Non-Destructive Evaluation for Boreal Tree Species Utilizing Acoustic Testing

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Abstract

Keywords: Acoustic Velocity Boreal, eFRI, Cambium, Defects, Modulus of Elasticity, non-destructive evaluation, Stress-wave Propagation, Timber, Wood Quality,

Standing trees pertain a level of uncertainty, in regards to yield and end-use. Thus, it may be feasible to analyse the forest, at the ground level, in order to allocate the timber resources accordingly. Through stress-wave propagation, a forester would attach a TreeSonic tester to the cambium in order to determine the wood quality. Furthermore, deviations and defects change the wave-speed (time-of-flight), where rot pockets, insect damage, and reaction wood can be detected by the change of TOF. This information is useful in respects of veneer logs, where the value is significantly higher compared to saw-logs or pulp. However, it is important to note that within the Boreal Forest, diameter-class largely influences product consideration. Thus, the broad objective of this thesis is to explore new market opportunities to give a competitive edge in the market. Therefore, using acoustic testing is a feasible non-destructive evaluation (NDE), in regard to efficiently assisting eFRI systems with wood quality. This is seen in the results, where the acoustic velocity values resulted significant. These values were used to calculate a predicted modulus of elasticity at 12%, which proved to have no significant difference from the actual MOE recorded from the destructive testing. This means that NDE can provide an accurate way to measure the "quality" of standing timber.

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Acknowledgments

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1.0 INTRODUCTION

Canada has a major advantage when it comes to the forest industry, because of the vast amount of available land, and the diverse landscape. Across Canada there are about 140 native tree species, which are divided into two distinct groups: hardwood and softwood. There are 31 native softwood species, which account for nearly 80% of the total merchantable timber (McMullins and McKnight 1981). Thus, the remaining merchantable volume consists of hardwoods, which generally serve a special purpose due to their wood attributes. Each wood type is graded for optimal usage depending upon the physical and mechanical properties since there are significant differences between species and site (Bowyer et al. 2007; Hoadley 2000; McMullins and McKnight 1981; USDA 2010). Thus, by combing different wood types, the industry can improve the quality and utilization of their resources. Therefore, having a better understanding of wood attributes will help optimize the forest sector's resources, finances and competitiveness (Zobel and Buijtenen 1989).

1.1 CANADA'S FOREST ENGINE

Canada is known as a forest nation that provides a wide range of economic, social and environmental benefits (McMullins and McKnight 1981). In 2013, the forest sector contributed $19.8 billion to Canada's GDP (Figure 1, Richards et al. 2015). This means that the forest industry has recovered significantly since the economic downturn in 2009. The reason for the market success is due to Canada's new approach, which consists of four streams: market development, operational efficiency, business process change and new product development (Miller 2010). This country has turned into a waste free forest industry, in which our waste material can be turned into a by-product. There are several different by-products from wood such as engineered products, extractives (chemicals), energy production, and eco-friendly household products; each creating profit and stimulating the economy (NRCAN 2016), as seen in Figure 1. This has allowed Canada to have one of the world's largest forest products trade balance (Richards et al. 2015).

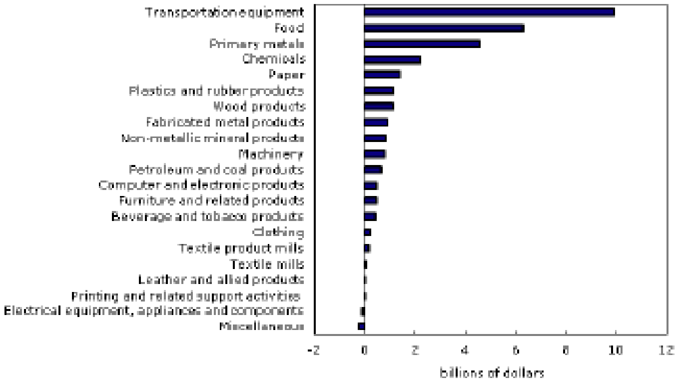

Figure 1. Manufacturing sales by industry in 2013 (Richards et al. 2015).

1.2.1. GEOGRAPHIC ZONE

The forests of Canada are divided into eight regions, each geographic zone, known as a biome, is characterized by broad uniformity in physical features and in composition of a dominant tree species. The biome of interest is the Boreal Forest, specifically of Northwestern Ontario (NWO). The Boreal Forest is dominated by a fire regime, which influences change in forest structure and composition. However, the forest is a complex and dynamic system that consists of multiple variables that can influence growth and yield characteristics (McMullins and McKinght 1981). For example, elevation can influence favourable growth for one species over another, or within a species (Zhang and Koubaa 2008). Thus, being able to understand how the growth properties are affected can help allocate and optimize our forest resources (Hoadley 2000; Zobel and Buijtenen 1989).

Northwestern Ontario is comprised of a portion of the Boreal Forest region and the Great Lakes- St. Lawrence Forest region (Figure 2; Racey et al. 1996). However, the Boreal region covers significantly more area. The forests of NWO consist of diverse mosaics of soil and vegetation characteristics. For example, pure, even-aged jack pine stands dominate on well-drained, sandy soils compare to black spruce, which dominate poorly drained soils (Miller 2010). Across the region, the temperature tends to be warmer the lower the latitude, with a mean annual temperature ranging from 0-3°C. However, the northern part of the region is generally much cooler, with a lower diversity than the more southern part (Bergeron 2000; Miller 2010; Racey et al. 1996).

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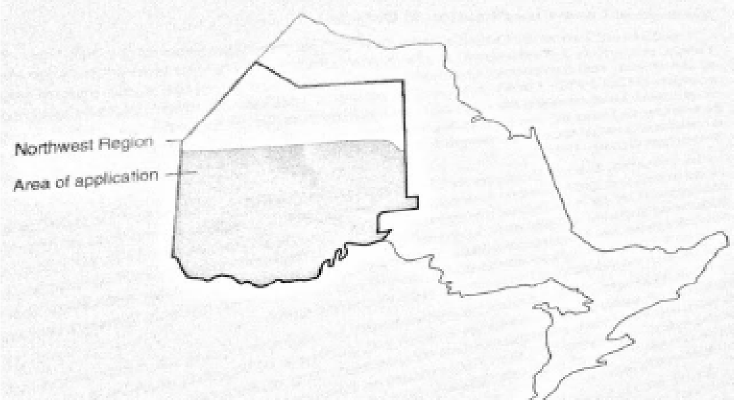

Figure 2. Map of Northwestern Ontario (Racey et al. 1996).

1.2.2. TREE SPECIES

There are 12 commercial species of interest in NWO. In this study, only five of these species were sampled from different site regimes. These five species are:

- Black spruce (*Picea mariana* (mill.) B.S.P.),
- Trembling aspen (*Populous tremuloides* Michx.),

- White birch (*Betula papyrifera* Marsh.),
- Balsam fir (*Abies balsamea* (L.) Mill.), and
- White spruce (*Picea glauca* (Moench) Voss).

However, there is a lack of information regarding acoustic attributes across geographic locations for Boreal species. This information is useful for the optimization of standing trees, and can improve the competitiveness of the forest industry (Lessard et al. 2013; Ross 2015).

1.3.1 OBJECTIVES

From an industry viewpoint, optimization of the forest is a key factor, where profit and revenue are part of the governing force. Thus, researchers are finding alternative ways to assess the quality of timber resources. However, quality is a broadly defined topic; for the purpose of this thesis, quality is defined as an indicator of strength and defect percentage. Furthermore, the objective of this thesis is to determine whether acoustic testing is a feasible application to use in the Boreal Forest. Historically, stress-wave propagation techniques have been used on large veneer logs, with positive feedback. However, very little testing has been done within the Boreal Forest. Therefore, this may be an opportunity that could increase revenue and profit, if it is feasible.

1.3.2 RESEARCH QUESTIONS

To ensure the objectives of this paper are met the following research questions were considered:

1. Are there differences between acoustic values for each species?
2. Is there a difference between acoustic values between sites?
3. Can we identify environmental and forest inventory variables that can be used to predict acoustic attributes?

1.3.3. NULL HYPOTHESIS

The Boreal Forest is a dynamic system; the variability across its macro-region is very little, but the variability between micro-regions is significant, where elevation is a major factor affecting growth and diversity. Thus, the null hypothesis is that the change between sites is too insignificant to make the characteristics within species statistically different. The alternative hypothesis is that a change between two microsites will be recognized, and that within a species will prove to be statistically different.

2.0 Literature Review

Trees vary greatly between species according to their physical and chemical makeup (Bowyer et al. 2007). Significant variations can occur within a stem, and thus, differences can occur within species (Panshin and de Zeeuw 1980). This means that the value of a tree may be affected according to its location and genetics. Therefore, it is essential to understand the distinct differences between tree growth and function between species (Bowyer et al 2007). This literature review will detail the basics of wood growth, macroscopic properties, juvenile versus mature wood, wood defects, wood attributes (physical, mechanical and chemical properties) and how they are influenced. The last section will cover acoustic testing, which is the main focus of this thesis.

2.1.0 TREE GROWTH

Tree growth occurs when sugars are converted into organic compounds through a process called photosynthesis. Essentially this process creates sugars from the sunlight (Wilson 1984). The sunlight is converted into glucose and oxygen from water and carbon dioxide by the chlorophyll and other structures present in the leaf or stem (Bowyer and Smith 2000; Bowyer et al. 2007). Figure 3 is an overview of how a tree grows and stores food, including the main growth components.

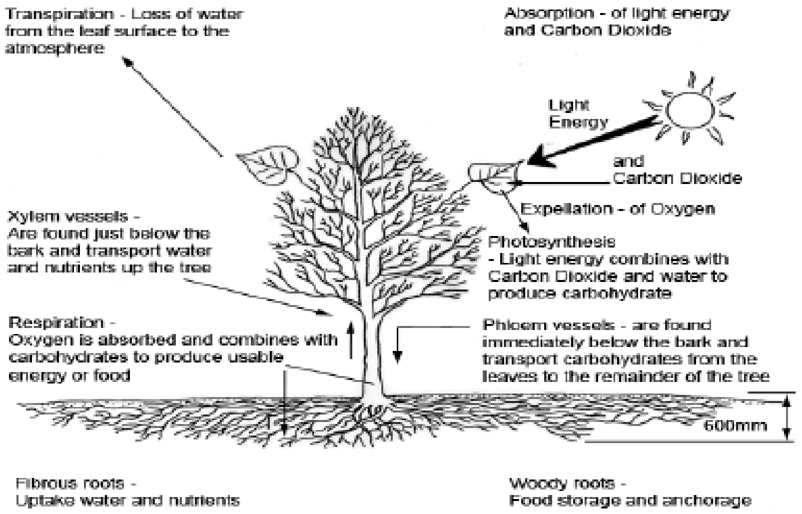

Figure 3. Tree Growth and Form (leics.gov.uk 2013).

The growth of a tree is mainly a result of its genetic inheritance, which is responsible for controlling the trees response to various environmental conditions. Thus, many species have developed growth strategies against specific environmental elements to successfully survive (Burns and Honkala 1990; Panshin and de Zeeuw 1980). The main adaptation in NWO is cold and drought hardiness, which allow the trees to recognize acceptable growing conditions (Miller 2010). These conditions are known as growing seasons, where the annual growth ring reflects the patterns of seasonal growth (Bowyer et al. 2007; Thibeault-Martel 2008). Thus, a tree will terminate, or initiate, annual growth by responding to change in the average air temperature, which occurs between 6 and 8°C, and ambient moisture (Thibeault-Martel 2008; Rossi et al.

2008). In the spring, when ideal moisture and temperature levels are present, a tree will transport stored nutrients from its roots up to the crown to aid in bud flush. Thus, wood growth begins after dormancy, and the growth rate increases when the leaves are functioning (Wilson 1984).

There are two zones of growth in a tree: height growth (apical meristem), which aids in crown growth; and diameter growth (lateral meristem), which helps support the expanding crown (Bowyer and Smith 2000; Panshin and de Zeeuw 1980; Wilson 1984). The current literature on wood growth and cambial activity has conflicting results. However, it is evident that cambial activity and wood growth are highly variable within a tree, species and between species (Bowyer and Smith 2000; Bowyer et al. 2007; British Columbia Forestry Service, 2002; McMullins and McKnight 1981; Zhang and Koubaa 2008).

2.1.1 HEIGHT GROWTH

Growth in height is accomplished through the division of specialized cells in the apices of the main stem, branches and roots (Wilson 1984; Bowyer and Smith 2000; Panshin and de Zeeuw 1980). These areas are zones of intense meristematic activity, referred to as apical meristems. Thus, the leave and shoot formation are predetermined the year before. When the cells of the apical meristem divide, they leave cells behind the meristem as it is pushed upward, with cells being added to the old ones similar to bricks on a wall creating the extension in height (Panshin and de Zeeuw 1980; Bowyer and Smith 2000). Figure 4 is an illustration of a general apical meristem. The mechanism which controls total height growth is uncertain, but the literature suggests that growth in height is strongly influenced by heredity and environment (Bowyer et al. 2007; Burns and Honkala 1990 Hoadley 2000). Thus, there is a great deal of variation between tree species and within a tree species when it comes to mature tree height (British Columbia Forestry Service, 2002).

