NONDESTRUCTIVE ASSESSMENT OF STANDING DOUGLAS-FIR TREES AND LOGS TO ESTIMATE LUMBER QUALITY

In Partial Fulfillment of the Requirements for the
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with a Major in Forest Products

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By
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Authorization to Submit Thesis

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Abstract

Studies have suggested that stress wave velocities in standing trees and harvested logs could be used to predict the stiffness of lumber and veneers produced from them. Many of the previous studies were limited to plantation grown timber, where little variation in quality and properties within trees exists. In addition, destructive samplings of small clear samples from restricted portions of a tree have often been used as a measure of the quality of an entire tree. Since a significant portion of western forested land is made up of naturally regenerated stands of timber having various ages, genetic stock, and growing conditions, the question remains whether stress wave velocity assessment can be used to predict lumber stiffness from this resource. The primary goal of this study was to assess the predictive ability of stress wave velocity measurements in standing trees and fallen logs from a naturally regenerated stand of Douglas-fir.

Thirty three Douglas-fir trees were selected for harvest based on their stress wave velocities in the standing trees. These trees represented the maximum amount of variation in stress wave measurements determined for the harvesting site. At the time the stress wave measurements were taken, increment cores were extracted and green density of the sapwood, the first inch of the wood, heartwood, and entire core were determined for each tree. The trees were felled, stress wave velocities of the butt logs measured, and the logs taken to a private sawmill for processing into 2x4 dimensional lumber.

The best correlations using stress wave velocities were found by calculating dynamic modulus of elasticity using the densities from the heartwood or entire core. These non-destructive measurements on standing trees provided a weak correlation with lumber stiffness. From the results of this study, the use of stress wave velocity measurements in standing trees to predict lumber stiffness does not appear to be feasible. However, stress wave velocity measurements taken on logs showed promise in predicting the stiffness of the resultant lumber. Further research is needed to develop a predictive model for assessing log quality based on stress wave velocity measurements.

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Table of Contents

List of Tables

List of Figures

Introduction

Recent studies suggest that stress wave velocity (SWV) measurements in standing trees and logs could be used to predict modulus of elasticity (MOE) in lumber or veneers. If stress wave velocities could accurately predict which trees were composed of high stiffness material more informed decisions could be made with regards to selective harvesting, modification of silvicultural techniques, or merchandizing harvested material. Timber buyers and sellers could also better assess timber based on quality differences in stands and locations.

In the late 1990's, a methodology for measuring stress wave velocity in standing timber was developed in Japan. This research showed that stress wave paths are basically straight through wood in both the longitudinal and radial directions. It also showed that driving nails (or probes) through the bark could increase the reproducibility of the stress wave measurements (Nanami, Nakamura, & Okuma, 1992 a). Another study by the same researchers showed that the dead weight of the standing tree had no effect on stress wave times, allowing future researchers to use either log or standing tree stress wave velocities for predictions of MOE. This study also noted that density changes with changes in moisture affected the stress wave velocity but did not address the specific effect (Nanami, Nakamura, & Okuma, 1992 b).

Later, stress wave velocity measurements on standing trees showed potential to predict the stiffness of resultant lumber. This research (Wang, et al., 2000) showed a reasonable coefficient of determination (R^2=0.69) between standing tree stress wave measurements and small clear specimens cut from the area in which the stress wave measured. This study also calculated an MOE based on the longitudinal wave equation:

$Equation\ 1$: $E_{SWV} = \frac{\rho}{g} V^2$

Where: $\rho = density\ of\ the\ material\ tested$

g = *acceleration due to gravity*

V = *stress wave velocity*

$E_{SWV} = dynamic\ MOE\ from\ tree\ stress\ wave\ velocity$

The density used in these equations was an average of the entire test section making no distinction between heartwood and sapwood. These researchers suggested that testing full size lumber specimens would show more useful information about the actual static properties of wood and their relationship to stress wave velocity. It was also suggested that taking stress wave measurements on multiple sides of the stem could improve predictions. This study noted problems with variability creating difficulty in predictions.

In a later study (Wagner, Gorman, & Wu, 2003), multiple stress wave velocity measurements taken on individual trees showed a slight improvement for predicting lumber MOE from standing trees. Velocities measured over increasingly greater distances did not improve correlation to lumber properties. The study also found that trees with high variation in lumber MOE showed the least correlation between stress wave velocity and the average of the lumber MOE. This suggests that the wood sampled in field stress wave velocity measurements may not capture the inherent characteristics and variability of wood influencing its MOE. By combining additional scans, longer scans, and transverse scans the highest coefficient of determination (R^2= 0.591) to average lumber MOE was reached. Such a sampling method requiring multiple scans at varying positions along a trees surface was not considered to be practical for assessing numerous trees at multiple sites.

More recently, a study in Scotland (Auty & Achim, 2008) was carried out to assess a new tool for measuring stress wave velocity in standing Scots pine for predicting clear wood MOE. Time of flight data measured with the ST300 (Director ST300, Fibre-gen, New Zealand) provided a reasonable coefficient of determination (R^2=0.53) between tree stress wave velocity and the modulus of elasticity of small clear samples taken from the sampled section.

The potential to correlate log stress wave velocity with lumber modulus of elasticity was demonstrated using balsam fir and eastern spruce trees (Ross, McDonald, Green, & Schad, 1997). A high coefficient of determination (R^2=0.80) was reported. This concept was later refined by using resonant frequencies instead of longitudinal stress wave velocities. It was shown that logs and lumber could be sorted for stiffness based on a stress wave time from resonant frequencies obtained from the HM200 (Director HM200, Fibre-gen, New Zealand) (Carter, Chauhan, & Walker, 2006).

Research in Idaho showed potential to sort Douglas-fir logs based on time of flight stress wave velocities to optimize high grade veneer recovery. This study (Rippy, Wagner, Gorman, Layton, & Bodenheimer, 2000) analyzed stress wave velocities in 35 foot logs and the resulting veneers from 8 foot boles. Based on this analysis, researchers concluded that the best wood for veneer properties came primarily from the bottom 17 feet of a tree. This research also indicated that stress wave analysis of Douglas-fir logs could sort logs for high grade veneer recovery based on a low coefficient of determination (R^2 = 0.35) between the inverse of stress wave velocities in veneers and logs.

Another recent study (Amishev & Murphy, 2008) focused on the use of stress wave techniques to predict veneer quality in Douglas-fir grown in western Oregon. Approximately 3000 veneer logs were produced from 1400 trees that had been assessed with the Director ST300. This study addressed stress wave velocity and the influence of DBH on stress wave velocity and found that DBH had little effect on predicting stress wave velocities. These researchers showed that veneer grade recovery had no significant correlation with stress wave velocity in standing trees. The standing tree stress wave velocities has a poor coefficient of determination (R^2=0.25) with the stress wave velocity measured in corresponding logs using the HM200 which was shown to correlate strongly to veneer recovery. Tree diameter also correlated very poorly with veneer recovery and stress wave velocity. The researchers also found inconsistent readings between multiple Director ST300 units, as well as significant variation between stress wave measurements taken on each side of the same tree.

Another study questioned the reliability and repeatability of time of flight stress wave velocity measurements in standing timber due to the difficulty of measuring wave arrival times in the field. Stress wave velocities measured over short distances, especially when there is a small measurement length to specimen diameter ratio, require sensitive equipment to accurately measure the arrival time of a stress wave. Equipment insensitivity can lead to variability in wave arrival time recordings. This study (Andrews, 2002) also explored the reasons for resonance methods typically yielding higher correlations to static MOE. The sensitivity of time of flight measurements of stress wave velocity were shown to be less reliable than resonance methods which are more robust to the effect of outside factors.

This study was designed to measure stress wave velocity in standing, naturally regenerated, Douglas-fir trees and fallen logs in order to compare the predictive ability of these methods to the dynamic modulus of elasticity in commercial-length lumber specimens. Previous studies that compared standing tree stress wave velocity measurements to wood properties were sometimes limited by sampling small clear specimens taken from the area in which the stress wave velocity was measured. Some of the previous studies were limited to plantation stands rather than naturally regenerated stands of timber. Many studies also excluded density from their predictions of resultant lumber MOE.

The primary goal of this study was to expand on the current knowledge and assess if the stress wave velocities measured in live trees growing in natural stands could be used to accurately estimate lumber MOE. This study also explored the differences in densities of the heartwood, sapwood, first inch of wood, and the entire increment core on standing tree calculations of MOE. These delineations were chosen because stress waves have been shown to travel in a straight line between probes which are typically limited to the first inch of the wood. The basis for comparison in this study was the dynamic MOE of 2x4’s cut from the butt log of trees obtained from a natural stand of Douglas-fir in northern Idaho. The dynamic MOE was verified using destructive testing on limited specimens. A third goal of the study was to assess log stress wave velocities and their ability to predict MOE in full size lumber.

