# AN ABSTRACT OF THE THESIS OF

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Abstract approved:

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Glen Murphy

To compete with other building materials, the wood products industry must find a way to increase value and lower costs. Wood stiffness is important for most wood uses. Value can be increased and costs can be lowered by sorting logs for stiffness in the woods using acoustic devices mounted on harvesters and processors in order to properly allocate logs to their processing destination. This decreases shipping costs because logs do not have to be reshipped if they are delivered directly to their final processing location and increases value recovery because only logs that are fit for the end use are processed.

The goal of this study was to determine if four increasingly more difficult-to-measure variables - length from the butt, acoustic velocity, bark percentage, and wood

density - can be used to predict the acoustic velocity variation along the length of a tree in Douglas-fir and thus improve the utility of acoustic devices as tools for the optimal bucking of trees into logs which have been sorted according to stiffness. Research was undertaken in five stands. Six trees were selected from each stand.

Time of flight (TOF) acoustic velocity measured across the bole of the tree had little value in predicting the longitudinal resonance acoustic velocity of a section of the tree. Although TOF across the bole was statistically significant it had a very low correlation coefficient and lacked the ability to accurately and precisely predict resonance acoustic velocity. Wood density, moisture content, and bark percentage were not significant predictors of resonance acoustic velocity of a section of a tree.

The use of tree length resonance acoustic velocities was found to be a statistically significant and strongly correlated predictor of acoustic velocity of tree section. Distance of a log section from the butt of the tree and distance of a section from the butt squared were statistically significant and strongly correlated predictors of acoustic velocity of tree sections.

Final models including resonance acoustic velocity measurements, distance from the butt, and distance from the butt squared were developed with high coefficients of determination ($R^2$ 0.849 using all tree length acoustic velocities (velocities taken every 3 meters up the tree that measured acoustic velocity of the entire tree after the previous 3 meter section), $R^2$ 0.827 using initial tree length acoustic velocity (acoustic velocity of the entire tree), and $R^2$ 0.678 using initial 3 meter log acoustic velocity). The models developed were found to be stand dependent, indicating a possible need for model calibration for each stand to be harvested.

Lower acoustic velocity in the butt of a tree due to high microfibril angle inhibits the predictive capability of models based on acoustic velocity measurements taken from the butt of the tree to predict acoustic velocity of 3 meter sections after the first 6 meters of the tree. Acoustic velocity models based on a 3 meter log acoustic velocity or tree length acoustic measured after the first 6 meters of the tree have been removed are the best predictors of the acoustic velocity of 3 meter sections after the first 6 meters of the tree. Final models based on measurements taken after the first 6 meters of the tree included resonance acoustic velocity measurements and distance from the butt had high coefficients of determination ($R^2$ 0.860 using third tree length acoustic velocity and $R^2$ 0.887 using third 3 meter section acoustic velocities). These models were also found to be stand dependent.

The use of either a single tree length acoustic velocity measurement or a single log acoustic velocity measurement with distance from the butt and/or distance from the butt squared has the potential to increase value recovery from a log by predicting the stiffness in that log and effectively matching it to its end use.

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# Estimating Spatial Changes in Acoustic Velocity in Felled Douglas-fir Stems

by
Bodie Dowding

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Bodie Dowding, Author

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# CHAPTER 1: INTRODUCTION

## Background

To compete with other building materials, the wood products industry must find a way to increase value and lower costs (Amishev 2008). One way to increase value is to properly allocate logs to their processing location. This decreases shipping costs because logs do not have to be reshipped if they are delivered directly to their final processing location and increases value recovery because only logs that are fit for the end use are processed.

Currently, trees are mainly sorted by visual grading, but wood properties vary greatly between logs that have been given the same grade based on visual grading (Wang et. al. 2007). Wood stiffness is one of the most important mechanical properties for most wood uses (Xu et. al. 2004). The structural use of wood depends on its engineering properties and stiffness is an important engineering property because it can be used as an indicator of the ability of wood to support loads and resist bending (Amishev 2008) but wood stiffness cannot be reliably predicted by visual grading (Edlund et. al. 2006). Acoustics can be used to non-destructively test wood for stiffness (Grabianowski et. al. 2006) and thus properly allocate logs to their end uses. Sorting logs by stiffness allows the exclusion of low stiffness logs at sawmills and veneer mills where high stiffness end products are desired. This exclusion of low stiffness wood can help mills avoid producing low quality/value structural lumber and veneer (Edlund et. al. 2006).

Acoustic velocity in wood can be used to predict wood stiffness according to the equation velocity$^2$*wood density = modulus of elasticity (MOE) (Grabianowski et. al. 2006) where MOE is wood stiffness.  Wood density is weakly correlated with acoustic velocity because thicker cells are denser and have a higher proportion of the stiff S2 cell layer (Chauhan and Walker 2006).  Two methods are used to measure acoustic velocity in wood; the resonance method and the time of flight (TOF) method.

Resonance acoustic velocity is measured by the time it takes for sound waves to bounce from one end of a log to the other end and uses a known log length to calculate acoustic velocity in a log.  "With acoustic resonance the entire cross section is assessed by the resonating wave and the calculated stiffness is for the cross sectional weighted average" (Grabianowski et. al. 2006).  Resonance acoustic velocity is not based on a single acoustic pass: multiple passes are involved (in some instances many hundreds) and excellent measurement repeatability is a consequence of this (Grabianowski et. al. 2006).  Because resonance acoustic velocity is an average of speed throughout the log it takes into account the speed of sound in bark which has few fibers and low stiffness and thus lowers the average acoustic velocity measurement for a tree (Chauhan and Walker 2006).  Due to the low frequency of the sound waves involved with resonance acoustic velocity, defects such as knots do not affect speed of sound measurements (Grabianowski et. al. 2006).

TOF acoustic velocity is a measurement of the time it takes for a sound wave to travel between two metal probes inserted into a log with a known distance between them (Wang et. al. 2007).  The known distance and time of travel is used to calculate acoustic velocity. TOF acoustic velocity has been measured with probes inserted on the same side of a tree with distance between the probes being in the longitudinal direction and with probes inserted in opposite sides of a tree with distance between them in the radial and longitudinal direction. TOF acoustic velocity has not been studied using probes inserted directly across the stem of a tree with the main distance difference in the radial direction. TOF acoustic velocity measured across the log with distance in the radial direction will travel fastest around the log in the stiff outer wood of the tree and not straight through the log through the less stiff juvenile wood (Mahon et. al. 2009).

## Rationale

Hand-held tools for measuring acoustic velocity in felled tree stems and logs are being used operationally or in trials in log yards and forests around the world, particularly in New Zealand, Australia, North America and the UK. These tools can be used directly by workers bucking logs for manual processing operations. They could also be used by log-graders for mechanized operations as per the approach suggested by Parker et al (1988); the log-grader would pre-record the acoustic velocity of each marked stem on a hand held computer, and then transfer the information to the on-board computer of the processing machine for later use when the stem is bucked into logs.

The use of mechanized harvesters and processors is increasing around the world. The ability of these systems to recover value from trees tends to be less than that of manual bucking, although not consistently so (Marshall and Murphy 2004).

With mechanization, on-board computers can provide a platform for novel measuring systems, such as acoustic velocity measurement, and optimal bucking. Devices that measure acoustic velocity and their applications on harvesters and processors are currently being studied by the forest products industry (Carter 2007).

Measurement of the acoustic velocity of logs after they have been cut can indicate whether they meet the minimum acoustic velocity thresholds specified for a particular log grade. This approach is also likely to lead to wastage and value loss if the acoustic velocity is found to be too low and the lengths of these logs do not exactly match alternative log products. A better approach would be to predict what the likely acoustic velocity of a log is before a saw cut is made. Understanding how acoustic velocity varies spatially within a tree should improve the chances of bucking the correct log lengths and lead to the proper sorting of logs to their end uses and to increased product quality and value.

The successful application of acoustic velocity measuring devices, whether it be for use with manual log making systems or for use on harvester and processor heads, will rely on the ability to accurately predict wood stiffness along the length of a tree's bole. A regression model that predicts stiffness along the length of a tree stem based on an acoustic velocity measurement at one or more locations of the stem would improve the utility of acoustic velocity measurement devices. To the best of our knowledge there is no model to predict the stiffness of wood in Douglas-fir logs based on acoustic velocity measurements at one or more points of the log.

## Study Goal

The goal of this study was to determine if four increasingly more difficult-to-measure variables - length from the butt, acoustic velocity of a tree or section of a tree, bark percentage of a tree section, and wood density of a tree section - can be used to predict the acoustic velocity variation along the length of a tree in Douglas-fir and thus improve the utility of acoustic devices as tools for the optimal bucking of trees into logs which have been sorted according to stiffness.

In order to accomplish this goal an experiment was designed to (a) determine the relationship between TOF acoustic velocity measured directly across a log in Douglas-fir and resonance acoustic velocity along the stem and (b) predict wood stiffness and acoustic velocity profile in Douglas-fir along the length of a tree stem with a regression model based on acoustic velocity measured at one or more points of a tree, tree wood density, and bark percentage.

Three hypotheses were tested: (1) resonance acoustic velocity would be negatively correlated with bark percentage (the percentage of a tree's cross sectional area that is taken up by bark), (2) a regression model based on acoustic velocity measured at one or more points of a tree, wood density at one or more points, and bark percentage at one or more points will explain at least 70% of the variation in resonance acoustic velocity in Douglas-fir at any one point along the length of a tree stem, and (3) wood stiffness increases from the ground to about 3 meters up the stem of the tree (Xu et. al. 2004) then it decreases as the top of the stem is approached.

In Chapter 2 of this thesis we examine the capability of single and multi-variable models to predict the resonance acoustic velocity of 3 meter sections of a stem. In Chapter 3 we examine differences in the butt log and how these differences affect resonance acoustic velocity prediction in 3 meter sections of a stem. In Chapter 4 we draw conclusions from the previous chapters.

# CHAPTER 2: TREE LENGTH ACOUSTIC VELOCITY

The successful use of acoustic velocity measuring devices to make log bucking decisions will rely on the ability to accurately predict wood stiffness along the length of a tree's bole. A regression model that predicts stiffness along the length of a tree stem based on an acoustic velocity measurement at one or more locations of the stem would improve the utility of acoustic velocity measurement devices.

The goal of this study was to predict the acoustic velocity variation along the length of a tree in Douglas-fir and thus improve the utility of acoustic devices as tools for the optimal bucking of trees into logs which have been sorted according to stiffness.

## Sample Selection

Trees were obtained from stands owned by Roseburg Forest Products in southwest Oregon. Five stands were selected in order to determine if acoustic velocity relationships were stand independent. Six trees were selected from each stand. Trees were selected by eye to be representative of the stand using attributes such as diameter, height, and amount of branches. Trees with obvious defects that may affect acoustic velocity readings such as scars, rot, or conk fungi were excluded. Tree selection was performed with the assistance of a contract supervisor from Roseburg Forest Products. Trees tested had ring counts of 36 to 78 years at the diameter breast height (DBH) measurement point. Tree DBH, total height, height to live crown, and age can be seen in Table1. The longitude, latitude and elevation of the site that the trees originated from were recorded and can be seen in Table 2.

