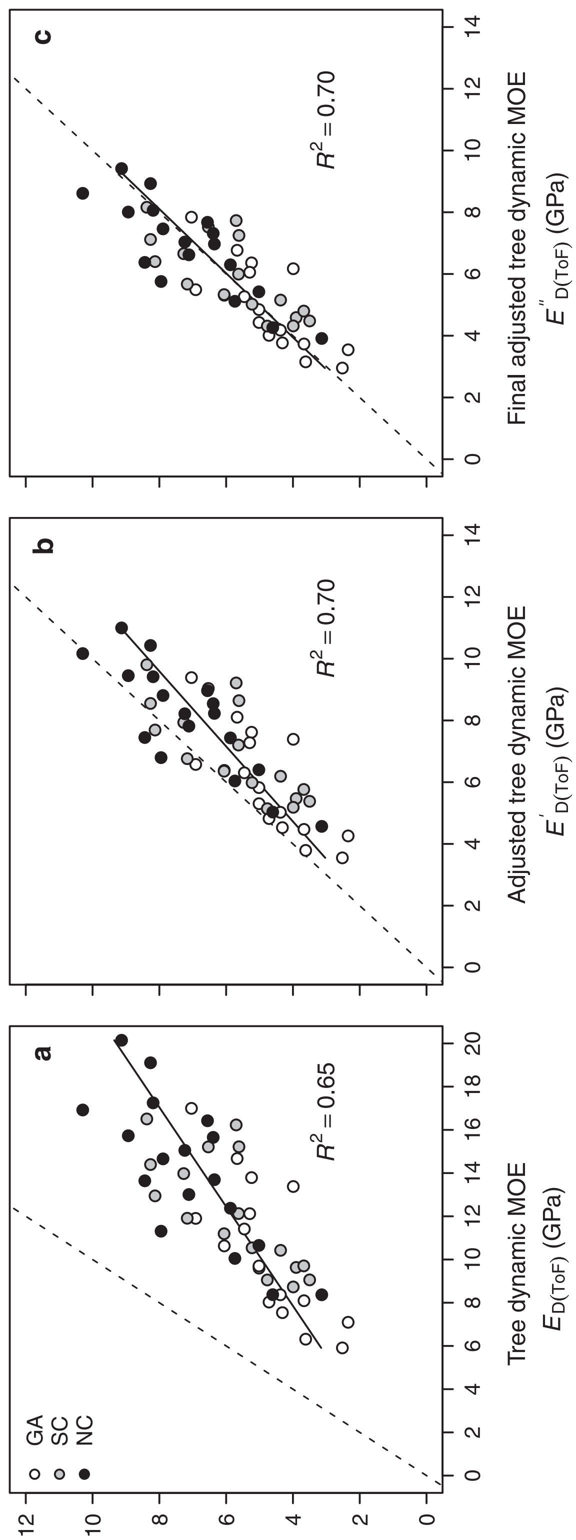


Fig. 4. Relationship between static modulus of elasticity (MOE) (E_S) and dynamic MOE estimated from unadjusted time-of-flight (ToF) velocities (*a*), adjusted ToF velocities by Poisson ratio (*b*), and adjusted ToF velocities by Poisson ratio and moisture content (*c*) in trees obtained from three genetic field tests (central Georgia (GA), southwestern South Carolina (SC), and North Carolina (NC) Atlantic coast). The segmented line represents the line of equivalence.

ities was observed, characterized by a coefficient of determination (R^2) of 0.81 and a root mean square error (RMSE) of 130.1 m/s. Tree velocities ranged from 2493.8 to 4484.3 m/s and were, on average, 32% higher than velocities measured on logs, which varied between 1909.9 and 3228.0 m/s. Deviation from the line of equivalence increased as velocity increased (Fig. 1). According to Chauhan and Walker (2006) and Grabianowski et al. (2006), the higher velocity measured by TreeSonic can be attributed to the fact that single-pass transit-time velocities are sensitive to the high localized stiffness of the outerwood, whereas resonance methods, such as the Director HM200 tool, assess area-weighted cross-sectional average stiffness.

Using the TreeSonic and Director HM200 on *P. taeda*, Mahon et al. (2009) also found a mean difference between tree and log velocities of over 30%. However, Chauhan and Walker (2006) and Wang et al. (2007*b*) reported differences lower than 32%. These authors used the Director HM200 for assessing log velocities, but the Fakopp 2D (Chauhan and Walker 2006) and a prototype acoustic tool (Wang et al. 2007*b*) were used to measure tree velocities. In addition, these studies were conducted on different species and over a greater age range. Thus, the magnitude of the mean difference between tree and log velocities appears to be associated to the instrument and material used.

