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Effectiveness of a nondestructive evaluation technique for assessing standing timber quality

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EFFECTIVENESS OF A NONDESTRUCTIVE EVALUATION TECHNIQUE FOR ASSESSING STANDING TIMBER QUALITY

By

Crystal L. Pilon

A THESIS

Submitted in partial fulfillment of the requirements

for the degree of

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2005

This thesis, "Effectiveness of a Nondestructive Evaluation Technique For Assessing Standing Timber Quality," is hereby approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE IN FORESTRY.

School of Forest Resources and Environmental Science

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Date: October 4, 2005

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(ABSTRACT)

The research presented in this thesis was conducted to further the development of the stress wave method of nondestructively assessing the quality of wood in standing trees. The specific objective of this research was to examine, in the field, use of two stress wave nondestructive assessment techniques.

The first technique examined utilizes a laboratory-built measurement system consisting of commercially available accelerometers and a digital storage oscilloscope. The second technique uses a commercially available tool that incorporates several technologies to determine speed of stress wave propagation in standing trees.

Field measurements using both techniques were conducted on sixty red pine trees in south-central Wisconsin and 115 ponderosa pine trees in western Idaho. After in-situ measurements were taken, thirty tested red pine trees were felled and a 15-foot-long butt log was obtained from each tree, while all tested ponderosa pine trees were felled and an 8½ -foot-long butt log was obtained, respectively. The butt logs were sent to the USDA Forest Products Laboratory and nondestructively tested using a resonance stress wave technique. Strong correlative relationships were observed between stress wave values obtained from both field measurement techniques. Excellent relationships were also observed between standing tree and log speed-of-sound values.

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Chapter 1 Introduction

Our forests are an extremely valuable resource. In addition to aesthetic and recreational value, our forests serve as a renewable source of raw material for an ever-increasing list of wood and fiber products. Wood is a highly variable material because of the stresses placed upon it by wind, weather, and genetics. Also, wood properties vary due to forest management regimes and soil composition. As a result, manufacturers and users of wood products are frequently frustrated when using wood because its properties can vary significantly (Brown *et al.* 1952). Manufacturers of wood products find it difficult to manufacture products with consistent properties, and users of wood products find that wood products are often subject to performance variability (Wang 1999).

Nondestructive evaluation (NDE) technologies have contributed significantly toward eliminating these inconsistencies (Bertholf 1965, Ross 1985, Kaiserlik and Pellerin 1977). By definition, NDE is the process of identifying the physical and mechanical properties of a material without altering its end-use capabilities and using this information to make decisions regarding appropriate applications. The development of NDE technologies and their use with wood has resulted in an increase in engineered wood-based materials that have well-defined performance characteristics. Various NDE technologies are used with wood-based materials, including those that utilize x-rays, chemical analyses, vibration properties, and sound transmission characteristics (Table 1, Ross and Pellerin 1994, Bucur 1985). Whereas most of these techniques are useful for determining wood properties, they are not always cost-effective and most cannot be used effectively in the field (Schad *et al.* 1996).

Table 1. Nondestructive evaluation techniques used to evaluate wood-based materials (Pellerin and Ross 1994, Bucur 1985).

Nondestructive Evaluation of Wood	
Evaluation of visual characteristics	**Chemical tests**
Color	Composition
Presence of defects	Presence of treatments
	• Preservatives
	• Fire retardants
Physical tests	**Mechanical tests**
Electrical resistance	Flexural stiffness
Dielectric properties	Proof loading
Vibrational properties	Bending
Wave propagation	Tension
Acoustic emissions	Compression
X-ray	Probes/coring

Currently, there is a strong interest in the development and use of a variety of NDE technologies to aid in the assessment of standing timber. Traditionally, trees have been selected for harvest on the basis of their visual characteristics (Green 1997). While visually assessing trees is useful for estimating the quality of wood in a tree, the assumption that visual tree characteristics are correlated to mechanical properties of the wood in a tree is not always reliable.

One technique that has been investigated as an aid in the evaluation of the quality of wood in standing timber uses sound transmission characteristics (Pellerin and Ross 2002). Research has shown, for example, that the speed at which a wave travels in wood is 1) dependent upon fiber angle (Kaiserlik and Pellerin 1977), 2) influenced significantly by the presence of certain types of decay or deterioration (Pellerin *et al.* 1985), and 3) influenced by the presence of knots (Gerhards 1981, 1982), all of which are important factors in determining timber quality. Stress-wave attenuation (or the rate at which a wave loses energy as it travels through wood) is another parameter that correlates with wood properties.

Chapter 2 Literature Review

2.1 Stress Wave Propagation

Different types of elastic waves can propagate in solids, depending on how the motion of the particles of the solid is related to the direction of propagation of the waves themselves and on the boundary conditions. The following is a summary of the various wave types in solids as summarized by Meyers (1994).

1. Longitudinal Waves (P Waves)

   Longitudinal waves correspond to the motion of the particles back and fourth along the direction of wave propagation such that particle motion is parallel to wave motion. Longitudinal waves that travel in three dimensions are known as dilatational waves.

2. Shear Waves (Distortional Waves)

   For shear waves, motion of the particles conveying the wave are perpendicular to the direction of the propagation of the wave. These waves are also referred to as distortional or transverse waves.

3. Surface Waves (Rayleigh Waves)

   Surface waves in solids (also referred to as Rayleigh waves) are analogous to waves on the surface of water. The particles move both up and down and back and forth, tracing out elliptical paths as the surface wave moves by. This type of wave is restricted to the region adjacent to the surface, and "particle" velocity (U_p) decreases very rapidly as the wave moves by.

4. Interfacial Waves (Stoneley Waves)

   When two semi-infinite media with different properties are in contact, these special waves form at their interface.

5. Waves in Layered Media (Love Waves)

   Named after the first person to study them (Love 1944), these wave types occur in layered media with different properties. For Love waves, the horizontal component of displacement can be significantly larger than the vertical component, a behavior not consistent with Rayleigh waves.

6. Bending (Flexural) Waves

   These waves involve propagation of flexure in a one-dimensional (bar) or two-dimensional configuration.

Among all these types of waves, longitudinal waves travel fastest and are most commonly used in property evaluation and defect detection.

2.2 Longitudinal Stress Wave Nondestructive Evaluation

The propagation of longitudinal (P) waves in solids is influenced in a complex manner by both the mechanical and physical properties of the medium (Jayne 1959, Pellerin 1965, Bertholf 1965, Kaiserlik 1977, Ross 1985). To describe the propagation of longitudinal stress waves for practical use, the complex expressions are commonly simplified to elementary, one-dimensional wave propagation theory as applied to an isotropic homogeneous material. For specimens that have lateral dimensions which are small compared with the wavelength of the propagating wave, this simplified theory yields the following equation relating the speed of propagation, C, to modulus of elasticity, MOE, and mass density, ρ (Pellerin and Ross 2002).

$$C = \sqrt{\frac{MOE}{\rho}}$$

The usefulness of this theory for wood could be considered dubious since wood and wood products are neither isotropic nor homogeneous (Brown *et al.* 1952). Research results, however, have shown that the propagation rate of stress waves is a good indicator of the quality of the wood through which the wave propagates (Tables 2 and 3).

Table 2. Summary of past research on nondestructive stress wave testing on lumber and wood composite products (Pellerin and Ross 2002).

Reference	Nondestructive evaluation technique	Material	Nondestructive evaluation parameter measured[a]	Static test	Reported properties	Comparison of nondestructive evaluation parameters and static properties (correlation coefficient *r*)
Kaiserlik and Pellerin (1977)	Longitudinal stress wave	Douglas-fir boards	C, E_d, δ	Tension	UTS	UTS and E_d, 0.84; UTS and combination of E_d, δ, 0.90
Pellerin and Morschauser (1974)	Longitudinal stress wave	Underlayment particleboard	C	Bending	E_{SB}, MOR	ESB, and C^2, 0.93-0.95 MOR and C^2, 0.87-0.93
Ross (1984), Ross and Pellerin (1988)	Longitudinal stress wave	Underlayment and industrial particleboard, structural panel products	C, E_d, δ	Tension	E_{ST}, UTS	E_{ST} and C^2, 0.98 E_{ST} and E_d, 0.98 UTS and C^2, 0.91 UTS and E_d, 0.93 UTS and 1/δ, 0.63 UTS and combination of E_d, 1/δ, 0.95
				Bending	E_{SB}, MOR	E_{SB}, and C^2, 0.97 E_{SB}, and E_d, 0.96 MOR and C^2, 0.93 MOR and E_d, 0.92 MOR and 1/δ, 0.70 MOR and combination of E_d, 1/δ, 0.97
				Internal bond	IB	IB and combination, 0.79
Fagan and Bodig (1985)	Longitudinal stress wave	Wide range of wood composites	C	Bending	MOR	Simulated and actual MOR distributions were similar
Vogt (1985)	Longitudinal stress wave	Medium-density fiberboard	C, E_d, δ	Tension	E_{ST}, UTS	E_{ST} and C^2, 0.90 E_{ST} and E_d, 0.88 UTS and C^2, 0.81 UTS and E_d, 0.88 Combination, 0.88
Vogt (1986)	Stress wave (through transmission)	Underlayment and industrial particleboard, structural panel products	C_t, E_{dt}	Internal bond	IB	IB and C_t^2, 0.70-0.72 IB and E_{dt}, 0.80-0.99

[a] C, speed of sound; C_t, speed-of-sound transmission through thickness; δ, logarithmic decrement; E_d, dynamic modulus of elasticity (MOE) from transverse vibration or stress-wave measurements; E_{dt}, dynamic MOE through thickness orientation; E_{SB}, MOE from static bending test; E_{ST}, MOE from static tension test; IB, internal bond; MOR, modulus of rupture; UTS, ultimate tensile stress.

Table 3. Research summary of correlation between nondestructive testing parameters and properties of degraded wood (Pellerin and Ross 2002).