Table 1. Characteristics of the sample trees for the five sites included in the study.

| Stand Name | Stand Number | Tree ID | DBH (mm) | Total Height (m) | Height to Live Crown (m) | Age (yrs.) |
|---|---|---|---|---|---|---|
| Paradise Flats | 1 | 1 | 205 | 26.3 | 18.7 | 41 |
| | | 2 | 424 | 38.1 | 22.4 | 48 |
| | | 3 | 368 | 33.6 | 17.2 | 49 |
| | | 4 | 421 | 36.9 | 19.0 | 48 |
| | | 5 | 279 | 30.6 | 20.6 | 45 |
| | | 6 | 355 | 33.9 | 22.1 | 52 |
| Rock Island Green | 2 | 1 | 375 | 33.6 | 20.0 | 53 |
| | | 2 | 330 | 29.0 | 18.4 | 47 |
| | | 6 | 317 | 28.7 | 16.6 | 47 |
| | | 7 | 365 | 29.0 | 17.5 | 58 |
| | | 8 | 335 | 28.4 | 17.8 | 50 |
| | | 9 | 373 | 33.0 | 18.1 | 52 |
| Oliphant Returns | 3 | 1 | 309 | 30.3 | 21.5 | 44 |
| | | 4 | 297 | 20.9 | 10.3 | 43 |
| | | 5 | 274 | 26.6 | 18.1 | 41 |
| | | 6 | 335 | 31.2 | 19.0 | 50 |
| | | 7 | 195 | 20.9 | 12.1 | 39 |
| | | 8 | 287 | 26.9 | 14.2 | 46 |
| Kirkendalli Lama | 4 | 1 | 292 | 23.9 | 13.3 | 35 |
| | | 3 | 309 | 29.0 | 11.8 | 35 |
| | | 4 | 530 | 38.4 | 15.1 | 78 |
| | | 5 | 495 | 30.3 | 15.1 | 73 |
| | | 8 | 314 | 29.6 | 17.8 | 36 |
| | | 9 | 274 | 26.6 | 16.3 | 37 |
| Vincent 28 Flats | 5 | 3 | 309 | 30.9 | 19.6 | 42 |
| | | 4 | 449 | 37.2 | 22.1 | 40 |
| | | 5 | 350 | 33.6 | 22.1 | 44 |
| | | 6 | 231 | 26.0 | 20.3 | 38 |
| | | 7 | 363 | 34.2 | 10.3 | 40 |
| | | 8 | 220 | 27.8 | 22.1 | 37 |

Table 2. Stand locations

| Stand Name | Stand Number | Longitude | Latitude | Elevation (m) |
|---|---|---|---|---|
| Paradise Flats | 1 | 43° 43’ | 123° 35’ | 235 |
| Rock Island Green | 2 | 43° 26’ | 123° 25’ | 675 |
| Oliphant Returns | 3 | 43° 20’ | 123° 22’ | 285 |
| Kirkendalli Lama | 4 | 43° 0’ | 123° 40’ | 455 |
| Vincent 28 Flats | 5 | 43° 43’ | 123° 46’ | 270 |

## Measurement and Processing Procedures

### Tree Processing

Trees were felled and limbed and the tops were removed at approximately 10 cm (~ 4”) diameter (over bark). This was done to eliminate the effect that limbs and tree tops can have on adding variation to the measured speed of resonance acoustic velocity (Amishev 2008). Acoustic signals do not return well off of limbs and tops because there is a lack of a clear ending surface for the signal to bounce back from. We recognize that delimbing and topping each tree before acoustic measurements were taken would not be a preferred operational practice. Controlling some of the causes of variation in this study was necessary because of the small sample size for each stand. In many cases, however, tree tops broke at diameters larger than 10 cm over bark when the tree was felled. When this happened the tree top was cut previous to the break and the diameter was recorded.

### Acoustic Velocity

The acoustic velocities of trees were measured when the trees were lying on the ground and, where possible, separated from other trees. If trees to be measured were touching other trees this was noted.

The IML Hammer TOF acoustic velocity device (IML Inc., Kennesaw, Georgia, USA) was used to measure TOF acoustic velocity. TOF acoustic velocity (km/sec) was measured directly across the tree at the base of the large end of the tree and then every one meter up the tree until the bucked top was reached. TOF acoustic velocity measurements taken at the end nearest the butt of each 3 meter section were used for prediction of resonance acoustic velocities of 3 meter sections. The TOF acoustic velocity signal was measured between screws placed in each side of the tree. Acoustic velocity signals recorded were an average of at least 3 acoustic velocity signals taken at a single location. Distance between the tops of the screws was measured with a pair of Haglof 95 cm calipers to the nearest tenth of a cm and then the screw lengths were subtracted to get the shortest distance the acoustic velocity signal could travel.

Resonance acoustic velocity (km/sec) was measured from the flat cut surface at the large end of the tree to the bucked top using the Director HM200 resonance acoustic velocity measurement device (Fibre-Gen, Christchurch, New Zealand). The tree was then bucked three meters up from the large end and resonance acoustic velocity was measured on the three meter section. Resonance acoustic velocity measurements were repeated as previously described for the new location of the large end of the tree. The process of cutting off the 3 meter section and measuring the remaining tree length and the 3 meter section acoustic velocity was repeated along the entire length of the tree. For most trees, diameter over and under bark to the nearest one cm was measured after bucking using a hand held measuring tape for the wide and narrow cross section of the tree trunk every three meters up the tree at the bucking point. For nine trees (trees 1, 2, 3, and 4 from Stand 1 and trees 1, 2, 6, 7, 8, and 9 from Stand 2), diameter over and under bark was measured to the nearest 1/8th of an inch using a hand held measuring tape for the wide and narrow cross section of the tree bucking location and then converted to cm. Diameters over and under bark were used to determine the bark percentage (bark area/ (xylem area + bark area) * 100).

### Moisture Content, Density, and Specific Gravity

Disks, approximately 3 cm thick, were cut at the initial large end of the tree and every 12 m up the tree. All disks were cut either the day the tree was felled or the day after. If the end the disk was cut from had been exposed for over 4 hours the disk was taken after the end had been trimmed to reduce the impact of drying on wet moisture content measurements. This was only a concern with the butt end of the tree because all other disks were cut soon after the tree was bucked.

Wedges were cut from these disks, bark was removed, and wedges were placed in plastic bags until they could be weighed. All wedges were weighed in their plastic bags to account for moisture that escaped the wedges. Wedges were weighed either the same day or the day after they were cut. Plastic bag weight was subtracted to get disk weight. Wedges from stand 1 trees 5 and 6 were reweighed 4 days after their initial weighing to check for potential moisture loss problems from plastic bags. Table 3 shows initial wedge weights and weights after 4 days in the plastic bags. In all wedges, moisture content change was less than 1%.

Table 3. Changes in wedge weights after 4 days in plastic bags

| Wedge | Initial Weight (g) | Weight after four days (g) | Moisture Content Percent Change |
|---|---|---|---|
| 151 | 438.17 | 435.96 | 0.50% |
| 152 | 267.91 | 265.30 | 0.97% |
| 153 | 250.49 | 248.59 | 0.76% |
| 161 | 541.50 | 543.10 | -0.30% |
| 162 | 501.68 | 498.85 | 0.56% |
| 163 | 242.10 | 240.20 | 0.78% |

Wedge 151 = stand 1, tree 5, wedge 1

Wedges for trees 1 to 4 from Paradise Flats were trimmed to below 100 g the day they were cut in order to not exceed scale capacity. It is likely these wedge moisture contents were somewhat lower than measured moisture contents since the wedges were placed back in the bags in which they were kept before they were trimmed and weighed along with the moisture that had escaped from the larger pre-trimmed wedge. Moisture from wood sweating was measured for a wedge and was found to be approximately 0.04 g which represents a moisture content of less than one percent.

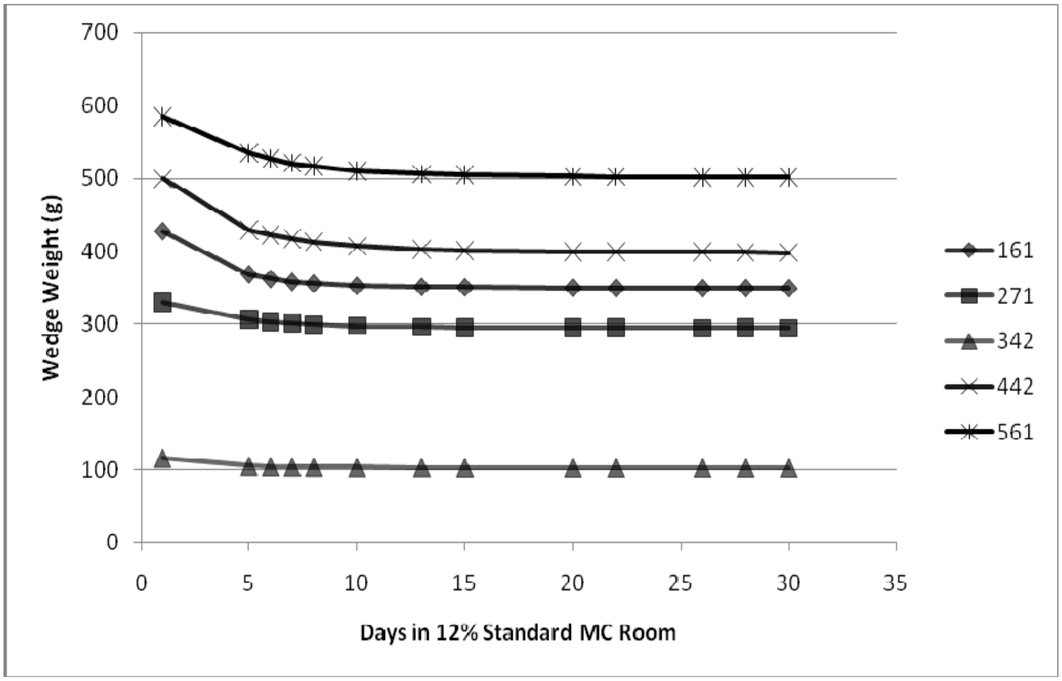
To determine density at the time of acoustic velocity testing volume measurements were undertaken using the Archimedes principle after the disks had been saturated to return them to green volume.

Once disks were weighed and measured for volume they were placed in a room at 30 degrees C and 20 percent relative humidity to be dried to moisture content of 12%. Weight losses of the disks were tracked for the thickest disks and once weight loss had stabilized disks were considered to be at 12% equilibrium moisture content. A graph of moisture content changes in the disks tracked can be seen in Figure 1.

Disks at 12% moisture content were weighed and wet moisture content was determined using calculated oven dry weight and known weight at time of testing. Moisture contents percentages are expressed on an oven dry wood basis.

Oven dry weight of disks was found by calculating the weight at 0% MC using known disk weight at 12% MC. Oven dry weight was then used with green volume to find basic (green) specific gravity.

Figure 1. Changes in wood weight over a 30 day period due to drying for the thickest wedge from each of the five stands.



Legend indicates the stand, tree, and disk identity; e.g. 161 = stand 1, tree 6, disk 1.

## Data Analysis

Data were analyzed using SAS 9.2. The dependent variable was the HM200 acoustic velocity of each 3 m section (HM200_3m). Individual variables were examined using a general linear model to determine their predictive capability for determining the acoustic velocity in each 3 meter log section along the length of the tree. These variables included:

- Diameter over bark (DOB) at the small end of the log
- Wood moisture content percent on an oven dry basis (MC)
- IML Hammer acoustic velocity across tree (IML_Vel)
- Wood density (Density)
- Bark percentage of cross sectional area (Bark)
- Basic Specific Gravity (SG)
- HM 200 remaining acoustic velocities of the initial tree length and all top lengths after bucking 3 m sections (HM200_Tree)
- HM 200 initial tree length acoustic velocity (HM200_InitTree)
- HM 200 acoustic velocity for the first 3 m section (HM200_Init3m)
- Distance from the butt of the tree (Dist).
- Distance from the butt of the tree squared ($\text{Dist}^2$).

