ACOUSTIC PROPERTIES OF FOUR CENTRAL BOREAL TREE SPECIES FOR POTENTIAL USE IN INSTRUMENTS

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THUNDER BAY, ONTARIO

April 2023

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An Undergraduate Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Honours Bachelor of Science in Forestry

Faculty of Natural Resources Management

Lakehead University

April 2023

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ABSTRACT

In resonance wood, acoustic velocity, density profiles, and ring characteristics play an important role. Multiple factors cause variation of these properties, like the difference between juvenile wood and mature wood, reaction wood, and disease. In this study, the acoustic velocity, density profile, and ring characteristics of four boreal species (black spruce, balsam fir, white birch, and trembling aspen) were tested and compared to the published values for resonance wood. There were significant differences ($\alpha < 0.01$) of acoustic velocity and density between species, and radial positions. Black spruce had the highest acoustic velocity at 6275 m/s and white birch had the highest density at 632 kg/m^3. When compared to the literature, the softwood species were within the range of values used in resonance wood, while the hardwood species were not. In conclusion, it is possible to use acoustic velocity, density profiles and ring characteristics to identify species to be used as resonance wood.

CONTENTS

FIGURES

TABLES

ACKNOWLEDGEMENTS

I would like to thank Dr. Mathew Leitch, my thesis supervisor, for guidance, feedback, and advice. I would also like to thank my second reader, Robert Glover. Additionally, I would like to thank Scott Miller, who helped with my statistical analysis, and guidance in characteristics to test. Finally, I would like to thank those who help in data collection: Clayton Temple and Eric Levesque.

1.0 INTRODUCTION

Wood plays an important role in the design and construction of many musical instruments. The properties of the wood can impact not only the acoustic response of the instrument, but its mechanical resistance, physical stability, visual aesthetics, and tactile properties (Brémaud 2012). In string instruments, the most important piece of wood is the soundboard. The sound of a single plucked, or bowed string is barely audible because it only moves a small volume of air. The soundboard transmits, amplifies, and radiates the vibrations of the string to produce a louder sound (Wegst 2006; Brémaud 2012). In complex string instruments, like the violin, the strings are attached to the soundboard via the bridge. The bridge transmits the vibrations of the string to the soundboard, which is connected to the backplate by the sound post and the ribs. The backplate is meant to contribute to radiating the sound (Wegst 2006). Different woods are used for different parts of the instruments. In western culture, resonance spruce (typically *Picea abies*) is used for the soundboard of a violin, while curly maple (typically *Acer pseudoplatanus*) is used for the backplate, ribs, and neck (Bucur 2006; Brémaud 2012). For guitar soundboards, resonance spruce is used but so are western hemlock (*Tsuga heterophylla*) and western redcedar (*Thuja plicata*) because the requirements are not as strict as for the violin (Delune 1977; Brémaud 2012). These species and others termed resonance wood are preferred for their regular anatomical structure and high acoustic properties (Bucur 2006).

1.1 OBJECTIVES

This study aims to identify the longitudinal acoustic velocities and densities of balsam fir (*Abies balsamea* (L.) Mill.), black spruce (*Picea mariana* (Mill.) B.S.P), white birch (*Betula papyrifera* Marsh.), and trembling aspen (*Populus tremuloides* Michx.) on a well-drained boreal mixedwood site. This study also aims to determine if these species could be considered for resonance wood in instrument making.

First, it is hypothesised that there is no significant difference in acoustic velocities and densities between species, axial positions, and radial positions. Also, it is hypothesised that boreal hardwood species in Northwestern Ontario (white birch and trembling aspen) will not display acoustic velocities and densities like curly maple making them suitable for resonance wood. The null hypothesis is that there is no significant difference between the acoustic velocity and density of white birch and trembling aspen and the acoustic velocity and density of hardwood species used in instruments. Finally, boreal softwood species in Northwestern Ontario (balsam fir and black spruce) will not display acoustic velocities and densities like resonance spruce making them suitable for resonance wood. The null hypothesis is that there is no significant difference between the acoustic velocity and density of black spruce and balsam fir and the acoustic velocity and density of softwood species used in instruments.

2.0 LITERATURE REVIEW

2.1 TREE SPECIES

2.1.1 European Spruce

European spruce (*Picea abies* (L.) Karst.), also known as Norway spruce, is the most prominent species in the Boreal forests of Northern and Eastern Europe and subalpine conifer forests of Central Europe (Caudullo et al. 2016). It has high climate tolerance and can even grow in extreme oceanic climates. Although it grows on most substrates, it is most common on deep acidic soils with enough moisture. It does not tolerate summer drought or waterlogged conditions well. European spruce is capable of being a pioneer and a climax species. As a shade tolerant species, it can survive for decades under a closed canopy waiting for an opening (Caudullo et al. 2016).

European spruce is considered a medium- to large-sized tree, ranging from 35 to 55 metres tall and 100 to 150 cm in diameter (Meier 2021a). It has an average specific gravity of around 0.41 and is typically used for dimensional lumber, pulp, Christmas trees, and musical instrument soundboards (Meier 2021a).

2.1.2 Balsam Fir

Balsam fir (*Abies balsamea* (L.) Mill.) can be found in the Canadian boreal forest from Newfoundland and Labrador west through Quebec and Ontario, and in scattered stands in north-central Manitoba and Saskatchewan to the Peace River Valley in northwestern Alberta (Frank 1990). In the United States, it is found in northern Minnesota eastward to the New England States. This area is mostly characterized by cool temperatures and abundant moisture. Optimal growth occurs in areas with a mean annual temperature of 2° to 4° C, and a mean annual precipitation ranging from 760 to

1100 mm. Balsam fir grows on many types of inorganic and organic soils originating from glaciation. They are characterized by a thick organic layer and a well-defined A_2 horizon. It grows best on wet-mesic sites where the pH of the upper organic layer is between 6.5 and 7.0. Balsam fir is a late-successional species with a strong ability to establish and grow under larger trees. Intraspecific competition becomes very important in sapling and small pole-sized stands of pure balsam fir (Frank 1990).

Balsam fir are considered a small- to medium-sized tree, ranging from 12 to 18 metres tall and 30 to 60 cm in diameter (Lindenbach-Gibson et al. 2006; Meier 2021b). It has an average specific gravity of around 0.36, lacks resin canals, and lacks ray tracheids (Hoadley 1990). It is typically used for dimensional lumber, pulp, and cooperage (Lindenbach-Gibson et al. 2006).

2.1.3 Black Spruce

Black spruce (*Picea mariana* (Mill.) B.S.P) ranges from northern Massachusetts to northern Labrador on the Atlantic coast west through Canada to the Pacific coast of Alaska (Viereck and Johnston 1990). Its southern limit ranges from northern New Jersey to Southern Minnesota, across south-central Saskatchewan and central British Colombia. The climate across this large area is cold with a moisture regime varying from humid to dry-subhumid. The mean annual temperatures range from 7° C (45° F) in the southern areas to -11° C (13° F) near the tree line. Mean annual precipitation also varies significantly across the range. It may be a high as 1520 mm in the Maritimes and as low as 150 mm in western Alaska. Black spruce usually grows on wet organic soils but is capable of remaining productive on a variety of soil types from deep humus to clays, sands, coarse till and shallow soils over bedrock. Black spruce can act as a pioneer and mid-to-late successional species. It is tolerant of shade but not as tolerant as balsam fir or eastern white cedar. It can grow in as little as 10 percent light availability but is much better in the open (Viereck and Johnston 1990).

Black spruce is considered a small-sized tree, ranging from 9 to 15 metres tall and 25 to 50 cm in diameter (Lindenbach-Gibson et al. 2006; Meier 2021c). It has an average specific gravity of around 0.40, small resin canals, and ray tracheids. It is typically used for dimensional lumber, and pulp (Lindenbach-Gibson et al. 2006).

2.1.4 Curly Maple

Curly maple is not a distinct species but a grain pattern that can be found in nearly all *Acer* species (Meier 2021d). A commonly used species that displays this grain pattern in Europe is the sycamore maple (*Acer pseudoplatanus* L.; Bucur 2006). It occurs in central and eastern Europe and the mountain systems of southern Europe (Pasta et al. 2016). It is unable to thrive in regions that are prone to drought and typically occurs on nutrient-rich soils in shady microsites like the bases of slopes and ravines. Sycamore maple rarely forms an entire forest, but it can dominate cooler and more humid environments.

Sycamore maple is considered a large-sized tree, ranging from 25 to 35 metres tall and 100 to 120 cm in diameter (Meier 2021d). It has an average specific gravity of around 0.62 and is typically used for veneer, pulp, crating, pallets, and instrument making (Meier 2021d).

2.1.5 White Birch

White birch (*Betula papyrifera* Marsh.), also called paper birch, has a range that follows to northern tree limit from Newfoundland and Labrador across the continent into northwest Alaska (Safford et al. 1990). Its southern limits are in Washington east into northern Idaho, the Great Plains of Canada, Montana, Nebraska, and the Front Range of Colorado, east in Minnesota, through the Great Lakes region and into New England. White birch is adapted to cold climates. It is found on the cooler north and east aspects and aspen are on the warmer north and west aspects of slope. It tolerates a large variety of precipitation amounts. In Alaska, mean annual precipitation is only about 300 mm while in eastern Canada averages around 1520 mm of precipitation annually. White birch can grow on almost any soil type, from steep rocky outcrops to flat muskegs. However, it grows best on deeper well-drained to moderately well-drained soils. Since it is shade intolerant, white birch is an early succession species (Safford et al. 1990).

White birch is considered a medium-sized tree, ranging from 20 to 30 metres tall and capable of reaching 60 to 100 cm in diameter (Lindenbach-Gibson et al. 2006; Meier 2021e). It has an average specific gravity of around 0.55, small to medium pores, and one- to five-seriate rays (Hoadley 1990). It is typically used for hardwood lumber, flooring, pallets, crating and millwork (Lindenbach-Gibson et al. 2006).

2.1.6 Trembling aspen

Trembling aspen (*Populus tremuloides* Michx.) grows as a single and in multi-stemmed clones across an extensive range in North America. It grows from Newfoundland and Labrador west across Canada along the northern tree limit to northwestern Alaska (Perala 1990). Through the Western United States, it is mostly found in the mountains from Washington to California and from Iowa and eastern Missouri, it ranges east to West Virginia, Pennsylvania, and New Jersey. It is also found in the mountains of Mexico. Climatic conditions vary greatly over the range of the species. It occurs where annual precipitation exceeds evapotranspiration. Trembling aspen grows on a variety of soils, from shallow and rocky to deep loamy sands and clays. The best growth is found on well-drained, loamy, and high-nutrient soils. This species is very intolerant of shade and is a very aggressive pioneer species (Perala 1990).

Trembling aspen is considered a medium-sized tree, ranging from 20 to 30 metres tall and 60 to 100 cm in diameter (Lindenbach-Gibson et al. 2006; Meier 2021f). It has an average specific gravity of around 0.38, small to very small pores, and uniseriate, homocellular rays (Hoadley 1990). It is typically used for oriented strand boards, oriented strand lumber, laminated veneer lumber, and pulp (Lindenbach-Gibson et al. 2006).

2.2 WOOD PROPERTIES

2.2.1 Physical Properties

Measuring the macroscopic and microscopic characteristics of resonance wood is important as they have a great influence on its acoustic properties (Bucur 2006). Macroscopic features to consider include the width and regularity of growth rings, the proportion of latewood, and the density patterns within growth rings. Microscopic features to consider include tracheid length, ray distribution patterns, microfibril angle and index of crystallinity.

