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# Strength and Stiffness Assessment of Standing Trees Using a Nondestructive Stress Wave Technique


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## Abstract

Nature's engineering of wood through genetics, stand conditions, and environment creates wide variability in wood as a material, which in turn introduces difficulties in wood processing and utilization. Manufacturers sometimes find it difficult to consistently process wood into quality products because of its wide range of properties. The primary objective of this study was to investigate the usefulness of a stress wave technique for evaluating wood strength and stiffness of young-growth western hemlock and Sitka spruce in standing trees. A secondary objective was to determine if the effects of silvicultural practices on wood quality can be identified using this technique. Stress wave measurements were conducted on 168 young-growth western hemlock and Sitka spruce trees. After *in situ* measurements, a 2-ft- (0.61-m-) long bole section in the test span was taken from 56 felled trees to obtain small, clear wood specimens. Stress wave and static bending tests were then performed on these specimens to determine strength and stiffness. Results of this study indicate that *in situ* stress wave measurements could provide relatively accurate and reliable information that would enable nondestructive evaluation of wood properties in standing trees.

The mean values of stress wave speed and dynamic modulus of elasticity for trees were in good agreement with those determined from small, clear wood specimens. Statistical regression analyses revealed strong relationships between stress wave properties of trees and static bending properties of small, clear wood specimens obtained from the trees. Regression models showed statistical significance at the 0.01 confidence level. Results of this study also demonstrate that the effect of silvicultural practices on wood properties can be identified with the stress wave properties of trees. This indicates that this nondestructive stress wave technique can be used to track property changes in trees and help determine how forests could be managed to meet desired wood and fiber qualities.


Keywords: nondestructive evaluation, standing trees, stress wave, wood strength, wood stiffness

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# Strength and Stiffness Assessment of Standing Trees Using a Nondestructive Stress Wave Technique

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## Introduction

Our forests are an extremely valuable resource. In addition to wildlife habitat and aesthetic and recreational purposes, forests serve as a renewable source of raw material for an ever-increasing list of wood and fiber products. Nature's engineering of wood through genetics, weather, and environment creates wide variability in wood as a material, which in turn introduces numerous difficulties in wood processing and utilization. Manufacturers sometimes argue that wood is difficult to consistently process into quality products because of the wide range of properties in this raw material. Users of wood products can be equally frustrated with the performance variability found in finished products.

Nondestructive evaluation (NDE) technology has contributed considerably toward eliminating these frustrations. In the forest products industry, NDE technology has been developed and is now used in structural product grading programs that result in engineered material with well-defined performance characteristics. Currently, there is a strong interest in developing and using new, cost-effective NDE technology to evaluate wood quality in standing trees. One NDE technique, which uses stress wave propagation characteristics, has received considerable attention. Stress-wave-based NDE techniques have been investigated extensively during the past few decades and have shown promise for predicting the mechanical properties of wood materials. Several wood and wood-based materials, including small, clear wood specimens, lumber, veneer, and wood-based composites, have been investigated. Recent research has focused on determining whether stress wave techniques could be used to determine the quality of logs. Several studies have shown a good relationship ($R^2$ = 0.44 to 0.89) between the stress-wave-based modulus of elasticity (MOE) of logs and the static MOE of lumber cut from logs (Aratake and others 1992, Aratake and Arima 1994, Arima and others 1990, Koizumi and others 1997a,b, Ross and others 1997, Sandoz and Lorin 1994).

Although research efforts have paved the way for the successful use of NDE with various wood materials, little effort has been extended to develop NDE techniques for use in grading or sorting trees for structural quality. Existing tree grading procedures in the United States consist of only visual assessments of tree quality (Green and McDonald 1998). These procedures do not incorporate MOE estimates of the wood in a tree. It is questionable whether the visual grading procedures currently used for trees adequately assess the potential quality of structural products to be manufactured from them, especially those in which MOE is of primary concern. It is expected that relating the MOE of wood in trees to lumber MOE holds great promise for improving the ability to select mature trees that have superior potential for the production of structural products. Considerable savings in material and processing costs could be realized if nondestructive tree sorting technology, based on anticipated final product quality, can be achieved. The addition of NDE techniques to visual assessment procedures could also ease industrial adaptation to a changing resource base that may result from increasing emphasis on ecological forest management.

The primary objective of this study was to investigate the usefulness of a stress wave technique for evaluating wood strength and stiffness of young-growth western hemlock and Sitka spruce in standing trees. A secondary objective was to examine whether the effect of silvicultural practices on wood quality can be identified using this technique.

# Fundamental Hypothesis

Stress wave propagation in wood is a dynamic process that is internally related to the physical and mechanical properties of wood. Several different types of waves can propagate in wood structures, such as longitudinal waves, shear waves, and surface (Rayleigh) waves. Of these waves, longitudinal waves travel fastest and are the most commonly used to evaluate wood properties. An in-depth examination of using longitudinal stress wave NDE technology with wood products is included in Ross and Pellerin (1994).

Two fundamental material properties are measured with longitudinal stress wave techniques: energy storage and energy dissipation. Energy storage is manifested as the speed at which a wave travels in a material. In contrast, the rate at which a wave attenuates is an indication of energy dissipation. Jayne (1959) hypothesized that these properties are controlled by the same mechanisms that determine the static behavior of such material. As a consequence, useful mathematical relationships between these properties and static elastic and strength behaviors should be attainable through statistical regression analysis.

This fundamental hypothesis has been successfully verified on clear wood, lumber products, wood-based composites, and logs using various stress wave techniques (Jayne 1959, Kaiserlik and Pellerin 1977, Pellerin 1965, Ross and Pellerin 1988, Ross and others 1997). However, the validity of this hypothesis on standing trees has not been tested. Compared with finished wood products, standing trees tend to have variable external and boundary conditions that greatly limit the application of stress wave techniques. Current stress wave methods for wood property evaluation are limited to wood members with a simple boundary condition, where one end of the material (in longitudinal direction) is usually accessible. Therefore, these methods are not adaptable to trees. In this study, we used a newly developed approach to conduct stress wave testing in standing trees (Wang and others, in press). A stress wave was induced into the tree in such a manner that it flowed primarily along the stem of the tree. We hypothesized that the characteristics of the resulting wave would be related to the mechanical properties of wood in the tree.