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Figure 4. An illustration of an apical meristem (National Gardening Association 2017).

2.1.2. DIAMETER GROWTH

Diameter growth of a tree occurs in the area known as the vascular cambium, which is a lateral meristematic zone. It is composed of a tangential band of cambial initial (fusiform and and ray initial) cells located directly beneath the inner bark. The vascular cambium layer sheaths the entire living portion of the tree, as seen in Figure 5. The cells present in the cambium can divide repeatedly in two different ways such as (Bowyer et al. 2007; Panshin and de Zeeuw 1980):

- periclinal divisions results in two new cells that are parallel to the growth ring where one cell remains in the cambium for further division, while the other cell becomes either a xylem cell, or a phloem cell bark cell; or
- anticlinal divisions results in two new cells perpendicular to the growth ring both, which both can divide and create new cells.

Anticlinal division allows the cambium to accommodate girth increases, as part of stem growth (Bowyer et al. 2007).

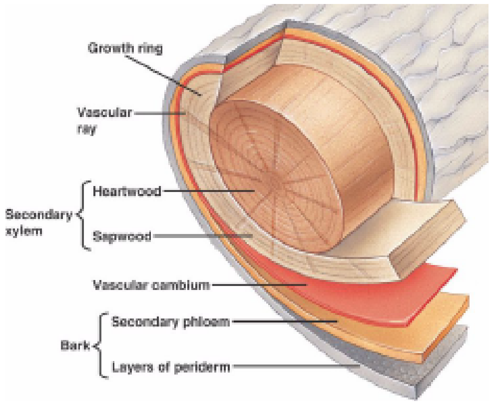

Figure 5. An illustration of a trees anatomy (Benwickclaybrained 2013).

Cell division occurs throughout the growing season, creating new xylem and phloem cells. Thus, Diameter growth can vary greatly within a stand or species. The factors that influence diameter growth include; stand density, age, site class of an ecosite, and moisture regime among various other interacting environmental components (Wilson 1984; Bowyer and Smith 2000). However, the literature suggests that heredity contributes the most for diameter growth in a tree, it is for this reason that diameter growth varies greatly within species and between species (Bowyer et al. 2007; Zhang and Koubaa 2008). Furthermore, the cambial sheath also covers wounds and branch stubs, which produces various types of wood as the tree ages. The lower branches will die off due to their inability to photosynthesize, becoming branch stubs. Once the branch stub deviations are covered, the tree produces its most desirable features for dimensional lumber, creating a stronger and clearer grained wood, as time progresses and new growth rings are laid over previous growth rings (Panish and de Zeeuw 1980; Bowyer et al. 2007; Wilson 1984).

2.2.0 FORMATION OF WOOD

After cell division, a newly created wood cell lies within the cambial zone. These longitudinally oriented cells increase in diameter and length, and begin to develop a secondary wall layer (Figure 6). Within the secondary cell wall layer, the cell begins to harden through the deposition of lignin during the secondary wall layer development. This process is referred to as lignification. Furthermore, rays run radially from pith to bark in the stem, which provide radial transport of the sap essential for the creation of cellulose, hemicellulose, and lignin in the newly formed wood cells (Bowyer et al. 2007; Panshin and de Zeeuw 1980; Zobel and Buijtenen 1989).

Figure 6 illustrates the development of the secondary cell wall, which consists of three distinct layers: S1, S2 and S3. The S1 layer is the outer most layer, forming on the inner surface of the primary wall. This layer is about four to six layers of microfibrils, and they are oriented almost perpendicular to the long axis of the cell. Similarly, the S2 layer forms inside the S1 layer, but is 8 to 30 times thicker. The layering can range from 30 microfibril layers in early wood to more than 120 layers in latewood. These microfibrils are oriented almost parallel to the long axis of the cell. Lastly, the S3 layer forms inside the S2 layer, but is as thick as the S1 layer with similar orientation (Bowyer et al. 2007; McMullins and McKnight 1981; Panshin and de Zeeuw 1980).

The S2 layer begins with a similar microfibril orientation as the S1 and S3 in the juvenile wood, however, in the mature wood the S2 microfibrils are almost at a right angle to the microfibrils in the S1 and S3. This increases the stiffness and strength of mature wood compared to juvenile wood, which is more flexible due to the alignment of all three S layers (McMullins and McKnight 1981; Panshin and de Zeeuw 1980). Since the S2 layer is the thickest layer, it accounts for the majority of the woods density. Thus, the development of the S2 layer has a significant effect on major wood attributes (Bowyer et al. 2007; McMullins and McKnight 1981; Panshin and de Zeeuw 1980). However, there is significant variation in S2 development within a stem and between species (McMullins and McKnight 1981; Panshin and de Zeeuw 1980).

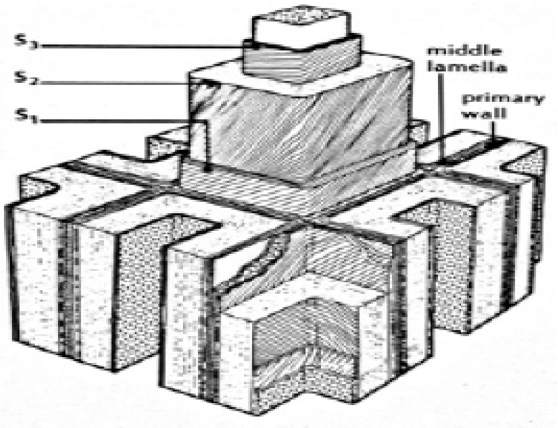

Figure 6. Layered cell-wall structure illustrating the orientation of the microfibrils within each layer (McMullins and McKnight 1981).

2.2.1 SOFTWOOD ANATOMY

Softwoods have a fairly simple cellular structure (Figure 7); longitudinal tracheids, radial rays and longitudinal and radial resin canals, but not all softwood species contain resin canals (Panshin and de Zeeuw 1980; Zobel and Buijtenen 1989). A longitudinal tracheid is a long wood cell with tapered ends. They are similar to a drinking straw, which gives a uniform honeycomb-like appearance in transverse section. These tracheids make up between 90 and 96% of the volume of all softwoods, and generally the trachieds are 3 to 8 mm long, hallow, and pitted (Panshin and de Zeeuw 1980). Whereas, rays are radially aligned strips of short brick-shaped parenchyma cells, as seen in Figure 7 (Panshin and de Zeeuw 1980; Zobel and Buijtenen 1989).

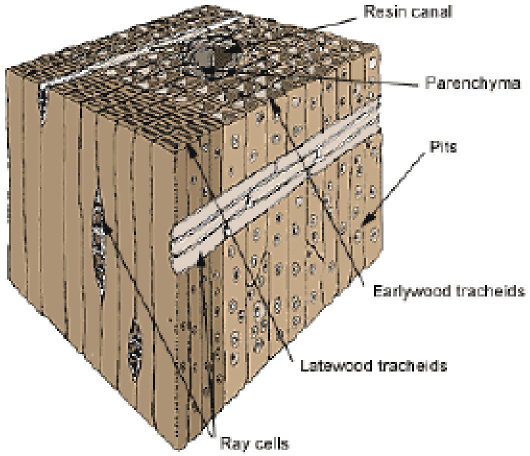

Figure 7. An illustration of softwood cells (Furniturelink 2016).

2.2.2. HARDWOOD ANATOMY

Hardwood cell structure, by contrast, is more complex than softwoods with considerable variability between species. Hardwoods have four major cell types: longitudinal fibres, vessels, parenchyma and radial ray cells (Bowyer et al. 2007; Panshin and de Zeeuw 1980; Zobel and Buijtenen 1989), as seen in Figure 8. The great variability between cell structures of hardwood species have a major effect on the quality and purpose of the end product, which is widely related to the size and distribution of ray and vessel elements (Zobel and Buijtenen 1989). A key difference of hardwoods is fibre length, where the average length for hardwood fibres ranges from 0.5 mm to 1.5 mm (Panshin and de Zeeuw 1980; Zobel and Buijtenen 1989). According to the literature, vessel elements cause printing issues, but at the same time can add bulk without adding material to the paper. Therefore, hardwoods are used in combination with softwoods to produce quality products in the pulp and paper industry, as well as specialty products (Araujo et al. 2015; Panshin and de Zeeuw 1980; Zobel and Buijtenen 1989).

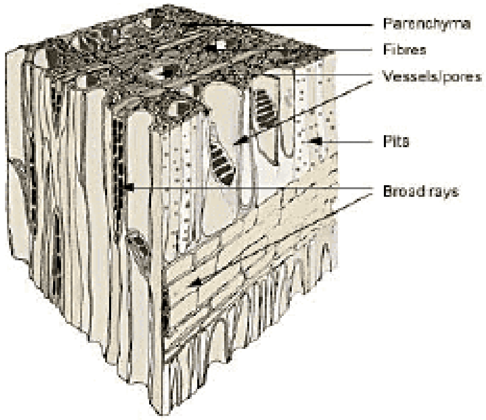

Figure 8. An illustration of a basic hardwood cell (Furniturelink 2016).

2.2.3 ANNUAL RING

The annual ring consists of alternating bands of early wood and latewood, the ratio however, depends on several factors. The strength of latewood is significantly greater than that of early wood (Bowyer et al. 2007). Thus ring width is a measurable parameter, which reflects the effects of environment on tree growth (Park et al. 2012). As seen in figure 9, latewood is the denser part of the annual ring, however, the average ring width has a higher proportion of early wood, meaning increasing the ring width would increase the amount of early wood (Zhang and Koubaa 2008). Araujo et al. (2015) observed similar trends, increased latewood percentage contributes to increased density. Thus, the distinct differences in mechanical properties exist between early wood and latewood, where variations of this ratio will have differing results (Bowyer et al. 2007; Park et al. 2012). Controlling this ratio is possible through stand density management, however noting the differences between the two zones explains the variances within species from differing locations as a factor of growth rate. Thus, for the purpose of this study, ring core samples are used as a cross-reference to provide more accurate results.

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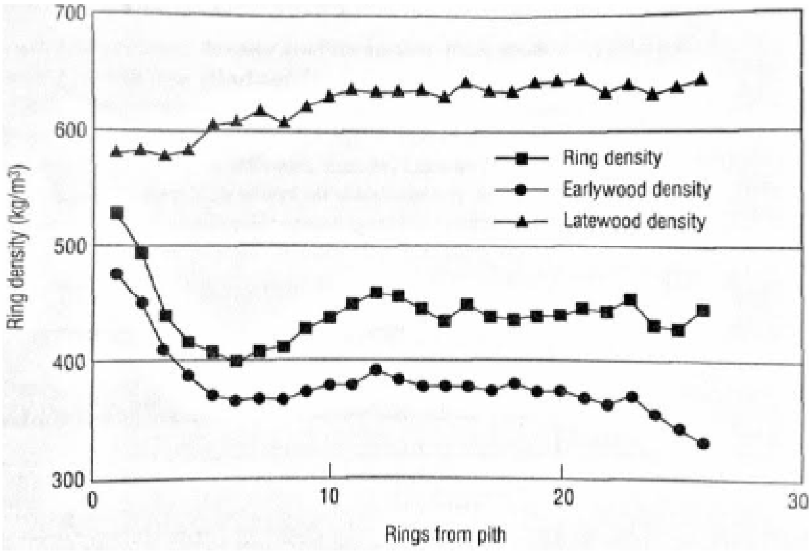

Figure 9. Radial variation of ring density in early wood and latewood for *Picea glauca* (Zhang and Koubaa 2008).

2.3.0. JUVENILE WOOD VERSUS MATURE WOOD

Wood produced by mature trees is referred to as mature wood, where as an immature tree produces juvenile wood. However, a maturing tree produces both juvenile and mature wood. Differences between the mature and juvenile wood are more pronounced in softwoods than hardwoods. Although in ring porous hardwoods, the improvements to the wood properties decrease over time (Panshin and de Zeeuw 1980; Zobel and Buijtenen 1989). Furthermore, wood growth in the bole of a maturing tree is restricted to tangential and radial growth, while the crown also grows in the longitudinal direction. Thus, the development of mature wood may be associated with the mechanism of self-pruning, which is associated with crown closure (Miller 2010; Panshin and de Zeeuw 1980).Therefore, an open grown tree with 100% live crown would produce less mature wood compared to a tree with 35% live crown. However, other factors influence mature wood development such as heredity, age, composition and site regime (Bowyer et al. 2007; Kretschmann 1998; Miller 2010; Panshin and de Zeeuw 1980;).