Reference	NDE technique	Material	Degradation agent	NDE parameter measured[a]	Static test	Reported properties	Comparison of NDE parameters and static properties (correlation coefficient *r*, unless noted)
Chudnoff *et al.* (1984)	Longitudinal stress wave (parallel to grain)	Decayed and sound mine props; 26 species or species groupings	–	E_d	Compression parallel to grain	E_c, UCS	E_c and E_d, 0.84-0.97 (all species combined, hardwoods, maple, and oaks) E_c and E_d, 0.73-0.81 (all species combined, southern pines, lodgepole pine) UCS and E_d, 0.85-0.95 (all species combined, hardwoods, maple, and oaks)
Pellerin *et al.* (1985)	Longitudinal stress wave (parallel to grain)	Small clear southern yellow pine specimens	Brown-rot fungi (*Gloeophyllum trabeum*)	C, E_d	Compression parallel to grain	UCS	UCS and C: 0.47 (control) 0.73 (exposed) 0.80 (control and exposed) UCS and E_d: 0.86 (control) 0.86-0.89 (exposed) 0.94 (control and exposed)
			Termites (subterranean)	C, E_d	Compression parallel to grain	UCS	UCS and C: 0.65 (control) 0.21 (exposed) 0.28 (control and exposed) UCS and E_d: 0.90 (control) 0.79 (exposed) 0.80 (control and exposed)
Rutherford (1987), Rutherford *et al.* (1987)	Longitudinal stress wave (perpendicular to grain)	Small, clear Douglas-fir specimens	Brown-rot fungi (*Gloeophyllum trabeum*)	C, E_d	Compression perpendicular to grain	E_c, UCS	E_c and C, 0.91 E_c and E_d, 0.94 UCS and C, 0.67-0.70 UCS and E_d, 0.79 UCS and MOE, 0.80
Patton-Mallory and De Groot (1989)	Longitudinal stress wave	Small, clear southern yellow pine specimens	Brown-rot fungi (*Gloeophyllum trabeum*)	C, root mean square Voltage frequency Content of received signal	Bending	Maximum moment, alkali solubility	Linear decrease in C and decrease in signal strength with increased wood degradation High-frequency components of signal attenuated in very early stages of decay.
Ross *et al.* (1992)	Longitudinal stress wave (perpendicular to grain)	Red oak and white oak lumber	Bacteria (*Clostridium* and *Erwinia* sp.)	C	None	Presence of infection	Decrease in C with presence of infection
Verkasalo *et al.* (1993)	Longitudinal stress wave (perpendicular to grain)	Red oak lumber	Bacteria (*Clostridium* and *Erwinia* sp.)	C	Tension perpendicular to grain	UTS, presence of infection	Decrease in C and UTS with presence of infection

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[a] AE, acoustic emission; C, speed of sound; E_c, modulus of elasticity (MOE) from static compression test; E_d, dynamic MOE from transverse vibration or stress wave measurements; MOR, modulus of rupture; UCS, ultimate compressive stress; UTS, ultimate tensile stress.

2.3 Longitudinal stress wave nondestructive evaluation of standing trees

A summary of research studies conducted to examine the use of longitudinal stress waves for evaluating standing trees is shown in Table 4.

Table 4. Summary of past research on nondestructive evaluation of standing trees using longitudinal stress-wave methods (Pellerin and Ross 2002).

Reference	Tree species	Nondestructive evaluation parameter[a]	Reported properties	Comparison of nondestructive evaluation parameter of trees and reported properties (correlation coefficient *r*)
Nanami *et al.* (1992)	Japanese cedar	ΔT	ΔT in logs	Good agreement (*r* was not reported)
Nanami *et al*. (1993)	Japanese cedar	C	MOE$_d$ of trees	0.77
Nakamura (1996)	Todo-fir and larch	C^2	MOE$_d$ of trees	0.94
Wang (1999), Wang *et al*. (2000b)	Western hemlock and Douglas-fir	C	C of small clear specimens	0.83
		MOE$_d$	MOE$_d$ of small clear specimens	0.75
		MOE$_d$	MOE$_s$ of small clear specimens	0.66
		MOE$_d$	MOR of small clear specimens	0.65 (western hemlock) 0.63 (Sitka spruce)
Huang (2000)	Loblolly pine	C	MOE$_v$ of lumber	0.71
Ikeda and Kino (2000)	Japanese cedar	C	MOE$_d$ of logs	0.56
Ikeda and Arima (2000)	Japanese cedar	C	MOE$_d$ of log	0.61-0.68
		C	MOE$_s$ of square timber	0.64
Ikeda *et al*. (2000b)	Japanese cedar	C	MOE$_d$ of logs	0.56
		C	Mean MOE$_d$ of logs	0.74-0.94
Ikeda *et al*. (2000a)	Hinoki	C	MOE$_d$ of logs	0.64-0.80
Wu *et al*. (2000)	Douglas-fir	C$_L$	MOE$_v$ of lumber	0.88
		C$_R$	MOE$_v$ of lumber	0.62
		C$_L^2$ C$_R^2$	MOE$_v$ of lumber	0.93
Wang *et al*. (2001b)	Western hemlock and Sitka spruce	C	C of small clear specimens	0.83
		MOE$_d$	MOE$_d$ of small clear specimens	0.75
		MOE$_d$	MOE$_s$ of small clear specimens	0.66
		MOE$_d$	MOR of small clear specimens	0.65 (western hemlock) 0.63 (Sitka spruce)

[a] ΔT, wave propagation time; C, C$_L$, stress wave speed in longitudinal direction; C$_R$, stress wave speed in radial direction; MOE$_d$, dynamic modulus of elasticity determined by stress wave method; MOE$_v$, modulus of elasticity determined by transverse vibration method; MOE$_s$, modulus of elasticity obtained from static bending tests; MOR, modulus of rupture obtained from static bending tests.

Of particular significance are the results of a study conducted by Wang (1999, 2000a). He developed the technique illustrated in Figure 1 and used it to evaluate, in the field, the properties of western hemlock and Sitka spruce trees. His technique utilized two spikes that were inserted into the tree at 45º to the bark surface, one at each end of a 4-ft span. Accelerometers were attached to the spikes using specially designed clamps. One spike was impacted to send the stress wave through the tree. The longitudinal wave propagated along the stem, and its passing sensed by the accelerometers, sending a signal to an oscilloscope (Figure 2). Stress-wave travel time was determined by locating the two starting points in the resulting waveform using the following equation:

$$\Delta t = t_2 - t_1$$

where:

Δt = stress-wave transmission time,

t_1 = time where first waveform rises, and

t_2 = time where second waveform rises

Figure 1. Illustration of stress wave propagation and measurement on side surface of a standing tree.

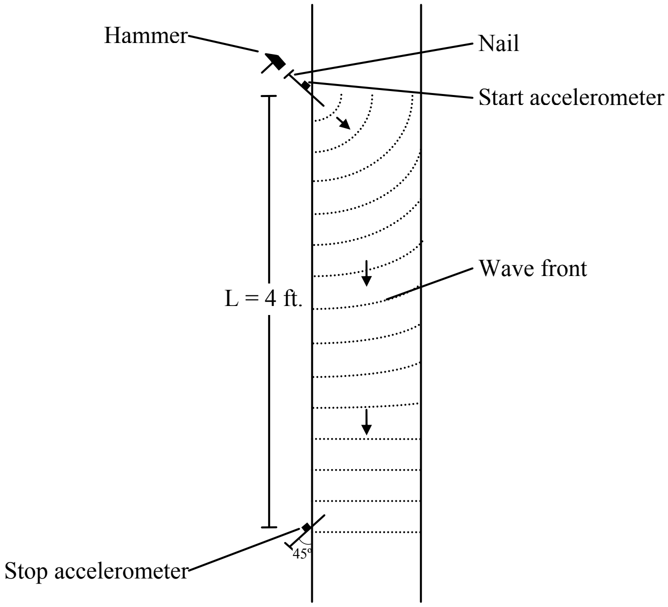
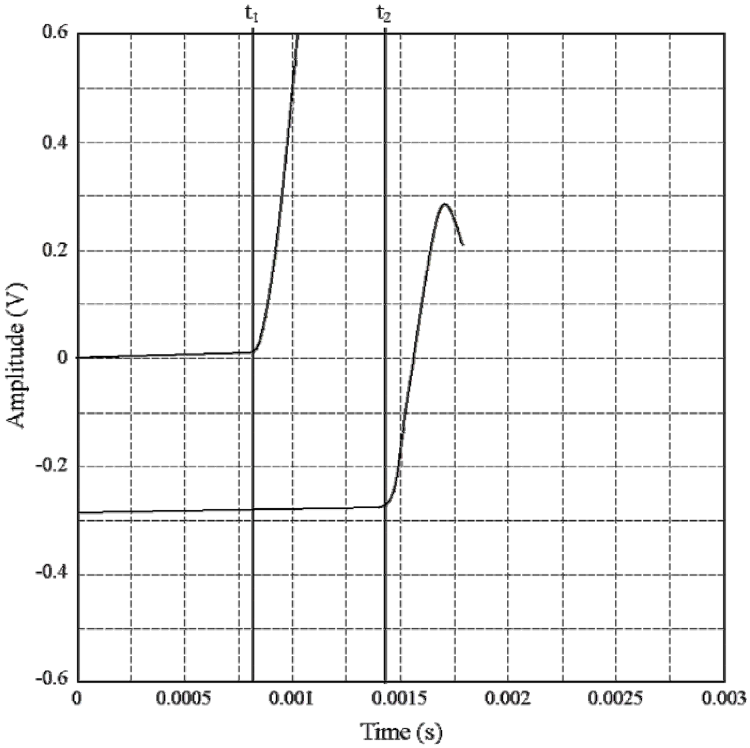


Figure 2. Typical waveforms observed by Wang (1999).



The ultimate goal of Wang's study was to find a nondestructive measurement technique to assess the relative quality of standing trees (Wang 2001a). Realizing that stress wave propagation in a highly anisotropic, heterogeneous material such as wood is very complex, he felt estimates of a material property of a tree may be made by a global treatment of stress wave propagation in the tree. Although the reported values from Wang's study are global estimates, he found that they can provide an indication of quality that can be used to assess the relative value of the wood in a standing tree.

Wang (1999) is notable for several reasons:

1. The study showed strong correlative relationships between *in situ* tree measurements and the properties of clear wood in the trees.
2. Based on his results, a commercially available tool was developed for assessing the mechanical properties of standing trees.

Chapter 3 Objectives

The objective of this study was to build upon the positive results of Wang (1999).

Specific objectives were to:

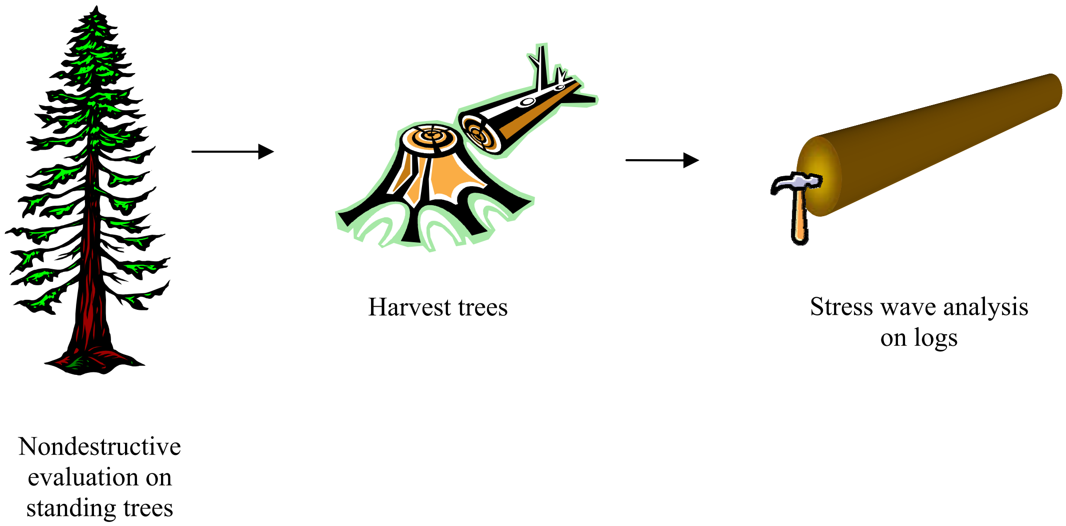
1. Examine the use of stress-wave NDE to assess the quality of wood in standing red pine and ponderosa pine timber.
2. Evaluate the use of the newly developed tool to assess the quality of standing red pine and ponderosa pine timber.