# Materials and Methods

The study sites selected were from the permanent plots of a stand density study, which are distributed across southeast Alaska in 59 installations. Trees, 84 western hemlock and 84 Sitka spruce (168 total), were selected from seven different sites. The stands were roughly 15, 20, 25, and 45 years old at the time of precommercial thinning and covered an unthinned control plot and three other plots that had received light, medium, or heavy thinning. These thinning treatments were performed to simulate a range of forest management practices. The ages of the stands ranged from 38 to 70 years old. From each plot, three western hemlock and three Sitka spruce trees that had diameters close to quadratic mean diameters were sampled. *In situ* stress wave testing was conducted on all selected trees. After field tests, 56 trees, one for each species in every thinning plot, were felled. A 2-ft- (0.61-m-) long bole section in the test span was cut from each felled tree, wrapped in plastic, and shipped to the Institute of Wood Research at Michigan Technological University (MTU) in Houghton, Michigan. The sections were then cut into small, clear specimens for further stress wave and destructive evaluation.

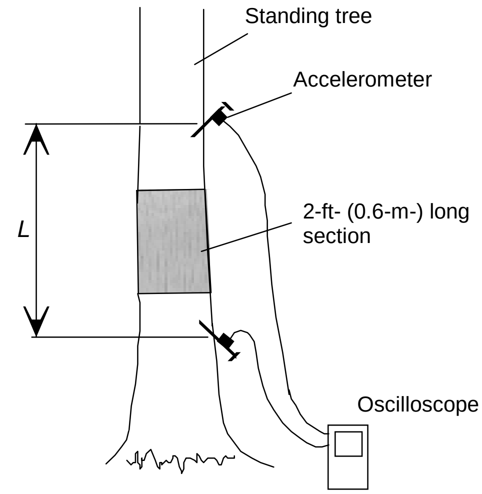


**Figure 1—Experimental setup used in field test (*L* = test span).**

## *In situ* Evaluation

A surface-attaching method was used to conduct *in situ* stress wave measurements in this study. The experimental setup consisted of two accelerometers, two spikes, a hand-held hammer, and a portable digital oscilloscope (Fig. 1). Two spikes were imbedded in the tree trunk at about 45° to the trunk surface, one spike at each end of the section to be assessed. Accelerometers were mounted on the spikes using two specially designed clamps.

A stress wave was introduced into the tree in the longitudinal direction by impacting the lower spike with the hand-held hammer. The resulting signals were received by start and stop accelerometers and recorded on an oscilloscope.

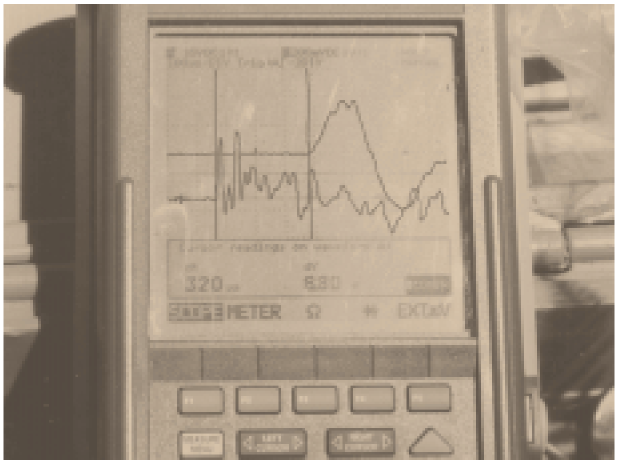

**Figure 2—Typical stress waveforms observed in a field test.**

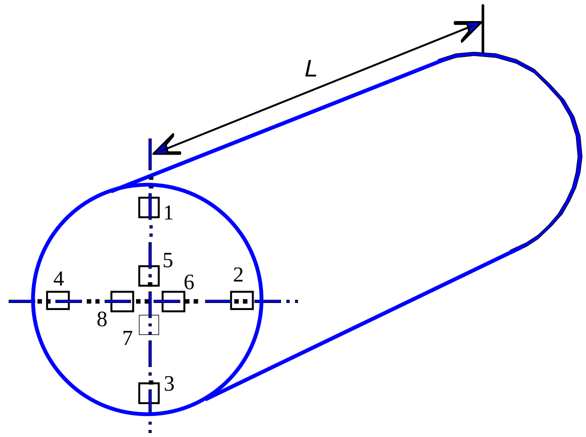


**Figure 3—Cutting pattern for small, clear wood specimens.**

Figure 2 shows typical stress waveforms observed for the trees. The stress wave transmission time was determined by locating the two leading edges of these waveforms. Stress wave speed (SWS) was then calculated by dividing the test span *L* by the measured stress wave transmission time *t*. Dynamic modulus of elasticity ($MOE_d$) was determined using a one-dimensional wave equation ($MOE_d = SWS^2\rho$, where $\rho$ is wood density). A span of 4 ft (1.22 m) was found to produce good readings and rapid measurements. Therefore, this span was used for all tree testing. The *in situ* stress wave tests were approximately centered across the 2-ft (0.61-m) section previously described.

## Laboratory Evaluation

After completion of *in situ* stress wave testing on the trees, the 56 bole sections cut from felled trees were shipped to MTU. All sections were still in a green state upon arrival. Eight 1- by 1- by 16-in. (25- by 25- by 406-mm) small, clear wood specimens were then cut from each section for additional stress wave and destructive evaluation of wood strength (MOR) and stiffness (MOE) (Fig. 3). For some sections, eight specimens were not obtained due to the small diameter of the bole section. In this case, two- to seven-specimens were cut from the bole section.

An experimental technique reported by Ross and others (1994) was used to obtain stress wave properties from the specimens. Static bending tests (destructive) were then performed on these specimens with a SATEC Universal Testing Machine (Satec Systems, Inc., Grove City, Pennsylvania). These tests were conducted according to ASTM D 143 (ASTM 1988), with the exception that a loading rate of 0.15 in/min (3.81 mm/min) was used rather than 0.05 in/min (1.27 mm/min) because of the large number of specimens and lack of available machine time. An average value from all eight (or fewer) specimens was assumed to be the average property of the section and was used for comparison with the MOE values obtained from the stress wave measurements on the standing trees.

After arriving at MTU, each 2-ft (0.61-m) section was weighed with a platform scale. Density was determined from the bulk weight and volume of the sections. This density and the SWS obtained from the field were used to determine $MOE_d$ of the standing trees. The green density of the small, clear wood specimens obtained from bole sections was also determined and used in stress wave evaluation of the specimens. Following each static bending test, a 1- by 1- by 1-in. (25- by 25- by 25-mm) sample was immediately cut, near the failure, from each specimen. Moisture content (MC) and dry density–specific gravity were then determined by the ovendry method.