Methods

The stress wave velocities of over seventy Douglas-fir trees were measured on mature trees located in a naturally regenerated area of the University of Idaho Experimental Forest. Stress wave velocity measurements were taken with a Director ST300. This equipment obtains a stress wave velocity using the time of flight method over a span of approximately three feet (one meter). Two sets of stress wave measurements were taken from opposite sides of each tree. The ST300 probes were not removed between measurements taken on the same side of each tree. All four stress wave velocities were averaged to produce one stress wave velocity for each tree. Though density was also used to predict MOE, this was not measured at this time. Average tree stress wave velocities in the 71 trees were found to range from 7,483 ft/sec to 16,632 ft/sec (2,280 m/s to 5,070 m/s).

Based on the range of stress wave velocities found to exist within the area of our study, we found thirty three trees to harvest based on a wide range of stress wave velocities. Trees were selected using the same method as before. Four stress wave measurements from two sides of the tree. For the trees selected, average stress wave velocities ranged from 7,485 ft/sec to 16,190 ft/sec (2,281 m/s to 4,935 m/s). Just as many trees were selected from the extremes of the distribution as near the mean. This effort should have resulted in a large range of wood quality and MOE values. Each tree selected was measured for diameter at breast height (DBH) which ranged from 12 inches to 23 inches and increment cored on each side of the tree between the ST300 probes. These cores were weighed in the field and density was obtained from the total core, the heartwood, the sapwood, and the first inch of the wood. The density data gathered can be found in Appendix A-2. This density was then used to calculate a dynamic MOE (E_{SWV}) using the tree stress wave velocity measurements.

Obvious negative growth characteristics were avoided in the trees sampled. The trees selected ranged from 12 to 22 inches (30 to 56 cm) in diameter at breast height. Tree ages were between 40 and 250 years with an average of 69 years. Two trees were substantially older (243 and 144 years) than the rest of the population. The properties of the selected trees can be found in Appendix A-1. The 25 foot (7.62 meter) butt logs were sawn from each tree and delivered to a local sawmill for processing. Stress wave velocities of 25 foot logs were measured with an HM200 which uses a resonance frequency to measure stress wave velocities. Log stress wave velocity ranged from 10,203 ft/sec to 13222 ft/sec (3110 m/s to 4030 m/s). These results can be found in Appendix A-3. An eight foot butt log from each tree was processed into 2x4 lumber. Grade recovery was not optimized during processing as would be done in commercial sawmill operations. The lumber was dried to 12% moisture content at the University of Idaho Forest Products Laboratory and stored in a conditioning room for equalization.

Every board was assigned an individual board number, density measured, and transverse vibration dynamic MOE (E_{TV}) measured with an EComputer (EComputer, Metriguard, Pullman, Washington). To verify that the transverse vibration technique was yielding reliable MOE (E_{Static}) values, 131 boards tested with a static bending test. Static bending tests were completed in accordance with ASTM Standard D198-99 (ASTM, 2001) on an Instron Universal Testing Machine model 5500R.

Pearson correlation analysis was conducted to assess the correlation between various variables in the dataset. A general linear model (univariate regression) was also conducted. All regressions were tested at the 95% confidence level. Residual plots were examined to assess whether bias existed in the estimate due to multicolinearity, nonlinearity, or data that were not normally distributed. However, we did not adjust for the systematic variance inherent in the ST300.

Results & Discussion

All of the boards were testing using a Metriguard EComputer that acquires an MOE using transverse vibration. During destructive testing, only 131 boards were actually broken. To verify that the EComputer was providing reliable E_{TV} measurements E_{Static} was compared to E_{TV}. This relationship is typically very strong and coefficients of determination higher than .90 have been found in previous studies (Pellerine & Ross, 2002). The relationship between the E_{Static} and the E_{TV} for this study resulted in a high coefficient of determination (R^2=0.87). This relationship verified that the EComputer was functioning correctly and providing very good approximations of E_{Static}. Furthermore, the E_{TV} value given by the EComputer could be used as a substitute for the E_{Static} of a given piece of lumber.

In order to assess which variables were correlated to one another and the significance of those correlations, a Pearson Correlation Table was conducted. The table in Appendix C-1 shows the relationship between density measurements and stress wave velocity measurements in standing trees. From this table, it can be seen that the total core density and the heartwood density are very highly correlated. In fact, 94% of the variance is shared between these two measurements. Because these measurements are so highly correlated the need to measure both densities in future studies is essentially eliminated. The sapwood density and the first inch of the wood density were also fairly well correlated sharing 60% of the variance.

Because stress waves have been shown to travel in a straight line between probes, this study was designed to explore if obtaining a more accurate measurement of density from between the ST300 probes would provide a more accurate assessment of a trees modulus of elasticity based on Equation 1. Given this hypothesis, either the density of the first inch of the wood or in the sapwood combined with the stress wave velocity should have provided the best prediction of the average modulus of elasticity of a tree.

A univariate regression was used to assess which single variable model would best predict E_{TV} given this data set. Instead of using the average E_{TV} of all the boards from a tree, all of the data were analyzed to encompass all the variation present in the samples. The summarized results of these regressions can be seen in Table 1.

Table 1 - Univariate regression results of density, stress wave velocity and composite variables

Board E_{TV} Regression Results (Univariate Regressions)			
Variable	**Unstandardized Beta**	**T Value**	**Adjusted R2**
Sapwood Density	-15073209.000	-4.768	0.013
Total Core Density	19057830.000	6.409	0.023
1st Inch Density	-20329507.000	-6.980	0.028
Heartwood Density	20504979.000	7.286	0.030
Rings Per Inch	29101.696	15.431	0.123
1st Inch E_{SWV}	0.174	15.555	0.125
Tree Stress Wave Velocity	53.589	16.204	0.135
Sapwood E_{SWV}	0.190	16.547	0.139
Total Core E_{SWV}	0.275	18.868	0.174
Heartwood E_{SWV}	0.304	19.235	0.180
Log Stress Wave Velocity	308.494	37.153	0.450

*All results significant at the 0.05 level.

As can be seen in Table 1, differing measurements of density provided no improved prediction of the dynamic MOE of lumber from a given tree over using the density of the entire core. In this study, calculating the E_{SWV} provided a 22.41% better prediction of E_{TV} than stress wave velocity alone. The heartwood E_{SWV} actually correlated slightly better than the total core E_{SWV} but only by 3.33%. The total core would already typically be taken during cruising operations. Therefore, best stress wave prediction with the lowest amount of handling, simply came from measuring the density of the total core and using this for a calculation of E_{SWV}.

Total Core E_{SWV} explains 17.4% of the variance in the stiffness of the resulting lumber. A regression of just the total core E_{SWV} prediction of E_{TV} is shown in Figure 1. A 95% Confidence Interval for the regression is also shown.

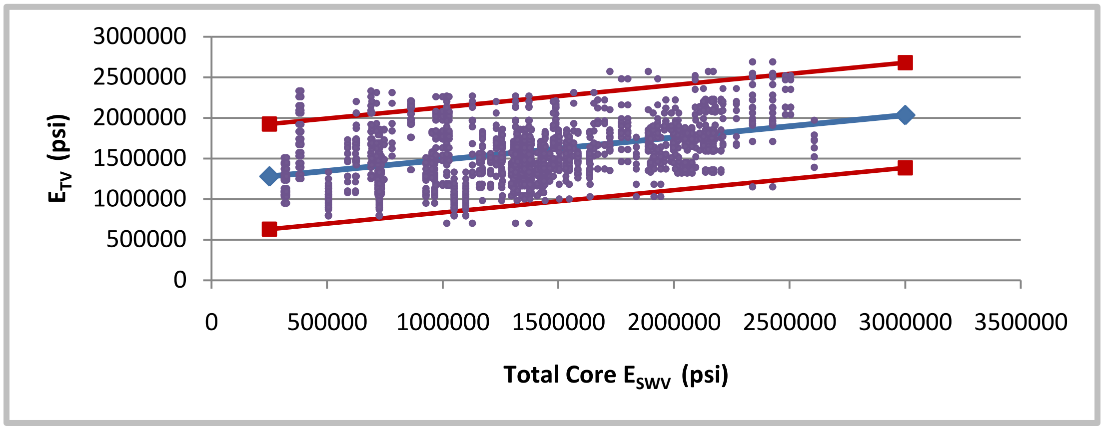

Figure 1- Relationship between the calculated modulus of elasticity (E_{SWV}) using standing stress wave velocities and the density of the total core and the dynamic modulus of elasticity of resultant lumber (E_{TV})

The equation for the regression line is shown in Equation 2.

$$Equation\ 2: \qquad E_{TV} = 2.75 * (Total\ Core\ E_{SWV}) + 1207818.7$$

Because the actual E_{TV} board data was regressed instead of averaged data, it is possible to see and understand the large amount of variation present in the board stiffness. The highly variable nature of naturally growing trees makes single variable predictions of E_{TV} problematic. Total core E_{SWV} alone can only explain 17.4% of the variance and gives us very little information about the stiffness of the resulting lumber without very large differences in total core E_{SWV}.