Changes in wood cell structure from juvenile wood to mature wood are significant in relation to wood characteristics and quality as seen in Figure 10. Mature wood consists of longer cell fibres and thicker cell walls with a higher percentage of latewood and a straighter fibril angle (Panshin and de Zeeuw 1980). In addition, mature wood has more lignin than juvenile wood and has thicker secondary walls. This leads to a higher density of up to 10 to 15% due to a thicker cell wall, particularly in the S2 layer compared to juvenile wood, thus mature wood has been observed to have a higher strength value by 15 to 30% (Kretschmann 1998; Mullens and McKinight 1981). The distinctive difference between mature wood and juvenile wood affect their potential end use; where higher proportions of juvenile wood decreases the value, because juvenile wood does not meet many standards (Bowyer et al. 2007; Mullens and McKinight 1981; Panshin and de Zeeuw 1980; Zobel and van Buijtenen 1989).

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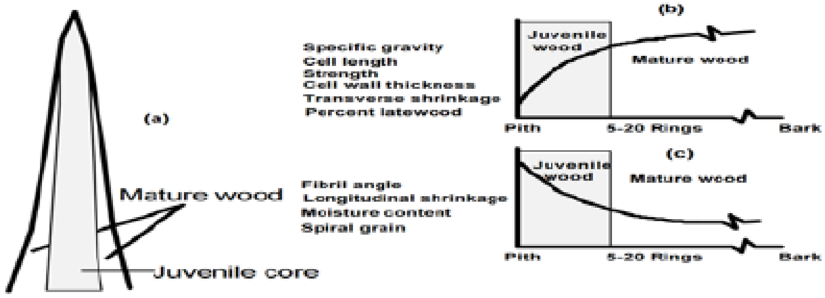

Figure 10. Effect of juvenile wood on physical and mechanical properties: (a) juvenile core located in interior of tree bole; (b) properties that increase from juvenile to mature wood; and (c) properties that decrease from juvenile to mature wood (Kretschmann 1998).

2.4.0. WOOD DEFECTS

As a tree grows it experiences many alterations over time in order to produce mature wood. In the process, trees can experience growing defects in relation to their environment or genetics (Panshin and de Zeeuw 1980; Bowyer et al. 2007). Thus, in this section reaction wood, knots and rot will be discussed, as they affect the overall quality and quantity of wood produced.

2.4.1. REACTION WOOD

Reaction wood is wood formed as a response to a triggering event that caused the tree to shift from its vertical axial position. Events like wind causing a tree to sway, a tree fallen over, or a tree produced through vegetative means can cause reaction wood to form in the main stem (Panshin and de Zeeuw 1980). Similarly, reaction wood forms to regulate the positioning of the lateral branches (Haygreen and Bowyer 1996). Reaction wood formation has also been seen to increase in plantation trees, referred to as spiral reaction wood, where wide spacing is utilized allowing the trees to sway in the wind longer before crown closure occurs, which also increases the amount of juvenile wood at the same time (Panshin and de Zeeuw 1980, Jozsa and Middleton 1994). There are two types of reaction wood: compression and tension wood, as seen in Figure 11.

In softwoods, the only reaction wood produced is compression wood. In hardwoods, tension wood is produced (Haygreen and Bowyer 1996, Panshin and de Zeeuw 1980, Jozsa and Middleton 1994). It is important to note that the name refers to the location of the reaction wood, being on the compression or tension side (Figure 11), and does not imply that the wood is formed under such stresses (Jozsa and Middleton 1994). Reaction wood forms misshapen annual rings that appear to be elongated or elliptical below the degree of lean. These rings will appear tight on the non-reaction wood side, referred to as opposite wood, and loose on the reaction wood side.

Compression wood can easily be identified by its color, which appears in a dull dark, reddish-brown hue (Jozsa and Middleton 1994, Haygreen and Bowyer 1996, Panshin and de Zeeuw 1980).

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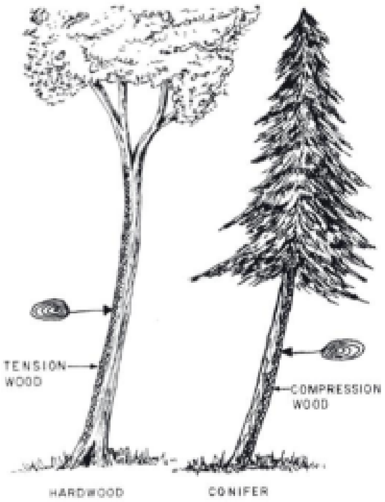

Figure 11. Reaction wood production in hardwoods and softwoods (Haygreen and Bowyer 1996)

In a cross-sectional view of compression wood, the tracheids are rounded, which leaves intercellular spaces where the tracheids come together. Jozsa and Middleton (1994) found that this affects the mechanical properties of the wood significantly. In addition, the S3 wall layer will be missing and the S2 microfibril angle is about 45 degrees from vertical, which is closer to the S1 and S3 layers (Panshin and de Zeeuw 1980; Jozsa and Middleton 1994; Bowyer et al. 2007). As well as, deep helical checks are formed in the cell walls at the S2 layer (Panshin and de Zeeuw 1980). Thus, reaction wood is undesirable for the forest industry, where it can be minimized with silviculture treatments. Treatments would include proper spacing, wind barriers, or well-planned sylvicultural acrtivites to mitigate adverse affects (Jozsa and Middleton 1994).

2.4.2. KNOTS

Knots in wood have a significant effect on wood properties and quality. Knots are the remnants of branch structures, which progressively become part of the wood structure with each annual growth increment (Bowyer et al. 2007; Panshin and de Zeeuw 1980). As mentioned earlier, trees increase in height and diameter to the point where the stand reaches crown closure. After this point, the lower branches of trees receive less sunlight and produce less photosynthate (Bowyer and Smith 2000). Thus, the productivity of these branches become inefficient to support and maintain growth, at which time the tree terminates the branch. Over time the branch will decay, fall off and leave a branch scar that will be integrated into the wood (Bowyer et al. 2007; Wangaard 1981, Panshin and de Zeeuw 1980; USDA 2010).

A live knot is when the branch is living at the time of integration. These knots are dark in color (generally red), tight, and inter-grown . However, if the branch is dead at the time of integration, it is called a dead knot (Panshin and de Zeeuw 1980; Bowyer et al 2007). At this point, the cambial tissues cease function and no longer is joined to cambial activity within the main stem. This causes a break in the continuity of the wood leaving a “loose” fragment of the branch, as seen in Figure 12. Thus, branch fragments that are dead at the time of inclusion produce less distorted grain (Bowyer et al. 2007; McMullins and McKnight 1981; Panshin and de Zeeuw 1980; Wangaard 1981).

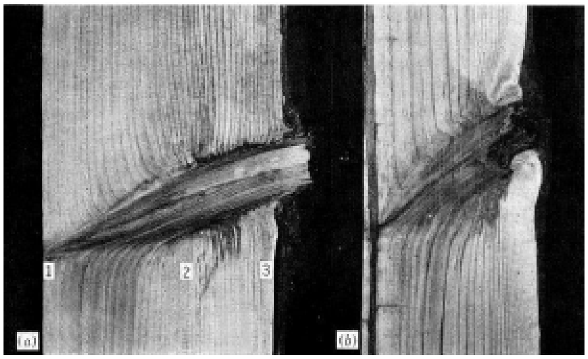

Figure 11. Longitudinal view of a stem inclusion of a branch to be knot. (1) shots the origin of the lateral branch, (2) shows the live (incorporated) knot, (3) shows the dead (unincorporated) spur. (b) Shows a live knot with a dead spur late in the "healing" process. (Panshin and de Zeeuw 1980)

Wood fibers found around knots tend to be abnormal, as seen in Figure 11b. This is due to the distortion of the cellular properties (Panshin and de Zeeuw 1980; Wangaard 1981). In addition, knot wood has more lignin and extractives, this contributes to increases in wood density observed with higher knot concentrations (McMullins and McKnight 1981; Bowyer et al. 2007; USDA 2010). However, the relative strength of lumber depends upon the type, size and location of the knot; where large dead-knots on the edge near the middle of a board, can move the board to a lower grade than compared to if the knot was not present. Whereas small knots, or intergrown-knots may not significantly influence the mechanical properties (Wangaard 1981; Bowyer et al. 2007) Thus, higher proportions of knot wood decrease the value of timber; where the mechanical properties may be acceptable for grading standards, but the overall influence of knots when present, will downgrade the structural grade (McMullins and McKnight 1981;

Bowyer et al. 2007). Therefore, only clear-grain lumber is consider number 1 structural grade (Miller 2010; USDA 2010)

2.4.3 ROT

In tree growth, rot is considered decay caused by fungus. This fungus is called either white or brown rot, depending upon the species inoculating the area (Bowyer et al 2007; Hoadley 2000). There are four factors necessary for wood decay: moisture, air, suitable temperature, and food (Wangaard 1981). When conditions become optimal, fungi spores begin to reproduce in thread-like hyphae. This is done by fungi inoculating between annual layers. The structural integrity of the wood decreases over time as the rot breaks down the continuity of the cellular structure. (Bowyer et al 2007; Hoadley 2000; Panshin and de Zeeuw 1980; Wangaard 1981). Thus, the mechanical and physical properties degrade in relation to the affected area. Therefore, the presence of rot lowers the quality and strength of wood (Bowyer et al 2007; Panshin and de Zeeuw 1980; Ross 2015).

2.5.0. WOOD ATTRIBUTES

Wood is studied using three axis planes: radial, tangential or cross-sectional (transverse). When wood is viewed in these three surfaces, it assists us to better identify tree species, cell characteristics, and wood properties (Hoadley 2000; Bowyer et al. 2007; Miller 2010). These attributes respond to three factors: environment, genotype, and phenotype, which cause several different effects (Panshin and de Zeeuw 1980; Burns and Honkala 1990). Some factors may cause poor quality such as knots or high proportions of reaction wood, which affect the chemical, mechanical and physical properties, however, proper care can result in a positive manipulation of these properties (Bowyer et al. 2007; Panshin and de Zeeuw 1980; Zhang and Koubaa 2008). For this reason, it is crucial for a forest manager to understand the sensitivity and preferences of specific species in order to optimize the desired end product(s).

2.5.1. MOISTURE CONTENT

Moisture content, or water, is found in the cell walls and the lumen of a wood cell. water held in the lumen, known as free water, varies from season to season. Whereas the water in the cell walls is known as bound water, which is held by surface tension (Panshin and de Zeeuw 1980). The total amount of water in the wood is referred to as the moisture content (MC); expressed as a percentage of the wood weight. The MC of wood is in constant fluctuation in response to the atmospheric conditions (relative humidity and temperature) surrounding the wood (Wangaard 1981; Bowyer et al. 2007). Even if the wood has been kiln dried, it will regain moisture if placed in a humid environment. Thus, MC is a physical property that can have a significant influence on the value of wood (Bowyer et al. 2007; Panshin and de Zeeuw 1980; Wangaard 1981; Zobel and Buijtenen 1989; USDA 2010).

There are 3 standard moisture contents used to compare wood characteristics; oven-dry (OD), nominal or air-dry (12% MC) and basic (30%) (Wangaard 1981; Miller 2010; USDA 2010). Thus, as wood dries, it loses the free water first, then the cell walls experience water loss, because the first water must evaporate completely. The point when the lumen contains no water, but the cell walls are saturated, is known as the fibre saturation point (FSP), which occurs between 25 to 30% MC. The wood characteristics do not change significantly due to the loss of free water, however below the FSP, wood begins to shrink or swell (Barrett and Lau 1994; Bowyer et al. 2007; USDA 2010).

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From table 1 it can be seen there is a general trend where moisture content reduces the strength properties of wood at varying degrees depending on species (Panshin and de Zeeuw 1980). In general, Bowyer et al. (2007) found that strength properties improve with reduced MC, where strength increases up to 6% per 1% reduction in MC below FSP. However, the degree moisture affects wood properties varies between species and within species and trees. Thus, MC is an element of the environment, which is then related to the growth parameters (Wangaard 1981; Panshin and de Zeeuw 1980; Bowyer et al. 2007). According to the literature, the most significant effect of moisture is on the latewood proportion created each year (Bowyer et al. 2007; McMullins and McKnight 1981; USDA 2010). Therefore, MC will affect the fibre attributes, and the possible usage of the wood, without proper conditioning (USDA 2010; Zobel and Buijtenen 1989)

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2.5.2. WOOD DENSITY

Density is referred to as the mass per unit volume of matter; expressed as either grams per cubic centimetre (g/cm^3) or kilograms per cubic metre (kg/m^3). Relative density at an oven-dry state (relative density $_{OD}$), also known as specific gravity, is the ratio of the density of oven-dry wood to the density of an equal volume of water at 4°C; since it's a ratio, it has no units (Bowyer et al. 2007; Hoadley 2000; Panshin and de Zeeuw 1980; Zobel and Buijtenen 1989). Literature indicates that relative density of wood is close related to most mechanical properties. thus, it is the most common wood property used for comparison; providing a means of measuring variation between species, within species and within a stem (Bowyer et al. 2007; McMullins and McKnight 1981; Panshin and de Zeeuw 1980). Therefore, density can be used an indicator of operational consideration (Bowyer et al. 2007; Wangaard 1981; USDA 2010; Zobel and Buijtenen 1989).