# Results and Discussion

## Physical Characteristics

Physical characteristics of the stands and destructively sampled trees are given in Table 1. The diameter at breast height of trees ranged from 3.7 to 14.8 in. (94 to 375 mm) for western hemlock and 3.2 to 21 in. (82 to 533 mm) for Sitka spruce. The tree heights varied from 37.1 to 98.4 ft (11.3 to 30.0 m) for western hemlock and 34.4 to 131.2 ft (10.5 to 40.0 m) for Sitka spruce. The average MC of western hemlock was 78.1% for heartwood and 132.9% for sapwood. The average MC for Sitka spruce was 59.2% for heartwood and 156.4% for sapwood. Note that for both species, the MC of sapwood was much greater than that of heartwood. Specific gravity ranged from 0.64 to 0.96 for western hemlock and from 0.61 to 0. 89 for Sitka spruce.

The effect of bark on stress wave propagation needs to be accounted for in the procedures to conduct *in situ* stress wave tests. The thickness of the bark may change with location along the stem. For both western hemlock and Sitka spruce,

**Table 1—Physical characteristics of stands and destructively sampled trees**

| | | | | Western hemlock[b] | | | | | Sitka spruce[b] | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Moisture content (%) | | | | | Moisture content (%) | |
| Site | Plot | Thinning treatment[a] | Stand age (years) | DBH (in.) | Height (ft) | SG (green) | Heart-wood | Sap-wood | DBH (in.) | Height (ft) | SG (green) | Heart-wood | Sap-wood |
| Harris River | 1071 | Control | 38 | 6.9 | 65.9 | 0.72 | 43.2 | 90.8 | 9.9 | 73.5 | 0.76 | 67.8 | 147.1 |
| | 1050 | Light | | 8.9 | 71.5 | 0.74 | 88.9 | 108.0 | 10.4 | 77.7 | 0.73 | 42.9 | 173.9 |
| | 1060 | Medium | | 11.0 | 65.0 | 0.83 | 85.1 | 141.6 | 14.0 | 73.2 | 0.74 | 44.1 | 181.3 |
| | 1080 | Heavy | | 10.0 | 62.1 | 0.77 | 90.4 | 146.6 | 16.6 | 80.7 | 0.71 | 40.1 | 178.9 |
| Thorne River | 24CT | Control | 70 | 9.6 | 81.4 | 0.68 | 36.6 | 95.1 | 17.7 | 138.5 | 0.71 | 56.4 | 98.5 |
| | 1910 | Light | | 11.6 | 97.3 | 0.75 | 49.8 | 86.7 | 19.7 | 124.3 | 0.70 | 45.2 | 93.4 |
| | 1890 | Medium | | 12.2 | 88.3 | 0.72 | 34.4 | 129.6 | 18.7 | 127.6 | 0.68 | 65.8 | 107.4 |
| | 1900 | Heavy | | 14.8 | 105.0 | 0.64 | 53.8 | 138.9 | 21.0 | 131.2 | 0.67 | 55.5 | 182.4 |
| Alder Creek | 1730 | Control | 63 | 9.1 | 96.5 | 0.80 | 51.3 | 89.2 | 12.2 | 105.3 | 0.77 | 78.1 | 167.5 |
| | 1740 | Light | | 10.6 | 93.2 | 0.76 | 44.1 | 105.7 | 13.7 | 104.7 | 0.76 | 42.1 | 181.1 |
| | 1760 | Medium | | 12.7 | 97.6 | 0.75 | 57.7 | 119.1 | 14.6 | 107.6 | 0.76 | 46.4 | 152.1 |
| | 1750 | Heavy | | 13.3 | 106.3 | 0.73 | 59.8 | 157.3 | 16.7 | 107.7 | 0.74 | 84.1 | 181.8 |
| Tuxekan | 1481 | Control | 50 | 8.0 | 72.7 | 0.84 | 41.6 | 137.8 | 11.4 | 96.9 | 0.73 | 59.8 | 126.4 |
| | 1470 | Light | | 8.6 | 83.7 | 0.95 | 91.3 | 106.9 | 13.0 | 99.5 | 0.69 | 60.5 | 188.6 |
| | 1450 | Medium | | 11.0 | 76.6 | 0.76 | 106.8 | 159.4 | 14.4 | 95.3 | 0.61 | 40.3 | 139.0 |
| | 1460 | Heavy | | 11.5 | 73.8 | 0.89 | 42.0 | 116.6 | 15.6 | 88.4 | 0.69 | 49.2 | 154.4 |
| Port Alice | 1211 | Control | 42 | 4.1 | 46.2 | 0.91 | | 149.6 | 5.4 | 61.6 | 0.82 | 40.4 | 120.0 |
| | 1190 | Light | | 7.6 | 62.7 | 0.85 | 80.9 | 153.6 | 8.9 | 70.1 | 0.74 | 49.6 | 197.1 |
| | 1180 | Medium | | 6.0 | 45.7 | 0.85 | 180.5 | 192.6 | 6.3 | 41.1 | 0.86 | 59.8 | 159.9 |
| | 1200 | Heavy | | 9.4 | 63.6 | 0.85 | 124.1 | 160.8 | 13.4 | 72.5 | 0.72 | 75.5 | 228.6 |
| Shrubby Island | 2021 | Control | 49 | 3.9 | 43.0 | 0.80 | | 110.3 | 5.6 | 48.5 | 0.79 | 36.2 | 125.7 |
| | 2010 | Light | | 8.0 | 61.8 | 0.87 | 90.4 | 156.3 | 9.2 | 71.3 | 0.74 | 86.4 | 159.3 |
| | 2040 | Medium | | 10.4 | 61.7 | 0.89 | 110.4 | 159.3 | 12.0 | 67.2 | 0.76 | 63.4 | 177.5 |
| | 2030 | Heavy | | 11.2 | 63.4 | 0.88 | 132.0 | 146.3 | 11.7 | 65.8 | 0.83 | 88.8 | 158.8 |
| Thomas Bay | 2061 | Control | 38 | 3.7 | 36.9 | 0.93 | | 90.6 | 3.2 | 34.5 | 0.89 | | 98.4 |
| | 2070 | Light | | 6.9 | 45.3 | 0.89 | 41.4 | 181.7 | 5.6 | 58.1 | 0.86 | 71.1 | 148.2 |
| | 2050 | Medium | | 8.2 | 47.2 | 0.96 | 118.3 | 166.5 | 7.6 | 52.2 | 0.86 | 67.4 | 161.5 |
| | 2080 | Heavy | | 8.9 | 49.7 | 0.83 | 97.8 | 124.2 | 10.1 | 57.5 | 0.79 | 82.2 | 190.2 |