Variables providing predictive capability were used to build multiple regression equations using a general linear model. Final multi-variable models used HM 200 readings (HM200_InitTree, HM200_Tree, and HM200_Init3m) and distance from the butt (Dist) as predictors and were tested for stand differences for both intercept and slope using stepwise backward regression. For all models, natural log (LN) and square root (SQRT) transformations were used to transform the dependent 3 meter section acoustic velocity. For all models the independent variable distance from the butt was transformed using LN and SQRT and was tested with and without 3 meter section transformations. Three models (one for all “tree length” HM200_Tree readings, one for the initial tree length HM200_InitTree reading, and one for the initial three meter log HM200_Init3m reading were used as predictors) were found to be the best predictors of HM200_3m acoustic velocities by calculating the root mean square error of the predicted acoustic velocity for each 3 meter segment. Root mean square error was calculated once the predicted value had been back transformed if transformations were used.

**Results**

Summary statistics for variables measured can be seen in Table 4. Summary statistics by stand for variables measured can be seen in the Appendix in Table A1.

Table 4. Summary statistics for variables measured.

| | DOB (cm) | MC (%) | IML_Vel (km/sec) | Density (g/cm³) | Bark (%) | HM200 InitTree (km/sec) | HM200 Init3m (km/sec) | SG |
|---|---|---|---|---|---|---|---|---|
| Average | 28.3 | 82 | 1.18 | 0.85 | 12.5 | 3.65 | 3.81 | 0.47 |
| St. Dev. | 9.2 | 23 | 0.18 | 0.08 | 3.6 | 0.19 | 0.23 | 0.04 |
| Min | 7.6 | 51 | 0.61 | 0.69 | 7.7 | 3.17 | 3.32 | 0.39 |
| Max | 59.0 | 152 | 1.49 | 1.05 | 23.6 | 4.01 | 4.25 | 0.55 |

A graph of IML hammer velocities as a function of distance from the butt can be seen for Stand 5 in Figure 2; this stand was selected as being representative of the five stands. Graphs for all stands can be seen in the Appendix in Figures A1 to A5. IML hammer velocities decreased gradually as distance from the butt increased. A graph of HM 200_3m velocities as a function of distance from the butt can be seen in

Figure 3. Graphs for all stands can be seen in the Appendix in Figures A6 to A10. HM200_3m velocities increased from the first 3 meter section and were greatest in the second and third 3 meter sections. HM200_3m velocities then decreased with height in the tree.

Figure 2. IML hammer TOF acoustic velocity (IML_Vel) from Stand 5

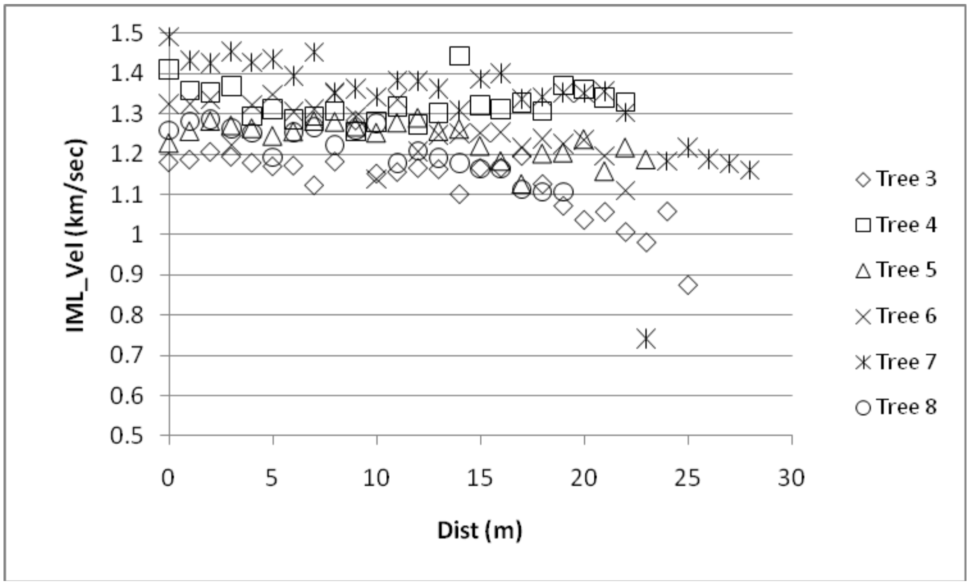
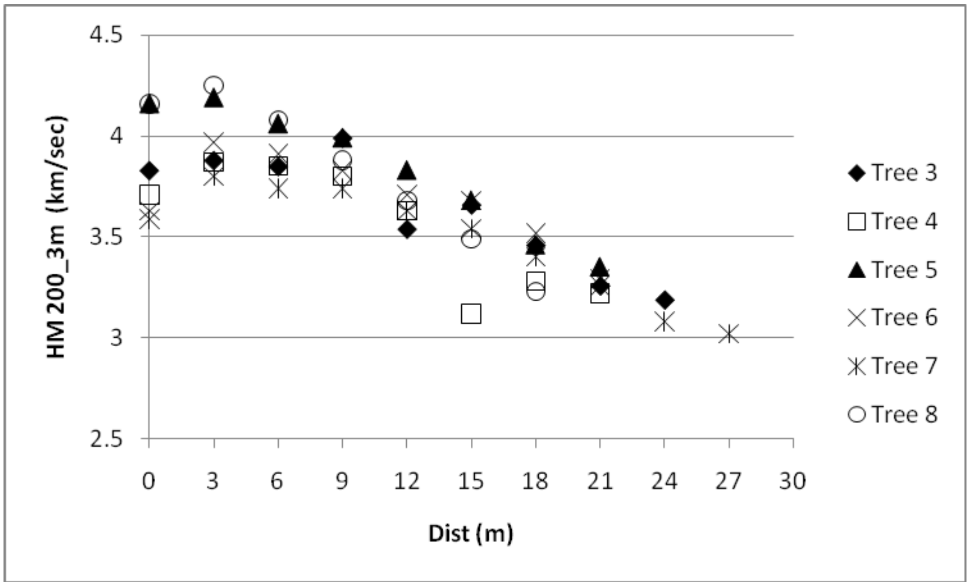


Figure 3. HM200 resonance acoustic velocity (HM200_3m) from Stand 5



**Single Predictor Models**

Diameter over bark was significant ($p < 0.0001$) in predicting resonance acoustic velocity of the 3 meter sections but it had a low R-Square value (0.130) (Appendix, Table A2). When diameter over bark was combined in the final model the R-Square increased from 0.796 to 0.799. This increase was very small and in order to keep the final model simple diameter over bark was not included.

Wood moisture content percentage was not significant ($p = 0.162$) in predicting resonance acoustic velocity of the 3 meter sections and was not included in the final model (Appendix, Table A3).

The IML Hammer readings were significant ($p = 0.004$) predictors of resonance acoustic velocity of the 3 meter sections but due to a low R-Square (0.036) they were not included in the final model (Appendix, Table A4).

Wood density was not a significant (p = 0.162) predictor of resonance acoustic velocity of the 3 meter sections and was not included in the final model (Appendix, Table A5).

Bark was not significant (p = 0.965) in predicting resonance acoustic velocity of the 3 meter sections and was not included in the final model (Appendix, Table A6).

SG was not significant (p = 0.965) in predicting resonance acoustic velocity of the 3 meter sections and was not included in the final model (Appendix, Table A7).

Table 5 shows the correlation of HM200_3m readings with HM200_Tree velocities. HM 200 tree length readings were significant (p < 0.001) in predicting resonance acoustic velocity of the three meter sections and had a high R-Square value (0.767). HM 200 tree length readings were included in the final model to predict resonance acoustic velocity of the 3 meter sections.

Table 5. Model parameters for HM200_3m vs. HM200_Tree

| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | -0.355 | 0.149 | -2.38 | 0.0180 |
| HM200_Tree | 1.169 | 0.043 | 27.24 | <.0001 |

Table 6 shows the correlation of distance of the 3 meter section from the butt of the tree with HM 200 3 meter section velocities. Distance of the 3 meter section from the butt of the log was a significant (p < 0.0001) predictor of the resonance acoustic velocity of the three meter sections and had a high R-Square value (0.478). Distance of the 3 meter section from the butt was included in the final model to predict resonance acoustic velocity of the 3 meter sections.

Table 6. Model parameters for HM200_3m vs. Dist

| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 4.015 | 0.028 | 145.57 | <.0001 |
| Dist | -0.032 | 0.002 | -14.39 | <.0001 |

Fit statistics for single-variables used to construct multi variable models can be seen in Table 7.

Table 7. Fit statistics for single-variable models predicting HM200_3m

| Predictors | R-Square | Coef Var | RMSE |
|---|---|---|---|
| HM200_Tree | 0.767 | 4.262 | 0.157 |
| Dist | 0.479 | 6.373 | 0.235 |

### Multi-Variable Models

Multi-variable models were initially constructed by ignoring potential differences between stands.

The model shown in Table 8 was the initial multi-variable model constructed. This model was constructed using Dist and HM200_Tree because these were the only two single variables that explained large amounts of the variation in HM200_3m acoustic velocities. Adding other single variables to the model had little effect on improving the fit of the model. This model was highly significant ($p < 0.0001$) and was able to explain 79.6% of the variation of the 3 meter section acoustic velocity readings. This model was built using tree length acoustic velocity readings that were taken every three meters up the tree.

Table 8. Model parameters for HM200_3m vs. HM200_Tree and Dist

| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 0.411 | 0.193 | 2.13 | 0.0341 |
| HM200_Tree | 0.978 | 0.052 | 18.75 | <.0001 |
| Dist | -.010 | 0.002 | -5.73 | <.0001 |

In order to see if the 3 meter acoustic velocity could be predicted using only the initial tree length reading, the tree length acoustic reading taken from the butt of the tree was used with distance from the butt as an additional predictor. The model shown in Table 9 was produced. This model was highly significant ($p < 0.0001$) and was able to explain 75.0% of the variation of the 3 meter section acoustic velocity readings. This shows that the 3 meter section acoustic velocity can be predicted using only two variables; the first tree length acoustic velocity and the distance from the butt.

Table 9. Model parameters for HM200_3m vs. HM200_InitTree and Dist

| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 0.636 | 0.217 | 2.93 | 0.0037 |
| HM200_InitTree | 0.925 | 0.059 | 15.64 | <.0001 |
| Dist | -0.032 | 0.002 | -20.52 | <.0001 |

In order to see if the 3 meter acoustic velocity could be predicted using a reading from the first log, the reading from the 3 meter butt section of the tree was used with distance from the butt as an additional predictor. The model shown in Table 10 was produced. This model was highly significant ($p < 0.0001$) and was able to explain 64.5% of the variation of the 3 meter section acoustic velocity readings. This shows that the 3 meter section acoustic velocity can be predicted using only the acoustic velocity from the first log of the tree and the distance from the butt.

Table 10. Model parameters for HM200_3m vs. HM200_Init3m and Dist

| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 1.749 | 0.221 | 7.90 | <.0001 |
| HM200_Init3m | 0.593 | 0.058 | 10.29 | <.0001 |
| Dist | -0.032 | 0.002 | -17.02 | <.0001 |

Fit statistics for multi-variable models can be seen in Table 11.

Table 11. Fit statistics for multi-variable models predicting HM200_3m

| Predictors | R-Square | Coef Var | RMSE |
|---|---|---|---|
| HM200_Tree and Dist | 0.796 | 3.990 | 0.147 |
| HM200_InitTree and Dist | 0.750 | 4.422 | 0.163 |
| HM200_Init3m and Dist | 0.645 | 5.267 | 0.194 |

All three initial multi-variable models were then reanalyzed with and without log and square root transformations and using stepwise backward regression to look for stand differences in both slope and intercept. $Dist^2$ was also added to all of the models in an attempt to account for the lower acoustic velocity of the initial 3 meter sections. A t-test for dependent samples was used to compare the first and second 3 meter section acoustic velocities. The second 3 meter sections had statistically higher acoustic velocities based on a 95% level of significance ($p<0.001$).

