Acoustic Evaluation of Thinning and Biosolid Fertilization Effects on Wood Quality of a Douglas-fir Stand

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Abstract

In this study, we examined the potential of using a time-of-flight (TOF) acoustic wave method to evaluate thinning and biosolid fertilization effects on acoustic velocity of trees and modulus of elasticity (MOE) of structural lumber in a 76-year-old Douglas-fir (*Pseudotsuga menziesii*, (Mirb., Franco)) experimental stand. The stand consisted of four treatments: control, thinned, biosolid fertilized, and a combined thinned and fertilized treatment, each with three replicates on 0.08 hectare plots. Four trees were selected in each plot using a stratified random sample based on the plot quadratic mean diameter, resulting in a total sample of 48 trees ranging from 14.2- to 53.3-cm diameter at breast height (DBH). The sample trees were first nondestructively tested using a TOF-based acoustic measurement system to obtain acoustic velocity in trees. The sampled trees were then harvested, bucked into merchantable-length stems and then mill-length logs that were sawn into lumber. Acoustic velocities of stems and logs and MOE of lumber were subsequently obtained. Our results indicated that biosolid fertilization had a statistically significant effect on acoustic velocities of trees, stems, and butt logs; thinning did not have a statistically significant effect on acoustic velocities; combining thinning with biosolids did not produce a change in acoustic velocity different from applying biosolids alone. These findings are consistent with the treatment effects that were reported on interannual ring specific gravity. At tree level, treatment had no significant effect on lumber stiffness.

Keywords: Acoustic velocity, biosolids, lumber, logs, trees, modulus of elasticity, thinning

Introduction

In-forest assessment of wood quality in individual trees and forest stands is important to both forest management decision-makers and forest operations. As world wood markets are becoming increasingly competitive and complex, forest companies are under economic pressure to control cost, sort and allocate forest materials to the most appropriate markets, and maximize the value of the forest at the time of harvest (Wang et al. 2007a, Amishev and Murphy 2008). Although forestry has many widely accepted field tools, sampling procedures, and models for gathering and summarizing data and making projections of growth, yield, and tree size, counterparts for wood quality assessment have lagged far behind (Briggs et al. 2008). One of the reasons for this lag has been a lack of simple field tools permitting rapid collection of wood quality data from trees in a stand or sample plot.

Historically, trees and stands have been selected for harvest based on visual assessment of tree quality (diameter, height, straightness, taper, frequency and size of tree branches, observable defects, etc.) and stand characteristics (age, species composition, habitat type, presence of insects and diseases, and silvicultural objectives). These procedures do not incorporate estimates of any intrinsic wood properties and thus do not adequately assess the potential quality of the end products that might be manufactured from the trees. With the development and rapid growth of new engineered wood products such as laminated veneer lumber (LVL), I-joists, and cross laminated timber (CLT), there has been a parallel growth in non-destructive assessment of the stiffness of raw wood materials that go into these products. In addition, concerns with design values of structural lumber graded with visual methods are creating demand for stiffness verification of visually graded structural lumber. These trends have renewed the interest of forest companies in field non-destructive testing tools that can be used for in-forest assessment of wood quality in terms of stiffness. Mills seeking to capture a price premium by producing high-valued engineered products find that it is very expensive to process logs or purchase timber stands that have low yields of products with the stiffness and strength levels desired by their customers.

In recent years, research has been conducted to examine the concept of using acoustic wave propagation methods to evaluate standing trees and forest stands for general wood quality and intrinsic wood properties (Wang 1999, Harris and Andrews 1999, Huang 2000, Addis et al. 2000, Lindstrom et al. 2002, Wang et al. 2001, 2007b). The research has led to the development and commercialization of a series of acoustic tools that allow rapid assessment of wood resource quality at early stages of the forest operational value chain (Harris et al. 2002, Carter et al. 2005, Huang 2005, Wang et al. 2006, 2008, Divos 2010, Carter 2011). One particular technique, which uses the time-of-flight (TOF) method to measure longitudinal acoustic velocity near the base of standing trees, provides a means for silviculturists, forest managers, and planners to be able to predict the stiffness potential of stands prior to harvest and to assist in valuation, stumpage purchase, and harvest scheduling decisions (Briggs et al. 2008).

Although many studies have investigated the relationships between tree and log acoustic velocity and between tree/log velocity and wood stiffness of small clear wood and lumber or veneer for a variety of species (Wang et al. 2001, 2007b, Grabianowski et al. 2006, Chauhan and Walker 2006, Amishev and Murphy 2008, Mora et al. 2009, Achim et al. 2011), less is known about how silvicultural practices affect acoustic velocity of trees in a stand, information that is important to managers wishing to make informed decisions to enhance stiffness and value of plantations (Briggs et al. 2008, Raymond et al. 2008, Lowell et al. 2014). In 1998, a Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stand, experimentally thinned and treated with bio-solids fertilization at age 55 in 1977, was scheduled for harvesting and provided an opportunity to evaluate the effects of these treatments on tree acoustic velocity and lumber quality. This study was initiated in conjunction with the mill recovery study conducted by the USDA Forest Service Pacific Northwest Research Station.