[a]Light, medium, and heavy thinning treatments correspond roughly to 8- by 8-, 12- by 12-, and 16- by 16-ft spacing.
[b]DBH, diameter at breast height of trees; SG, specific gravity; 1 in. = 25.4 mm, 1 ft = 0.3048 m.

thickness of the bark at breast height ranged from 0.16 to 0.28 in. (4 to 7 mm). In the *in situ* stress wave measurements, the spikes used to mount the accelerometers were pounded into the trunk about 0.75 to 1.25 in. (19 to 32 mm), which was deep enough to go through the bark. We believe that this procedure eliminated or minimized the effect of bark on stress wave measurement.

## Stress Wave Properties

Stress wave properties obtained from trees and small, clear specimens are tabulated in Table 2. In trees, the measured SWS ranged from 9,016 to 13,698 ft/s (2,748 to 4,175 m/s) for western hemlock and 9,787 to 13,858 ft/s (2,983 to 4,224 m/s) for Sitka spruce. The average value for Sitka spruce was about 5% greater than that for western hemlock. In the specimens, the measured SWS ranged from 8,241 to 12,461 ft/s (2,512 to 3,798 m/s) for western hemlock and 8,714 to 13,215 ft/s (2,656 to 4, 028 m/s) for Sitka spruce. The average value for Sitka spruce was about 6% greater than that for western hemlock. For both species, the average SWS measured in trees was very close to that measured in the small, clear specimens. We observed that the average speed in trees was only 2.5% greater than that in small, clear samples for western hemlock and only 1.2 % greater for Sitka spruce. Statistical analyses indicated no significant difference between the mean SWS in trees and that in small, clear specimens.

**Table 2—Stress wave and mechanical properties of western hemlock and Sitka spruce**

| Property[a] | Western hemlock | | | | Sitka spruce | | | |
|---|---|---|---|---|---|---|---|---|
| | Mean | Standard deviation | Min. | Max. | Mean | Standard deviation | Min. | Max. |
| | | | | Tree | | | | |
| SWS (ft/s) | 11,066 | 1,147 | 9,016 | 13,698 | 11,575 | 982 | 9,787 | 13,858 |
| $MOE_d$ ($\times 10^6$ lb/in$^2$) | 1.37 | 0.292 | 1.00 | 2.02 | 1.41 | 0.255 | 1.01 | 1.97 |
| | | | | Small, clear specimen | | | | |
| SWS (ft/s) | 10,801 | 1,099 | 8,241 | 12,461 | 11,437 | 1,070 | 8,714 | 13,215 |
| $MOE_d$ ($\times 10^6$ lb/in$^2$) | 1.35 | 0.22 | 0.97 | 1.89 | 1.39 | 0.225 | 0.95 | 1.84 |
| $MOE_s$ ($\times 10^6$ lb/in$^2$) | 1.07 | 0.24 | 0.6 | 1.69 | 0.99 | 0.214 | 0.53 | 1.59 |
| MOR (lb/in$^2$) | 6,729 | 1,040.90 | 4,660 | 10,640 | 5,323 | 922.4 | 3,297 | 7,490 |

[a]SWS, stress wave speed; $MOE_d$, dynamic modulus of elasticity determined by stress wave method; $MOE_s$, static modulus of elasticity determined by static bending test; MOR, modulus of rupture; 1 ft/s = 0.3048 m/s, 1 lb/in$^2$ = 6.894 kPa.

From *in situ* measurements, $MOE_d$ ranged from 1.00 to $2.02 \times 10^6$ lb/in$^2$ (6.89 to 13.93 GPa) for western hemlock and 1.01 to $1.97 \times 10^6$ lb/in$^2$ (6.96 to 13.58 GPa) for Sitka spruce. For small, clear specimens, $MOE_d$ ranged from 0.97 to $1.89 \times 10^6$ lb/in$^2$ (6.69 to 13.03 GPa) for western hemlock and 0.95 to $1.84 \times 10^6$ lb/in$^2$ (6.55 to 12.68 GPa) for Sitka spruce. Average $MOE_d$ for Sitka spruce was 3% greater than that for western hemlock. For both species, the average $MOE_d$ determined from *in situ* measurements was in good agreement with that obtained from small, clear specimens. Compared with the $MOE_d$ of small, clear specimens, the $MOE_d$ of trees increased about 1.5% for both species. Statistical comparison analyses indicated no significant differences between the mean $MOE_d$ of trees and the mean $MOE_d$ of small, clear specimens.

## Static Bending Properties

Results from static bending tests indicated that the static modulus of elasticity ($MOE_s$) ranged from 0.60 to $1.69 \times 10^6$ lb/in$^2$ (4.14 to 11.65 GPa) for western hemlock and 0.53 to $1.59 \times 10^6$ lb/in$^2$ (3.65 to 10.96 GPa) for Sitka spruce. The average $MOE_s$ value for western hemlock was about 8% greater than that for Sitka spruce. However, different results were observed in stress wave properties; that is, the average SWS and $MOE_d$ of hemlock were about 3% to 6% less than those of Sitka spruce. There could be several reasons for this. First, the stems of many western hemlock trees had irregular shapes (not round) and showed much more variation of surface conditions and more frequent occurrence of wood defects (e.g., compression wood) than did Sitka spruce trees. This could cause measurement error in the *in situ* stress wave measurement and bulk density determination. Second, *in situ* stress wave measurements of this study were conducted on only one side of the stem. For western hemlock trees, as a result of variable surface conditions and different physical and mechanical properties that can occur on different sides of the stems, one measurement may not be enough to predict the global properties of the wood. Third, as a result of the relatively small stem diameter, the number of small, clear wood specimens cut from western hemlock sections ranged from two to eight, whereas most of the Sitka spruce sections were big enough to cut eight specimens. Uneven sampling between western hemlock and Sitka spruce could affect the estimated global properties.