As stated in Hutchins (1978), regularity between and within growth rings is very important for good acoustical properties. The frequency of annual ring width plays a major role in determining the use of the wood; the tight distributions of small rings in resonance spruce are used in guitars and violins while the large distributions of a variety of ring sizes are used as structural lumber (Holz 1984). The average ring width and the proportion of latewood also influence wood quality (Holz 1984). As seen in Table 1, the proportion of latewood found in soundboards for violins, guitars and piano hardly surpasses 25%. Ring width also significantly affects acoustic colour and tonal sound (Branstatter 2016). Narrow rings create a hard, demure sound, while rough and broad rings create a flannel and hollow sound. Finally, both ring width, and to a greater importance, latewood proportion contribute to the density of the wood, in turn influencing the velocity of the wood (Figure 1; Bucur 2006).

Table 1. Physical and mechanical characteristics of different quality Norway spruce (Holz 1984).

Wood quality for	Density (kg/m^3)	Annual ring parameters Width (mm)	Latewood (%)	V_{RR} (m/s)	E_R (10^8 N/m^2)	Tan δ (10^{-2})
Guitar	413	1.08	21	1,190	5.9	1.8
Violin	528	1.46	26	1,380	10.0	1.8
Piano	463	1.64	25	1,110	5.7	1.6
Other stringed instruments	456	2.65	41	510	12.0	2.8
Boat building	378	4.25	13	730	1.9	2.2

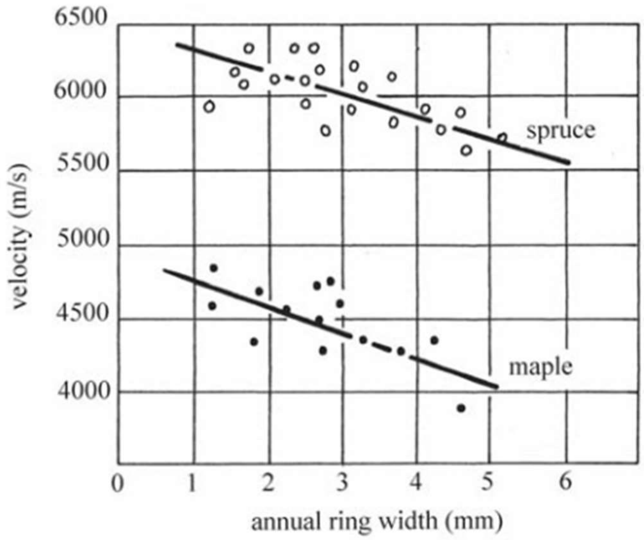


Figure 1. Ultrasonic velocity and annual ring width in resonance wood (Bucur 1984).

The density of a substance is known as the ratio of its mass to its volume and is expressed in kilograms per cubic meter (kg m^{-3}; Glass and Zelinka 2021). Specific gravity is the ratio of the density of a substance to the density of water (1000 kg m^{-3}). For reference, a material with a density of 400 kg m^{-3} has a specific gravity of 0.400. In wood, mass and volume depend on moisture content (Glass and Zelinka 2021). The density of oven dried wood can vary from tree to tree and species to species. Most species fall between 320 and 720 kg m^{-3}, but it can range from 160 kg m^{-3} for balsa to more than 1040 kg m^{-3} for some tropical species. To make comparisons between species, a standard basis is required. As shown in Table 2, specific gravity (G) can reference to its volume at any moisture content, but the mass must be oven dried. In the case of density (ρ), the volume can be oven dry, green, or at a set moisture content (MC).

Table 2. Expressions for specific gravity and density of wood (Glass and Zelinka 2021).

Symbol	Mass basis	Volume basis
G_0	Ovendry	Ovendry
G_b (basic specific gravity)	Ovendry	Green
G_{12}	Ovendry	12% MC
G_x	Ovendry	x% MC
ρ_0	Ovendry	Ovendry
ρ_{12}	12% MC	12% MC
ρ_x	x% MC	x% MC

[a] x is any chosen moisture content.

Many factors influence specific gravity, mainly by their effect on growth patterns (Zobel and Van Buijtenen 1989). These factors include site quality, fertilization, stocking, growth rate, and provenance, but the most important is growth rate. For example, in overly ideal growing conditions, trees have a tendency to form thinner-walled cells (Schmidt and Smith 1961). Measurements of specific gravity can be greatly inflated due to unusual deposits of extractives, like resins in the heartwood of some conifers, and around knots or near wounds caused by insect, frost, or ring shake damage.

As shown in Table 3, there are very specific microscopic qualities needed for resonance wood (Bucur 1980). These anatomical qualities play an important role in resonance wood. For example, rays induce anisotropy, meaning that the material exhibits properties of different values when measured at different angles (Schleske 1990). Even the mineral constituents of the cell walls, measured in an index of crystallinity, have an impact on wood properties (Bucur 2006).

Table 3. Anatomical description of resonance wood (Bucur 1980).

Anatomic elements	Species
Tracheids	*Spruce*: 20–40 µm in diameter in radial plane in earlywood and smaller in latewood. Small, bordered pits in one row on the radial walls. Pits leading to ray parenchyma piceoid, small, quite uniform in size, with distinct border. Generally two in cross-field, in a single row
	Fir: 25–65 µm in diameter in radial plane in earlywood, 10–25 µm in late wood. Bordered pits in one row or very rarely paired on the radial walls. Pits leading to ray parenchyma taxodioid, small, quite uniform in size, with distinct border. One to four per cross-field
	Curly maple: fiber tracheids, thick-walled, medium to very coarse. Very vari able in length from 0.01–3 mm
Rays	*Spruce*: two types – uniseriate and fusiform; uniseriate rays numerous (80–100 rays/cm) and 1–25 cells in height. Fusiform rays scatter, with a transverse resin canal, 3–5 seriate through the central position, tapering above and below to uniseriate margins like the uniseriate rays, up to 16 cells in height, end walls nodular with indentures; ray tracheids in both types of rays usually restricted to one row on the upper and lower margins, nondentate
	Fir: uniseriate, very variable in length (1–50 cells), consisting wholly of ray parenchyma, numerous up to 80 rays/cm
	Curly maple: up to 5 mm in height along the grain, homocellular, 1–20 (mostly 2–10) seriate, ray-vessel pitting similar to intervessel type
Resin canal	*Spruce*: thick-walled epithelium, longitudinal canals, small, with 125 µm diameter, usually rare, about 22 canals/cm^2; transverse canal much smaller
	Fir: normal resin canals wanting; longitudinal traumatic canals sometimes present, sporadic in widely separated rings, arranged in a tangential row which frequently extends for some distance along the ring
	Curly maple: wanting
Vessels	*Spruce and fir*: wanting
	Curly maple: solitary, 25–150 µm in diameter, 30–50 vessels/mm^2, simple for the most part, occasionally scalariform, a few bars, intervessel pits oval, orbicular, widely spaced, 50 µm in diameter

2.2.2 Wood Acoustics

There are multiple measurements used to identify the quality of resonance wood. They range from simple anatomical grading to the study of acoustic-elastic properties. The most common measurements related to acoustics include the density and the acoustic velocity of the material (ρ and V, respectively). These measures can be used to deduce acoustic impedance (V×ρ) which is the amount of resistance an acoustic flow encounters as it passes through the material (Morgan and Vajuhudeen 2014) and acoustic radiation (V/ρ) which is the force exerted by an acoustic flow on the absorbing material (Torr 1984). As shown in Table 4 and 5, these values vary between and within species. Manzo et al. (2021) also found that resonance spruce has a range of acoustic velocities between 4891.30 and 6818.18 m/s. Meanwhile, Dinulica et al. (2023) found that sycamore maple wood used in instruments has a range from 3750 to 4238 m/s.

Table 4. Dynamic elastic constants and velocities of spruce (*Picea* spp.) used for musical instruments (Haines 1979).

Species	Density (kg/m^3)	Velocity (m/s)				Young's moduli (10^8 N/m^2)		Shear moduli (10^8 N/m^2)	
		V_{LL}	V_{RR}	V_{TL}	V_{TR}	E_L	E_R	G_{TL}	G_{TR}
Spruce	480	5,600	1,200	1,307	359	150	7.4	8.2	0.62
	440	600	1,100	1,215	316	160	5.0	6.5	0.44
Sitka spruce	480	5,200	1,700	1,581	309	130	13	12	0.46
	460	5,200	1,500	1,062	242	130	11	5.1	0.27
Red spruce	480	6,300	950	1,060	277	90	4.8	5.4	0.37
	450	5,700	1,300	1,192	305	150	7.9	6.4	0.42
White spruce	480	5,200	1,600	1,241	306	130	12	7.4	0.45
	460	5,700	1,600	1,224	339	150	12	6.9	0.53

Table 5. Acoustic and elastic constants of maple (*Acer* spp.) used for musical instruments (Haines 1979).

Density (kg/m^3)	Velocity (m/s)		Young's moduli (10^8 N/m^2)		Shear moduli (10^8 N/m^2)		Logarithmic decrement	
	V_{LL}	V_{RR}	E_L	E_R	G_{TL}	G_{TR}	$2\pi \tan \delta_L$	$2\pi \tan \delta_L$
Maple (*Acer platanoides*)								
750	3,800	1,700	110	20	17	0.89	3.7	6.1
Silver maple (*Acer saccharinum*)								
760	3,800	1,900	110	26	13	0.49	4.1	6.7
Sycamore (*Acer pseudoplatanus*)								
630	3,700	1,600	87	16	–	–	4.7	7.0
Curly maple (*Acer pseudoplatanus*)								
580	4,491	2,379	117	13.8	–	–	-	–

2.2.3.1 Acoustic Measurement Methods

Acoustic waves are only able to reveal characteristics that are of similar size to their wavelengths (Bucur 1996). For this reason, it is important to use the proper technique when looking for specific properties. There are two main methods of acoustic velocity measurement, time-of-flight (TOF) and resonance testing.

The TOF approach measures the travel time of the wave between two sensors that are hammered into the sample (Hansen 2006; Wang 2013). It can be applied to standing trees, logs, timber, and wood-based panels. A mechanical or ultrasonic impact is used to send a longitudinal wave through the sample, and the time delay of the signal across the known distance between the sensors are used to calculate the velocity of the wave. Therefore, the calculation is based on only one observation. This problem is overcome by repeating the test multiple times to obtain more reliable results (Hansen 2006).

Comparatively, resonance-based testing measures hundreds of acoustic pulses resonating in a log, providing a weighted average of acoustic velocities (Wang 2013). However, it requires two cut ends and cannot be used on standing trees (Hansen 2006). Resonance-based testing only uses one acoustic sensor mounted at one end of the sample. A mechanical wave is initiated and the sensor records hundreds of observations as the pulse goes forward and backwards through the log (Hansen 2006; Wang 2013). The resonance-based method is more accurate than the TOF method, and is often used as a standard to validate TOF measurements (Andrews 2003).