Further investigation would be needed with destructive data from multiple sites and various locations to assess if E_{SWV} values could be used to distinguish between sites with large differences in quality. It is very difficult to draw conclusions about these data due to the high amount of variation present and the small sample size present in this dataset.

The stress wave velocities in logs were also assessed regarding their predictive value of E_{TV}. The stress wave velocities measured in the logs were compared to E_{TV} shown in Figure 2 with a 95% confidence interval.

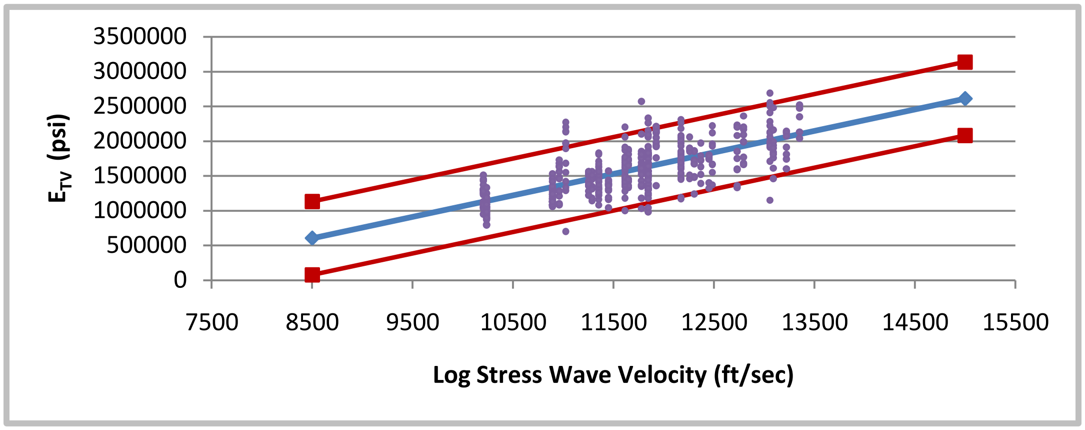

Figure 2 - Relationship between log stress wave velocities and the dynamic modulus of elasticity of resultant lumber (E_{TV})

Figure 2 confirms prior studies and shows that there is a meaningful relationship between the log stress wave velocity and the E_{TV} of the boards from that log. Log stress wave velocity measurements, as a single variable, explain 45% of the variance in the stiffness of the resulting lumber. The equation for the regression in Figure 2 is shown in Equation 3.

$$Equation\ 3: \qquad E_{TV} = 308.494 * (Log\ Stress\ Wave\ Velocity) - 2018732$$

The relationship between the stress wave velocity in the logs and standing trees was also investigated. These results can be seen in Figure 3. This figure shows a coefficient of determination ($R^2 = 0.44$) between the stress wave velocity in standing trees and stress wave velocity in the logs. This is an improvement from the results reported on Douglas-fir in Oregon where R^2 values of 0.25 were reported (Amishev & Murphy, 2008). This difference could suggest that it would be difficult to use stress wave analysis to compare predicted strengths in different species, locations, or comparing measurements taken by different tools or users, which would significantly reduce its practical applications. In the case of this study, the tree stress wave velocities correlated poorly with final products regardless of correlations between tree and log stress wave velocities.

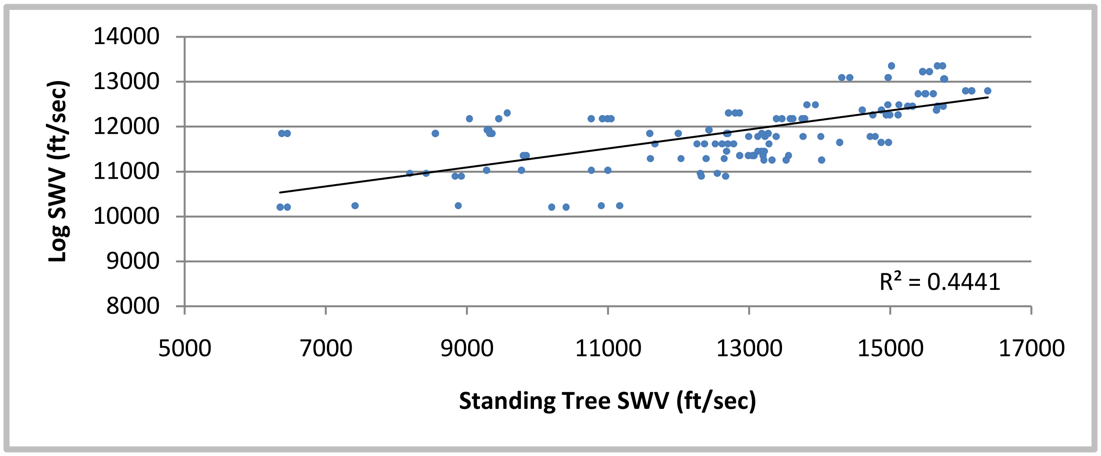

Figure 3 - Relationship between standing tree stress wave velocity measurements and log stress wave velocity measurements

One important finding was the amount of variation E_{TV} measurements from a single tree. Figure 4 shows the mean E_{TV} of all the boards from a single tree and error bars representing one standard deviation. Figure 4 shows that as the average E_{TV} increased for a given tree, the variation in E_{TV} between boards also increased. The number of boards per tree ranged from five to twenty two boards.

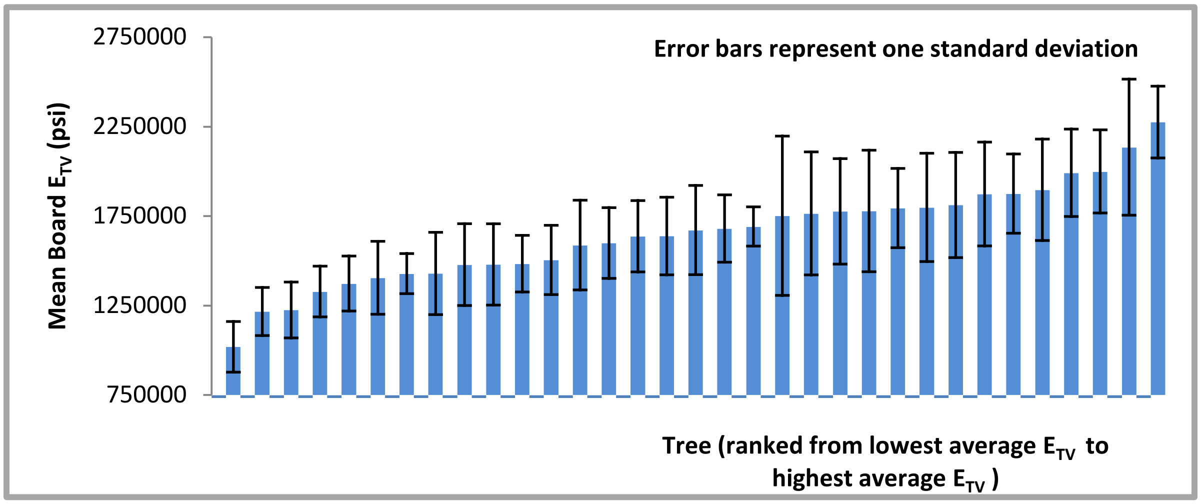

Figure 4 - Variation in board dynamic modulus of elasticity (E_{TV})

The variation shown in Figure 4 would suggest difficulty in predicting trees with higher average E_{TV} because of the greater variation in wood stiffness in lumber resulting from those trees. Most trees contained a portion of lumber that was of poor stiffness. Some trees had high stiffness lumber in addition to low stiffness lumber. The trees with high stiffness lumber typically had a significant amount of low stiffness lumber resulting in lumber with a higher variation in E_{TV}. The high amount variation observed in resultant lumber makes predictions from one or two measurements on standing trees problematic.