There is a direct relationship between density and strength, where the higher the relative density the higher the strength of the mature wood. In additional the plane of the wood affects strength, for example wood is up to 10 times stronger longitudinally than radially (Miller 2010; Mullens and McKinight 1981; Wangaard 1981; USDA 2010). Relative density also effects the anatomical structure, pulp yield, heat transmission, and the shrinking and swelling of wood, which are important factors influencing end-product potential (Bowyer et al. 2007; Zobel and Buijtenen 1989). The strength properties may be higher, but the interconnections of the internal structure of the wood will affect the overall quality, where the physical and chemical makeup affect the mechanical properties (Mullens and McKinight 1981; Wangaard 1981). For example, reaction wood has this effect, as mentioned earlier, the loss of the S3 layer and stiffening of the S2 (Mullens and McKinight 1981).

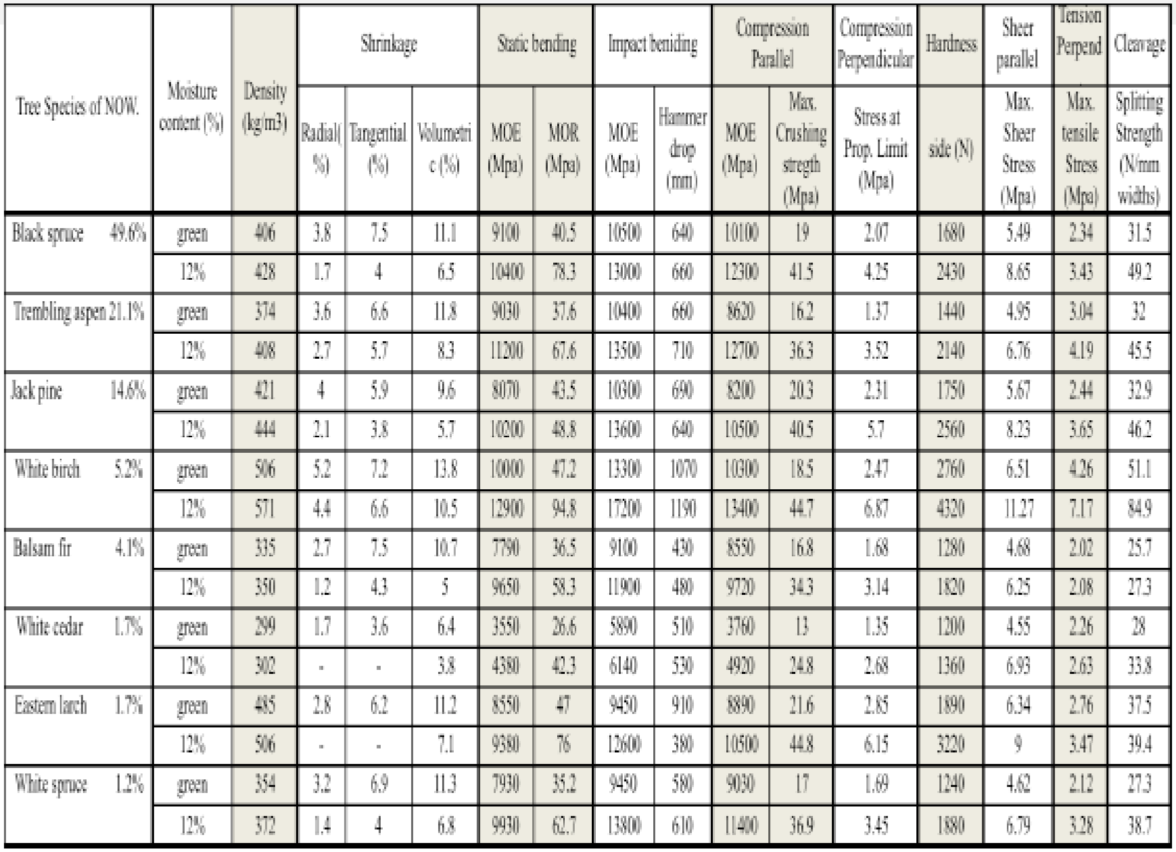
Density is used to create a general profile for a tree, however, there may be significant variance within a stem, related to site factors and heritage (Bowyer et al. 2007; Miller 2010; Panshin and de Zeeuw 1980). The literaute supports that density varies between radial and axial positions throughout the stems of tree species (Bowyer et al. 2007; Miller 2010; Panshin and de Zeeuw 1980; Wangaard 1981; Zobel and van Buijtenen 1989). In respect to age, the juvenile zone has differing properties than the mature zone (McMullins and McKnight 1981). Thus, if entire stem could be utilized for different end-uses based upon the density profile through the tree, the value of standing timber can be increased (Miller et al. 2017; USDA 2010). Therefore, density should be used to rather assist in the understanding of the internal properties of a tree (Miller 2010).

2.5.3 MECHANICAL PROPERTIES

Mechanical properties are observed when a material is subjected to an applied external force (USDA 2010). Theses are important properties to understand as they are directly related to the end use characteristics and manufacturing processes. In Canada, they are generally reported as an average with respect to a species (Table 1), they attempt to give a fair estimate for the species throughout the growth range and are limited to species of commercial interest (Jessome 2000). The testing of various species consists of standardized tests of small, defect free specimens at a set moisture condition for comparison. As well, large specimens can be tested, in respect to standard lumber grades, where that strength data can be derived based on the number of defects (Miller 2010; USDA 2010).

The two most common strength values reported for wood are modulus of elasticity (MOE) and modulus of rupture (MOR) from static bending. Elasticity implies that deformations produced by low stress are completely recoverable after loads are removed; whereas high stress loads may cause failure or deformation (Bowyer et al. 2007; USDA 2010; Wangaard 1981). MOE is a measure of resistance to bending; or a measure of rigidity. MOR is a measure of resistance to bending; or a measure of the maximum load-carrying capacity of the beam at failure. Both these values are obtained through a static bending test (Bowyer et al. 2007; Hoadley 2000; Miller 2010; Panshin and de Zeeuw 1980; Wangaard 1981). Other common mechanical properties that can be tested are compression parallel and perpendicular to the grain, tension parallel and perpendicular to the grain, hardness, impact, shear parallel to the grain, and nail and screw pull (Hoadley 2000; USDA 2010).

Table 1. Physical and mechanical properties of northwestern Ontario tree species (Jessome 2000).



Tree Species of NOW.	Moisture content (%)	Density (kg/m3)	Shrinkage			Static bending		Impact beniding		Compression Parallel		Compression Perpendicular	Hardness	Sheer parallel	Tension Perpend	Cleavage
			Radial(%)	Tangential (%)	Volumetric (%)	MOE (Mpa)	MOR (Mpa)	MOE (Mpa)	Hammer drop (mm)	MOE (Mpa)	Max. Crushing stregth (Mpa)	Stress at Prop. Limit (Mpa)	side (N)	Max. Sheer Stress (Mpa)	Max. tensile Stress (Mpa)	Splitting Strength (N/mm widths)
Black spruce 49.6%	green	406	3.8	7.5	11.1	9100	40.5	10500	640	10100	19	2.07	1680	5.49	2.34	31.5
	12%	428	1.7	4	6.5	10400	78.3	13000	660	12300	41.5	4.25	2430	8.65	3.43	49.2
Trembling aspen 21.1%	green	374	3.6	6.6	11.8	9030	37.6	10400	660	8620	16.2	1.37	1440	4.95	3.04	32
	12%	408	2.7	5.7	8.3	11200	67.6	13500	710	12700	36.3	3.52	2140	6.76	4.19	45.5
Jack pine 14.6%	green	421	4	5.9	9.6	8070	43.5	10300	690	8200	20.3	2.31	1750	5.67	2.44	32.9
	12%	444	2.1	3.8	5.7	10200	48.8	13600	640	10500	40.5	5.7	2560	8.23	3.65	46.2
White birch 5.2%	green	506	5.2	7.2	13.8	10000	47.2	13300	1070	10300	18.5	2.47	2760	6.51	4.26	51.1
	12%	571	4.4	6.6	10.5	12900	94.8	17200	1190	13400	44.7	6.87	4320	11.27	7.17	84.9
Balsam fir 4.1%	green	335	2.7	7.5	10.7	7790	36.5	9100	430	8550	16.8	1.68	1280	4.68	2.02	25.7
	12%	350	1.2	4.3	5	9650	58.3	11900	480	9720	34.3	3.14	1820	6.25	2.08	27.3
White cedar 1.7%	green	299	1.7	3.6	6.4	3550	26.6	5890	510	3760	13	1.35	1200	4.55	2.26	28
	12%	302	-	-	3.8	4380	42.3	6140	530	4920	24.8	2.68	1360	6.93	2.63	33.8
Eastern larch 1.7%	green	485	2.8	6.2	11.2	8550	47	9450	910	8890	21.6	2.85	1890	6.34	2.76	37.5
	12%	506	-	-	7.1	9380	76	12600	380	10500	44.8	6.15	3220	9	3.47	39.4
White spruce 1.2%	green	354	3.2	6.9	11.3	7930	35.2	9450	580	9030	17	1.69	1240	4.62	2.12	27.3
	12%	372	1.4	4	6.8	9930	62.7	13800	610	11400	36.9	3.45	1880	6.79	3.28	38.7

2.5.4. CHEMICAL PROPERTIES

Wood is principally composed of carbon, hydrogen and oxygen, which contributes to the physical and chemical make-up of wood (Bowyer et al. 2007). The main chemical elements are cellulose, hemicellulose and lignin. Due to the chemical arrangement, lignin acts as glue binding the cellulose and hemicellulose together. Thus, wood is noted to be stronger than steal, in respect to per unit of weight (Bowyer et al. 2007; McMullins and McKnight 1981; Panshin and de Zeeuw 1980). However, the chemical components may contribute to the strength of wood, but mainly affect the pulping industry (Zobel and Buijtenen 1989).

Cellulose is a major component of the wood and the main structural element of the trees fibres. It is a polyachride formed from simple sugars only, which affects the shrinking and swelling of wood (Bowyer et al. 2007; McMullins and McKnight 1981; Panshin and de Zeeuw 1980). Cellulose content is greater in softwood than hardwood, 40 to 50% compared to 15-30%, respectively, and variability is greater for hardwood species due to the vessels (McMullins and McKnight 1981). Whereas, hemicellulose is formed from a number of sugars, most importantly glucose, galactose, mannose, xylose and arabinose (McMullins and McKnight 1981; Panshin and de Zeeuw 1980).The content is about 25-30% within softwoods, and is greater than 40% in hardwoods (McMullins and McKnight 1981).

Lignin is associated with cell wall stiffness and with reducing enzymatic degradation of the cell wall. It is essentially the glue that binds cell wall components together as well as individual cells together at the middle lamella (McMullins and McKnight 1981; Panshin and de Zeeuw 1980). On the other hand, lignin is a major obstacle to overcome in the chemical pulp industry . Therefore, a lower or higher lignin content will be favorable depending on the industry in question (Araujo et al. 2015; Zobel and Buijtenen 1989). As well, lignin content is proportional to tracheid surface area, on average 25-35% in softwoods. Lignin content is less in hardwood species, on average 20%. Lignin content is influenced by growing factors, where stress and internal properties affect the proportion of lignin (McMullins and McKnight 1981; Panshin and de Zeeuw 1980).

2.6.0. INFLUENCING WOOD ATTRIBUTES

The challenge for the forestry industry is to manage Canada's forest in a way that the wood produced is of quality required to meet the appropriate end use. Trees produce wood to support the vertical growth of the crown either by transporting essentials between the roots and crown, or by supporting the structure of the crown (McMullins and McKnight 1981). This allows the tree to maintain vertical position over shorter competing vegetation to capture more sunlight. However, forest managers are concerned with what influences changes in the growth patterns of a tree that may result in altered wood properties. Therefore, it is important to understand what affects wood growth naturally before considering silvicultural treatments (Panshin and de Zeeuw 1980; Bowyer and Smith 2000).