The specific objective of this study was to test the following hypothesis concerning the effects of thinning and biosolids treatments in the Douglas-fir stand: treatments caused no differences in 1) tree acoustic velocity; 2) log acoustic velocity, and 3) modulus of elasticity (MOE) of the dimensional lumber produced from the stand. The goal of our data analysis was to determine if acoustic velocity measured on trees and logs can be used to assess treatment effects.

Experimental Procedures

The study site was located on the University of Washington's Charles Lathrop Pack Experimental Forest near Eatonville, WA (Figure 1). The Douglas-fir stand naturally regenerated following a severe fire in 1922. When the study was established in 1977, the stand was estimated to be 55 years old and was heavily stocked with approximately 1977 trees/ha with about 75% under 18 cm in diameter at breast height (DBH) (Edmonds and Cole 1980, Sonne et al. 2004). During 1977, half of the stand was commercially thinned, which reduced density to about 250 trees per acre. Six 0.2-ac plots were randomly located in each of the thinned and unthinned portions of the stand. In the winter of 1977–1978, three plots in the thinned and unthinned areas were randomly selected and treated with 104.3 tons/ha of dewatered sewage (18% solids) depositing a 2.54 cm depth of biosolids (hereafter, fertilization with dewatered sewage application is referred to as biosolids treatment). Retreatment with 51.9 tons/ha occurred in 1980 and 1989, and the thinned area received a second commercial thinning in 1995. The site was scheduled for final harvest in 1998, providing the opportunity to evaluate the effects of the sequence of treatments on wood quality from various aspects, including 1) log and lumber visual grade and value (Sonne et al. 2004); 2) interannual ring specific gravity (Kantavichai et al. 2010); and 3) tree acoustic velocity and lumber stiffness (this study). Table 1 summarizes initial and final stand characteristics.

Table 1—Initial and final stand conditions

Treatment	Quad. mean DBH (cm)		Total height (m)		Trees/ac	
	1977	1998	1977	1998	1977	1978
Control	16.7	23.4	26.2	33.8	842	551
Biosolids	16.9	27.0	24.4	33.5	702	388
Thin	21.4	31.0	24.4	31.4	262	158
Thin/biosolids	22.0	35.4	24.1	32.9	250	120

Figure 1—Douglas-fir experimental stand located in Eatonville, Washington.

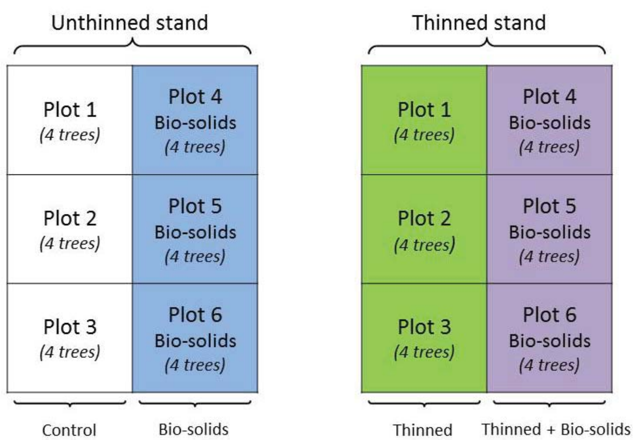

Figure 2—Experimental plots selected for the study.

In 1998, four trees in each plot (48 trees in total) were selected for field acoustic measurements. The tree samples were selected using a stratified random sample based on the plot quadratic mean diameter. Figure 2 shows the schematic of the experimental plots and tree samples selected for this study. We conducted acoustic measurements near the base of 48 sample trees using a prototype TOF measurement system. The setup consisted of two accelerometers, two spikes, a hand-held hammer, and a portable Fluke 97 50 MHz Scopemeter (Fluke UL Ltd, Norfolk, UK). Two spikes were inserted into the tree trunk at about a 45 degree angle 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 (Wang et al. 2001). An acoustic wave was introduced into the tree in 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 the Scopemeter. The TOF was determined by locating the two leading edges of the waveforms displayed. Acoustic velocity was then calculated by dividing the test span by the measured TOF (average of three readings). A span of 1.22 m was found to produce consistent readings and rapid measurements. Therefore, this span was used for all tree testing.

Following field acoustic measurements, the 48 sample trees were harvested, cut into merchantable length stems with a small end diameter of 15.2 cm, and then bucked into 171 mill-length logs (4.88 m). All stems and mill-length logs were acoustically tested using a resonance acoustic method to obtain acoustic velocity values for the stems and logs.