After destructive sampling, it was possible to correlate only the trees that had low amounts of variation within the boards produced from those trees. The trees that resulted in E_{TV} values with the smallest amount of variation (coefficient of variation (COV) less than 0.12) correlated much better with Total Core E_{SWV} and the Log Stress Wave Velocities. It should be noted that the two oldest trees (140 and 240 years old) showed little variation but still correlated poorly and were removed from this analysis. These regressions are summarized in Table 2. These regressions are also graphed in Figure 5 and Figure 6.

Table 2 - Univariate regression results using only trees with dynamic modulus of elasticity (E_{TV}) coefficient of variation less than 12%

Board E_{TV} Regression Results in Trees with E_{TV} Coefficient of Variation Less Than 12% (Univariate Regressions)				
Variable	**Unstandardized Beta**	**T Value**	**Significance**	**Adjusted R2**
Total Core E_{SWV}	0.434	19.466	0.000	0.477
Log Stress Wave Velocity	334.894	30.892	0.000	0.697

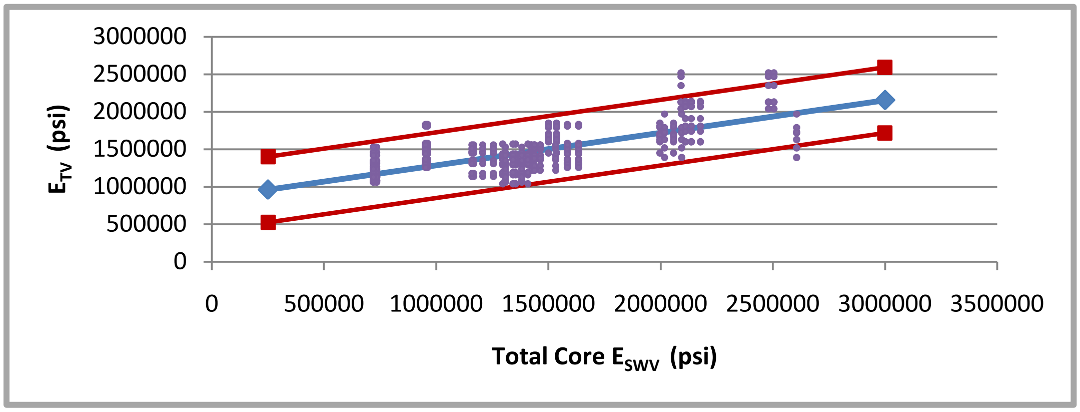

Figure 5 - Relationship between total core density and stress wave velocity measurement calculation of standing tree modulus of elasticity (Total Core E_{SWV}) and board dynamic modulus of elasticity (E_{TV}) when coefficient of variation in board in E_{TV} is less than

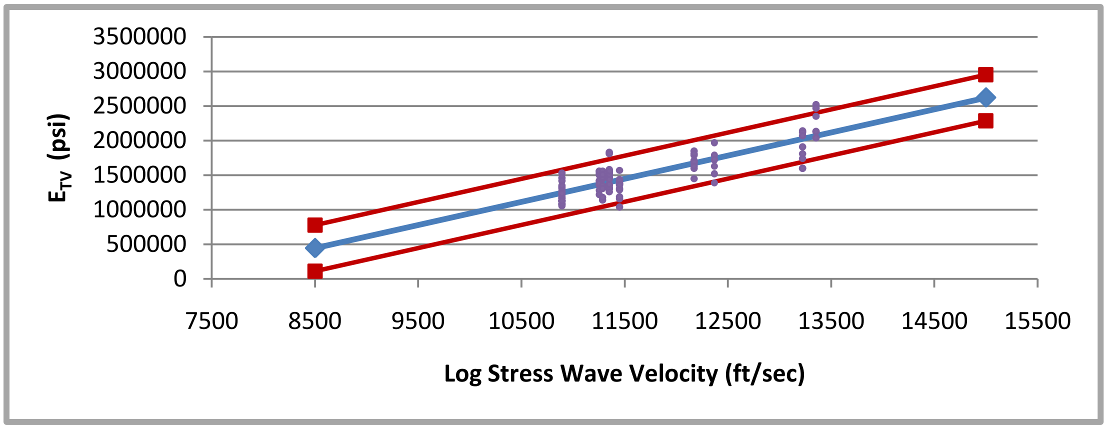

Figure 6 - Relationship between log stress wave velocity measurements and board dynamic modulus of elasticity (E_{TV}) when coefficient of variation in E_{TV} is less than 12%

An R^2 value of 0.477 between E_{SWV} and E_{TV} was found when limiting the analysis to only those trees that had little variation. The increased correlation was demonstrated for both the Log Stress Wave Velocities and the Total Core E_{SWV}. These results indicate that in situations where stand characteristics (age, genetics, and growing conditions) are controlled, like plantations, E_{SWV} and log stress wave velocity may predict wood stiffness much better. In these limited situations, the variation between trees is reduced making predictions much more feasible. In wild stands, this improvement is only gained after the lumber was assigned an E_{TV} and therefore does not improve the prediction of a tree's properties. These findings are very similar to past studies that looked into removing trees with high amounts of variation (Wagner et al. 2003).

Conclusion & Recommendations

Stress wave velocity measurements in standing trees can only provide a limited prediction of the actual lumber quality in those trees. The trees with higher stress wave velocities are more likely the trees with the highest quality lumber. However, the correlations are weak and high variation in both stress wave velocities and lumber MOE make predictions very difficult. Inherent within tree variation in naturally regenerated stands of timber seems to have resulted in a weak relationship between standing tree stress wave velocity measurements and the resultant lumber modulus of elasticity. These findings support those found by Amishev and Murphy (2008) in their work with natural stands of Douglas-fir.

Despite suggestions in previous literature that the stress wave path in standing trees follows a straight line between the probes, we found that modulus of elasticity calculated with stress wave velocity and the density of the sapwood was not as predictive as calculating modulus of elasticity using stress wave velocity and heartwood density or the density of the entire increment core. The inhomogeneous nature of wood has potential to distort the stress wave boundaries as a wave propagates through the material which may affect the path and arrival times of a stress wave in standing trees.

The trees with the least variation in lumber stiffness correlated much better than the trees with greater amounts of variation in lumber stiffness. It was not possible to tell, however, from the stress wave velocities which trees had high amounts of variation and which trees had low amounts of variation. Therefore, this improved correlation is only meaningful when the trees are destructively sampled but does not improve predictive ability of lumber stiffness from standing tree stress wave velocities. At this time, stress wave velocity measurements in standing trees may not provide researchers, mill owners, or timber sellers and buyers significant additional information about the quality of standing timber.

However, the log stress wave velocity measurements proved to be reliable indicators of wood quality. As prior research has shown, the resonance method of acquiring a stress wave velocity appears to capture the full volume and length of the log and an improved correlation to lumber stiffness is one result. The resonance method should be capable of predicting log value, especially when machine stress rating of lumber is possible and a premium is placed on high stiffness material. This technique could also be used to select stiff logs for various markets where structural properties are important and direct weaker logs to more appropriate applications.

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Appendix A: Field Sampling Data

Appendix A-1 – Standing Tree Stress Wave Velocity Data

Appendix A-2 – Tree Density from Increment Cores

Appendix A-3 –25’ Log Stress Wave Velocity Measurement

Appendix A-1 Standing Tree Stress Wave Velocity Data

Tree	DBH (in)	Estimated Rings per Inch	Estimated Age	Stress Wave Velocity Side 1 (ft/sec)		Stress Wave Velocity Side 2 (ft/sec)	
				#1	#2	#1	#2
101	18.5	6.19	57.3	13583	13787	13465	13623
102	15.7	6.62	52	14029	13525	13324	13209
103	15.4	7.22	55.6	13224	13123	12995	13766
104	15.5	7.4	57.4	14971	14971	14428	14315
105	14.2	8.76	62.2	16383	16068	16154	16154
106	12	8.97	53.8	14993	15113	14755	14943
107	16.3	6.26	51	13198	13559	12989	13048
108	16.1	7.1	57.2	12680	13216	13175	13123
109	12.1	10.4	62.6	15020	15020	15668	15742
114	12.3	10.3	63.4	15315	15249	15751	15669
115	15.8	7.04	55.6	14017	13384	14716	14788
117	16.5	5.24	43.2	12549	12309	8190	8422
118	17.8	5.87	52.2	12618	13282	12781	11665
119	14.1	10.5	74.3	9572	12803	12865	12707
120	18.4	5.24	48.2	13270	12701	11996	11593
121	22.2	5.14	57.1	10407	10203	6353	6456
122	13.2	9.04	59.7	9037	9451	13753	13386
123	18.4	7.09	65.2	8553	8553	6377	6456
124	16.6	6.93	57.5	10920	10762	10994	11044
125	14.9	7.38	55	12035	11601	12647	12391
126	14.1	8.23	58	15123	14967	13819	13940
127	22	7.52	82.7	13072	12868	9843	9801
128	20.1	5.61	56.4	12262	12367	12700	12520
129	14.4	8.94	64.3	15612	15505	15395	15494
130	17.2	7.84	67.4	13179	12680	9358	9325
131	12.4	8.1	50.2	15657	15657	14604	14876
133	22.2	7.32	81.3	11165	10905	7415	8878
134	19.8	9.68	95.9	10765	10998	9773	9279
135	20.1	9.35	93.9	12666	12322	8921	8832
136	16.3	29.8	243	9289	9310	12432	12432
139	18	16	144	15769	15769	15762	15762
140	12.8	8.59	55	15558	15461	15459	15459
141	16.7	7.18	60	14975	14873	14284	14284