To explore the relationship between tree and log acoustic velocities further, 69 data points obtained from the work of Mahon et al. (2009) were added to the 60 trees used in this study. This data set consisted of acoustic velocities measured on *P. taeda* trees (ranging from 13 to 22 years old) and velocities measured on butt logs cut from the same trees. The relationship between tree and log acoustic velocities for the "enhanced" data set (n = 129) was similar to that found for the original 60 trees, with an R^2 = 0.80, RMSE = 153.1 m/s, and a mean difference of 32% between ToF- and resonance-based stress-wave velocities.

In addition, and despite the reduced number of data points, analysis by site gave similar results for GA (R^2 = 0.82; RMSE = 123.7 m/s) and NC sites (R^2 = 0.86; RMSE = 109.6 m/s). However, a drop in the association (R^2 = 0.57; RMSE = 141.5 m/s) was observed for the SC sites, presumably because of the reduced velocity range. When the individual test sites are considered, i.e., site–age combination, relationships (R^2) between tree and log velocities ranged from 0.71 to 0.97, the exception being the 15-year-old trees from SC that showed an R^2 = 0.38.

Some studies have reported a negative relationship between acoustic velocity (or stiffness derived from it) and breast-height diameter (DBH) (e.g., Lasserre et al. 2005; Chauhan and Walker 2006). Furthermore, a method for adjusting ToF velocity based on a simple nonlinear model with DBH and V_R as independent variables has been proposed (Wang et al. 2007*a*, 2007*b*). However, in this study such relationships were not observed for trees (R^2 = 0.02) or logs (R^2 = 0.05), and in all cases the estimated coefficient associated with DBH using the nonlinear model were not significantly different from zero. Similar findings were reported by Mahon et al. (2009).

From these results we can conclude that the inherent differences between V_{ToF} and V_R will always result in standing-tree estimates of stiffness ($E_{D(ToF)}$) higher than those observed in logs ($E_{D(R)}$).

Adjusted tree acoustic velocity

To obtain adjusted tree velocities (V'_{ToF}) using the dilatational theory approach proposed by Andrews (2003) and Wang et al. (2007*b*), Poisson ratios (ν) derived from eq. 3 were calculated for each site–age combination (Table 2). The mean (±SE) V_{ToF}/V_R ratio was 1.32 (±0.01), and the resultant ν was 0.366. This value was very close to the ratio of 0.370 suggested for dry wood in softwoods and hardwoods (see Wang et al. 2007*b*).

As shown in Table 2, ν ranged from 0.358 to 0.376 and was consistently lower in younger trees. After correction, the relationship between tree and log acoustic velocity hardly changed (R^2 = 0.81; RMSE = 129.5 m/s); however, most of the bias initially observed was removed (Fig. 2). Adjusted tree velocities ranged from 1932.3 to 3313.2 m/s, and the mean difference of 32% dropped to almost 0 (0.02%).

These results suggest overestimation of E_D when assessing standing trees can be greatly reduced or eliminated by correcting V_{ToF} based on V_R, i.e., $E'_{D(ToF)} \approx E_{D(R)}$. Further analysis indicates that individual estimates of Poisson ratios may not be required, as the relationship between V'_{ToF}, using individual ν values, and V'_{ToF}, using the overall ratio ν = 0.366, was very strong with R^2 = 0.98 and RMSE = 50.11 m/s.

TreeSonic velocity and outerwood stiffness

The literature frequently mentions that when applied to standing trees, the stress wave technique measures the MOE of the outermost rings only. For example, Grabianowski et al. (2006) found that standing-tree acoustic measurements were strongly associated with acoustic measurements obtained on lumber cut adjacent to the bark (R^2 = 0.89) and moderately correlated with corewood velocities (R^2 = 0.74).

In this work, TreeSonic velocities measured on standing trees in combination with green-wood density values, derived from X-ray densitometry data collected on each segment and the average moisture content of the wood measured at breast height, were used to calculate stiffness at breast height ($E_{D(ToF)}$ using eq. 2) in consecutive 10 mm steps measured from bark to pith. The association between $E_{D(ToF)}$ and the weighted SilviScan MOE ($E_{D(SS)}$), for the different cumulative distances, was moderate ranging from R^2 = 0.64 (RMSE = 2.0 GPa) to R^2 = 0.73 (RMSE = 1.3 GPa), as shown in Fig. 3.