The final model using all tree length (HM200_Tree) readings and distance from the butt as predictors for the 3 meter section acoustic velocities is shown in Table

12. This model found the intercepts of Stands 4 and 5 to be significantly different from the other three stands (p = 0.0080 and 0.0257 respectively) but no slope differences were found between stands. Both Dist and Dist$^2$ were significant in this model. This model had a high R-Square of 0.849 and a RMSE of 0.128.

Table 12. Model parameters for HM200_3m vs. HM200_Tree, Dist, and Dist$^2$

| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 0.459 | 0.169 | 2.71 | 0.0072 |
| HM200_Tree | 0.944 | 0.046 | 20.59 | <.0001 |
| Dist | 0.020 | 0.004 | 4.83 | <.0001 |
| Dist$^2$ | -.0014 | 0.000 | -7.96 | <.0001 |
| S4 | -.060 | 0.022 | -2.68 | 0.0080 |
| S5 | -.048 | 0.021 | -2.25 | 0.0257 |

The final model using the initial tree length (HM200_InitTree) reading and distance from the butt as predictors for the 3 meter section acoustic velocity can be seen in Table 13. This model found the intercepts of Stands 4 and 5 to be significantly different from the other three stands (p = 0.0014 and 0.0194 respectively). Slopes from Stand 1, 4, and 5 were found to be significantly different from slopes from the other two stands (p = 0.0110, 0.0002, and 0.009 respectively). Dist$^2$ was significant in this model but not Dist. This model had a high R-Square of 0.827 and a RMSE of 0.137.

Table 13. Model parameters for HM200_3m vs. HM200_InitTree and $Dist^2$

| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 0.746 | 0.191 | 3.90 | 0.0001 |
| HM200_InitTree | 0.879 | 0.052 | 16.85 | <.0001 |
| $Dist^2$ | -0.002 | 0.000 | -18.73 | <.0001 |
| S4 | -0.105 | 0.032 | -3.24 | 0.0014 |
| S5 | -0.076 | 0.032 | -2.36 | 0.0194 |
| $Dist^2$*S1 | 0.0003 | 0.0001 | 2.57 | 0.0110 |
| $Dist^2$*S4 | 0.0006 | 0.0002 | 3.75 | 0.0002 |
| $Dist^2$*S5 | 0.0005 | 0.0001 | 3.37 | 0.0009 |

The final model using the initial 3 meter log (HM200_Init3m) reading and distance from the butt as predictors for the 3 meter section acoustic velocities (LN transformation) is shown in Table 14. The intercepts of all five stands were found to be significantly different from each other. $Dist^2$ was not significant in this model. The model had an R-Square value of 0.678 and a RMSE of 0.185 (recalculated after back transformations were made).

Table 14. Model parameters for HM200_3m (LN transformation) vs. HM200_Init3m and Dist

| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 0.911 | 0.077 | 11.85 | <.0001 |
| HM200_Init3m | 0.135 | 0.020 | 6.87 | <.0001 |
| Dist | -.009 | 0.000 | -17.98 | <.0001 |
| S2 | -.033 | 0.011 | -2.97 | 0.0033 |
| S3 | -.051 | 0.013 | -3.99 | <.0001 |
| S4 | -.051 | 0.011 | -4.65 | <.0001 |
| S5 | -.034 | 0.011 | -3.21 | 0.0015 |

Fit statistics for multi-variable models considering stand differences can be seen in Table 15.

Table 15. Fit statistics for multi-variable models with stand differences predicting HM200_3m

| Predictors | R-Square | Coef Var | RMSE |
|---|---|---|---|
| HM200_Tree, Dist, and Dist$^2$ | 0.849 | 3.458 | 0.128 |
| HM200_InitTree and Dist | 0.827 | 3.718 | 0.137 |
| HM200_Init3m and Dist | 0.678 | 3.990 | 0.052 |

## Discussion

To increase the value recovery from mechanical harvesters industry should look at improved scanning, forecasting, and optimization systems to assist operators in log making (Marshall and Murphy, 2004). A forecasting system that more accurately forecasts both stem form and quality may yield higher net value recovery results (Marshall and Murphy 2004). In this study we have looked at models for forecasting acoustic velocity as a surrogate for wood stiffness.

### Single Predictor Models

Diameter over bark was significant in predicting resonance acoustic velocity of the 3 meter sections but had a low R-Square of 0.130. The significance of diameter over bark in predicting acoustic velocity of the 3 meter sections can likely be attributed to the relationship that diameter has with height and that height has with microfibril angle. Microfibril angle is responsible for a rapid increase in stiffness in the vertical direction (Xu et. al. 2004) and is a major determinant of wood modulus of elasticity (Evans and Ilic, 2001). Acoustic velocity of the 3 meter sections was shown to decrease with a decrease in diameter. This relationship would be expected because as the top of the tree is approached tree diameter decreases and the proportion of juvenile wood with a high microfibril angle increases. This increase in microfibril angle would cause the decrease in acoustic velocity. One possible explanation of why diameter was such a weak predictor of acoustic velocity of the 3 meter sections is that trees that are grown faster and have the same diameter as slower grown trees will have larger percentages of juvenile wood and thus higher microfibril angles which will slow acoustic velocity. In this data set it is likely that larger diameter trees were grown faster since all trees measured were of similar age (average 46 yr., SD 9.7 yr., range 36 - 78 yr. at DBH). This would cause larger diameter trees to have higher proportions of juvenile wood and slower acoustic velocities countering the effect of decreasing microfibril angle with decreasing diameter along the length of the tree stem.

Wood moisture content percentage was not significant in predicting resonance acoustic velocity of the 3 meter sections. Acoustic velocities are lower in wet wood as compared to dry wood but with MC% above 40% there is little effect on acoustic velocity (Carter et. al. 2004). Wedge moisture content measured varied from 51 to 151% on an oven dry basis. The finding that moisture content is not a predictor of acoustic velocity agrees with Carter et. al. (2004). It is possible that moisture content does affect acoustic velocity but that it is does not have as much of an effect as other factors such as microfibril angle. The experiment conducted did not look at changing moisture content in the same logs but at moisture contents and acoustic velocities between different logs. It would be beneficial to conduct a future study where a number of logs are repeatedly measured for acoustic velocity as their moisture content changes.

The IML Hammer TOF acoustic readings were a significant predictor of HM200_3m resonance acoustic velocity but accounted for less than 4% of the variation. This did not agree with previous research that “a strong relationship was found between tree velocity (TOF) and log velocity (HM200)” (Wang et. al. 2007) and the correlation coefficient comparing TOF and resonance velocities on the logs was 0.96 (Grabianowski et. al. 2006). However Amishev, (2008) found that for Douglas-fir there is a weak coefficient of determination of 0.25 between sound velocities of standing trees measured by the TOF method and the corresponding speed in the butt logs, measured by the resonance based method. One possibility for the difference of the results of this study and those of previous studies is that in previous studies TOF acoustic velocity was measured in the longitudinal direction of the stem while in this study it was measured across the stem. In practice the velocity of sound in a log is roughly five times greater in the longitudinal than in the radial direction (Chuahan et. al. 2005). Properties vary greatly in wood depending on its orientation. A sound wave traveling across the stem would have to travel perpendicular to most of the cells and microfibrils in the tree since the majority are oriented in the longitudinal direction while a sound wave travelling in the longitudinal direction would travel along the length of the majority of the cells and microfibrils. Usually velocities are higher in the radial than in the tangential direction (Maurer et. al. 2006). This suggests that the sound wave passed across the stem can be assumed to travel straight though the stem and not around it. The difference in travel route of the sound waves across the stem in this study and along the stem in past studies is the likely cause of the differing results of the TOF measurement to predict a resonance measurement.

It was observed, but not recorded, that TOF acoustic velocity signals measured across the stem varied greatly at the same location.  Amishev (2008) also observed that substantial variability occurred from hit to hit within each side of the tree using a Director ST300 TOF acoustic velocity tool.  Previous research has found that the inherent accuracy and robustness of the resonance method provides a significant advantage over TOF measurement (Wang and Ross et. al. 2007).  In this study the resonance method was observed to yield repeatable results for the same location while the TOF results varied for the same location.

Density of the wood wedges was not a significant predictor of the resonance acoustic velocity of the 3 meter sections.  The densities of the wedges measured varied from 0.69 to 1.05 g/cm$^3$ and with this large of a spread of densities it would be expected that if there were an effect of density on acoustic velocity it would have emerged.  The findings that density was not significant in predicting acoustic velocity is in line with previous research by Chauhan and Walker, (2006) who found that density was not a significant predictor of acoustic velocity.

Hypothesis 1, that resonance acoustic velocity would be negatively correlated with bark percentage, was not supported in this study.  Bark percentage of cross sectional area was not significant in predicting resonance acoustic velocity of the 3 meter sections.  These findings did not agree with previous studies.  A small experiment in a mill yard on 81 Douglas-fir logs found an average increase in resonance acoustic velocity of 4.6% for debarked logs, (Amishev, 2008) and another study found that removal of bark increased dynamic MOE by an average of 8.3% in 11 yr old radiata pine (Lasserre et. al. 2007). Grabianowski et. al. (2006) found that bark slows resonance acoustic velocity readings. In these previous studies the same logs were compared with and without bark. In the current study logs were not debarked but the percentage of their cross sectional area that was bark was recorded. This percentage varied up the trees but for butt logs average bark percentage varied from 13 to 23%. Bark would be expected to influence resonance acoustic velocity because resonance acoustic velocity is a weighted average of the entire cross section of a specimen (Grabianowski et. al. 2006). This cross sectional weighted average would take into account the bark which has a lower stiffness and thus lower acoustic velocity than wood and would cause the acoustic velocity to fall. It is likely that other differences between trees such as microfibril angel have a much larger effect on acoustic velocity than bark and the effect that bark would have is dominated by and lost in these other factors.

SG was not significant in predicting resonance acoustic velocity of the 3 meter sections. SG and acoustic velocity are both known to be good predictors of stiffness and as a result they would be expected to be related. Lachenbruch et. al. (2010) found that density at 12% MC (density at 12% is directly related to SG) had a poor correlation (R = 0.36) with acoustic velocity. Findings in this study are closely aligned with findings in previous studies.

HM 200 tree length (HM200_Tree) readings were significant in predicting resonance acoustic velocity of the three meter sections and accounted for almost 77% of the variation in HM200_3m readings. This result agrees with Amishev (2008) who found that the measured acoustic velocity of the whole tree can be a good predictor of the wood stiffness for each log produced from that tree based on log length and position up the stem. “The velocity measured by resonance frequency obeys the law of mixtures and is controlled by the volume weighted average stiffness of the material” (Chuahan et. al. 2005). It would follow that because a whole tree acoustic velocity measurement is a measurement of the weighted average of the tree, the measurement would be able to give indication of acoustic velocity variation along the stem.

Distance of the 3 meter section from the butt of the log was significant in predicting resonance acoustic velocity of the 3 meter sections and accounted for almost 48% of the variation in HM200_3m readings. Acoustic velocity of the 3 meter sections was shown to decrease with increasing distance from the butt of the log. This decrease in acoustic velocity as you move toward the top end of the tree is logical because microfibril angle is a major determinant of wood modulus of elasticity (Evans and Ilic, 2001) and as you move further toward the top of a tree the proportion of juvenile wood with a high microfibril angle increases causing a decrease in acoustic velocity.