2.2.3.2 Effect of the Environment

Under optimal conditions (normal room temperature, 60−65% relative humidity, and 8−10% moisture content of wood), the acoustical and mechanical properties of wood are optimal (Bucur 2006). In reality, temperature and relative humidity are continuously changing and affecting wood properties. Thompson (1979) showed that tone quality, frequency, and mode shapes in instrument plates, are significantly influenced by temperature and relative humidity. For example, for mode 2 of a free violin backplate, at 15% relative humidity the frequency was 336 Hz, and at 79% relative humidity the frequency was significantly lower at 313 Hz. This difference in frequency is important for professional musicians.

2.2.3.3 Modified Wood

The use of modification to preserve wood from exterior elements has been done for centuries, dating back to the Vikings burning the surface of fences to make them more durable (FTWA 2003). Chemical impregnation of wood has been used since the early 19th century in the preservation of railroad ties against decay and insect damage

(Freeman et al. 2003). More recently, wood modification has been used to improve timber quality for instrument use (Ahmed and Adamopoulos 2018).

The process to thermal modification causes changes in wood structure and chemical reactions (FTWA 2003). The largest change is the thermic degradation of hemicelluloses. The changes begin to occur at about 150 ºC and continue as the temperature increases in stages. The main results of thermal modification include reduced shrinkage and swelling due to changes in moisture, lower equilibrium moisture content, removal of several extractives, increased density, and improved durability (FTWA 2003).

Ahmed and Adamopoulos (2018) tested the efficacy of modified wood as a material for instruments in three humidity levels (dry, standard, and wet). They tested thermally modified wood (ash, aspen and birch), acetylated wood (beech, maple and radiata pine), melamine- and phenol formaldehyde-treated beech and furfurylated Scots pine (Kebony Scots pine). They found that most modified woods had great acoustic quality in any humidity level, including a low damping constant. The furfurylated Scots pine and phenol formaldehyde-treated beech showed poor acoustic quality. They also found acetylated wood to have low equilibrium moisture content and high dimensional stability, more stable than most natural resonance wood species. The results of this paper suggest that modified wood can be used to replace endangered and expensive wood species used today.

2.3 WOOD VARIABILITY

Since wood grows under a multitude of conditions across the globe, it contains a large amount of variability within and between trees (Zobel and Van Buijtenen 1989).

There are many factors that influence this variability, from the environment to genetics and their interactions.

2.3.1 Radial Variability

One of the biggest changes within a tree occurs radially, from pith to bark (Zobel and Van Buijtenen 1989). The most important radial transition involves the concept of juvenile and mature wood (Zobel and Van Buijtenen 1989). Juvenile wood is the wood produced by the cambium near the centre of the tree and has characteristics that differ from the wood formed at a certain number of rings from the pith, called mature wood. This difference is far more important in pines than in other softwoods, and even less important in most hardwoods. The characteristics (cell length, microfibril angle, and specific gravity) vary significantly throughout juvenile wood and reach a more or less constant value in the mature wood (Dadswell 1958).

Another radial variation is the transition from earlywood to latewood within rings. In many softwood species, the transition from earlywood to latewood is believed to be caused by changes in apical activity (Larson 1960; Mitchell 1961). In other words, while the apical meristem is active (i.e., the tree is growing apically), there is an increased auxin production that perpetuates the production of large-diameter, thin-walled cells. Inversely, when the apical meristem is dormant, auxin production is reduced and thick-walled cells, a characteristic of latewood, are produced. The transition has also been connected to nutrition, day length, and moisture availability (Larson 1969).

2.3.2.1 Radial Variability in Softwoods

Most softwoods all follow a similar trend in radial variability for many properties, like moisture content, specific gravity, and tracheid length (Zobel and Van Buijtenen

1989). When excluding the heartwood, that forms in trees older than 30 years, most trees tend to have a high moisture content near the pith, which decreases towards the bark (Curro 1960). An inverse relationship has been measured for specific gravity, where it increases from pith to bark but reaches a plateau in the mature wood (Bunn 1981). Bunn (1981) also found that in the case of tracheid length, most species usually have short tracheids near the pith followed by a sharp increase through the juvenile wood and leveling off in the mature wood.

2.3.2.2 Radial Variability in Hardwoods

Hardwood species have several different patterns of variation from pith to bark (Zobel and Van Buijtenen 1989). For poplar species, specific gravity and fiber length both increased with distance from the pith (Inokuma et al. 1956; Yanchuck et al. 1983). In diffuse-porous hardwoods, fiber wall thickness increases outwards from the pith, causing an increase in specific gravity (Wheeler 1987).

2.3.2 Axial Variability

Many tree species have wood properties that vary axially, from the bottom to the top of the tree (Zobel and Van Buijtenen 1989). In general, for both diffuse-porous hardwoods and softwoods, specific gravity and tracheid length decrease from the base to the top of the tree (Wilcox and Pong 1971; Einspahr et al. 1972). Moisture content also varies significantly with height in the tree (Zobel and Van Buijtenen 1989).

2.3.3 Reaction Wood

Reaction wood causes major variation in wood properties (Zobel and Van Buijtenen 1989). Its formation usually involves eccentric radial growth of the stem (Dadswell 1960). In softwoods, it is formed on the lower side of leaning stems and is called compression wood. In hardwoods, it is formed of the upper side of leaning stems and is called tension wood (Dadswell 1960).

2.3.3.1 Compression Wood

Softwood trees form compression wood on the underside of leaning stems when a tree is not straight (McElwee and Zobel 1962). It is also produced around branches and sometimes from a physiological upset. There can be considerable amounts of compression wood depending on the form of the tree and the number of branches; Carmicheal (1969) found that Canadian softwoods contained 5.3% to 26.1% by volume of compression wood. Compression wood has an important impact on wood shrinkage because of its flat microfibril angle (Zobel and Van Buijtenen 1989). It has very little effect radially or tangentially but can increase shrinkage longitudinally tenfold (from 0.3% to 3%). Furthermore, compression wood can have a specific gravity that is up to two times higher than normal wood (Timell 1986). Even though it has a higher specific gravity, compression wood does not follow the mechanical properties that would be expected from a given specific gravity. Compared to normal wood, compression wood has lower stiffness and modulus of elasticity, but higher hardness and side compression (Banks 1957).

2.3.3.2 Tension Wood

Hardwood trees form tension wood on the upper side of leaning stems and on the upper side of branches (Barefoot 1963). It is characterized by the lack of cell wall lignification and an internal gelatinous layer in the fibers. It was found that tension wood has a higher tendency to cause warping and collapse in boards as well as increased shrinkage compared to normal wood (Zobel and Van Buijtenen 1989). Tension wood also has a higher specific gravity than normal wood (Kaeiser and Boyce 1964).

2.3.4 Disease

In aging forests, the primary cause of variation in wood properties are heart and root rots that affect the bole (Zobel and Van Buijtenen 1989). These are normally caused by two types of fungi. The first type attacks the cell walls, causing white and brown rot. The second type attacks the stored food in the wood, causing little structural damage other than slight discoloration. Through the degradation of solid wood components, rot causes a significant decrease in specific gravity (Espinoza et al. 2005). It also tends to have a much higher moisture content.

3.0 MATERIALS AND METHODS

3.1 STUDY AREA

The study took place in the Jack Haggerty Forest. The Jack Haggerty Forest consists of just over 1000 ha of forested Crown land controlled and managed by Lakehead University's Faculty of Natural Resources Management. It is in the Fowler and Jacques Townships, approximately 36 km northwest of Thunder Bay, Ontario. Latitudes of the south and north boundaries are 48˚38" and 48˚40", respectively. The east and west boundaries are described by longitudes 89˚20" and 89˚25", respectively (Figure 2; Anderson 2006). Specifically, the trees were harvested at the inventory training site on the west side of the forest, off Island Lake Road (Figure 3).

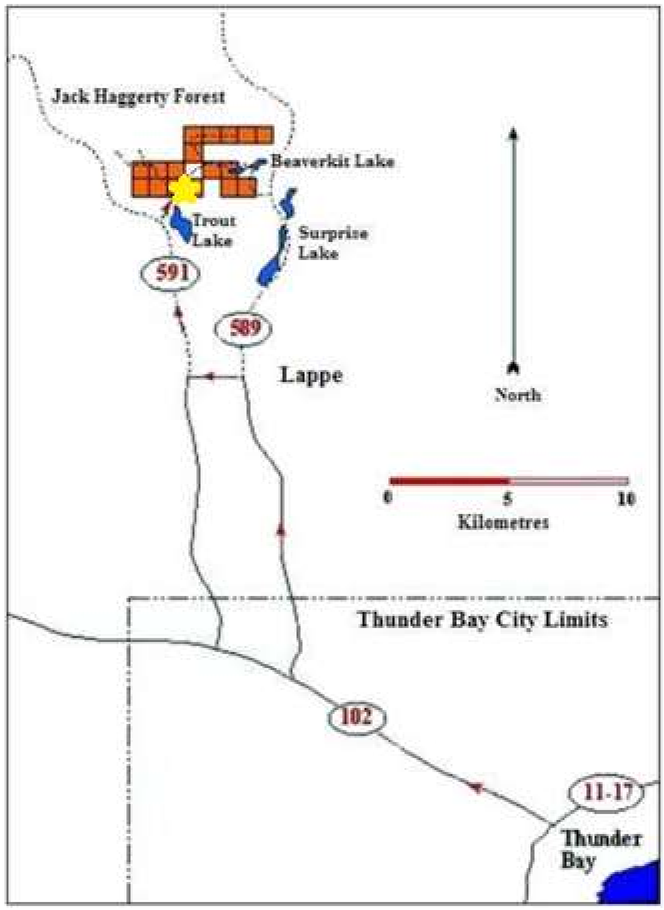


Figure 2. Location of and access to the Jack Haggerty Forest (Anderson 2006).

Figure 3. Location of the study area in the Jack Haggarty Forest.

The Jack Haggerty Forest takes place on the Canadian Shield and soil materials are primarily ground moraine and outwash plain formed by glaciers during the Pleistocene period (Anderson 2006). Soil deposits range from shallow to moderately deep (5 cm – 3 m) of loams, silts, and sands. There is a moderate presence of stones and rocks. In the Thunder Bay region, the mean annual temperature is 2.5°C and the mean annual precipitation is around 710 mm (Anderson 2006).

3.2 FIELD SAMPLING

The trees were randomly selected within the study area. The trees were of merchantable size (diameter greater than 10 cm) and with relatively good form (Figure 4).

Figure 4. The logs of each species before sample preparation.

3.3 SAMPLE PREPARATION

Each log was cut into metre-long bolts with diameters of at least 10 cm and labeled on the bottom of each bolt with species and bolt number from the bottom. On the top and bottom of each log, delineations were made to show every inch increment from the pith along each main azimuth (i.e., North, South, East, and West; Figure 5). The direction of each azimuth was the same for each log within a species but differed between the species (i.e., geographic azimuths were not used).

Figure 5. Delineations on the bottom of the balsam fir logs.

3.4 DETERMINATION OF ACOUSTIC VELOCITY

A Fakopp TreeSonic acoustic device was used to measure time of flight (TOF) acoustic velocities at each point delineated on each log. The device consists of two probes, one with a start sensor and the other with a stop sensor, a portable scopemeter, and a hammer. The two probes were angled towards each other and inserted into the top and bottom of each log (Figure 6 and Figure 7). Three records of TOF were measured and averaged to obtain one estimate of TOF acoustic velocity for each azimuth delineation on each log of each tree. A velocity determination equation, found in the Treesonic user's guide (2012) was used:

$$V[m/s] = 1000*distance[mm] / (Mean\ FAKOPP\ read\ out[\mu s]+1.5)$$

Temperature and moisture content were taken in each of the test sites to correct the acoustic measurement. Since moisture ranged from 12% to 85%, we had to correct it using ASTM D4442. The resulting values were compared to the acoustic velocity values in Table 4 for balsam fir and black spruce, and Table 5 for trembling aspen and white birch.