Figure 3 shows that as the amount of transition wood and (or) corewood increases, the relationship between $E_{D(ToF)}$ and $E_{D(SS)}$ increasingly diverges from the line of equivalence. After a distance of 3 cm, the degree of association between the two estimates remained relatively constant with a small drop in R^2 when the whole breast-height section was used, mainly as a consequence of the reduction in the range of weighted stiffness values calculated from SilviScan. This figure also illustrates one of the main assumptions behind the ToF method when applied to standing trees: single-pass transit-time velocities are sensitive to the high localized stiffness of the outerwood.

Note that $E_{D(ToF)}$ and $E_{D(SS)}$ are both measures of dynamic MOE, and for this reason, the relationship between these estimates is less biased than the one observed between $E_{D(ToF)}$ and $E_{D(R)}$. However, SilviScan uses air-dry density and the amplitude of the azimuthal X-ray diffraction intensity profile of the sample to calculate stiffness, while $E_{D(ToF)}$ uses green density and acoustic velocity. So, for any given distance from the bark, the dynamic MOE is calculated using different wood properties, and care must be taken when comparing both estimates.

These results also suggest that SilviScan can be used as an alternative to traditional static bending tests. An advantage is that complete radial profiles for MOE can be obtained, while the main disadvantage is cost. For *P. radiata*, Raymond et al. (2007) found a very strong association (R^2 = 0.93) between SilviScan MOE measured on subsamples obtained from both ends of static bending specimens. In this work, the association between $E_{D(SS)}$, measured on the radial sections obtained at breast height, and E_S, measured on static bending specimens, was strong (R^2 = 0.83; RMSE = 0.93 GPa), but not as high as that reported by Raymond et al. (2007), probably because stiffness values were measured in this study at different heights and on different samples (not cut from the end of static bending samples as per Raymond et al. (2007)).

Breast-height versus whole-log wood properties

To incorporate the concept of effective density (eq. 5) in the calculation of $E''_{D(ToF)}$ (eq. 6), estimates of ρ and MC are required. Measurements of these wood properties are usually taken at breast height for practical reasons, although as Auty and Achim (2008) point out, this technique may raise questions about the applicability of the results to describe whole-stem properties.

Following Downes et al. (1997), log green density (ρ_L) and log moisture content (MC_L) were calculated as volume-weighted averages of the mean sectional properties derived from the disks extracted at 1.5 m intervals. For breast-height wood properties, the values of green density (ρ_{DBH}) and moisture content (MC_{DBH}) measured on additional disks obtained at 1.4 m were used. A summary of these properties is given in Table 2. Very strong associations between ρ_L and ρ_{DBH} (R^2 = 0.82, RMSE = 14.8 kg/m^3), and between MC_L and MC_{DBH} (R^2 = 0.83, RMSE = 0.6%) were found, suggesting that $E_{D(ToF)}$ can be reasonably approximated by using ρ* derived from measurements at breast height.

Static MOE and tree dynamic MOE

Most of the studies dealing with acoustic determinations of stiffness in standing trees assume that E_S is a measure of the "true" MOE of the wood (e.g., Wang et al. 2001; Eckard 2007; Raymond et al. 2008), and this assumption is the basis for the corrections suggested to determine $E''_{D(ToF)}$ (e.g., Wang and Chuang 2000; Andrews 2003; Wang et al. 2007*b*). In this section, a sequential analysis is given to illustrate the effects of these adjustments on dynamic MOE estimates obtained from TreeSonic measurements.

To obtain a representative estimate of the weighted E_S in butt logs, it was defined (for this study) that a minimum of four static bending specimens per wood billet were required. Owing to this restriction, only 52 of the 60 trees originally sampled were used in this section (GA: n = 17, SC: n = 17, NC: $n = 18$). Trees removed ($n = 8$) were either too small to provide the minimum number of clearwood samples or the wood specimens had defects that limited their use, such as an excessive number of knots. These problems when using small trees for the determination of E_S are not uncommon, and as Lindström et al. (2002) point out, most of the standards for the determination of MOE in small clear specimens are applicable only to large mature trees because young or small-sized trees rarely display pronounced internodes, and obtaining more than one or two defect-free samples per billet is difficult.

