MECHANICAL PROPERTIES OF BLACK SPRUCE WOOD SUBJECTED TO DIFFERENT SILVICULTURAL TREATMENTS

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ABSTRACT

Black spruce is one of the most common commercial softwoods in Northwestern Ontario. Its abundance, along with its physical and mechanical properties, make it a very important species for commercial harvesting. Its physical and mechanical properties make it suitable for infrastructure and load-bearing purposes, and knowing how these characteristics can be maximized for the best quality lumber of important. The way trees are managed while they are growing affects what kind of mechanical properties they end up with when they are harvested, particularly in regard to thinning levels. This thesis examines the effects of light and heavy thinning on Black spruce physical and mechanical properties, and which of the two produces the better properties, particularly for the purpose of wood quality.

Nine trees were taken from a forest near Beardmore, Ontario, where thinning treatments were applied. There were three different treatment types in total: light thinning, heavy thinning, and control. The trees were harvested after 15 years and cut into sticks, where they were tested for properties, including modulus of elasticity and modulus of rupture, according to the ASTM standards. The sticks were then cut into compression and density cubes and tested for compression parallel to grain and density also according to the corresponding standards. These tests were all done with the sticks and cubes at 12% moisture content. After the density measurements were taken, the density cubes were dried in an oven and tested for density again at 0% MC. Data analysis was done using R studio and results found that light thinning produced the best physical and mechanical properties consistently compared to the heavy thinning and control plots.

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ACKNOWLEDGEMENTS

I would like to thank my supervisor, Dr. Mathew Leitch, who helped me throughout the entire process of obtaining the data for this thesis, as well as helping me write it by editing and making suggestions. I would also like to thank Keith Hautala, who agreed to be my second reader for this thesis. I also would like to express my gratitude to Seung-Il Lee, who helped me with analyzing the data using R Studio so I could form my conclusions and final opinions. Finally, I would like to thank Greg Fraser for helping me with collecting the data for this thesis. This never would have been completed without the help of these individuals.

INTRODUCTION

This undergraduate thesis involves testing the properties of *Black spruce* (Mill.) wood that has been subjected to different silvicultural treatments. The tests primarily relate to the mechanical properties of the wood. Different silvicultural treatments applied to trees affect how they grow, and those effects on growth significantly influence various properties of that trees wood. These properties may need to be manipulated to be a certain way due to their use in infrastructure or other projects that humans use them for, especially mechanical properties like bending strength. Therefore, knowing exactly how different silvicultural treatments affect the strength properties of commercial tree species is important for the proper use of the wood they provide.

This subject is being examined because while there is a significant amount of literature on Black spruce and how it is affected by various forms of management, research that tests its mechanical properties in relation to management isn’t as common. Due to Black spruce being a commonly used commercial wood species, quantifying its mechanical properties can help to give a better idea of how to manage it if it's being used for infrastructure or similar purposes. In addition to expanding that catalogue of knowledge on mechanical properties and how they are affected by differing management practices, it would also help in determining which silvicultural practices are best for creating wood that works best for specific purposes.

The work for this thesis will be conducted in the Lakehead University Wood Science and Testing Facility (LUWSTF) located in the Braun Building on the Lakehead University Campus in Thunder Bay, Ontario. The lab has equipment that is used to store the wood samples that have been subjected to the different silvicultural treatments (conditioning chamber), as well as the equipment that will be used to test the mechanical properties of the wood (universal wood testing machines). The target type of data that will be collected in this experiment is quantifying the strength properties (Modulus of Elasticity, Modulus of Rupture, Compression Parallel to the Grain, and Density) of the samples subjected to the different treatments. The literature I plan to review for this thesis will be existing data on Black spruce, its mechanical properties, how it is managed, and how that management affects its growth and properties. This can be used to obtain a better understanding of the silvicultural treatments that this thesis covers and help draw conclusions based on the results of the experiment.

The question that I want to answer with this thesis is whether silviculture systems that favour slower tree growth cause an increase in the mechanical properties of the wood they produce. Typically, slower tree growth leads to smaller growth rings, which typically means the tree has stronger mechanical properties. However, there are also other factors to consider when managing trees in terms of how they grow. I am interested in seeing what silvicultural practices create the strongest wood under the presented conditions.

OBJECTIVE

As mentioned previously, the main question I hope to answer is what silvicultural techniques create the best mechanical properties in Black spruce wood. I am particularly interested in learning if trees that experienced slower growth will have better mechanical properties. The work to answer these questions will be done in the LUWSTF on the Lakehead University Campus in Thunder Bay, as they have the equipment needed to conduct this experiment. The Black spruce samples will be subjected to tests on universal wood testing machines that are used to determine the exact strength properties of wood. I hope to use the data provided from this experiment to answer my questions about the wood's mechanical properties.

Assessing the differences in properties of the wood subjected to the different treatments compared to trees that grow naturally and undisturbed will provide insight into exactly how thinning effects wood from a quality perspective. If a difference is found that is also significant enough, these results and their implications can be applied to management strategies in regards to use of timber, if harvesting is being done. They can also apply to use planning in terms of the wood volume after it is harvested, specifically, what wood is best for a given purpose.

HYPOTHESIS

The hypothesis for this thesis is: silvicultural treatments that favour slower growth of Black spruce trees will result in wood with better mechanical and strength properties. If this hypothesis is disproven, then that either means treatments that create faster growth do not cause an increase in strength properties or growth rate is not correlated to strength properties, at least without influence from other factors. The results of this hypothesis will be used to formulate a final opinion on the effects of different silvicultural treatments on Black spruce wood mechanical properties.

LITERATURE REVIEW

RANGE

Black spruce is Ontario's boreal forest's most common tree species (Ontario 2019). It often grows in large, mostly pure stands within the boreal region (Ontario 2019; Payette and Delwaide 1994) and makes up roughly 30% of Ontario’s growing stock in volume (Ontario 2019). Figure 1 displays the relative occurrence of Black spruce in Ontario. It forms a latitudinal belt across Ontario in the central-northern portion of the province. It is less common in the farthermost north and south parts of Ontario, where the forest is more approaching tundra in the north and Deciduous and Great Lakes St. Lawrence forest zone in the south.

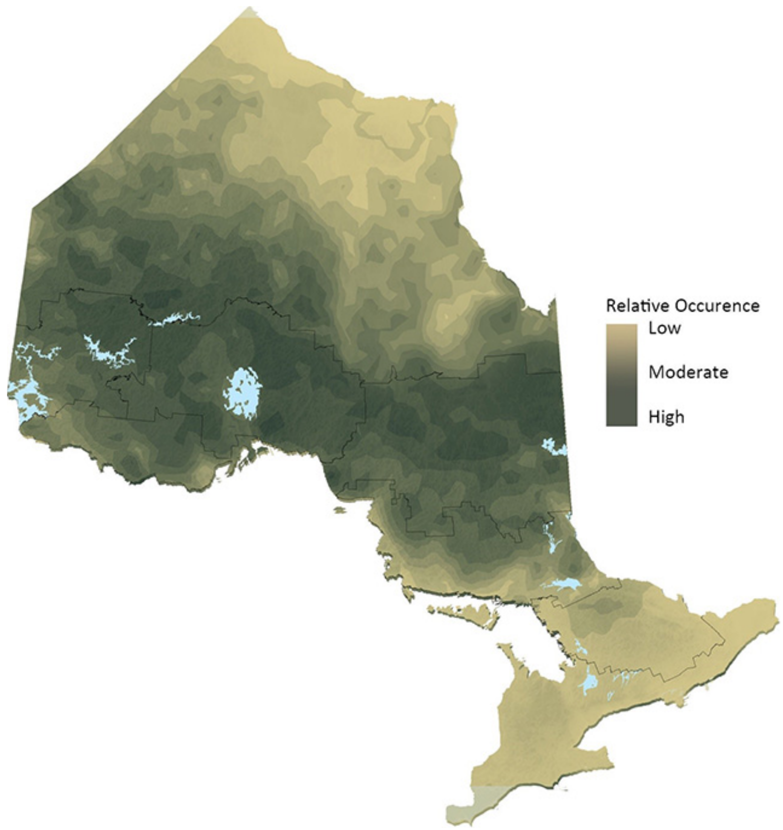

Figure 1. Map of Black spruces relative occurrence in Ontario (Ontario 2019).

Black spruce is most common in the northern portion of Ontario for a number of reasons, one being its ability to survive cold climates and tolerate winter exposure (Payette and Delwaide 1994). Its range extends to Northwestern Canada and goes as far as the northern tree line (Viereck and Johnston 1990). It is also worth noting that the commercial range for Black spruce is considerably less than its total geographic range (Viereck and Johnston 1990).

GROWTH

Characteristics

Black spruce is very commonly found in colder climates (Viereck and Johnston 1990) due to its ability to regenerate via layering, which allows it to tolerate freezing temperatures and large amounts of snow (Payette and Delwaide 1994). Black spruce also grows more commonly on permafrost sites than other species of spruce, mostly due to Black spruce growing on poorly drained sites (Wirth et al. 2008). This is because the permafrost restricts drainage on the site, limiting the growth of species like white spruce (Wirth et al. 2008).

Black spruce can be found across a variety of stands and environments (Oboite and Comeau 2019). Pure stands have soils with poor drainage, poor nutrient regimes, thick layers of peat and are often in lowland areas (Oboite and Comeau 2019). This is different from most deciduous stands, where soils have adequate drainage and plentiful nutrients (Oboite and Comeau 2019). Black spruce can grow in mixed stands but is more common in pure, lowland stands. In mixed stands, Black spruce can commonly be seen alongside Jackpine, Balsam fir, White spruce, trembling aspen, and White birch (Oboite and Comeau 2019).

Height growth of Black spruce is rather slow, ranging from 5-15 meters at 50 years of age (Johnston 1979). It is capable of surviving under extreme stress (Oboite and Comeau 2019), but growth rate on organic sites is related to the amount of nutrients that the site receives from nearby flowing water (Johnston 1979). The most productive pure Black spruce stands are generally found when the growing environment has a significant amount of decaying woody material (Viereck and Johnston 1990).

Requirements

As previously mentioned, Black spruce most commonly grows on poorly drained sites with a large amount of organic material comprising the soil bed. However, it can still be found in other types of stands, such as mixed woods. Black spruce is able to tolerate poor growing conditions (British Columbia N.d.), which is why it is able to grow in sites that other species cannot due to the poor conditions, such as lowland sphagnum bogs and swamps.

Climate change is believed to be having a negative effect on Black spruce populations due to the warming climate melting the permafrost that keeps Black spruce stands waterlogged (Wirth et al. 2008). Wirth et al. (2008) reported in a study on climate change's effect on Black and White spruce that the warming climate and increasing fire frequency in Alaska is causing the permafrost to melt at a faster rate than it could come back. This will cause White spruce, as well as other species in the region, to replace Black spruce in abundance (Wirth et al. 2008). The warming temperatures can also contribute to this process due to new species being able to survive the cold climate that only Black spruce could previously.

PROPERTIES

Physical

Density

Wood density is an important factor in assessing and determining the strength properties of wood (Reid et al. 2009; Liu et al. 2007). It's a predictor of mechanical properties such as strength, stiffness, and hardness (Liu et al. 2007), which are important to consider when planning projects where the wood will serve any kind of load-bearing purpose. Wood density is commonly linked to tree growth rate, where slower growth creates high density and, therefore, better mechanical properties (Larjavaara and Landau 2010).

Density also determines paper quality, which is important because the creation of pulp and paper is one of the most common uses for Black spruce wood (Zhang and Morgenstern 1995). Black spruce is also used in construction projects (Larjavaara and Landau 2010). This is likely due to its slower growth rate, which allows for high density and better mechanical properties as a result. However, due to its nature as a softwood species, Black spruce is still less dense than most hardwood species.

Density is a significant determining factor for the end uses of wood (Vincent et al. 2011) and is important to know when deciding how it will be used. However, studies have found that wood density is not strongly affected by growing conditions, particularly the variable conditions created by thinning. In a study by Vincent et al. (2011), various black spruce stands in Quebec, Canada, were subjected to commercial thinning to evaluate how physical and mechanical properties like density and MOE were affected. The study found that the density of trees in thinned stands was not significantly impacted by the thinning (Vincent et al. 2011). Figure 2 illustrates the differences in ring density in the treated stands, as well as control stands used for comparison of the effects of thinning. The commercial thinning had little effect on the density of the trees after the treatment, even lowering it to a degree.