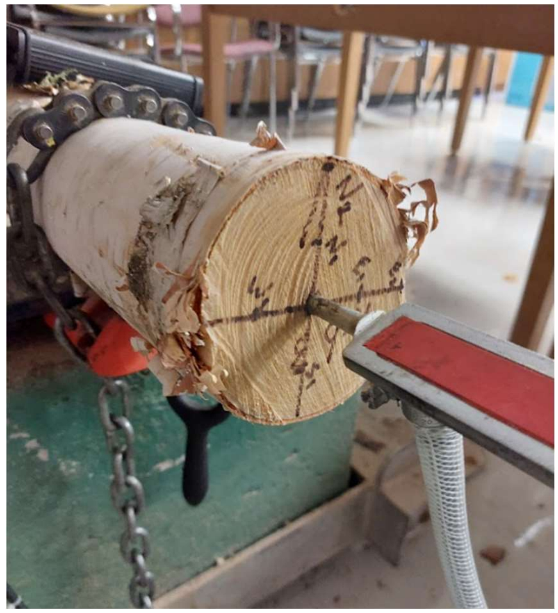


Figure 6. The start probe being inserted into the bottom of log Wb3.

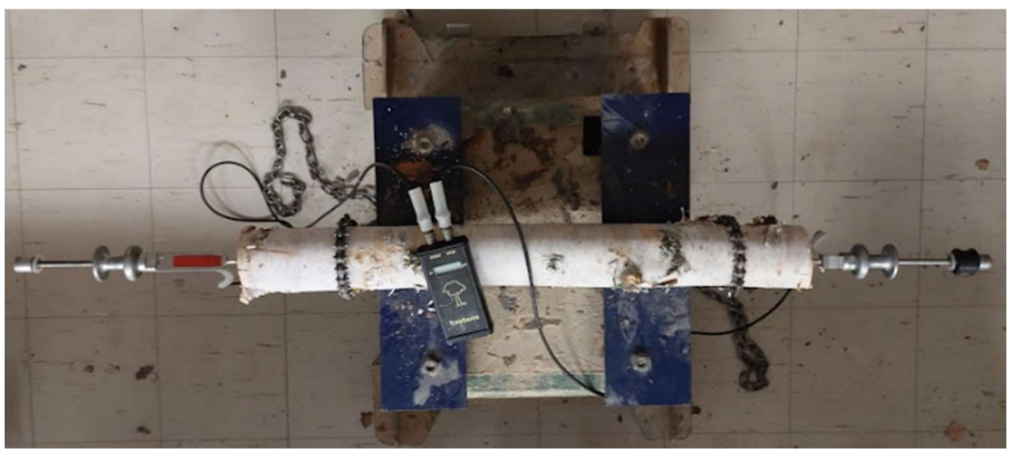


Figure 7. Both probes inserted into log Wb3.

3.5 DETERMINATION OF DENSITY PROFILE

Approximately an inch was cut off the top and bottom of each log and sawn into cubes corresponding to each delineation used for previous tests. The cubes were dried to 12% moisture content in a conditioning chamber set to 65% relative humidity and 20°C and densities were calculated using ASTM standard D2395, Method B – Volume by Water Immersion (Figure 8). Afterwards, the cubes were dried again to 0% moisture content and measured using the same ASTM standard, giving 12% MC and 0% MC density values. The resulting values were compared to the density values in Table 4 for balsam fir and black spruce, and Table 5 for trembling aspen and white birch.

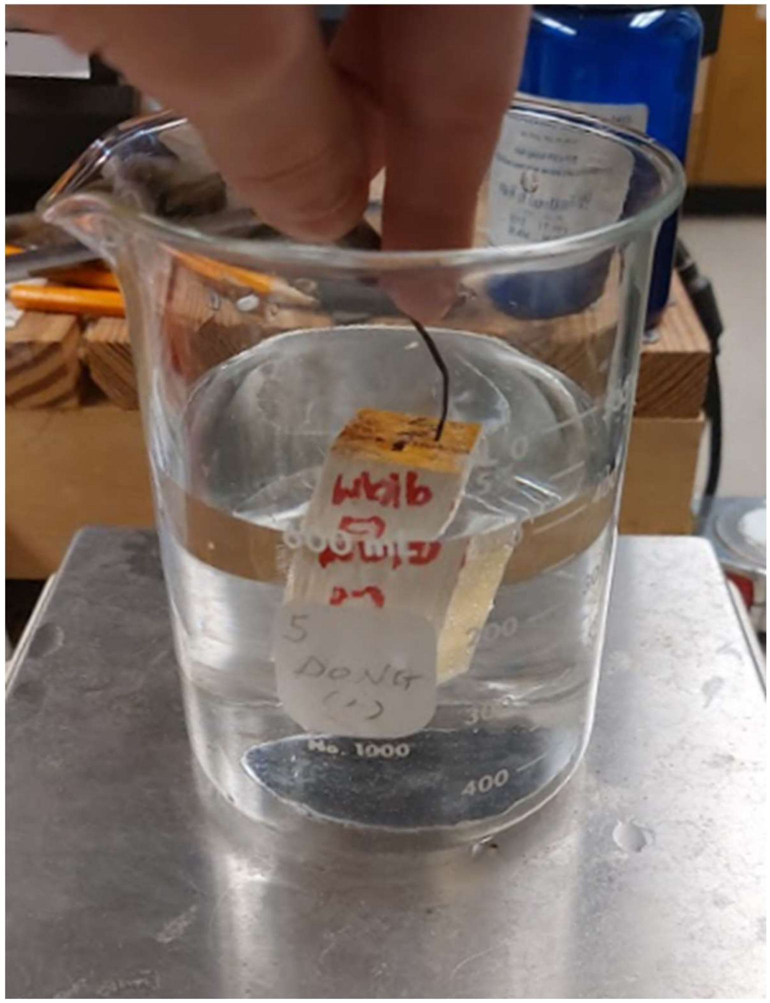


Figure 8. Density measurement using the water immersion method.

3.6 RING COUNT

The end of each density cube was sanded to make annual rings more visible. Once sanded, the width of the piece was measured to the nearest hundredth of a centimeter and rings were counted (Figure 9). The number of rings per centimeter was determined by dividing the number of rings by the width of the piece. The average width of the rings in a piece was determined by dividing the width of the piece by the number of rings. These values were compared to the values in Table 1 to see what type of instrument it could be used in.

Figure 9. Black spruce density cube showing annual growth rings.

3.7 STATISTICAL DESIGN

The statistical analysis was run on “R” version 4.2.3 (Shortstop Beagle), a free statistical comparison software produced by The R Foundation for Statistical Computing. Data was analyzed under assumption testing, at the 99% confidence limit ($\alpha = 0.01$). Data was tested for normality using the Shapiro-Wilk Test, and homogeneity of variance using the Bartlett Test. An analysis of variance (ANOVA) test was used to identify any interactions and significant differences. Finally, a Tukey post hoc multiple comparisons of means was used to describe the variance within the data pool.

4.0 RESULTS

4.1 ASSUMPTIONS TESTING

The data collected included acoustic velocity, wood density, ring width, and number of rings per centimeter, which was tested statistically under three assumptions for parametric data: data independence, data normality, and homogeneity of variance. Data independence was satisfied by ensuring the testing procedure for all samples was the same. The second assumption was met through the Shapiro-Wilk test of normality, where all the variables were found to be normally distributed. For example, the normal distribution of acoustic velocities had a Shapiro-Wilk value of 0.99266 and a probability of outcome (p-value) of 0.8509. The third assumption was satisfied through the Bartlett test of homogeneity, where all variables were found to have homogeneity. Acoustic velocity had a Bartlett K-value of 23.862 at 3 degrees of freedom, and a p-value of 2.67e-05. The assumptions tested were all met, allowing for further statistical analysis.

4.2 ACOUSTIC VELOCITIES

The mean acoustic velocity of the balsam fir log was 205 m/ns and a corrected value of 5495 m/s (Table 6). The bottom bolt (Bolt 1) had a velocity of 200 m/ns and a corrected value of 5646 m/s. The middle bolt (Bolt 2) had a velocity of 208 m/ns and a corrected value of 5471 m/s. The top bolt (Bolt 3) had a velocity of 213 m/ns and a corrected value of 5495 m/s.

Table 6. Mean acoustic velocities (m/ns) and corrected mean acoustic velocity (m/s) of each balsam fir bolt.

Mean	Mean Acoustic Velocity (m/ns)	Corrected Mean Acoustic Velocity (m/s)

Bolt 1	200	5646
Bolt 2	208	5471
Bolt 3	213	5368
Total	205	5495

The mean acoustic velocity of the black spruce log was 168 m/ns and a corrected value of 6275 m/s (Table 7). The bottom bolt (Bolt 1) had a velocity of 175 m/ns and a corrected value of 6614 m/s. The middle bolt (Bolt 2) had a velocity of 172 m/ns and a corrected value of 6053 m/s. Finally, the top bolt (Bolt 3) had a velocity of 161 m/ns and a corrected value of 6157 m/s.

Table 7. Mean acoustic velocity (m/ns) and corrected mean acoustic velocity (m/s) of each black spruce bolt.

Mean	Mean Acoustic Velocity (m/ns)	Corrected Mean Acoustic Velocity (m/s)
Bolt 1	175	6614
Bolt 2	172	6053
Bolt 3	161	6157
Total	168	6275

The mean acoustic velocity of the trembling aspen log was 202 m/ns and a corrected value of 5786 m/s (Table 8). The bottom bolt (Bolt 1) had a velocity of 218 m/ns and a corrected value of 5471 m/s. The middle bolt (Bolt 2) had a velocity of 193 m/ns and a corrected value of 5740 m/s. Finally, the top bolt (Bolt 3) had a velocity of 183.5 m/ns and a corrected value of 6147 m/s.

Table 8. Mean acoustic velocity (m/ns) and corrected mean acoustic velocity (m/s) of each trembling aspen bolt.

Mean	Mean Acoustic Velocity (m/ns)	Corrected Mean Acoustic Velocity (m/s)
Bolt 1	218	5471
Bolt 2	193	5740
Bolt 3	183	6147
Total	202	5786

The mean acoustic velocity of the white birch log was 191 m/ns and a corrected value of 5896 m/s (Table 9). The bottom bolt (Bolt 1) had a velocity of 192 m/ns and a corrected value of 5834 m/s. The middle bolt (Bolt 2) had a velocity of 195 m/ns and a corrected value of 6024 m/s. Finally, the top bolt (Bolt 3) had a velocity of 195 m/ns and a corrected value of 5829 m/s.

Table 9. Mean acoustic velocity (m/ns) and corrected mean acoustic velocity (m/s) of each white birch bolt.

Mean	Mean Acoustic Velocity (m/ns)	Corrected Mean Acoustic Velocity (m/s)
Bolt 1	192	5834
Bolt 2	188	6024
Bolt 3	195	5829

Total	191	5896

According to the ANOVA test, there were a significant differences between species ($F_{3,92} = 40.5$, $p < .01$), radial positions ($F_{2,92} = 30.7$, $p < .01$), and the interaction of species and radial positions ($F_{6,92} = 5.9$, $p < .01$; Figure 10).