A moderate and biased relationship ($R^2 = 0.65$, RMSE = 1.09 GPa) between $E_{D(ToF)}$ and E_S was observed when tree dynamic MOE was calculated using eq. 2, V_{ToF}, and the average green density measured at breast height (Fig. 4*a*).

Considering the biased relationship found between V_{ToF} and V_R, the results shown in Fig. 4*a* were not surprising. TreeSonic overestimated static MOE values in all cases, and the deviation from the line of equivalence increased as stiffness increased. Wang et al. (2007*b*) make the same observation and point out that tree velocities measured by the ToF method cannot be directly used for assessing wood quality in standing trees. However, we support the assessment of standing trees if it is carried out with the objective of providing rapid information for ranking purposes and not with the goal of finding the "true" MOE of the trees, i.e., the bias should not be a limitation for using acoustics tools such as TreeSonic. This assumes the bias is consistent from tree to tree and that no interactions exist.

After calibrating V_{ToF} on V_R as described in eq. 3, the relationship between E_S and $E''_{D(ToF)}$, calculated using eq. 4 and the average green density measured at breast height, showed a small improvement ($R^2 = 0.70$, RMSE = 1.02 GPa). More importantly the bias of the relationship decreased (Fig. 4*b*) compared with that observed when using $E_{D(ToF)}$.

If, in addition, we incorporate the concept of effective density instead of green density (eq. 5) in the calculation of stiffness, the bias in the relationship between $E''_{D(ToF)}$, given by eq. 6, and E_S is almost totally removed ($R^2 = 0.70$, RMSE = 1.0 GPa), as shown in Fig. 4*c*.

The initial V_{ToF} values were corrected by taking into account the differences observed with the corresponding velocities (V_R) of the logs and the differences in moisture content of the wood. Figure 4*c* shows that the dynamic MOE estimates obtained in standing trees, after correction, were in good agreement with the weighted static MOE values measured by static bending.

Although the degree of association between $E''_{D(ToF)}$ and E_S was only moderate, the fact that the corrected relationship was close to the line of equivalence, suggests that further improvements on the degree of association between the variables can be achieved through a better control of other sources of experimental error, such as the technique used for recording the ToF in the field and the preparation of the static bending samples.

Conclusions

The results of this study showed that acoustic velocities derived from ToF measurements in standing trees can be successfully used for the nondestructive evaluation of wood stiffness when tree velocities are adjusted for differences between dilatational waves (measured in trees) and resonance waves (measured in logs) and after accounting for differences in wood moisture content of the trees.

After correction, adjusted dynamic MOE estimates from tree acoustic measurements were in good agreement with static MOE values measured on small clearwood samples obtained from the same trees. The bias frequently reported in the literature, when comparing these two measures of stiffness, was not observed.

Acoustic estimates of MOE on standing trees largely depend on how the data are processed and the reference method used. There are obvious differences between dynamic and static MOE estimates that suggest that a direct comparison of values may not be appropriate.

When comparing dynamic estimates of MOE, stiffness estimated from acoustic velocity in trees was well correlated with stiffness measured by SilviScan for the 3 cm of wood closest to the bark. At greater distances, the effects of increasing amounts of transition and corewood in the samples was reflected as an increased bias in the relationship between the MOE estimates (although not necessarily in the degree of association given by R^2).

To implement the adjusted ToF method to obtain a measure of stiffness in standing trees, estimates of green density and moisture content are required. These wood properties can be measured on increment cores extracted from a subsample of the trees under assessment. The results presented in this work are based on the average green density and moisture content measured on each test site, suggesting that individual wood properties are not required to obtain accurate MOE estimates from tree acoustic velocities. The adjustment methods described in this work can be easily implemented to assess a large number of individuals in tree breeding programs for selection based on wood stiffness.

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References

Andrews, M. 2002. Wood quality measurement — *son et lumière*. N.Z. J. For. **47**: 19–21.

Andrews, M.K. 2003. Which acoustic speed? *In* Proceedings of the 13th International Symposium on Nondestructive Testing of Wood. *Edited by* F.C. Beall. Forest Products Society, Madison, Wis. pp. 159–165.

ASTM Standard D 143-94. 2007. Standard test methods for small clear specimens of timber. ASTM International, West Conshohocken, Pa. Available at www.astm.org [accessed 5 November 2008].