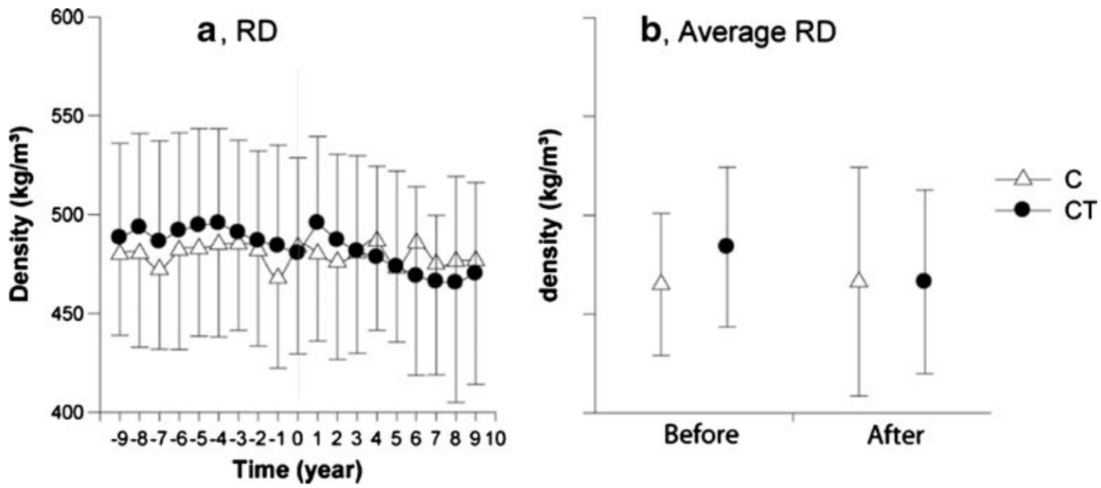

Figure 2. Ring density of Black spruce (*Picea mariana*) in treated and control stands before and after commercial thinning (Vincent et al. 2011).

Mechanical properties of wood, like Modulus of Elasticity (MOE) and Modulus of Rupture (MOR), are known to be determined by physical properties (Alteyrac et al. 2006). Wood density is commonly believed to have the most significant impact on these properties (Alteyrac et al. 2006). However, the degree of its impact compared to other physical properties can vary (Alteyrac et al., 2006). Alteyrac et al. (2006) conducted a study to examine the degree to which mechanical properties like MOE and MOR are affected by physical properties like wood density. It was found that tree ring density had a more significant effect on MOE than it did on MOR (Alteyrac et al., 2006). Figure 3 displays the relationships between density and MOE and MOR, respectively.

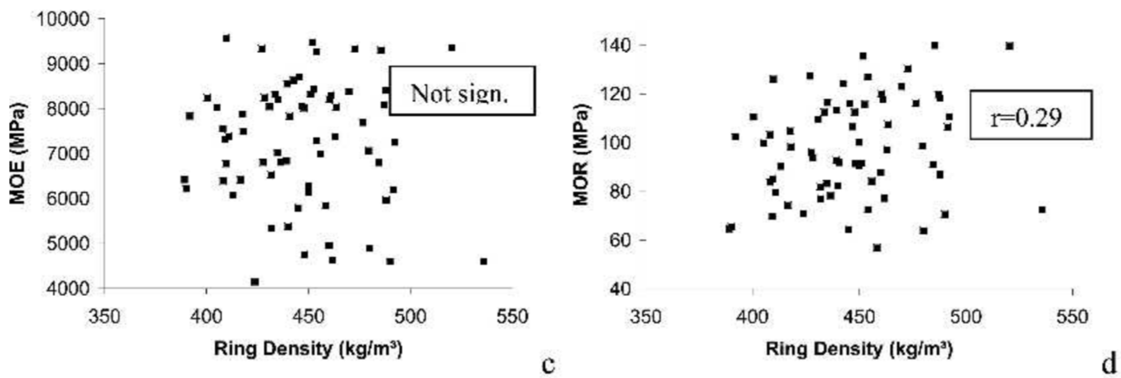

Figure 3. How density affects MOE and MOR in Black spruce (Alteyrac et al., 2006).

<u>Moisture Content</u>

Moisture content is another important variable to consider when assessing wood characteristics. Changes in the moisture content of wood can affect several properties, such as shrinkage, swelling, strength, MOE, and rigidity (Dietsch et al. 2015). Black spruce can grow well on both wet and dry sites, and this has a degree of influence on the moisture content. Krause and Lemay (2022) conducted a study on Black spruce moisture content on wet and dry sites and found that the amount of moisture in the stem of the tree itself didn’t change very much, but the amount in the secondary twigs and branches did. This shows the sites that Black spruce trees grow on don’t have a large bearing on physical properties in terms of moisture content. Nevertheless, it is still an important parameter to pay attention to when planning construction projects and harvest operations.

There are various conditions for wood density measurement relating to moisture content. The first is when the wood is at 12% MC, the second is at 0% MC. The third condition is referred to as “green”, which is the MC the wood has when it has not had the opportunity to dry after being harvested (International Timber 2016). These different conditions of testing exist because the amount of moisture content in wood changes its physical size (Smith 2023). ASTM standards, such as D-4761 exist to regulate testing the proper conditions for the wood, such as 12% moisture content (ASTM 2003). Wood is known to expand physically with greater MC and shrink with less (Smith 2023), which can affect its mechanical properties.

Knowing moisture content is important for determining end uses for wood, as it can affect wood's mechanical properties and make it more or less applicable for a given purpose depending on the amount. Table 1 from Kretschmann (2010) displays various mechanical properties of several North American tree species, as well as how they are affected by having full (green) and 12% moisture content. The modulus of rupture and modulus of elasticity are consistently higher with 12% moisture content for all species presented. This shows that higher moisture content can prove detrimental to wood in terms of mechanical properties and that optimizing it is important for infrastructure.

Table. 1. Mechanical properties of various tree species in Canada with green and 12% moisture content (Modified from Kretschmann 2010).

Common Species Names	Moisture Content	Modulus of Rupture (kPa)	Modulus of Elasticity (Mpa)
Spruce, black	Green	42,000	9,500
	12%	74,000	11,100
Spruce, white	Green	34,000	7,900
	12%	65,000	9,600
Pine, eastern white	Green	34,000	6,800
	12%	59,000	8,500
Pine, jack	Green	41,000	7,400
	12%	68,000	9,300
Pine, red	Green	40,000	8,800
	12%	76,000	11,200
Fir, Balsam	Green	38,000	8,600
	12%	63,000	10,000

Moisture content can be measured in several ways, one of which is the mass-over-volume method under ASTM 2395. This method involves placing the wood on a scale to determine its mass (g) and then placing it in water to determine its volume (cm^3) via displacement (ASTM 2395-02 2008). The mass is then divided by the volume to get the density of the wood (ASTM 2395-02 2008). This can be done while the wood is dry or at green moisture but the ASTM 2395 standard is for 12% moisture content (ASTM 2395-02 2008).

Mechanical

Modulus of Elasticity

Modulus of elasticity is defined as "a materials ability to resist elastic deformation when stress is applied to it" (Team Xometry 2023). In other words, it is the point before a material cannot flex back into its natural shape after stress is put on it, essentially being a measure of stiffness. It is an essential parameter to consider when assessing the mechanical properties of wood, as it is useful for determining if certain wood or materials can be used in a load-bearing structure. Elements of a structure such as wood beams are commonly subjected to bending that causes deformations and shape changes in the wood (Babiak et al. 2018). This is especially important to monitor for Black spruce because it is used in infrastructure or any kind of load-bearing purposes. Liu et al. (2007) did a study of the MOE on the trees in a Black spruce forest in Eastern Canada and found that the average MOE was 12,235 MPa.

Compared to other commercial tree species used in North America, Black spruce has a slightly above-average modulus of elasticity (at 12% MC). Table 2 from Kretschmann (2010) displays the MOE of Black spruce and a number of other commercially valuable species grown and harvested in Canada and exported to the United States. The MOE of Black spruce is noticeably higher than many commercial hardwood and softwood species such as Balsam fir, various pines, and more. However, it still pales in comparison to some other commercial species like Trembling aspen and Douglas fir. This is not inherently bad, however, because an exceedingly high MOE indicates that a material is stiffer, which can be unsuitable depending on what purpose it will be used for.

Table 2. Modulus of elasticity (MPa) for numerous North American commercial tree species at 12% MC (Modified from Kretschmann 2010).

Species	Modulus of elasticity (MPa)
Trembling aspen	11,200
Western redcedar	8,200
Yellow cedar	11,000
Douglas fir	13,600
Balsam fir	9,600
Eastern hemlock	9,700
Eastern white pine	9,400
Jack pine	10,200
Lodgepole pine	10,900
Red pine	9,500
Black spruce	10,500
White spruce	10,000
Tamarack	9,400

Modulus of Rupture

The modulus of rupture (MOR) is another measure of wood's mechanical properties and is similar to the modulus of elasticity but is not the same. It is defined as “the measure of a specimen's strength before rupture” (The Wood Database N.d.). It essentially quantifies how much force a material can take before breaking. It is different from the modulus of elasticity in that it is used to determine a species' "overall strength" rather than deflection (The Wood Database N.d.). The same study mentioned previously from Liu et al. (2007) also monitored the modulus of rupture on a Black spruce stand in Eastern Canada and found that the average MOR was 58.98 MPa. Table 3 shows the previously mentioned results found in the study by Liu et al. (2007).

Table 3. MOE and MOR of Black spruce taken from natural stands (Modified from Liu et al. 2007).

Properties	Mean	Standard Deviation	Minimum	Maximum
MOE (Mpa)	12,235	1890	8593	16,568
MOR (Mpa)	58.98	14.79	30.59	94.97

Modulus of elasticity and modulus of rupture tests are typically done simultaneously and involve applying mechanical stress to the wood until it ruptures. The tests are generally done according to standards that specify how, and in what conditions the wood should be tested. One such testing method is the third point loading test, which involves loading the wood onto a device that has a point for support at each end, and a third point in the middle that applies pressure to the wood (ASTM 2003). The most common standard for wood that involves this test is ASTM-D4761, and it includes things like the moisture percentage the wood is to be tested in, being 12% (ASTM 2003).

Black spruce has a rather high modulus of rupture compared to other North American commercial softwoods like Pines and Firs (at 12% MC). This means that it can withstand a higher amount of stress before the risk of rupture. Black spruce is mainly used for pulp but also lumber (Farrar 1995), meaning it is important to know the limit of stress that the wood can take if it is going to be used for a load-bearing purpose. The species' comparatively high MOR, along with its abundance in Northwestern

Ontario, is what makes it so commonly used for commercial construction. Table 4 displays the MOR for Black spruce alongside several other commercial softwoods that grow in Northwestern, Ontario.

Table 4. Modulus of rupture (kPa) for Black spruce and other commercial softwood species in Northwestern Ontario (12% MC) (Modified from Kretschmann 2010).

Species	Modulus of Rupture (kPa)
Black spruce	74,000
White spruce	65,000
Eastern white pine	59,000
Jack pine	68,000
Red pine	76,000
Balsam fir	63,000
Subalpine fir	59,000

Compression Parallel to Grain

Compression testing is a type of mechanical stress testing in which pressure is placed parallel, perpendicular, or at an angle to the wood grain (Yuan et al. 2021). The longitudinal axis of wood is parallel to the fiber (grain) (Kretschmann 2010), meaning this test puts stress on the fibers of wood at various angles. Compression parallel to grain puts pressure on the wood’s longitudinal axis and shortens the cells (Yuan et al. 2021). The figure below displays a visual representation of a compression parallel to grain test, with pressure being put on both ends of the wood parallel to the fibers.

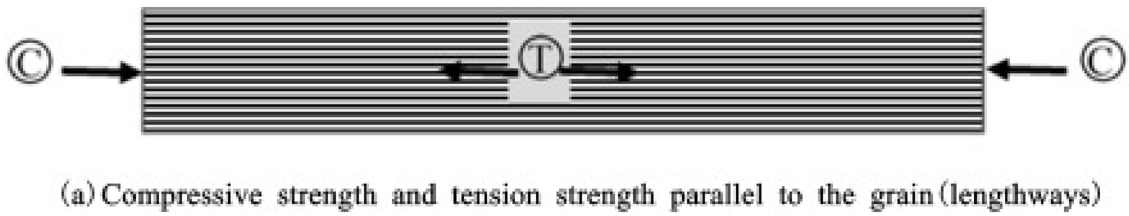

Figure 4. Visual representation of a compression parallel to wood grain test (Modified from Yuan et al. 2021).

Alongside MOE and MOR, this is a common test for determining wood mechanical properties. It assesses the wood's ability to support loads that put pressure on its longitudinal axis, such as buildings wall frames. Therefore, it is a very important characteristic to know when planning any kind of construction project, as, like MOE and MOR, it varies with species. Table 5 below displays compression parallel to grain for Black spruce and several other commercial softwood species commonly found in Northwestern Ontario (12%). Similar to the modulus of rupture for the same species, Black spruce is noticeably higher than all other species presented except for Red pine. This further presents Black spruce's importance as a commercial species in Ontario, as it has considerably impressive mechanical properties among the commercial softwoods in the region to go along with its substantial abundance.

Table 5. Compression parallel to grain (kPa) for various commercial softwoods in Northwestern Ontario (12% MC) (Modified from Kretschmann 2010).