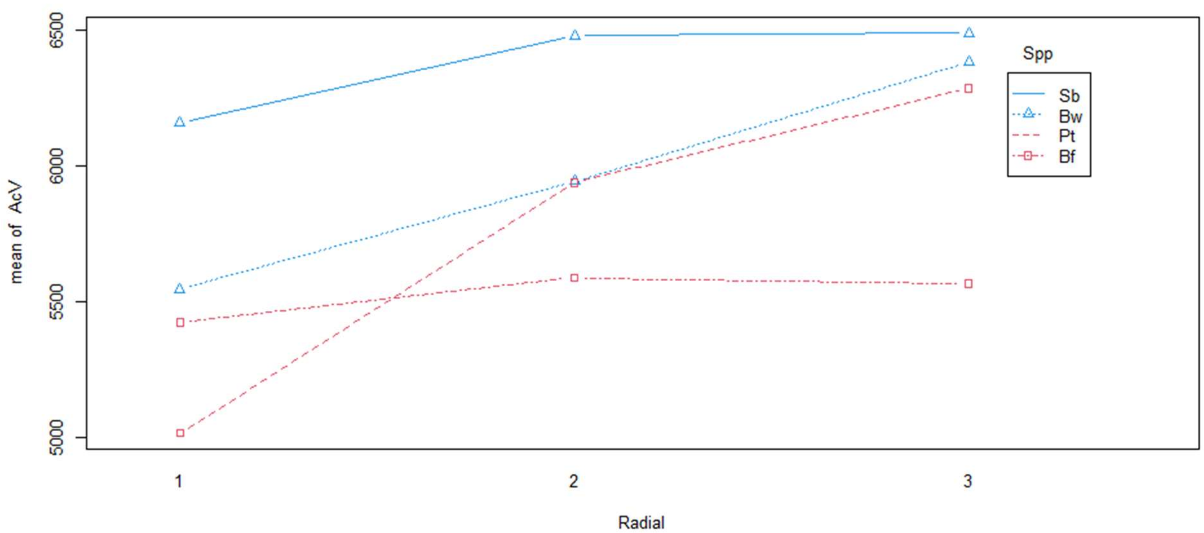
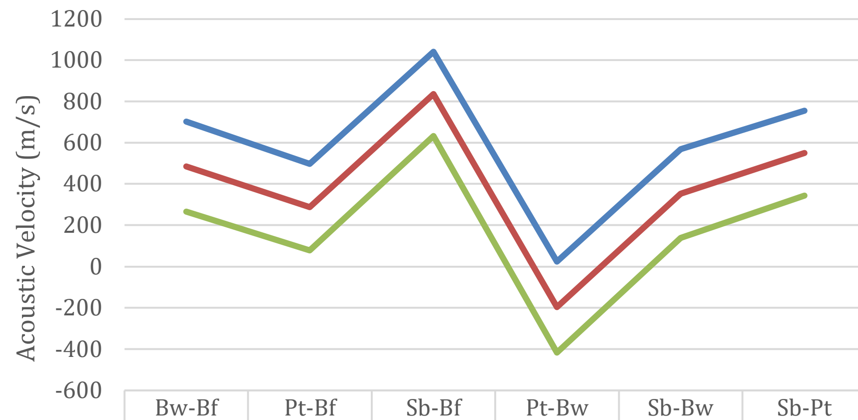


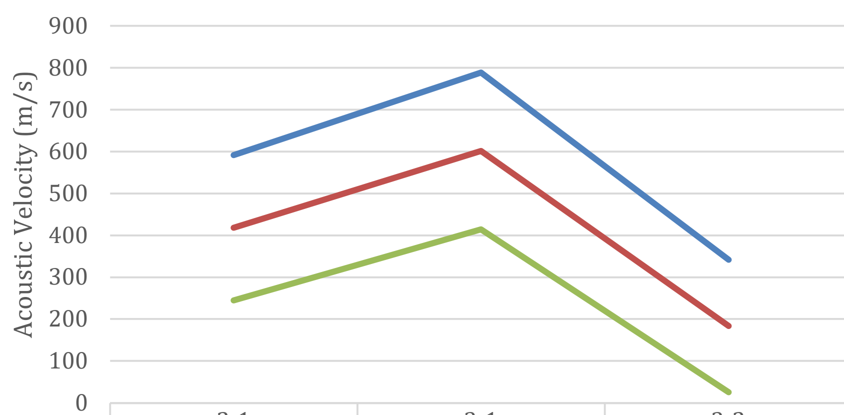
Figure 10. Comparison of mean acoustic velocity values of each species by radial position.

According to the Tukey Multiple Comparisons of Mean Post Hoc test, there were significant differences in acoustic velocity values between all species combinations except for trembling aspen and white birch (Figure 11). There were also significant differences between the first and second radial positions, and the first and third radial positions (Figure 12).



	Bw-Bf	Pt-Bf	Sb-Bf	Pt-Bw	Sb-Bw	Sb-Pt
Upper	702.37	496.59	1040.27	24.17	568.14	754.82
Difference	483.77	287.46	836.72	-196.31	352.95	549.26
Lower	265.17	78.33	633.18	-416.79	137.76	343.7
Adjusted p-value	0.000	0.003	0.000	0.099	0.000	0.000

Figure 11. Post Hoc results for acoustic velocities between species, where the red line shows the difference in values, the blue line show the upper limit, and the green line shows the lower limit.



	2-1	3-1	3-2
Upper	591.14	789.1	342.22
Difference	417.91	601.99	184.07
Lower	244.68	414.87	25.94
Adjusted p-value	0.0000003	0	0.018286

Figure 12. Post Hoc results for acoustic velocities between radial positions, where the red line shows the difference in values, the blue line show the upper limit, and the green line shows the lower limit.

4.3 DENSITY PROFILES

At 12% moisture content (MC), the mean densities of the top and bottom of each bolt of the balsam fir log were 0.449 and 0.425, respectively (Table). At 0% moisture content, the mean densities of the top and bottom of each bolt of the balsam fir log were 0.403 and 0.383, respectively.

Table 11. Mean top and bottom densities of each balsam fir bolt at 0 and 12% MC.

Mean	Top Density (12% MC)	Bottom Density (12% MC)	Top Density (0% MC)	Bottom Density (0% MC)
Bolt 1	0.441	0.435	0.408	0.404
Bolt 2	0.429	0.429	0.386	0.384
Bolt 3	0.476	0.410	0.414	0.361
Total	0.449	0.425	0.403	0.383

At 12% moisture content (MC), the mean densities of the top and bottom of each bolt of the black spruce log were 0.586 and 0.575, respectively (Table 12). At 0% moisture content, the mean densities of the top and bottom of each bolt of the black spruce log were 0.537 and 0.518, respectively.

Table 12. Mean top and bottom densities of each black spruce bolt at 0 and 12% MC.

Mean	Top Density (12% MC)	Bottom Density (12% MC)	Top Density (0% MC)	Bottom Density (0% MC)
Bolt 1	0.581	0.560	0.534	0.518
Bolt 2	0.566	0.549	0.518	0.513
Bolt 3	0.613	0.617	0.558	0.523

Total	0.586	0.575	0.537	0.518

At 12% moisture content (MC), the mean densities of the top and bottom of each bolt of the trembling aspen log were 0.438 and 0.434, respectively (Table). At 0% moisture content, the mean densities of the top and bottom of each bolt of the trembling aspen log were 0.400 and 0.396, respectively.

Table 13. Mean top and bottom densities of each trembling aspen bolt at 0 and 12% MC.

Mean	Top Density (12% MC)	Bottom Density (12% MC)	Top Density (0% MC)	Bottom Density (0% MC)
Bolt 1	0.404	0.403	0.376	0.374
Bolt 2	0.440	0.434	0.394	0.394
Bolt 3	0.471	0.466	0.430	0.421
Total	0.438	0.434	0.400	0.396

At 12% moisture content (MC), the mean densities of the top and bottom of each bolt of the white birch log were 0.613 and 0.632, respectively (Table 14). At 0% moisture content, the mean densities of the top and bottom of each bolt of the white birch log were 0.571 and 0.580, respectively.

Table 14. Mean top and bottom densities of each white birch bolt at 0 and 12% MC.

Mean	Top Density (12% MC)	Bottom Density (12% MC)	Top Density (0% MC)	Bottom Density (0% MC)
Bolt 1	0.605	0.603	0.562	0.555

Bolt 2	0.620	0.672	0.577	0.623
Bolt 3	0.614	0.619	0.576	0.562
Total	0.613	0.632	0.571	0.580

According to the ANOVA test, there were significant differences between species ($F_{3,90} = 343.9$, $p < .01$), radial positions ($F_{2,90} = 19.1$, $p < .01$), axial positions ($F_{2,90} = 9.4$, $p < .01$) and the interaction of species and radial positions ($F_{6,92} = 5.4$, $p < .01$; Figure 13).

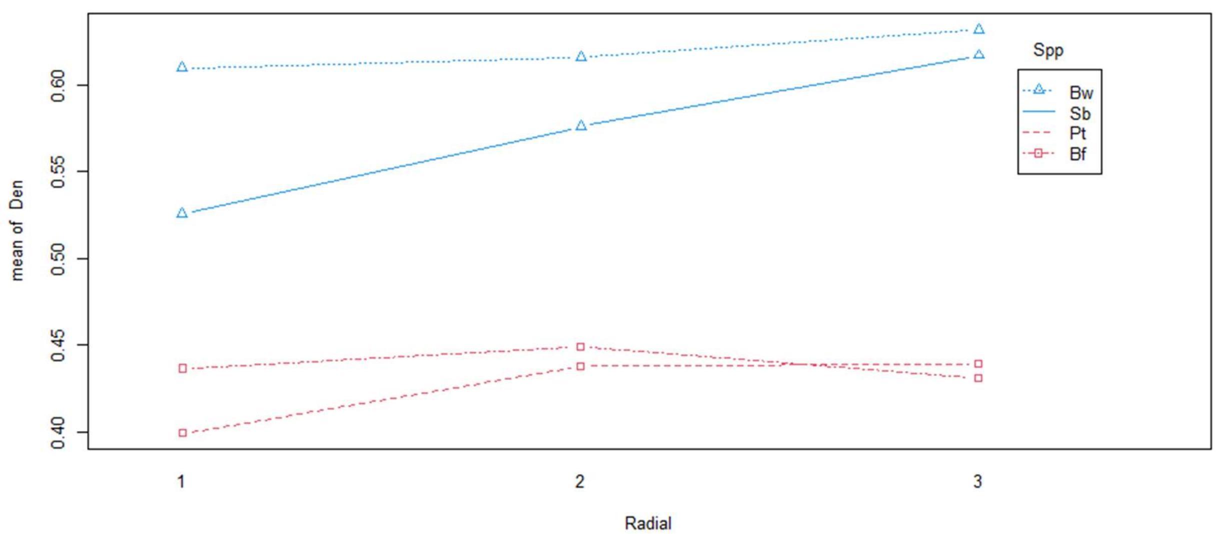
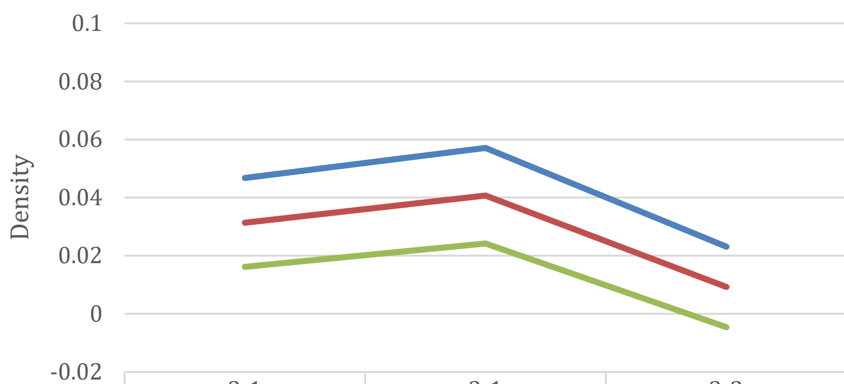


Figure 13. Comparison of mean density values of each species by radial position.