### Multi-variable Models

The first multi-variable model constructed included both the HM 200 tree length (HM200_Tree) readings and distance from the butt as predictor variables. It accounted for close to 80% of the variation in HM200_3m acoustic velocity. This model uses the tree length acoustic velocity readings from the base of every 3 meter section and the distance from the butt of the tree of the 3 meter section to predict the acoustic velocity of the 3 meter section. While it is not feasible in a production operation to cut a tree every 3 meters to get an acoustic velocity reading, this model does demonstrate that the tree length reading and distance of the log from the butt could be used to predict the acoustic velocity in a log.

In order to develop a more practical model for predicting the resonance acoustic velocity of individual sections of a tree only the first tree length resonance acoustic velocity (HM200_InitTree) and the distance of the 3 meter section from the butt were used as predictor variables. This second model was highly significant and accounted for close to 75% of the variation in acoustic velocity. With the use of this model a tree could have one acoustic velocity measurement taken from the butt along the entire length of the tree to the breakpoint or top cut and, with a known length, the acoustic velocity in any portion of the tree could be predicted. This would be highly advantageous for an acoustic velocity device mounted on a harvester or processor head because the tree would only have to be handled once to determine an acoustic velocity profile along the stem.

Often the length of a tree to the breakpoint or top cut is not known when it is being handled by a harvester or processor. In this case an acoustic velocity reading on a whole tree would have to be based on an estimated tree length which would add to any errors associated with the model. To overcome this a third model was developed that uses the acoustic velocity of the first 3 meter section of the tree and the distance from the butt to determine acoustic velocity down the length of the tree. This model was also highly significant and accounted for almost 65% of the variability in HM200_3m acoustic velocity. With the use of this model an acoustic velocity profile can be developed for a tree with only the acoustic velocity of the first log and the known distance of a section of the tree from the butt.

In all three initial multi-variable models using resonance acoustic velocities and distance from the butt as predictors for 3 meter section acoustic velocity, resonance acoustic velocities were positively correlated with the 3 meter section acoustic velocities and distance from the butt was negatively correlated with the 3 meter section acoustic velocities. These positive and negative correlations had the same direction to those found when using resonance acoustic velocity and distance from the butt separately to predict the 3 meter section acoustic velocity.

There were significant differences in the predicted acoustic velocity profile between stands for all three final models that were constructed. For the models using HM200_Tree and HM200_Init3m as predictor variables the differences were constant and did not depend on the distance from the butt. For the model using HM200_InitTree as a predictor variable stand difference were also linked to distance from the butt.  Since stand differences were found it may be necessary to develop a simple procedure for calibrating acoustic profile models for each stand to be harvested.

Of the three final models produced the model using initial tree length acoustic velocity with $Dist^2$ to predict the 3 meter section acoustic velocity would be the most desirable to use because it has a higher correlation coefficient than the model that uses the first log as a predictor and it only required the log to be handled once.  The model that uses all tree length acoustic velocities to predict 3 meter section acoustic velocities is impractical in harvest operations because it requires many measurements and would be likely to negatively impact log processing productivity.

The use of either the single tree length acoustic velocity measurement or the first log acoustic velocity measurement has the potential to increase value recovery from a log because that log could be more effectively matched to its end use based on its stiffness.

Hypothesis 3, wood stiffness increases from the ground to about 3 meters up the stem of the tree (Xu et. al. 2004) then it decreases as the top of the stem is approached was substantiated.  Figure 3 shows the acoustic velocity of the sample trees in stand 5 increasing from the initial 3 meter section to the second 3 meter section and decreasing down the log from there.  Other stands showed the acoustic velocity increasing as far out as the third 3 meter section and then decreasing as the end of the tree was approached.  More detailed analysis and discussion of acoustic differences in the butt log is provided in Chapter 3.

The applications of the results of this study are limited to Douglas-fir because it was the only species tested. All five stands were located in southwest Oregon and due to variation by geographic region the results of this study should be used with care when applying them to Douglas-fir in other geographic regions. Trees tested varied in age from 36-78 years and this study may not be applicable to trees outside of this age range. Trees tested were selected to be free of visible defects such as sweep, rot, and scaring and trees with these characteristics may have different acoustic velocity profiles due to their defects. All trees were tested either the day they were felled or the day following felling. In production operations trees often are left in the brush for weeks before being brought to the landing where they can be tested for acoustic velocity. Due to drying, acoustic velocity profiles may differ if trees are not tested immediately after felling.

Future research should be directed to mitigate the limitations of this study. Species other than Douglas-fir should be tested to determine how acoustic velocity profiles vary between species. Douglas-fir trees should be tested from regions with growing conditions that differ from those in southwest Oregon to see if regional differences in trees affect acoustic velocity profile. Trees with defects such as sweep, rot, and scarring should be tested to see how these defects affect acoustic velocity profiles. Trees should be tested for acoustic velocity at varying times after felling to see how acoustic velocity profiles vary as moisture content decreases.

# CHAPTER 3: ACOUSTIC DIFFERENCES IN THE BUTT LOG

## Background

In the previous chapter it was shown that the use of either a single tree length acoustic velocity measurement or the first log acoustic velocity measurement can be used to predict the stiffness of sections of a tree and to increase value recovery. This increase in value will come from matching logs to their end uses by stiffness.

Previous research using radiata pine has shown wood stiffness increases from the ground to about 3 meters up the stem of the tree (Xu et. al. 2004) then it decreases as the top of the stem is approached. This study has shown a similar pattern for acoustic velocity in Douglas-fir. This lower acoustic velocity in the butt of a tree causes the acoustic velocity in Douglas-fir to increase for approximately the first 6 meters from the butt of the tree and then decrease afterwards. The acoustic velocity profile of Douglas-fir is very close to a straight line after the first 6 meters of the butt, as can be seen in Chapter 2, Figure 3. This decrease in acoustic velocity at the butt of a Douglas-fir log is a likely cause of variation in models predicting acoustic velocity at points along the length of a log. To test the effect of the lower acoustic velocity of the butt of a stem on acoustic velocity profile models, models were compared for their ability to predict 3 meter sectional acoustic velocities (HM200_3m). The best model using the initial tree length (HM200_InitTree) reading with distance from the butt was compared to the best model using the third tree length (HM200_6mTree) reading with distance from the butt. The best model using the initial 3 meter log (HM200_Init3m) reading with distance from the butt was compared to the best model using the third 3 meter log (HM200_6m3m) reading with distance from the butt. Figure 4 illustrates acoustic measurements used to construct models.

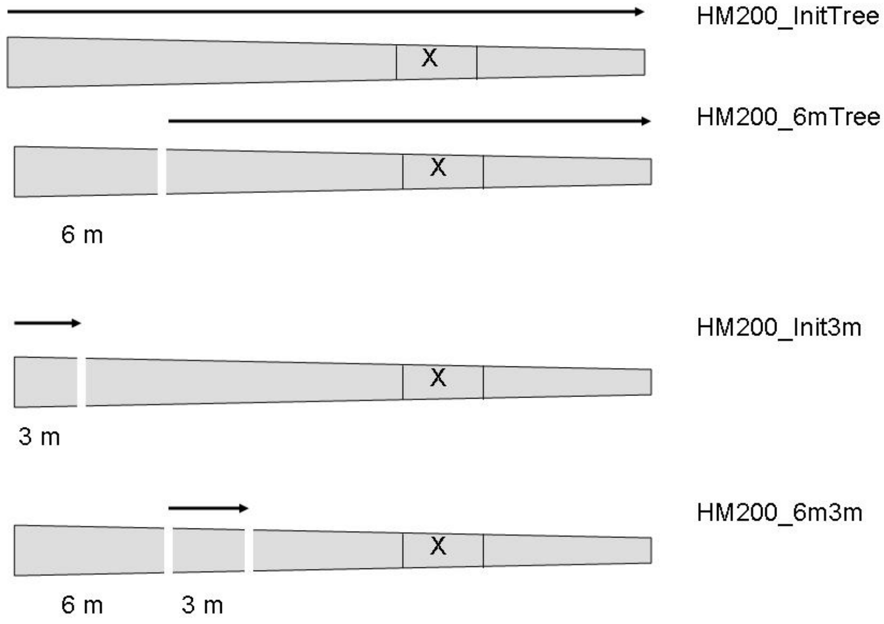


Figure 4. Four approaches for predicting acoustic velocity in a section of stem based on prior measurements. The objective is to predict the acoustic velocity of the section of stem marked X, where X can be located anywhere further up the tree. In the top approach a prior acoustic velocity measurement is taken from the butt of the stem to the top (HM200_InitTree). In the second approach the bottom 6 m section of the tree is removed, then a prior acoustic velocity measurement is taken from the new butt to the top of the tree (HM200_6mTree). In the third approach the bottom 3 m section of the tree is removed, then a prior acoustic velocity measurement is taken from the butt of this section to the top of the section (HM200_Init3m). In the fourth approach the bottom 6m section is removed, then a 3 m section is removed and a prior acoustic velocity measurement is taken of this 3 m section (HM200_6m3m).

Sample selection, tree processing procedures, and acoustic velocity measurements were the same as described in Chapter 2. Some of the information is repeated in this chapter for completeness.

## Sample Selection

Trees were obtained from stands owned by Roseburg Forest Products in southwest Oregon. Five stands were selected in order to determine if acoustic velocity relationships were stand independent. Six trees were selected from each stand. Trees were selected by eye to be representative of the stand using attributes such as diameter, height, and amount of branches. Trees with obvious defects that may affect acoustic velocity readings such as scars, rot, or conk fungi were excluded. Tree selection was performed with the assistance of a contract supervisor from Roseburg Forest Products. Trees tested had ring counts of 36 to 78 years at the diameter breast height (DBH) measurement point. Tree DBH, total height, height to live crown, and age can be seen in Table1. The longitude, latitude and elevation of the site that the trees originated from were recorded and can be seen in Table 2.

## Measurement and Processing Procedures

### Tree Processing

Trees were felled and limbed and the tops were removed at approximately 10 cm (~ 4”) diameter (over bark). This was done to eliminate the effect that limbs and tree tops can have on adding variation to the measured speed of resonance acoustic velocity (Amishev 2008). Acoustic signals do not return well off of limbs and tops because there is a lack of a clear ending surface for the signal to bounce back off of.

We recognize that delimbing and topping each tree before acoustic measurements were taken would not be a preferred operational practice. Controlling some of the causes of variation in this study was necessary because of the small sample size for each stand. In many cases, however, tree tops broke at diameters larger than 10 cm over bark when the tree was felled. When this happened the tree top was cut previous to the break and the diameter was recorded.

### Acoustic Velocity

The acoustic velocities of trees were measured when the trees were lying on the ground and, where possible, separated from other trees. Resonance acoustic velocity (km/sec) was measured from the flat cut surface at the large end of the tree to the bucked top using the Director HM200 resonance acoustic velocity measurement device (Fibre-Gen, Christchurch, New Zealand). The tree was then bucked three meters up from the large end and resonance acoustic velocity was measured on the three meter section. Resonance acoustic velocity measurements were repeated as previously described for the new location of the large end of the tree. The process of cutting off the 3 meter section and measuring the remaining tree length and the 3 meter section acoustic velocity was repeated along the entire length of the tree.

## Data Analysis

Data were analyzed using SAS 9.2. The dependent variable was the HM200 acoustic velocity of each 3 m section (HM200_3m). Multi variable models were examined using a general linear model to determine their predictive capability for determining the acoustic velocity in each 3 meter log section along the length of the tree. These models included:

- HM 200 full tree length acoustic velocity excluding initial 6 meters (HM200_6mTree) with distance from the butt of the tree (Dist).
- HM 200 full tree length acoustic velocity (HM200_InitTree) with distance from the butt of the tree squared ($\text{Dist}^2$).
- HM 200 acoustic velocity for the third 3 m section (HM200_6m3m) with distance from the butt of the tree (Dist).
- HM 200 acoustic velocity for the first 3 m section (HM200_Init3m) with distance from the butt of the tree (Dist).

