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NONDESTRUCTIVE EVALUATION OF SALVAGE WHITE SPRUCE

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NONDESTRUCTIVE EVALUATION OF SALVAGE WHITE SPRUCE

By

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Abstract

Knowledge of wood quality in dead standing trees is an important topic with recent increases in defoliation across North America. Obtaining wood quality information for defoliated trees would help stakeholders in the timber products industry sort and sell salvaged material for the highest possible value. This research investigates the ability to measure wood quality of white spruce *(Picea glauca)* after spruce budworm *(Choristoneura fumiferana)* attack using acoustic nondestructive evaluation. We compared stress wave velocities measured on standing trees to trees' visual appearance. After harvest and processing of selected trees into bolts, standing-tree stress wave velocities were compared to bolt acoustic velocities. We found that tree appearance offers only coarse information on tree and bolt acoustic measurements. Tree-level measurements provide a good indicator of expected bolt-level acoustic evaluation throughout the height of defoliated white spruce. Future work should focus on correlating bolt-level acoustic measurements to lumber quality for salvage white spruce.

1 Introduction

1.1 Overview

Changes in forest health affect both the value and application of forest products - particularly products derived from wood. Management actions to improve forest health require collaboration between ecology, silviculture and forest products fields (Skog et al. 1995). Prescriptions to improve forest health may pressure the forest products industry to utilize nontraditional or lower quality timber (Myers 2004). Knowledge of wood quality is important to achieve industry utilization of alternative timber sources and provide sustainable solutions to forest health problems. We endeavored to determine the wood quality of defoliated white spruce *(Picea glauca)* an effort to increase the utilization and value of trees affected by the spruce budworm *(Choristoneura fumiferana)*. Recent increase in defoliation caused by the spruce budworm in the Great Lakes Region (MIDNR 2016, 2017, 2018) indicate that management and utilization of defoliated softwood species will become increasingly important in the coming years. Measuring wood quality of defoliated trees allows stakeholders to utilized timber affected by the spruce budworm for the highest possible value.

1.2 Literature Review

1.2.1 Spruce Budworm Ecology

The spruce budworm is endemic to the Great Lakes Region and poses little threat to forest health at low population levels. Spruce budworm larvae prefer to feed on host trees' current year foliage (MacLean 1984). During spruce budworm outbreaks, or increases in population size, high levels of balsam fir *(Abies balsamea)* and spruce *(Picea spp.)* mortality occur due to consecutive defoliation spanning several years (Boulanger et al. 2012). Spruce budworm populations fluctuate between 30-50 years of low levels followed by 10-15 years of higher outbreak population levels (MIDNR 2016). The incidence and intensity of spruce budworm outbreaks have increased since the beginning of the 1900's (Boulanger et al. 2012). Knowledge of wood quality in trees defoliated by the spruce budworm is important to properly manage forests and limit economic loss.

1.2.2 Softwood Lumber Quality

Traditional methods of evaluating softwood wood quality are outlined below. Newer nondestructive acoustic technologies to evaluate wood quality, that may are pertinent to salvage operations, will also be discussed. Quality of softwood lumber in the U.S. is typically defined based on either visual grading or a combination of both nondestructive machine evaluation and visual grading (Kretschmann 2010). In the U.S. the major tree species defoliated by the spruce budworm are categorized into the Spruce-Pine-Fir (South) species combination (AWC 2011). Stress grades define design strength properties which include: bending, tension parallel and perpendicular to grain, shear, compression parallel and perpendicular to grain, and modulus of elasticity (MOE) (AWC 2011). These design properties are used to engineer structures or products composed of lumber within a given species combination and grade (AWC 2011). Visually graded lumber utilizes visual indicators, or defects, to infer a reduced lumber strength. Within a species, strength properties of clear wood are reduced by visual indicators present on a given piece of lumber (Kretschmann 2010). Some indicators that reduce the strength properties of lumber and determine its visual grade include knots, sloped grain, very low density and decay (Kretschmann 2010). Strength ratios are reduction factors that correspond to these visual indicators and are multiplied by strength properties of clear wood for appropriate reduction (Kretschmann 2010). The visual indicator providing the lowest strength ratio is used to infer the strength of a given piece of lumber (Kretschmann 2010). Machine graded lumber is categorized as either machine-stress-rated (MSR) lumber or machine-evaluated-lumber (MEL) (Kretschmann 2010). Design properties of machine graded lumber are inferred based on their established relationships with MOE considering MSR lumber or density in the case of MEL (Kretschmann 2010). The combination of MOE value and visual knot assessment offers a more accurate prediction of lumber strength – for this reason machine graded lumber must be visually graded as well (Kretschmann 2010). While softwood lumber quality is definitive, well-studied and used in industry, definitions of softwood tree quality are much more ambiguous.

1.2.3 Softwood Tree Quality

The USDA Forest Service Forest Inventory Analysis (FIA) provides guidance for data acquisition on the quality of live and dead standing trees (Forest 2007). While this publication's main purpose is not to specifically determine wood quality of standing trees it directs users to record data that can be used to infer wood quality, or wood quality problems, of standing trees. Dead standing trees are defined into decay classes, ranging from 1 to 5, within the FIA (Forest 2007). Decay class 1 represents dead standing trees potentially containing the highest quality wood that have all branches intact, retain all bark, and show limited sapwood decay (Forest 2007). Decay class 5 represents dead standing trees with the poorest wood quality that have no branches, a broken top, and severely decayed wood (Forest 2007). The FIA also instructs damages noticed on live trees to be recorded. Some notable tree damages that likely correlate to poor wood quality include cankers, fruiting bodies, foliage damage or discoloration, loss of dominant stem, broken or dead branches, and many branches (Forest 2007). While systems are in place to monitor and evaluate the quality of softwood trees little effort is made by industry in the Great Lakes Region to assess the quality of logs and bolts produced from softwood trees. In this area softwood timber is typically purchased by the ton (907 kg). Mills that purchase softwood timber presumably don't grade bolts and logs due to the large volumes of softwood purchased and processed. However, acoustic nondestructive evaluation methods can assess wood quality of both logs and standing trees and may be beneficial in sorting and grading salvage timber.

1.2.4 Nondestructive Evaluation of Wood

More recent technological developments in the evaluation of wood quality utilize acoustic nondestructive technology and have the ability to infer the intrinsic wood quality of trees and logs. Jayne (1959) reported that the vibrational properties, or acoustic behavior, of wood can be correlated to the material's MOE. Ross et al. (1997) observed a strong correlation in log dynamic MOE, calculated using logs' longitudinal stress wave velocity, and lumber MOE for balsam fir *(Abies balsamea)* and spruce *(Picea spp.)*. Wang et al. (2001) measured longitudinal stress wave velocity on standing Sitka spruce *(Picea stichensis)* and Western hemlock *(Tsuga heterophylla)*, as well as small wood specimens produced from the trees' boles. They discovered that dynamic MOE calculated on the standing trees correlated well with both dynamic and static MOE measured on the small wood specimens (Wang et al. 2001). After these early studies showed the applicability of measuring wood quality with acoustics, tools that measure acoustic velocity in logs and trees have been developed and commercialized (Wang, Carter et al. 2007). These tools have the ability to increase profits in the forest products sector by efficiently sorting logs and standing trees, according to wood quality, early in the product chain (Wang, Carter et al. 2007). More recent research has shown the ability to model wood quality at various heights of Douglas-fir *(Pseudotsuga menziesii)* based on acoustic nondestructive evaluation measured at low heights (Wang et al. 2013; Dowding and Murphy 2011). Most studies investigating the relationships between acoustic velocity and intrinsic wood quality have been conducted on live standing trees and logs produced from trees which were alive at harvest. However, Wang et al. (2002) correlated dynamic MOE calculated from longitudinal stress wave velocity to static MOE in a sample that contained some jack pine *(Pinus banksiana)* bolts which were dead at the time of harvest. Also, longitudinal stress wave measurements have also been used to sort small red oak *(Quercus spp.)* logs that were attacked by borers (Wang et al. 2009). Deploying acoustic nondestructive evaluation to sort dead trees and bolts, specifically white spruce killed from spruce budworm defoliation, could be important in sorting timber that is expected to have a high level of variation.

1.3 Outline of Present Study

A challenge when marketing dead standing trees is an unpredictable decline in postmortem wood quality (Basham 1984). As a result, dead standing trees are often marketed for low-value products due to assumed poor wood quality. Estimating wood quality in salvage and pre-salvage timber sales will help stakeholders market timber for a higher value and may offset economic loss in spruce and fir stands defoliated by the spruce budworm. Nondestructive evaluation of dead standing white spruce prior to or shortly after harvest could help in predicting the extent of decay and stiffness (MOE) of wood in measured trees. This greater knowledge of wood quality should help stakeholders market timber for the highest potential value. We measured acoustic velocity in both live and dead white spruce standing trees prior to harvest and bolts, produced from the measured trees, post-harvest to determine the intrinsic wood quality and the extent to which salvage white spruce can be graded and sorted.

First, in chapter 2 we investigated the ability to infer wood quality of standing salvage white spruce based on trees' visual appearance - the current method of judging quality of standing trees. To accomplish this comparison three visual categories of defoliated white spruce, ranging from live to dead trees with poor appearance, were created. Acoustic nondestructive measurements of longitudinal and transverse stress wave velocity were conducted on white spruce representing each of the three visual categories in a defoliated stand near Iron River, MI. Generalized linear models were utilized to determine whether or not visual category significantly explains difference in longitudinal and transverse stress wave velocities respectively. Our analysis indicated visual categories were not useful to infer transverse stress wave velocity of salvage white spruce. The visual categories provided only coarse information on longitudinal stress wave velocity measurements on standing salvage white spruce.

Secondly, chapter 3 utilized nondestructive acoustic data from both the standing trees and bolts produced from the respective trees. Utilizing mixed effects models, we determined the ability of longitudinal stress wave velocity measured on standing trees to infer the longitudinal stress wave velocity of bolts produced from their respective trees. Also, in chapter 3 we used mixed effects models to investigate within tree changes in salvage white spruce longitudinal velocity by height. Differences in bolt longitudinal velocity by visual category are investigated using Tukey's test as well. We found that standing tree measurements and height are significant variables in models that infer bolt longitudinal stress wave velocity within salvage white spruce. Bolt longitudinal stress wave velocity generally decreases with height. An exception to this trend are low longitudinal stress wave velocities measured in the lowest bolts produced from dead white spruce –likely indicating decay is present in these bolts. Lastly, a significant difference in bolt longitudinal stress wave velocity was found between bolts produced from trees that were alive and dead in June 2017.

2 Tree Visual Appearance vs Standing NDE

2.1 Abstract

Knowledge of wood quality in dead standing trees is becoming an important topic with recent increases in defoliation across North America. Obtaining wood quality information for individual trees would help stakeholders in the timber products industry sort and sell salvaged material for the highest possible value. This research investigates the ability to measure wood quality of white spruce *(Picea glauca)* after spruce budworm *(Choristoneura fumiferana)* attack using acoustic nondestructive evaluation. We nondestructively compared wood quality measurements to visual appearance of standing trees – industry's current approach to judging wood quality of salvage trees. To accomplish this comparison three visual categories of defoliated white spruce, ranging from live to dead trees with poor appearance, were created. Acoustic nondestructive measurements of longitudinal and transverse stress wave velocity were conducted on white spruce representing each of the three visual categories in a defoliated stand near Iron River, MI. Generalized linear models were utilized to determine whether or not visual category significantly explains difference in longitudinal and transverse stress wave velocities respectively. Longitudinal velocities significantly differed between the live and poorest visual categories. Transverse velocities did not differ by visual category. While tree appearance provides coarse insight on intrinsic wood quality, based on longitudinal stress wave velocity, its recommended to measure salvage white spruce wood quality to ensure timber is utilized for the highest possible value.