Chapter 4 Methods

4.1 Tree Selection

A diagram that illustrates key components of this study is shown in Figure 3. Sixty red pine (*Pinus resinosa*) trees and 115 ponderosa pine (*Pinus ponderosa*) trees were selected for in-field testing.

Figure 3. Nondestructive testing of trees followed by nondestructive testing of logs.



The red pine trees were on a site located in south central Wisconsin. A photograph of the stand is shown in Figure 4. These trees were planted in a sandy loam soil in the mid 1950’s using a 6’ by 6’ spacing. This stand was first thinned in the 1970’s with the removal of every other row of trees. In 1992, the stand had a basal area of 148 ft^2/acre, with an average DBH of 8.7 inches. At that time, trees were selectively harvested which resulted in residual basal area of 105 ft^2/acre. Before making measurements on the trees, we conducted an initial visual assessment of the site. We noted that the site had 55 rows and 40 columns of trees. Using a random number generator, we randomly selected 60 trees for testing and harvest. DBH for the 60 trees ranged from 7 to 14 inches.

Figure 4. Wisconsin red pine trees (Arena, WI).

A photograph of several ponderosa pine trees used in this study is shown in Figure 5. There trees were located in a stand on the Boise National Forest located approximately six miles southwest of Idaho City, Idaho. The soil type for the stand was sandy loam from decomposed granite. The stand was planted in 1961 with a 6' by 6' spacing and was thinned to a 10' by 10' spacing in 1977. One hundred and fifteen test trees were randomly selected from a two-acre plot for analysis based on diameter classes of 6 to 15-inch DBH (Table 5) Of the one hundred and fifteen test trees, twenty five were tested with the commercial tree testing tool due to time constraints and equipment availability.

Figure 5. Idaho ponderosa pine trees (Boise National Forest, ID).

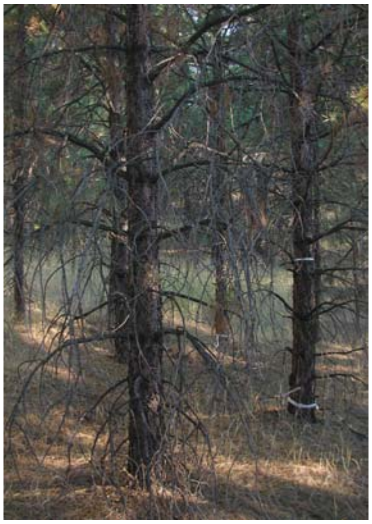


Table 5. Diameter classes of ponderosa pine trees.

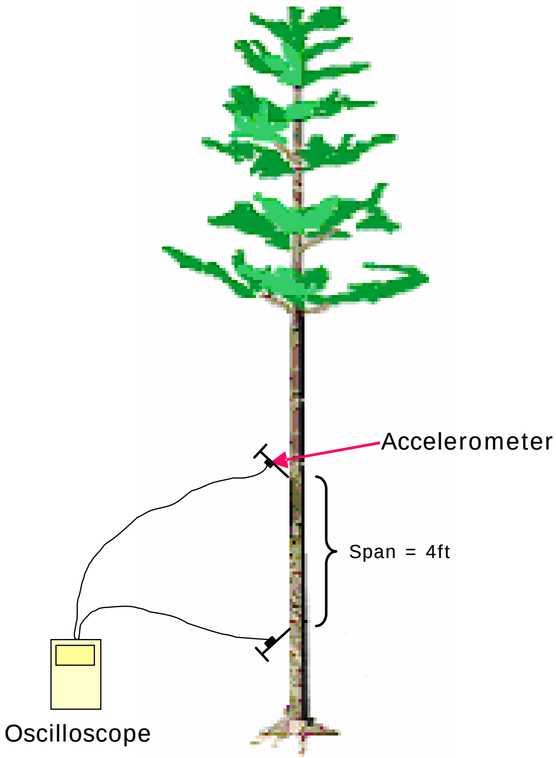
Diameter class (in.)	Number of trees tested
6-8	43
8-10	31
10-12	25
12-15	16

4.2 Experimental Techniques

4.2.1 Laboratory-based equipment

The experimental setup developed by Wang *et al.* (2000b) is shown in Figure 6. The setup consisted of two Columbia Model 3021 accelerometers, two 60-penny spikes, and a Fluke Model DM548810 Scopemeter. The two spikes were embedded into the trunk of a tree at angle of approximately 45º to the trunk's surface with a measured span of 4 feet. Accelerometers were then mounted on the spikes using specially designed clamps, as shown in Figure 7. A stress wave was introduced into the tree so as to flow in the longitudinal direction by impacting the lower spike with a hammer. The resulting signals were received by the start and stop accelerometers and recorded on the oscilloscope (Figure 8). The stress wave

Figure 6. Laboratory-based experimental setup using two probes inserted 45º into tree stem and two accelerometers wired to an oscilloscope.



transmission time was determined by locating the two leading edges of the waveforms.

Figure 7. Accelerometer clamped onto a spike embedded into stem at 45º to grain.

Figure 8. Start and stop signals from accelerometers shown on oscilloscope.

4.2.2 *Commercial tree assessment tool*

Based on the positive results of Wang (1999), fibre-gen (Auckland, New Zealand) undertook an intensive effort to develop a tree assessment tool for field use. They based their design on Wang's (1999) laboratory technique. The resulting tool (Figure 9) consists of transmitting and receiving probes coupled to a PDA via wireless technology. A built-in laser in the receiving probe is aimed at a target on the transmitting probe for alignment purposes. A pulse echo ultrasound system is used to determine the distance between the probes. To determine the quality of the wood, sound waves are induced into the stem by impacting the transmitting probe with a hammer. Stress-wave speed is automatically calculated and shown on the built-in LCD screen on the receiving probe. Infrared data transmission is used to send the information to the PDA.

Figure 9. Setup of commercial tree assessment tool includes specially-designed probes and a PDA for wireless data collection.

4.3 *Harvesting of trees*

All selected ponderosa pine trees were harvested and sixty-nine 8½-ft ponderosa pine butt logs were shipped to the USDA Forest Products Laboratory (FPL) for further analysis. Not all logs were shipped due to transportation constraints. Table 6 shows a summary, by diameter class, of the logs shipped to FPL.

Table 6. Diameter classes of ponderosa pine logs sent to the USDA Forest Products Laboratory (Madison, WI) for further testing.

Diameter class (in.)	Number of logs sent to FPL
6-8	24
8-10	22
10-12	14
12-15	9

Thirty red pine trees were harvested and bucked into 15-ft logs. These logs were then shipped to the FPL for further analysis.

4.4 Laboratory evaluation of logs

Speed of sound transmission for each log was determined using a resonance stress wave technique (Director HM 200, fibre-gen, Auckland, New Zealand). This technique involves impacting one end of the log, and then monitoring the movement of the wave within the log. A schematic diagram that illustrates wave motion in the logs is shown in Figure 10. Upon impact a compression wave is generated and immediately begins moving down the log. As particles at the leading edge of the wave become excited, particles at the trailing edge come to rest. After traveling the length of the log, the wave impinges on the free end of the log and is reflected as a tensile wave traveling back down the log. Photographs illustrating the equipment used to measure log speed of sound values are shown in Figures 11 and 12.

Figure 10. Travel of compression wave along log. The forward-moving wave impinges on the free end of the log, is reflected as a tensile wave, and begins to travel back down the log (Pellerin and Ross 2002).

Figure 11. Log acoustic properties measured with a resonance stress wave technique using the Director HM200.

Figure 12. Determining acoustic properties of red pine logs with Director HM200 (fibre-gen, Auckland, New Zealand).

4.5 Analysis of data

Mathematical correlation models between measurements made with both standing tree measurement techniques were of the following form:

$$y = a + bx$$

where:

y = stress wave speed value for standing tree observed using laboratory equipment (ft/s),

x = stress wave speed value for standing tree observed using commercial tree assessment tool (ft/s),

a = y-intercept of regression line (ft/s), and

b = regression coefficient, or slope of regression line.

Linear regression analysis of the data was used to determine values for a and b.

Similarly, the mathematical regression model between standing tree and log stress wave speed values were of the following form:

$$y = a + bx$$

where:

y = stress wave speed value for standing tree (ft/s),

x = stress wave speed value for log (ft/s),

a = y-intercept of regression line (ft/s), and

b = regression coefficient, or slope of regression line.

Chapter 5 Results and Discussion

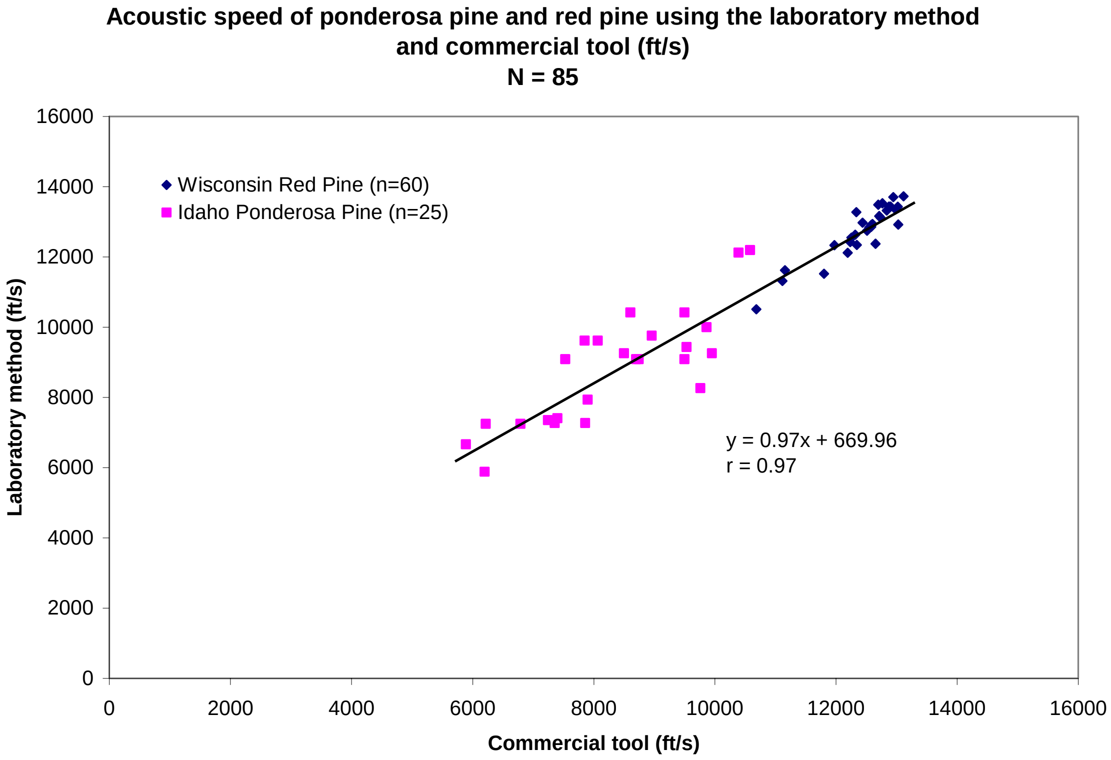
5.1 Statistical relationship between laboratory-based method and commercial tree assessment tool (red pine and ponderosa pine)