The logs were subsequently sawn into lumber with a portable WoodMizer™ sawmill. Sawing was limited to producing a 20.3-cm maximum width board and the majority of the lumber was 5.1 cm thick. Less than 10% of the volume was 2.5-cm thick jacket boards. Each piece of lumber was given a number that could be traced to the original log, tree, and treatment. The lumber was kiln dried, planed on four sides, and then E-rated using the E-computer (Metriguard Inc., Pullman, Washington), a transverse vibration testing equipment. The modulus of elasticity (MOE) of each piece of lumber was determined by the following equation:

$$MOE = \frac{f_r^2 W L^3}{2.46 I g}$$

Where
f_r —resonant frequency (Hz);
W—lumber weight (kg);
L—lumber span (m);
I—moment of inertia (m^4);
g—acceleration due to gravity (9.8 m/s^2).

Data Analysis

This study produced an interrelated acoustic data set from a stratified Douglas-fir tree sample across differing silvicultural treatments: 1) Acoustic velocity of 48 sample trees (12 trees per treatment × 4 treatments); 2) Acoustic velocity of 48 merchantable stems; 3) Acoustic velocity of 48 butt logs; and 4) Acoustic velocity of 171 mill-length logs obtained from 48 sample trees. All lumber pieces that could be sawn from the parent trees were assessed for stiffness. The lumber MOE data was then collated at the tree level to calculate volume-weighted mean lumber MOE.

Simple linear regression analyses were first conducted to examine the relationships between the tree velocity and stem/butt log velocities and between tree velocity and tree DBH. Statistical comparison analyses were used to examine the effect of treatment variables on wood quality in terms of acoustic velocity and lumber MOE. A linear mixed effects model was fit to the data. Experimental plots were treated as random effects. Thinning, biosolids, and the thinning/biosolids interaction were treated as fixed effects. Plot statistics (for example, median, minimum, maximum) are presented graphically in box plots to show the effects of treatments on the acoustic velocities measured in trees, merchantable stems and butt logs, and the lumber MOE.

Results and Discussion

Acoustic velocities measured in trees, stems, and butt logs

Table 2 tabulates the statistics of acoustic velocities measured in trees, full-length stems, and butt logs. Distributions of acoustic velocities are shown in Figure 3. The velocity ranged from 3225 to 4763 m/s for standing trees, 3275 to 4416 m/s for stems, and 3805 to 4565 m/s for butt logs. Tree velocity had higher values than the stem and butt log velocities. This is consistent with what has been found in other studies (Wang 2013).

Figure 4 presents the plot of individual tree velocity versus tree DBH. One data point that had the lowest tree velocity (3225 m/s) was identified as a possible outlier. This tree had the largest DBH (53.3 cm) and thickest bark (4–5 cm) among all sample trees and was the first tree tested in the field. Based on the large velocity discrepancy observed for this tree and the recollection of the testing situation, we suspect that when this tree was tested, the sensor probes were likely not inserted into the trunk deeply enough to fully penetrate the bark and thus affected the TOF measurements (prolonged acoustic wave travel time and thus resulted in a low tree velocity). This technical issue was not recognized at the time of field testing and thus was left uncorrected. We decided not to include this data point in our analyses.

Overall, there is a general trend of decreasing tree velocity with tree DBH at tree level. The lower tree velocity with increased DBH seems associated with the higher growth rate in trees, which adversely affects specific gravity and stiffness of wood. It is also evident that there was a large variation in tree velocity for trees within the same diameter class. This may well reflect the natural variation among individual trees as well as the effects of prescribed treatments.

The accuracy and reliability of TOF measurements on standing trees are typically evaluated through a direct comparison with the corresponding log resonance measurements. Figure 5 shows the linear relationships between measured tree velocity and the corresponding stem/butt log velocities. The coefficient of determination (R^2) was 0.33 and 0.48 when the tree velocity was regressed against the butt log velocity and stem velocity, respectively. The strength of this relationship is moderate, but weaker than those obtained from Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) (R^2 = 0.85-0.93, Wang et al. 2008), Douglas-fir (R^2 = 0.65, Briggs et al. 2008), radiata pine (*Pinus radiata* D. Don) (R^2=0.89, Chauhan and Walker 2006), and Loblolly pine (*Pinus taeda* L.) (R^2 = 0.81, Mora et al. 2009). Two possible causes could contribute to this lower correlation: 1) this was the first time that our TOF prototype measurement system with a manually operated Fluke ScopeMeter was used in field application (1998). Determination of TOF was based on the cursor measurement of the time arrivals of both impact and receiving signals. One of the goals of this field trial was to test the TOF measurement system and determine the applicability of the TOF approach in standing trees. The user had not yet developed operating experience with the system so the TOF data might be more variable. 2) The Douglas-fir sample trees tested in this study were in a 76-year-old mature stand, much older than the trees tested in the studies referenced above. Mature Douglas-fir trees have relatively thicker bark, which might have caused some measurement errors when the sensor probes were not inserted into the trunk deeply enough.