2.2 Introduction

A challenge when marketing dead standing trees is an unpredictable decline in postmortem wood quality (Basham 1984). As a result, dead standing trees are often marketed for low-value products due to assumed poor wood quality. Estimating wood quality in salvage and pre-salvage timber sales will help stakeholders market timber for the highest value. One species of particular interest to the salvage timber market in the Great Lakes Region is white spruce *(Picea glauca)*. Three consecutive years of tree defoliation increase, from 2015 to 2017, indicate this region is entering the next spruce budworm *(Choristoneura fumiferana)* outbreak (MIDNR 2016, 2017, 2018). Spruce and fir stands affected by the spruce budworm decrease in value. Also, tree mortality caused by the spruce budworm may increase wildfire severity (Stocks 1987) and create a public safety hazard (Johnson 1981). Discovering a higher-value use of salvaged white spruce affected by the spruce budworm could increase the utilization of this wood and ease the economic, environmental and safety problems associated with spruce budworm outbreaks. Nondestructive evaluation of dead standing white spruce prior to harvest could help in predicting the extent of decay and stiffness (MOE) of wood in measured trees. This greater knowledge of wood quality should help stakeholders market timber for the highest potential value. Measuring wood quality, via nondestructive evaluation, of every tree within salvage or pre-salvage harvests may not always be feasible or economical. Therefore, investigating correlations between tree appearance and measured nondestructive evaluation could help stakeholders sort white spruce trees by wood quality rather quickly during a salvage harvest.

The development of technologies that determine wood quality through nondestructive evaluation of standing live trees, and their application is increasing. Acoustic nondestructive evaluation measures the speed of a stress wave traveling through the longitudinal or transverse plane of a standing tree's stem. These stress wave measurements are relatively simple to obtain and can provide information on intrinsic wood quality (Ross 2015). Improved knowledge of intrinsic wood quality in standing trees may help stakeholders sort and market timber to increase revenue (Wang, Carter, et al. 2007).

Two specific nondestructive measurements of interest are longitudinal and transverse stress wave velocity. The time of flight method is commonly used to calculate these stress wave velocities in standing trees (Wang 2013). This method utilizes two probes, one sending and one receiving, to be placed in the sapwood of a tree's bole. Time of flight simply refers to the amount of time taken for acoustic energy, specifically the leading edge of a stress wave, to travel from the sending to receiving probe (Wang 2013). Acoustic energy is produced with a tap of a hammer against the sending probe. The placement of probes on a tree's bole determines the travel direction of the stress wave relative to the anatomical direction - along the longitudinal (Figures 2.2 and 2.3) or transverse planes (Figure 2.4). Time of flight measurements with the probes placed along the stem of a tree will calculate longitudinal stress wave velocity. Transverse stress wave velocity is calculated by placing the probes on opposing sides of a tree's bole at the same height.

Longitudinal and transverse stress wave velocities correlate to trees' intrinsic wood quality (Ross 2015). The stress wave velocity along the stem's longitudinal and transverse directions provides different information, and therefore indicate different wood quality characteristics. For example, Wang et al. (2001) showed that dynamic modulus of elasticity (MOE) estimated from longitudinal stress wave speed measurements on standing trees correlates well with statically determined MOE. Likewise, in a literature review Legg and Bradley (2016) report several other studies have correlated dynamic MOE, estimated using longitudinal stress wave velocity, to static MOE successfully. On the other hand, measurements of transverse stress wave velocity are typically used to indicate decay, or lack thereof, within the bole of standing trees (Wang et al. 2004). Transverse stress waves can travel directly across the diameter of a sound tree. Internal decay causes the path of transverse stress waves to deviate towards the cambium, or circumference, of the transverse plane resulting in a lower stress wave velocity. Therefore, internal decay within standing trees of the same species can be predicted by a reduced transverse velocity (Wang et al. 2004). To date, most studies of nondestructive evaluation that investigate longitudinal or transverse stress wave velocities, and their implications of intrinsic wood quality, have focused on live standing trees.

While a substantial effort has been made to interpret the wood quality using acoustic measurements on live standing trees, little is known about the ability of acoustic nondestructive evaluation to predict intrinsic wood quality of dead standing trees. Wang et al. (2002) found that longitudinal stress wave velocity can predict the static modulus of elasticity (MOE) in both live and dead jack pine *(Pinus banksiana)* logs. However, nondestructive evaluation for the jack pine study was conducted on butt logs rather than standing trees (Wang et al. 2002). While the 2002 study is applicable in determining the value of salvaged jack pine post-harvest, little information is available on the application of nondestructive evaluation to aid in sorting dead standing trees. Also, considering the difference in appearance between live and dead standing trees little is written about correlation of tree appearance, the prevalent method of grading salvage timber, to nondestructive wood quality measurements.

Our aim is to help develop and demonstrate techniques, so that stakeholders may efficiently sort and sell affected white spruce for the highest possible value. The objective of this study is to measure wood quality in white spruce affected by the spruce budworm using nondestructive evaluation, and compare wood quality assessments to trees' visual appearance. To accomplish this objective 149 white spruce trees representing three visual appearance categories from a defoliated stand near Iron River, MI were selected. Acoustic nondestructive evaluation, measuring longitudinal and transverse stress wave velocity, was conducted on selected trees. Linear regression was then used to determine if visual appearance significantly explained variation in acoustic nondestructive evaluation.

2.3 Methods

2.3.1 Study Site

The selected study site is a planted white spruce stand located on the Ottawa National Forest, Iron River Ranger District 9 miles West of Iron River, MI (46º 5.1333' North, 88º 47.516' West). Wabeno-Goodwit silt loams and monico loam are the predominant soil types within the stand (USDA 2017). Slopes within the stand range from 0 to 15% (USDA 2017). Annual normal temperature for this area ranges between -15 and 27ºC (NOAA 2011) and average annual precipitation is 78 cm (NOAA 2018). White spruce were planted into a northern hardwood mixed stand at an unknown date (T. Frank, personal communication, March 2, 2017). Analysis of cores produced from live trees, at a height of 0.15 m, suggests the white spruce were planted in the mid- to late-1940's. A large portion of white spruce within the stand were defoliated by the spruce budworm during inspection in June 2017. The condition of individual white spruce within the stand varied greatly from tree to tree. Some of the trees were completely defoliated and dead while other white spruce appeared alive and vigorous. The site index for white spruce within the stand is 49 (Carmean et al. 1989). The year which the current spruce budworm attack began noticeably defoliating white spruce within stand is unknown (T. Frank, personal communication, March 2, 2017). However, an increase in spruce budworm defoliation in Michigan's Western Upper Peninsula began in 2014 (MIDNR 2016).

2.3.2 Field Data Collection

Three distinct visual categories were created to determine the efficacy of predicting wood quality of white spruce based on appearance. Visual categories were defined with guidance from pertinent literature before selecting trees in the field (Basham 1984, 1986; Barrette et al. 2015). Tree selection, for all categories, occurred in June 2017. Category 1 (n=50) included trees with any amount of visible green foliage. Basham (1984) states that live trees which have been heavily defoliated by the spruce budworm will contain wood of the same quality as unaffected trees. Category 1 was defined to include living white spruce with wood quality expected to be equal to that of a healthy, unaffected trees. Wood quality of Category 1 trees could also represent timber produced from harvests intended to minimize loss from expected spruce budworm outbreaks. These preventative harvests are suggested by the Michigan DNR (2017). Category 2 (n=49) included white spruce trees with no visible green foliage. Category 2 trees had reddish-brown foliage and most of the fine, needle-bearing, branches intact. Basham (1986) found that time since death was a good indicator of wood decay in balsam fir (Abies balsamea) attacked by the spruce budworm. White spruce within category 2 were assumed to have recently died due to the presence of fine branches and attached brown foliage. Category 2 was defined to include dead trees with a wood quality typically assumed to be suitable for salvage harvests. Lastly, category 3 represented dead standing white spruce with the poorest visual appearance. Category 3 trees (n=50) were characterized as having no visible green foliage and most fine, needle bearing branches absent. Trees with no visible green foliage and broken tops were also included in category 3. Insect and fungal attack along trees' stems are the major cause of post mortem wood decay (Basham 1984, 1986; Barrette et al. 2015). We assumed standing trees with no green foliage and few fine branches would have been dead for some time and would have poorer wood quality - resulting from a longer duration of aggressive insect and fungi damages. Category 3 was defined to include dead trees with wood quality typically assumed to be unsuitable for salvage. Figure 2.1 includes pictures of trees representing each visual category. Trees were selected in June 2017 from a stand that was commercially harvested in October 2017. Tree selection was conducted to include an even proportion of trees between the three visual categories based on the above visual category descriptions. One tree within visual category 2 was found to be balsam fir. Thus, category 2 contained 49 trees that were used in data analysis. To minimize disruption to the commercial harvest, study trees were selected in clusters that contained between 12 to 59 trees.

Figure 2.1. White spruce trees representing visual category 1 (left), 2 (center), and 3 (right).

The first of two methods used to measure longitudinal stress wave velocity on all selected white spruce (n = 149) was carried out with the Fakopp 1D Microsecond Timer (Fakopp Enterprise, Agfalva, Hungary). To measure longitudinal stress wave velocity transmit and receiving probes were inserted into the sapwood of each study tree at a 45 degree angle pointed towards each other. The probes were vertically spaced 1.2 m apart on the East side of each tree (Figure 2.2) - allowing for a redundant measurement of longitudinal stress wave velocity to occur at the same location of each tree. The sending probe was located at a height of 2.0 m while the receiving probe was inserted at a height of 0.8 m - making the longitudinal measurements centered on breast height of each tree (1.4 m). The Fakopp 1D Microsecond timer measures the time (microseconds) taken for the leading edge of a stress wave to travel from the sending to receiving probe. Longitudinal velocity is then calculated via Equation 1.1 below:

Equation 1.1. $$V_{LSW} = d/t$$

Where V_{LSW} is the longitudinal stress wave velocity, d is the distance between sending and receiving probes (1.2 m for all measurements), and t is the time taken for the stress wave to travel between probes. A time of flight was recorded after a technician tapped the sending probe 3-5 times and noticed readings ranging within 0.02 microseconds of each other. Three repetitions of this process was carried out on each tree. Three longitudinal stress wave velocities were calculated (Equation 1.1). The average of the three recorded velocities was used for data analysis.

Figure 2.2. Longitudinal time of flight measurement using the Fakopp 1D Microsecond Timer.

Longitudinal stress wave velocities were also measured on each tree using the Hitman ST300 (fibre-gen Ltd., Christchurch, New Zealand) tool. Care was taken to place the Hitman ST300 probes in the same locations as the Fakopp 1D Microsecond Timer's probes to reduce measurement bias. The Hitman ST300 contains sensors that determine the distance between each probe. This tool also contains hardware and software to compute and display average longitudinal stress wave velocity, based on the time of flight and computed distance between probes, after 6-10 iterations of striking the sending probe with a hammer (Figure 2.3). This process was conducted three times to produce three longitudinal stress wave velocities per tree that were recorded. The average of these three velocities was calculated and used for data analysis.

Figure 2.3. Longitudinal stress wave velocity measurements using the Hitman ST300.

Transverse stress wave velocity was measured on each tree using the Fakopp 2D Microsecond Timer (Fakopp Enterprise, Agfalva, Hungary). These measurements were taken at breast height (1.4 m) on each tree. Transverse stress wave velocity was measured in two orthogonal directions, North-South and East-West, on each tree. The Fakopp 2D Microsecond Timer measures the time (microseconds) taken for a stress wave to travel from the sending to receiving probe – working on the same principals as the Fakopp 1D described above. To measure transverse velocity, sending and receiving probes were inserted horizontally in to the sapwood of each tree at opposite sides of the bole (Figure 2.4). The sending probe was tapped with a hammer 3-5 times until the technician noticed readings ranging within 0.02 microseconds of each other. This consistent time was recorded. This procedure was repeated to produce three recorded time of flights. Tree diameter was measured and recorded at the probes' location to be used in the velocity calculations (Equation 2.2).

Equation 2.2. $$V_{TSW} = D/t$$

Where V_{TSW} is transverse stress wave velocity, D is tree diameter at the point of measurement, and t is the time taken for the leading edge of a stress wave to travel from probe to probe. This protocol was carried out on the North-South and East-West axis of each trees' bole. Thus, six transverse stress wave velocities were calculated per tree – three in the North-South direction and three in the East-West direction. The average of these six velocities was used in data analysis.

Figure 2.4. Transverse Stress Wave measurement using the Fakopp 2D Microsecond Timer.