Appendix A-2 Tree Density from Increment Cores

Tree	Total Core Density (lbs/in^3)		Heartwood Density (lbs/in^3)		Sapwood Density(lbs/in^3)		First Inch Density(lbs/in^3)	
	Side 1	Side 2	Side 1	Side 2	Side 1	Side 2	Side 1	Side 2
101	0.0290	0.0263	0.0413	0.0343	0.0222	0.0204	0.0322	0.0322
102	0.0209	0.0193	0.0296	0.0296	0.0221	0.0187	0.0338	0.0342
103	0.0298	0.0281	0.0342	0.0361	0.0260	0.0235	0.0339	0.0329
104	0.0231	0.0201	0.0314	0.0361	0.0232	0.0209	0.0304	0.0329
105	0.0221	0.0205	0.0271	0.0270	0.0233	0.0211	0.0285	0.0305
106	0.0237	0.0208	0.0322	0.0331	0.0235	0.0204	0.0318	0.0303
107	0.0201	0.0174	0.0306	0.0330	0.0226	0.0195	0.0324	0.0336
108	0.0216	0.0185	0.0328	0.0346	0.0209	0.0185	0.0314	0.0344
109	0.0248	0.0226	0.0325	0.0343	0.0271	0.0247	0.0331	0.0324
114	0.0232	0.0217	0.0271	0.0274	0.0225	0.0212	0.0288	0.0288
115	0.0258	0.0236	0.0327	0.0344	0.0266	0.0247	0.0334	0.0340
117	0.0234	0.0195	0.0336	0.0343	0.0235	0.0200	0.0332	0.0345
118	0.0105	0.0073	0.0326	0.0331	0.0243	0.0218	0.0314	0.0337
119	0.0218	0.0203	0.0299	0.0299	0.0224	0.0211	0.0295	0.0295
120	0.0220	0.0193	0.0300	0.0310	0.0234	0.0205	0.0305	0.0328
121	0.0239	0.0221	0.0357	0.0345	0.0209	0.0172	0.0344	0.0356
122	0.0234	0.0213	0.0287	0.0307	0.0234	0.0200	0.0320	0.0342
123	0.0252	0.0221	0.0339	0.0353	0.0249	0.0220	0.0311	0.0327
124	0.0225	0.0196	0.0305	0.0322	0.0226	0.0196	0.0307	0.0330
125	0.0232	0.0204	0.0338	0.0335	0.0202	0.0184	0.0239	0.0251
126	0.0235	0.0196	0.0325	0.0337	0.0234	0.0201	0.0333	0.0353
127	0.0256	0.0237	0.0336	0.0351	0.0266	0.0239	0.0357	0.0354
128	0.0241	0.0212	0.0337	0.0367	0.0257	0.0229	0.0368	0.0378
129	0.0242	0.0212	0.0356	0.0379	0.0242	0.0211	0.0332	0.0377
130	0.0210	0.0184	0.0356	0.0368	0.0222	0.0190	0.0317	0.0347
131	0.0285	0.0258	0.0389	0.0408	0.0254	0.0221	0.0392	0.0389
133	0.0236	0.0202	0.0360	0.0377	0.0247	0.0222	0.0360	0.0360
134	0.0304	0.0261	0.0376	0.0402	0.0317	0.0297	0.0383	0.0393
135	0.0231	0.0203	0.0316	0.0374	0.0247	0.0228	0.0329	0.0383
136	0.0267	0.0242	0.0353	0.0383	0.0258	0.0232	0.0351	0.0371
139	0.0252	0.0242	0.0305	0.0284	0.0262	0.0244	0.0363	0.0363
140	0.0237	0.0206	0.0337	0.0365	0.0244	0.0205	0.0355	0.0383
141	0.0248	0.0203	0.0329	0.0388	0.0249	0.0210	0.0332	0.0371

Appendix A-3 – 25' Log Stress Wave Velocity Measurement

Tree	Stress Wave Velocity #1 (ft/sec)	Stress Wave Velocity #2 (ft/sec)
101	12,172	12,172
102	11,253	11,253
103	11,778	11,778
104	13,058	13,123
105	12,828	12,762
106	12,258	12,258
107	11,352	11,352
108	11,483	11,417
109	13,353	13,353
114	12,467	12,434
115	11,778	11,778
117	10,958	10,958
118	11,614	11,614
119	12,303	12,303
120	11,844	11,844
121	10,203	10,203
122	12,172	12,172
123	11,844	11,844
124	12,172	12,172
125	11,286	11,286
126	12,434	12,533
127	11,352	11,352
128	11,614	11,614
129	12,730	12,730
130	11,844	11,844
131	12,369	12,369
133	10,203	10,269
134	11,024	11,024
135	10,892	10,892
136	11,909	11,942
139	13,058	13,058
140	13,255	13,189
141	11,647	11,647

Appendix B: Testing Data

Appendix B-1 – Nondestructive Testing

Appendix B-2 – Static Bending

Appendix B-1 – Nondestructive Testing

Board	Tree	Density (lbs/in^3)	E_{TV} (psi)	Rings Per Inch
1	139	0.025	2,550,000	10.84
2	115	0.019	2,570,000	6.23
3	140	0.020	2,140,000	10
4	140	0.019	1,600,000	7.14
5	124	0.021	2,050,000	6.62
6	134	0.024	2,200,000	4.88
7	101	0.020	1,710,000	4.98
8	129	0.022	2,230,000	8.19
9	109	0.021	2,040,000	10.31
10	120	0.020	1,660,000	5.02
11	121	0.017	1,050,000	4.53
12	135	0.019	1,130,000	6.55
13	105	0.019	1,680,000	8
14	102	0.019	1,360,000	8.02
15	114	0.020	1,740,000	5.62
16	119	0.017	1,490,000	7.28
17	133	0.021	1,250,000	9.05
18	121	0.017	1,050,000	10.11
19	131	0.022	1,630,000	5.11
20	140	0.020	2,120,000	11.61
21	120	0.020	1,760,000	12.16
22	129	0.020	1,850,000	4.04
23	103	0.021	1,640,000	13.29
24	121	0.017	1,430,000	8.77
25	120	0.021	1,640,000	5.56
26	121	0.018	1,030,000	4.62
27	115	0.021	1,850,000	3.61
28	128	0.020	1,620,000	8.05
29	135	0.021	1,330,000	5.11
30	136	0.021	2,050,000	9.86
31	120	0.020	1,350,000	24.27
32	133	0.020	890,000	4.14
33	121	0.017	1,230,000	4.32
34	115	0.019	1,690,000	7.41
35	133	0.020	1,160,000	7.56
36	139	0.022	2,060,000	9.5
37	135	0.019	1,170,000	13.41
38	119	0.021	1,860,000	7.32
39	109	0.023	2,350,000	7.53
40	115	0.019	1,770,000	9.45
41	107	0.019	1,640,000	7.65
42	135	0.019	1,130,000	5.77
43	119	0.020	1,680,000	8.88
44	115	0.021	1,650,000	6.15
45	119	0.020	1,720,000	8.38