Treatment effects on acoustic velocity of trees, stems, and butt logs

Figure 6 provides boxplots of acoustic velocity of standing trees, stems, and butt logs versus treatment variables. The dark horizontal lines are the median values. Biosolid treatment was found to have a statistically significant effect on acoustic velocities measured in standing trees (p-value = 0.0243), stems (p-value = 0.0041), and butt logs (p-value = 0.0024). The effect on mean velocity for the plots that received biosolid treatment was –138 m/s from a base of 4400 m/s in standing trees, –192 m/s from a base of 4014 m/s in stems, and –156 m/s from a base of 4360 m/s in the butt logs. This finding is in agreement with the SG responses following the treatment (Kantavichai et al. 2010). In a parallel study of the same experimental plots, Kantavichai et al. (2010) examined the effect of thinning and biosolid fertilization on interannual ring specific gravity of the sample trees and found that biosolids significantly decreased SG, which is consistent with other studies involving application of fertilizer (Cahill and Briggs 1992) or biosolids (Briggs et al. 1986). Specific gravity averaged 0.517 over 1978–1989 without biosolids treatment and was reduced to 0.466 by biosolids. The significant decrease in SG explains the decreased acoustic velocity associated with biosolids treatment.

Table 2—Acoustic velocity measured in sample trees, merchantable stems, and butt logs

Treatment	DBH (cm)		Tree velocity (m/s)		Stem velocity (m/s)		Butt log velocity (m/s)	
	Mean	Stdev.	Mean	Stdev.	Mean	Stdev.	Mean	Stdev.
Control	29.0	11.49	4401	174.4	4061	216.0	4300	148.1
Biosolids	30.9	10.03	4232	215.9	3788	297.4	4162	149.0
Thin	32.9	6.43	4399	231.0	3977	141.7	4323	117.9
Thin/biosolids	37.5	8.65	4158	354.7	3780	180.4	4121	180.4

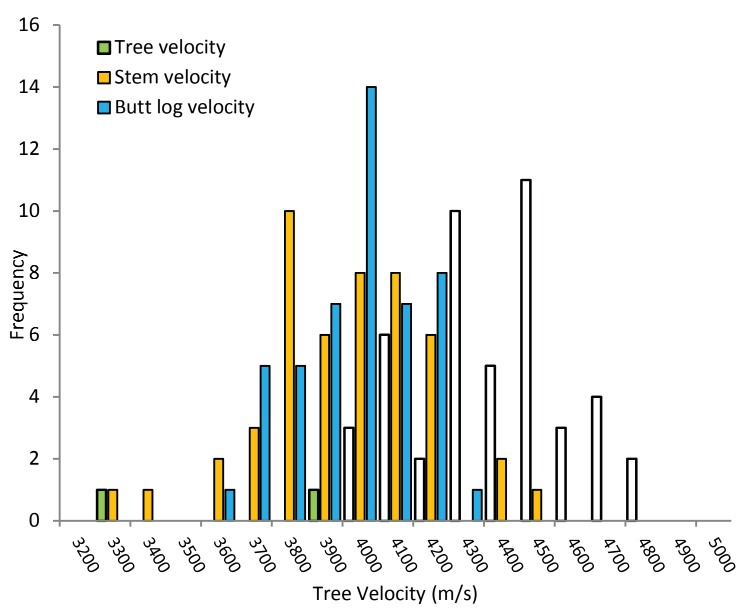

Figure 3—Histograms of acoustic velocities measured on Douglas-fir sample trees and the merchantable stems and butt logs obtained from the sample trees.

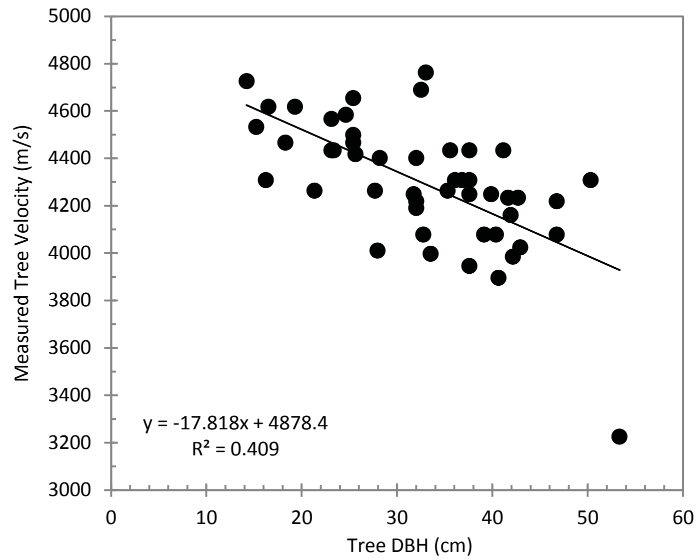

Figure 4—Relationship between tree velocity and tree DBH for the Douglas-fir sample trees.