Moisture content affects the acoustic velocity of wood (Gao et al. 2018; Chan et al. 2011; Legg and Bradley 2016; Yamasaki et al. 2017). Stems of trees attacked by the spruce budworm are expected to undergo a reduction in moisture content after death (Basham 1984). Differences in moisture content were believed to exist between live and dead white spruce in this study. Therefore moisture content of each tree was measured to account for effects on longitudinal and transverse stress wave measurements during data analysis. Moisture content was calculated by taking wood samples from each tree. The white spruce study trees were harvested in October 2017 for analysis and use on related studies. During this time a 7.6 cm thick disc was cut from the lower end of the each trees' butt log. Discs were labeled and placed in a plastic bag to reduce moisture loss during transport. In the lab a 5.1 cm by 5.1 cm prism was cut from each disc. All prisms intersected the pith of their respective disc and spanned the disc's diameter (Figure 2.5). After being cut from the disc wet weight of each wood sample was recorded. The prisms were then placed back into their respective plastic bags and stored in a freezer for one month. Cores were oven dried in batches at a temperature of 105 ºC for 7 days. Oven weights of each sample was then measured. Equation 2.3, below, shows the calculation used to determine moisture content based on wet and oven dry weight.

Equation 2.3. $$MC\% = \frac{Wet - OD}{OD} * 100\%$$

Where MC% represents the % moisture content by oven-dry mass, OD represents oven-dry mass, and Wet represents wet mass.

Figure 2.5. Example of a disc (left) wood core (right) used to determine moisture content.

2.3.3 Data Analysis

Generalized linear models with follow up Tukey's multiple comparison tests were used to determine if the three unique visual categories, defined above, can explain differences in longitudinal and transverse stress wave velocities, respectively. The program R (version 3.5.1) was used for data analysis (R 2018). Within R, the package multcomp was utilized to conduct Tukey's multiple comparison tests between the three visual categories (Hothorn et al. 2008). Three generalized linear models were created in R to determine whether visual category and moisture content explained variations in the nondestructive measurements conducted on standing trees. All models were evaluated on an alpha value of 0.05 (□ = 0.05). A sample size of 149 was used each variable in all models. First, Model 2.1, below, was used to determine if visual categories and moisture content explained differences between longitudinal stress wave velocities measured with the Fakopp 1D tool.

Model 2.1. $$Y_{ij} = \mu + \alpha_i + ß_j$$

Dependent variable Y_{ij} represents longitudinal stress wave velocity measured with the Fakopp 1D Microsecond Timer on each study tree. μ represents the model's intercept. α_i is an independent variable representing the visual category of each tree. $ß_j$ is an independent variable representing the $\log_{10}$ transformation of moisture content of wood samples produced from each tree. Moisture content data was transformed to achieve normality.

Secondly, Model 2.2 was used to determine whether visual category and moisture content significantly explained variation in longitudinal stress wave velocity measured with the Hitman ST300.

Model 2.2. $Y_{ij} = \mu + \alpha_i + ß_j$

Dependent variable Y_{ij} represents the longitudinal stress wave velocity measured with the Hitman ST300. μ represents the model's intercept. α_i is an independent variable representing visual category. $ß_j$ is an independent variable representing the $\log_{10}$ transformation of moisture content.

Third, Model 2.3 was created to determine whether visual category and moisture content are significant variables in explaining variation in transverse stress wave velocity.

Model 2.3. $Y_{ij} = \mu + \alpha_i + ß_j$

Y_{ij} is the dependent variable representing transverse stress wave velocity measured with the Fakopp 2D Microsecond Timer. Transverse stress wave velocities were raised to the fourth power to obtain normality. μ represents the model's intercept. α_i is an independent variable representing visual category. $ß_j$ is an independent variable representing the $\log_{10}$ transformation of moisture content.

2.4 Results

2.4.1 Longitudinal Stress Wave Velocity

Fakopp 1D Microsecond Timer

Mean values of longitudinal stress wave velocity within each visual category are displayed in Figure 2.6 below. Dead trees, visual categories 2 and 3, appear to have higher mean longitudinal stress wave velocities than live trees within visual category 1 (Figure 2.6). This indicates that a false positive may be occurring causing longitudinal stress wave velocity in the dead standing trees to be higher than live trees. Differences in moisture content (Figure 2.9) between live, visual category 1, and dead, visual categories 2 and 3, trees may account for the increase in longitudinal stress wave velocity in dead trees.

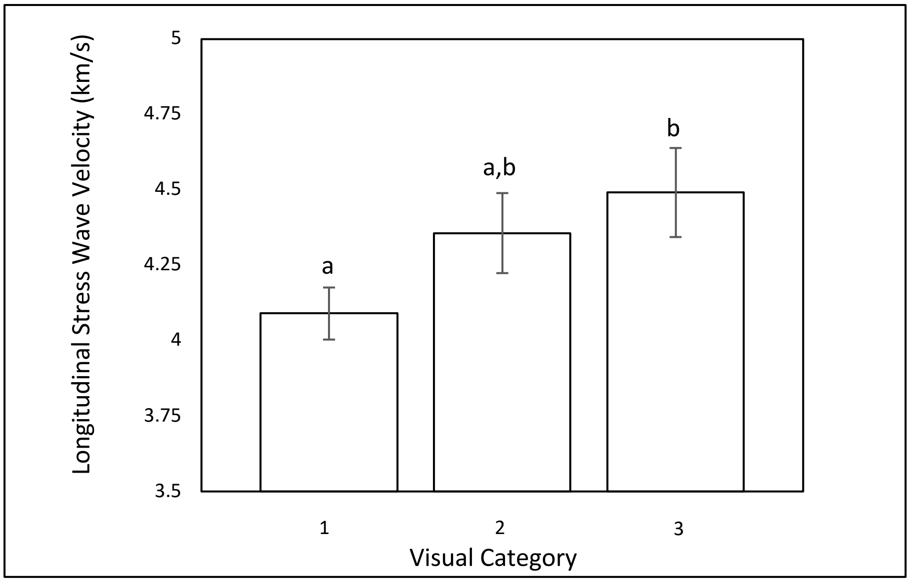

Figure 2.6. Mean longitudinal stress wave velocity (km/s) by visual category. Stress wave velocity was measured with the Fakopp 1D Microsecond Timer. Error bars represent the 95% confidence interval of mean values and were calculated using standard error of the mean.

Table 2.1, below, displays the analysis of deviance for Model 2.1 – determining whether visual category and moisture content significantly explain variation in longitudinal stress wave velocity measured with the Fakopp 1D. Both visual category ($p < 0.001$) and moisture content ($p < 0.001$) are informative in explaining differences in longitudinal stress wave velocity measured with the Fakopp 1D Microsecond Timer.

Table 2.1. Analysis of deviance results of generalized linear model that used visual category (Vis. Cat.) and moisture content (MC) to explain variation in Fakopp 1D longitudinal stress wave velocity. An asterisk (*) indicates significant results for the given variable.

	DF	Deviance	Residual DF	Residual Deviance	F	P-Value
Null			148	32.22		
Vis. Cat.	2	4.16	146	28.05	12.68	< 0.001*
MC	1	4.23	145	23.82	5.77	< 0.001*

After confirming significant results for Model 2.1 Tukey's multiple comparison test was used to determine whether mean longitudinal stress wave velocities, measured with the Fakopp 1D instrument, significantly differed by visual category. The results of this multiple comparisons test are shown in Table 2.2 below. Visual categories 1 and 2 do not have significantly different means ($p = 0.219$). Visual categories 1 and 3 have means that significantly differ ($p = 0.005$). Visual categories 2 and 3 also do not have significantly different means ($p = 0.286$). These results indicate that the best and poorest visual categories significantly differ. Category 2, created to represent mid-range trees, did not significantly differ from the other categories. These results suggest the ability to asses wood quality of category 2 trees based on appearance is limited.

Table 2.2. Tukey's multiple comparisons of mean longitudinal stress wave velocities measured with the Fakopp 1D tool by visual category. An asterisk (*) indicates categories which significantly differ.

	Estimate	Standard Error	Z-Value	P-Value
Cat. 1- Cat. 2	0.14	0.09	1.66	0.219
Cat. 1- Cat. 3	0.26	0.09	3.1	0.005*
Cat. 2 - Cat. 3	0.12	0.08	1.51	0.286

Hitman ST300

Mean values of longitudinal stress wave velocity measured with the Hitman ST300 instrument were also analyzed to determine if differences between visual categories existed. Mean values of these measurements, separated by visual category, are seen in Figure 2.7 below. Longitudinal stress wave velocity, measured with the Hitman ST300, is higher in dead trees, visual categories 2 and 3, compared to live trees within visual category 1 (Figure 2.7) - suggesting that a false positive is occurring. This false positive is similar to that seen in the Fakopp 1D longitudinal velocity measurements (Figure 2.6).

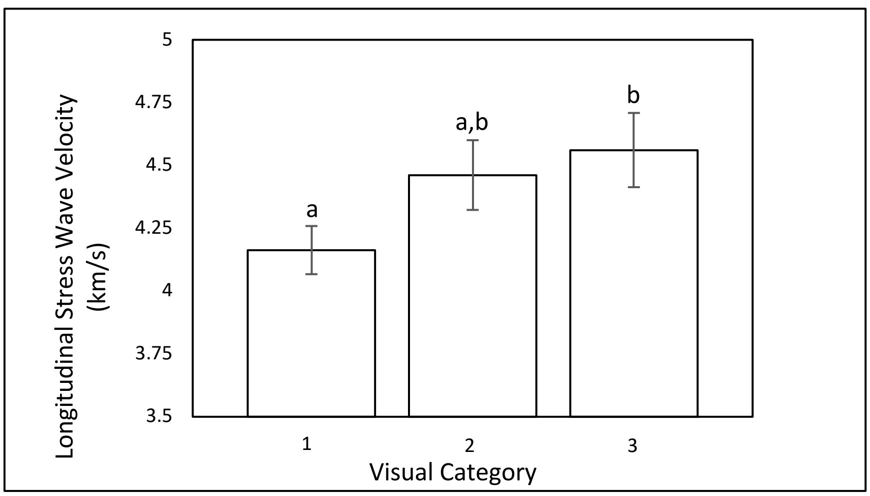

Figure 2.7. Mean longitudinal stress wave velocity (km/s) by visual category. Stress wave velocity was measured with the Hitman ST300. Error bars represent the 95% confidence interval of mean values and were calculated using standard error of the mean.

Table 2.3, below, displays an analysis of deviance table for Model 2.2 – determining if visual category and moisture content significantly explain differences in longitudinal stress wave velocity measured with the Hitman ST300. Both visual category ($p < 0.001$) and moisture content ($p < 0.001$) are significant in explaining variation in longitudinal stress wave velocity measured with the Hitman ST300 tool.

Table 2.3. Analysis of deviance results of generalized linear model that used visual category (Vis. Cat.) and moisture content (MC) to explain variation in Hitman ST300 longitudinal stress wave velocity. An asterisk (*) indicates significant results for the given variable.

	DF	Deviance	Residual DF	Residual Deviance	F	P-Value
Null			148	34.27		
Vis.Cat.	2	4.29	146	29.98	12.59	< 0.001*
MC	1	5.31	145	24.67	31.21	< 0.001*

After confirming significant generalized linear model results (Model 2.2), Tukey's multiple comparisons test was used to determine if mean longitudinal stress wave velocities differed between the three visual categories. The multiple comparisons results are shown below in Table 2.4. Visual categories 1 and 2 did not have significantly different mean longitudinal stress wave velocities ($p = 0.157$). Visual categories 1 and 3 mean longitudinal stress wave velocities were significantly different ($p = 0.013$). Visual categories 2 and 3 did not have significantly different mean longitudinal stress wave velocities ($p = 0.556$). These findings were very similar to the analysis of longitudinal stress wave velocity measured with the Fakopp 1D Microsecond Timer.

Table 2.4. Tukey's multiple comparisons of mean longitudinal stress wave velocities measured with the Hitman ST300 tool by visual category. An asterisk (*) indicates categories which significantly differ.

	Estimate	Standard Error	Z-Value	P-Value
Cat. 1- Cat. 2	0.16	0.09	1.84	0.157
Cat. 1- Cat. 3	0.24	0.09	2.82	0.014*
Cat. 2 - Cat. 3	0.09	0.08	1.03	0.556

Comparison of Longitudinal Stress Wave Tools

Both instruments used to measure longitudinal stress wave velocity, the Hitman ST300 and the Fakopp 1D Microsecond Timer, produced similar model and multiple comparisons results. Therefore longitudinal stress wave velocity inferences in the discussion will pertain to both instruments.