Appendix B-1 – Nondestructive Testing

Board	Tree	Density (lbs/in^3)	E_{TV} (psi)	Rings Per Inch
46	121	0.018	950,000	4.91
47	139	0.024	2,500,000	11.51
48	121	0.017	1,310,000	5.77
49	139	0.022	2,130,000	9.8
50	115	0.020	1,820,000	8.33
51	139	0.025	2,520,000	17.06
52	130	0.018	1,220,000	6.61
53	129	0.019	1,590,000	7.72
54	139	0.024	2,410,000	23.5
55	120	0.021	1,800,000	4
56	119	0.021	1,850,000	10.71
57	109	0.022	2,130,000	8.67
58	121	0.017	1,510,000	4.82
59	135	0.020	1,310,000	11.89
60	140	0.019	1,740,000	7.58
61	120	0.020	1,830,000	5.9
62	140	0.019	1,910,000	7.55
63	115	0.019	1,750,000	6.11
64	129	0.022	2,200,000	9.2
65	121	0.017	1,370,000	5.41
66	127	0.017	1,310,000	5.03
67	121	0.018	1,130,000	4.7
68	119	0.021	1,730,000	8.56
69	140	0.020	2,070,000	7.74
70	136	0.022	2,200,000	16.19
71	115	0.019	1,350,000	5.02
72	108	0.017	1,160,000	4.74
73	123	0.020	1,300,000	5.81
74	135	0.019	1,170,000	18.49
75	129	0.019	1,750,000	8.46
76	120	0.020	1,500,000	3.91
77	128	0.021	1,690,000	6.22
78	135	0.019	1,080,000	6.21
79	136	0.022	1,940,000	164.55
80	139	0.025	2,690,000	11.16
81	130	0.022	1,570,000	7.93
82	107	0.019	1,710,000	5.45
83	135	0.019	1,080,000	6.29
84	135	0.021	1,530,000	8.11
85	131	0.020	1,790,000	9.66
86	140	0.019	1,810,000	8.15
87	131	0.022	1,970,000	8.53
88	121	0.018	1,300,000	6.67
89	130	0.020	1,310,000	6.04
90	136	0.023	2,170,000	21.85
91	123	0.020	1,250,000	6.04
92	122	0.023	2,310,000	8.59

Appendix B-1 – Nondestructive Testing

Board	Tree	Density (lbs/in^3)	E_{TV} (psi)	Rings Per Inch
93	121	0.018	1,290,000	4.06
94	136	0.023	2,120,000	17.5
95	124	0.020	1,780,000	5.81
96	119	0.020	1,240,000	6.88
97	124	0.020	1,820,000	9.38
98	129	0.021	2,080,000	13.22
99	126	0.019	1,660,000	9.17
100	135	0.020	1,460,000	9.8
101	120	0.019	1,820,000	5.63
102	136	0.021	2,130,000	20.69
103	108	0.017	1,290,000	7.39
104	123	0.020	1,390,000	4.23
105	117	0.019	1,210,000	5.02
106	120	0.019	1,320,000	6.04
107	121	0.018	1,260,000	4.49
108	121	0.017	1,080,000	5.07
109	101	0.022	1,790,000	4.1
110	109	0.023	2,520,000	14.08
111	121	0.017	1,100,000	4.38
112	136	0.020	1,760,000	16.13
113	121	0.017	1,250,000	7
114	102	0.018	1,280,000	5.56
115	136	0.022	2,150,000	19.53
116	120	0.021	1,790,000	3.98
117	107	0.019	1,160,000	7.33
118	135	0.019	1,350,000	13.26
119	102	0.018	1,540,000	6.67
120	107	0.019	1,410,000	4.92
121	120	0.020	1,800,000	4.69
122	131	0.020	1,720,000	7.14
123	114	0.020	1,800,000	8.78
124	109	0.022	2,130,000	9.47
125	130	0.020	1,860,000	16.67
126	123	0.020	1,570,000	4.36
127	102	0.018	1,500,000	10.32
128	129	0.019	1,330,000	7.38
129	120	0.020	1,380,000	3.66
130	120	0.019	1,180,000	7.77
131	130	0.019	1,520,000	7.31
132	108	0.018	1,390,000	7.14
133	135	0.020	1,140,000	13.86
134	135	0.019	1,420,000	7.84
135	108	0.017	1,380,000	6.58
136	139	0.017	1,150,000	15.96
137	109	0.023	2,470,000	10.14
138	120	0.018	980,000	9.02
139	135	0.019	1,230,000	11.9

Appendix B-1 – Nondestructive Testing

Board	Tree	Density (lbs/in^3)	E_{TV} (psi)	Rings Per Inch
140	135	0.018	1,200,000	8.84
141	108	0.018	1,440,000	8.84
142	107	0.019	1,220,000	5.6
143	125	0.018	1,450,000	6.88
144	131	0.021	1,730,000	9.39
145	135	0.020	1,270,000	7.17
146	136	0.021	1,980,000	13.6
147	136	0.024	1,980,000	15.52
148	133	0.018	1,130,000	8.76
149	107	0.020	1,620,000	7.19
150	101	0.021	1,850,000	8.07
151	120	0.019	1,560,000	4.58
152	120	0.020	1,800,000	5.11
153	114	0.019	1,320,000	10.53
154	124	0.021	1,800,000	5.81
155	107	0.018	1,220,000	8.7
156	136	0.019	1,360,000	17.58
157	129	0.018	1,360,000	7.74
158	107	0.018	1,270,000	7.89
159	136	0.020	1,920,000	19.2
160	134	0.020	1,970,000	7.22
161	102	0.019	1,520,000	5.23
162	140	0.018	1,600,000	8.91
163	136	0.024	2,210,000	20.23
164	130	0.017	1,300,000	6.59
165	130	0.019	1,630,000	6.8
166	107	0.019	1,080,000	5.97
167	130	0.018	1,490,000	8.92
168	135	0.019	1,060,000	7.88
169	108	0.017	1,040,000	4.35
170	135	0.019	1,080,000	11.34
171	131	0.020	1,520,000	6.25
172	130	0.018	1,310,000	5.08
173	102	0.019	1,560,000	4.85
174	130	0.018	1,470,000	6.4
175	119	0.020	1,480,000	7.3
176	125	0.019	1,470,000	7.86
177	114	0.020	1,770,000	13.16
178	125	0.017	1,350,000	7.69
179	135	0.020	1,240,000	7.84
180	130	0.017	1,040,000	8.28
181	107	0.020	1,580,000	5
182	124	0.021	1,970,000	6.63
183	115	0.019	1,590,000	6.97
184	125	0.011	1,140,000	8.38
185	119	0.013	1,670,000	7.84
186	139	0.014	1,710,000	29.91

Appendix B-1 – Nondestructive Testing

Board	Tree	Density (lbs/in^3)	E_{TV} (psi)	Rings Per Inch
187	108	0.018	1,420,000	7.59
188	107	0.020	1,420,000	6.54
189	125	0.017	1,180,000	6.78
190	124	0.020	1,740,000	5.88
191	135	0.020	1,130,000	5.49
192	139	0.020	1,990,000	17.71
193	107	0.018	1,330,000	5.06
194	131	0.020	1,390,000	5.42
195	108	0.018	1,190,000	7.96
196	107	0.019	1,470,000	8.33
197	130	0.019	1,690,000	5.17
198	120	0.020	1,740,000	6.93
199	125	0.018	1,310,000	7.5
200	107	0.018	1,250,000	5.94
201	124	0.018	1,470,000	5.7
202	130	0.020	1,790,000	9.58
203	130	0.018	1,320,000	5.98
204	114	0.020	1,400,000	10.43
205	126	0.021	2,220,000	9.73
206	107	0.019	1,670,000	5.13
207	114	0.020	1,790,000	11.69
208	102	0.017	1,220,000	6.58
209	129	0.020	1,600,000	7.53
210	130	0.019	1,650,000	10.24
211	125	0.018	1,560,000	7.72
212	125	0.018	1,510,000	6.21
213	135	0.020	1,090,000	7.65
214	108	0.018	1,310,000	8.72
215	102	0.018	1,420,000	5.41
216	133	0.018	1,130,000	5.77
217	105	0.019	1,660,000	9.79
218	108	0.018	1,370,000	7.41
219	121	0.017	1,450,000	5.79
220	141	0.020	1,430,000	9.62
221	106	0.020	1,870,000	7.35
222	122	0.020	1,530,000	9.64
223	103	0.022	1,560,000	10.51
224	121	0.017	1,090,000	4.68
225	122	0.021	1,930,000	11.35
226	118	0.020	1,720,000	7.93
227	141	0.019	1,420,000	7.89
228	127	0.022	1,500,000	7.57
229	108	0.018	1,570,000	6.55
230	124	0.019	1,190,000	6.83
231	108	0.018	1,360,000	7.97
232	123	0.021	1,440,000	12.9
233	141	0.021	1,670,000	6.08