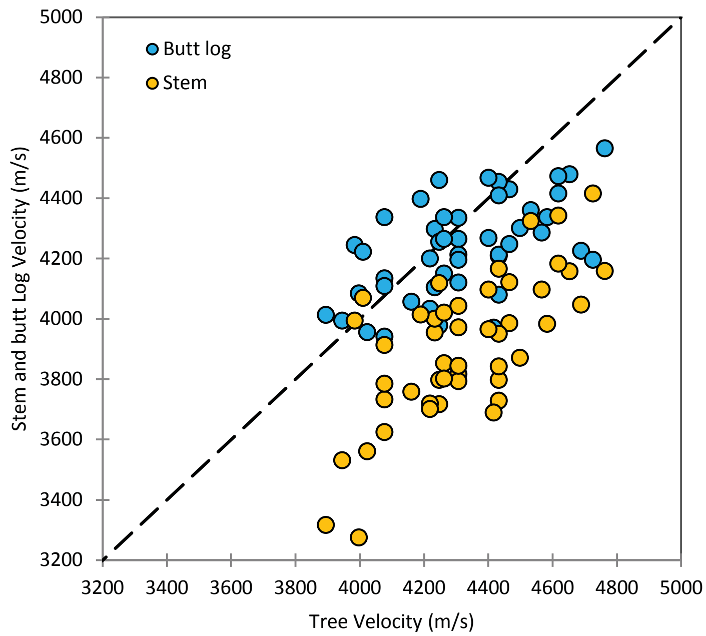

Figure 5—Relationships between tree velocity and stem/butt log velocity for the Douglas-fir sample trees.

Thinning treatment, on the other hand, did not have a statistically significant effect on acoustic velocities measured in standing trees (p-value = 0.7271), stems (p-value = 0.6065), and butt logs (p-value = 0.7280). The mean acoustic velocity only dropped 46 m/s in standing trees, 36 m/s in stems, and 69 m/s in butt logs from the base velocities of the control plots. This finding is different from those reported in some previous research. Wang et al. (2001) observed a decrease in tree velocity in young-growth Sitka spruce and western hemlock stands that had received medium and heavy thinning treatments. Briggs et al. (2008) reported lower acoustic velocity with increased DBH associated with the thinning in the 45- and 51-year-old Douglas-fir installations. In contrast, Carter et al. (2005) found that thinning increased acoustic velocity in a stand with a late season moisture deficit. Briggs et al. (2008) reported that two young Douglas-fir installations (32- and 36-years old) exhibited increasing acoustic velocity with decreasing stand density and with increasing DBH. Differences in species, site conditions, and types of thinning produced seemingly contradictory thinning effects.

With respect to the immediate effect of thinning, we would expect that a thinning that removes smaller DBH trees from plots is removing the trees with higher SGs and thus higher acoustic velocities so that the mean acoustic velocity of the residual plots will likely be immediately lowered. However, for the plots under consideration in the current study, Kantavichai et al. (2010) found that thinning increased latewood width but did not change latewood percentage, earlywood SG or latewood SG, and the overall effect on SG was found not statistically significant. This could help explain why there was no significant change in acoustic velocity associated with thinning in this study. The temperature and precipitation data over the 1978–1989 response analysis period suggest that the Douglas-fir experiment stand at the Charles Lathrop Pack Forest may experience soil moisture deficit (SMD) in the summer (Kantavichai et al. 2010). Some studies report that water stress reduces growth and promotes latewood formation, which increases SG (Brix 1972, Cregg et al. 1988). However, extreme summer water stress can stop growth and production of latewood, reduce latewood percentage, and reduce SG (Bowyer et al. 2007). This effect was considered to be the situation on the drought-prone site of this study (Kantavichai et al. 2010).

Same as the SG response reported by Kantavichai et al. (2010), combining thinning with biosolids did not produce a change in acoustic velocity different from the change caused by applying biosolids alone. In contrast, others (Briggs et al. 1986, Cahill and Briggs 1992) report that combining thinning with fertilization or biosolids lowered SG more than either treatment alone. Larson et al. (2001) noted that the response of SG to treatments is likely to be site-specific, depending on the local soil, temperature, and precipitation conditions. We would also expect this dependence to apply to the acoustic velocity of trees.

Treatment effect on mean lumber MOE

Figure 7 shows a boxplot of volume-weighted mean lumber MOE versus treatment variables. The dark horizontal lines are the median values. We did not find a statistically significant effect of treatment on mean lumber MOE (p-value = 0.6614). The volume weighted mean lumber MOEs were 15.5, 15.3, 16.1, and 14.9 GPa for the control, biosolids, thinning, and thinning and biosolid treatments respectively. This indicates that there was no significant reduction in stiffness due to the prescribed treatments.