Results from static bending tests also indicated that the modulus of rupture (MOR) ranged from 4,660 to 10,640 lb/in$^2$ (32.13 to 73.35 MPa) for western hemlock and from 3,297 to 7,490 lb/in$^2$ (22.73 to 51.64 Mpa) for Sitka spruce. The average MOR values were 6,729 lb/in$^2$ (46.39 MPa) for western hemlock and 5,323 lb/in$^2$ (36.70 MPa) for Sitka spruce. These values agree with those from the *Wood Handbook* (Forest Products Laboratory 1999).

## Stress Wave and Static Bending Relationship

We used statistical analyses to quantify the relationships of stress wave properties to static bending properties. Results obtained from various regression analyses are summarized in Table 3.

Figure 4 shows the relationship of SWS measured in standing trees to that measured in the small, clear specimens cut from the trees. The SWS of the specimens was an average value taken from eight (or fewer) specimens obtained from each bole section. Analyses revealed a strong relationship between SWS in trees and that in small, clear specimens. The correlation coefficient ($r = 0.83$) was highly significant at the 0.01 confidence level. The average SWS measured in trees was 11,066 ft/s (3,373 m/s), which was very close to the average SWS of 10,800 ft/s (3,292 m/s) measured in the small, clear specimens. This suggests that the stress wave NDE technique

**Table 3—Relationships between $MOE_d$ and mechanical properties of small, clear specimens obtained from tested trees[a]**

| | | Linear regression model $y = a + b x$ | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Mechanical properties of small, clear specimen[b] | x: $MOE_d$ of trees | | | | x: $MOE_d$ of small, clear specimen | | | |
| Species | *y* | *a* | *b* | *r*[c] | $S_{yx}$[c] | *a* | *b* | *r*[c] | $S_{yx}$[c] |
| Western hemlock | $MOE_d$ | 0.597 | 0.5788 | 0.73 | 0.1604 | — | — | — | — |
| | $MOE_s$ | 0.6288 | 0.3189 | 0.63 | 0.1169 | 0.1751 | 0.6659 | 0.92 | 0.0929 |
| | MOR | 4,360.6 | 1,709.09 | 0.65 | 594.89 | 3,816.80 | 2,148.47 | 0.68 | 765.46 |
| Sitka spruce | $MOE_d$ | 0.4958 | 0.6267 | 0.77 | 0.1359 | — | — | — | — |
| | $MOE_s$ | 0.394 | 0.4236 | 0.78 | 0.0873 | 0.1618 | 0.6217 | 0.91 | 0.0848 |
| | MOR | 2,769.6 | 1,853.88 | 0.63 | 596.13 | 2,513.30 | 2,083.84 | 0.69 | 667.06 |
| Western hemlock and Sitka spruce combined | $MOE_d$ | 0.5455 | 0.5972 | 0.75 | 0.1462 | — | — | — | — |
| | $MOE_s$ | 0.5355 | 0.3526 | 0.66 | 0.1105 | 0.1641 | 0.6447 | 0.91 | 0.096 |
| | MOR | 3,072.70 | 2,139.81 | 0.56 | 994.53 | 3,072.70 | 2,139.81 | 0.56 | 994.53 |

[a]Small, clear wood specimens were tested in static bending according to ASTM D143 standards (ASTM 1988).
[b]$MOE_d$, dynamic modulus of elasticity determined by stress wave method; $MOE_s$, static modulus of elasticity of small, clear specimens; MOR, modulus of rupture of small, clear specimens.
[c]*r*, correlation coefficient; $S_{yx}$, standard error of estimate.

used in this study provided relatively accurate and reliable stress wave information, therefore enabling the prediction of wood properties in standing trees.

Laboratory investigation verified that strong relationships existed between $MOE_d$ and static properties (MOE and MOR) for small, clear wood specimens. Figure 5 shows the relationship between $MOE_d$ and $MOE_s$ for small, clear specimens obtained from the trees. The correlation coefficient was 0.91 for the two species combined. The linear regression analyses indicated that the developed regression models were statistically significant at the 0.01 confidence level. Figure 6 shows the relationship between $MOE_d$ and MOR for the small, clear specimens. The correlation coefficient was slightly lower for the combined species. However, good relationships were observed between $MOE_d$ and MOR if the two species were considered separately. The correlation coefficients were found to be 0.68 for western hemlock and 0.69 for Sitka spruce. The developed regression models were statistically significant at the 0.01 confidence level.

Relationships between $MOE_d$ of trees and $MOE_d$ and $MOE_s$ of small, clear specimens are shown in Figures 7 and 8. Constants for the linear regression models and correlation coefficients are summarized in Table 3. Results indicate that good relationships existed between the $MOE_d$ of trees and the $MOE_d$ and $MOE_s$ of small, clear specimens cut from the trees. The correlation coefficient for $MOE_d$ of trees compared with $MOE_s$ of small, clear specimens was less than that for $MOE_d$ of trees compared with the $MOE_d$ of small, clear specimens. This could be attributed to the variation in static tests as a result of the small size of the specimen and the specimen cutting method. Statistical regression analyses also revealed different correlation coefficients for western hemlock and Sitka spruce (Table 3). The *r* values of $MOE_d$ of trees compared with $MOE_s$ and $MOE_d$ of small, clear specimens for western hemlock were less than those for Sitka spruce. Again, this could have been caused by the western hemlock, uneven sampling, and relatively small size of small, clear specimens. We believe that improvements could be achieved by conducting *in situ* stress wave measurements on two sides of the stem for western hemlock trees or by using larger specimens (lumber, timber, or stem section) instead of small, clear specimens to destructively determine static properties.

Figure 9 shows the relationship between $MOE_d$ of trees and the MOR of small, clear specimens. The $MOE_d$ of trees correlated reasonably well with the MOR of small, clear specimens. Correlation coefficients *r* were found to be 0.65 for western hemlock and 0.63 for Sitka spruce. However, the *r* value decreased to 0.56 when the two species were combined.

## Silvicultural Practices

The quality and properties of wood are generally affected by silvicultural practices, especially the silvicultural control of stand density. Some silvicultural practices not only might increase the biomass production of trees but also might improve the quality of the wood in trees. In this study, the effect of thinning treatments on both stress wave and static bending properties were examined. Results are summarized in Table 4, with $MOE_d$ (trees) and $MOE_s$ (small, clear specimens) values listed in decreasing order. The highest MOE values (dynamic and static) for both western hemlock and Sitka spruce were in the control stands (70%) and the stands that received light thinning (30%). Whereas, the lowest MOE values (dynamic and static) were observed in stands that received heavy (64%) and medium (32%) thinning.