2.6.1. GENETICS

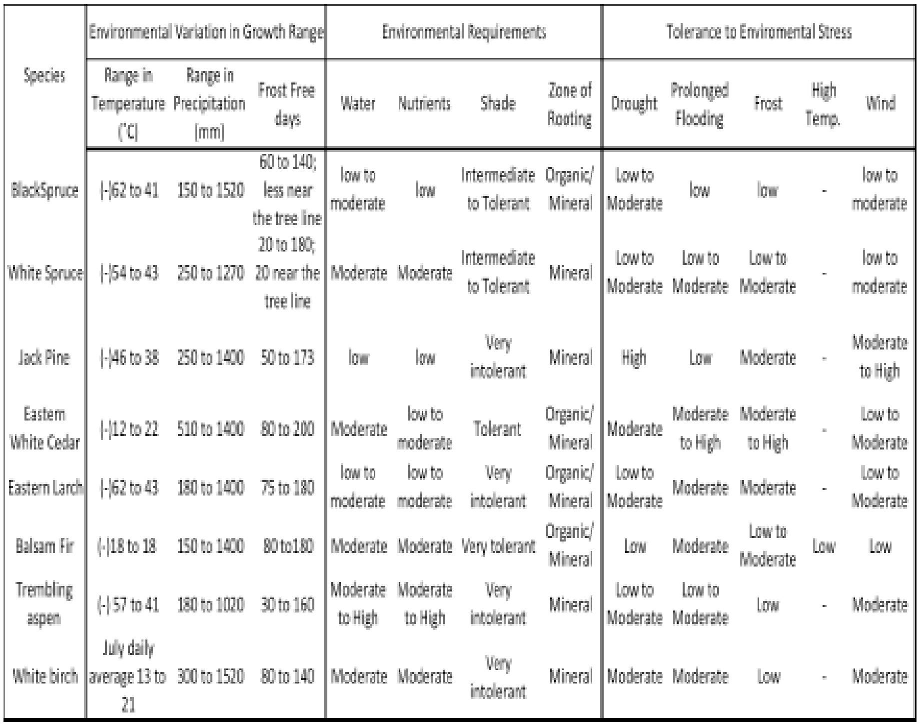
Genetics have a large influence on the relative success of an individual tree, because heredity has the greatest affect on a trees response to its surrounding environment, determining the growth pattern and form of the tree (Bowyer et al. 2007). Thus genetics can be divided into genotype and phenotype. Where genotype is the heredity of the individual seed bank, and the phenotype is the result of the offspring within the environment. However, the literature clearly indicates that genetics, not environment, has a greater affect on wood characteristics (Wangaard1981; Bowyer and Smith 2000; Eriksson and Ekberg 2001).

2.6.2. ENVIRONMENT/ SITE REGIME

Climate and site play an important role in tree growth, and many studies have reported correlations between quality attributes and climatic variables (Lessard et al. 2013). Environmental factors can be mitigated through silvicultural treatments such as delaying harvest or fertilization. However, these treatments are site specific, and may require a number of treatments to achieve the desired result (Burns and Honkala 1990; Miller 2010; Zhang and Koubaa 2008). Table 2 presents the vast differences in growth preferences between NWO tree species. However, we cannot assume that the wood characteristics for these species will be unchanged under different site regimes. Studies from Zhang and Koubaa (2008) have shown significant differences in wood quality between site locations, which may be attributed to climatic differences between sites. Thus, it is understood that wood attributes are influenced by both genetics and environmental factors (Burns and Honkala 1990; Eriksson and Ekberg 2001; Lessard et al. 2013).

The factor that influences site regime significantly are the edaphic conditions. Where the combination of nutrient availability, soil moisture, temperature, and porosity all influence the relative success of a species on the site (Kimmins 1987) . Many studies have found that wet sites may cause nutrient exchange problems, even may drown some species, as well as, increase the likelihood of heart rot. In other cases, better quality wood attributes can be found on upland or slope sites, where drainage is efficient (Bowyer et al. 2007; Zhang and Koubaa 2008). In addition, temperature also affects the available nutrients in the soil, where cold soil has a lower nutrient availability, and warmer soils promote decomposition processes, and the soil activity is increased (Bowyer et al. 2007; Kimmins 1987).

Table 2. Environmental variation, requirements, and stresses for the NWO tree species of interest (Burns and Honkala 1990; Miller 2010: Zhang and Koubaa 2008).



Species	Environmental Variation in Growth Range			Environmental Requirements				Tolerance to Enviromental Stress				
	Range in Temperature (˚C)	Range in Precipitation (mm)	Frost Free days	Water	Nutrients	Shade	Zone of Rooting	Drought	Prolonged Flooding	Frost	High Temp.	Wind
BlackSpruce	(-)62 to 41	150 to 1520	60 to 140; less near the tree line	low to moderate	low	Intermediate to Tolerant	Organic/ Mineral	Low to Moderate	low	low	-	low to moderate
White Spruce	(-)54 to 43	250 to 1270	20 to 180; 20 near the tree line	Moderate	Moderate	Intermediate to Tolerant	Mineral	Low to Moderate	Low to Moderate	Low to Moderate	-	low to moderate
Jack Pine	(-)46 to 38	250 to 1400	50 to 173	low	low	Very intolerant	Mineral	High	Low	Moderate	-	Moderate to High
Eastern White Cedar	(-)12 to 22	510 to 1400	80 to 200	Moderate	low to moderate	Tolerant	Organic/ Mineral	Moderate	Moderate to High	Moderate to High	-	Low to Moderate
Eastern Larch	(-)62 to 43	180 to 1400	75 to 180	low to moderate	low to moderate	Very intolerant	Organic/ Mineral	Low to Moderate	Moderate	Moderate	-	Low to Moderate
Balsam Fir	(-)18 to 18	150 to 1400	80 to180	Moderate	Moderate	Very tolerant	Organic/ Mineral	Low	Moderate	Low to Moderate	Low	Low
Trembling aspen	(-) 57 to 41	180 to 1020	30 to 160	Moderate to High	Moderate to High	Very intolerant	Mineral	Low to Moderate	Low to Moderate	Low	-	Moderate
White birch	July daily average 13 to 21	300 to 1520	80 to 140	Moderate	Moderate	Very intolerant	Mineral	Moderate	Moderate	Low	-	Moderate

2.7.0 ACOUSTIC VOLOCITY

Acoustic velocity is measured in meters per second squared $(m/s)^2$, which is conducted through Acoustic testing. This can be preformed through a non-destructive (insignificant to the trees health) or destructive testing method of predicting the mechanical and physical properties of wood (Miller et al. 2017; Ross 2015). However, acoustic instruments are relatively new in forestry, but they have proven to be an effective and accurate predictor of wood mechanical properties (Legg and Bradley 2016; Mochan et al. 2009). These instruments focus on stess-wave propagation, which moves through the log. Thus, stress-waves can be produced in two ways:

Comment [11]:

- Time-of-Flight (TOF) method, or
- the Resonance method (Hansen 2006).

The Time-of-Flight method measures the time taken for a sound wave to travel between two sensors. This method requires a physical impact to produce longitudinal vibrations across the wood. Typically, the testing is repeated through replications to ensure the accuracy of the acoustic reading (Miller et al. 2017; Mochan et al. 2009; Ross 2015). This measurement only gives an acoustic velocity for the last few radial positions; meaning that the calculated attributes will only reflect outer stem wood just under the bark (Legg and Bradley 2016). The Resonance method requires the tree to be felled, where a stress wave is projected through the wood, between cut ends. This method is more accurate since the sample set is greater (Hansen 2006). In addition, this method can give an average velocity for the bolt rather than just the outer stem wood (Legg and Bradley 2016).

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According to Mochan et al. (2009), standing timber has a strong relationship to the same stem felled in respect to acoustic velocity. This correlation suggests that acoustics can be used to predict wood properties without having to remove the tree. However, wood is an anisotropic material, where the properties are directionally dependent (Panshin and de Zeeuw 1980). This means that within a stem, there may be significant internal variation that can affect the acoustic velocity by dampening or accelerating it (Ross 2015; Wangaard 1981). There are studies that show a strong correlation between MOE and acoustic velocity (Legg and Bradley 2016; Leitch and Miller 2017). This suggests MOE can be predicted in a standing tree using the TOF method

(Ross 2015). However, this value would be representative of the last few radial positions (Legg and Bradley 2016).

Generally, moisture content has a significant impact on the velocities in wood. According to Gerhards (1982), velocity decreases by 1% when moisture content increases by 1%. Similarly, an increase in temperature by one degree Celsius causes a drop in the wave propagation speed. This is because water becomes denser as temperature decreases (Ross 2015). In addition, Hansen (2006) found that the propagation speed had a 4% difference between clear and knotty wood, which is attributed to the physical and mechanical properties of the knots. As well, knot whorls can affect the propagation speed, dependening on the angle at which the knot is produced to the vertical axis (Hansen 2006). As mentioned earlier, juvenile wood is less dense and has a higher microfibril angle (Figure 10). Thus, juvenile wood increases the propagation speed (Hansen 2006, Gerhards 1982). Reaction wood, however, effects the propagation speed directionally; longitudinal direction gives a lower velocity, and tangential direction gives a higher velocity in compression wood when compared to normal wood. This is a result of the physical and anatomical structure (Ross 2015). Finally, velocities are effected by decay and wood anomalies, which dampen the acoustic velocities by breaking the continuity of the wood (Hansen 2006; Ross 2015).

3.0 Methods and Materials

This study was completed in accordance with the American Society for Testing and Materials (ASTM) international standard for testing and the International Organization for Standardization (ISO). Density calculations followed the ASTM Standard Test Methods for

Density and Specific Gravity (Relative Density) of Wood and Wood-Based Materials Designation: D2395-14 (2017). Refer to the Appendix section to see the recorded data.

3.1 STUDY DESIGN

This study is part of a greater project with the Forestry Futures Trust operational demonstration project 'eFRI with Wood Metrics', lead by LUWSTF. Two permanent growth plots (PGP) off the Boreal road were utilized for this study, PGP 56-007 and PGP 56-013 (GPS coordinates 48.363704, -90.249356 and 48.395855; -90.089838, respectively), as seen in Figure 13 In these plots, the field crew recorded all the diameters of the previously marked trees using a DBH tape. As well, the heights were recorded using a vertex, acoustic values were recorded using a TreeSonic tester, and the crown coverage was recorded too. In addition, the lead species and co-dominant species were indicated. This data was used to select the replicate trees located within a 120-metre destructive buffer zone. This created a test sample plot (TSP), in order to conduct a destructive evaluation for comparison. Thus, the TSP is selected to be representative of the PGP.

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Each site consisted of five species: *Picea mariana*, *Picea glauca*, *Abies balsamea*, *Betula papyrifera*, and *Populus tremuloides*. For the dominant and codomiant species on each site, we selected a large, medium and small diameter class to understand the site productivity better. The selected trees were then subject to an acoustic test conducted 50 cm above ground with a 1-meter distance between probes on the north face. When the bottom probe is hit, it gives an acoustic value by sending a stress-wave to the receiving probe. Then tree cores were harvested using a 12-mm increment corer from each tree that received acoustic testing and placed in labelled tubes. This is done to gain age and green density values in the lab. Once the needed parameters were recorded, the tree was cut down to obtain the metre marked out from the acoustic test. The

Comment [14]:

remaining tree was left on site for natural decay, and the sample logs were transported to the mill site. The tree core samples were placed into a freezer to keep their conditions as close to the true green condition as possible.

3.2. STUDY AREA

Since this is part of a greater project, the study area was randomly chosen from the existing KTTD growth and yield tables to represent two different sites. PGP 56-007 represents a dominant hardwood, mixedwood stand, while PGP 56-013 represents a conifer dominant, mixwood stand. The two plots are found off the Marks lake Road and Boreal road, respectively. This is about 40 minutes Northwest of thunder bay, located in the Dog-River Matatwin Forest, as seen in Figure 13.

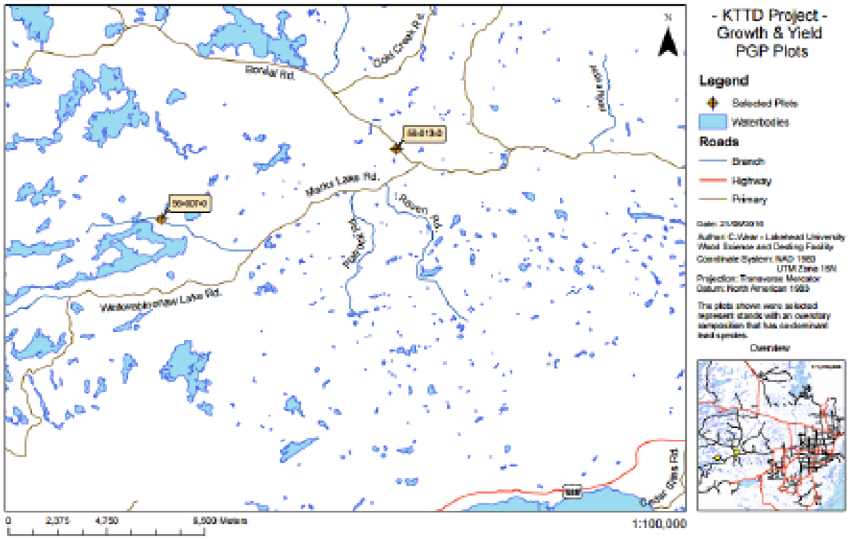

Figure 13. A map of the PGP plots 56-013 and 56-007 located off the Boreal road and Marks Road, respectively.