The relationship of stress-wave speed in red pine and ponderosa pine trees using measurements from the laboratory-based method and commercial tree assessment tool are represented in Table 7 and Figure 13. Linear correlation analysis was performed, resulting in a regression coefficient of 0.97, indicating a 98% similarity in values of the laboratory method and commercial tree assessment tool. The y-intercept represents the stress wave speed of the laboratory method when the commercial tool has a value of zero, indicating the commercial tool gave stress wave speeds 670 ft/s lower than the laboratory method. Standard error for the data set is 636 ft/s, while the correlation coefficient is 0.97. Linear correlation analysis performed separately on red pine and ponderosa pine data gave regression coefficients of 0.72 and 0.70, and y-intercepts of 3291 ft/s and 2141 ft/s, respectively. Y-intercept values indicate the commercial tool provides stress wave speed values lower than the laboratory method, and according to the regression coefficients, the difference is about 30%. Correlation coefficients and standard error values were 0.93 and 224 ft/s for red pine and 0.83 and 758 ft/s for ponderosa pine. Overall the commercial tool gave stress wave speed values lower than the laboratory method, and there was more variability in ponderosa pine data than red pine data. These variations may be attributed to the following factors: 1) The ponderosa pine trees were tested with the commercial tree assessment tool in its early stages of development. As the tool was refined and optimized, stronger relationships between the commercial tool and the laboratory technique data were found, as were present in the red pine study. 2) For the laboratory-based method, the placement of accelerometers on the spikes could have affected the calculated stress wave speed. The spikes are inserted into the tree four feet apart, where the span measurement is taken at the point where the spike enters the tree. The actual span of the stress wave measurement is the distance between accelerometers, not the distance between spikes. The accelerometers can be clamped anywhere along the length of the spike, causing a discrepancy between the recorded span (the distance between spikes) and the actual span (the distance between accelerometers), thus affecting the calculation of stress wave speed. The commercial tree assessment tool has probes with built-in accelerometers, so the location of the accelerometers on the spike are consistent. Also, a measuring tape is used to measure the span for the laboratory method, while the commercial tool measures the distance between accelerometers using ultrasound, resulting in a more accurate and consistent measurement.

Table 7. Statistical relationship of stress wave speed in red pine and ponderosa pine trees using the commercial tree assessment tool (Y) and laboratory-based technique (X).

		Linear Regression Model: $y = a + bx$			
Series	n	a	b	r	S_{yx}
Red pine	60	3291	0.72	0.93	224
Ponderosa pine	25	2141	0.70	0.83	758

Figure 13. Relationship of stress wave speed in red pine and ponderosa pine trees using the laboratory stress wave method and the commercial tool.



5.2 *Relationship between standing tree and log evaluation (red pine and ponderosa pine)*

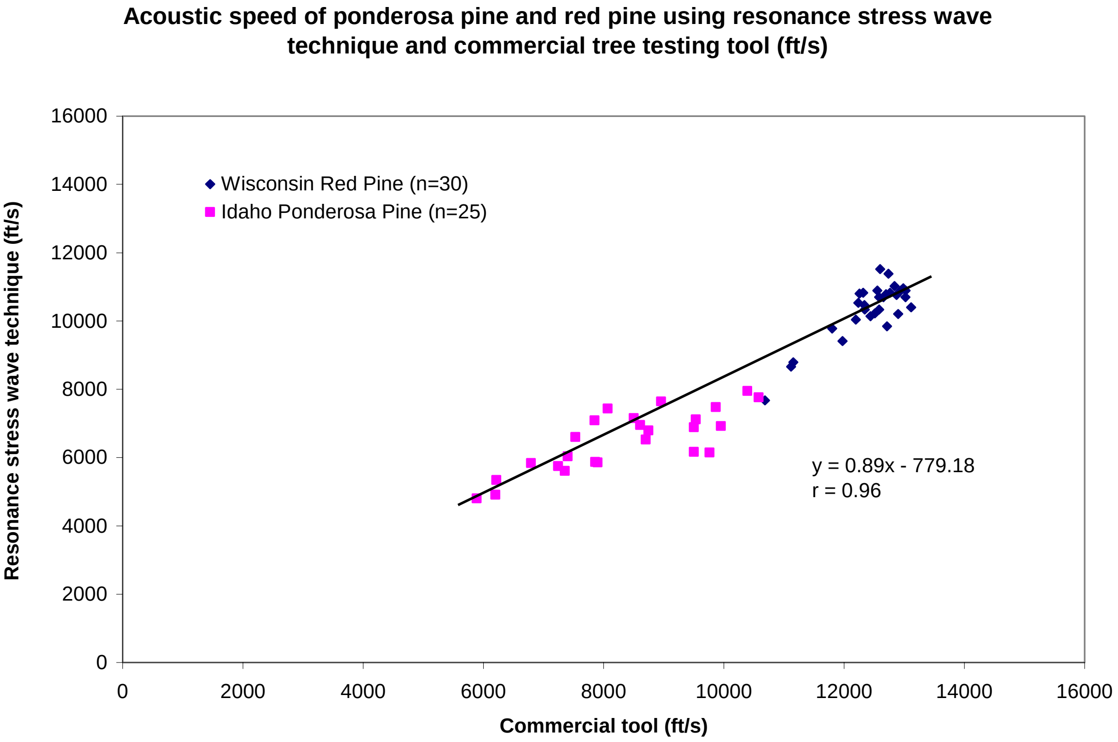
Linear regression analysis was used to analyze the relationship between the stress-wave speed of trees and logs using two different nondestructive evaluation tools (Table 8 and Figure 14). Stress wave speed of trees found using the commercial tree assessment tool were compared to the stress wave speed of logs using the resonance stress-wave tool. Linear regression analysis was performed, resulting in a correlation coefficient of 0.96 and standard error of 604 ft/s for the data set. The regression coefficient is 0.89 and the y-intercept is 779 ft/s, indicating the stress wave speed values of trees are about 10% higher than those of the logs. These data agree with prior studies where stress wave values from logs were lower than those from trees (Wang *et al.* 1999, 2000b, 2001b). The deviation of tree velocity from log velocity may be attributed to these factors: 1) Different wave propagation mechanisms exist for the two different acoustic measurement techniques. According to Wang (2005), stress waves are induced into a tree by indirect impact (through a probe) on the side surface of the trunk, resulting in a dilatational wave through the wood. For logs, stress waves are introduced by a direct impact on the end of the log, resulting in a one dimensional longitudinal wave traveling along the longitudinal axis of the log. Because dilatational waves travel faster than plane waves in materials (Wang 2005), it is plausible that stress waves will travel faster in trees. 2) Stress wave measurements on trees are time-of-flight measurements, where only the first pass of the sound wave is measured. The resonance stress wave technique measures over 150-200 passes of the log length, providing an average of many individual measurements. Principles of statistics state that variation is dependent upon sample size; therefore, there may be more variation in standing tree data. 3) Different measurement techniques may result in varying spans for the two acoustic measurement methods. The probes of the commercially available tree assessment tool must pass through the bark of the tree and into the cambium to effectively emit stress wave signals through the tree. To measure the stress wave speed in logs, the cross-section of the log is impacted directly without having to go through bark and without using a spike to transmit the wave. On the tree measurements, the length between the accelerometer, where the stress wave is sensed, and the cambium of the tree, where the stress wave begins going through wood, may be large enough to affect the stress wave speed of the wood in the tree; whereas for the log measurements, the accelerometer is placed directly on the face of the log, reducing the chance for error in span measurements. 4) The anisotropy of wood may contribute to differences between tree and log stress wave values. When trees are analyzed, the stress wave enters the wood perpendicularly from the side and has to travel through growth rings and layers of xylem before it attains a longitudinal-traveling path. Once it begins traveling along the stem of the tree, it passes through the wood cells more easily because they are oriented in a longitudinal direction.

Knowing that the 10% difference in stress wave speed between trees and logs may be due to wave properties, accelerometer placement, and wood anisotropy, it is concluded that tree stress wave speeds measured with the commercial tree assessment tool strongly correlate with log stress wave speeds. These results suggest that the commercial tree assessment tool gives stress-wave data similar to that of the laboratory-based measurement method, indicating its usefulness as a tool for predicting timber quality.

Table 8. Relationship of stress wave speed in red pine and ponderosa pine trees using the commercial tree assessment tool (Y) and logs using resonance-based stress wave technique (X).

		Linear Regression Model: y = a + bx			
Species	n	a	b	r	S_{yx}
Red pine	30	6129	0.61	0.85	311
Ponderosa pine	25	2146	0.52	0.80	538

Figure 14. Relationship of stress wave speed of trees and logs using data from the commercial tool and the log resonance stress wave technique.