According to the Tukey Multiple Comparisons of Mean Post Hoc test, there were significant differences in density values between all species combinations except for trembling aspen and balsam fir (Figure 14). There were also significant differences between the first and second radial positions, and the first and third radial positions (Figure 15). Finally, there were significant differences between bolts 1 and 3, and bolts 2 and 3 (Figure 16).

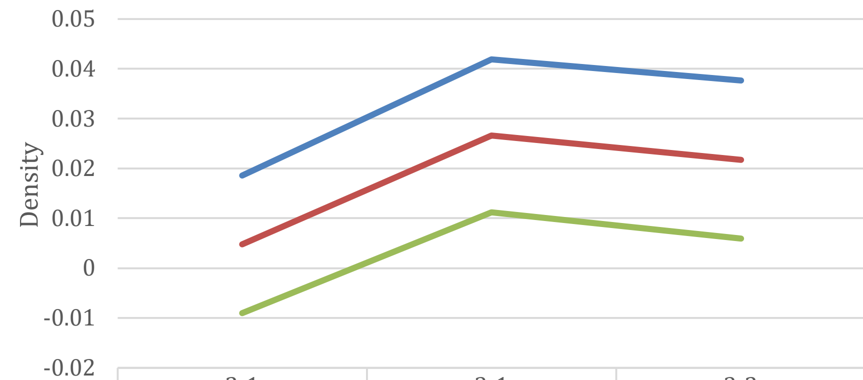
	Bw-Bf	Pt-Bf	Sb-Bf	Pt-Bw	Sb-Bw	Sb-Pt
Upper	0.1989	0.0075	0.149	-0.1712	-0.0296	0.1602
Difference	0.1797	-0.0109	0.1311	-0.1906	-0.0486	0.1421
Lower	0.1605	-0.0293	0.1132	-0.21	-0.0675	0.124
Adjusted p-value	0.000	0.411	0.000	0.000	0.000	0.000

Figure 14. Post Hoc results for density between species, where the red line shows the difference in values, the blue line show the upper limit, and the green line shows the lower limit.



	2-1	3-1	3-2
Upper	0.0467	0.0572	0.0232
Difference	0.0314	0.0408	0.0093
Lower	0.0162	0.0243	-0.0046
Adjusted p-value	0.000	0.000	0.252

Figure 15. Post Hoc results for density between radial positions, where the red line shows the difference in values, the blue line show the upper limit, and the green line shows the lower limit



	2-1	3-1	3-2
Upper	0.0186	0.0419	0.0376
Difference	0.0048	0.0266	0.0217
Lower	-0.009	0.0112	0.0059
Adjusted p-value	0.683	0.000	0.004

Figure 16. Post Hoc results for density between axial positions, where the red line shows the difference in values, the blue line show the upper limit, and the green line shows the lower limit.

4.4 RING WIDTH

The mean ring width of the balsam fir log was 1.36 mm. The bottom bolt (Bolt 1) had a mean ring width of 1.38 mm. The middle bolt (Bolt 2) had a mean ring width of 1.29 mm. Finally, the top bolt (Bolt 3) had a mean ring width of 1.42 mm.

The mean ring width of the black spruce log was 1.44 mm. The bottom bolt (Bolt 1) had a mean ring width of 1.30 mm. The middle bolt (Bolt 2) had a mean ring width of 1.35 mm. Finally, the top bolt (Bolt 3) had a mean ring width of 1.66 mm.

The mean ring width of the trembling aspen log was 3.21 mm. The bottom bolt (Bolt 1) had a mean ring width of 3.38 mm. The middle bolt (Bolt 2) had a mean ring width of 2.87 mm. Finally, the top bolt (Bolt 3) had a mean ring width of 3.29 mm.

The mean ring width of the white birch log was 2.56 mm. The bottom bolt (Bolt 1) had a mean ring width of 2.38 mm. The middle bolt (Bolt 2) had a mean ring width of 2.41 mm. Finally, the top bolt (Bolt 3) had a mean ring width of 2.89 mm.

According to the ANOVA test, there were significant differences between species ($F_{3,100} = 82.6$, $p < .01$; Figure 17).

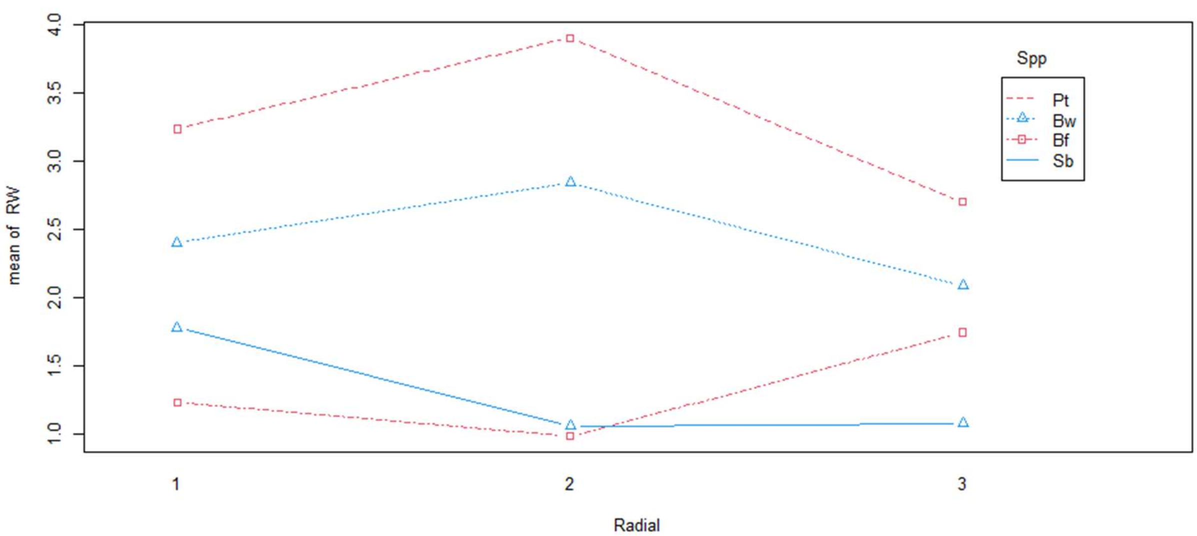
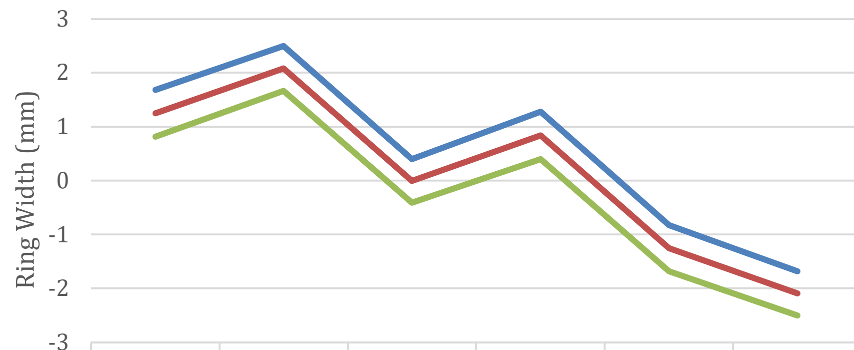


Figure 17. Comparison of mean ring width values of each species by radial position.

According to the Tukey Multiple Comparisons of Mean Post Hoc test, there were significant differences in ring widths between all species combinations except for black spruce and balsam fir (Figure 18).



	Bw-Bf	Pt-Bf	Sb-Bf	Pt-Bw	Sb-Bw	Sb-Pt
Upper	1.6836	2.5008	0.399	1.2751	-0.8262	-1.6814
Difference	1.2483	2.0843	-0.0064	0.836	-1.2547	-2.0907
Lower	0.813	1.6679	-0.4117	0.3969	-1.6832	-2.5
Adjusted p-value	0.000	0.000	1.000	0.000	0.000	0.000

Figure 18. Post Hoc results for ring widths between species, where the red line shows the difference in values, the blue line show the upper limit, and the green line shows the lower limit.

4.5 RINGS PER CENTIMETER

The mean number of rings per centimeter of the balsam fir log was 8.30. The bottom bolt (Bolt 1) had a mean number of rings per centimeter of 8.42. The middle bolt (Bolt 2) had a mean number of rings per centimeter of 8.15. Finally, the top bolt (Bolt 3) had a mean number of rings per centimeter of 8.32.

The mean number of rings per centimeter of the black spruce log was 13.48. The bottom bolt (Bolt 1) had a mean number of rings per centimeter of 14.21. The middle bolt (Bolt 2) had a mean number of rings per centimeter of 14.54. Finally, the top bolt (Bolt 3) had a mean number of rings per centimeter of 11.69.

The mean number of rings per centimeter of the trembling aspen log was 3.39. The bottom bolt (Bolt 1) had a mean number of rings per centimeter of 3.08. The middle bolt (Bolt 2) had a mean number of rings per centimeter of 3.98. Finally, the top bolt (Bolt 3) had a mean number of rings per centimeter of 3.11.

The mean number of rings per centimeter of the white birch log was 4.11. The bottom bolt (Bolt 1) had a mean number of rings per centimeter of 4.50. The middle bolt (Bolt 2) had a mean number of rings per centimeter of 4.27. Finally, the top bolt (Bolt 3) had a mean number of rings per centimeter of 3.57.

According to the ANOVA test, there were significant differences between species ($F_{3,92}$ = 186.92, $p < .01$), radial positions ($F_{2,92}$ = 12.24, $p < .01$), and the interaction of species and radial positions ($F_{6,92}$ = 12.58, $p < .01$; Figure 19).