3.3. DESTRUCTIVE TESTING

The sample logs were then milled into boards using a Woodmizer LT-40H Portable Bandsaw Sawmill, with the first board retaining the cambium, and the last board retaining the pith. Each board was labelled, and the rest of the cant was thrown away. Each board was taken into the LUWSTF wood lab, and stacked for drying until the wood reached approximately 15% moisture content. From the milled boards, they were further refined into 30 cm in length x 2.5 cm width x 2.5 cm thick boards that were cut right after the butt-flare. Following this, a grid was produced on the end face (see figure 14), which mapped out 2 cm by 2 cm sticks with replicates on either side of the middle sample. The boards were cut into 3 test sticks and each stick was labelled to correspond with its orientation in the log (according to the grid markings). Then the sticks were placed into the conditioning chamber for 2 weeks at 20 degrees Celsius and 65 percent relative humidity to gain 12 percent MC.

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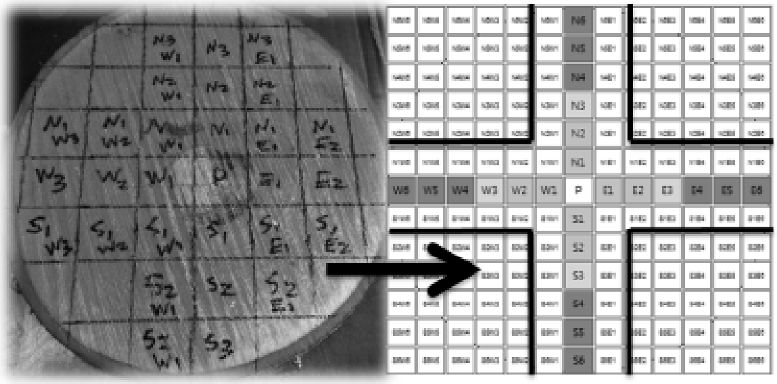

Figure 14. LUWSTF modified test procedure. (LUWSTF 2017)

The sticks, once at 12 percent MC, are ready for destructive testing and obtaining density cubes. MOE testing is restricted to the mature wood/outside wood (closest to the cambium) of each tree with a minimum of 4 test specimens. Before starting MOE testing, the thickness and width of the sample specimens are recorded with small calipers in centimetres. Then, they are placed on the Tinius Olsen H10KT universal wood testing machine to gain MOE and MOR values using the 3-point flexure tool following the ASTM standard 469/469M-14. Once the sample stick broke, it is taken off the machine, and values were produced and recorded by the Tinius Olsen Test Navigator Software. Where no deviations occur, a 1-inch density cube is marked and labelled from each test stick. After each sample set is tested, all the samples sticks have a density cube labelled and cut for testing. All the dimensions and significant values for each sample is recorded into the Wood Science App.

Figure. 15. The specimens after the MOE testing with density cubes marked.

3.4. LAB PROCESSING

After the sticks are refined into density cubes following MOE testing they are placed in a drying chamber. To obtain density values the water displacement method (Figure 16) was performed following ASTM standard- D2395-14, where the specific gravity of water is 1 in 4-

degree Celsius water. First the mass of the cube is recorded on a four-point scale, then the cube is dunked in a 500-ml beaker of water set on a balance giving a weight in grams, as seen in Figure 1. This is also the volume in cm^3. The mass is divided by the volume and multiplied by 1000, to gain the density value in Kg/m^3. This data was recorded in a Microsoft Excel spreadsheet. Once all cubes were recorded, they were placed in the oven at 70°C for 48 ours to reach oven-dry MC. Then the cubes were subject to the same process to gain the OD density with green volume, giving the specific gravity, or relative density. This value is used to compare to the literature to see how similar our results are to the standards.

Figure 16. An illustration of the water displacement method to obtain density. (LUWSTF 2017)

After the density testing, the tree cores were taken out of the freezer, and the length was recorded with a ruler in centimeters. Then the thickness and width was taken three times, then averaged, using the same calipers. This is used with the length to produce a volume using the cylinder formula for volume. Then the cores are cut flush with a micro razor at the pith, and then placed on a holder for easy handling. Each core's rings are counted for age, then separated into mature and juvenile wood, as illustrated in Figure 17. Juvenile wood was determined as the first rings from the pith out towards the bark, past this point is marked the mature wood zone. A yellow stain may be used if the growth rings are unclear. After, the cores were cut into mature and juvenile sections, retaining complete growth rings, the bark was cut off using the micro razor. Each section (juvenile and mature) was measured and recorded. All the significant parameters were inputted into the Wood Science App. This ring analysis further supported the effectiveness of the acoustic testing, by drawing conclusions between destructive testing and ring analysis.

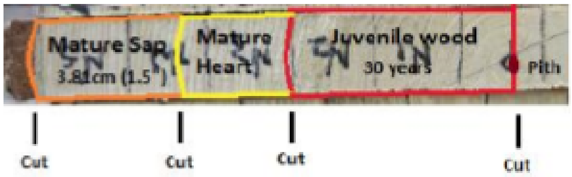

Figure 17. Cross sectional view of a sample strip with wood component breakdown. (LUWSTF 2017)

3.5. STATISTICAL DESIGN

The statistical analysis was run on "R" version 3.2.3 (Wooden Christmas-Tree), a free statistical computation software produced by The R Foundation for Statistical Computing. R is under the care of The Institute for Statistics and Mathematics Wirtschaftsunicersitat Wien, Vienna, Austria. Data was statistically analyzed in R at the 95% confidence limit ($\alpha = 0.05$). The sample sets were chosen to reflect one another to gain a representative comparison between sites. Thus, if a species was not present in both sites, it was not selected for testing e.g. *Pinus banksiana* occurred on site 56-007 but not on 56-013. This ensures that the experiment is balanced. In addition, a brass bar was used to calibrate the TreeSonic's accuracy, since the brass bar has a known acoustic velocity and is isotropic. This process can also be used to calibrate different acoustic tools as seen in Figure 18, and produce a correlation value that can be used as a correction factor to ensure the accuracy of the experiment. The R^2 value was 0.9504, as seen in Figure 19.

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Furthermore, the data sets were analyzed under assumptions testing. Data was tested for normality using Shapiro-Wilk, and homogeneity of variance using the Bartlett Test. An analysis of variance (ANOVA) test was used to define any interactions and significant data groups. As well, a Tukey post hoc multiple comparisons of means was computed to describe the data pool of the observed variance. Lastly, Pearson's product moment correlation was used to define the degree of linear correlation between two variables, which is used to correlate to the brass bar test.

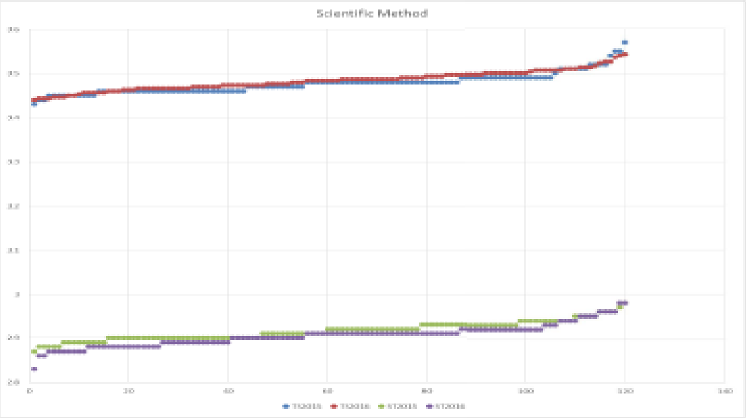

Figure 18. A comparison for accuracy of the 2016 LUWSTF ST-500 and TreeSonic brass-bar test to our results. (LUWST F 2017)

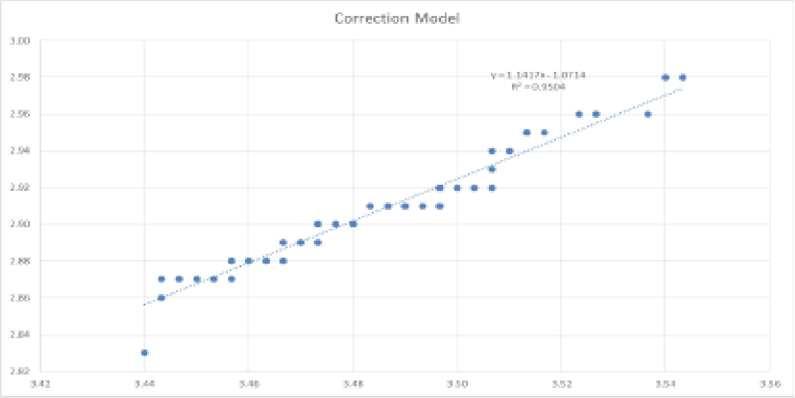

Figure 19. A correction model derived from the brass-bar test.

4.0 Results

The statistical results represent the interpreted outputs of the assumptions testing, analysis of variance (ANOVA), and Pearson's Product Moment Correlation Coefficient (PPMCC) at the 95% ($\alpha = 0.05$) probability.

4.1 ASSUMPTIONS TESTING

The data collected consisted of age, wood density, MOE, MOR and acoustic velocity, which was tested statistically under three assumptions for parametric data. The first, to observe data independence; next for data normality; and then for homogeneity of variance. Assumption one was satisfied by ensuring the sample procedure used for all procedures were the same. The second assumption was met through the Shapiro-Wilk test of normality; where all the variables were found to be normally distributed. Figure 20 illustrates the normal distribution of density (WD), which had a Shapiro-Wilk value (W) of 0.95329 and probability of outcome (p-value) of 0.4637. The third assumption was satisfied through the Bartlett test of homogeneity, where all variables were found to have homogeneity (Figure 21). Density$_{OD}$ had a Bartlett K-value of 0.23026 at one degree of freedom, and a p-value of 0.6313. The assumptions tested were all met, allowing for further statistical analysis.

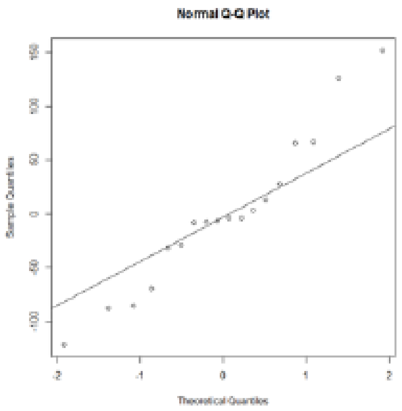

Figure 20. Shapiro-Wilk test of normality displaying normal distribution of density; where W = 0.95329 and p = 0.4637 (LUWSTF 2017).

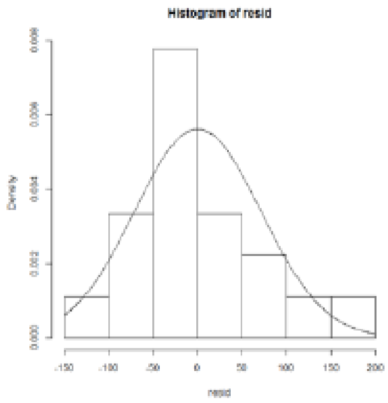

Figure 21. Bartlett test of homogeneity displaying the homogeneous distribution of density; where k = 0.23026 and p = 0.61313 (LUWSTF 2017).

4.2 WOOD DENSITY

The analysis of wood density (at oven dry), through the water displacement technique, showed the sites are not statistically different, however, between and within species variance occured. This was processed through an ANOVA test to display the ratio of variances, and any significant differences between wood density (WD, kg/m³) and the variables; where a p-value is derived from the F ratio found in the ANOVA. Thus, the analysis of variance between SITE and WD was insignificant ($F1,80 = 0.057$, $p < 0.05$), as shown in Figure 20; meaning the null hypothesis is accepted, that is there is no statistical difference between sites. However, the relationship between WD and species did have significant variance ($F1,80= 12.390$, $p < .05$), as seen in Figure 22.

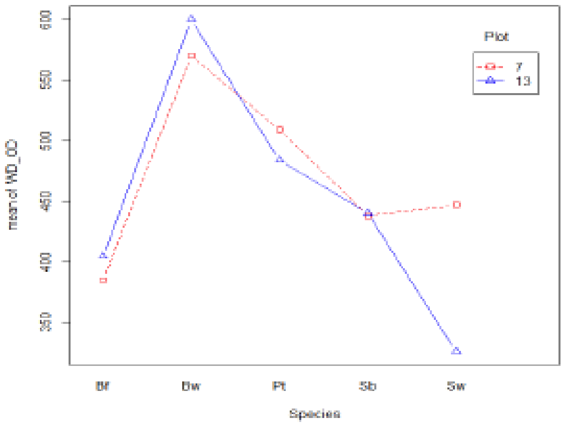

Figure 22. A graphical illustration of the mean WD_{OD} across sites.

A Tukey Multiple Comparisons of Mean Post Hoc test was used to describe where the significant differences are found, while using a 95% confidence limit. This showed that birch (Bw) is the only statistically different species relative to wood density; where the significant differences only existed between Bw:Bf and Sw:Bw, as shown in Table 3. Thus, the interactions between the remaining groups relative to wood density is insignificant.