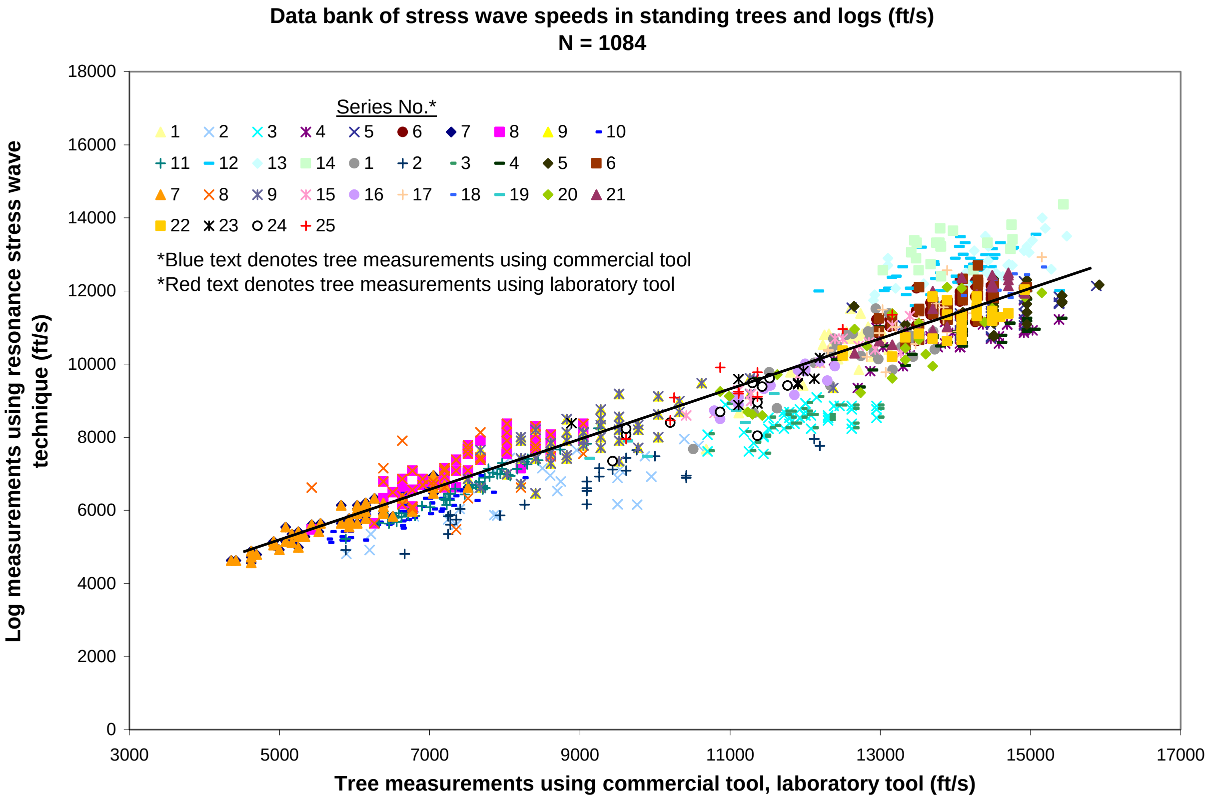
5.3 *Statistical relationship of trees and logs (worldwide data set)*

To this date, numerous studies using the laboratory-based method and commercial tree assessment tool on stress-wave analysis of standing trees have been conducted on trees from ecosystems around the world. Trees from different environments with varying types of soil, moisture, and sunlight will produce wood with different specific gravities, structures, and homogeneity. Stress-wave analysis is applicable for all types of wood and is largely species- and density-independent. Table 9, Figure 15, and Table 10 summarize the results of all standing timber studies available to the author to date. The data found with the commercial tree assessment tool fit on the same regression line as the data found with the laboratory-based method, confirming the predictability of wood quality using the commercial tree assessment tool. Regression information is shown in Table 9 with a correlation coefficient of 0.95 and a regression coefficient of 0.71, indicating an average difference between tree and log values of almost 30%. The y-intercept of 1354 ft/s indicates the values of logs being higher than those of trees.

Table 9. Relationships between stress-wave speed of trees and logs using the commercial tree assessment tool and laboratory-based method for entire data population.

		Linear Regression Model: y = a + bx				
			X: Stress-wave speed of logs using resonance stress-wave technique (ft/s)			
Series	n	Y: Equipment used for stress-wave speed of trees (ft/s)	a	b	r	S_{yx}
All data	1084	Commercial tool and laboratory method	1354	0.71	0.95	768

Figure 15. Data bank of stress-wave analysis on logs and standing trees using the commercial tree assessment tool and laboratory-based method.



Statistical data for each individual series are shown in Table 10 with correlation coefficient values ranging from 0.35 to 0.98, standard errors from 117 to 592 ft/s, and regression coefficient values ranging from 0.24 to 0.99. Some data series have lower correlation coefficients, higher standard errors or smaller regression line slopes for a number of reasons: 1) The commercial tree assessment tool has undergone continual improvement since the first version was created in 2004. Some of the data in this chart were measured with the prototype version of the tool, where problems were found and improvements were made. As the tool was refined, the relationship between tree and log data became stronger. 2) Some data sets have very few data points, as low as six samples. Principles of statistics state that variation is dependent upon sample size, so when the sample size is low, there will be greater variation. Sometimes it is not economically viable for a researcher to use the appropriate amount of samples in a study. For example, the Sitka spruces measured in Alaska were in a temperate rainforest littered with fallen logs and rotten trees; it was a challenge to fell an appropriate number of trees in a limited amount of time. 3) User error can also contribute to data variation. The studies completed in New Zealand, for example, were conducted by different individuals than those in the United States. Each person taking measurements could interpret the data in different ways which could lead to data further variation.

Table 10. Data bank of relationships between stress-wave speed of trees and logs using the commercial tree assessment tool, laboratory-based method, and resonance stress wave technique.

				Linear Regression Model: y = a + bx				
Series No.	Species	Location	n	Y: Equipment used for stress-wave speed of trees (ft/s)[a]	X: Stress-wave speed of logs using resonance stress-wave technique (ft/s)			
					a	b	r	S_{yx}
1	Red pine	Wisconsin	30	Commercial tool	6129	0.61	0.85	311
				Laboratory method	-428	0.84	0.78	524

				Linear Regression Model: y = a + bx				
				Y: Equipment used for stress-wave speed of trees (ft/s)[a]	X: Stress-wave speed of logs using resonance stress-wave technique (ft/s)			
Series No.	Species	Location	n		a	b	r	S_{yx}
2	Ponderosa pine	Idaho	25	Commercial tool	2146	0.52	0.80	538
				Laboratory method	1997	0.51	0.92	342
3	Radiata pine 1	Australia	39	Commercial tool	3871	0.38	0.58	312
				Laboratory method	3881	0.38	0.58	313
4	Radiata pine 2	Australia	39	Commercial tool	4154	0.47	0.71	395
				L	4165	0.47	0.71	396
5	Radiata pine 3	Australia	39	C	8016	0.24	0.34	395
				L	8036	0.24	0.34	396
6	Radiata pine 4	Australia	40	C	2905	0.62	0.61	388
				L	2913	0.62	0.61	389
7	Radiata pine 5	New Zealand	50	C	1513	0.72	0.94	195
				L	1513	0.72	0.94	195
8	Radiata pine 6	New Zealand	50	C	1415	0.77	0.87	342
				L	2710	0.60	0.69	525
9	Radiata pine 7	New Zealand	50	C	2505	0.60	0.79	450
				L	2505	0.60	0.79	450
10	Radiata pine 8	New Zealand	50	C	44	0.87	0.98	116
11	Radiata pine 9	New Zealand	50	C	1311	0.69	0.90	217
12	Douglas fir A	Oregon	45	C	6432	0.44	0.53	424
13	Douglas fir B	Oregon	26	C	5666	0.50	0.68	419
14	Douglas fir C	Oregon	20	C	6297	0.49	0.60	401
15	Sitka spruce	Alaska	15	L	-457	0.86	0.94	298
16	Western hemlock	Alaska	15	L	-172	0.82	0.89	235
17	Jack pine	Michigan	18	L	-112	0.83	0.73	544
18	White birch	Michigan	9	L	-724	0.88	0.88	247
19	Ponderosa pine	Oregon	6	L	1281	0.66	0.93	297
20	Slash pine A	Louisiana	25	L	422	0.76	0.85	591
21	Slash pine B	Louisiana	24	L	-2300	0.99	0.87	345
22	Loblolly pine	Louisiana	26	L	2246	0.64	0.75	356
23	Red oak 1	Missouri	10	L	4385	0.44	0.83	305
24	Red oak 2	Missouri	11	L	1389	0.68	0.81	457
25	Red oak 3	Missouri	10	L	-785	0.92	0.94	382

[a] C, commercial tool; L, Laboratory method

Chapter 6 Conclusions

Based on the results of this study, the following conclusions can be made:

1. The commercial tree assessment tool provides values similar to those of the laboratory-based method, demonstrating the commercial tree assessment tool's usefulness in determining the quality of standing timber.
2. Stress-wave measurement values from standing trees are similar to those from logs. Log values can be predicted from standing tree values indicating that standing timber quality can be accurately and reliably measured with stress-wave analysis.
3. The data collected in this study correlate with the worldwide standing timber data bank, confirming the usefulness of stress wave analysis across a range of tree species and ecosystems.

Based on these results, it is concluded that the commercial tree assessment tool is useful in determining the quality of standing trees. This research can be expanded on by using the commercial tree assessment tool to test trees from sites of different thinning and pruning regimes, using stress-wave analysis to establish forest quality and to help make future management decisions.

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Appendix

Appendix A. Supply list for testing standing trees

Tree Testing Supply List	
Director ST300	**Scopemeter**
The night before:	**The night before:**
☐Charge PDA	
☐Arrange/gas vehicle	☐ Arrange/gas vehicle
Bring:	**Bring:**
☐Voltmeter	☐Voltmeter
☐Extra Batteries (AA)	☐Extra Batteries (C)
☐Tape measure	☐Tape measure
☐Director case	☐Scopemeter case
☐Wrenches	☐Hammer
☐Director	☐Scopemeter
☐Hammer	☐Spikes
☐Wires for computer	☐Extra wires
☐Thermometer	☐Extra accelerometer
☐Orange vests	☐Orange vests
☐Crayon for marking trees	☐Crayon for marking trees
☐Spray paint	☐Spray paint
☐Tree marking tape	☐Tree marking tape
☐Pencils	☐Pencils
☐Write-in-rain paper	☐Write-in-rain paper

Appendix B. Data sheet for tree measurements

Crew ___________ Location ____________

Date ___________ Temperature ____________

Tree	DBH (in)	Stress Wave Readings (usec)					Span (ft)	Note
		1	2	3	Average	ft/µs		
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
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19								
20								
21								
22								
23								
24								
25								
26								

Appendix C. Data sheet for stress wave log measurements.