ASTM Standard D 2395 - 07a. 2007. Standard test methods for specific gravity of wood and wood-based materials. ASTM International, West Conshohocken, Pa. Available at www.astm.org [accessed 5 November 2008].

Auty, D., and Achim, A. 2008. The relationship between standing tree acoustic assessment and timber quality in Scots pine and the practical implications for assessing timber quality from naturally regenerated stands. Forestry, **81**(4): 475–487. doi:10.1093/forestry/cpn015.

Carter, P., Chauchan, S., and Walker, J. 2006. Sorting logs and lumber for stiffness using director HM200. Wood Fiber Sci. **38**: 49–54.

Chauhan, S.S., and Walker, J.C.F. 2006. Variations in acoustic velocity and density with age, and their interrelationships in radiata pine. For. Ecol. Manage. **229**(1–3): 388–394. doi:10.1016/j.foreco.2006.04.019.

Chauhan, S., Donnelly, R., Huang, C.-L., Nakada, R., Yafang, Y., and Walker, J. 2006. Wood quality: multifaceted opportunities. Primary wood processing. Principles and practice. 2nd. ed. Chapter 6. Springer, Dordrecht, The Netherlands. pp. 159–202.

Cherry, M.L., Vikram, V., Briggs, D., Cress, D.W., and Howe, G.T. 2008. Genetic variation in direct and indirect measures of wood stiffness in coastal Douglas-fir. Can. J. For. Res. **38**: 2476–2486. doi:10.1139/X08-087.

Downes, G.M., Hudson, I.L., Raymond, C.A., Dean, G.H., Michell, A.J., Schimleck, L.R., Evans, R., and Muneri, A. 1997. Sampling plantation eucalypts for wood and fibre properties. CSIRO, Collingwood, Australia.

Eckard, J.T. 2007. Rapid screening for solid wood quality traits in clones of Loblolly pine (*Pinus taeda* L.) by indirect measurements. Master's thesis, Department of Forestry and Environmental Resources, North Carolina State University, Raleigh, N.C.

Evans, R. 2006. Wood stiffness by X-ray diffractometry. *In* Characterization of the cellulosic cell wall. Chapter 11. *Edited by* D. Stokke and L. Groom. Blackwell Publishing, Ames, Iowa. pp. 138–146.

Gerhards, C.C. 1975. Stress wave speed and MOE of sweetgum ranging from 150 to 15% MC. For. Prod. J. **25**: 51–57.

Grabianowski, M., Manley, B., and Walker, J.C.F. 2006. Acoustic measurements on standing trees, logs and green lumber. Wood Sci. Technol. **40**(3): 205–216. doi:10.1007/s00226-005-0038-5.

Ilic, J. 2001. Variation of the dynamic elastic modulus and wave velocity in the fibre direction with other properties during the drying of *Eucalyptus regnans* f. Muell. Wood Sci. Technol. **35**(1-2): 157–166. doi:10.1007/s002260000075.

Kumar, S., Jayawickrama, J.S., Lee, J., and Lausberg, M. 2002. Direct and indirect measures of stiffness and strength show high heritability in a wind-pollinated radiata pine progeny test in New Zealand. Silvae Genet. **51**: 256–261.

Lasserre, J.P., Mason, E., and Watt, M. 2004. The influence of initial stocking on corewood stiffness in a clonal experiment of 11-year-old *Pinus radiata* D. Don. N.Z. J. For. **49**: 18–23.

Lasserre, J.-P., Mason, E.G., and Watt, M.S. 2005. The effects of genotype and spacing on *Pinus radiata* [D. Don] corewood stiffness in an 11-year old experiment. For. Ecol. Manage. **205**(1–3): 375–383. doi:10.1016/j.foreco.2004.10.037.

Lindström, H., Harris, P., and Nakada, R. 2002. Methods for measuring stiffness of young trees. Holz als Roh-und Werkstoff, **60**: 165–174. doi:10.1007/s00107-002-0292-2.

Lindström, H., Harris, P., Sorensson, C.T., and Evans, R. 2004. Stiffness and wood variation of 3-year old *Pinus radiata* clones. Wood Sci. Technol. **38**: 579–597. doi:10.1007/s00226-004-0249-1.

Mahon, J.M., Jr., Jordan, L., Schimleck, L.R., Clark, A., III, and Daniels, R.F. 2009. A comparison of sampling methods for a standing tree acoustic device. South. J. Appl. For. **33**(2): 62–68.