2.4.2 Transverse Stress Wave Velocity

Fakopp 2D Microsecond Timer

Mean transverse stress wave velocity values were analyzed by visual category to determine if significant differences existed between categories. Mean transverse stress wave velocities are shown in Figure 2.8 below. Less variation in mean transverse stress wave velocity across visual categories (Figure 2.8) exists in comparison to differences in mean longitudinal stress wave velocities (Figures 2.6 and 2.7).

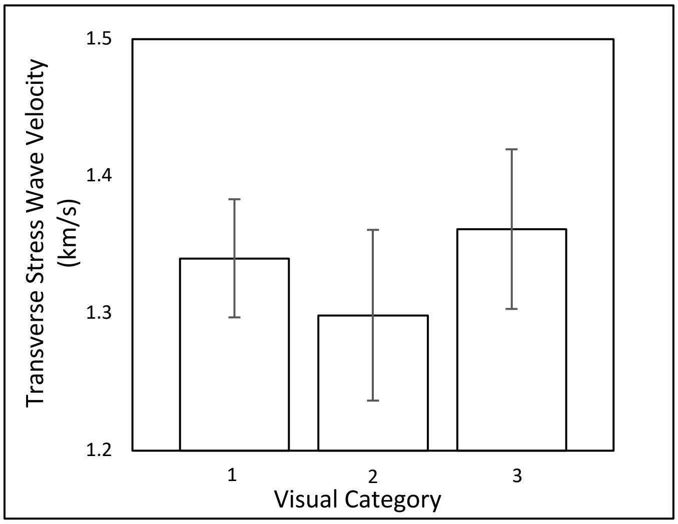

Figure 2.8. Mean transverse stress wave velocities (km/s) by visual category. Error bars represent a 95% confidence interval of mean values and were calculated using standard error of the mean.

The results of Model 2.3 are stated in a deviance table (Table 2.5) below. Table 2.5 indicates that neither visual category ($p = 0.118$) or moisture content ($p = 0.484$) significantly explain variation in transverse stress wave velocity. As this model failed to produce significant results no follow-up Tukey's test was conducted.

Table 2.5. Analysis of deviance results of generalized linear model that used visual category (Vis. Cat.) and moisture content (MC) to explain variation in Fakopp 2D transverse stress wave velocity.

	DF	Deviance	Residual DF	Residual Deviance	F	P-Value
Null			148	316.47		
Vis. Cat.	2	9.19	146	307.27	2.17	0.118
MC	1	0.08	145	307.2	0.04	0.848

2.4.3 Moisture Content

Mean moisture content (% by oven-dry weight) for the three visual categories are shown in Figure 2.9 below. The contrast between living (category 1) and dead (categories 2 and 3) white spruce moisture content suggests that considerable decline in post-mortem moisture content occurred. This contrast confirms the need to account for moisture content as a covariate in our analysis.

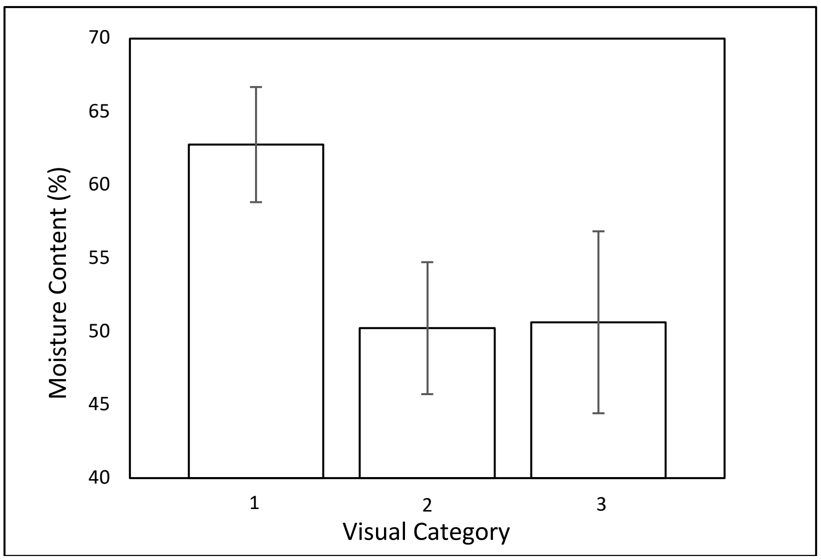

Figure 2.9. Mean moisture content (% by oven-dry weight) by visual category. Error bars represent the 95% confidence interval of mean values and were calculated using standard error of the mean.

2.5 Discussion

2.5.1 Longitudinal Stress Wave Velocity

Coarse information on longitudinal stress wave velocity can be predicted from using the visually assessed categories of decay. This finding is important as longitudinal stress wave velocity measured on standing trees correlates to MOE of wood within measured trees (Legg and Bradley 2016; Wang, Ross, et al. 2007; Wang et al. 2001). Visual categories 1 and 3 represent white spruce with significantly different wood quality, based on longitudinal velocity measurements. Therefore we suggest sorting white spruce that meet category 1 or 3 descriptions based on their respective visual indicators. However, white spruce that meet the category 2 description, trees with no visible green needles that had most fine branches intact, could not be differentiated from the living (category 1) or poorest (category 3) trees. These findings suggests that category 2 trees represent a wider range of longitudinal stress wave velocities. To increase the value of timber produced from trees within visual category 2 longitudinal velocity should be measured. Measuring wood quality of category 2 trees will help loggers and foresters sort them into appropriate markets which may increase financial returns. For example, measuring longitudinal stress wave velocity of category 2 trees would help a loggers sort the trees into either pulp or lumber markets. Conducting nondestructive evaluation on standing trees prior to a salvage harvest may be cost prohibitive. However, technological advances like felling heads with incorporated nondestructive evaluation equipment are commercially available (fibre-gen 2018). Using felling heads that contain nondestructive evaluation tools would enable the evaluation and sorting of salvaged timber at the time of harvest. Evaluating and sorting trees during a harvest should reduce costs associated with conducting nondestructive evaluation.

2.5.2 Transverse Stress Wave Velocity

Visual appearance could not significantly explain variation in transverse stress wave velocity of the white spruce trees in this study. Transverse stress wave velocity correlates to the extent of internal decay in standing trees (Wang et al. 2004). We anecdotally noticed a tendency of dead (categories 2 and 3) study trees to show more decay in sapwood near the cambium than heartwood upon harvest. Measurement bias may have been introduced if the Fakopp 2D probes were inserted beyond this decayed sapwood region and a disproportionate amount of sound wood was measured. Perhaps a more likely reason the analysis of transverse stress wave velocities failed to show differences between visual categories was the general lack of heart rot in study trees. Significant heart rot was assumed to exist in a majority of the study white spruce. This was not the case as only one tree, of 149 trees in the study, was found to have heart rot upon harvest. The lack of heart rot likely led to more uniform transverse stress wave velocities (Figure 2.8) compared to stands that contain individuals with varying amounts of heart rot. Measuring transverse stress wave velocity to determine the presence of internal decay is recommended rather than relying on visual appearance. Information on the extent of internal decay may be determined using transverse velocity measurements (Wang et al. 2004). This information and could be helpful to stakeholders, such as loggers, pulp, and stud mills when valuating or purchasing standing timber.

2.5.3 Limitations

One challenge when using stress wave velocity to sort both live and dead trees is the need to account for moisture content differences. Lower moisture content in dead trees (visual categories 2 and 3) likely caused longitudinal stress wave velocity to increase (Figures 2.6 and 2.7). However, mean moisture content in all visual categories is above fiber saturation point (FSP) (Figure 2.9). Changes in moisture content below FSP are expected to have greater effect on longitudinal stress wave velocity than changes in moisture content above FSP (Gao et al. 2018; Chan et al. 2011). Chan et al. (2011) reported a decrease of 10 m/s in longitudinal stress wave velocity per 1% increase in moisture content – considering unfrozen radiata pine *(Pinus radiata)* ranging from 43 to 84% moisture content. We assume that moisture content differences affected longitudinal stress wave velocities in this study - even though stress wave velocities were calculated on wood with moisture content above FSP.

Analysis of several studies that measured longitudinal velocity on live standing trees didn't account for moisture content variations in analysis (Wang et al. 2001; Bérubé-Deschênes et al. 2016; Lenz et al. 2013). This is likely because measurements were made on live trees with relatively consistent moisture content values. The need for moisture content data to interpret stress wave velocity findings makes acoustic nondestructive evaluation slightly more difficult to interpret. Future work could overcome this challenge by creating a reduction factor for longitudinal stress wave velocity measured on dead trees. A standard reduction factor would make comparisons between live and dead trees, within a species, simple and allow for easier industry adoption of acoustic nondestructive evaluation.

2.5.4 Future Work

The second challenge of applying acoustic nondestructive testing to dead trees is the lack of correlation to known mechanical properties. Ross (2015) summarizes many studies that have correlated acoustic nondestructive evaluation to mechanical properties of live trees. However, little information is available regarding relationships of acoustic measurements on dead standing trees to static measurements of internal wood properties. Accurate estimation of mechanical properties, like MOE, predicted from acoustic measurements of dead standing trees would provide important knowledge to industry. For example knowledge of the relationship between longitudinal stress wave velocity and MOE would help a lumber mill decide whether or not to run salvaged bolts. To benefit industry future work should focus on correlating acoustic nondestructive measurements to mechanical properties for dead standing white spruce. Also, correlations of standing-tree acoustic measurements to nondestructive lumber measurements, taken at standard conditions, could provide information on wood properties of dead standing trees. One such lumber-level measurement is transverse vibration. Correlating tree-level measurements to lumber transverse vibration should be easier to attain and would provide accurate information on static properties.

2.6 Conclusion

The ability to predict intrinsic wood quality of dead standing white spruce based solely on visual cues is limited. Nondestructive evaluation, using acoustic measurements, offers a better prediction of wood quality and can help sort dead standing white spruce for appropriate utilization. With recent increase in defoliation caused by the spruce budworm, the ability to infer wood quality of salvage trees becomes valuable. This inference may allow land managers and the forest products industry to increase value by asserting known quality attributes to salvage timber. Future work that correlates acoustic measurements of dead standing trees to known and commonly referenced mechanical properties will aid in appropriate utilization of salvaged timber.

3 Analysis of Tree and Bolt NDE

3.1 Abstract

Knowledge of wood quality in dead standing trees is becoming an important topic with recent increases in defoliation across North America. Obtaining information on wood quality attributes for defoliated trees and logs may help stakeholders in the lumber products industry sort and sell salvaged material for the highest possible value. This research investigates the ability to measure wood quality of white spruce *(Picea glauca)* after spruce budworm *(Choristoneura fumiferana)* attack using acoustic nondestructive evaluation. First, we obtained tree- and bolt-level acoustic measurements on a sample of defoliated white spruce from Iron River, MI. The condition of sample trees ranged from live trees to dead trees that appeared unmerchantable. Mixed effects models were created to determine if tree-level acoustic measurements taken at breast height (1.4 m) could infer acoustic velocity measured on bolts produced from all heights of the sample trees. Mixed effects models were also utilized to determine within-tree variation in bolt acoustic velocity and differences between live and dead bolt acoustic velocities. We found that tree-level acoustic measurements are good indicators of wood quality throughout the height of defoliated white spruce. Also, bolt longitudinal velocity generally decreased with height - with the exception of the lowest bolts in dead trees which had very low longitudinal stress wave velocities. Our results show that acoustic nondestructive evaluation is applicable for use on dead standing white spruce. Future work should focus on correlating bolt-level acoustic measurements to lumber quality of salvage white spruce.

3.2 Introduction

Acoustic nondestructive evaluation of trees and logs gives useful information on intrinsic wood quality attributes (Ross 2015). Nondestructive tools that measure the acoustic velocity of a tree or log have been developed and can predict the modulus of elasticity (MOE) of interior wood (Ross 2015). Knowledge of intrinsic wood properties aids in sorting trees and logs prior to or after harvest according to known wood quality attributes. Revenue and profits may be increased if the wood products industry takes advantage of the ability to sort trees and logs early in the product chain via acoustic evaluation (Wang, Carter, et al. 2007). Longitudinal stress wave velocity is one nondestructive acoustic measurement currently being utilized to grade and sort trees and logs.