Table 3. The significant interactions resulting from the Post-hoc test.

WD: Species Interactions		
Interactions	**Adjusted p- value**	**Significance**
Bw-Bf	0.0001303	Significant
Pt-Bf	0.0073035	No difference
Sb-Bf	0.3497799	No difference
Sw-Bf	0.9984877	No difference
Pt-Bw	0.0529442	No difference
Sw-Bw	0.0006249	Significant
Sb-Bw	0.0025316	No difference
Sb-Pt	0.2788967	No difference
Sw-Pt	0.0313375	No difference
Sw-Sb	0.4655889	No difference

4.2 MODULUS OF ELASTICITY

The assumptions testing for the modulus of elasticity (MOE_12 - MPa) resulted in a moderately strong Shapiro-Wilk test; where W=0.96496 and the p-value = 0.6994. As for the Bartlett test, MOE_12-MPa by Plot gave a K-value of 3.8779 at one degree of freedom and p = 0.04893. Thus, MOE follows similar trends as the other variables under the assumption testing.

The ANOVA test was used to determine if there were any significant differences between MOE and the other variables. This test resulted in no statistical difference between MOE and plot and diameter class. However, the species versus MOE was statistically different, as seen in Figure 23.

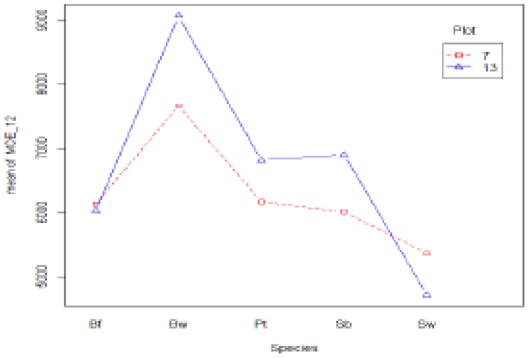

Figure 23. A graphical illustration of the mean MOE_12-MPa across sites.

4.3 MODULUS OF RUPTURE

The assumptions testing for the modulus of rupture (MOR_12 - MPa) resulted in a moderately strong Shapiro-Wilk test; where W= 0.95494 and the p-value = 0.5076. As for the Bartlett test, MOR by Plot gave a K-value of 6.3979 at one degree of freedom and p = 0.01143. Thus, MOR follows similar trends as the other variables under the assumption testing.

This test resulted in no statistical difference between MOR and plot (Figure 24) , as well as diameter class. However, the species versus MOR was statistically different. This can be observed by comparing the species in Figure 24.

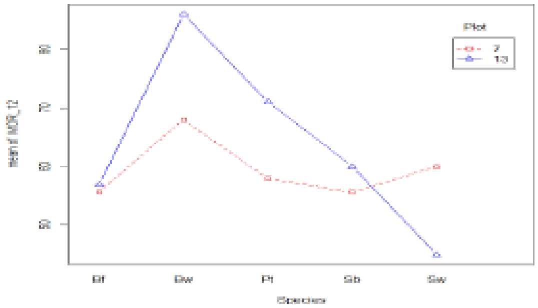

Figure 24. A graphical illustration of the mean MOR_12-MPa across sites.

4.4 WOOD DENSITY FSP

The analysis of wood density at the fibre saturation point (WD_{FSP}), through the water displacement technique, resulted in a weak normality correlation; where $W = 0.94418$ and $p = 0.341$. Whereas the WD_{FSP} had a Bartlett K-value of 0.33457 at one degree of freedom, and a p-value of 0.563.

An ANOVA test was used to display the ratio of variances, and any significant differences between the wood density (WD_{FSP}, kg/m^3) and the variables. The analysis of variance between SITE and WD_{FPS} was insignificant ($F_{(1,10)} = 1.116$, $p < 0.05$), meaning the null hypothesis is accepted, that is there is no statistical difference between sites. As well, the affect between diameter-class and site was also insignificant where $F_{(2,10)} = 0.136$, $p < 0.05$. However, the relationship between WD_{FPS} and species was significant ($F_{(4,10)} = 5.072$, $p > .05$), as seen in figure 25.

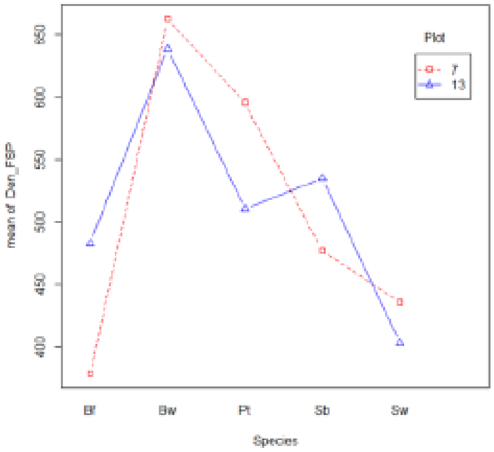

Figure 25. A graphical illustration of the mean density $_{(FSP)}$ for each species.

4.5 ACOUSTIC VELOCITY

Under the assumptions testing, the Acoustic velocity (AV-km/s) compared to the plot resulted in a strong W correlation; where W = 0.98732 and p-value = 0.9947. The Bartlettt test resulted in a K-value of 0.24756 at one degree of freedom, and a p-value of 0.6188.

An ANOVA test was run to test for differences between the average acoustic velocity (AV - km/s) and other main effects. This test showed the inverse result of the previous ANOVA tests, where the difference between $AV_{km/s}$ and species was insignificant ($F_{(4,10)} = 3.380$, $p < .05$), and the difference between $AV_{km/s}$ and site , or diameter-class, was significant at a 95% probability distribution; ($F_{(1,10)} = 7.818$, $p > .05$) and ($F_{(2,10)} = 9.310$, $p > .05$) respectively. Site had a P-value of 0.01892 and diameter-class had a P-value of 0.00521. Thus, Figure 26 is a graphical illustration of the significant difference between sites for the species.

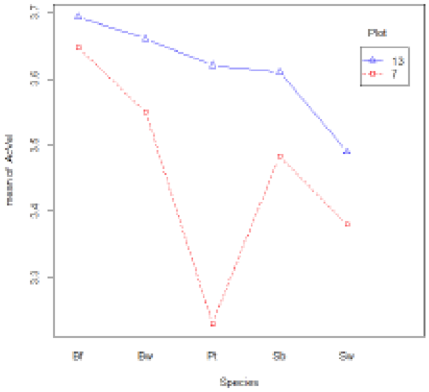

Figure 26. A graphical illustration of the mean acoustic velocity $_{(m/s)}{}^{2}$ for each species.

4.6 ACTUAL VERSUS PREDICTED MOE

An ANOVA test was performed to determine if there are any significant differences at a 95% confidence limit, using the Predicted versus Actual for both MOE_12-Kpa and wood density (kg/m^3). This test assisted in making a correlation model to correct any errors, as presented in Figure 27. Thus, the accuracy of the predicted results are increased when following the standard MOE corrective methods to condition the wood. This is important for valid comparison.

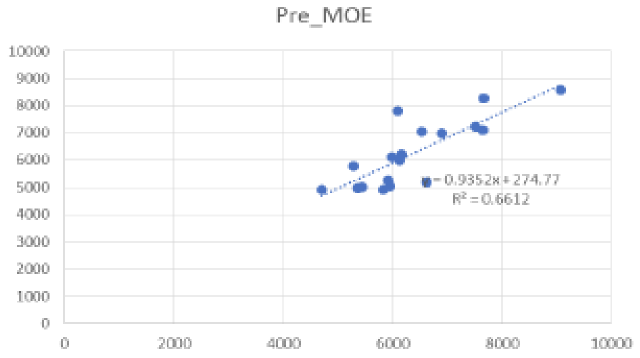

Figure 27. A graphical representation of the predicted MOE_12-KPa.

The predicted MOE_12-MPa is illustrated in Figure 27. This relationship had an R^2 value of 0.6612, which is a moderately strong correlation. Thus, the ANOVA test for the Actual versus Predicted MOE_12-MPa was statistically insignificant for each factor and a 99.9 % probability (Figure28B). Thus, the using the predicted MOE to assess the wood characteristics is feasible Figure 28 is an illustration of each variable, where the visible significance between the Predicted (blue) and Actual (red) results is a linear difference; either stating yes or no.

The ANOVA test for Actual versus Predicted wood density$_{FSP}$ showed insignificant differences for each of the factors. Figure 28A is an integration graph for the plot versus the mean wood density$_{Fsp}$; where the visible difference does not mean there is a statistical difference.

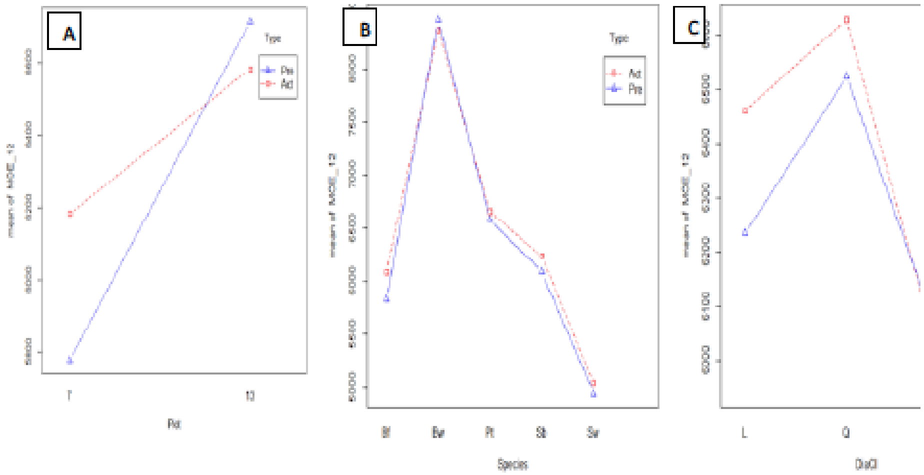

Figure 28. An illustration of the actual versus predicted MOE_12- KPa; where A. is plot, B. is Species and C. is diameter-class.

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4.6 CORRELATION TESTING

To determine the relationship of dependence between two variables a Pearson's Product Moment Correlation Coefficient (PPMCC) was calculated. The correlative values were classified in five classes from very low to very high using Theresa and Pelones' (2011) table of correlation coefficient interpretation.

A PPMCC test was preformed between MOE_12-MPa and wood density $_{FPS}$ using significance at a 95% confidence limit, where p= 3.182e-07. The correlation resulted in a moderately-strong coefficient, where the r^2 value was 0.7357.

4.7. INTRODUCTION OF WOOD STRATA

The data set was further divided into mature and juvenile wood, since there are known differences between mature and juvenile wood. Thus, the data was run through an ANOVA test to see any additional significance for MOE_12-MPa and wood density$_{FSP}$.

The ANOVA test for MOE_12-MPa show significant differences for each factor, where $p > 0.05$. Figure 29 is an illustration of the mean MOE for each site, which shows clear differences between sites. The ANOVA test for wood density$_{FSP}$, however, only resulted in significance for species and strata, whereas plot and diameter class were insignificant.

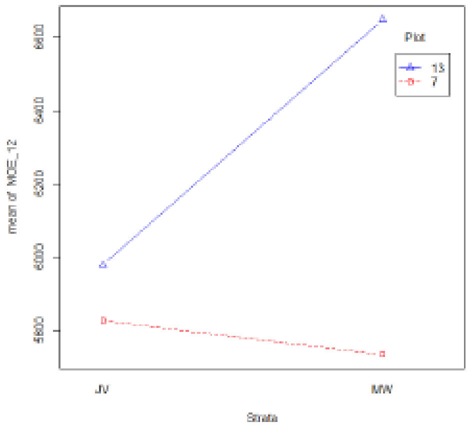

Figure 29. An illustration of the mean MOE_12-KPa versus the strata for plot 7 and 13.

A Tukey Multiple Comparisons of Mean Post Hoc test was used to describe where the significant differences were found, while using a 95% confidence limit (Table 4). This showed that only Sb- Bf have no difference. Thus, the interactions between the remaining groups have an adjusted p-value less than 0.05, confirming that wood density$_{FSP}$ for the species is statistically different, as presented in Table 4.

Table 4. The significant interactions resulting from the Post-hoc test.

WD: Species Interactions		
Interactions	Adjusted p- value	Significance
Bw-Bf	0.0000000	Significant
Pt-Bf	0.0000000	Significant
Sb-Bf	0.0005717	Significant
Sw-Bf	0.7743172	No difference
Pt-Bw	0.0000004	Significant
Sw-Bw	0.0000000	Significant
Sb-Bw	0.0000000	Significant
Sb-Pt	0.0179177	Significant
Sw-Pt	0.0000000	Significant
Sw-Sb	0.0002482	Significant

5.0 Discussion

There are two distinctions within the specimen pool shown in the results:

- Hardwood and softwood; and
- Mature and juvenile wood.