Final multi-variable models used HM 200 readings (HM200_6mTree and HM200_6m3m) and distance from the butt (Dist) as predictors and were tested for stand differences for both intercept and slope using stepwise backward regression. For all models, natural log (LN) and square root (SQRT) transformations were used to transform the dependent 3 meter section acoustic velocity. Four models (one using the third tree length HM200_6mTree readings, one using the first tree length HM200_InitTree readings, one using the third three meter log HM200_6m3m readings, and one using the first three meter log HM200_Init3m readings) were found to be the best predictors of HM200_3m acoustic velocities by calculating the root mean square error of the predicted acoustic velocity for each 3 meter segment. Root mean square error was calculated once the predicted value had been back transformed if transformations were used.

The best model using HM200_6mTree with Dist was compared to be best model using HM200_InitTree with $Dist^2$ by comparing root mean square error of predicted values of HM200_3m past the first 6 meters of the tree. The best model using HM200_6m3m with Dist was compared to be best model using HM200_Init3m with Dist by comparing root mean square error (RMSE) of predicted values of HM200_3m past the first 6 meters of the tree.

## Results

The final model using third tree length HM200_6mTree readings and distance from the butt as predictors for the 3 meter section acoustic velocities is shown in Table 16. This model found the intercepts of Stands 4 and 5 to be significantly different from the intercept of stand 1 (p = 0.0001 and 0.0232 respectively). Slopes from Stand 4, and 5 were found to be significantly different from the slope of stand 1 (p = 0.0011 and 0.0379 respectively). This model had a high R-Square of 0.860 and a RMSE of 0.106 when predicting HM200_3m acoustic velocities after the first 6 meters of the tree.

Table 16. Model parameters for HM200_3m vs. HM200_6mTree and Dist

| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 1.295 | 0.185 | 7.00 | <.0001 |
| HM200_6mTree | 0.844 | 0.051 | 16.56 | <.0001 |
| Dist | -0.051 | 0.002 | -20.77 | <.0001 |
| S4 | -0.259 | 0.065 | -3.98 | 0.0001 |
| S5 | -0.144 | 0.063 | -2.29 | 0.0232 |
| Dist*S4 | 0.015 | 0.005 | 3.32 | 0.0011 |
| Dist*S5 | 0.009 | 0.004 | 2.09 | 0.0379 |

The final model using the initial tree length HM200_InitTree readings and distance from the butt squared as predictors for the 3 meter section acoustic velocity can be seen in Table 17. This model found the intercepts of Stands 4 and 5 to be significantly different from the intercept of stand 1 (p = 0.0014 and 0.0194 respectively). Slopes from Stand 1, 4, and 5 were found to be significantly different from slope of stand 1 (p = 0.0110, 0.0002, and 0.009 respectively). This model had a RMSE of 0.107 when predicting HM200_3m acoustic velocities after the first 6 meters of the tree.

Table 17. Model parameters for HM200_3m vs. HM200_InitTree and $Dist^2$

| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 0.746 | 0.191 | 3.90 | 0.0001 |
| HM200_InitTree | 0.879 | 0.052 | 16.85 | <.0001 |
| $Dist^2$ | -0.002 | 0.000 | -18.73 | <.0001 |
| S4 | -0.105 | 0.032 | -3.24 | 0.0014 |
| S5 | -0.076 | 0.032 | -2.36 | 0.0194 |
| $Dist^2$*S1 | 0.0003 | 0.0001 | 2.57 | 0.0110 |
| $Dist^2$*S4 | 0.0006 | 0.0002 | 3.75 | 0.0002 |
| $Dist^2$*S5 | 0.0005 | 0.0001 | 3.37 | 0.0009 |

The model using HM200_6mTree with Dist (RMSE 0.106) was a better predictor of HM200_3m acoustic velocities past the first 6 meters of the tree than the model using HM200_InitTree with $Dist^2$ (RMSE 0.107).

The final model using third tree length HM200_6m3m readings and distance from the butt as predictors for the 3 meter section acoustic velocities is shown in Table 18. This model found the intercepts of Stands 2 and 4 to be significantly different from intercept of stand 3 (p = <0.0001 and 0.0340 respectively). Slopes from Stand 1, 4, and 5 were found to be significantly different from the slope of stand 3 (p = <0.0001, 0.0002, and <0.0001 respectively). This model had a high R-Square of 0.887 and a RMSE of 0.099 when predicting HM200_3m acoustic velocities after the first 6 meters of the tree.

Table 18. Model parameters for HM200_3m vs. HM200_6m3m and Dist

| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 1.294 | 0.206 | 6.27 | <.0001 |
| HM200 | 0.752 | 0.052 | 14.42 | <.0001 |
| Dist | -0.055 | 0.002 | -25.41 | <.0001 |
| S2 | 0.126 | 0.028 | 4.43 | <.0001 |
| S4 | -0.122 | 0.057 | -2.14 | 0.0340 |
| Dist*S1 | 0.011 | 0.002 | 4.93 | <.0001 |
| Dist*S4 | 0.016 | 0.004 | 3.79 | 0.0002 |
| Dist*S5 | 0.010 | 0.002 | 5.40 | <.0001 |

The final model using the initial 3 meter log (HM200_Init3m) reading and distance from the butt as predictors for the 3 meter section acoustic velocities (LN transformation) is shown in Table 19. The intercepts of all five stands were found to be significantly different from each other. Dist$^2$ was not significant in this model. The model had a RMSE of 0.155 (recalculated after back transformations were made) when predicting HM200_3m acoustic velocities after the first 6 meters of the tree.

Table 19. Model parameters for HM200_3m (LN transformation) vs. HM200_Init3m and Dist

| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 0.911 | 0.077 | 11.85 | <.0001 |
| HM200_Init3m | 0.135 | 0.020 | 6.87 | <.0001 |
| Dist | -.009 | 0.000 | -17.98 | <.0001 |
| S2 | -.033 | 0.011 | -2.97 | 0.0033 |
| S3 | -.051 | 0.013 | -3.99 | <.0001 |
| S4 | -.051 | 0.011 | -4.65 | <.0001 |
| S5 | -.034 | 0.011 | -3.21 | 0.0015 |

The model using HM200_6m3m with Dist (RMSE 0.099) was a better predictor of HM200_3m acoustic velocities past the first 6 meters of the tree than the model using HM200_Init3m with Dist (RMSE 0.155).

## Discussion

Both models using HM200 acoustic velocity readings from 6 meters past the butt of the log were better predictors of models using HM200 acoustic velocity readings from the base of the tree. The ability to better predict HM200_3m acoustic velocities with models based on readings that exclude the first 6 meters of the tree is due to the different properties of this first 6 meter section of the tree when compared to the rest of the tree.

The models based on the HM200_6mTree and HM200_InitTree (RMSE 0.106 and 0.107 respectively) had little difference between them when compared to the differences between the models based on HM200_6m3m and HM200_Init3m (RMSE 0.099 and 0.155 respectively). The entire tree length reading can overcome some of the differences of the butt of the tree because the entire length of the tree is assessed by the resonating wave and the measured acoustic velocity is a weighted average (Grabianowski et. al. 2006). The model based on HM200_Init3m only took into account the acoustic velocity of the first 3 meters of the tree which has properties that vary greatly from the rest of the tree.

In radiata pine a cone of low stiffness wood with the wide base of the cone at the butt of the tree is caused by high microfibril angle (Xu et. al. 2004). According to Lachenbruch et. al. (2010) acoustic velocity is strongly determined by microfibril angle. The lower acoustic velocity at the base of a Douglas-fir tree appears to be from a similar cone of wood with high microfibril angle that is found in radiata pine. This high microfibril angle at the base of the tree is likely the reason that models based on readings that exclude the initial 6 meters of the tree are better at predicting HM200_3m acoustic velocities after the first 6 meters of the tree than models that are based on readings from the base of the tree. Although it seems likely the cause of the lower acoustic velocity in the butt log is due to microfibril angle, it is interesting to note that fiber diameter and length in poplar have been shown to follow a similar pattern to that of acoustic velocity in Douglas-fir. Both fiber diameter and length increase from the base of the tree to about 5.6 meters and then decrease towards the top of the tree (Sheng-zuo and Wen-zhong, 2003). This is further evidence that the structure of the butt log is unique when compared to the rest of the tree.

# CHAPTER 4: CONCLUSION

The main purpose of this study was to determine if acoustic velocity, length from the butt, wood density, and bark percentage could be used to predict the acoustic velocity variation along the length of a tree in Douglas-fir. TOF acoustic velocity measured across the bole of the tree had little value in predicting the longitudinal resonance acoustic velocity of a section of the tree. Although TOF across the bole was statistically significant it had a very low correlation coefficient and lacked the ability to accurately and precisely predict resonance acoustic velocity. Wood density, moisture content, and bark percentage were not significant predictors of resonance acoustic velocity of a section of a tree.

The use of all tree length resonance acoustic velocities was found to be a statistically significant and strongly correlated predictor of acoustic velocity of tree sections. Distance of a log section from the butt of the tree and distance of a section from the butt squared were found to be statistically significant and strongly correlated predictors of acoustic velocity of tree sections. Final models including resonance acoustic velocity measurements, distance from the butt, and distance from the butt squared were developed with high coefficients of determination ($R^2$ 0.849 using all tree length acoustic velocities, $R^2$ 0.827 using initial tree length acoustic velocity, and $R^2$ 0.678 using initial 3 meter log acoustic velocity). The models developed were found to be stand dependent, indicating a possible need for model calibration for each stand to be harvested. The use of either the single tree length acoustic velocity measurement or the first log acoustic velocity measurement with distance from the butt and/or distance from the butt squared has the potential to increase value recovery from a log by predicting the stiffness in that log and more effectively matching it to its end use.

Lower acoustic velocity in the butt of a tree inhibits the predictive capability of models based on acoustic velocity measurements taken from the butt of the tree to predict acoustic velocity of 3 meter sections after the first 6 meters of the tree. The lower acoustic velocity at the base of a tree appear to be due to high microfibril angle in a cone of low stiffness wood in the butt of a tree with the wide base of the cone at the base of the tree. Entire tree length readings taken from the butt of the tree are better predictors of 3 meter sectional acoustic velocity than the first 3 meter log acoustic velocity. This is because the entire length of the tree is assessed by the resonating wave of a tree length measurement and the measured acoustic velocity is a weighted average of the tree (Grabianowski et. al. 2006) while the model based on the first 3 meter log only takes into account the acoustic velocity of the first 3 meters of the tree. Acoustic velocity models based on acoustic velocities measured after the first 6 meters of the tree are the best predictors of the acoustic velocity of 3 meter sections after the first 6 meters of the tree.

With the production of a reliable acoustic measuring device that could be mounted on a processor or harvester head and the use of acoustic profile models, Douglas-fir logs could be sorted for stiffness while they are processed.