The mean lumber MOE at tree level was derived from MOE measurements of all possible pieces of lumber that could be produced from each tree, and then aggregated at the tree level. There was considerable quantities of wood that went to chips during the lumber conversion process. The lumber recovery rate is affected by log diameter, log taper, and the sawing techniques used. In addition, all lumber was processed and dried. Lumber MOE was measured at kiln-dried condition (moisture content less than 19%); In contrast, the acoustic velocity measured on a standing tree, stem, and butt log reflects the global stiffness of the tree/stem/butt log in green condition. A significant discrepancy between these two different measures is expected. This is evidenced by the low correlation between mean lumber MOE and acoustic velocities of the sample trees (r = 0.074, p-value = 0.6210), stems (r = 0.159, p-value = 0.2868), and butt logs (r = 0.387, p-value = 0.0072).

By treatment, the plots that received both the thinning and biosolids treatment had the lowest mean lumber MOE (14.9 GPa). This agrees with what we observed in acoustic variables (tree velocity, stem velocity, and butt log velocity) in Figure 6. The plots that received only the thinning treatment exhibited higher lumber MOE than the plots that received the biosolid or combined treatments, which is also

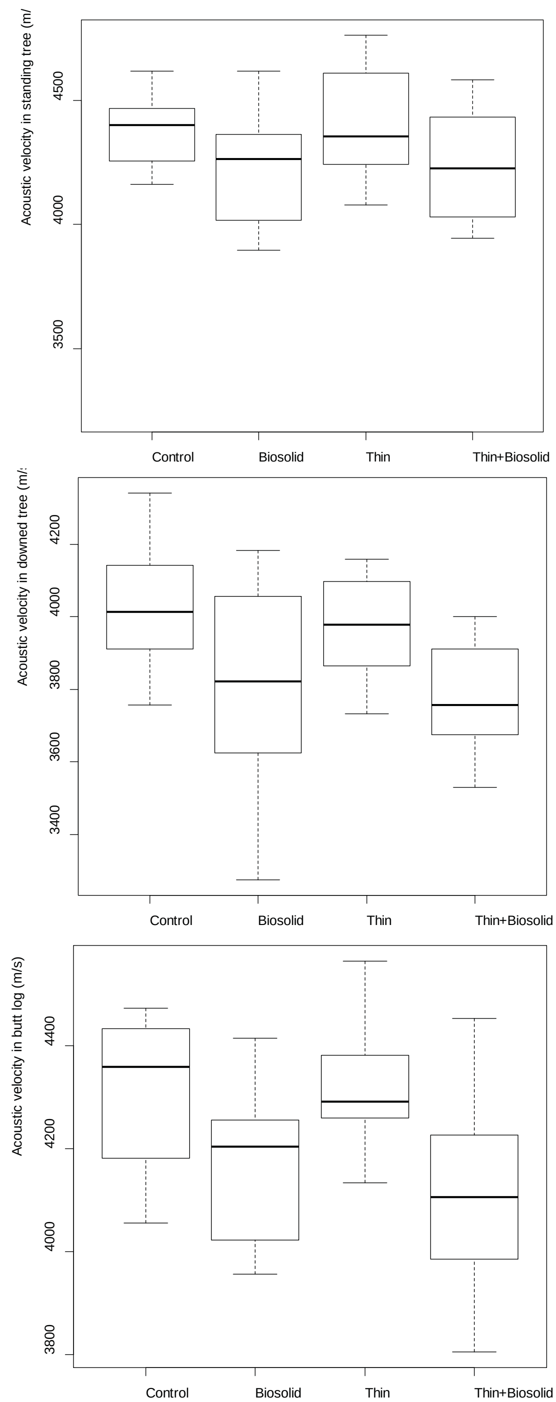

Figure 6—Effect of treatments on tree, stem, and butt log velocities.

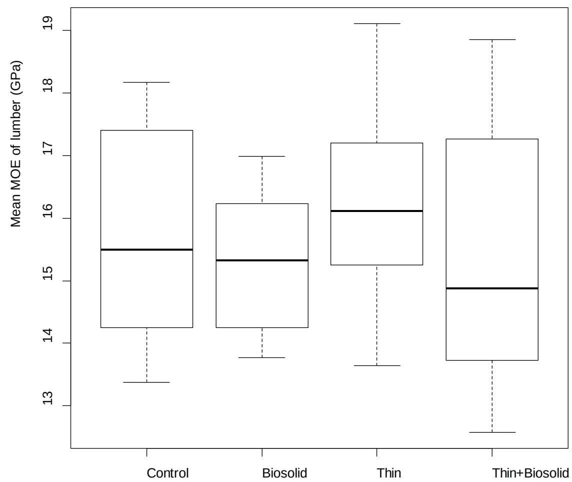

Figure 7—Effect of treatments on lumber MOE.