Within these groups, the statistical differences between the examined factors shows that the two sites are different from one another. However, operational decisions are not based upon statistical significance but rather biological significance; where biological significance reflects human judgement, and may appear contradictory to the statistical results (Binkley 1998). In the wood products sector the best example of this is lumber machine stress grades, where a range of values makes-up significance even though there is statistical variance within the range of a machine grade (Barrett and Lau 1994). This is relevant, because there are known differences between properties relative to mature and juvenile wood (Barrett and Lau 1994; Kretchmen 1998), which may be disregarded because of the linear modeling systems used in forest management (Armstrong 1999). This system creates averages, which Binkley (1998) suggests does not exist in nature. This means that the true potential of standing timber is underestimated.

Thus, the design of this experiment misrepresents site difference, because only two sites are chosen, which limits the statistical analysis to merely indicating there was a difference.

As seen in the results there are slight differences between site 7 (softwood dominant) and site 13 (hardwood dominant); where the average age was 47 years old. However, there was a variance in age between sites within species. For example, the average age of black spruce on site 7 was 67 years old while black spruce on site 13 was 49 years old, refer to Table 5 in the Appendix. The range of age difference between sites within species had a minimum range of 18 years for black spruce, and a maximum range of 35 years difference between trembling aspen grown on site 7 and 13. The average age difference of was 24 years. Thus, age is one factor accounting for the difference in properties. Wangraad (1981) agrees that age is attributed to observed differences. However, the wood density and MOE/MOR did not show the sites to be statistically different. This may be attributed to the fact that these are microsites within the same region. A study from Burns and Honkala (1990) found that most observed differences are due to the individual stem within the same provenance; where Kimmins (1987) highlights that topography and historical events are the major differences typically observed between the two sites. Bowyer et al. (2007) and Panshin and de Zeeuw (1980) supports this notion, where they found slope and drainage have a significant affect on the physical and mechanical properties of wood. Therefore, the difference between the sites are a factor of growth rate.

Panshin and de Zeeuw (1980) highlights there are significant differences between diameter-class and wood strata, which Kretchmen (1998) supports by highlighting the differences between the mature and juvenile zone (Figure 10), although diameter class proved to be insignificant for most variables. Thus, the relative proximity of the two sites may cause the statistical difference to be insignificant. This has been shown by Zhang and Koubaa (2008) where they found very little significance between sites of similar elevation for many eastern softwoods, such as white spruce. However, differing elevations have differing growing rates in relation to the site factors and environment. Thus, Kudela and Lagana (2010) agrees that latitude influenced the physical and mechanical properties of wood; where in the studies, there were observed density differences in Norway spruce and Scot pine throughout the Scandinavian provinces. Therefore, latitude (elevation) has a direct affect upon growth rate and wood characteristics.

The only result that showed the sites to be statistical difference was acoustic velocity. This is attributed to the fact that time of flight acoustic measurement gives a representation of the cambial region subject to the acoustic evaluation, as Legg and Bradley (2016) mentioned; this will only reflect outer stem wood just under the bark. This means that there is simply a difference, but not to the degree of severity, which is a common concept missed by forest managers (Armstrong 1999; Binkley 1998). Thus, we know there is distinctions between the species, however the data set needs further analyzing to understand the severity of the differences. This is done by using predicted results calculated from wet properties into dry following standard calculations (Leitch and Miller 2017); which Wangaard (1981) notes that age, green density and acoustic velocity is needed to calculate MOE. Thus, LUWSTF developed a methodology to predict MOE; where the wood moisture must be above FSP (30%) and wood temperature between 10 and 20 degree Celsius. Therefore, we must extract ring core samples and preserve them to create an accurate predicted MOE at 12% MC to use for further analysing.

5.2 SIGNIFANCE OF WOOD DENSITY

Wood density (WD) is an important indicator of wood strength used to assess wood quality (USDA 2010). Thus, WD differences can result in significant value change, where the timber may gain or lose value accordingly to its mechanical properties. Zhang and Koubaa (2008) found that white spruce from the east coast is ideal for high-grade structural lumber although the density is lower compare to Alaskan grown spruce, which had a very high density; making it stiff with low shear strength, rendering the Alaskan spruce lower grade material. The average WD of each tree species within this study does correspond with published values, where deviations may have occurred because of age. For example, Jessome (2000) presents WD for white spruce as 372 kg/m3 and in this study, it was found to be 387 kg/m3. Similar trends were found for all species in the study. In addition, it has also been shown in the literature that age has a significant effect on WD (Panshin and de Zeeuw 1980; Bowyer et al. 2007; Zhang and Koubaa 2008; USDA 2010). Therefore, growth rate must be considered when evaluating density, because growth rate influences internal mechanisms of wood (Panshin and de Zeeuw 1980; Wangaard 1981; Zobel and Buijtenen 1989).

The results showed slight differences in wood density between site 7 and site 13, which can be seen in Figure 22. According to Bowyer et al. (2007) this difference in WD can be attributed to site factors, such as slope and drainage, or age difference. However, there is no statistical difference between wood density and site. The only distinction observed that account for this variability is that there are two distinctive species groups: hardwood and softwood. Therefore, in microsites another indicator, such as acoustic velocity, should be used to assess differences within standing trees (Mackenzie et al 2011).

5.3.0 INDUSTRY SIGNIFICANCE

There is a direct correlation between acoustic velocity (AcVel) and WD, which Ross (2015) found that AcVel will change accordingly to the wood density. In a study by Ross (2015) it was found that changes in AcVel and WD relative to changes in moisture content in wood above FSP were highly correlated in wood. Mochan et al. (2009) found that acoustic velocity will change accordingly to density relative to the moisture content in wood. This enables predictive assumption testing, which the model proved to have a moderate-strong correlation to the actual MOE. This means density can be used along with AcVel to predict MOE in wood above FSP (Bucur 2006; Mochan et al. 2009; Ross 2015). Since density is used as an indicator for strength and mechanical properties, acoustic velocity provides valid feedback to be analyzed. Therefore, acoustic testing can be a useful non-destructive technique to analyze a standing tree (Bucur 2006; Ross 2015). However, it is important to correct wood density from oven dry to FSP in order to use acoustic velocity to predict MOE from density above FSP (Leitch and Miller 2017).

Understanding the interrelationships between wood characteristics is important, because changes in wood growth can significantly affect the wood quality (Panshin and de Zeeuw 1980; Zobel and Buijtenen 1989; Zhang and Koubaa 2008). From an industry viewpoint, any change that results in a lower rate of return is undesirable. Kretchemen (1998) found that mechanical properties change as a result of age, where there exist distinct differences between mature and juvenile wood, as seen when the data was separated into strata. The literature supports this notion; however, site factors contribute greatly to observed mechanical property differences within species (McMullins and McKnight 1981; Burns and Honkala 1990; Eriksson and Ekberg 2001; Bowyer et al. 2007; Zhang and Koubaa 2008; Lessard et al. 2013). Findings from the Forest Products Laboratory (1999) reports that the magnitude of variance within the selected wood properties are:

- MOR up to16% variance,
- MOE up to 22% variance,

- compression parallel to grain up to 18% variance,
- hardness up to 20% variance, and
- relative densityOD up to 10% variance.

Thus, published values for mechanical properties of Canadian wood species are an average, as Jessome (2000) mentioned. In regard to Ontario, there has not been many case studies used to produce these values, more specifically Northwestern Ontario. Miller (2010) notes that wood from Ontario has superior wood qualities. Thus, the value of our timber resources may be underestimated.

The significance of this thesis is the correlation of acoustic velocity to wood density and MOE. Both these factors are important for determining the quality by giving a grade for in-service use. Machine-stress-rated (MSR) grading uses non-destructive mechanical testing equipment, which measures and sorts the stiffness of the lumber into various MOE grades (USDA 2010; Ross 2015). However, visual grading oversees the MSR grading for any missed defects (NLGA 2003). According to Stiemer (2010) MSR grading eliminates tree species in regards to material selection by engineers. This means MSR grades are versatile, utilizing multiple tree species from several different sources. Thus, MSR grading presents Northwestern Ontario an opportunity to better market the high-density underutilized species from the Boreal Forest (Miller 2010). This will allow for higher quality products that will utilize our resources efficiently (Stiemer 2010).

In relation to acoustic testing, this application is feasible for product allocation and control. The value does not change for raw material in the Boreal Forest having conducted Acoustic testing. This is because the end-use is either for pulp or saw logs (Miller 2010; Leitch and Miller 2017). Thus, the expenses paid to the surveyor will not gain profit for the industry.

Although the ability to map the resource to understand where the cream of the crop is and where the milk is, will be very valuable to industry to remain competitive and meet market demand more efficiently and quickly. However, MSR grading allows for optimal utilization of timber resources to create appropriate MOE grades once the sawlogs get to a sawmill (Stiemer 2010). This means that the lower valued stems can be turned into value-added products for greater profit margins. Ross (2015) indicates that acoustic testing is feasible for value added products, where acoustic waves can help determine the interior quality of value added products such as laminated strand lumber (LSL). Void space and resin pockets can be detected, but it is size dependent, which inevitably effects the MOE and MOR (Mochan et al. 2009, Hansen 2006; Ross 2015). Thus, acoustic testing can be used for quality control and grading standards as well as for resource mapping as has been shown by Leitch and Miller (2017).

6.0 Conclusion

In conclusion, the Null hypothesis is accepted; there is no difference between sites for density, and MOE/MOR. This is because the design of the experiment is based upon averages, meaning that there is no average differences noticed between sites. However, the Acoustic values do show that the sites are statistically different. The underlying assumption of this thesis is that this is a linear relationship, where the assumption will be valid or invalid. Thus, the experimental design is not representative to show the degree of the differences, but rather if there is a difference. From the literature, we know that there are distinctive differences between species and within species. In order to interpret the significance between sites and species, the data was stratified to represent distinctive differences. From these results, there are two distinctive categories:

- hardwood and softwood; and
- juvenile and mature wood.

The feasibility of acoustic testing proves to provide valid information for the forestry industry. For field testing, this application is great for timber allocation with the known correlations to density and MOE. Gathered acoustic values can be used to estimate the average $\text{Density}_{\text{FSP}}$ and MOE of a standing tree, but there will be variance throughout the stem. However, small diameter-class species of the Boreal are not as valuable as large diameter-class species of south-eastern Ontario; where shade-tolerant hardwoods typically serve a special purpose. Thus, the feasibility within the Boreal Forest is limited to wood characteristic mapping, which is important for enhancing our eFRI systems, and improving our future timber resources. Therefore, the application of acoustic testing in the Boreal region serves a better purpose for quality control and grading, especially for value-added products. Additionally, for the above mentioned landscape mapping to determine the quality of species, meaning lumber grades, across the landscape.

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8.0 Appendix

Table 5. The recorded and calculated results.

Plot	Tree	Sample	Species	Age	DB	Ht	WD_OD	MOR_12	MOE_12	Pre_MOE	MOE FSP	Density FSP	AcVel
7	9	N1	Bf	35	21.3	13.3	440	58	6613	6518	5307	489	
7	9	N2	Bf	35	21.3	13.3	404	61	7097	5951	5695	450	
7	9	N3	Bf	35	21.3	13.3	330	46	5040	4923	4044	367	3.55
7	3	N1	Bw	30	13.5	12.0	535	63	6855	8035	5501	594	
7	3	N2	Bw	30	13.5	12.0	570	68	7670	8262	6156	633	3.60
7	5	N4	Pt	76	34.8	23.4	508	64	8267	7605	6635	564	
7	5	N5	Pt	76	34.8	23.4	509	58	6166	6218	4948	566	3.55
7	1	N1	Sb	67	21.5	15.8	488	61	5832	7292	4680	543	
7	1	N2	Sb	67	21.5	15.8	457	63	5172	5246	4150	508	3.79
7	10	N2	Sw	55	17.4	15.0	344	49	5079	4984	4076	383	
7	10	N3	Sw	55	17.4	15.0	447	60	5361	4967	4302	497	3.78
13	2	N3	Bf	62	25.9	18.4	368	54	5865	5366	4706	409	
13	2	N4	Bf	62	25.9	18.4	378	58	5438	5001	4364	420	3.58
13	7	N1	Bw	49	17.1	16.0	583	79	9076	8809	7283	652	
13	7	N2	Bw	49	17.1	16.0	600	86	10374	8581	8325	671	3.66
13	5	N3	Pt	41	26.1	20.8	507	78	9383	7592	7530	567	
13	5	N4	Pt	41	26.1	20.8	515	75	9392	7212	7537	576	3.55
13	3	N0	Sb	49	12.3	15.9	412	55	6018	6066	4829	458	
13	3	N1	Sb	49	12.3	15.9	440	60	6901	6978	5538	489	3.61
13	8	N1	Sw	34	18.5	11.6	319	41	4708	4583	3778	357	
13	8	N2	Sw	34	18.5	11.6	326	45	4444	4914	3566	365	3.79