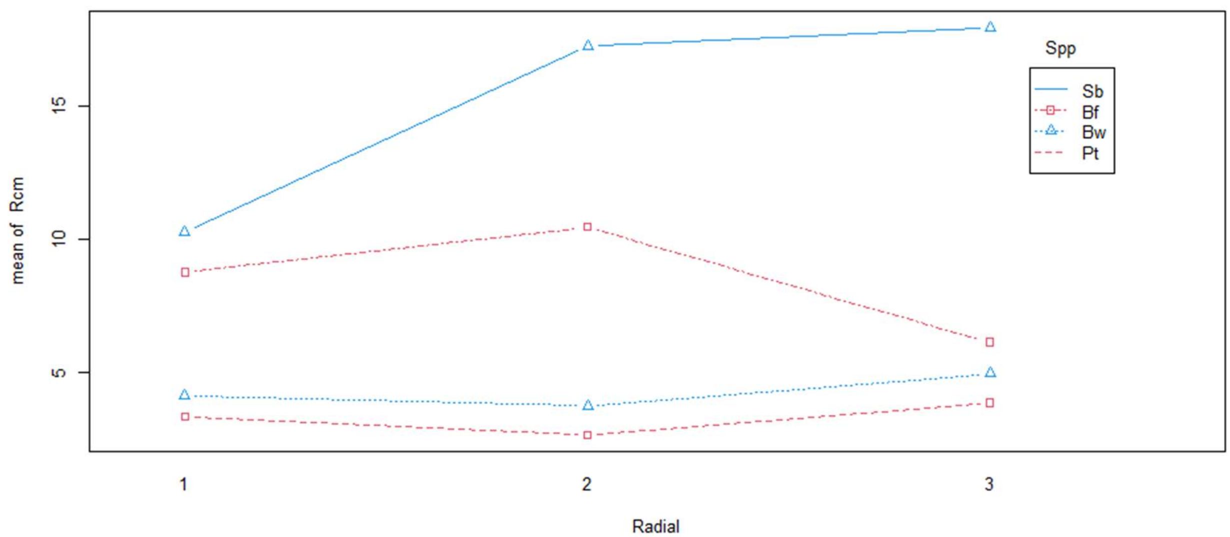
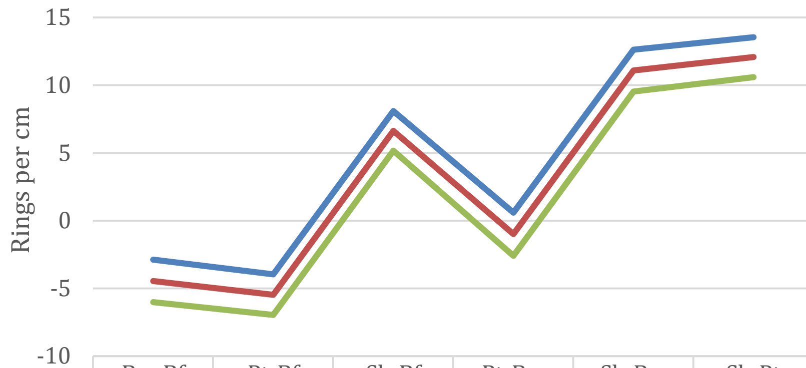


Figure 19. Comparison of mean ring per centimeter values of each species by radial position.

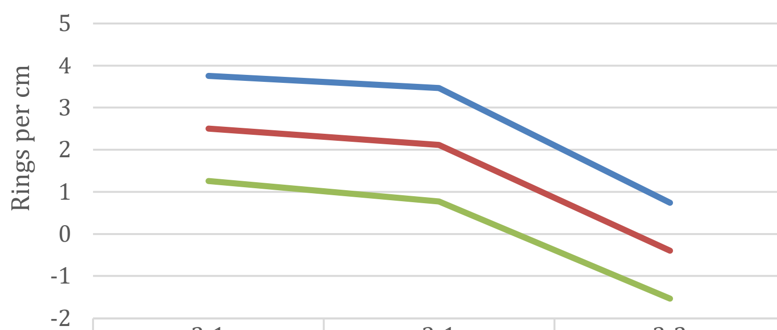
According to the Tukey Multiple Comparisons of Mean Tukey Multiple Comparisons of Mean Post Hoc test, there were significant differences in rings per centimeter between all species combinations except for trembling aspen and white birch

(Figure 20). There were also significant differences between the first and second radial positions, and the first and third radial positions (Figure 21).



	Bw-Bf	Pt-Bf	Sb-Bf	Pt-Bw	Sb-Bw	Sb-Pt
Upper	-2.8805	-3.9543	8.0834	0.5818	12.626	13.5579
Difference	-4.4544	-5.46	6.6179	-1.0056	11.0723	12.0779
Lower	-6.0283	-6.9657	5.1524	-2.593	9.5229	10.5978
Adjusted p-value	0.000	0.000	0.000	0.352	0.000	0.000

Figure 20. Post Hoc results for rings per centimeter between species, where the red line shows the difference in values, the blue line show the upper limit, and the green line shows the lower limit.



	2-1	3-1	3-2
Upper	3.7563	3.4629	0.7452
Difference	2.509	2.1157	-0.3934
Lower	1.2618	0.7685	-1.5319
Adjusted p-value	0.000	0.001	0.690

Figure 21. Host Hoc results for rings per centimeter between radial positions, where the red line shows the difference in values, the blue line show the upper limit, and the green line shows the lower limit.

4.6 COMPARISON TO PUBLISHED VALUES

When compared to the published values in Haines (1979) of density and acoustic velocity for softwood resonance species, black spruce had the highest values, while balsam fir shared the lowest density with “Spruce” and was among the lowest acoustic velocities (Figure 22).

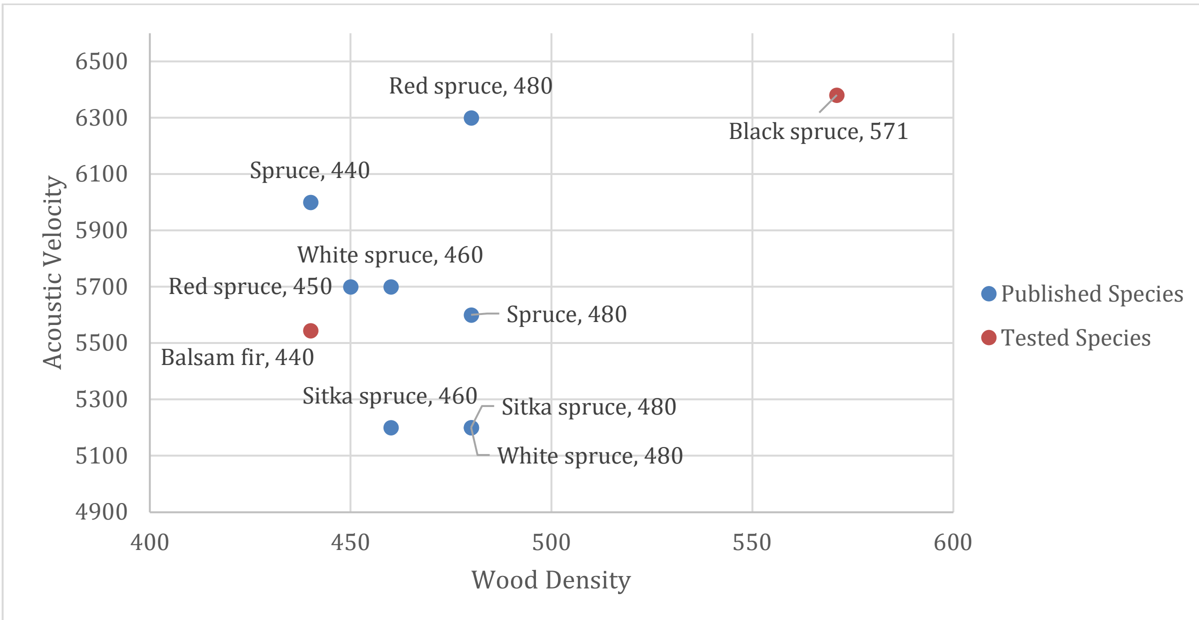


Figure 22. Comparison of the effect of density on acoustic velocity in tested (red) and published (blue) softwood species.

When compared to the published values in Haines (1979) of density and acoustic velocity for hardwood resonance species, the tested species have higher acoustic velocities (Figure 23).

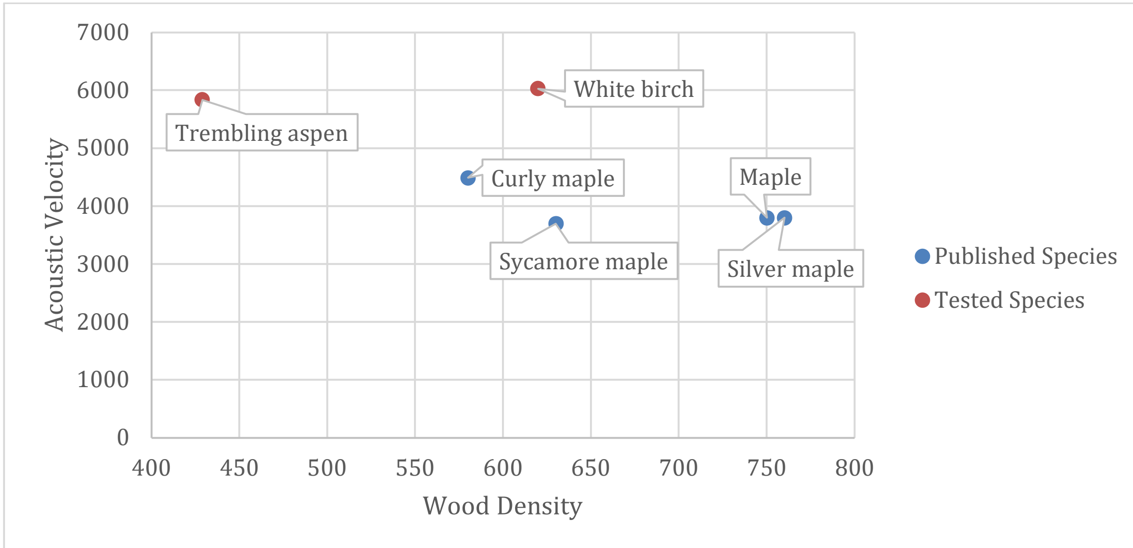


Figure 23. Comparison of the effect of density on acoustic velocity in tested (red) and published (blue) hardwood species.

Finally, when compared to the ranges of acoustic velocities in Manzo et al. (2021) and Dinulica et al. (2023), the softwood species are within the range, while the hardwood species are above the range (Figure 24). The range of softwood acoustic velocities are based off a study by Manzo et al. (2021), who looked at the range of acoustic values used in Norway spruce piano soundboards. Meanwhile, the range of hardwood acoustic velocities are based off a study by Dinulica et al. (2023), who looked at the range of acoustic values used in sycamore maple wood used in instruments.

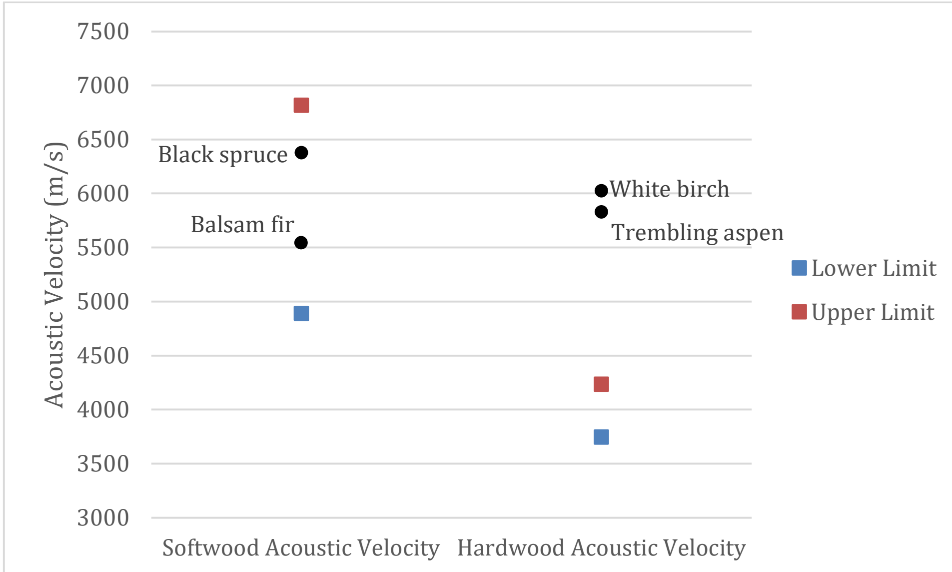


Figure 24. Comparison of tested acoustic velocity values to the published ranges.