Table 3—Ranking of treatment based on mean acoustic velocity and mean lumber MOE

Property	High → Low			
Tree velocity	Control	Thin	Biosolid*	Thin + Biosolid*
Stem velocity	Control	Thin	Biosolid*	Thin + Biosolid*
Butt log velocity	Control	Thin	Biosolid*	Thin + Biosolid*
Lumber MOE	Thin	Control	Biosolid	Thin + Biosolid

* Significant at 5% level.

consistent with what we observed in acoustic variables. When the plots are ranked by mean acoustic velocity and mean lumber MOE, we noticed that the rank orders by mean acoustic velocities are consistent for the tree velocity, stem velocity, and butt log velocity; and the rank order by mean lumber MOE is generally consistent with that by acoustic velocity, except for the control and thinning plots (Table 3).

Conclusions

The effects of thinning and biosolid fertilization treatments on wood quality in a 76-year-old Douglas-fir stand were evaluated using a time-of-flight acoustic wave method. Field acoustic testing produced an interrelated acoustic data set from a stratified tree sample across control, thinned, biosolid fertilized, and combined treatments. Lumber stiffness data was collated to derive weighted mean lumber MOE at tree level. Analysis of the results indicated the following:

1. There was a general trend of decreasing tree velocity with increasing tree DBH across all experiment plots. There was a large variation in tree velocity for trees within the same diameter class, underlining the property variation among individual trees.
2. Biosolid fertilization treatment had a statistically significant effect on acoustic velocities measured in standing trees, stems, and butt logs; thinning did not have a statistically significant effect on acoustic velocities; the combined thinning with biosolids treatment could not be statistically distinguished from the biosolids treatment. These findings are consistent with the treatment effects on interannual ring specific gravity reported for the same sample of trees.
3. The thinning, biosolids, and combined treatments had no statistically significant effects on the mean lumber stiffness of a tree.

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References

Addis T, Buchanan AH, Walker JCF. 2000. Selecting trees for structural timber. Holz Roh-Werkst 58:162–167.

Amishev D, Murphy GE. 2018. In-forest assessment of veneer grade Douglas-fir logs based on acoustic measurement of wood stiffness. Forest Products Journal 58(11): 42–47.

Achim A, Paradis N, Carter P, Hernandez RE. 2011. Using acoustic sensors to improve the efficiency of the forest value chain in Canada: A case study with laminated veneer lumber. Sensors 11:5716–5728.

Bowyer JL, Schmulsky R, Haygreen JG. 2007. Forest product and wood science. 5th ed. Blackwell Publishing, Oxford, UK.

Briggs DG, Smith WR. 1986. Effects of silvicultural practices on wood properties—a review. In, Douglas-fir: stand management for the future. College of Forest Resources, University of Washington, Seattle, Washington, USA. Contrib. no. 55. pp 246-257.

Briggs DG, Merifi F, Smith WR. 1986. Effect of sludge on wood properties – a conceptual review with results from a 60-year old Douglas-fir stand. In: The Forest Alternative: For Treatment and Utilization of Municipal and Industrial Wastes. Chp. 22, Edited by DE Cole, CL Henry and WL Nutter. University of Washington Press, Seattle, Wash. pp. 246–257.

Briggs DG, Thienel G, Turnblom EC, Lowell E, Dykstra D, Ross RJ, Wang X, Carter P. 2008. Influence of thinning on acoustic velocity of Douglas-fir trees in western Washington and western Oregon. In: Proceedings of the 15th International Symposium on Nondestructive Testing of Wood. September 10-12, 2007, Duluth, MN, USA. Forest Products Society: Madison, WI, USA. pp. 113–123.

Brix H. 1972. Nitrogen fertilization and water effects on photosynthesis and earlywood-latewood production in Douglas-fir. Canadian Journal of Forest Research 2(4): 467–478.

Cahill JM, Briggs DG. 1992. Effects of fertilization on wood quality and tree value. In: Proceedings of Forest Fertilization: Sustaining and Improving Nutrition and Growth of Western Forests. February 12–14, 1991, Seattle, WA, University of Washington, College of Forest Resources. pp. 145–161.

Carter P, Briggs D, Ross RJ, Wang X. 2005. Acoustic testing to enhance western forest values and meet customer wood quality needs. PNW-GTR-642, In: Harrington, CA, Schoenholtz SH, eds. Productivity of Western Forests: A Forest Products Focus. USDA Forest Service, Pacific Northwest Research Station, Portland, Oregon. pp. 121–129.

Carter P. 2011. Real-time measures of wood quality—transition from research to application. In: Proceedings, 17th International Nondestructive Testing and Evaluation of Wood Symposium, September 14-16, 2011, University of West Hungary, Sopron, Hungary. pp. 34–39.