The time of flight method is commonly used to calculate longitudinal stress wave velocities in standing trees (Wang 2013). This method utilizes two probes, one sending and one receiving, placed in the sapwood along the longitudinal direction of a tree's bole (Figure 3.2 and Figure 3.3). Time of flight simply refers to the amount of time taken for acoustic energy, specifically the leading edge of a stress wave, to travel from the sending to receiving probe (Wang 2013). Acoustic energy is produced with a tap of a hammer against the sending probe. In contrast to tree-level measurements, acoustic resonance is used to determine the longitudinal stress wave velocity in logs and bolts. Resonance is the frequency at which a stress wave reflects from end to end within a log after energy is introduced with the strike of a hammer. Transducers on nondestructive acoustic tools are held against one end of a log, detect resonance frequency, and calculate longitudinal stress wave velocity after log length is entered into the tool.

Previous research has measured longitudinal stress wave velocity in both standing trees (Wang et al. 2001; Carter et al. 2005) and logs (Wang et al. 2002; Ross et al. 1997) before milling the trees' bole or logs into lumber or wood specimens and statically measuring MOE. Statically determined MOE of intrinsic wood was successfully correlated to the longitudinal stress wave velocity measured on trees or logs (Wang et al. 2001; Carter et al. 2005; Wang et al. 2002; Ross et al. 1997). Furthermore, research has been carried out that shows correlation between the longitudinal stress wave velocity on standing trees and the longitudinal stress wave velocity measured on the trees' lowest respective log (Wang et al. 2001; Wang, Ross, and Carter 2007). In addition Wang et al. (2013) and Dowding and Murphy (2011) found that wood quality of Douglas-fir logs can be modeled by using log acoustic velocity and height as explanatory variables.

Using acoustic nondestructive evaluation to explain differences of wood quality within dead standing trees is less studied. Few studies have applied nondestructive evaluation technology to determine wood quality of dead trees. Wang et al. (2002) correlated dynamic MOE calculated from longitudinal stress wave velocity to static MOE in a sample that contained some jack pine *(Pinus banksiana)* bolts which were dead at the time of harvest. Longitudinal stress wave measurements have also been used to sort red oak *(Quercus rubra)* black oak *(Quercus velutina)* and scarlet oak *(Quercus coccina)* logs that were attacked by the red oak borer *(Enaphalodes rufulus)* (Wang et al. 2009). Still, relatively little effort has been made on the stand level to sort dead standing timber or model the wood quality of dead standing trees using nondestructive evaluation. The ability to infer wood quality of dead standing trees and logs is important to ensure salvaged timber is efficiently utilized, and the application of acoustic nondestructive evaluation could be informative.

A challenge when marketing dead standing trees is an unpredictable decline in postmortem wood quality (Basham 1984). As a result, dead standing trees are often marketed for low-value products due to assumed poor wood quality. Estimating wood quality in salvage timber sales will help stakeholders market timber for the highest possible value. One species of particular interest to the salvage timber market in the Great Lakes Region is white spruce (*Picea glauca*). Three consecutive years of tree defoliation increase, from 2015 to 2017, indicate this region is entering the next spruce budworm (*Choristoneura fumiferana*) outbreak (MIDNR 2016, 2017, 2018). Spruce and fir stands affected by the spruce budworm decrease in value. Also, tree mortality caused by the spruce budworm may create a public safety hazard (Johnson 1981). Discovering a higher-value use of salvaged white spruce (*Picea glauca*) affected by the spruce budworm could increase the utilization of this wood and ease the economic and safety problems associated with spruce budworm outbreaks. Nondestructive evaluation of dead standing white spruce trees and bolts produced from these trees could help in determining the wood quality of salvaged material. This greater knowledge of wood quality should help stakeholders sort and market timber for the highest potential value.

Our aim is to apply nondestructive acoustic techniques to salvaged timber so that stakeholders may efficiently sort and sell affected white spruce for the highest possible value. We approached this challenge with the following research questions:

1) Do tree-level measurements of longitudinal stress wave velocity provide information on bolt-level measurements of longitudinal stress wave velocity throughout the height of white spruce trees?

2) Considering a harvest that includes both live and dead white spruce, does bolt longitudinal velocity change with height?

3) Does a trees visual appearance offer indications of mean bolt stress wave velocity?

To accomplish this objective white spruce trees were salvaged from a defoliated stand near Iron River, MI. Acoustic nondestructive evaluation, measuring longitudinal stress wave velocity, was conducted on the standing trees near breast height (1.4 m). Longitudinal stress wave velocities were measured on the resulting bolts and relationships between tree- and bolt-level measurements were investigated. Variation in bolt longitudinal stress wave velocity by height was also investigated using linear regression.

3.3 Methods

3.3.1 Study Site

The selected study site is a planted white spruce stand located on the Ottawa National Forest, Iron River Ranger District 9 miles West of Iron River, MI (46° 5.1333' North, 88° 47.516' West). Wabeno-Goodwit silt loams and monico loam are the predominant soil types within the stand (USDA 2017). Slopes within the stand range from 0 to 15% (USDA 2017). Annual normal temperature for this area ranges between -15 and 27ºC (NOAA 2011) and average annual precipitation is 78 cm (NOAA 2018). White spruce were planted into a northern hardwood mixed stand at an unknown date (T. Frank, personal communication, March 2, 2017). Analysis of cores produced from live trees at a height of 0.15 m suggests the white spruce were planted in the mid- to late-1940's. A large portion of white spruce within the stand were defoliated by the spruce budworm during inspection in June 2017 and the condition of individual white spruce within the stand varied greatly from tree to tree. Some of the trees were completely defoliated and dead while other white spruce appeared alive and vigorous. The site index for white spruce within the stand is 49 (Carmean et al. 1989). The year which the current spruce budworm attack began noticeably defoliating white spruce within stand is unknown (T. Frank, personal communication, March 2, 2017). However, an increase in spruce budworm defoliation in Michigan's Western Upper Peninsula, the region our stand resides in, began in 2014 (MIDNR 2016).

3.3.2 Field Data Collection

All field data was collected in June 2017, beginning with the selection of 150 sample trees from three distinct visual categories (Figure 3.1). Trees were selected from a stand that was commercially harvested in October 2017. Tree selection was conducted to include an even proportion of trees between three visual categories based on the below visual category descriptions. To minimize disruption to the commercial harvest, study trees were selected in clusters that contained between 12 to 59 trees.

Visual categories were defined with guidance from pertinent literature before selecting trees in the field (Basham 1984, 1986; Barrette et al. 2015). Category 1 (n=50) included trees with any amount of visible green foliage. Basham (1984) states that live trees which have been heavily defoliated by the spruce budworm will contain wood of the same quality as unaffected trees. Category 1 was defined to include living white spruce with wood quality expected to be equal to that of a healthy, unaffected trees. Wood quality of Category 1 trees could also represent live timber produced from harvests intended to minimize loss from expected spruce budworm outbreaks. These preventative harvests are suggested by the Michigan DNR (MIDNR 2017). Category 2 (n=49) included white spruce trees with no visible green foliage. Category 2 trees had reddish-brown foliage and most of the fine, needle-bearing, branches intact. Basham (1986) found that time since death was a good indicator of wood decay in balsam fir *(Abies balsamea)* attacked by the spruce budworm. White spruce within category 2 were assumed to have recently died due to the presence of fine branches and attached brown foliage. Category 2 was defined to include dead trees with a wood quality assumed to be suitable for salvage harvests. One tree within visual category 2 was found to be a balsam fir. Thus, category 2 contained 49 trees that were used in data analysis. Lastly, category 3 represented dead standing white spruce with the poorest visual appearance. Category 3 trees (n=50) were characterized as having no visible green foliage and most fine, needle bearing branches absent. Trees with no visible green foliage and broken tops were also included in category 3. Insect and fungal attack along trees' stems are the major cause of post mortem wood decay (Basham 1984, 1986; Barrette et al. 2015). We assumed standing trees with no green foliage and few fine branches would have been dead for some time and would have poorer wood quality as a result of more insect and fungi exposure. Category 3 was defined to include dead trees with wood quality typically assumed to be unsuitable for salvage.

Figure 3.1. White spruce trees representing visual category 1 (left), 2 (center), and 3 (right).

Longitudinal stress wave velocity was measured on all white spruce (n = 149) using a Fakopp 1D Microsecond Timer (Fakopp Enterprise, Agfalva, Hungary) and Hitman ST300 (fibre-gen Ltd., Christchurch, New Zealand). To measure longitudinal stress wave velocity using the Fakopp 1D transmitting and receiving probes were inserted into the sapwood of each study tree at a 45 degree angle pointed towards each other. The probes were vertically spaced 1.2 m apart on the east side of each tree centered at breast height (1.4 m). The Fakopp 1D Microsecond timer measures the time (microseconds) taken for the leading edge of a stress wave to travel from the sending to receiving probe. Longitudinal velocity is then calculated using Equation 3.1 below:

Equation 3.1. $$V_{LSW} = d/t$$

Where V_{LSW} is the longitudinal stress wave velocity, d is the distance between sending and receiving probes (1.2 m for all measurements), and t is the time taken for the stress wave to travel between probes. A time of flight was recorded after a technician tapped the sending probe 3-5 times and noticed readings ranging within 0.02 microseconds of each other (Figure 3.2). Three repetitions of this process were carried out on each tree and three longitudinal stress wave velocities were calculated (Equation 4). The average of the three recorded velocities was used for data analysis.

Figure 3.2. Longitudinal time of flight measurement using the Fakopp 1D Microsecond Timer.

Longitudinal stress wave velocities were also measured on each tree using the Hitman ST300 (Figure 3.3). Care was taken to place the Hitman ST300 probes in the same locations as the Fakopp 1D Microsecond Timer's probes to reduce measurement bias. The Hitman ST300 contains sensors that determine the distance between each probe. This tool also contains hardware and software to compute and display average longitudinal stress wave velocity, based on the time of flight and computed distance between probes, after 6-10 iterations of striking the sending probe with a hammer. This process was conducted three times to produce three longitudinal stress wave velocities per tree that were recorded. The average of these three velocities was calculated and used for data analysis.

Figure 3.3. Longitudinal stress wave velocity measurements using the Hitman ST300.

3.3.3 Tree Harvest and Bolt Labeling

In October 2017, the white spruce were harvested concurrently with a commercial timber sale that took place in the same stand. Prior to harvest and standing tree evaluation, each study tree was numbered (001-150) and labeled using an aluminum tag which was attached to the tree near ground level. Study trees were left standing while other trees within the harvest were felled, bucked, and stacked. This tedious process ensured timber from the study and commercial harvest remained separate. A cut-to-length harvester then felled and bucked each study tree into 2.7 m long bolts. The minimum bolt small end diameter (SED) for timber used in the study was 11 cm. Care was taken by the harvester operator to place the bolts adjacent to each trees' respective stump - which contained the tree identification tag. The highly-skilled harvester operator also took care to arrange the bolts according to height as they were being bucked (Figure 3.4). To summarize, bolts from each study tree were arranged in a row from lowest to highest and were located adjacent to the bolts' respective stump. The organization of study trees and timber during the harvest made it possible to label each bolt by its respective tree number and height.

Figure 3.4. Harvest of white spruce used for this study. Care was taken to accurately label bolts by tree number and height.

Tree number, bolt height, and visual category were written on each end of all study bolts (n = 661). Bolt height was recorded as categorical data and labeled alphabetically. The lowest bolt on each tree received an 'A' label, the second lowest received a 'B' label, and ascending bolts were labeled with letters that descended the alphabet as bolt height increased. The tallest trees in this study produced 8 bolts with their highest bolt being labeled 'H.' Figure 3.5, below, shows how bolt height was recorded and the labeling method for bolts. Table 3.1, below, displays the sample size of white spruce bolts by visual category and height. Category 1 shows 49 bolts in the 'A' position. This is because one tree in category 1 had excessive heart rot in the lowest bolt. The harvester operator cut off the hollow portions of the tree before bucking the tree into bolts and the lowest bolt was in the 'B' height position. Also, four category 2 trees had 'A' position bolts broken during harvest. This is why only 44 'A' position bolts were recovered from category 2 trees.