Appendix B-1 – Nondestructive Testing

Board	Tree	Density (lbs/in^3)	E_{TV} (psi)	Rings Per Inch
234	141	0.021	1,860,000	6.79
235	122	0.021	1,620,000	9.7
236	103	0.022	1,760,000	6.55
237	141	0.019	1,450,000	6.36
238	122	0.022	1,840,000	10
239	118	0.021	1,700,000	4.56
240	106	0.019	1,460,000	9.85
241	101	0.020	1,700,000	3.19
242	118	0.022	1,740,000	3.87
243	141	0.019	1,330,000	8.72
244	127	0.020	1,300,000	4.64
245	118	0.022	1,620,000	3.75
246	123	0.021	1,530,000	13.01
247	106	0.019	1,510,000	7.84
248	101	0.021	1,670,000	5.6
249	123	0.024	2,330,000	5.06
250	127	0.022	1,580,000	11.81
251	121	0.018	1,310,000	3.7
252	106	0.020	2,060,000	8.89
253	127	0.020	1,460,000	4.33
254	127	0.021	1,470,000	16.99
255	118	0.020	1,420,000	6.85
256	141	0.020	1,720,000	5.61
257	127	0.022	1,530,000	10.2
258	118	0.021	1,660,000	6.45
259	126	0.020	1,550,000	7.02
260	106	0.020	1,900,000	10.59
261	127	0.020	1,530,000	6.31
262	123	0.021	1,740,000	4.41
263	127	0.021	1,350,000	6.07
264	121	0.016	1,280,000	4.68
265	141	0.021	1,880,000	6.25
266	127	0.022	1,320,000	5.29
267	127	0.021	1,550,000	6.08
268	126	0.022	2,120,000	9.17
269	123	0.023	2,150,000	5.1
270	127	0.022	1,510,000	9.87
271	123	0.021	1,680,000	7.43
272	133	0.019	1,060,000	12.55
273	101	0.020	1,450,000	4.55
274	139	0.023	2,280,000	14.1
275	133	0.019	800,000	4.3
276	126	0.020	1,960,000	8.46
277	127	0.022	1,830,000	8.24
278	118	0.021	1,280,000	6.32
279	141	0.019	1,360,000	8.05
280	123	0.023	2,060,000	9.93

Appendix B-1 – Nondestructive Testing

Board	Tree	Density (lbs/in^3)	E_{TV} (psi)	Rings Per Inch
281	123	0.024	2,260,000	7.85
282	126	0.020	1,670,000	7.34
283	127	0.017	1,260,000	6
284	123	0.023	1,920,000	4.51
285	133	0.018	920,000	6.71
286	101	0.020	1,690,000	7.61
287	127	0.017	1,370,000	5.63
288	133	0.018	1,050,000	4.45
289	123	0.021	1,830,000	5.47
290	127	0.021	1,440,000	9.69
291	122	0.022	2,180,000	8.05
292	141	0.021	1,810,000	6.28
293	126	0.022	1,930,000	7.45
294	101	0.020	1,690,000	6.36
295	133	0.019	990,000	6.67
296	103	0.021	1,180,000	4.62
297	133	0.019	940,000	5.46
298	133	0.019	1,030,000	5.88
299	133	0.019	1,330,000	13.66
300	103	0.022	1,520,000	7.27
301	133	0.018	1,090,000	5.98
302	133	0.019	1,050,000	7.51
303	126	0.021	1,370,000	6.38
304	103	0.021	1,430,000	7.5
305	127	0.021	1,560,000	7.04
306	123	0.023	2,090,000	3.79
307	101	0.020	1,600,000	7.97
308	133	0.018	1,190,000	7.44
309	101	0.020	1,810,000	11.39
310	133	0.020	870,000	7.37
311	133	0.018	1,020,000	4.76
312	133	0.018	800,000	9.63
313	103	0.022	1,640,000	4.49
314	133	0.019	960,000	4.76
315	133	0.018	790,000	5.67
316	123	0.021	1,670,000	9.27
317	103	0.022	1,640,000	5.06
318	127	0.021	1,810,000	7.84
319	101	0.020	1,630,000	8.82
320	133	0.019	980,000	5.54
321	105	0.020	1,770,000	9.63
322	128	0.021	1,000,000	4.28
323	139	0.022	1,910,000	14.8
324	124	0.020	1,740,000	8.51
325	102	0.018	1,360,000	8.65
326	128	0.021	1,580,000	5.38
327	128	0.020	1,350,000	6.25

Appendix B-1 – Nondestructive Testing

Board	Tree	Density (lbs/in^3)	E_{TV} (psi)	Rings Per Inch
328	104	0.022	1,460,000	7.25
329	124	0.022	2,070,000	8.55
330	104	0.019	1,840,000	6.79
331	106	0.021	1,850,000	8.19
332	104	0.019	1,760,000	7.6
333	135	0.017	1,130,000	10.43
334	139	0.025	1,960,000	29.7
335	128	0.021	1,760,000	7.83
336	105	0.021	1,990,000	7.38
337	104	0.019	1,810,000	17.24
338	104	0.020	1,990,000	7.28
339	105	0.022	2,090,000	8.85
340	117	0.019	1,280,000	4.79
341	128	0.021	1,720,000	4.75
342	115	0.024	2,100,000	6.52
343	128	0.019	1,580,000	5
344	NA	0.019	1,610,000	8.62
345	104	0.019	1,610,000	7.77
346	103	0.021	1,370,000	8
347	124	0.019	1,540,000	6.67
348	128	0.021	1,180,000	5.58
349	124	0.020	1,840,000	6.2
350	134	0.024	2,270,000	6.91
351	105	0.021	1,990,000	9.36
352	104	0.022	2,480,000	9.21
353	141	0.021	1,740,000	4.7
354	117	0.019	1,080,000	6.29
355	105	0.021	2,170,000	8.07
356	134	0.023	1,680,000	17.69
357	118	0.021	1,470,000	7.77
358	117	0.020	1,640,000	4.28
359	103	0.021	1,030,000	8.03
360	139	0.023	2,220,000	14.48
361	128	0.020	1,480,000	6
362	128	0.021	1,400,000	5.54
363	117	0.020	1,560,000	3.89
364	124	0.023	2,260,000	7.19
365	128	0.019	1,370,000	3.6
366	134	0.022	1,420,000	13.41
367	117	0.020	1,480,000	3.66
368	124	0.019	1,630,000	6.5
369	117	0.018	1,280,000	4.98
370	118	0.023	1,870,000	4.86
371	NA	0.020	1,840,000	8.82
372	124	0.019	1,170,000	7.69
373	115	0.020	1,810,000	8.7
374	128	0.022	1,640,000	5.51

Appendix B-1 – Nondestructive Testing

Board	Tree	Density (lbs/in^3)	E_{TV} (psi)	Rings Per Inch
375	104	0.020	1,940,000	7.33
376	128	0.022	1,630,000	6
377	134	0.023	1,290,000	5.26
378	117	0.018	1,100,000	6.15
379	115	0.020	1,610,000	5.8
380	139	0.022	1,930,000	16.96
381	106	0.020	1,900,000	10.07
382	118	0.022	1,690,000	4.93
383	102	0.019	1,420,000	6.98
384	118	0.021	1,910,000	7.89
385	124	0.022	2,020,000	7.59
386	139	0.022	2,120,000	19.28
387	118	0.020	1,460,000	5.97
388	122	0.021	1,690,000	7.23
389	105	0.022	2,360,000	8.26
390	117	0.021	1,680,000	7.21
391	128	0.019	1,440,000	4.5
392	104	0.021	2,160,000	6.82
393	102	0.020	1,560,000	4.29
394	134	0.024	1,890,000	8.33
395	118	0.023	2,060,000	4.94
396	117	0.019	1,460,000	4.85
397	134	0.022	1,970,000	7.86
398	124	0.020	1,770,000	6
399	134	0.023	1,960,000	7.09
400	134	0.023	700,000	5.92
401	128	0.019	1,370,000	4.31
402	128	0.021	1,510,000	4.86
403	128	0.020	1,490,000	5.15
404	118	0.021	1,500,000	5.4
405	133	0.018	1,090,000	5.95
406	118	0.021	1,420,000	6.57
407	133	0.017	900,000	5.54
408	134	0.023	1,330,000	6.93
409	141	0.020	1,650,000	7.57
410	118	0.024	2,200,000	6.56
411	117	0.020	1,730,000	4.73
412	128	0.023	1,770,000	5.68
413	134	0.022	1,550,000	9.24
414	134	0.024	2,140,000	11.97
415	128	0.020	1,480,000	10.74
416	105	0.021	2,200,000	9.46
417	124	0.023	2,080,000	5.52
418	117	0.020	1,630,000	7.04
419	134	0.025	2,130,000	25
420	102	0.019	1,380,000	9.34
421	104	0.020	1,900,000	6.32

Appendix B-1 – Nondestructive Testing

Board	Tree	Density (lbs/in^3)	E_{TV} (psi)	Rings Per Inch
422	141	0.020	1,450,000	6.34
423	120	0.021	1,640,000	7.76