Crew ______________________________

Date ______________________________

Log #	Diameters (in)			Length (ft)	Weight (lb)	Density (lb/ft^3)	Stress Wave Times (µsec)				Speed (ft/s)	Note
	Top	Center	Butt				1	2	3	Average		
1												
2												
3												
4												
5												
6												
7												
8												
9												
10												
11												
12												
13												
14												
15												
16												
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18												
19												
20												
21												
22												
23												
24												

Red Pine; Arena, Wisconsin

Standing tree assessment																
				Director ST300 (1/24/05)								Scopemeter (1/24/05)				
				Distance												
Tree	Row	Column	DBH (in.)	in.	ft	1	2	3	average	SWS (ft/s)	SWS (µs/ft)	1	2	3	SWS (ft/s)	SWS (µs/ft)
1	1	4	12.9	45.2	3.8	337	341	335	338	11155	89.65	324	324	324	11626	86.02
2	1	9	12.9	50.8	4.2	327	325	332	328	12907	77.48	312	312	320	13453	74.33
3	1	24	9.7	47.8	4.0	357	359	359	358	11116	89.96	352	352	352	11316	88.37
4	1	35	9.0	48.5	4.0	347	347	342	345	11704	85.44	332	332	332	12174	82.14
5	3	10	10.8	52.9	4.4	356	354	362	357	12337	81.06	332	332	332	13278	75.31
6	3	34	10.5	48.5	4.0	329	329	333	330	12235	81.73	324	324	328	12423	80.49
7	5	4	11.9	52.9	4.4	352	348	351	350	12583	79.47	344	344	336	12915	77.43
8	5	14	10.1	52.1	4.3	329	327	325	327	13277	75.32	312	312	312	13916	71.86
9	5	22	10.6	50.8	4.2	336	336	337	336	12587	79.45	332	328	328	12854	77.80
10	5	28	11.6	46.3	3.9	296	300	303	300	12875	77.67	292	292	292	13213	75.68
11	7	11	11.5	49.7	4.1	309	307	300	305	13564	73.72	304	304	304	13624	73.40
12	8	24	11.0	50.1	4.2	335	331	328	331	12601	79.36	320	320	320	13047	76.65
13	9	5	10.3	51.8	4.3	339	343	338	340	12696	78.76	320	320	320	13490	74.13
14	9	16	11.2	50.1	4.2	339	338	338	338	12340	81.04	320	320	320	13047	76.65
15	10	18	10.4	47.0	3.9	289	287	288	288	13600	73.53	280	280	280	13988	71.49
16	11	30	9.4	52.6	4.4	334	341	339	338	12968	77.11	324	324	324	13529	73.92
17	13	18	10.1	49.7	4.1	313	310	313	312	13275	75.33	308	304	304	13564	73.72
18	15	15	12.1	46.9	3.9	310	311	316	312	12513	79.91	308	308	304	12745	78.46
19	15	25	10.2	48.4	4.0	319	314	321	318	12683	78.84	308	308	308	13095	76.36
20	16	8	9.2	51.1	4.3	327	332	328	329	12943	77.26	308	312	312	13707	72.95
21	16	9	10.0	53.3	4.4	347	348	343	346	12837	77.90	332	332	336	13325	75.05
22	16	12	11.3	47.5	4.0	318	317	316	317	12487	80.08	312	312	316	12633	79.16
24	21	26	8.2	47.6	4.0	317	308	311	312	12714	78.66	304	300	300	13164	75.97
25	21	31	9.0	50.0	4.2	336	341	343	340	12255	81.60	332	332	332	12550	79.68
26	23	10	11.1	45.0	3.8	310	309	297	305	12282	81.42	288	292	292	12901	77.51
27	24	10	10.3	47.8	4.0	339	329	342	337	11832	84.52	336	336	336	11855	84.35
28	25	17	10.4	48.8	4.1	327	328	330	328	12386	80.74	316	316	320	12815	78.03
29	26	31	9.8	51.2	4.3	335	335	335	335	12736	78.52	328	324	324	13115	76.25
30	27	26	10.2	48.3	4.0	303	297	309	303	13284	75.28	296	296	296	13598	73.54
31	29	11	10.1	49.3	4.1	309	310	314	311	13210	75.70	316	312	316	13056	76.59
32	31	13	10.2	52.1	4.3	333	335	332	333	13025	76.78	336	336	336	12922	77.39
33	31	24	9.7	47.8	4.0	307	309	312	309	12877	77.66	304	300	304	13161	75.98
34	31	28	9.8	50.5	4.2	332	333	328	331	12714	78.65	316	316	316	13318	75.09
35	31	40	9.8	51.8	4.3	335	336	335	335	12873	77.68	324	320	320	13434	74.44
36	32	20	9.0	44.1	3.7	292	290	293	292	12600	79.37	284	284	284	12940	77.28
37	32	26	10.4	51.6	4.3	331	334	335	333	12900	77.52	320	320	320	13438	74.42
38	35	29	10.8	52.5	4.4	325	322	317	321	13615	73.45	304	304	308	14329	69.79
39	36	15	11.9	47.2	3.9	303	306	302	304	12953	77.20	300	304	304	12996	76.95
40	37	7	10.5	47.5	4.0	321	318	319	319	12396	80.67	312	312	316	12633	79.16
41	38	24	11.8	48.7	4.1	312	314	312	313	12980	77.04	308	300	304	13350	74.91
42	40	3	9.6	51.7	4.3	321	323	325	323	13338	74.97	316	324	316	13520	73.97
43	40	17	9.6	46.0	3.8	345	338	342	342	11220	89.13	336	340	340	11319	88.35
44	40	28	12.1	49.3	4.1	329	331	322	327	12551	79.68	320	320	320	12839	77.89
45	41	7	9.4	47.4	4.0	322	317	321	320	12344	81.01	324	320	316	12344	81.01
46	41	10	9.4	51.4	4.3	330	331	330	330	12967	77.12	312	316	316	13612	73.46
47	42	11	9.9	49.0	4.1	310	316	314	313	13032	76.73	316	308	308	13144	76.08
48	43	39	10.5	46.9	3.9	322	317	313	317	12316	81.19	312	308	308	12635	79.15
49	44	7	9.8	49.9	4.2	334	325	327	329	12652	79.04	336	336	336	12376	80.80
50	44	14	12.3	46.2	3.9	305	306	295	302	12748	78.44	300	296	292	13007	76.88
51	45	22	12.8	44.8	3.7	318	312	319	316	11802	84.73	324	324	324	11523	86.79
52	46	4	10.3	46.1	3.8	295	303	305	301	12763	78.35	284	284	284	13527	73.93
53	46	8	11.3	47.7	4.0	304	302	310	305	13019	76.81	296	296	296	13429	74.47
54	46	10	10.0	47.0	3.9	298	296	302	299	13114	76.26	284	284	288	13727	72.85
55	46	40	11.2	47.9	4.0	324	330	328	327	12195	82.00	336	328	324	12120	82.51
56	47	9	10.7	47.0	3.9	299	301	305	302	12983	77.02	296	292	292	13352	74.89
57	49	37	13.7	45.4	3.8	319	316	313	316	11973	83.52	304	304	312	12337	81.06
58	50	2	12.6	49.2	4.1	332	326	331	330	12437	80.41	316	316	316	12975	77.07
59	52	16	12.9	46.3	3.9	309	300	311	307	12582	79.48	300	300	300	12861	77.75
60	53	32	7.4	44.4	3.7	346	346	347	346	10683	93.60	352	352	352	10511	95.14
61			12.7	50.0	4.2	314	318	321	318	13116	76.24	312	312	312	13355	74.88

Appendix D. Raw Data.

Red Pine; Arena, Wisconsin

	Log assessment (2/9/05)									
	Dimensions (in)					Volume (in^3)	Weight (lb)	Average Density (lb/ft^3)	Director HM SWS	
Tree	Butt	Center	Top	Diameter	Radius				ft/s	µs/ft
1	42.75	37.00	31.50	11.78	5.89	19609	551	48.55	8793	113.73
3	31.75	27.75	23.50	8.83	4.42	11030	301	47.15	8661	115.46
5	33.75	31.25	30.00	9.95	4.97	13988	384	47.44	10466	95.55
6	33.25	28.25	26.50	8.99	4.50	11431	342	52.15	11188	89.38
7	38.50	35.50	31.25	11.30	5.65	18052	487	46.62	10335	96.76
13	32.75	29.25	27.00	9.31	4.66	12255	379	53.44	10783	92.74
18	38.00	33.50	31.50	10.66	5.33	16075	498	53.53	10225	97.80
20	29.50	27.25	27.00	8.67	4.34	10636	309	50.20	10892	91.81
21	32.75	28.50	26.50	9.07	4.54	11635	426	63.27	11024	90.71
24	34.50	30.00	27.00	9.55	4.77	12892	346	46.38	9843	101.60
25	29.50	25.25	25.00	8.04	4.02	9132	265	50.14	10800	92.59
29	27.75	25.25	23.75	8.04	4.02	9132	250	47.30	11385	87.83
32	32.25	29.50	27.50	9.39	4.70	12465	376	52.12	10892	91.81
35	31.00	28.00	26.25	8.91	4.46	11230	333	51.24	10761	92.93
36	28.75	27.00	25.00	8.59	4.30	10442	334	55.27	11516	86.84
37	32.50	30.25	28.00	9.63	4.81	13107	360	47.46	10203	98.01
44	31.71	35.95	41.13	11.44	5.72	18515	499	46.57	10892	91.81
45	32.50	27.25	25.25	8.67	4.34	10636	306	49.71	10335	96.76
48	34.50	30.75	28.50	9.79	4.89	13544	396	50.52	10827	92.36
49	27.75	25.00	23.00	7.96	3.98	8952	254	49.03	10696	93.49
51	41.25	38.75	31.50	12.33	6.17	21508	337	27.07	9777	102.28
52	36.50	37.50	30.25	11.94	5.97	20143	510	43.75	10761	92.93
53	36.00	32.00	30.00	10.19	5.09	14668	438	51.60	10696	93.49
54	33.00	29.50	28.50	9.39	4.70	12465	382	52.95	10400	96.15
55	38.25	32.25	30.25	10.27	5.13	14898	432	50.11	10039	99.61
56	34.50	30.25	28.75	9.63	4.81	13107	384	50.62	10958	91.26
57	47.25	39.25	39.00	12.49	6.25	22067	631	49.41	9416	106.20
58	41.25	35.50	31.00	11.30	5.65	18052	545	52.17	10138	98.64
59	41.50	37.50	33.75	11.94	5.97	20143	559	47.95	10696	93.49
60	24.50	19.50	16.25	6.21	3.10	5447	174	55.20	9285	107.70

Appendix D. Raw Data.

Ponderosa Pine; Boise National Forest, Idaho (9/9/04-9/11/04)

		Speed (ft/s)					
				Director HM			
Tree No.	DBH (in.)	Scopemeter	Director ST	1	2	3	Avg.
14	14.6	10417	8605	7021	6923	6923	6956
15	11.3	12195	10580	7776	7776	7776	7765
26	11.5	9615	7850	7152	7054	7054	7087
30	9.6	9091	9500	12336	12336	12336	6168
31	9.2	9756	8956	7644	7644	7644	7644
32	7.8	8264	9762	12303	12303	12303	6152
38	9.6	7407	7400	12073	12073	12073	6037
39	9.1	7937	7900	11745	11745	11680	5862
47	12.6	10417	9500	6923	6923	6824	6890
49	7.2	5882	6200	9843	9843	9810	4916
50	9.1	6667	5890	9580	9646	9580	4808
53	8.5	9615	8067	7448	7448	7415	7437
56	6.6	9259	9950	6923	6923	6923	6923
69	12.3	12121	10390	7940	7940	7972	7951
88	11.4	10000	9864	7480	7480	7480	7480
92	10.0	9091	8700	6529	6529	6529	6529
99	6.6	7353	7242	5774	5741	5741	5752
100	7.5	9434	9532	7119	7119	7119	7119
101	8.2	9091	8744	6791	6791	6791	6791
102	7.6	9259	8500	7152	7152	7152	7152
103	7.9	7273	7858	5873	5873	5873	5873
106	6.9	7273	7354	5676	5577	5577	5610
111	6.8	7246	6790	11680	11680	11680	5840
113	7.9	9091	7529	6398	6398	6398	6605
115	8.0	7246	6216	5348	5348	5348	5348