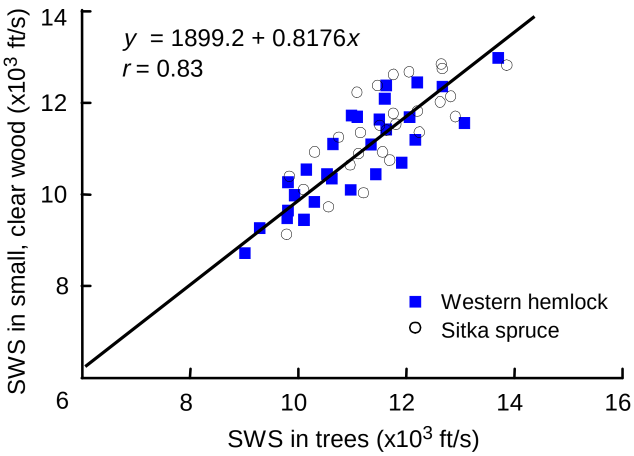


**Figure 4—Relationship of stress wave speed (SWS) measured in trees to SWS measured in small, clear specimens obtained from trees (1 ft/s = 0.3048 m/s).**

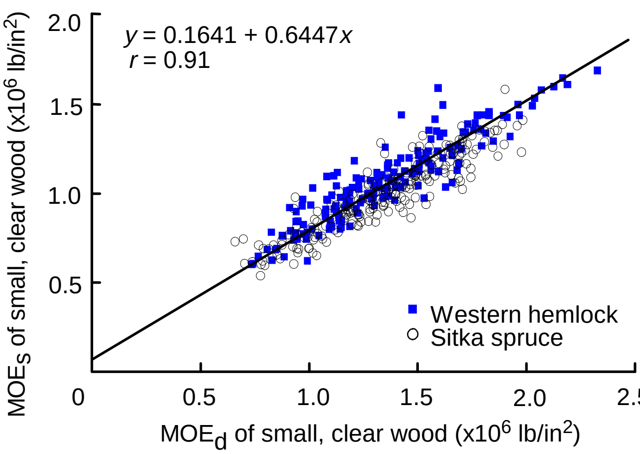


**Figure 5—Relationship of $MOE_d$ to $MOE_s$ for small, clear specimens (1 lb/in$^2$ = 6.894 kPa).**

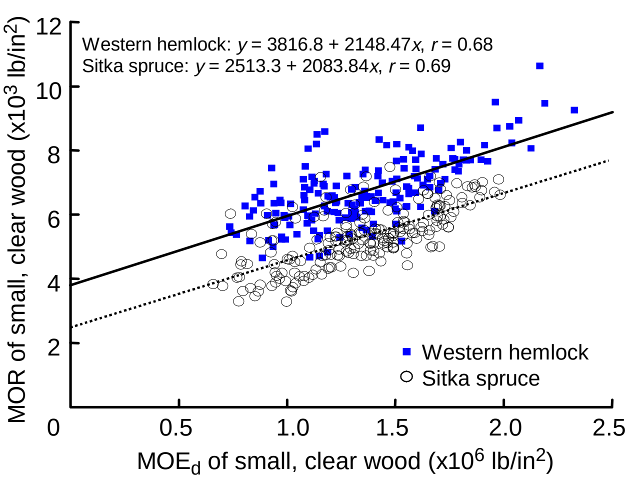


**Figure 6—Relationship of $MOE_d$ to MOR for small, clear specimens (1 lb/in$^2$ = 6.894 kPa).**

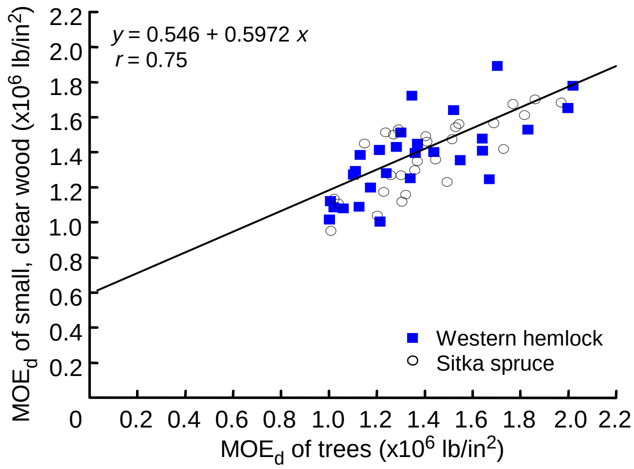


**Figure 7—Relationship of $MOE_d$ of trees to $MOE_d$ of small, clear specimens (1 lb/in$^2$ = 6.894 kPa).**

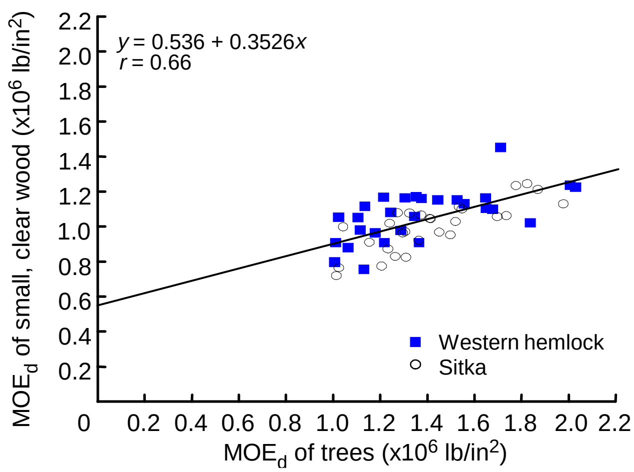


**Figure 8—Relationship of $MOE_d$ of trees to $MOE_s$ of small, clear specimens (1 lb/in$^2$ = 6.894 kPa).**

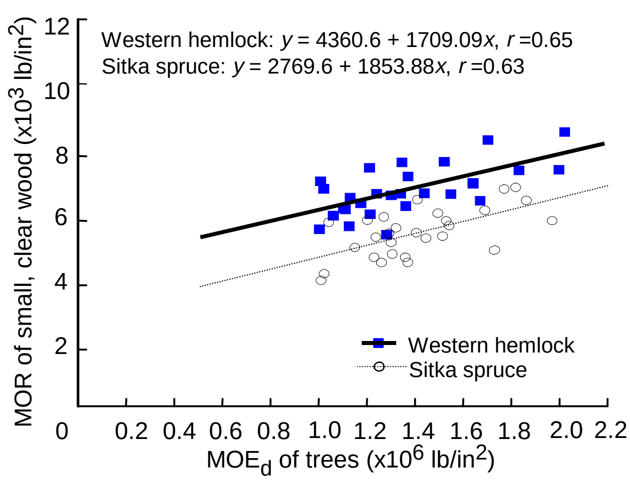


**Figure 9— Relationship of $MOE_d$ of trees to MOR of small, clear specimens (1 lb/in$^2$ = 6.894 kPa).**

**Table 4—Thinning effects on stress wave and static bending properties[a]**

| MOE ($\times 10^6$ lb/in$^2$)[b] | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Harris River | | Thorne River | | Alder Creek | | Tuxekan | | Port Alice | | Shrubby Island | | Thomas Bay | |
| $MOE_d$ | $MOE_s$ | $MOE_d$ | $MOE_s$ | $MOE_d$ | $MOE_s$ | $MOE_d$ | $MOE_s$ | $MOE_d$ | $MOE_s$ | $MOE_d$ | $MOE_s$ | $MOE_d$ | $MOE_s$ |
| Western hemlock | | | | | | | | | | | | | |
| 1.39, C | 1.1,C | 1.32, C | 1.16, C | 1.98, C | 1.22, C | 1.51, L | 1.45, L | 1.66, C | 1.17, C | 2, L | 1.22, L | 1.33, L | 0.9, C |
| 1.23, M | 1.09, L | 1.31, M | 1.15, M | 1.56, L | 1.16, L | 1.43, C | 1.12, C | 1.42, L | 1.15, L | 1.63, C | 1.15, C | 1.2, M | 0.9, L |
| 1.09, L | 1.08, M | 1.27, L | 1.11, H | 1.38, M | 1.15, M | 1.2, H | 1.05, M | 1.37, M | 1.05, H | 1.63, C | 1.1, H | 1.16, C | 0.79, H |
| 1.07, H | 0.87, H | 1.1, H | 0.9, L | 1.14, H | 0.98, H | 1.07, M | 0.96, H | 1.36, H | 0.97, M | 1.57, H | 1.07, M | 1.04, H | 0.75, M |
| Sitka spruce | | | | | | | | | | | | | |
| 1.63, C | 1.12, C | 1.51, C | 1.11, C | 1.65, L | 1.06, C | 1.45, C | 1.09, C | 1.58, C | 1.23, C | 1.75, C | 1.21, C | 1.75, L | 1.24, L |
| 1.15, L | 0.99, L | 1.32, L | 1.07, M | 1.62, C | 1.05, L | 1.28, L | 0.96, H | 1.33, M | 1.06, M | 1.53, L | 1.02, L | 1.45, M | 1.04, M |
| 1.1, H | 0.82, H | 1.22, M | 1.06, L | 1.42, M | 1.04, M | 1.26, H | 0.92, L | 1.25, L | 1.01, L | 1.52, h | 0.96, M | 1.27, C | 0.96, H |
| 1.04, M | 0.71, M | 1.22, H | 0.87, H | 1.18, H | 0.9, H | 1.18, M | 0.82, M | 1.09, H | 0.76, H | 1.43, M | 0.95, H | 1.24, H | 0.77, C |

[a]$MOE_d$ and $MOE_s$ are tabulated in decreasing order for each site, with the letter after each entry indicating the level of thinning (C, control; L, light thinning; M, medium thinning; H, heavy thinning.)
[b]1 lb/in$^2$ = 6.894 kPa; $MOE_d$, dynamic modulus of elasticity of wood in a tree determined by the stress wave method; $MOE_s$, static modulus of elasticity of small, clear specimen determined by static bending test.