Species	Compression Parallel to Grain (kPa)
Black spruce	41,000
White spruce	35,000
Eastern white pine	33,100
Jack pine	39,000
Red pine	41,900
Balsam fir	36,400
Subalpine fir	33,500

COMMON SILVICULTURAL TREATMENTS

Because of Black spruce's ability to tolerate and grow in a variety of stand conditions, it can be managed under all three silvicultural systems used in Ontario, Clearcut, Shelterwood, and Selection (Ontario 2019). However, it is most commonly managed under the clearcut system in Ontario (Ontario 2019). This is likely due to its abundance in Northern Ontario and the predominant use of the clearcut system in that portion of the province. Another reason would be the tendency of black spruce to be wind thrown if exposed. One of the most common Black spruce harvest methods is retaining younger stems during harvest and focusing machinery on small travel corridors to minimize disturbance to the forest floor and promote advance regeneration (Ontario 2019). Winter harvesting is also common for Black spruce due to the conditions of the stands in which they mostly grow making it difficult to use heavy machinery without causing substantial amounts of disturbance during summer months (Ontario 2019).

Managed Black spruce stands are commonly subjected to pre- and post-harvest treatments that are meant to ensure proper growth and low mortality. Common pre- and post-harvest treatments for Black spruce stands include prescribed burns, planting, and commercial thinning (Ontario 2019). These are commonly done to free up growing space for young stems and to promote advanced growth and regeneration (Ontario 2019). These treatments will have effects on mechanical properties due to the changes in the growth of the stems afforded by the different growing conditions.

THINNING

Thinning is a practice that can be used in high-density forest stands to free up growing space and improve growing conditions and wood quality (Forestry Commission

2015; Gonçalves 2021; Kerr and Haufe 2011). It can have several positive and negative impacts on things like competition species composition, diameter growth rate, timber value, risk of damage from abiotic sources or mortality, and volume of wood (Gonçalves 2021; Kerr and Haufe 2011). Thinning treatments can be developed and prescribed based on management objectives (Gonçalves 2021; Kerr and Haufe 2011), leaving flexibility in how they can be carried out. Thinning can be carried out on a percentage basis, often referred to as intensity, or through tree marking (Forestry Commission 2015; Gonçalves 2021). Tree marking is the practice of visually evaluating the forest stand and determining what trees to remove during the thinning based on management objectives, and other things like vigour and species of trees (Forestry Commission 2015; Gonçalves 2021).

Intensity is the other method of determining the degree to which thinning takes place (Forestry Commission 2015; Kerr and Haufe 2011). It is based on the percent of basal area or trees that are removed from the entire stand, and there exist set percentage classes that are used (Forestry Commission 2015; Gonçalves 2021). The three classes are light, moderate, and heavy thinning (Gonçalves 2021; Kerr and Haufe 2011). Light thinning constitutes the removal of <25% of the trees, and <20% of the basal area, moderate thinning is 50% of trees and 20-35% of the basal area, and heavy thinning is >50% of trees and >35% basal area (Gonçalves 2021).

Thinning is mainly done to free up growing space in a forest stand and allow trees to grow under less harsh conditions with the goal of better-quality wood (Forestry Commission 2015; Gonçalves 2021; Kerr and Haufe 2011), as well as provide an intermediate timber supply (Forestry Commission 2015). The degree of density and competition in a forest stand decreases with heavier thinning levels, and different species and canopy levels react differently (Gonçalves 2021). Thinning affects wood differently depending on its intensity. Light thinning causes trees to have more even growth rings with smaller diameter growth compared to heavy thinning (Gonçalves 2021). Heavy thinning causes trees to have larger, more irregularly shaped growth rings (Gonçalves 2021). This leads to the notion that light thinning creates better wood quality and heavy thinning creates more wood quantity (Gonçalves 2021).

Different thinning levels and forest stands' reactions to them are important to know when planning the stand's management direction. Radial growth is one of the most important parameters to consider if a stand is being thinned with the intention of harvesting it after a growing period. Table 6 shows the results of a study conducted by Soucy et al. (2012) on the effects of light and heavy thinning on the merchantable diameter of upland black spruce immediately after, 15 years after, and 33 years after the treatment. Purely from a diameter standpoint, the heaviest thinning caused the most diameter growth after the 33-year growth period, though it should be noted that it was lower than the lighter thinning earlier on and didn’t surpass it until sometime after the first 15 years.

Table 6. Mean merchantable diameter of upland Black spruce immediately and 15 and 33 years after thinning treatments (Modified from Soucy et al. 2012)

Thinning (%)	Immediately after treatment	15 years after treatment	33 years after treatment
		DBH (cm)	
0	11.8	12.6	14
25	11.6	12.5	14.1
50	11	12.6	14.5

As mentioned, thinning also increases the diameter growth of a stem. However, this effect also extends to the width of the tree’s growth rings. Vincent et al. (2011)

conducted a study on black spruce wood quality after thinning and found that ring width significantly increased over the 20-year growing period. This may not be problematic if the trees in the stand aren't going to be used for any sort of load-bearing purposes, but it could be problematic if they are because of the weaker mechanical properties that wide growth rings give trees. Figure 5 displays the results of the study conducted by Vincent et al. (2011) for the earlywood and latewood in the trees. Both the earlywood and latewood widths were steadily decreasing in the years before the thinning treatment and started to increase significantly a few years after.

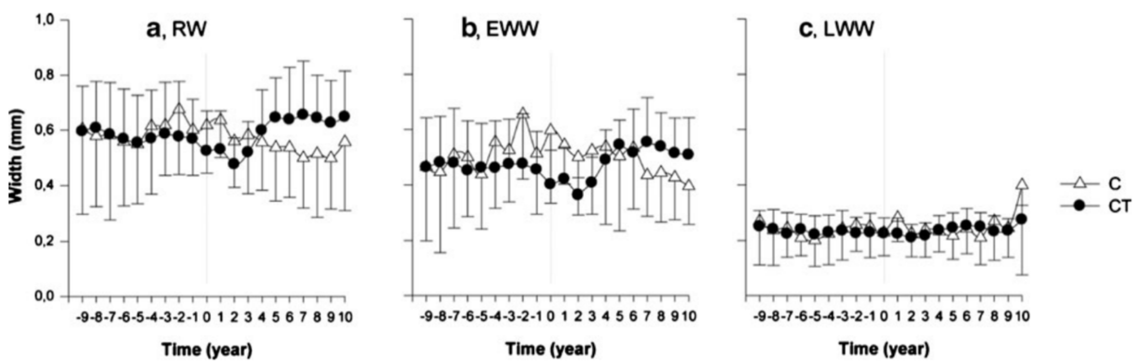

Figure 5. Earlywood (a) and latewood (b) width (mm) in the years after thinning black spruce stands compared to an un-thinned stand (c) (Vincent et al. 2011).

METHODS AND MATERIALS

STUDY AREA

The wood samples used in this thesis were provided from another study that was conducted involving Black spruce growth affected by silviculture treatments. The wood samples were collected from three Black spruce plantations located in the Superior Forest and Central Plateau in the boreal sections of northwestern Ontario (Levesque 2023). All three plantations are found within 50 km of Beardmore, Ontario (Levesque

2023). All sites had Permanent Sample Plots (PSP) set up, and each site had various treatments applied to its trees (Levesque 2023). Figure 6 displays the locations of the three study plantations, along with the treatments that were applied to them.

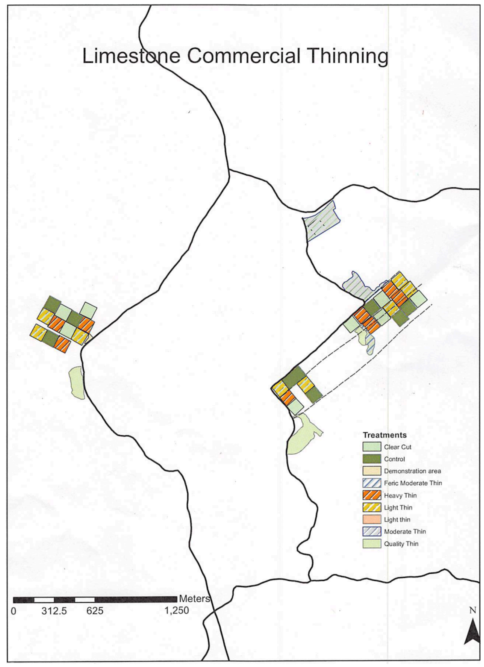

Figure 6. Map of the study area and treatments applied to each PSP (Levesque 2023).

EXPERIMENTAL DESIGN

Each site in the study area had multiple replicates of various silvicultural treatments done to them, totalling 33 between all three sites. The treatments applied included light thinning (LT), heavy thinning (HT), quality thinning (QT), and control (C) sites to compare the data against (Levesque 2023). Control, light thinning, and heavy thinning are the three main treatments that are relevant to this study. Permanent sample plots were set up in each of the study sites and each tree was measured for height, height to lowest live branch, DBH, acoustic velocity, and a 12mm increment core was taken (Levesque 2023). The North side of the tree was also identified and marked with spray paint. In total, 328 trees were measured, 205 were non-destructively measured and 123 destructively (Levesque 2023).

SAMPLE COLLECTION

Once the treatments were applied, the trees were left to grow for 15 years. After this, measurements and samples were taken from each tree to be tested. 1.5-metre bolts were taken from the bottom of each tree and returned to the Lakehead University Portable Milling Site for initial processing on a Wood Mizer LT40HD portable band sawmill. Each log was placed on the mill and with its North marker facing up so boards were sawn perpendicular to the North face of the log and labelled from 1 at the North labelled side and increasing numbers on the boards as the log was milled. Labels for board numbers were put on as the boards came off the mill and the logs boards were re-piled in order as they were sawn and then brought back to the LUWSTF for further processing. Each board was sawn into 1-inch thick pieces (Levesque 2023). From there, the boards were dried to 15% moisture content (tested every few days with portable moisture meters) and cut into 30 cm boards (Levesque 2023), with a 30 cm section being taken from each end of the 1.5-meter logs. The base of the log had a "B" in its label and the top of the lag had a "T" in its label. The 30 cm boards were then cut into 2 cm x 2 cm x 30 cm test sticks. The labelling of the boards is follows the position within the stem, where the North, East, South and West azimuths are labelled as is the test stick number from the pith in all directions. Each stick, therefore, has the label on it PGP#, TREE #, Board # (North=1), Axial position (1 is the lowest), Stick label (radial position from the pith (east or west)), and Group number (A is post-treatment, B is pre-treatment, and C is juvenile and before treatment). The sticks were then stored in a conditioning chamber to attain an equilibrium moisture content of 12% from the chamber being set at 65% relative humidity, and 20°C.

Three trees were in each of the three types of plots used for this thesis. Plot 19 (P19) was subjected to heavy thinning, and trees 6, 7, and 9 were harvested, cut, and labelled to be tested. Plot 20 (P20) was the lightly thinned plot, having trees 1, 2, and 4 being harvested. Lastly, Plot 21 (P21) was the control plot, having trees 11, 13, and 15.

PHYSICAL PROPERTY TESTING

The main physical property tested across all trees for this thesis was density. Density was taken at three different MC levels for this thesis: green, 12%, and oven-dried. However, it should be noted that 12% and oven-dried were the only two conditions used for the results analysis. The trees examined for this thesis were measured for density at two different periods. The first was the on-site measurements taken before the trees used in this experiment were felled. Increment cores were taken from the standing trees at around 50 cm above the ground, after which they were measured and weighed for green density (Levesque 2023). For 12% and oven-dried density, the 30 cm sticks were cut into 8 cm^3 density cubes after mechanical property testing was done and stored in the conditioning chamber to be brought to 12% MC. The cubes were then tested for density in the LUWSTF using the previously mentioned submersion method following the ASTM 2395 standards. The cubes were then placed in the oven in the LUWSTF for approximately five days until they were dried. The same density testing process was then repeated following the ASTM 2395 standards.

MECHANICAL PROPERTY TESTING

The samples from the experiment were tested for their mechanical properties in the LUWSTF. Properties that were tested include Modulus of Elasticity (MOE), Modulus of Rupture (MOR), and Compression Parallel to Grain. The tests were performed in the LUWSTF at 12% moisture content and following the ASTM D4761 standard on Tinius Olsen H10KT and H50KT Universal Wood Testing Machines using a Tinius Olsen 3-point testing tool and compression parallel to the grain testing tool. The results were used to assess and quantify the effects that different silviculture treatments have on wood mechanical properties.

STATISTICS

Statistical analysis of the data was done using R Studio, version 12.1+402. There were five different parameters that were evaluated and compared, MOE, MOR, compression parallel to grain, density at 12% MC, and dry density. The parameters were compared to the plot numbers (19 to 21) and treatment types separately to see if there was any kind of relationship. The five datasets were first tested for overdispersion, with varying results depending on the value found (>1 overdispersed). After the dispersion test, a generalized linear model (GLM) based on a negative binomial distribution was applied with a significance level of 0.05. If a statistically significant difference was found, a Tukey Multiple Comparison Test was applied with a significance level of 0.05 to evaluate the difference between both trees (P19T6 to P21T15) and treatment types (C= Control, Lt= Light thinning, and Ht= Heavy Thinning). Finally, boxplots were created to visually inspect the variability in results among the trees and treatment types that were found in each of the five types of tests.