Red Oak; Iron County, Missouri

		Tree assessment (laboratory method)		Log assessment (Director HM 200)						
				Log length			Stress wave speed (µs/ft)			
Tree No.	DBH (in.)	Stress wave time (µs)	wave speed (µs/ft)	in.	ft	in.	1	2	3	Average
Red Oak 1 - Doe Run Buick, age 30 years; July 13, 2004										
A- 1	8.4	450	112.5	129.75	10	10	8432	8366	8366	8388
A- 2	6.5	352	88.0	122.50	10	3	9482	9482	9482	9482
A- 3	6.5	334	83.5	102.00	8	6	9810	9810	9810	9810
A- 4	7.6	336	84.0	126.00	10	6	9449	9449	9449	9449
A- 5	7.9	360	90.0	125.50	10	6	8858	8858	8924	8880
A- 6	7	352	88.0	121.50	10	2	8924	8924	8924	8924
A- 7	7.1	328	82.0	124.75	10	5	10171	10171	10171	10171
A- 8	6.5	360	90.0	126.50	10	7	9580	9613	9580	9591
A- 9	6.4	330	82.5	122.50	10	3	9744	9744	9318	9602
A- 10	7	336	84.0	124.50	10	5	9482	9482	9482	9482
A- 11	5.8	376	94.0							
A- 12	7.7	384	96.0							
A- 13	7.3	336	84.0							
A- 14	6.2	344	86.0							
A- 15	7.1	376	94.0							
A- 16	6.1	336	84.0							
A- 17	7	336	84.0							
A- 18	7.8	346	86.5							
A- 19	7.6	350	87.5							
A- 20	7.3	338	84.5							
A- 21	7.1	336	84.0							
A- 22	8.1	352	88.0							
A- 23	7.3	344	86.0							
A- 24	7.9	328	82.0							
A- 25	7.3	330	82.5							
A- 26	6.6	320	80.0							
A- 27	6.9	352	88.0							
A- 28	5.6	360	90.0							
A- 29	7.3	350	87.5							
A- 30	6.7	344	86.0							
Red Oak 2 - B-Day, age 60+ years; July 14, 2004										
A- 31	11.6	347	86.8	126.50	10	7	9613	9613	9613	9613
A- 32	9	340	85.0	128.00	10	8	9416	9416	9416	9416
A- 33	9.1	376	94.0							
A- 34	10.6	416	104.0	127.50	10	8	8235	8235	8235	8235
A- 35	9.1	350	87.5	128.75	10	9	9383	9383	9383	9383
A- 36	10.1	368	92.0							
A- 37	10.5	360	90.0							
A- 38	11.3	360	90.0							
A- 39	6.3	372	93.0							
A- 40	10.1	416	104.0	127.25	10	7	8071	8071	8071	8071
A- 41	12	360	90.0							
A- 42	9.8	380	95.0							
A- 43	9.6	368	92.0							
A- 44	6.5	352	88.0	125.50	10	6	8038	8038	8038	8038
A- 45	7.7	370	92.5							
A- 46	9.9	364	91.0							
A- 47	8.1	352	88.0	126.25	10	6	8957	8957	8957	8957
A- 48	7.2	376	94.0							
A- 49	7.7	368	92.0	127.00	10	7	8694	8694	8694	8694
A- 50	10	360	90.0							
A- 51	7.9	424	106.0	128.00	10	8	7349	7349	7349	7349
A- 52	10.5	364	91.0							
A- 53	5.9	390	97.5							
A- 54	8.1	352	88.0							
A- 55	8.2	380	95.0							
A- 56	8	360	90.0							
A- 57	9.5	368	92.0							

Red Oak; Iron County, Missouri

		Tree assessment (laboratory method)		Log assessment (Director HM 200)						
Tree No.	DBH (in.)	Stress wave time (µs)	wave speed (µs/ft)	Log length			Stress wave speed (µs/ft)			
				in.	ft	in.	1	2	3	Average
A- 58	9.8	360	90.0							
A- 59	8.9	354	88.5	126.50	10	7	9482	9482	9482	9482
A- 60	9.9	392	98.0	127.25	10	7	8399	8399	8399	8399
Red Oak 3 - Logan, July 15, 2004										
A- 61	10	392	98.0							
A- 62	11.3	384	96.0							
A- 63	11.2	336	84.0							
A- 64	13.1	320	80.0	127.50	10	8	10958	10958	10958	10958
A- 65	7.7	336	84.0							
A- 66	12.8	368	92.0							
A- 67	12	390	97.5	127.50	10	8	9088	9088	9088	9088
A- 68	6.7	360	90.0	128.75	10	9	9383	8825	9383	9197
A- 69	10.1	360	90.0	126.25	10	6	9252	9252	9252	9252
A- 70	11.3	368	92.0							
A- 71	8.9	376	94.0							
A- 72	8.8	352	88.0	127.50	10	8	9088	9088	9154	9110
A- 73	11.1	376	94.0							
A- 74	8	336	84.0							
A- 75	10.5	334	83.5							
A- 76	10.3	416	104.0	130.00	10	10	7907	7972	7972	7950.3
A- 77	9.4	352	88.0	129.00	10	9	9777	9777	9777	9777
A- 78	9.5	320	80.0							
A- 79	11.9	328	82.0							
A- 80	11.2	336	84.0							
A- 81	9.2	368	92.0	120.50	10	7	9908	9908	9908	9908
A- 82	10.2	328	82.0							
A- 83	9.1	392	98.0	128.50	10	9	8465	8465	8465	8465
A- 84	9.2	328	82.0							
A- 85	9.5	304	76.0	128.00	10	8	11352	11352	11352	11352
A- 86	10.3	344	86.0							
A- 87	8.4	344	86.0							
A- 88	8.7	368	92.0							
A- 89	10.5	380	95.0							
A- 90	8.2	376	94.0							

Appendix D. Raw Data.

Radiata Pine; Australia

Radiata Pine 1				Radiata pine 2			
	Velocity (ft/s)				Velocity (ft/s)		
Tree No.	Scopemeter	ST 300	HM 200	Tree No.	Scopemeter	ST 300	HM 200
1	12985	12951	8530	41	14952	14913	11221
2	12652	12619	8858	42	14952	14913	11975
3	11748	11718	8235	43	14952	14913	11155
5	12985	12951	8760	44	14098	14061	10466
6	11748	11718	8596	45	14098	14061	10564
7	11475	11445	8005	46	14098	14061	10925
8	12336	12303	8465	47	14512	14475	10696
9	10727	10699	8071	48	13336	13301	9941
10	10965	10936	8891	49	14098	14061	11089
11	12035	12003	8596	50	14098	14061	10761
12	12985	12951	8858	52	14098	14061	10466
13	12652	12619	8366	53	14098	14061	10860
14	10727	10699	7612	54	13706	13670	10761
15	11214	11185	8137	55	14098	14061	11746
16	12035	12003	8694	56	15419	15379	11221
17	11748	11718	8694	57	14952	14913	10860
18	11475	11445	8038	58	12985	12951	10991
19	12108	12077	8596	59	14952	14913	10925
20	12652	12619	8760	60	13899	13863	11155
21	11542	11512	8530	61	13336	13301	10400
22	12035	12003	8924	62	14952	14913	11746
23	11818	11788	8694	63	12413	12381	10105
24	12183	12151	9088	64	14620	14582	10564
25	11962	11931	8760	65	13706	13670	10696
26	11610	11580	8301	66	14620	14582	10761
27	12413	12381	8858	67	12733	12700	9351
28	12652	12619	8235	68	14729	14691	11089
29	11890	11859	8366	69	11343	11313	9580
30	11542	11512	8235	70	14729	14691	11089
31	11278	11249	7612	71	13899	13863	10564
32	11818	11788	8366	72	13998	13961	10860
33	11343	11313	7841	73	12900	12866	9810
34	12492	12459	8858	74	13802	13766	10466
35	11962	11931	8530	75	13899	13863	11155
36	11818	11788	8530	76	13899	13863	11516
37	11475	11445	7546	77	13426	13391	10236
38	12108	12077	8235	78	15066	15027	10925
39	12336	12303	8530	79	13071	13037	10466
40	12336	12303	8596	80	14406	14369	11089

Radiata Pine; Australia

Radiata pine 3				Radiata pine 4			
	Velocity (ft/s)				Velocity (ft/s)		
Tree No.	Scopemeter	ST 300	HM 200	Tree No.	Scopemeter	ST 300	HM 200
81	14098	14061	10893	121	14512	14475	11188
82	12652	12619	11549	122	14098	14061	11319
83	15419	15379	11844	123	14952	14913	12074
84	14952	14913	11778	124	14098	14061	11844
86	15419	15379	11844	125	13518	13483	10630
87	13336	13301	11057	126	13706	13670	11418
88	14952	14913	11385	127	13518	13483	11418
89	13706	13670	11549	128	12985	12951	11221
90	14512	14475	10761	129	13336	13301	10499
91	15419	15379	11647	130	13706	13670	11483
92	14512	14475	11155	131	14302	14265	12271
93	14952	14913	11614	132	13518	13483	12074
94	15419	15379	11680	133	14302	14265	12205
95	14952	14913	12271	134	13518	13483	11057
96	14952	14913	11385	135	14302	14265	11844
97	14512	14475	12074	136	14512	14475	11910
98	14512	14475	11450	137	13899	13863	11647
99	15419	15379	11680	138	14512	14475	11778
100	15917	15875	12139	139	13899	13863	11450
101	14512	14475	11910	140	14512	14475	11221
102	14512	14475	10729	141	14302	14265	12664
103	14952	14913	11385	142	14302	14265	11155
104	14098	14061	10827	143	13158	13124	11024
105	14952	14913	11057	144	14098	14061	12303
106	14512	14475	11549	145	13518	13483	11483
107	14512	14475	11647	146	13706	13670	11352
108	14098	14061	11778	147	14512	14475	12139
109	14512	14475	11385	148	12985	12951	10860
110	14512	14475	12008	149	13158	13124	11221
111	14098	14061	11778	150	13899	13863	11221
112	14098	14061	11155	151	13899	13863	11188
113	14512	14475	11549	152	14098	14061	11713
114	14512	14475	11319	153	14098	14061	11975
115	14512	14475	11089	154	14302	14265	12205
116	14512	14475	11910	155	14512	14475	11811
117	14098	14061	11319	156	13899	13863	11385
118	14512	14475	12303	157	13706	13670	11680
119	14098	14061	11385	158	14098	14061	11811
120	14098	14061	10761	159	14302	14265	12139
				160	13706	13670	11483