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# APPENDIX

Figure A1. Stand 1 IML_Vel by tree as a function of distance from the butt

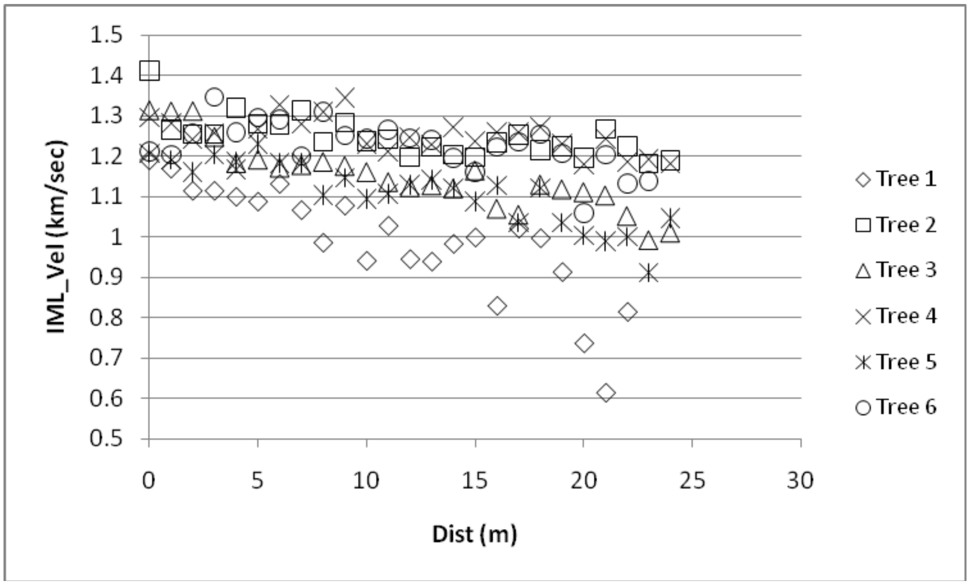

Figure A2. Stand 2 IML_Vel by tree as a function of distance from the butt

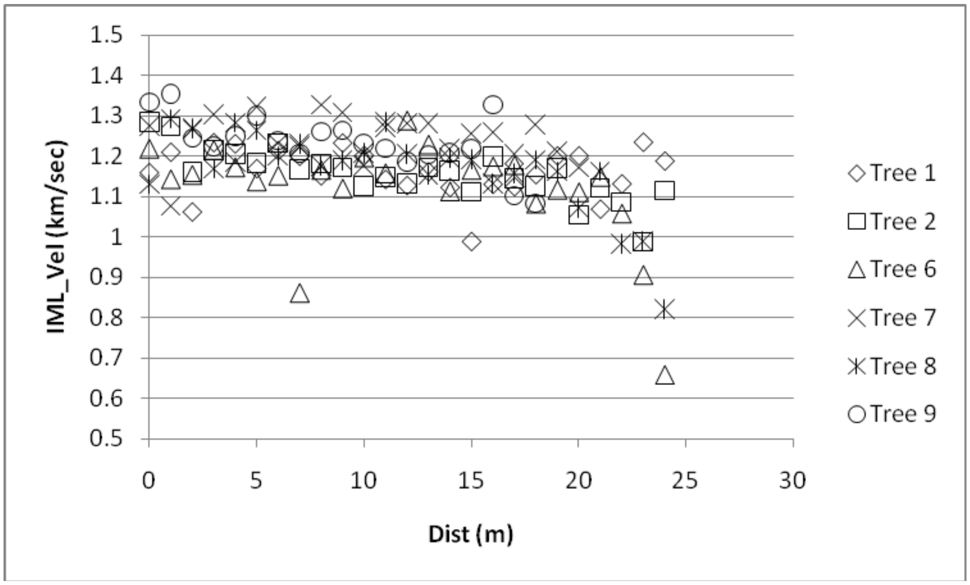

Figure A3. Stand 3 IML_Vel by tree as a function of distance from the butt

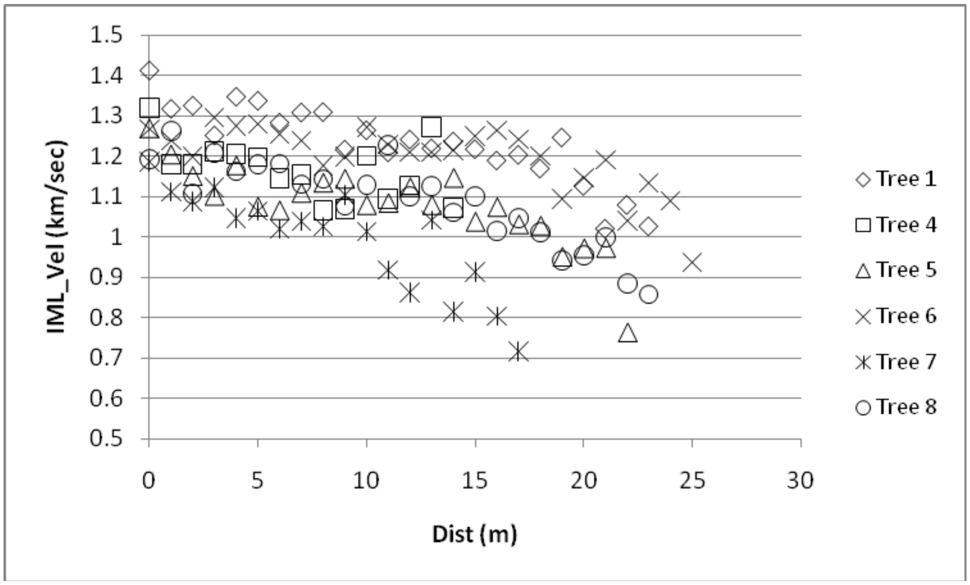

Figure A4. Stand 4 IML_Vel by tree as a function of distance from the butt

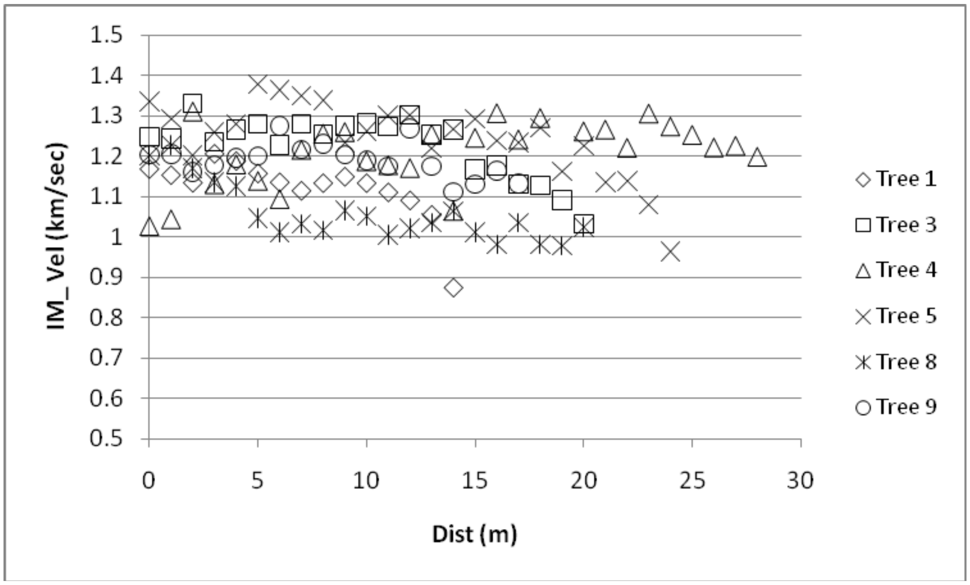

Figure A5. Stand 5 IML_Vel by tree as a function of distance from the butt

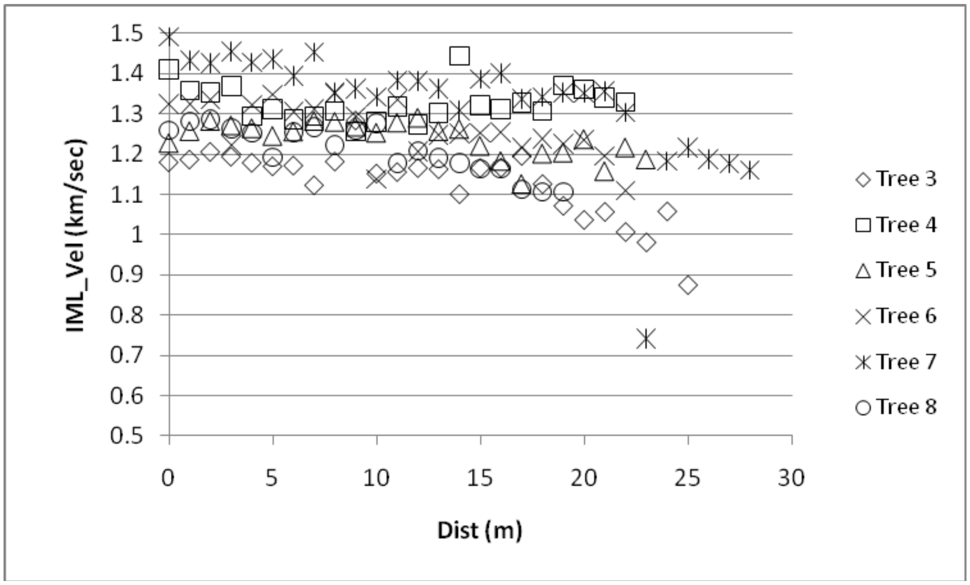

Figure A6. Stand 1 HM200_3m velocities by tree as a function of distance from the butt

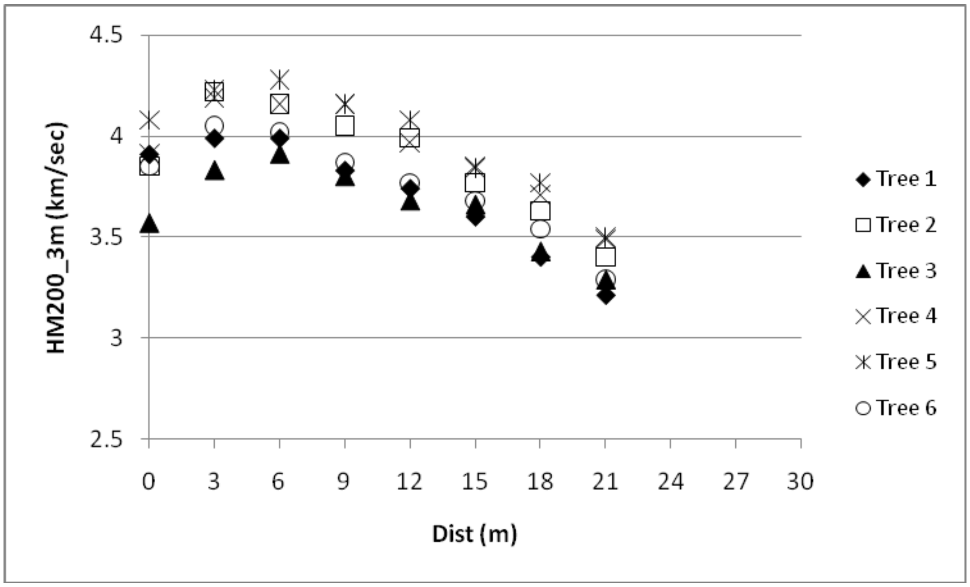

Figure A7. Stand 2 HM200_3m velocities by tree as a function of distance from the butt