RESULTS

The MOE data was found to be overdispersed when comparing all the trees as well as the treatments, with dispersion values of 1.041 and 1.035 respectively. The negative binomial distribution was then applied to the data to compare the trees and the treatments against each other, producing a value of 2.2e-16 for the trees and 0.062 for the treatments. This means a statistically significant relationship was found for the trees, but not between the treatments. The multiple comparison was then applied to compare the MOE results of each tree and treatment to see if the results suggest statistically significant differences. Tables 7 and 8 display the results of the multiple comparison tests between the nine trees and the three treatments for MOE, respectively. Of the 36 comparisons between the nine trees, 14 were found not to have statistically significant differences in the MOE values, while the remaining 22 did. No statistically significant differences were found when comparing the treatment types against each other.

Table 7. Tukey multiple comparison test for MOE (MPa) results between all nine trees (P<0.05).

Trees Compared	P Value
P19T7 VS P19T6	0.961
P19T9 VS P19T6	< 0.001
P20T1 VS P19T6	1.000
P20T2 VS P19T6	0.997
P20T4 VS P19T6	0.008
P21T11 VS P19T6	0.519
P21T13 VS P19T6	0.001
P21T15 VS P19T6	< 0.001
P19T9 VS P19T7	< 0.001
P20T1 VS P19T7	0.936
P20T2 VS P19T7	1.000
P20T4 VS P19T7	0.239
P21T11 VS P19T7	0.994
P21T13 VS P19T7	< 0.001
P21T15 VS P19T7	< 0.001
P20T1 VS P19T9	< 0.001
P20T2 VS P19T9	< 0.001
P20T4 VS P19T9	0.094
P21T11 VS P19T9	< 0.001
P21T13 VS P19T9	< 0.001
P21T15 VS P19T9	0.984
P20T2 VS P20T1	0.992
P20T4 VS P20T1	0.005
P21T11 VS P20T1	0.448
P21T13 VS P20T1	0.002
P21T15 VS P20T1	< 0.001
P20T4 VS P20T2	0.047
P21T11 VS P20T2	0.905
P21T13 VS P20T2	< 0.001
P21T15 VS P20T2	< 0.001
P21T11 VS P20T4	0.816
P21T13 VS P20T4	< 0.001
P21T15 VS P20T4	0.004
P21T13 VS P21T11	< 0.001
P21T15 VS P21T11	< 0.001
P21T15 VS P21T13	< 0.001

Table 8. Tukey multiple comparison test for MOE (Mpa) results between three treatment types (P<0.05).

Treatments Compared	P Value
Ht VS C	0.984
Lt VS C	0.141
Lt VS Ht	0.083

Figures 7 and 8 display boxplots comparing the MOE results between all trees and all treatment types, respectively. As per the results of the negative binomial distribution and multiple comparison tests, there is not much variability between the three treatments. However, some observable differences include the control trees having generally the most range in MOE values, especially in the interquartile range. The heavy and light-thinning trees had less range in values and that interquartile part of that range contained slightly lower values on average compared to control. The lightly thinned trees had the lowest median MOE and generally contained the lowest MOE values in its spread. For the trees, visible trends can be seen for the two thinned stands compared to the control stand, where there is significantly more variability across the three trees. Overall, the three trees from plot 19 appear to have the most consistently high MOE, with trees 6 and 7 having similar results and tree 9 having noticeably higher values. Plot 20 has similar results, but the MOE values are generally lower across the three trees, with tree 2 having the most variability of all nine. The control plots has the most variability across the three trees, with tree 13 having the lowest values in its range out of all nine trees and tree 15 having the most.

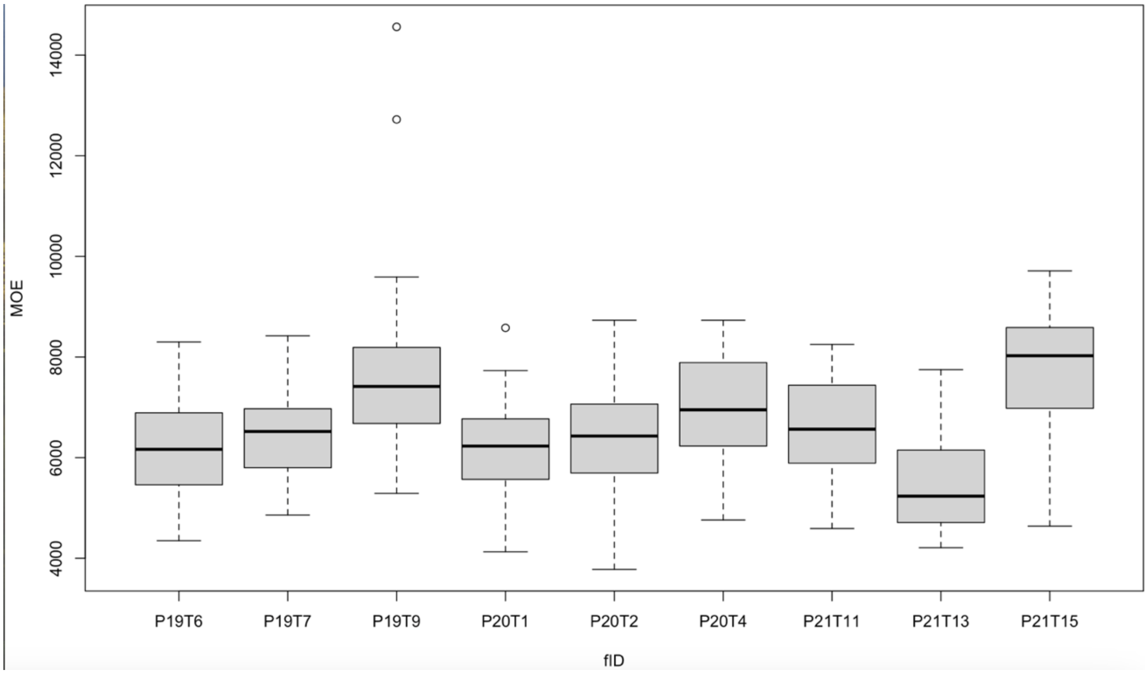

Figure 7. Boxplot graph of MOE (MPa) between all nine trees.

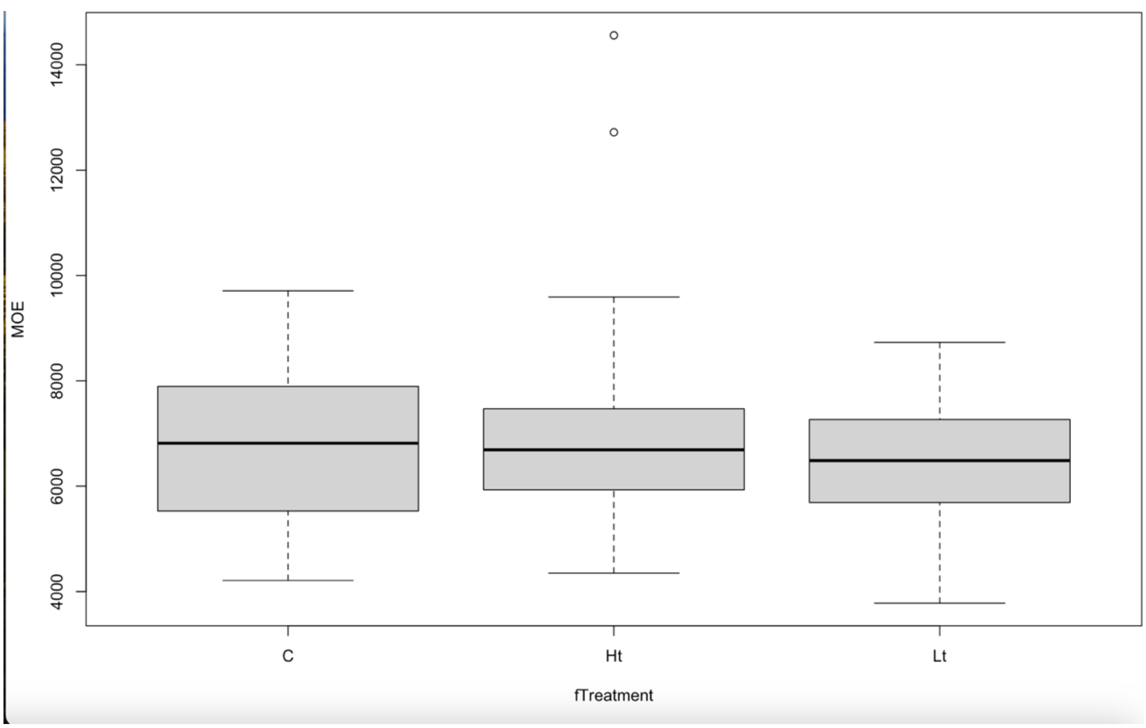

Figure 8. Boxplot graph of MOE (MPa) between the three treatments.

The MOR data produced dispersion values of 0.951 when comparing trees, and 1.001 when comparing treatments, meaning the trees were not overdispered but the treatments were by a slight margin. The negative binomial distribution produced a value of 2.2e-16 for the trees and 5.395e-10 for the treatments, meaning both have statistically significant differences in their results. Tables 9 and 10 show the results of the multiple comparison test on the MOR values between the nine trees, and the three treatments, respectively. For trees, 15 of the 36 comparisons were found to have statistically significant differences in their results, while the remaining 21 did not. For the treatments, the control trees were found to have results significantly different from both thinning's, which did not have significantly different results from each other.

Table 9. Tukey multiple comparison test for MOR (MPa) results between all nine trees ($P<0.05$).

Trees Compared	P Value
P19T7 VS P19T6	0.016
P19T9 VS P19T6	< 0.001
P20T1 VS P19T6	0.007
P20T2 VS P19T6	0.021
P20T4 VS P19T6	< 0.001
P21T11 VS P19T6	< 0.001
P21T13 VS P19T6	0.005
P21T15 VS P19T6	< 0.001
P19T9 VS P19T7	0.797
P20T1 VS P19T7	1.000
P20T2 VS P19T7	1.000
P20T4 VS P19T7	0.979
P21T11 VS P19T7	0.625
P21T13 VS P19T7	1.000
P21T15 VS P19T7	< 0.001
P20T1 VS P19T9	0.899
P20T2 VS P19T9	0.483
P20T4 VS P19T9	1.000
P21T11 VS P19T9	1.000
P21T13 VS P19T9	0.988
P21T15 VS P19T9	< 0.001
P20T2 VS P20T1	1.000
P20T4 VS P20T1	0.995
P21T11 VS P20T1	0.762
P21T13 VS P20T1	1.000
P21T15 VS P20T1	< 0.001
P20T4 VS P20T2	0.867
P21T11 VS P20T2	0.312
P21T13 VS P20T2	0.995
P21T15 VS P20T2	< 0.001
P21T11 VS P20T4	0.996
P21T13 VS P20T4	1.000
P21T15 VS P20T4	< 0.001
P21T13 VS P21T11	0.945
P21T15 VS P21T11	< 0.001
P21T15 VS P21T13	< 0.001

Table 10. Tukey multiple comparison test for MOR (Mpa) results between three treatment types (P<0.05).

Treatments Compared	P Value
Ht VS C	<1e-04
Lt VS C	<1e-04
Lt VS Ht	0.351

Figures 9 and 10 display boxplots of the MOR results for the nine trees and three treatments, respectively. Between the two thinned plots, plot 20 has more consistent and generally higher MOR values than plot 19. Plot 20 appears to have a noticeably large spread of results, particularly in Tree 1. However, the difference isn't large, and Tree 7 has a similarly large spread, so it's feasible to say that Plot 20 overall has higher MOR results between its three trees compared to Plot 19. Similarly to MOE, Plot 21 has substantially different results between its three trees, both in terms of how high the MOR values are on average and the size of the spread.

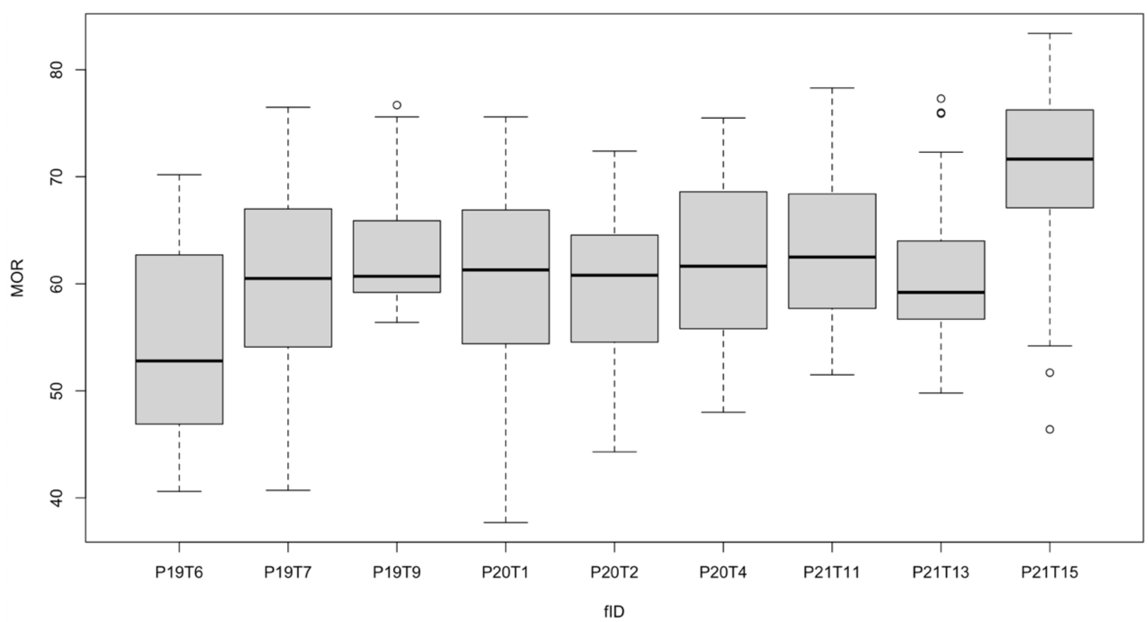

Figure 9. Boxplot graph of MOR (MPa) between all nine trees.