Appendix B-2 – Static Bending

Board	Tree	E_{Static} (10^6psi)	Flexural Strength (psi)	Moister Content	Specific Gravity (12% MC)
1	139	2.54	9,170	14.31%	0.6
4	140	1.41	7,070	12.09%	0.44
13	105	1.57	5,460	13.83%	0.45
14	102	1.24	4,800	12.95%	0.45
15	114	1.62	7,990	13.05%	0.44
17	133	0.87	3,180	14.80%	0.45
18	121	0.99	4,160	13.80%	0.42
20	140	2.08	9,850	12.52%	0.48
26	121	0.92	4,290	13.44%	0.46
28	128	1.41	530	13.52%	0.48
30	136	1.92	6,250	13.08%	0.53
37	135	1.07	3,910	12.07%	0.45
39	109	2.18	10,160	14.08%	0.58
41	107	1.41	5,750	11.81%	0.49
44	115	1.55	6,130	13.64%	0.48
45	119	1.76	8,050	12.68%	0.53
53	129	1.44	4,950	13.03%	0.47
57	109	1.82	6,950	13.21%	0.52
61	120	1.60	5,830	12.51%	0.49
65	121	1.25	5,130	13.09%	0.4
67	121	0.98	3,300	12.95%	0.43
69	140	1.87	7,820	13.09%	0.47
70	136	1.73	10,400	13.27%	0.52
72	108	1.03	5,020	13.27%	0.47
75	129	1.55	4,630	13.16%	0.41
77	128	1.53	7,160	14.07%	0.52
79	136	1.64	6,350	13.59%	0.58
80	139	2.17	5,700	14.55%	0.58
85	131	1.61	6,020	12.34%	0.53
91	123	1.18	5,910	12.90%	0.46
92	122	1.90	6,440	13.73%	0.53
96	119	1.07	5,500	12.48%	0.47
98	129	1.89	6,320	12.79%	0.49
111	121	0.97	3,310	12.61%	0.39
116	120	1.51	6,650	12.42%	0.49
122	131	1.59	7,500	12.72%	0.46
123	114	1.69	9,270	12.47%	0.48
124	109	2.19	11,090	13.82%	0.55
125	130	1.61	7,890	12.66%	0.5
127	102	1.44	8,270	13.12%	0.42
128	129	1.27	5,880	12.95%	0.41
129	120	1.21	5,900	12.26%	0.5
132	108	1.33	4,900	13.03%	0.42
134	135	1.43	7,450	12.50%	0.5
137	109	2.21	9,230	13.85%	0.52
138	120	0.98	7,180	12.11%	0.46

Appendix B-2 – Static Bending

Board	Tree	E_{Static} (10^6psi)	Flexural Strength (psi)	Moister Content	Specific Gravity (12% MC)
148	133	0.97	4,200	12.24%	0.43
151	120	1.51	8,200	12.25%	0.47
153	114	1.39	9,340	12.74%	0.47
159	136	1.82	10,520	12.52%	0.47
163	136	1.74	7,170	13.53%	0.55
164	130	1.23	7,200	11.60%	0.39
165	130	1.51	7,430	12.43%	0.43
166	107	0.92	2,960	11.26%	0.46
168	135	1.00	3,870	11.32%	0.47
184	125	1.10	3,700	12.75%	0.42
185	119	1.58	7,220	12.85%	0.46
186	139	1.27	1,580	13.68%	0.54
188	107	1.36	8,140	11.65%	0.45
189	125	1.09	5,030	12.25%	0.38
193	107	1.39	6,390	12.16%	0.45
194	131	1.23	4,500	12.37%	0.5
195	108	1.13	3,800	13.25%	0.4
197	130	1.69	7,040	12.71%	0.48
199	125	1.20	4,530	11.56%	0.46
205	126	2.00	9,060	13.76%	0.53
207	114	2.04	9,450	12.94%	0.47
208	102	1.15	3,840	12.77%	0.42
211	125	1.28	7,250	11.69%	0.48
216	133	1.10	3,850	12.92%	0.4
220	141	1.19	5,030	12.48%	0.45
221	106	1.94	10,020	12.82%	0.49
222	122	1.51	8,120	13.61%	0.49
223	103	1.61	6,760	12.37%	0.53
230	124	1.23	4,150	13.01%	0.43
232	123	1.28	3,800	12.94%	0.52
235	122	1.55	6,810	13.33%	0.49
236	103	1.69	10,270	13.48%	0.56
241	101	1.62	8,650	13.32%	0.48
242	118	1.46	6,370	12.98%	0.52
243	141	1.32	6,000	12.89%	0.5
247	106	1.46	4,800	12.72%	0.46
248	101	1.37	6,540	14.38%	0.47
249	123	1.97	9,380	14.53%	0.54
250	127	1.06	4,110	14.44%	0.51
252	106	1.88	10,100	13.66%	0.48
255	118	1.26	5,530	12.25%	0.48
256	141	1.32	5,430	12.28%	0.5
258	118	1.69	8,990	13.16%	0.53
263	127	1.08	3,710	13.50%	0.47
265	141	1.68	5,790	Sample Lost	Sample Lost
268	126	1.81	7,410	12.37%	0.47

Appendix B-2 – Static Bending

Board	Tree	E_{Static} (10^6psi)	Flexural Strength (psi)	Moister Content	Specific Gravity (12% MC)
274	139	1.99	7,810	13.60%	0.5
275	133	0.86	320	14.66%	0.41
282	126	1.42	4,480	14.14%	0.47
289	123	1.60	7,990	13.77%	0.5
291	122	1.95	7,000	14.28%	0.52
303	126	1.24	4,820	15.05%	0.52
305	127	1.26	3,440	13.75%	0.5
309	101	1.59	7,530	14.16%	0.5
318	127	1.72	9,270	15.23%	0.51
321	105	1.96	8,030	14.16%	0.49
322	128	0.90	3,290	12.77%	0.53
337	104	1.65	6,410	13.91%	0.47
342	115	1.74	8,910	13.29%	0.51
345	104	1.41	6,000	13.69%	0.44
348	128	1.06	5,270	13.47%	0.54
350	134	2.14	11,600	14.07%	0.57
352	104	2.15	9,040	Sample Lost	Sample Lost
354	117	1.08	5,380	13.89%	0.43
355	105	1.92	6,700	14.56%	0.49
359	103	1.03	3,130	12.13%	0.56
364	124	1.76	9,210	14.32%	0.51
369	117	1.09	5,180	14.22%	0.42
370	118	1.72	5,960	13.88%	0.58
372	124	1.26	5,140	13.00%	0.48
373	115	1.72	8,940	13.76%	0.5
375	104	1.80	8,670	14.06%	0.49
379	115	1.52	5,430	13.88%	0.47
380	139	1.87	10,500	13.56%	0.52
385	124	1.92	9,500	14.68%	0.52
386	139	2.06	10,400	13.90%	0.54
388	122	1.52	7,420	13.25%	0.58
396	117	1.26	7,400	13.62%	0.45
399	134	1.64	5,070	13.98%	0.54
400	134	0.72	2,450	13.18%	0.49
411	117	1.63	9,320	14.09%	0.49
416	105	1.89	7,620	14.29%	0.49
418	117	1.20	7,390	14.33%	0.46
419	134	0.98	5,460	13.81%	0.62

Appendix C: Pearson Correlation Table

Appendix C-1 – Pearson Correlation for Density Variables

Appendix C-1 – Pearson Correlation for Density Variables

	Stress Wave Velocity	Total Core Density	Heartwood Density	Sapwood Density	1st Inch Density
Stress Wave Velocity					
Pearson Correlation	1.000	-0.038	-0.001	-0.166	-0.200
Significance (2 Tailed)	-	0.117	0.968	0.000	0.000
Sample Size	1684.000	1684.000	1684.000	1684.000	1684.000
Total Core Density					
Pearson Correlation	-0.038	1.000	0.972	0.520	0.419
Significance (2 Tailed)	0.117	-	0.000	0.000	0.000
Sample Size	1684.000	1684.000	1684.000	1684.000	1684.000
Heartwood Density					
Pearson Correlation	-0.001	0.972	1.000	0.412	0.286
Significance (2 Tailed)	0.968	0.000	-	0.000	0.000
Sample Size	1684.000	1684.000	1684.000	1684.000	1684.000
Sapwood Density					
Pearson Correlation	-0.166	0.502	0.412	1.000	0.774
Significance (2 Tailed)	0.000	0.000	0.000	-	0.000
Sample Size	1684.000	1684.000	1684.000	1684.000	1684.000
1st Inch Density					
Pearson Correlation	-0.200	0.286	0.286	0.774	1.000
Significance (2 Tailed)	0.000	0.000	0.000	0.000	-
Sample Size	1684.000	1684.000	1684.000	1684.000	1684.000