Chauhan SS, Walker JCF. 2006. Variation in acoustic velocity and density with age, and their interrelationships in radiata pine. Forest Ecololgy Management 229: 388–394.

Cregg BM, Dougherty PM, Hennessey TC. 1988. Growth and wood quality in young loblolly pine trees in relation to stand density and climate factors. Canadian Journal of Forest Research 18(7): 851–858.

Divos F. 2010. Acoustic tools for seedling, tree and log selection. In: Proceedings, The Future and Quality Control for Wood & Wood Products, May 4-7, 2010, Edinburgh Napier University: Edinburgh, UK. p. 5.

Edmonds RL, Cole DW. 1980. Use of dewatered sludge as an amendment for forest growth: Vol III—Management and biological implications. Center for Ecosystem Studies, College of Forest Resources, University of Washington, Seattle, WA. 120 pp.

Grabianowski M, Manley B, Walker JCF. 2006. Acoustic measurements on standing trees, logs and green lumber. Wood Science Technology 40: 205–216.

Harris PD, Andrews MK. 1999. Tools and acoustic techniques for measuring wood stiffness. Emerging Technologies for Evaluating Wood Quality for Processing, 3rd Wood Quality Symposium Rotorua and Melbourne. Forest Industry Engineering Association, New Zealand.

Harris P, Petherick R, Andrews M. 2002. Acoustic resonance tools. In: Proceedings, 13th International Symposium on Nondestructive Testing of Wood, August 19-21, 2002, Berkeley, CA, pp. 195–201.

Huang CL. 2000. Predicting lumber stiffness of standing trees. In: Proceedings, the 12th International Symposium on Nondestructive Testing of Wood, University of Western Hungary, Sopron, September 13-15, 2000. pp. 173–179.

Huang CL. 2005. System and method for measuring stiffness in standing trees, US patent no. 6,872545.

Kantavichai R, Briggs DG, Turnblom EC. 2010. Effect of thinning, fertilization with biosolids, and weather on interannual ring specific gravity and carbob accumulation of a 55-year-old Douglas-fir stand in western Washington. Canadian Journal of Forest Research 40: 75–82.

Larson PR, Kretschmann DD, Clark A III, Isebrands JG. 2001. Formation and properties of juvenile wood in southern pines: a synopsis. USDA Forest Service. FPL-GTR-129. Madison, Wis.

Lindstrom H, Harris P, Nakada R. 2002. Methods for measuring stiffness of young trees. Holz Roh-Werkst 60:165–174.

Lowell EC, Todoroki CL, Dykstra DP, Briggs DG. 2014. Linking acoustic velocity of standing Douglas-fir trees to veneer stiffness: a tree-log-product study across thinning treatments. New Zealand Journal of Forestry Science 44(1): 1–16.

Mora CR, Schimleck LR, Isik F, Mahon JM, Clark A III, Daniels RF. 2009. Relationship between acoustic varaibles and different measures of stiffness in standing *Pinus taeda* trees. Canadian Journal of Forest Research 39:1421–1429.

Raymond CA, Joe B, Anderson DW, Watt DJ. 2008. Effect of thinning on relationships between three measures of wood stiffness in *Pinus radiata*: standing trees vs. logs vs. short clear specimens. Canadian Journal of Forest Research 38: 2870–2879.

Sonne E, Turnblom E, Briggs D, Becker G. 2004. Log and lumber grades and value from a Douglas-fir stand years after thinning and biosolids fertilization. WJAF 19(1): 34–41.

Wang X. 1999. Stress wave-based non-destructive evaluation (NDE) methods for wood quality of standing trees. Dissertation, Michigan Technological University, Houghton, Michigan. 187 p.

Wang X, Ross RJ, McClellan M, Barbour RJ, Erickson JR, Forsman JW, McGinnis GD. 2001. Nondestructive evaluation of standing trees with stress wave method. Wood and Fiber Science 33(4):522–533.

Wang X, Ross RJ, and others. 2006. System for and method of performing evaluation techniques on a log or round timber. US patent no. 7,043,990; New Zealand patent no. 527,569.

Wang X, Carter P, Ross RJ, Brashaw BK. 2007a. Acoustic assessment of wood quality of raw forest materials—a path to increased profitability. Forest Products Journal 57(5):6–14.

Wang X, Ross RJ, Carter P. 2007b. Acoustic evaluation of wood quality in standing trees. Part I. Acoustic wave behaviour. Wood and Fiber Science 39(1):28–38.

Wang X, Sharplin N, Carter P, Ross RJ. 2008. Method and apparatus for evaluation of standing timber. U.S patent no. 7,418,866 B2.

Wang X. 2013. Acoustic measurements on trees and logs: a review and analysis. Wood Science Technology 47:965–975.