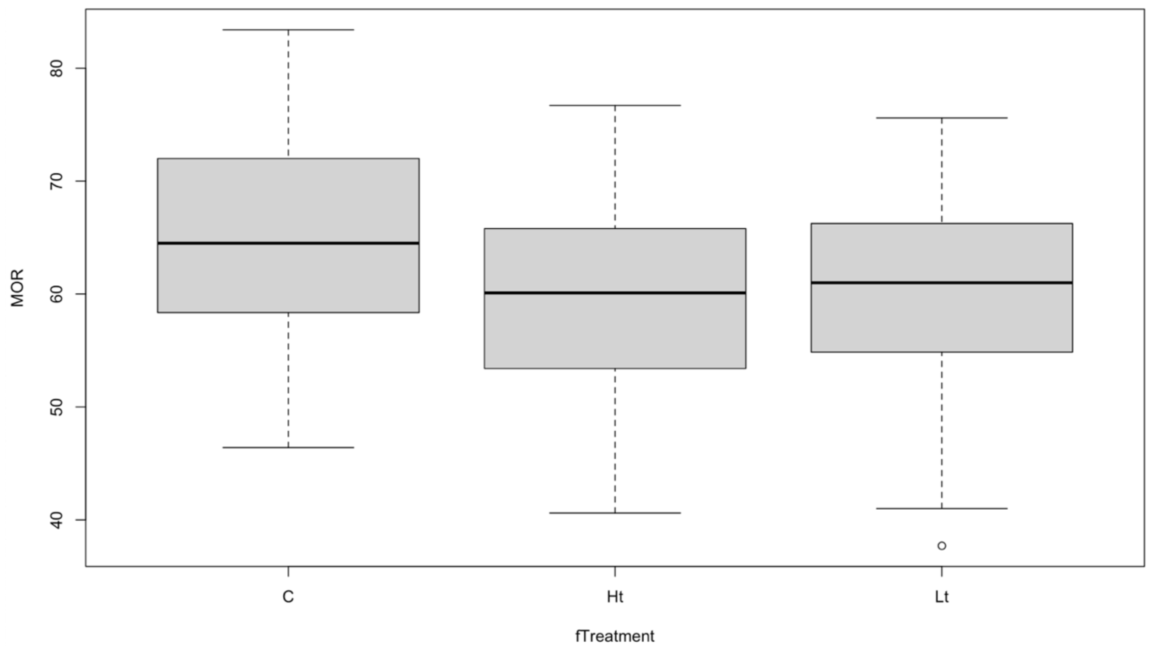

Figure 10. Boxplot graph of MOR (MPa) between the three treatments.

The compression parallel to grain data produced a dispersion value of 0.737 for trees and 0.929 for treatments. The negative binomial distribution produced values of 2.2e-16 for trees and 0.002 for treatments, meaning both are statistically significant. Tables 11 and 12 show the multiple comparison results for trees and treatments for compression parallel to grain, respectively. For the trees, 13 of the 36 comparisons showed statistically significant results. For the treatments, the control plot showed significant difference in the results compared to both thinning treatments, but the thinning treatments did not have statistically significant results from each other.

Table 11. Tukey multiple comparison test for compression parallel to grain (MPa) results between all nine trees (P<0.05).

Trees Compared	P Value
P19T7 VS P19T6	< 0.001
P19T9 VS P19T6	< 0.001
P20T1 VS P19T6	< 0.001
P20T2 VS P19T6	< 0.001
P20T4 VS P19T6	0.301
P21T11 VS P19T6	0.011
P21T13 VS P19T6	0.760
P21T15 VS P19T6	< 0.001
P19T9 VS P19T7	0.993
P20T1 VS P19T7	1.000
P20T2 VS P19T7	1.000
P20T4 VS P19T7	0.556
P21T11 VS P19T7	0.998
P21T13 VS P19T7	0.283
P21T15 VS P19T7	< 0.001
P20T1 VS P19T9	1.000
P20T2 VS P19T9	0.990
P20T4 VS P19T9	0.083
P21T11 VS P19T9	0.784
P21T13 VS P19T9	0.029
P21T15 VS P19T9	0.002
P20T2 VS P20T1	1.000
P20T4 VS P20T1	0.356
P21T11 VS P20T1	0.984
P21T13 VS P20T1	0.157
P21T15 VS P20T1	< 0.001
P20T4 VS P20T2	0.435
P21T11 VS P20T2	0.996
P21T13 VS P20T2	0.195
P21T15 VS P20T2	< 0.001
P21T11 VS P20T4	0.952
P21T13 VS P20T4	1.000
P21T15 VS P20T4	< 0.001
P21T13 VS P21T11	0.754
P21T15 VS P21T11	< 0.001
P21T15 VS P21T13	< 0.001

Table 12. Tukey multiple comparison test for compression parallel to grain (Mpa) results between three treatment types (P<0.05).

Treatments Compared	P Value
Ht VS C	0.002
Lt VS C	0.036
Lt VS Ht	0.533

Figures 11 and 12 show the boxplot results for compression parallel to grain for the nine trees and the three treatments respectively. Plot 20 appears to have the most consistent max stress point, with tree 4 being the only tree that has slightly different results. Plot 19 is somewhat similar, but there is more range in values and tree 17 has some of the highest values in its upper range out of all the trees from the thinned plots. However, it also has some of the lowest max stress values out of all nine trees with tree 6. The control trees have the most variability between the three them, with tree 15 having the highest max stress points overall and in terms of its range.

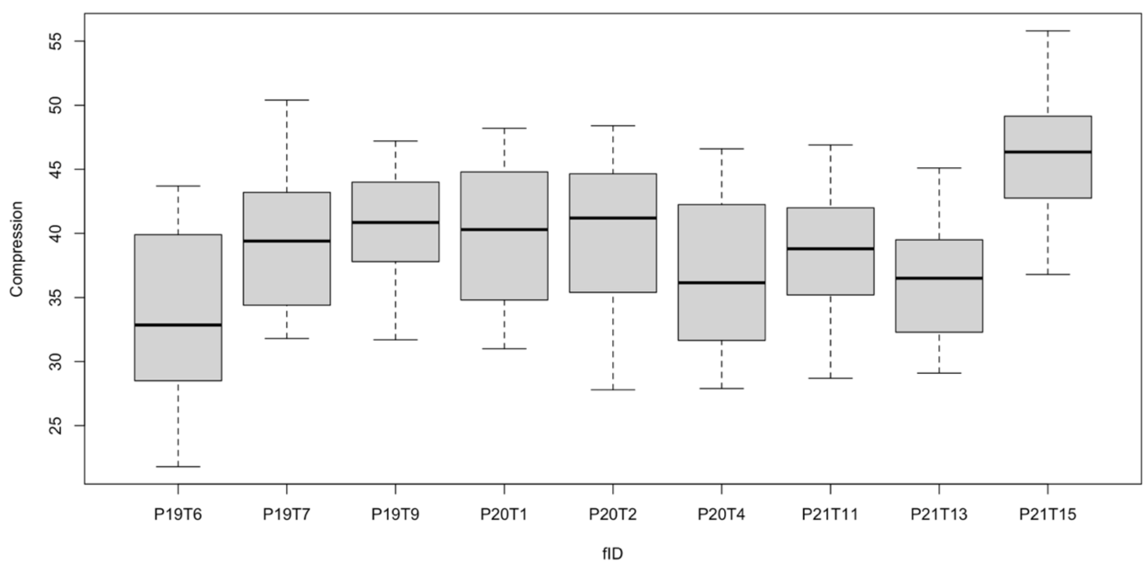

Figure 11. Boxplot graph of compression parallel to grain (MPa) between all nine trees.

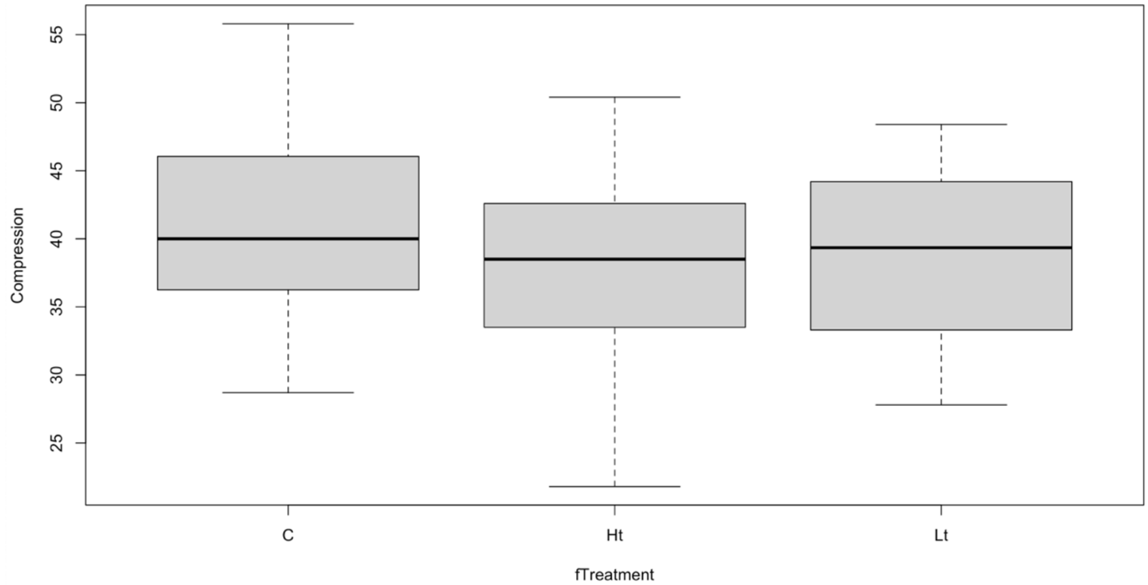

Figure 12. Boxplot graph of compression parallel to grain (MPa) between the three treatments.

The dry density results produced dispersion values of 0.002 for the trees and 0.003 for the treatments, indicating very little dispersion in the results. The negative binomial distribution mirrored these results, producing a value of 0.999 for the nine trees and 0.976 for the three treatments. This shows that there is almost no difference in the results for dry density, meaning the multiple comparison test is unnecessary for the dry density data.

Figures 13 and 14 display the boxplot results for the dry density tests for the nine trees, and the three treatments, respectively. Due to the boxplot exaggerating the small differences between the tree's density values, differences can be seen, though they are very small and not statistically significant. However, it can be seen that Plots 19 and 20 have very similar density values, with Plot 20 having mostly higher density overall compared to Plot 19. Plot 21 has the most variability between its three trees, with tree 15 having the highest density values throughout its rather small range. These differences, however, are still not significant enough to consider when assessing the results of the testing. This is even more prominent when comparing the three treatments, which have even less variability between them.

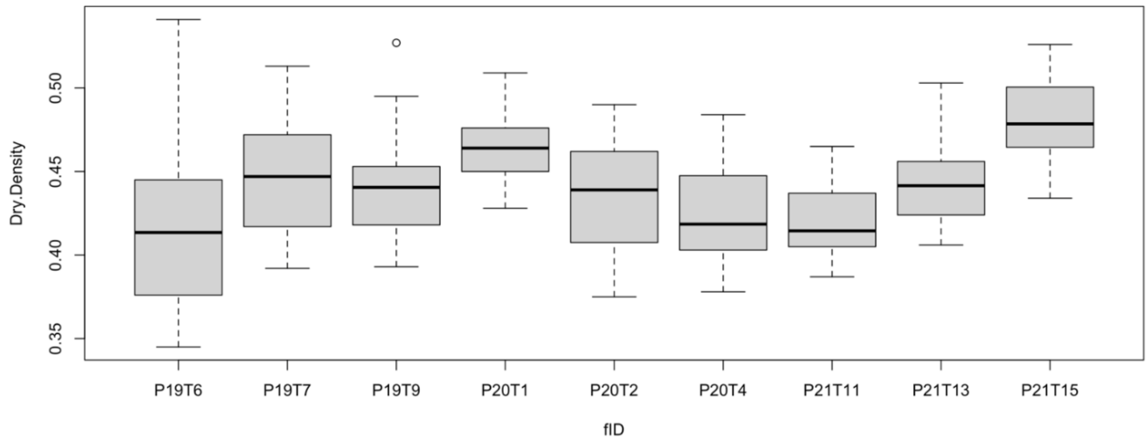

Figure 13. Boxplot graph of dry density (g/cm3) between all nine trees.