Matheson, A.C., Dickson, R.L., Spencer, D.J., Joe, B., and Ilic, J. 2002. Acoustic segregation of *Pinus radiata* logs according to stiffness. Ann. For. Sci. **59**(5-6): 471–477. doi:10.1051/forest:2002031.

Pellerin, R.F., and Ross, R.J. J. 2002. Characteristics of wood, fundamental hypothesis, and static bending nondestructive evaluation methods. *In* Nondestructive evaluation of wood. Chapter 1. *Edited by* R.F. Pellerin and R.J. Ross. Forest Products Society, Madison, Wis. pp. 3–12.

Raymond, C.A., Joe, B., Evans, R., and Dickson, R.L. 2007. Relationship between timber grade, static and dynamic modulus of elasticity, and SilviScan properties for *Pinus radiata* in New South Wales. N. Z. J. For. Sci. **37**: 186–196.

Raymond, C.A., Joe, B., Anderson, D.W., and Watt, D.J. 2008. Effect of thinning on relationships between three measures of wood stiffness in *Pinus radiata*: standing trees vs. logs vs. short clear specimens. Can. J. For. Res. **38**: 2870–2879. doi:10.1139/X08-124.

Roth, B.E., Li, X., Huber, D.A., and Peter, G.F. 2007. Effects of management intensity, genetics and planting density on wood stiffness in a plantation of juvenile loblolly pine in the southeastern USA. For. Ecol. Manage. **246**(2–3): 155–162. doi:10.1016/j.foreco.2007.03.028.

Schimleck, L.R., and Evans, R. 2002. Estimation of wood stiffness of increment cores by near infrared spectroscopy: the development and application of calibrations based on selected cores. IAWA J. **23**: 217–224.

Schimleck, L.R., Jones, P.D., Clark, A., III, Daniels, R.F., and Peter, G.F. 2005. Near infrared spectroscopy for the nondestructive estimation of clear wood properties of *Pinus taeda* L. from the southern United States. For. Prod. J. **55**: 21–28.

R Development Core Team. 2008. R: A language and environment for statistical computing. Available from http:/www.r-project.org [accessed 24 March 2009].

Toulmin, M.J., and Raymond, C.A. 2007. Developing a sampling strategy for measuring acoustic velocity in standing *Pinus radiata* using the TreeTap time of flight tool. N. Z. J. For. Sci. **37**: 96–111.

Waghorn, M.J., Mason, E.G., and Watt, M.S. 2007. Influence of initial stand density and genotype on longitudinal variation in modulus of elasticity for 17-year-old *Pinus radiata*. For. Ecol. Manage. **252**(1–3): 67–72. doi:10.1016/j.foreco.2007.06.019.

Wang, S.-Y., and Chuang, S.-T. 2000. Experimental data correction of the dynamic elastic moduli, velocity and density of solid wood as a function of moisture content above the fiber saturation point. Holzforschung, **54**(3): 309–314. doi:10.1515/HF.2000.052.

Wang, X., and Ross, R.J. 2002. Nondestructive evaluation of green materials — recent research and development activities. *In* Nondestructive evaluation of wood. *Edited by* R.F. Pellerin and R.J. Ross. Forest Products Society, Madison, Wis. pp. 149–171.

Wang, X., Ross, R.J., Erickson, J.R., and Ligon, J.B. 2000. Nondestructive evaluation of trees. Exp. Tech. **24**(6): 27–29. doi:10.1111/j.1747-1567.2000.tb01345.x.

Wang, X., Ross, R.J., McClellan, M., Barbour, R.J., Erickson, J.R., Forsman, J.W., and McGinnis, G.D. 2001. Nondestructive evaluation of standing trees with a stress wave method. Wood Fiber Sci. **33**: 522–533.

Wang, X., Carter, P., Ross, R.J., and Brashaw, B.K. 2007*a*. Acoustic assessment of wood quality of raw forest materials — a path to increased profitability. For. Prod. J. **57**: 6–14.

Wang, X., Ross, R.J., and Carter, P. 2007*b*. Acoustic evaluation of wood quality in standing trees. Part I. Acoustic wave behavior. Wood Fiber Sci. **39**: 28–38.

Wielinga, B., Raymond, C.A., James, R., and Matheson, A.C. 2009. Effect of green density values on *Pinus radiata* stiffness estimation using stress-wave technique. N.Z. J. For. Sci. **39**: 71–79.