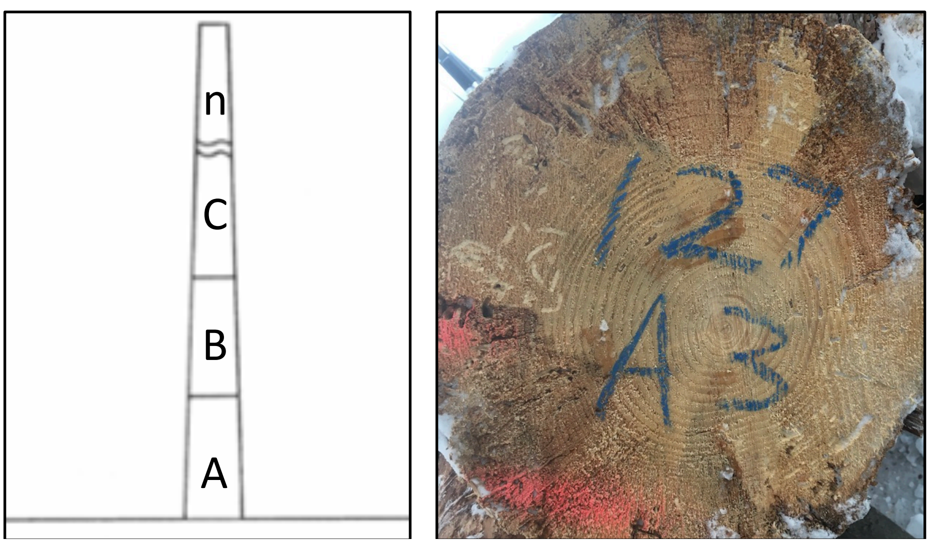

Figure 3.5. A diagram of bolt height notation within a study tree (left). Example of a bolt label (right) – '127' is the tree identification number, 'A' signifies this is the lowest bolt, and '3' indicates the bolt was produced from a visual category 3 tree.

Table 3.1. Bolt sample size by height (Ht.) and visual category (Cat.).

Ht.	A	B	C	D	E	F	G	H	Total By Cat.
Cat. 1	49	50	50	48	42	29	13	3	284
Cat. 2	45	49	42	31	15	5	0	0	187
Cat. 3	50	47	46	34	12	1	0	0	190
Total by Ht.	144	146	138	113	69	35	13	3	
								Total Bolts =	661

3.3.4 Bolt Nondestructive Evaluation

Bolts were transported to Michigan Technological University (Houghton, MI) in October 2017 for nondestructive evaluation and processing. Longitudinal stress wave velocity was measured on each bolt during October and November 2017. Bolt longitudinal stress wave velocity was measured using the Hitman HM200 (fibre-gen Ltd., Christchurch, New Zealand). The Hitman HM200 measures the resonance, or reflection, of longitudinal stress waves in a log or bolt after energy is produced by a hammer's strike to one end of a log (Legg and Bradley 2016). Bolt length, in meters, is entered into the tool and longitudinal stress wave velocity (km/s) is calculated by the HM200 after striking the end of the bolt with a hammer (Figure 3.6). Three measurements of longitudinal stress wave velocity were calculated on each bolt. The average stress wave velocity of the three measurements, for each bolt, was used for data analysis.

Figure 3.6. The Hitman HM200 measuring longitudinal stress wave velocity on a study bolt.

3.3.5 Data Analysis

Two mixed effects models were created to examine the relationship between standing tree wood quality measurements and the wood quality of bolts produced from the respective white spruce trees. The program R (version 3.5.1) was used for data analysis (R 2018). Within R, the package *nlme* was utilized to conduct the mixed effects models (Pinheiro et al. 2017) and the package *MuMln* was used to calculate coefficients of determination (r^2) (Nakagawa and Schielzeth 2013). The models were evaluated on an alpha level of 0.05 ($\alpha = 0.05$). Two different measurements of standing tree longitudinal stress wave velocity, measured with the Hitman ST300 and Fakopp 1D Microsecond Timer, were utilized in respective models. The models were used to determine if tree-level measurements and height could explain variation in bolt longitudinal stress wave velocity. First, a model describing the ability of the ST300 and height to explain variation in bolt longitudinal velocities is seen below (Model 3.1).

Model 3.1. $Y_{ijk} = \mu + \alpha_i + ß_{j(i)} + €_{ijk}$

Dependent variable Y_{ijk} is bolt longitudinal stress wave velocity measured with the Hitman HM200. μ is a constant value representing the intercept. α_i is an independent variable representing tree longitudinal stress wave velocity, as a fixed effect, measured with the Hitman ST300. $ß_{j(i)}$ is also an independent variable representing the bolt height as a fixed effect. $€_{ijk}$ is a random effect to account for the nesting of bolts within trees. Second, Model 3.2, below, describes the ability of the tree-level longitudinal stress wave velocity measured with the Fakopp 1D Microsecond Timer and height to explain variation in bolt longitudinal stress wave velocities.

Model 3.2. $Y_{ijk} = \mu + \alpha_i + ß_{j(i)} + €_{ijk}$

Dependent variable Y_{ijk} is bolt longitudinal stress wave velocity measured with the Hitman HM200. μ is a constant value representing the intercept. α_i is an independent variable representing tree longitudinal velocity, as a fixed effect, measured with the Fakopp 1D Microsecond Timer. $ß_{j(i)}$ is also an independent variable representing the bolt height as a fixed effect. Lastly, $€_{ijk}$ is a random effect to account for the nesting of bolts within trees.

Linear mixed effect models were also utilized to determine if a relationship existed between bolt longitudinal stress wave velocity and height within white spruce trees. To answer this question Model 3.3 was created in the program R. Again, the package nlme was utilized (Pinheiro et al. 2017) and the models were evaluated on an alpha level of 0.05 ($\alpha = 0.05$).

Model 3.3. $Y_{ijk} = \mu + \alpha_i + ß_{j(i)} + €_{ijk}$

Dependent variable Y_{ijk} is bolt longitudinal stress wave velocity measured with the Hitman HM200. μ is a constant value representing the intercept. α_i is an independent variable representing the bolt height as a fixed effect. $ß_{j(i)}$ is an independent variable representing visual category as a fixed effect. $€_{ijk}$ is a random effect to account for the nesting of bolts into trees. We included visual category in Model 3.3 to determine if the variable is associated with different trends in the variation of bolt longitudinal stress wave velocity by height. Accordingly, additional models were developed to examine the relationship between bolt height and stress wave velocity in live and dead trees (Models 3.4 and 3.5).

Model 3.4. $Y_{ij} = \mu + \alpha_i + €_{ij}$

Model 3.5. $Z_{ij} = \mu + \alpha_i + €_{ij}$

Dependent variable Y_{ij} is bolt longitudinal stress wave velocity of live trees (belonging to visual category 1) measured with the Hitman HM200. Dependent variable Z_{ij} represents bolt longitudinal stress wave velocity of dead trees (visual categories 2 and 3) measured with the Hitman HM200. μ is a constant value representing the intercept. α_i is an independent variable representing the bolt height or position as a fixed effect, and $€_{ij}$ is a random effect to account for the nesting of bolts within trees.

Where these mixed effects models indicated a statistically significant variables, the R package *multcomp* was utilized to conduct Tukey's multiple comparison tests among visual categories as well as different bolt heights (Hothorn et al. 2008).

3.4 Results

3.4.1 Relationship Between Bolt and Tree Stress Wave Velocity

Model 3.1 estimates the ability of bolt height and standing-tree longitudinal stress wave velocity, measured with the Hitman ST300, to explain variations in bolt longitudinal stress wave velocity. Table 3.2, below, displays analysis of deviance for Model 3.1 and shows that both the Hitman ST300 measurements and bolt height are statistically significant variables when explaining bolt longitudinal stress wave velocities ($p < 0.001$). This indicates that bolt longitudinal stress wave velocity of living and dead white spruce bolts can be inferred using longitudinal stress wave velocity measured near breast height (1.4 m) and bolt height. The marginal coefficient of determination for Model 3.1 is 0.375 ($r^2 = 0.375$) – indicating that 37.5% of variation in bolts longitudinal stress wave velocity can be accounted for by tree level stress wave velocity measurements using the Hitman ST300, given the bolt height (Nakagawa and Schielzeth 2013).

Table 3.2. Model 3.1 deviance table - determining the effectiveness of bolt height and tree-level acoustic velocity (measured with the ST300) to infer bolt acoustic velocity. Asterisks (*) indicate significant variables.

	Num DF	Den DF	F-Value	P-Value
Intercept	1	505	16729	< 0.001*
Bolt Height	7	505	51.50	< 0.001*
Hitman ST300 Velocity	1	147	70.79	< 0.001*

A graphic depiction of the Model 3.1's ability to predict bolt level measurements from tree longitudinal velocity and height is seen in Figure 3.7, below. This figure suggests that the prediction of bolt longitudinal stress wave speed is more accurate at lower heights within a tree. Observed values of bolt longitudinal stress wave velocity were more widely spread away from the model's predicted value as height increased, showing tree level measurements are less accurate at explaining bolt level measurements as height increased.

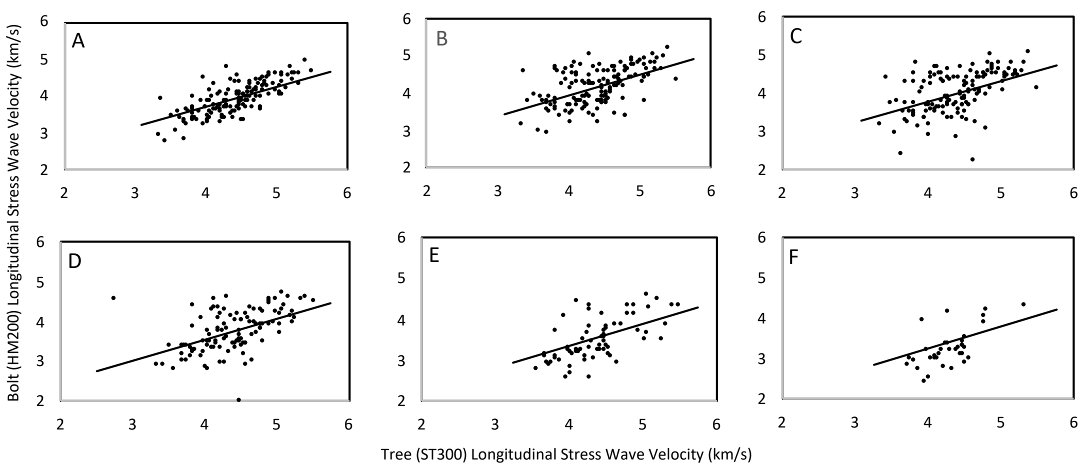

Figure 3.7. Standing tree longitudinal stress wave velocity measured with the Hitman ST300, on x-axes, paired with bolt longitudinal stress wave velocity measured with the Hitman HM200 on y-axes. The solid lines represent the linear relationship between standing tree and bolt longitudinal velocities predicted using Model 3.1. Each scatter plot represents data of a respective bolt height (see labels in the plots' upper left corner). Bolts G and H are not included due to small sample sizes.

Model 3.2 was created to determine the ability of bolt height and longitudinal stress wave velocity measured on standing trees with the Fakopp 1D to explain variations in bolt longitudinal stress wave velocity. The analysis of deviance table for Model 3.2 is found below (Table 3.3). Table 3.3 indicates both tree-level measurements of longitudinal stress wave velocity and height are significant variables in predicting bolt longitudinal stress wave velocity ($p < 0.001$). The marginal coefficient of determination for Model is 0.394 ($r^2 = 0.394$) (Nakagawa and Schielzeth 2013).

Table 3.3. Model 3.2 deviance table - determining the effectiveness of bolt height and tree-level acoustic velocity (measured with the Fakopp 1D) to infer bolt acoustic velocity. Asterisks (*) indicate significant model variables.

	Num DF	Den DF	F-Value	P-Value
Intercept	1	505	17521	< 0.001*
Bolt Height	7	505	51.74	< 0.001*
Hitman ST300 Velocity	1	147	81.40	< 0.001*

The model's ability to predict longitudinal stress wave speed, measured with the Hitman HM200, is graphically shown in Figure 3.8, below. As height increases the ability of the Fakopp 1D to predict bolt longitudinal stress wave velocity tends to decrease. Increasing distances of bolt longitudinal stress wave observations from the model's prediction with height suggests that ability of tree level measurements to explain bolt longitudinal stress wave velocity decreases with height.