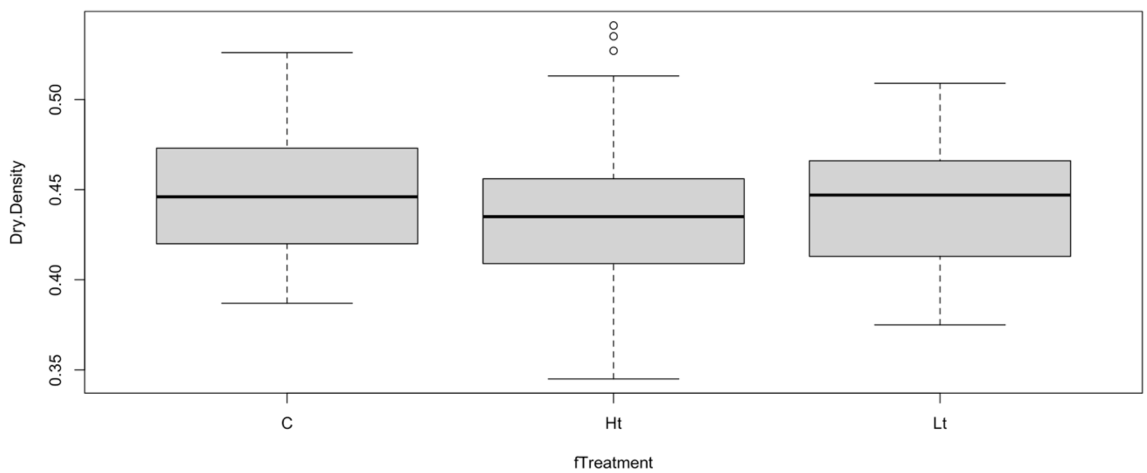

Figure 14. Boxplot graph of dry density (g/cm3) between the three treatments.

Finally, the density at 12% MC yielded similar results to dry density in terms of the dispersion values, which were 0.002 for the trees and 0.003 for the treatments. For the negative binomial distribution, the nine trees yielded a value of 0.999 and the treatments a value of 0.972. This means that there are also no statistically significant results between the density of the trees when comparing them individually or as the treatments they are a part of.

Figures 15 and 16 display box plots for the 12% density results for all nine trees and three treatments, respectively. There is slightly more variability in the results compared to dry density. However, the general trends of which trees have the highest values and highest ranges are still similar. The trees in Plot 21 (control) have overall the highest density between all three, with slightly less variability than Plot 19's trees. Tree 6 from Plot 19 has some of the highest density values out of the entire set, but they appear outside the interquartile range. Plot 20 has the lowest range of density results of the three treatment types and slightly higher density values overall compared to Plot 19. These results are very similar to those of the dry density, showing that the lightly thinned plot has trees with higher density than those of the heavily thinned plot.

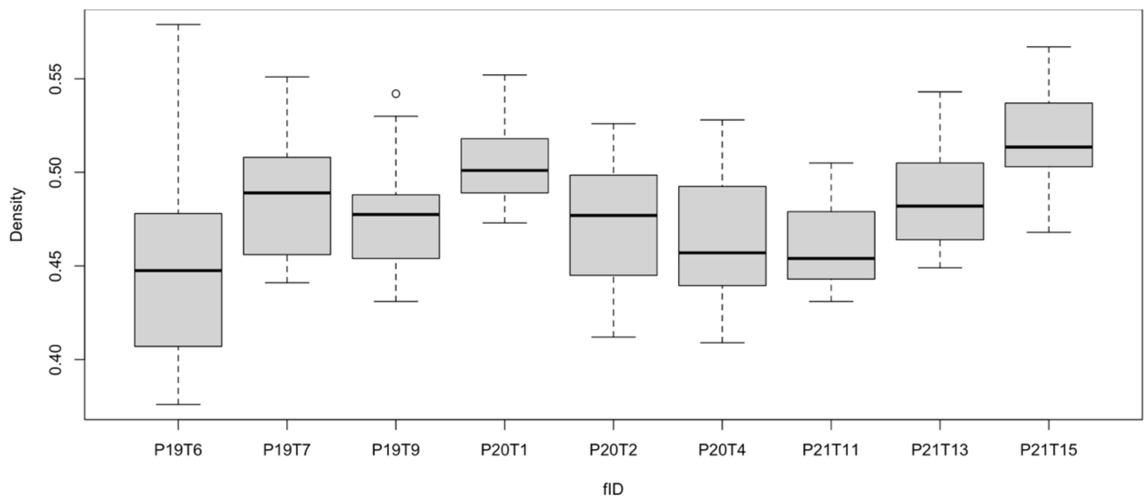

Figure 15. Boxplot graph of density (g/cm3) at 12% MC between all nine trees.

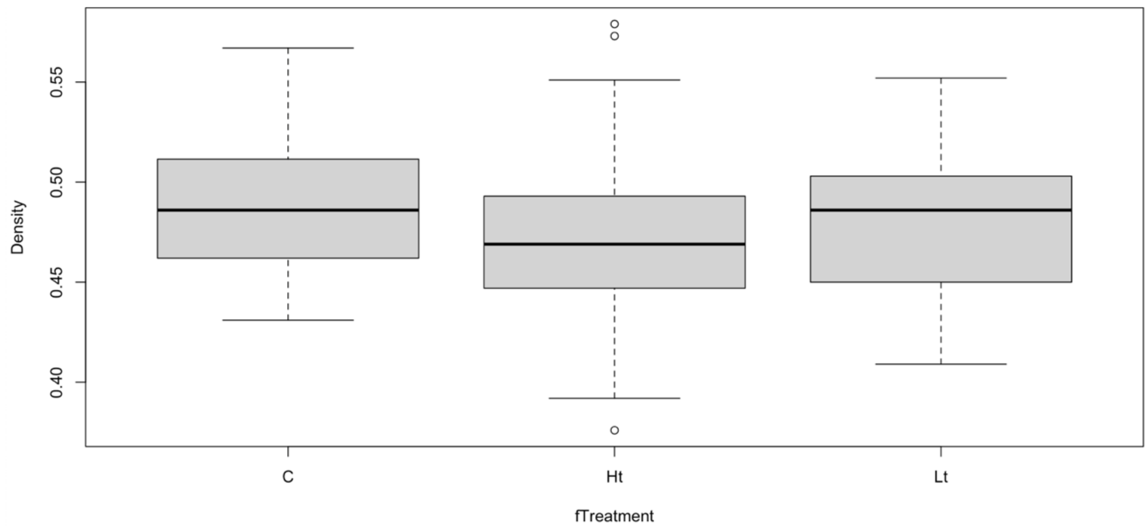

Figure 16. Boxplot graph of density (g/cm3) at 12% MC between the three treatments.

DISCUSSION

From testing the modulus of elasticity, modulus of rupture, compression parallel to grain, dry density, and density at 12% moisture content, the trees from the control plot generally had the highest properties, but they were sometimes by very slight margins depending on the property type. The trees from the control plot also had generally the most variability in them, meaning they had some of the highest and lowest values out of the entire range in most of the property types. For example, the trees from the control plot had generally the highest range in MOE of the three treatment types. However, its MOE values were not significantly different from trees from the thinned plots, as per what is visually observable from the box plot, as well as the results of the multiple comparison test. These results are mirrored in the other four property types, where control has the highest values in its interquartile range but also the highest range overall. Since the control stand was not thinned at all, it was not subjected to any release from competition, meaning its growth was likely slower, which can be used to explain this.

This result is supported by the findings of the literature review, where the act of thinning is meant to regulate a wood supply (Forestry Commission 2015) so that good timber can be harvested immediately. Without the thinning treatment, the conditions aren't appropriate to support consistently higher mechanical properties. Some trees may end up having stronger mechanical properties in control plots due to several possible scenarios, but the results won't be as consistent as the thinning treatments because they are meant to free up growing conditions and make them uniform for the entire stand (Forestry Commission 2015; Gonçalves 2021; Kerr and Haufe 2011).

Results for the two thinning treatments show that the trees from the lightly thinned plots generally had higher values in most properties. The only exception was the modulus of elasticity, where the heavily thinned plot had slightly higher values in its range and a smaller interquartile range compared to the lightly thinned plot. Aside from this, however, the lightly thinned plot had generally higher values within its ranges and smaller ranges in terms of the interquartile, and the entire range. The negative binomial distribution test stating a lack of statistically significant results can be due to the trees simply not having enough time to grow to produce significantly different results, as they only had 15 years. The study from Soucy et al. (2012) (table 6) displays how longer growth periods can influence diameter growth, where the lighter thinning had a higher average diameter in the early years after the thinning but was surpassed by the heavier thinning by the time 30 years had passed after the thinning. This means that had the trees involved in this thesis been given more time to grow, different or more exaggerated results may have been found. Despite the test displaying no significant differences between the two thinning types compared to the control plot, slight differences can be observed in the boxplots. They allow a closer look at the differences in the results between the three treatments, and the ability to surmise differences in the range of results and which plots produced generally higher values. These results mostly align with those found in the literature review, where the lighter thinning produces generally better mechanical properties (Gonçalves 2021). The trees from the heavily thinned plot may have had a higher MOE than those from the lightly thinned plot due a number of factors not accounted for, such as differences in growing conditions. However, this may simply be a product of a small sample size, as other studies similar to this generally use more trees to get better, less subtle results, such as the study from Vincent et al. (2011) using 35 trees.

With these results, the hypothesis of this thesis can be accepted because the two plots that had more oppressive growth conditions became the ones to produce the trees with the higher physical and mechanical properties. The more open growing conditions of the heavily thinned plot likely caused the trees to be able to grow more freely and fast, but in turn, this caused them not to develop as strong physical and mechanical properties as the trees in the plots that had conditions that forced them to grow slower. This leaves more room for the trees to develop slower, which is a characteristic of light thinning treatments that results in generally smaller growth rings and higher-density wood (Gonçalves 2021). These characteristics lead to stronger physical and mechanical properties (Gonçalves 2021). The results didn’t completely support the hypothesis, mostly due to the differences in the MOE results and small differences in the values found in the results, but the majority still support that it is correct.

CONCLUSION

This thesis reviewed the literature on the physical and mechanical properties of Black spruce (mainly those related to commercial uses) and assessed how those properties are affected by heavy versus light thinning treatments compared to natural, undisturbed growth. Its purpose was to get an idea of what thinning level creates the best physical and mechanical properties for infrastructure purposes. Since Black spruce is one of the most common softwood trees in Northwestern Ontario and is commonly used for infrastructure and load-bearing purposes, this is valuable knowledge. With the results found from the testing done at the LUWSTF, light thinning appears to be the best thinning level to create the best physical and mechanical properties, as heavy thinning results in slightly weaker properties and while not thinning at all can produce properties even stronger than those of light thinning, there is much more variability in the results. This means that light thinning is the best for maximizing the mechanical properties of wood that is to be used for load-bearing purposes, as it achieves the best balance of high properties and consistency of those properties in different trees.

As for some potential sources of unreliability or variation in results that could be the subject of further future research, larger sample sizes would be beneficial to help obtain more narrow ranges of results, as this study only used three trees per plot to base its results upon. Longer growing periods after treatment can also likely see different results, as the results of this thesis are somewhat different than those of thinning studies that have had longer growing periods of the treatment, such as the study conducted by Soucy et al. (2012) mentioned previously. Finally, more detailed data analysis that can more closely evaluate the differences between traits like density may be beneficial to be able to see a better distinction between how density is affected by moisture content levels.

The results of this thesis can be applied to real-world management strategies for Black spruce trees, as they give insight into what thinning level between light and heavy works best for maximizing growth-related properties. Given how common Black spruce is in Ontario and how much it is used for infrastructure, this knowledge is important to have and can be applied when deciding on the end uses for wood in commercial tree stands. Knowing what thinning level creates the best quality wood the most consistently is vital information to have, especially in forests that are harvested for commercial lumber.