This indicated that lower density stands exhibited a trend toward decreased stress wave and static bending properties.One limitation to this study was that only one sampled tree for each species was cut from each stand. Therefore, statistically, the obtained stress wave and static properties may not fully reflect wood properties for the entire stand. However, our results demonstrated that the effect of silvicultural practices on static bending properties of wood can be successfully identified by stress wave $MOE_d$. The typical trends of stress wave and static bending characteristics as a result of thinning regimes are illustrated in Figures 10 and 11. The stress-wave-based tree MOE follows the same trend with $MOE_s$ as thinning level changes. These results are encouraging and indicate that the nondestructive stress wave technique used in this study may be used to track wood property changes in trees and determine how forests could be managed to meet desired wood and fiber qualities.

# Conclusions

Based on the results of this study, we conclude the following:

1. *In situ* stress wave measurements provide relatively accurate and reliable stress wave information that could be used to assess the mechanical properties of wood in standing trees. Statistical regression analyses indicate that strong relationships exist between stress wave properties of standing trees and the strength and stiffness of small, clear specimens obtained from trees.
2. Stress wave speed (SWS) measured in trees ranged from 9,016 to 13,698 ft/s (2,748 to 4,175 m/s) for western hemlock and from 9,787 to 13,858 ft/s (2,983 to 4,224 m/s) for Sitka spruce. Dynamic modulus of elasticity ($MOE_d$) of wood in trees ranged from 1.00 to 2.02 × $10^6$ lb/in$^2$ (6.89 to 13.93 GPa), with a mean of 1.37 × $10^6$ lb/in$^2$ (9.44 GPa)for western hemlock and 1.01 to 1.97 × $10^6$ lb/in$^2$ (6.96 to 13.58 GPa), with a mean of 1.41 × $10^6$ lb/in$^2$ (9.72 GPa) for Sitka spruce. In this study, the mean values of SWS and $MOE_d$ of trees from both species are in agreement with those determined from small, clear specimens.
3. The effect of the silvicultural practice of thinning on wood properties can be identified with the stress wave technique used in this study. As practices change, stress-wave-based $MOE_d$ of wood in trees basically follows the same trend as $MOE_s$. Results indicate that the nondestructive stress wave technique used in this study may also be used to track wood property changes in trees and determine how forests could be managed to meet desired wood and fiber qualities.
4. Although good correlations were observed in this study between stress wave properties of standing trees and static bending properties of small, clear specimens obtained from the trees, significant variability in static tests because of the small size of specimens and the specimen cutting methods did create some problems in predictive relationships. In future studies, we suggest that larger specimens (lumber, timber, or stem section) be used to determine static properties.