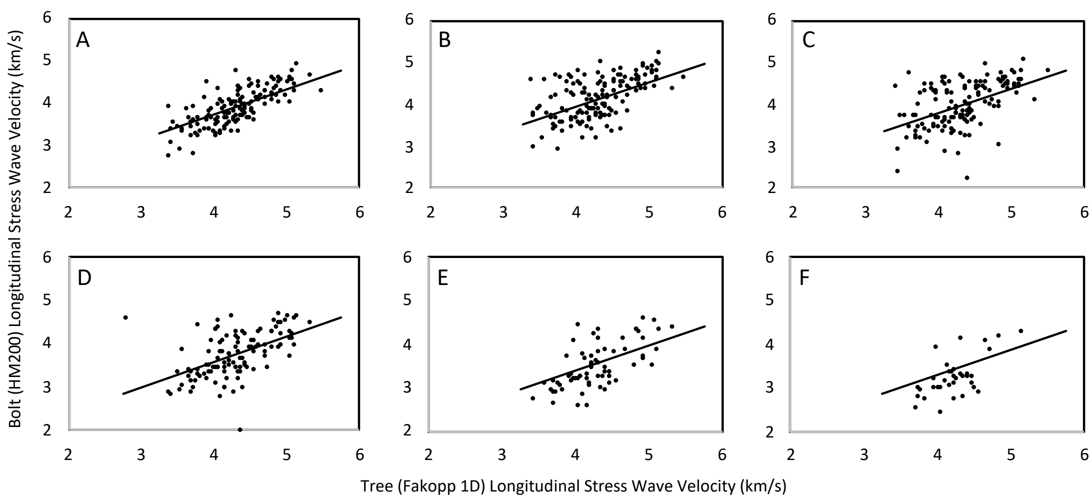

Figure 3.8. Standing tree longitudinal stress wave velocity measured with the Fakopp 1D, on x-axes, paired with bolt longitudinal stress wave velocity measured with the Hitman HM200 on y-axes. The solid lines represent the linear relationship between standing tree and bolt longitudinal velocities predicted using Model 3.2. Each scatter plot represents data of a respective bolt height (see labels in the plots' upper left corner). Bolts G and H were not included due to small sample sizes.

3.4.2 Influence of Height on Bolt Longitudinal Stress Wave Speed

Model 3.3 investigates the ability of height and visual category to explain variation in bolt longitudinal stress wave velocity. Table 3.4, below, describes the significance of Model 3.3 and indicates both height and visual category are statistically significant variables in explaining variation in bolt longitudinal stress wave velocity ($p < 0.001$).

Table 3.4. Model 3.3 deviance table – determining the effectiveness of bolt height and visual category to infer bolt longitudinal stress wave velocity. Asterisks (*) indicate significant model variables.

	Num DF	Den DF	F-Value	P-Value
Intercept	1	505	19694	<0.001*
Bolt Height	7	505	52.73	<0.001*
Visual Category	2	146	57.46	<0.001*

Based on the significant results of Model 3.3 a follow-up Tukey's Test was conducted to determine if significant differences in bolt longitudinal stress wave velocity existed between the three visual categories. The Tukey's Test (Table 3.5) shows that longitudinal stress wave velocity of bolts from visual category 1 trees significantly differ from those in visual categories 2 and 3 ($p < 0.001$). Further, visual categories 2 and 3 do not significantly differ from each other ($p = 0.73$). These results indicate bolt longitudinal velocities significantly differed between trees that were alive (visual category 1) and dead (visual categories 2 and 3) during the June 2017 tree assessment. Therefore, two mixed effects models were created to examine the relationship of bolt longitudinal stress wave velocity and height for live and dead white spruce respectively.

Table 3.5. Results of Tukey's test used to determine if bolt longitudinal stress wave velocity differed by visual category. Live (category 1) and dead (categories 2 and 3) bolts had significantly different stress wave velocities. Asterisks (*) indicate groups with significantly different mean bolt longitudinal velocities.

Visual Categories	Estimate	Std. Error	Z-Value	P-Value
1-2	0.57	0.07	8.33	<0.0001*
1-3	0.68	0.07	9.94	<0.0001*
2-3	0.11	0.07	1.54	0.730

Influence of Height on Bolt Longitudinal Stress Wave Speed – Live Trees

Model 3.4 was used, to determine if bolt longitudinal velocity significantly changed with height considering live (visual category 1) trees only. The deviance table (Table 3.6) below shows that bolt height is a significantly related to differences in bolt longitudinal stress wave velocity of bolts produced from trees that were alive during the June 2017 tree assessment ($p < 0.001$).

Table 3.6. Model 3.4 deviance table – determining the effectiveness of bolt height to infer changes in live bolt longitudinal stress wave velocity. Asterisks (*) indicate significant model variables.

	Num DF	Den DF	F-Value	P-Value
Intercept	1	227	7760	< 0.001*
Bolt Height	7	227	152.94	< 0.001*

A follow-up Tukey's Test was conducted to determine which bolt heights were significantly different from each other. Results of the Tukey's Multiple Comparisons Test are displayed in Table 3.7 below.

Table 3.7. Results of Tukey's test used to determine if bolt longitudinal stress wave velocities from live trees differed by height. Asterisks (*) indicate bolt heights with significantly different mean longitudinal velocities.

Bolts	Estimate	Std. Error	Z-Value	P-Value
A-B	0.09	0.03	3.44	0.011
A-C	-0.07	0.03	-2.7	0.107
A-D	-0.26	0.03	-10.22	<0.001*
A-E	-0.41	0.03	-15.65	<0.001*
A-F	-0.58	0.03	-19.55	<0.001*
A-G	-0.74	0.04	-18.23	<0.001*
A-H	-0.9	0.08	-11.42	<0.001*
B-C	-0.15	0.02	-6.18	<0.001*
B-D	-0.35	0.03	-13.7	<0.001*
B-E	-0.5	0.03	-19.02	<0.001*
B-F	-0.67	0.03	-22.49	<0.001*
B-G	-0.83	0.04	-20.38	<0.001*
B-H	-0.98	0.08	-12.52	<0.001*
C-D	-0.19	0.03	-7.6	<0.001*
C-E	-0.35	0.03	-13.18	<0.001*
C-F	-0.52	0.03	-17.33	<0.001*
C-G	-0.67	0.04	-16.6	<0.001*
C-H	-0.83	0.08	-10.56	<0.001*
D-E	-0.16	0.03	-5.86	<0.001*
D-F	-0.33	0.03	-10.85	<0.001*
D-G	-0.48	0.04	-11.85	<0.001*
D-H	-0.64	0.08	-8.11	<0.001*
E-F	-0.17	0.03	-5.57	<0.001*
E-G	-0.33	0.04	-7.96	<0.001*
E-H	-0.48	0.08	-6.12	<0.001*
F-G	-0.16	0.04	-3.68	0.005*
F-H	-0.31	0.08	-3.92	0.002*
G-H	-0.16	0.08	-1.87	0.545

Considering bolts produced from trees that were alive during inspection in June 2017, bolt longitudinal stress wave velocity differed among the bolt heights. A notable exception was found in Bolt A longitudinal stress wave velocities that were not significantly different from Bolt C longitudinal stress wave velocities - suggesting there is no difference between the first and third lowest bolts of a live white spruce. The lack of significant differences between the two highest bolt positions, bolts G and H, may have been caused by a small sample size. Mean longitudinal stress wave velocity of each bolt height are graphically shown in Figure 3.9, below. The Tukey's test and associated mean stress wave velocities suggest that longitudinal stress wave velocities generally decreased as height increased within living white spruce in this study. A notable exception is found in bolt A which, based on the Tukey's test, has a significantly lower stress wave velocity than bolt B.

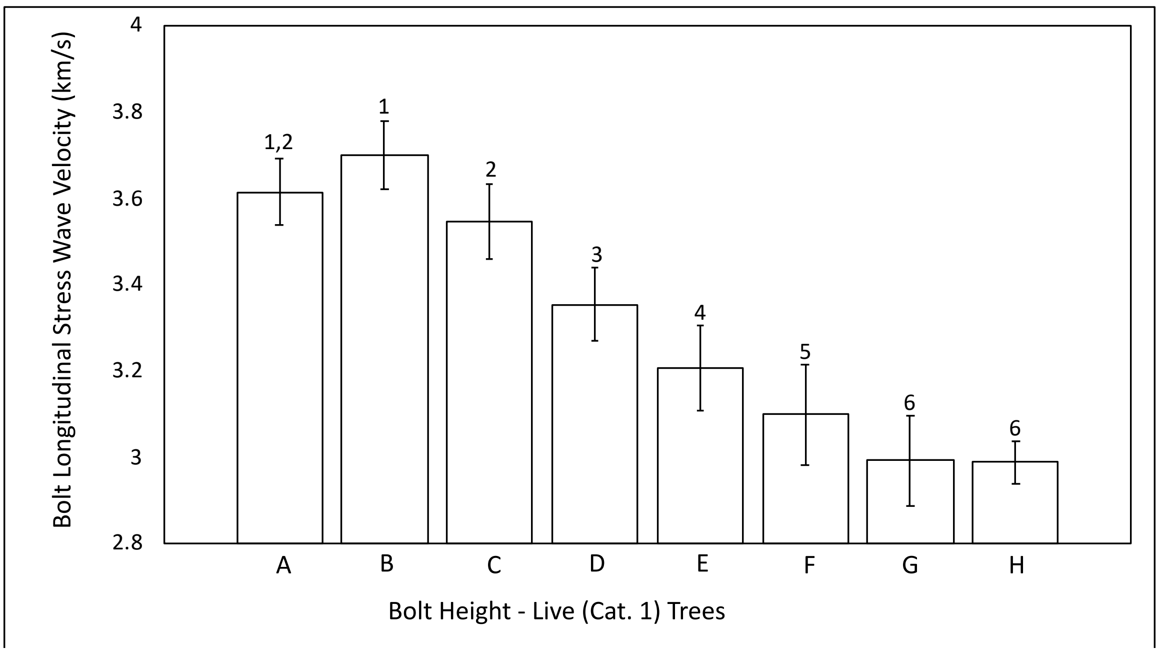

Figure 3.9. Mean bolt longitudinal stress wave velocity (km/s) by bolt height for bolts produced from visual category 1 trees. Error bars represent a 95% confidence interval of the mean and were calculated using standard deviation.

Changes in Longitudinal Stress Wave Velocity and Height – Dead Trees

Model 3.5 was used to determine if bolt longitudinal velocity significantly changed with height considering dead trees only. Bolt height significantly explains differences in bolt longitudinal stress wave velocity. Table 3.8, below, displays the deviance results of Model 3.5.

Table 3.8. Model 3.5 deviance table – determining the effectiveness of bolt height to infer changes in dead bolt longitudinal stress wave velocity. Asterisks(*) indicate significant model variables.

	Num DF	Den DF	F-Value	P-Value
Intercept	1	273	12092	<0.001*
Bolt Height	5	273	17.99	<0.001*

A Tukey's test was conducted to determine which bolt heights contained significantly different longitudinal stress wave velocities - regarding bolts produced from trees that were dead in June 2017. Table 3.9, below, displays the results of the Tukey's Test.

Table 3.9. Results of Tukey's test used to determine if bolt longitudinal stress wave velocities from dead trees differed by height. Asterisks (*) indicate bolt heights with significantly different mean longitudinal velocities.

Bolts	Estimate	Std. Error	Z-Value	P-Value
A-B	0.33	0.05	6.34	<0.001*
A-C	0.17	0.05	3.16	0.017*
A-D	-0.08	0.06	-1.31	0.759
A-E	-0.28	0.08	-3.39	0.008*
A-F	0.04	0.16	0.24	0.999
B-C	-0.16	0.05	-3.04	0.024*
B-D	-0.41	0.06	-6.92	<0.001*
B-E	-0.61	0.08	-7.42	<0.001*
B-F	-0.29	0.16	-1.81	0.43
C-D	-0.25	0.06	-4.13	<0.001*
C-E	-0.45	0.08	-5.42	<0.001*
C-F	-0.13	0.16	-0.81	0.962
D-E	-0.2	0.08	-2.37	0.147
D-F	0.12	0.16	0.71	0.978
E-F	0.32	0.17	1.88	0.387

The Tukey's Test comparing longitudinal stress wave velocities between bolt heights of dead trees shows a lower proportion of significant differences compared to the live bolt analysis. However, trends do exist in the analysis of dead bolt longitudinal velocity and height. Results of the dead bolt Tukey's test and mean longitudinal stress wave velocity by dead bolt height are graphically shown in Figure 3.10, below. Generally bolt longitudinal stress wave velocity decreased as bolt height increased. Again an exception to this trend is seen in bolt A which had a significantly lower mean longitudinal stress wave velocity that bolt B. Longitudinal stress wave velocity in bolt height F was not significantly different than any other bolt categories. The small sample size of bolt F is likely the reason this position was not found to be significantly different from any other bolt heights.