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APPENDICES

APPENDIX I

RAW CONSOLIDATED DATA

Treatment	Sample ID	Sample No.	MOE (MPa)	MOR(MPa)	Max Stress (MPa) (Compression)	Density (12% MC) (g/cm3)	Density (Dry) (g/cm3)
Ht	P19T6	1.1E1A	6890	64.9	42.6	0.499	0.458
Ht	P19T6	1.1W1B	6530	66.6	37.9	0.453	0.419
Ht	P19T6	1.1W2A	8110	69.4	42.9	0.496	0.459
Ht	P19T6	1.2E1A	6770	62.4	40.9	0.452	0.419
Ht	P19T6	1.2E2A	7050	65.5	43.7	0.474	0.452
Ht	P19T6	1.2W1A	6920	61.9	42.5	0.492	0.453
Ht	P19T6	2.1E1C	4350	40.6	21.8	0.376	0.345
Ht	P19T6	2.1E2B	5200	44.6	27.1	0.398	0.357
Ht	P19T6	2.1E3A	6350	62.2	41.3	0.459	0.448
Ht	P19T6	2.1W1C	5560	46.8	31.2	0.410	0.376
Ht	P19T6	2.1W2A	6910	70.2	40.5	0.527	0.489
Ht	P19T6	2.2E1C	4680	44.8	32.9	0.403	0.368
Ht	P19T6	2.2E2A	7090	59.7	41.9	0.471	0.432
Ht	P19T6	2.2W1C	5080	48.5	26	0.400	0.366
Ht	P19T6	2.2W2C	5580	52.3	32.3	0.396	0.367
Ht	P19T6	2.2W3A	7590	65.9	42.3	0.504	0.469
Ht	P19T6	3.1E1C	5570	44.6	27.9	0.426	0.387
Ht	P19T6	3.1E2C	5800	43.7	27.4	0.392	0.364
Ht	P19T6	3.1E3A	7270	66.5	39.7	0.490	0.448
Ht	P19T6	3.1W1C	5300	46.7	28.8	0.428	0.399
Ht	P19T6	3.1W2C	5980	40.9	24.7	0.398	0.367
Ht	P19T6	3.1W3A	8300	68.5	37.5	0.573	0.535
Ht	P19T6	3.2E1C	5490	50.9	29.1	0.447	0.408
Ht	P19T6	3.2E2C	5970	46.5	31.8	0.410	0.376
Ht	P19T6	3.2E3A	7020	62.9	42.8	0.483	0.433
Ht	P19T6	3.2W1C	4980	46.9	31.1	0.432	0.392
Ht	P19T6	3.2W2C	6200	45.4	28	0.394	0.361
Ht	P19T6	3.2W3A	6880	67	42.1	0.579	0.541
Ht	P19T6	4.1E1C	7290	45.4	29.5	0.478	0.436
Ht	P19T6	4.1E2C	6770	50.3	39.9	0.405	0.371
Ht	P19T6	4.1E3A	7700	66.2	30.1	0.458	0.416
Ht	P19T6	4.1W1C	4830	49.1	30.4	0.481	0.439
Ht	P19T6	4.1W2C	6130	47	28.1	0.395	0.366

Treatment	Sample ID	Sample No.	MOE (MPa)	MOR(MPa)	Max Stress (MPa) (Compression)	Density (12% MC) (g/cm3)	Density (Dry) (g/cm3)
Ht	P19T6	4.1W3A	6690	53	32.8	0.448	0.417
Ht	P19T6	4.2E1C	4970	47.1	29.3	0.466	0.428
Ht	P19T6	4.2E2C	6280	49.7	30.6	0.407	0.374
Ht	P19T6	4.2E3A	8010	68.4	42.6	0.472	0.440
Ht	P19T6	4.2W1C	5980	48.2	27.3	0.414	0.378
Ht	P19T6	4.2W2A	6570	61.1	33.5	0.473	0.445
Ht	P19T6	5.1E1B	6110	57.9	27.4	0.427	0.389
Ht	P19T6	5.1E2A	6530	62.7	36	0.451	0.414
Ht	P19T6	5.1W1C	5050	47.9	27.9	0.403	0.369
Ht	P19T6	5.1W2A	5150	46.9	34.7	0.419	0.390
Ht	P19T6	5.2E1C	5820	55.1	27.7	0.422	0.388
Ht	P19T6	5.2E2A	5720	59.4	39.9	0.467	0.429
Ht	P19T6	5.2W1C	5380	48.5	28.5	0.406	0.379
Ht	P19T6	5.2W2A	5220	53	34.7	0.429	0.413
Ht	P19T6	6.1E1A	6470	59.2	36.9	0.490	0.452
Ht	P19T6	6.1W1A	5460	52.6	38.1	0.438	0.408
Ht	P19T6	6.2E1A	6860	62.6	36.4	0.480	0.452
Ht	P19T7	1.1E1B	6000	61.5	39.4	0.482	0.435
Ht	P19T7	1.1E2A	6530	60.6	43.5	0.523	0.475
Ht	P19T7	1.1W1B	6510	60.9	37.4	0.459	0.424
Ht	P19T7	1.1W2A	6610	67.1	42.5	0.513	0.474
Ht	P19T7	1.2E1B	6030	57.8	40.2	0.468	0.437
Ht	P19T7	1.2E2A	6800	64.7	43.2	0.498	0.457
Ht	P19T7	1.2W1B	7260	66.4	41.2	0.526	0.488
Ht	P19T7	1.2W2A	6970	62.3	44.4	0.511	0.473
Ht	P19T7	2.1E1C	5640	54.1	31.9	0.446	0.409
Ht	P19T7	2.1E2B	5490	50.8	36.1	0.456	0.417
Ht	P19T7	2.1E3A	6520	62.7	43	0.498	0.456
Ht	P19T7	2.1W1C	4860	50	31.9	0.469	0.421
Ht	P19T7	2.1W2C	6300	51.1	34.7	0.457	0.420
Ht	P19T7	2.1W3A	7430	68.6	45.2	0.537	0.500
Ht	P19T7	2.2E1C	5130	51.1	32.3	0.452	0.412
Ht	P19T7	2.2E2B	5960	54.4	37.4	0.452	0.417
Ht	P19T7	2.2E3A	5950	60.1	41.8	0.512	0.468
Ht	P19T7	2.2W1C	5320	52.5	32.9	0.454	0.421
Ht	P19T7	2.2W2B	6060	54.7	37.9	0.451	0.417
Ht	P19T7	2.2W3A	7470	67.7	41.3	0.532	0.495
Ht	P19T7	3.1E1C	5700	53.4	31.8	0.442	0.404

Treatment	Sample ID	Sample No.	MOE (MPa)	MOR(MPa)	Max Stress (MPa) (Compression)	Density (12% MC) (g/cm3)	Density (Dry) (g/cm3)
Ht	P19T7	3.1E2B	6090	56.6	32.1	0.451	0.408
Ht	P19T7	3.1E3A	8420	76.5	43.7	0.504	0.460
Ht	P19T7	3.1W1C	4900	42.6	38.7	0.492	0.447
Ht	P19T7	3.1W2C	7370	60.5	34.3	0.444	0.408
Ht	P19T7	3.1W3A	7940	69.9	42.1	0.498	0.468
Ht	P19T7	3.2E1C	5980	52.7	33	0.455	0.413
Ht	P19T7	3.2E2C	5740	54.2	34.3	0.456	0.410
Ht	P19T7	3.2E3A	6550	71.3	42.5	0.505	0.458
Ht	P19T7	3.2W1C	5750	47.1	31.8	0.503	0.459
Ht	P19T7	3.2W2C	6930	59.5	35	0.449	0.411
Ht	P19T7	3.2W3A	7980	74.2	39.7	0.509	0.476
Ht	P19T7	4.1E1C	5070	40.7	33.6	0.441	0.392
Ht	P19T7	4.1E2B	6710	48.9	34.4	0.456	0.416
Ht	P19T7	4.1E3A	8040	64.6	43.2	0.490	0.447
Ht	P19T7	4.1W1C	5850	57.6	32.7	0.463	0.422
Ht	P19T7	4.1W2B	6540	56.3	38	0.468	0.425
Ht	P19T7	4.1W3A	6830	66.1	49.8	0.544	0.504
Ht	P19T7	4.2E1C	5800	59.1	35.1	0.460	0.420
Ht	P19T7	4.2E2C	5010	51.5	36.8	0.444	0.405
Ht	P19T7	4.2E3A	6940	63.1	42	0.489	0.450
Ht	P19T7	4.2W1C	5460	55.9	38.1	0.465	0.428
Ht	P19T7	4.2W2A	5930	62.9	43.9	0.519	0.483
Ht	P19T7	5.1E1A	6620	70.7	47.4	0.504	0.467
Ht	P19T7	5.1W1B	6760	73.8	43.3	0.492	0.452
Ht	P19T7	5.1W2A	7200	67	50.4	0.523	0.482
Ht	P19T7	5.2E1A	7650	69.7	46.7	0.508	0.473
Ht	P19T7	5.2W1B	7420	73.4	47.8	0.504	0.472
Ht	P19T7	5.2W2A	7660	72.7	47.7	0.551	0.513
Ht	P19T9	1.1E1A	8940	65.8	45.1	0.486	0.449
Ht	P19T9	1.1W1B	7770	68.8	43.4	0.486	0.446
Ht	P19T9	1.1W2A	7250	69.4	42.9	0.505	0.466
Ht	P19T9	1.2E1A	8550	76.7	45.1	0.497	0.457
Ht	P19T9	1.2W1A	7560	72.6	47.2	0.530	0.491
Ht	P19T9	2.1E1B	6450	57.4	36.1	0.431	0.395
Ht	P19T9	2.1E2A	9380	59.8	44.2	0.484	0.446
Ht	P19T9	2.1W1B	6520	59.2	38.6	0.463	0.425
Ht	P19T9	2.1W2B	7090	57.1	40.3	0.451	0.409
Ht	P19T9	2.1W3A	8600	67.6	45.7	0.494	0.456

Treatment	Sample ID	Sample No.	MOE (MPa)	MOR(MPa)	Max Stress (MPa) (Compression)	Density (12% MC) (g/cm3)	Density (Dry) (g/cm3)
Ht	P19T9	2.2E1B	6440	59.2	40.5	0.455	0.418
Ht	P19T9	2.2E2A	8370	62	45.7	0.476	0.446
Ht	P19T9	2.2W1B	6290	60.4	38.1	0.436	0.406
Ht	P19T9	2.2W2B	7080	64.1	41.8	0.478	0.441
Ht	P19T9	2.2W3A	7640	66.1	45.8	0.493	0.462
Ht	P19T9	3.1E1C	7900	56.8	37.1	0.453	0.416
Ht	P19T9	3.1E2B	7080	60.4	38.7	0.465	0.429
Ht	P19T9	3.1E3A	8380	62.6	43.7	0.529	0.527
Ht	P19T9	3.1W1C	5290	56.6	34.6	0.485	0.440
Ht	P19T9	3.1W2C	7100	63.2	38.6	0.445	0.405
Ht	P19T9	3.1W3A	9030	71	44.5	0.487	0.450
Ht	P19T9	3.2E1C	7350	59.8	36.4	0.476	0.438
Ht	P19T9	3.2E2B	7720	62.5	38.5	0.454	0.418
Ht	P19T9	3.2E3A	7360	60.2	43.6	0.510	0.468
Ht	P19T9	3.2W1C	6270	61.9	36.3	0.498	0.456
Ht	P19T9	3.2W2C	6600	57.8	38.5	0.444	0.405
Ht	P19T9	3.2W3A	7250	69.2	41.2	0.484	0.447
Ht	P19T9	4.1E1C	6870	56.5	34.3	0.451	0.409
Ht	P19T9	4.1E2B	7790	64.7	36.2	0.485	0.448
Ht	P19T9	4.1E3A	6580	69.7	43.7	0.542	0.495
Ht	P19T9	4.1W1C	5540	57	32.2	0.483	0.444
Ht	P19T9	4.1W2C	7590	60.3	33.2	0.456	0.418
Ht	P19T9	4.1W3A	9480	75.6	45.2	0.488	0.453
Ht	P19T9	4.2E1C	7690	59	36.3	0.450	0.412
Ht	P19T9	4.2E2C	7700	67.2	39.1	0.466	0.476
Ht	P19T9	4.2E3A	7470	60.4	44	0.514	0.467
Ht	P19T9	4.2W1C	5500	56.4	36.8	0.488	0.444
Ht	P19T9	4.2W2C	6990	57.7	31.7	0.440	0.406
Ht	P19T9	4.2W3A	12720	74.8	42.3	0.495	0.462
Ht	P19T9	5.1E1B	7590	58.2	38.4	0.491	0.445
Ht	P19T9	5.1E2A	14560	59.6	45	0.516	0.468
Ht	P19T9	5.1W1C	5930	58.7	34.5	0.432	0.393
Ht	P19T9	5.1W2C	5780	57.3	38.7	0.438	0.399
Ht	P19T9	5.1W3A	7470	64.1	41.9	0.474	0.439
Ht	P19T9	5.2E1C	6850	65.9	38.3	0.439	0.407
Ht	P19T9	5.2E2B	6280	59.4	39.5	0.466	0.428
Ht	P19T9	5.2E3A	9160	61	44.4	0.478	0.440
Ht	P19T9	5.2W1C	6680	62.2	37.8	0.447	0.413