Radiata Pine; New Zealand

Radiata Pine 5				Radiata Pine 6				Radiata Pine 7			
	Velocity (ft/s)				Velocity (ft/s)				Velocity (ft/s)		
Tree No.	Scopemeter	ST 300	HM 200	Tree No.	Scopemeter	ST 300	HM 200	Tree No.	Scopemeter	ST 300	HM 200
1	4623	4623	4560	51	7510	7510	7776	101	9045	9046	7776
2	5249	5249	4987	52	6769	6769	6562	102	9776	9776	8333
3	6147	6148	6201	53	7510	7510	7087	103	9045	9046	8137
4	6508	6508	5840	54	8408	8408	8301	104	8214	8214	6726
5	6147	6148	5774	55	8027	8027	7612	105	8214	8214	7415
6	5546	5546	5643	56	7350	7351	7382	106	11264	11264	9613
7	5249	5249	5413	57	7510	7510	7677	107	9521	9521	8563
8	6636	6636	6332	58	7197	7197	6627	108	8408	8408	7415
9	6147	6148	6135	59	8408	8408	8071	109	9278	9278	8760
10	5926	5926	5643	60	7510	7510	7546	110	9045	9046	7907
11	5338	5338	5282	61	7675	7676	7448	111	7675	7676	6627
12	6035	6035	6037	62	8027	8027	8137	112	8214	8214	7907
13	4919	4920	5053	63	7197	7197	6923	113	10044	10044	9121
14	4919	4920	5151	64	7197	7197	7152	114	10325	10325	8990
15	6769	6769	5971	65	6508	6508	6496	115	10044	10044	8629
16	5926	5926	5709	66	6769	6769	6037	116	8824	8824	7415
17	7510	7510	6627	67	7350	7351	7087	117	10622	10622	9482
18	7049	7049	6956	68	8408	8408	7776	118	8824	8824	8137
19	6035	6035	6135	69	8027	8027	7907	119	8611	8612	7841
20	5429	5429	5610	70	6906	6907	6693	120	9521	9521	9187
21	6147	6148	5971	71	6636	6636	6857	121	8611	8612	7579
22	5522	5522	5413	72	8611	8612	7480	122	9278	9278	8333
23	5080	5080	5151	73	8027	8027	8366	123	7675	7676	7644
24	6383	6384	6102	74	9045	9046	7907	124	7510	7510	6857
25	7197	7197	6693	75	6636	6636	6398	125	9521	9521	7907
26	6035	6035	5643	76	6383	6384	6791	126	8408	8408	6463
27	6263	6264	6332	77	6769	6769	7087	127	10325	10325	8694
28	6147	6148	6201	78	6906	6907	6857	128	8214	8214	7415
29	5926	5926	5774	79	8611	8612	8071	129	8824	8824	8498
30	6035	6035	5906	80	7049	7049	6693	130	9045	9046	8137
31	7049	7049	6627	81	6769	6769	6102	131	8824	8824	7513
32	5820	5821	6135	82	7197	7197	7087	132	10044	10044	8005
33	5926	5926	5709	83	6906	6907	6693	133	12373	12373	9351
34	5249	5249	5282	84	7197	7197	6627	134	9278	9278	8498
35	5163	5164	5118	85	8611	8612	7841	135	9278	9278	8005
36	4999	4999	4921	86	8408	8408	7677	136	8408	8408	8202
37	6383	6384	5906	87	7049	7049	6791	137	8824	8824	7907
38	7049	7049	6463	88	6263	6264	5643	138	8027	8027	6988
39	5080	5080	5545	89	9045	8027	7546	139	8214	8214	8005
40	5926	5926	5545	90	9045	9046	8366	140	8214	8214	7415
41	5163	5164	5348	91	7675	9046	8137	141	8611	8612	7284
42	5080	5080	5151	92	7675	7676	7382	142	9278	9278	7710
43	6383	6384	6201	93	6636	7676	7907	143	9521	9521	7349
44	4355	4355	4626	94	6636	6636	6168	144	9521	9521	8202
45	6383	6384	5971	95	5429	6636	6627	145	9776	9776	8202
46	4623	4623	4889	96	7350	5429	5479	146	9045	9046	8137
47	5820	5821	5643	97	8214	7351	6627	147	9776	9776	7710
48	4623	4623	4724	98	6383	8214	7152	148	9521	9521	8333
49	4419	4420	4626	99	7510	6384	6332	149	8824	8824	8498
50	4694	4694	4790	100	6897	7510	7021	150	11264	11264	9187

Radiata Pine; New Zealand

Radiata Pine 8			Radiata Pine 9					
	Velocity (ft/s)			Velocity (ft/s)			Velocity (ft/s)	
Tree	ST 300	HM 200	Tree	ST 300	HM 200	Tree	ST 300	HM 200
151	6614	5578	201	8298	7260	247	7939	7005
152	6942	6595	202	7741	6614	248	6805	5850
153	5919	5414	203	8075	6942	249	9245	8247
154	5823	5414	204	6587	5919	250	7215	6281
155	6083	5709	205	6626	5823	251	8298	7260
156	6986	5906	206	7007	6083	252	7741	6614
157	6892	6103	207	7899	6986	253	8075	6942
158	6596	5971	208	7733	6892	254	6587	5919
159	7143	6037	209	7340	6596	255	6626	5823
160	7372	6562	210	7783	7143	256	7007	6083
161	7662	6956	211	8445	7372	257	7899	6986
162	7410	6529	212	8737	7662	258	7733	6892
163	7326	6398	213	8307	7410	259	7340	6596
164	6693	5742	214	8263	7326	260	7783	7143
165	6121	5184	215	7615	6693	261	8445	7372
166	5809	5282	216	6897	6121	262	8737	7662
167	5222	4922	217	6439	5809	263	8307	7410
168	6454	5643	218	5879	5222	264	8263	7326
169	6619	5709	219	7273	6454	265	7615	6693
170	5921	5250	220	7565	6619	266	6897	6121
171	6663	6168	221	6715	5921	267	6439	5809
172	7293	6135	222	7707	6663	268	5879	5222
173	5850	5217	223	7964	7293	269	7273	6454
176	5660	5118	224	7704	6623	270	6715	5921
177	6272	5643	225	6321	5660	271	7707	6663
178	6673	5906	226	7264	6272	272	7964	7293
179	6918	6332	227	7526	6673	273	7565	6619
180	5688	5414	228	7795	6918			
181	6570	6267	229	6561	5688			
182	6435	5611	230	7707	6570			
183	6676	5971	231	7466	6435			
184	7136	6332	232	7664	6676			
185	5808	5184	233	7963	7136			
186	6623	5512	234	6550	5808			
187	7128	5971	235	7564	6623			
188	7038	6037	236	8165	7128			
189	7608	6267	237	7839	7038			
190	5640	5217	238	8573	7608			
191	6460	5643	239	6456	5640			
192	6318	5676	240	7248	6460			
193	5874	5184	241	7188	6318			
194	6975	6332	242	6714	5874			
195	6148	5873	243	8046	6975			
196	7823	6496	244	7224	6148			
197	6774	5807	245	9089	7823			
198	7005	6201	246	7659	6774			

Appendix D. Raw Data.

Douglas fir; Oregon

Slash Pine; Louisiana

Velocity (ft/s)						Velocity (ft/s)			
Douglas fir A		Douglas fir B		Douglas fir C		Slash Pine A		Slash Pine B	
ST 300	HM 200	ST 300	HM 200	ST 300	HM 200	ST 300	HM 200	ST 300	HM 200
13463	11600	14631	12400	14760	13416	11429	8596	12658	10302
14758	13156	14915	13100	13476	12894	11299	8629	13158	10531
13052	12008	14140	12500	14241	12566	11236	8694	12987	10630
14202	12566	15485	13500	13672	12730	10989	9121	13333	10892
14200	12894	14151	12200	13810	12402	12739	9219	13514	10925
14500	12894	13579	12200	13036	12566	10870	9252	13699	10925
12182	12000	14419	12500	13804	13222	13158	9613	13889	11024
13346	11900	15278	12600	13511	12566	11628	9711	14085	11122
13668	11900	14400	13500	13415	13058	13699	9941	14085	11220
14104	13000	14953	13222	13971	13648	13333	10116	14085	11319
13715	12800	15196	13714	13810	13222	13605	10269	13699	11516
14189	12666	12928	11900	15440	14370	13333	10433	14286	11909
13724	12730	14982	13058	14429	13320	12821	10499	14286	11909
13800	12500	13101	12894	14736	13156	13514	10674	14925	11942
14000	12894	13205	12073	13454	13386	12658	10958	13699	11992
13800	12008	12909	11745	13798	13714	14085	11056	14493	12106
14600	13320	15029	13386	13749	13322	13514	11122	14706	12139
13300	12664	14716	12730	14750	13812	14388	11155	14493	12139
14300	12336	14436	12828	13487	13320	13158	11385	14493	12205
14240	12730	14540	12500	13790	13320	14493	11395	14706	12303
13719	11680	14694	12700			14493	11527	14085	12369
15388	12008	14251	13100			14925	11833	14706	12434
14341	12566	15156	14000			15152	11953	14493	12434
14052	13222	14439	13222			14085	12073	14706	12500
13212	12402	14757	12700			13889	12106		
14032	12238	13101	12700						
14530	12992								
13803	12336								
14006	12402								
14309	12828								
14778	13189								
13734	12336								
14367	12664								
14403	12992								
14481	12664								
14373	12664								
14494	13156								
13110	12073								
14196	12238								
15073	13550								
13400	12073								
14069	13484								
14130	13320								
13156	12372								
13550	13196								

Alaska, Michigan, Oregon and Louisiana data

Velocity (ft/s)					
Sitka spruce; Alaska		Western Hemlock; Alaska		White birch; Michigan	
ST 300	HM 200	ST 300	HM 200	ST 300	HM 200
11905	9678	12000	10007	14545	12019
11111	9285	10870	8497	15152	12653
10417	8596	11450	9318	14760	12467
13393	11319	11538	9416	14706	11920
12397	10696	12195	10072	14925	12445
12848	10597	12000	9875	14085	11874
12712	10499	12295	9547	14493	12314
12500	10696	11858	9154	13468	11002
13158	11056	12000	9810	14706	11822
12195	10039	12397	9941		
11278	9186	11029	9088		
12931	10400	11111	9088		
11278	8990	11905	9843		
13274	10302	11111	8891		
10791	8661	10791	8727		
Jack Pine; Michigan		Ponderosa pine; Oregon		Loblolly pine; Louisiana	
ST 300	HM 200	ST 300	HM 200	ST 300	HM 200
13468	10553	11080	8734	13158	10203
13201	11013	11204	8403	13158	10203
13072	9777	9132	7424	12500	10236
13514	11188	11587	9191	12500	10367
13514	10827	9639	7899	13889	10630
12987	10849	9901	7474	14085	10663
14235	11395			13699	10696
13746	11658			13333	10728
15152	12927			13514	10827
13889	10871			14085	10860
12308	10368			14085	11024
12308	10389			14493	11188
13889	12566			14085	11286
13841	11242			14599	11286
12821	10203			14286	11319
14035	10892			14085	11319
13841	11549			13889	11352
13029	11494			14706	11385
				14706	11385
				14493	11450
				14286	11483
				14286	11549
				13889	11745
				14286	11844
				13699	11844
				14925	12041