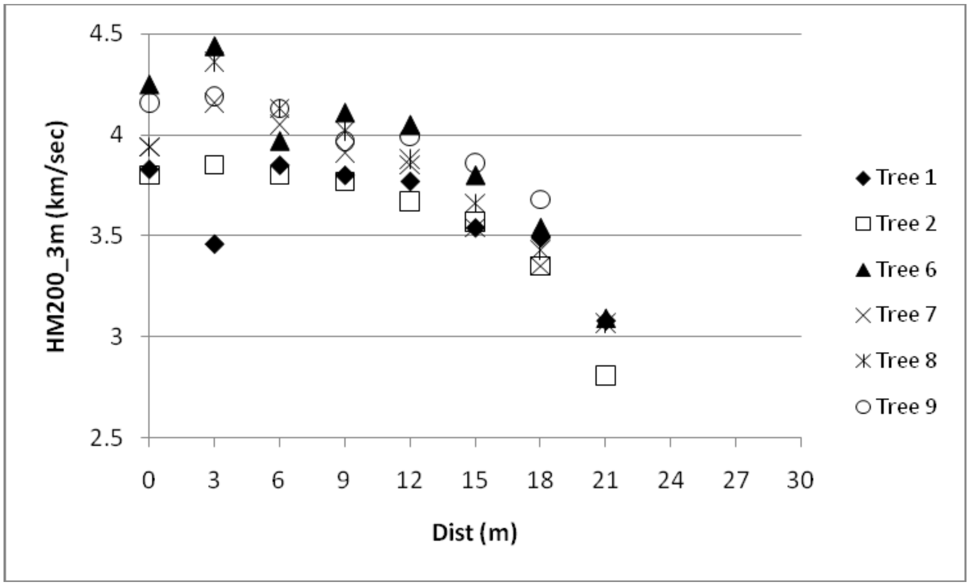

Figure A8. Stand 3 HM200_3m velocities by tree as a function of distance from the butt

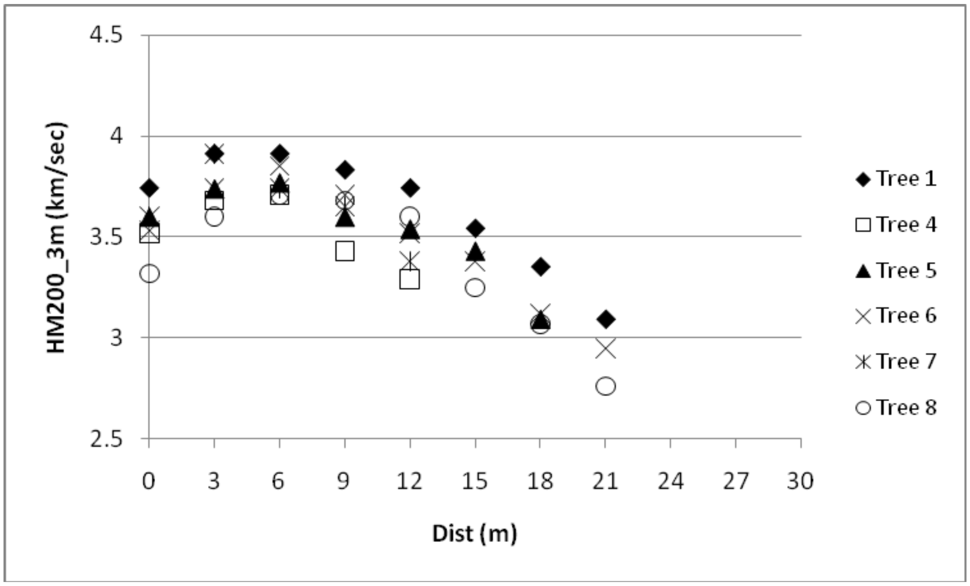

Figure A9. Stand 4 HM200_3m velocities by tree as a function of distance from the butt

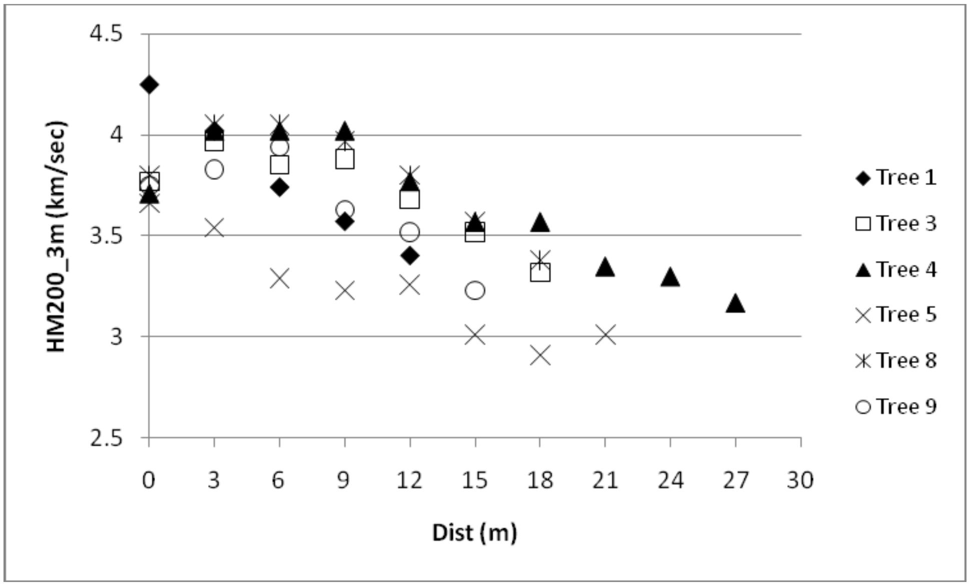

Figure A10. Stand 5 HM200_3m velocities by tree as a function of distance from the butt

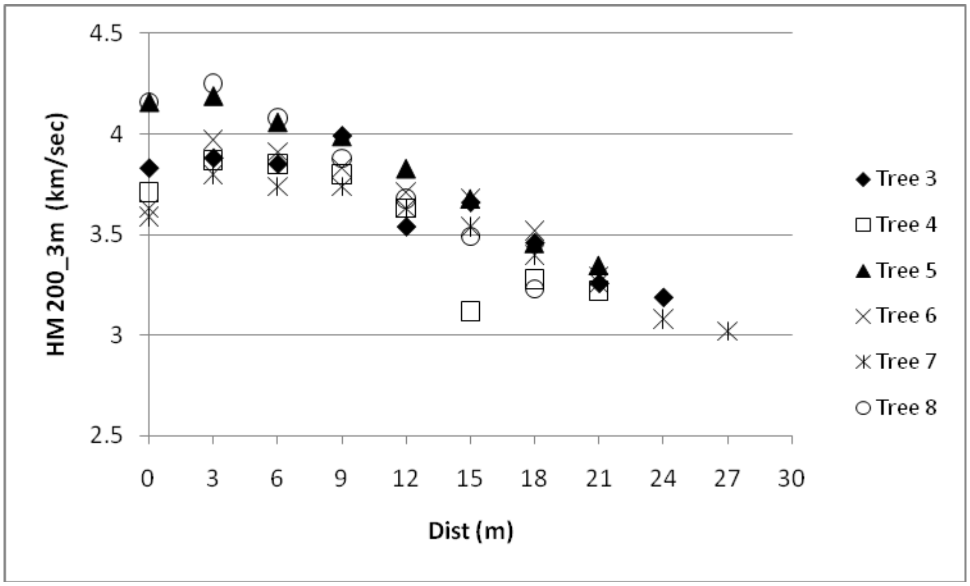

Table A1. Summary statistics by stand for variables measured

| | DOB (cm) | MC (%) | IML_Vel (km/sec) | Density g/cm$^3$ | Bark (%) | HM 200 InitTree (km/sec) | HM 200 Init3m (km/sec) | SG |
|---|---|---|---|---|---|---|---|---|
| Stand 1 | | | | | | | | |
| Average | 27.8 | 84 | 1.16 | 0.81 | 11.5 | 3.77 | 3.86 | 0.45 |
| St Dev | 9.3 | 27 | 0.12 | 0.08 | 3.7 | 0.13 | 0.17 | 0.04 |
| Min | 7.6 | 51 | 0.61 | 0.69 | 5.0 | 3.59 | 3.57 | 0.39 |
| Max | 46.6 | 132 | 1.41 | 1.00 | 19.2 | 3.94 | 4.08 | 0.54 |
| Stand 2 | | | | | | | | |
| Average | 27.2 | 90 | 1.18 | 0.88 | 11.9 | 3.74 | 3.99 | 0.47 |
| St Dev | 7.1 | 26 | 0.10 | 0.08 | 3.1 | 0.17 | 0.18 | 0.03 |
| Min | 13.3 | 63 | 0.66 | 0.79 | 6.5 | 3.53 | 3.80 | 0.42 |
| Max | 434.0 | 145 | 1.35 | 1.05 | 19.1 | 4.01 | 4.25 | 0.52 |
| Stand 3 | | | | | | | | |
| Average | 22.9 | 74 | 1.13 | 0.85 | 14.2 | 3.44 | 3.55 | 0.49 |
| St Dev | 6.3 | 16 | 0.13 | 0.07 | 3.3 | 0.09 | 0.14 | 0.04 |
| Min | 10.5 | 62 | 0.72 | 0.71 | 7.3 | 3.34 | 3.32 | 0.42 |
| Max | 36.7 | 121 | 1.41 | 0.97 | 27.9 | 3.58 | 3.74 | 0.55 |
| Stand 4 | | | | | | | | |
| Average | 30.8 | 83 | 1.18 | 0.88 | 13.7 | 3.61 | 3.82 | 0.49 |
| St Dev | 10.4 | 18 | 0.1 | 0.08 | 4.3 | 0.22 | 0.21 | 0.04 |
| Min | 16.0 | 54 | 0.87 | 0.72 | 6.7 | 3.17 | 3.66 | 0.41 |
| Max | 58.4 | 119 | 1.38 | 1.03 | 23.1 | 3.79 | 4.25 | 0.54 |
| Stand 5 | | | | | | | | |
| Average | 32.3 | 80 | 1.25 | 0.83 | 12.0 | 3.69 | 3.85 | 0.46 |
| St Dev | 9.3 | 26 | 0.11 | 0.08 | 3.5 | 0.12 | 0.26 | 0.05 |
| Min | 13.4 | 51 | 0.74 | 0.74 | 4.6 | 3.48 | 3.59 | 0.41 |
| Max | 59.0 | 152 | 1.49 | 1.03 | 17.0 | 3.82 | 4.16 | 0.53 |

Table A2. Fit statistics and model parameters for HM200_3m vs. DOB

| R-Square | Coeff Var | Root MSE |
|---|---|---|
| 0.130 | 8.230 | 0.303 |

| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 3.317 | 0.067 | 49.47 | <.0001 |
| DOB | 0.013 | 0.002 | 5.80 | <.0001 |

Table A3. Fit statistics and model parameters for HM200_3m vs. MC

| R-Square | Coeff Var | Root MSE |
|---|---|---|
| 0.032 | 6.762 | 0.252 |

| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 3.686 | 0.044 | 83.39 | <.0001 |
| MC | 0.001 | 0.000 | 1.41 | 0.1625 |

Table A4. Fit statistics and model parameters for HM200_3m vs. IML_Vel

| R-Square | Coeff Var | Root MSE |
|---|---|---|
| 0.036 | 8.659 | 0.319 |

| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 3.116 | 0.197 | 15.83 | <.0001 |
| IML_Vel | 0.000 | 0.000 | 2.92 | 0.0039 |

Table A5. Fit statistics and model parameters for HM200_3m vs. Density

| R-Square | Coeff Var | Root MSE |
|---|---|---|
| 0.031810 | 6.762 | 0.252 |

| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 4.285 | 0.394 | 10.88 | <.0001 |
| Density | -0.668 | 0.472 | -1.42 | 0.1620 |

Table A6. Fit statistics and model parameters for HM200_3m vs. Bark

| R-Square | Coeff Var | Root MSE | | |
|---|---|---|---|---|
| 0.000 | 8.821 | 0.325 | | |

| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 3.691 | 0.078 | 47.26 | <.0001 |
| Bark | -0.026 | 0.601 | -0.04 | 0.9650 |

Table A7. Fit statistics and model parameters for HM200_3m vs. SG

| R-Square | Coeff Var | Root MSE | | |
|---|---|---|---|---|
| 0.000 | 6.871 | 0.256 | | |

| Parameter | Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|
| Intercept | 3.757 | 0.239 | 15.70 | <.0001 |
| SG | -0.059 | 0.504 | -0.12 | 0.907 |