5.0 DISCUSSION

5.1 ACOUSTIC VELOCITIES

Based on the ANOVA analyses, there were significant differences between the acoustic velocities of each species ($p < 0.01$). Black spruce had the highest acoustic velocity of all tested species. When compared to the published values, the acoustic velocity is greater than any other tested softwood (Haines 1979). There were no significant differences between axial positions ($p > 0.01$). Its bottom log had the highest velocity followed by the top and middle logs. This was most likely caused by the lower presence of branches and knots in the bottom log, compared to the top two logs. The lower presence of branches and the associated compression wood would result in a lower specific gravity (McElwee and Zobel 1962). There was a significant difference between radial positions ($p < 0.01$). The second radial position had the highest velocity followed by the third and first radials. Since the second and third radial positions would contain mature wood and the first radial position would contain juvenile wood, their properties would be more stable and have a better acoustic velocity (Dadswell 1958).

White birch had the second highest acoustic velocity of all tested species. When compared to the published values, the acoustic velocity is greater than any other tested hardwood (Haines 1979). There were no significant differences between axial positions ($p > 0.01$). Its middle log had the highest velocity, followed by the bottom and top logs. There was a significant difference between radial positions ($p < 0.01$). The third radial position had the highest velocity followed by the second and first radials. The third radial position would contain the stable properties of mature wood, resulting in a better acoustic velocity (Dadswell 1958).

Trembling aspen had the third highest acoustic velocity of all tested species. When compared to the published values, it is higher than all other resonance wood species (Haines 1979). There were no significant differences between axial positions ($p > 0.01$). Its top log had the highest velocity, followed by the middle and bottom logs. This was most likely caused by the larger proportion of rot found in the core of the bottom two logs (Figure 25; Espinoza et al. 2005). There was a significant difference between radial positions ($p < 0.01$). The third radial position had the highest velocity followed by the second and first radials. Again, rot found in the first and second radial positions would affect the acoustic velocity of the wood (Espinoza et al. 2005).

Figure 25. Bottom view of the three trembling aspen logs.

Balsam fir had the lowest acoustic velocity of all tested species. When compared to the published values, it is only higher than Sitka spruce and white spruce with a density of 460 kg/m^3 (Haines 1979). There were no significant differences between axial positions ($p > 0.01$). The bottom log had the highest velocity followed by the middle and top logs. This was most likely caused by the lower presence of branches and knots, and their associated compression wood, in the bottom log, compared to the top two logs (Timell 1986). There was a significant difference between radial positions ($p < 0.01$). The second radial position had the highest velocity followed by the third and first radials.

The acoustic testing methodology could be improved by testing all the samples at their green moisture content. This would allow for easier comparisons to the published data without any manipulations.

5.2 DENSITY PROFILES

Based on the ANOVA analyses, there were significant differences between the density values of each species ($p < 0.01$). White birch had the highest density of all tested species. When compared to the published values, the density values were greater than all other tested hardwood species (Haines 1979). There were significant differences between axial positions. Its middle log had the highest density followed by the top and bottom logs. The middle and top logs had a greater number of knots and tension wood, having a greater specific gravity than normal wood found in the bottom log (Kaeiser and Boyce 1964). There was a significant difference between radial positions ($p < 0.01$). The third radial position had the highest density followed by the second and first radials. Again, the third radial position has more stable, mature wood than the second and first radial positions. The mature wood, combined with the presence of knots and tension wood, would cause a higher specific gravity (Kaeiser and Boyce 1964; Zobel and Van Buijtenen 1989).

Black spruce had the second highest acoustic velocity of all tested species. When compared to the published values, the density values were greater than any other tested softwood (Haines 1979). There were significant differences between axial positions ($p < 0.01$). Its top log had the highest density, followed by the middle and bottom logs. This was most likely caused by the higher presence of branches and knots, and the associated compression wood in the top log, compared to the bottom two logs (Timell 1986). There was a significant difference between radial positions ($p < 0.01$). The third radial position had the highest density followed by the second and first radials. The third radial had a high presence of knots, compression wood, and mature wood, resulting in a higher specific gravity (Bunn 1981; Timell 1986).

Balsam fir had the third highest density values of all tested species. When compared to the published values, it had the lowest density values among softwoods (Haines 1979). There were significant differences between axial positions ($p < 0.01$). Its bottom log had the highest velocity followed by the middle and top logs. This was most likely caused by the higher presence of branches and knots in the top log, compared to the top two logs (Timell 1986). There was a significant difference between radial positions ($p < 0.01$). The second radial position had the highest density followed by the first and third radials.

Trembling aspen had the lowest density values of all tested species. When compared to the published values, it had the lowest density values among hardwoods (Haines 1979). There were significant differences between axial positions ($p < 0.01$). Its top log had the highest density, followed by the middle and bottom logs. This was most likely caused by the larger proportion of rot found in the core of the bottom two logs (Figure 24; Espinoza et al. 2005). There was a significant difference between radial positions ($p < 0.01$). The third radial position had the highest density followed by the second and first radials. The lack of rot and presence of mature wood and tension wood from knots in the third radial position would cause a higher specific gravity (Kaeiser and Boyce 1964; Zobel and Van Buijtenen 1989; Espinoza et al. 2005).

The density testing methodology could be improved by measuring the densities at the same moisture content as the acoustic velocity testing (i.e., green). This would allow for easier data comparisons without extra manipulations.

5.3 RING WIDTH

Based on the ANOVA analyses, there were significant differences between the ring widths of each species ($p < 0.01$). Trembling aspen had the greatest ring width of all tested species. When compared to the published values, this wood would not be used for instrument making (Holz 1984). There were no significant differences between axial positions ($p > 0.01$). Its bottom log had the greatest ring width followed by the top and middle logs. There was no significant difference between radial positions ($p > 0.01$). The second radial position had the greatest ring width followed by the third and first radials. This indicates that there was a period of increased growth while the second radial position was growing, compared to the third and first radial positions (Herman et al. 1998). In other words, the tree was released of competition approximately midway through its life.

White birch had the second highest acoustic velocity of all tested species. When compared to the published values, this wood would not be used for instrument making (Holz 1984). There were no significant differences between axial positions ($p > 0.01$). Its top log had the greatest ring width, followed by the middle and bottom logs. There was no significant difference between radial positions ($p > 0.01$). The second radial position had the greatest ring width followed by the first and third radials. This indicates that there was a period of increased growth while the second radial position was growing, compared to the third and first radial positions (Herman et al. 1998). In other words, the tree was released of competition approximately midway through its life.

Balsam fir had the third highest ring width values of all tested species. When compared to the published values, this wood could be used violins, pianos, and other stringed instruments (Holz 1984). There were no significant differences between axial positions ($p > 0.01$). Its top log had the greatest ring width values followed by the bottom and middle logs. There was no significant difference between radial positions ($p > 0.01$). The third radial position had the greatest ring width followed by the first and second radials. This indicates that there was a period of increased growth while the third radial position was growing, compared to the first and second radial positions (Herman et al. 1998). In other words, the tree was released of competition approximately in the later stages of its life.

Black spruce had the lowest ring width values of all tested species. When compared to the published values, this wood could be used for pianos and other stinged instruments (Holz 1984). There were no significant differences between axial positions ($p > 0.01$). Its top log had the greatest ring width values, followed by the middle and bottom logs. There was no significant difference between radial positions ($p > 0.01$). The first radial position had the greatest ring width followed by the third and second radials. This indicates that there was a period of increased growth while the first radial position was growing, compared to the third and second radial positions (Herman et al. 1998). In other words, the tree encountered competition approximately midway through its life.

5.4 RINGS PER CENTIMETER

Based on the ANOVA analyses, there were significant differences between the ring widths of each species ($p < 0.01$). Trembling aspen had the greatest ring width of all tested species. When compared to the published values, this wood would not be used for instrument making (Holz 1984). There were no significant differences between axial positions ($p > 0.01$). Its bottom log had the greatest ring width followed by the top and middle logs. There was a significant difference between radial positions ($p < 0.01$). The first radial position had the most rings per centimeter followed by the third and second radials. This indicates that the tree was slower growing early in its life and was eventually released from competition (Koga et al. 2002).

White birch had the second highest acoustic velocity of all tested species. When compared to the published values, this wood would not be used for instrument making (Holz 1984). There were no significant differences between axial positions ($p > 0.01$). Its top log had the greatest ring width, followed by the middle and bottom logs. There was a significant difference between radial positions ($p < 0.01$). The third radial position had the most rings per centimeter followed by the first and second radials. This indicates that the tree was slower growing late in its life, likely because of competition (Koga et al. 2002).

Balsam fir had the third highest ring width values of all tested species. When compared to the published values, this wood could be used violins, pianos, and other stringed instruments (Holz 1984). There were no significant differences between axial positions ($p > 0.01$). Its top log had the greatest ring width values followed by the bottom and middle logs. There was a significant difference between radial positions ($p < 0.01$). The second radial position had the most rings per centimeter followed by the first and third radials. This indicates that the tree was slower growing midway through in its life and was eventually released from competition (Koga et al. 2002).

Black spruce had the lowest ring width values of all tested species. When compared to the published values, this wood could be used for pianos and other stinged instruments (Holz 1984). There were no significant differences between axial positions ($p > 0.01$). Its top log had the greatest ring width values, followed by the middle and bottom logs. There was a significant difference between radial positions ($p < 0.01$). The second radial position had the most rings per centimeter followed by the third and first radials. This indicates that the tree was slower growing midway through its life and was eventually released from competition (Koga et al. 2002).

5.6 NEXT STEPS

The next steps for this study would be to expand the investigation to include more site information. The study should also include a greater number of sample trees with a diameter at breast height of over 30 cm. This would allow for more robust statistical analyses. Additional properties should be tested to include all the main criteria for the wood used in musical instruments. These include acoustic properties and density, to show the acoustical performance of the wood, the proportion of mature wood, or wood produced after 30 years of growth, to show dimensional stability, the proportion of wood free from knots and defects, to show homogeneity of the grain, the mechanical properties, primarily MOE, to show the flexibility and plasticity of the wood.

6.0 CONCLUSION

In conclusion, acoustic velocity, density, and ring characteristics play an important role in resonance wood. Multiple factors cause variation in these properties, like the difference between juvenile wood and mature wood, reaction wood, and disease. In this study, we reject the null hypothesis that there is no significant difference in acoustic velocity and density between species, axial positions, and radial positions. We also reject the null hypotheses that there is no significant difference between the acoustic velocity and density of white birch and trembling aspen and the acoustic velocity and density of hardwood species used in instruments. Finally, we reject the null hypothesis is that there is no significant difference between the acoustic velocity and density of black spruce and balsam fir and the acoustic velocity and density of softwood species used in instruments. In all, this study has shown that it is possible to use acoustic velocity, density profiles and ring characteristics to identify species to be used as resonance wood.

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