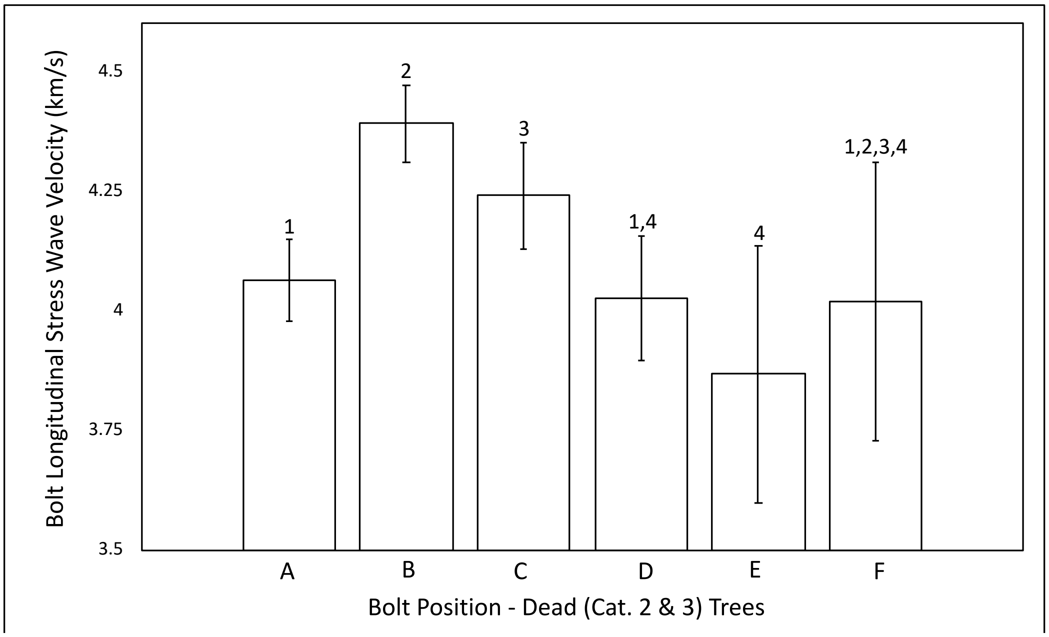

Figure 3.10. Mean bolt longitudinal stress wave velocity (km/s) by bolt height for bolts produced from trees within visual categories 2 and 3. Error bars represent a 95% confidence interval of the mean and were calculated using standard deviation.

3.5 Discussion

3.5.1 Relationship Between Bolt and Tree Stress Wave Velocity

We found that wood quality in both live and dead white spruce varied by height. Measurements of longitudinal velocity taken near breast height (1.4 m) on standing trees ca n provide information on wood quality at greater heights (marginal r2 = 0.375 and 0.394 for Model 3.2 and Model 3.2 respectively). However the ability of standing tree measurements to infer wood quality throughout a tree appears to decrease as height increases. This is likely due to an increasing proportion of juvenile wood as height increases (Carter et al. 2005). Carter et al. (2005) explain that logs produced from greater heights, within a tree, generally have lower longitudinal stress wave velocities due to a greater proportion of low-stiffness juvenile wood. This is likely the reason our models' prediction of bolt longitudinal velocity appeared to be less accurate as height increased (Figure 3.7 and Figure 3.8).

Few other published studies focused on the ability to infer wood quality at various tree heights from longitudinal stress wave velocity measurements taken at breast height. Most studies that compared tree- to log-level measurements of longitudinal stress wave velocity did so by measuring the lowest log only (Wang, Ross, and Carter 2007; Wang et al. 2001; Wang and Ross 2008). However, Rais et al. (2014) successfully correlated dynamic MOE, calculated using longitudinal stress wave velocity, between standing Douglas-fir *(Pseudotsuga menziesii)* and each of the three logs produced from the respective trees – with the logs organized by height. In addition, Dowding and Murphy (2011) found that log longitudinal velocity, at various heights within Douglas-fir trees, could be modeled using height and longitudinal velocity of the tree's lowest log.

Rais et al. (2014) found that the correlation of determination in longitudinal stress wave velocity from trees to logs also decreased as log height increased. Our analysis of Model 3.1 and Model 3.2 was limited to producing one r2 for all bolts in the sample as opposed to an r2 value for the models' estimation of longitudinal velocity at each bolt height. However, scatter plots of tree and bolt level longitudinal stress wave velocity measurements (Figure 3.7 and Figure 3.8) show a lower correlation in bolts E and F is likely. The ability to infer a large proportion of a tree's wood quality from acoustic measurements taken near breast height (1.4 m) benefits stakeholders involved in salvage operations, particularly those including white spruce.

These results indicate that land managers may be able to infer timber quality from easy to obtain measurements gathered on standing trees. Gathering wood quality information on a stand level would be very useful in when valuating salvage harvests which are expected to include trees with highly variable wood quality (Basham 1984). In addition, loggers and others who purchase standing timber could increase revenue of salvage stands by obtaining acoustic nondestructive evaluation on standing trees and selling the timber for a higher value based on known quality.

Similar results were obtained from models that utilized tree longitudinal stress wave velocity measured with the Hitman ST300 and Fakopp 1D to explain variation in bolt longitudinal velocity. Therefore, the above discussion of tree-level to bolt-level measurements applies to both the Hitman ST300 and Fakopp 1D instruments.

3.5.2 Influence of Height on Bolt Longitudinal Stress Wave Speed

Bolt longitudinal stress wave velocity of living and dead white spruce generally decreased as height increased. The general trend of decreasing bolt longitudinal velocity as height increased in this study was noticed in other studies as well (Carter et al. 2005; Rais et al. 2014). Similarly, Wang et al. (2013) found that log height has a significant negative relationship with the dynamic MOE of Douglas-fir lumber. In the present study, an exception to the trend of decreasing longitudinal velocity as bolt height increases was seen in acoustic velocities from bolt positions A and B. Both live and dead trees showed a significantly lower longitudinal velocity in the lowest bolt A compared to bolt B (the second lowest bolt). Carter et al. (2005) provide instances where the lowest log within Douglass-fir and ponderosa pine *(Pinus ponderosa)* trees also have lower longitudinal velocities compared to the adjacent higher log. They state that the lowest portion of a tree's bole has lower density and higher microfibril angle which could manifest into lower longitudinal stress wave velocity (Carter et al. 2005).

The disparity between bolt A and B stress wave velocities in this study appeared to be much greater among the dead white spruce (Figure 3.9 and Figure 3.10) with bolt A producing lower velocities. Anecdotally, we noticed a greater amount of decay within the A-position bolts produced from visual category 2 and 3 trees when handling bolts. We assume the larger extent of decay observed in bolt A of dead white spruce manifested into a lower mean stress wave velocity - although no analysis was conducted on visual observations of bolt decay. Therefore, the lowest bolt of dead standing white spruce in this study could be segregated upon harvest due to poor wood quality. A likely scenario may entail delivering the lowest bolts within a salvage spruce stand to a pulp mill and marketing the remaining salvaged timber to a lumber mill. Another option to segregate the poor quality wood located near ground-level could be to fell dead standing white spruce from a height of 3 m – leaving the lower portion of the trees' stems standing. This would facilitate the harvest and salvage of higher-quality timber while enhancing wildlife habitat by retaining portions of dead standing trees (Davis 1983).

3.5.3 Future Work

The present study found significant correlation between acoustic velocity measured on salvaged standing trees and harvested bolts. Also, within tree changes in bolt acoustic velocity were found to be significant – with longitudinal velocity generally decreasing as height increased. The next logical study pertaining to utilization of salvaged white spruce is to investigate the ability to correlate lumber or wood quality to bolt acoustic velocity. Several studies have investigated the relationship of bolt longitudinal stress wave velocity from live trees to the quality of internal lumber or wood samples (Wang et al. 2001; Wang et al. 2013; Wang et al. 2009; Butler et al. 2017; Ross et al. 1997). However, few studies have correlated bolt acoustic velocity to wood quality attributes, like static MOE, dynamic MOE (calculated using transverse vibration), or visual grade, of standing dead trees. Demonstrating the ability of acoustic nondestructive evaluation to correlate to common indices of wood quality is an important step to promote industry's inclusion of salvage timber into a higher-value product chain.

3.6 Conclusion

Standing-tree measurements of longitudinal stress wave velocity can infer wood quality at various heights of both live and dead white spruce. This knowledge should help in accurately sorting salvage timber at the stand level prior to harvest. The general decline in longitudinal stress wave velocity, analyzed on live and dead white spruce separately, as height increases is in agreement with other literature on the topic. However, the drastically lower longitudinal velocity in the lowest bolts (bolt A) of dead trees in this study suggest that the lowest portion of salvage trees should be segregated and used as a lower value product or retained on the stand. Future work correlating bolt longitudinal stress wave velocity to quality of lumber produced from salvaged white spruce bolts may help aid in industry adoption of acoustic nondestructive evaluation to sort dead standing trees.

4 Thesis Conclusion

In chapter 2 we concluded that visual appearance, a common way to assess quality of standing trees, offers only coarse information pertaining to wood quality. Standing tree longitudinal velocities significantly differed between the live (category 1) and poorest (category 3) visual categories. This indicates the wood quality of salvage white spruce should be measured rather than assumed – especially for trees that fall within visual category 2 which likely represent the greatest range in wood quality. Another conclusion of chapter 2 was that transverse velocities did not differ by visual category. The first data analysis in chapter 3 focused on comparisons between standing tree and bolt longitudinal stress wave velocities. We found that tree-level acoustic measurements are good indicators of wood quality, defined by bolt longitudinal stress wave velocity, throughout the height of both live and dead white spruce. This finding suggests that using longitudinal stress wave velocity as a basis for tree-level sorting before a white spruce salvage harvest is feasible. Other analysis in chapter 3 found that bolt longitudinal velocity generally decreased with height - with the exception of the lowest bolts in dead trees which had very low longitudinal stress wave velocities. The slow longitudinal stress wave velocity of the lowest bolts produced from dead trees indicates a majority of decay occurred at this location. If similar conditions exist in other defoliated white spruce stands the lowest bolt should be segregated due to poor wood quality. Our results from chapters 2 and 3 show that acoustic nondestructive evaluation is applicable for use on dead standing white spruce and has potential to increase the value of this timber source.

The present study confirms the applicability of acoustic nondestructive evaluation on a dead standing trees and their respective bolts. The forest products could benefit from using acoustic evaluation to sort and grade dead standing timber and bolts produced from dead standing trees. Utilizing acoustic nondestructive evaluation on dead timber may allow stakeholders to increase the value of a lower-cost timber supply by confirming wood quality and, when possible, sell salvaged timber with adequate wood quality to high-value markets. Also, using acoustic measurements to sort timber at the stand improves efficiency by ensuring that timber is delivered to appropriate buyers based on desired wood quality. Future work that demonstrates the ability of salvaged log- and tree-level acoustic nondestructive evaluation to infer the wood quality of lumber will aid in determining applicable markets, and perhaps new markets, for salvaged timber.

A logical direction for future research on the utilization of salvaged white spruce is to assess the quality of lumber produced from defoliated trees. One can expect the forest products industry to require knowledge of lumber attributes like visual grade, MOE, presence of decay, and borer infestation before attempting to use salvaged timber to produce higher value products. Also, when comparing wood quality of healthy and defoliated white spruce, kiln-dry lumber will have a similar moisture content making it easier to compare wood produced from live and dead trees. Transverse vibration is a fast nondestructive measurement to infer MOE of lumber pieces. A study that correlated bolt longitudinal stress wave velocity to transverse vibration of respective lumber could increase industry awareness and utilization of nondestructive evaluation to increase value of salvaged white spruce timber.

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