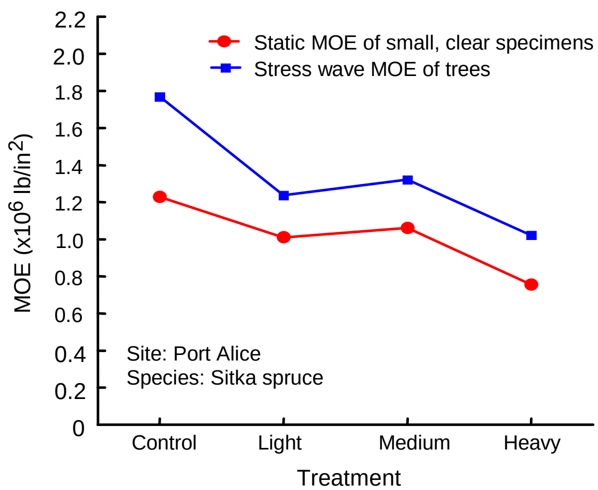


**Figure 10—Modulus of elasticity (MOE) of Sitka spruce as a function of thinning treatment (light, medium, heavy) (1 lb/in$^2$ = 6.894 kPa).**

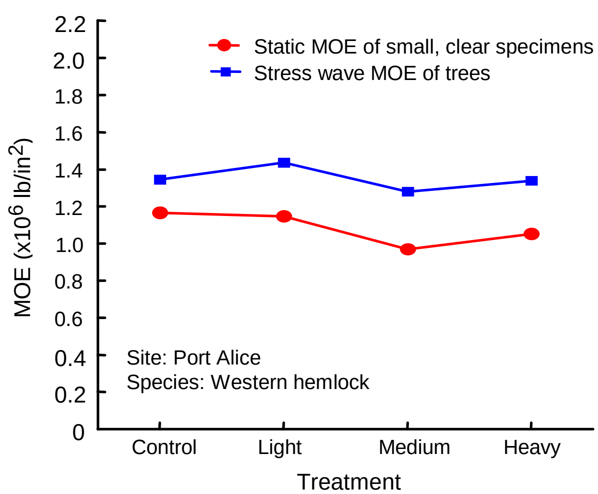


**Figure 11—Modulus of elasticity (MOE) of western hemlock as a function of thinning treatment (light, medium, heavy) (1 lb/in$^2$ = 6.894 kPa).**

# References


**ASTM.** 1988. Standard methods for testing small clear specimens of timber. ASTM D 143. Philadelphia, PA: American Society for Testing and Materials.

**Aratake, S.; Arima, T.** 1994. Estimation of modulus of rupture (MOR) and modulus of elasticity (MOE) of lumber using higher natural frequency of log in pile of logs. II. Possibility of application for sugi square lumber with pith. Mokuzai Gakkaishi. 40(9): 1003–1007.

**Aratake, S.; Arima, T.; Sakoda, T.; Nakamura, Y.** 1992. Estimation of modulus of rupture (MOR) and modulus of elasticity (MOE) of lumber using higher natural frequency of log in pile of logs. Possibility of application for sugi scaffolding board. Mokuzai Gakkaishi. 38(11): 995–1001.

**Arima, T.; Maruymura, N.; Maruyama, S.; Hayamura, S.** 1990. Natural frequency of log and lumber hit with hammer and applications for production processing. In: Proceedings, 1990 International timber engineering conference; 1990 October 23–25; Tokyo, Japan. Tokyo, Japan: Science University of Tokyo. p. 527–533.

**Forest Products Laboratory.** 1999. Wood handbook: Wood as an engineering material. Gen. Tech. Rep. FPL–GTR–113. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 463 p.

**Green, D.W.; McDonald, K.A**. 1998. Inferences from growing trees backwards. In: Timber management toward wood quality and end-product values. Proceedings, CTIA/IUFRO international wood quality workshop; 1997 August 18–22; Quebec City, Canada.

**Jayne, B.A.** 1959. Vibrational properties of wood as indices of quality. Forest Products Journal. 9(11): 413–416.

**Kaiserlik, J.H; Pellerin, R.F.** 1977. Stress wave attenuation as an indicator of lumber strength. Forest Products Journal. 27(6): 39–43.

**Koizumi, A.; Iijima, Y.; Sasaki, T.; Kawai, Y.; Okazaki, Y.; Nakatani, H.** 1997a. Strength properties of sugi (*Cryptomeria japonia*) grown in Akita Prefecture I: Young's moduli of logs. Mokuzai Gakkaishi. 43(1): 46–51.

**Koizumi, A.; Iijima, Y.; Sasaki, T.; Okazaki, Y.** 1997b. Strength properties of sugi (*Cryptomeria japonia*) grown in Akita Prefecture II: Mechanical properties of lumber. Mokuzai Gakkaishi. 43(2): 210–214.

**Pellerin, R.F.** 1965. A vibrational approach to nondestructive testing of structural lumber. Forest Products Journal. 15(3): 93–101.

**Ross, R.J.; Pellerin, R.F.** 1988. NDE of wood-based composites with longitudinal stress waves. Forest Products Journal. 38(5): 39–45.

**Ross, R.J.; Pellerin, R.F.** 1994. Nondestructive testing for assessing wood members in structures: A review. Gen. Tech. Rep. FPL–GTR–70 (Rev.) Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 40 p.

**Ross, R.J.; De Groot, R.C.; Nelson, W.J.** 1994. Technique for nondestructive evaluation of biologically degraded wood. Experimental Tech. 18(5): 29–32.

**Ross, R.J.; McDonald, K.A.; Green, D.W.; Schad, K.C.** 1997. Relationship between log and lumber modulus of elasticity. Forest Products Journal. 47(2): 89–92.

**Sandoz, J.L; Lorin, P.** 1994. Standing tree quality assessment using ultrasound. In: Proceedings, First European symposium on nondestructive evaluation of wood; 194 September 21–23; Sopron, Hungary. Sopron, Hungary: Sopron, Hungary University of Sopron. Vol. 2, p. 493–502.

**Wang, X.; Ross, R.J.; Erickson, J.R.; Ligon, J.B. [in press].** Technique for nondestructive evaluation of standing trees. Experimental Techniques.