Treatment	Sample ID	Sample No.	MOE (MPa)	MOR(MPa)	Max Stress (MPa) (Compression)	Density (12% MC) (g/cm3)	Density (Dry) (g/cm3)
Ht	P19T9	5.2W2A	9590	60.3	41.2	0.461	0.431
Ht	P19T9	6.1E1B	6790	59.9	42.4	0.477	0.437
Ht	P19T9	6.1E2A	8420	61	44.4	0.488	0.447
Ht	P19T9	6.1W1A	8190	65.3	43.3	0.476	0.441
Ht	P19T9	6.2E1A	7850	67.4	46.1	0.483	0.437
Ht	P19T9	6.2W1A	7250	59.8	42.6	0.469	0.436
Lt	P20T1	1.1E1A	5920	67.8	33.2	0.510	0.474
Lt	P20T1	1.1W1A	5910	69.3	40.3	0.504	0.471
Lt	P20T1	1.1W2A	6910	66.9	45.2	0.504	0.467
Lt	P20T1	1.2E1A	6650	69.9	46.3	0.506	0.469
Lt	P20T1	1.2W1A	6800	68.4	45.9	0.510	0.474
Lt	P20T1	2.1E1B	5050	54.3	38.5	0.479	0.449
Lt	P20T1	2.1E2A	7390	61	46.4	0.512	0.473
Lt	P20T1	2.1W1C	5600	61.3	33.5	0.476	0.441
Lt	P20T1	2.1W2B	5840	53.4	37.1	0.473	0.428
Lt	P20T1	2.1W3A	7270	66.8	46.1	0.520	0.478
Lt	P20T1	2.2E1B	6230	60.7	44.2	0.497	0.464
Lt	P20T1	2.2E2A	6370	60.8	36.2	0.492	0.451
Lt	P20T1	2.2W1B	6240	60.4	33.8	0.484	0.440
Lt	P20T1	2.2W2A	6980	63.7	43.1	0.484	0.447
Lt	P20T1	3.1E1C	5070	37.7	31.2	0.485	0.449
Lt	P20T1	3.1E2C	6060	57.5	35.4	0.489	0.450
Lt	P20T1	3.1E3A	7510	75.4	46.4	0.518	0.476
Lt	P20T1	3.1W1C	5460	54.7	31.4	0.512	0.471
Lt	P20T1	3.1W3A	8580	75.6	36.6	0.485	0.447
Lt	P20T1	3.2E1B	6680	61.4	45.8	0.507	0.472
Lt	P20T1	3.2E2A	6520	64.8	41.6	0.477	0.451
Lt	P20T1	3.2W1C	4730	52.1	44.5	0.541	0.499
Lt	P20T1	3.2W2B	5420	45	35.2	0.501	0.459
Lt	P20T1	3.2W2C	7470	65.3	32.9	0.479	0.439
Lt	P20T1	3.2W3A	7730	67.4	42.5	0.496	0.462
Lt	P20T1	4.1E1C	5060	56	31.9	0.552	0.505
Lt	P20T1	4.1E2C	5570	55.7	35.4	0.494	0.454
Lt	P20T1	4.1E3A	7590	75.3	42.2	0.489	0.451
Lt	P20T1	4.1W1C	4130	47.5	31.9	0.513	0.469
Lt	P20T1	4.1W2B	5150	47.2	34.7	0.486	0.448
Lt	P20T1	4.1W3A	6600	66.4	41.5	0.517	0.476
Lt	P20T1	4.2E1C	5240	52.9	34.4	0.544	0.509

Treatment	Sample ID	Sample No.	MOE (MPa)	MOR(MPa)	Max Stress (MPa) (Compression)	Density (12% MC) (g/cm3)	Density (Dry) (g/cm3)
Lt	P20T1	4.2E2C	6250	62	37.3	0.493	0.461
Lt	P20T1	4.2E3A	5870	59.2	43.3	0.506	0.466
Lt	P20T1	4.2W1C	4700	41	32.9	0.491	0.455
Lt	P20T1	4.2W2C	5670	52.1	34.8	0.475	0.440
Lt	P20T1	4.2W3A	7570	68.7	48.2	0.521	0.480
Lt	P20T1	5..1E2A	6360	66.5	37.9	0.498	0.456
Lt	P20T1	5..1W2A	6800	64.7	43.8	0.491	0.459
Lt	P20T1	5..2E3A	6400	54.4	37.2	0.492	0.446
Lt	P20T1	5..2W2A	6770	70	44.2	0.529	0.488
Lt	P20T1	5.1E1B	5700	59.7	31	0.496	0.459
Lt	P20T1	5.1W1B	5190	48.1	36.5	0.534	0.497
Lt	P20T1	5.2E1B	5140	57.3	44.8	0.536	0.498
Lt	P20T1	5.2E2B	5680	52.9	41.8	0.485	0.446
Lt	P20T1	5.2W1B	6060	61.4	46.2	0.524	0.490
Lt	P20T1	6.1E1A	6050	66	46.1	0.544	0.506
Lt	P20T1	6.2E1A	6670	70.5	47.7	0.530	0.488
Lt	P20T1	6.2W1A	6500	70.8	47.5	0.526	0.490
Lt	P20T2	1.1E1A	5820	64	44.3	0.494	0.455
Lt	P20T2	1.1W1B	6300	69.1	44	0.498	0.461
Lt	P20T2	1.1W2A	6490	65.3	46.3	0.502	0.468
Lt	P20T2	1.2E1A	6480	64.2	45	0.501	0.462
Lt	P20T2	1.2W1B	6790	68.3	46.1	0.479	0.455
Lt	P20T2	1.2W2A	6740	67.5	46.4	0.505	0.464
Lt	P20T2	2.1E1B	5920	60	35.8	0.445	0.408
Lt	P20T2	2.1E2B	6640	59.7	40.6	0.478	0.442
Lt	P20T2	2.1E3A	8230	68.2	46.8	0.504	0.475
Lt	P20T2	2.1W1B	5590	55.6	36.5	0.453	0.420
Lt	P20T2	2.1W2B	6430	62.8	44	0.498	0.461
Lt	P20T2	2.1W3A	6470	63.2	45.3	0.504	0.467
Lt	P20T2	2.2E1B	6100	62.7	43.6	0.477	0.439
Lt	P20T2	2.2E3A	7980	67	48.4	0.519	0.473
Lt	P20T2	2.2W1C	5980	57.3	37.9	0.439	0.402
Lt	P20T2	2.2W2A	6980	65.6	46.5	0.526	0.481
Lt	P20T2	2.2W2B	5720	59.2	41.2	0.473	0.438
Lt	P20T2	3.1E1C	4980	46.6	27.9	0.445	0.401
Lt	P20T2	3.1E2B	7090	55.6	35.9	0.441	0.406
Lt	P20T2	3.1E3A	7630	71.6	47.1	0.524	0.490
Lt	P20T2	3.1W1C	4140	49.6	28.6	0.445	0.404

Treatment	Sample ID	Sample No.	MOE (MPa)	MOR(MPa)	Max Stress (MPa) (Compression)	Density (12% MC) (g/cm3)	Density (Dry) (g/cm3)
Lt	P20T2	3.1W2C	5780	49.9	31.1	0.420	0.382
Lt	P20T2	3.1W3B	7180	57.9	39.3	0.462	0.424
Lt	P20T2	3.1W4A	8100	68.8	43.8	0.465	0.465
Lt	P20T2	3.2E1C	4600	52.3	27.8	0.499	0.454
Lt	P20T2	3.2E2C	5200	44.3	29.8	0.413	0.375
Lt	P20T2	3.2E3B	6780	55	36	0.438	0.407
Lt	P20T2	3.2E4A	7590	72.4	46.9	0.517	0.466
Lt	P20T2	3.2W1C	4730	46.3	29.9	0.428	0.391
Lt	P20T2	3.2W2B	6870	60	40.7	0.480	0.438
Lt	P20T2	3.2W3A	7140	62.8	44.6	0.499	0.462
Lt	P20T2	4.1E1C	5280	48.9	28.6	0.415	0.381
Lt	P20T2	4.1E2C	7350	61.9	38	0.450	0.408
Lt	P20T2	4.1E3A	8730	70.4	44.8	0.521	0.481
Lt	P20T2	4.1W1C	3780	47	28.4	0.466	0.435
Lt	P20T2	4.1W2C	5030	45.3	30.8	0.422	0.381
Lt	P20T2	4.1W3B	6390	55.5	36.9	0.454	0.421
Lt	P20T2	4.1W4A	8010	65.7	44.9	0.492	0.441
Lt	P20T2	4.2E1C	4460	52.4	31	0.495	0.450
Lt	P20T2	4.2E2C	7460	53.5	30.2	0.424	0.401
Lt	P20T2	4.2E3C	7040	61	37.4	0.435	0.399
Lt	P20T2	4.2E4A	6960	68.2	46.5	0.507	0.473
Lt	P20T2	4.2W1C	5810	53.8	30.4	0.418	0.386
Lt	P20T2	4.2W2C	6550	60.8	38	0.444	0.415
Lt	P20T2	4.2W3A	7770	65.4	45.5	0.496	0.455
Lt	P20T2	5.1E1C	5280	52.9	31.8	0.447	0.407
Lt	P20T2	5.1E2B	7460	59.6	37.4	0.458	0.425
Lt	P20T2	5.1E3A	7310	63.4	44.1	0.512	0.471
Lt	P20T2	5.1W1C	5310	54.5	30.3	0.412	0.375
Lt	P20T2	5.1W2B	6440	53.9	35	0.438	0.401
Lt	P20T2	5.1W3A	6160	62.4	41.6	0.497	0.450
Lt	P20T2	5.2E1C	5220	53.5	29.1	0.437	0.411
Lt	P20T2	5.2E2B	6380	54.6	38	0.449	0.416
Lt	P20T2	5.2E3A	7460	61.6	45.8	0.497	0.456
Lt	P20T2	5.2W1C	5360	53.6	31.3	0.413	0.377
Lt	P20T2	5.2W2B	6990	57.2	39.4	0.454	0.418
Lt	P20T2	5.2W3A	8200	64.6	43.3	0.482	0.440
Lt	P20T2	6.1E1B	6000	60.3	41.6	0.469	0.435
Lt	P20T2	6.1E2A	5810	59.8	44.6	0.502	0.465

Treatment	Sample ID	Sample No.	MOE (MPa)	MOR(MPa)	Max Stress (MPa) (Compression)	Density (12% MC) (g/cm3)	Density (Dry) (g/cm3)
Lt	P20T2	6.1W1B	5330	62.2	41.3	0.463	0.424
Lt	P20T2	6.1W2A	5530	58.7	43.5	0.487	0.439
Lt	P20T2	6.2E1B	6270	64.5	41.1	0.488	0.453
Lt	P20T2	6.2E2A	6440	61.8	44.7	0.489	0.449
Lt	P20T2	6.2W1B	5670	63.3	42.1	0.466	0.435
Lt	P20T2	6.2W2A	6520	63.3	45.1	0.504	0.466
Lt	P20T2	7.1W1A	5750	64.9	44.1	0.494	0.462
Lt	P20T2	7.2W1A	5900	70.4	44.3	0.507	0.466
Lt	P20T4	1.1E1B	5960	62.4	33.2	0.434	0.397
Lt	P20T4	1.1E2A	7110	67.1	38.9	0.473	0.435
Lt	P20T4	1.1W1B	5670	60.9	36.7	0.409	0.420
Lt	P20T4	1.1W2A	7050	67.7	42.4	0.525	0.474
Lt	P20T4	1.2E1A	6860	72.7	40	0.496	0.458
Lt	P20T4	1.2W1A	8180	74.2	46.4	0.528	0.484
Lt	P20T4	2.1E1C	4760	48.3	28.9	0.453	0.403
Lt	P20T4	2.1E2C	6550	48	32.4	0.425	0.381
Lt	P20T4	2.1E3A	7750	66.1	41.8	0.482	0.444
Lt	P20T4	2.1W1C	4860	49.7	29.4	0.444	0.403
Lt	P20T4	2.1W2B	7040	60.7	33.4	0.441	0.403
Lt	P20T4	2.1W3A	8510	75.5	42.7	0.494	0.448
Lt	P20T4	2.2E1C	5630	56.2	31.4	0.440	0.400
Lt	P20T4	2.2E2C	7470	55.9	34.2	0.425	0.386
Lt	P20T4	2.2E3A	7570	65.5	42.3	0.480	0.439
Lt	P20T4	2.2W1C	6290	58.2	36.5	0.440	0.405
Lt	P20T4	2.2W2A	8400	69.5	44.9	0.507	0.467
Lt	P20T4	3.1E1C	5700	53	27.9	0.460	0.416
Lt	P20T4	3.1E2C	6680	57	30.3	0.420	0.378
Lt	P20T4	3.1E3A	8660	71.6	41.7	0.486	0.447
Lt	P20T4	3.1W1C	5750	51.3	30.3	0.455	0.413
Lt	P20T4	3.1W2C	7260	50.5	32.2	0.434	0.397
Lt	P20T4	3.1W3A	8730	60.2	41.4	0.497	0.453
Lt	P20T4	3.2E1C	6850	56.9	30.7	0.462	0.419
Lt	P20T4	3.2E2C	7130	59.1	34.1	0.419	0.382
Lt	P20T4	3.2E3A	8310	73	42.6	0.494	0.452
Lt	P20T4	3.2W1C	6170	52	30.1	0.458	0.418
Lt	P20T4	3.2W2C	7830	65.1	33.6	0.449	0.410
Lt	P20T4	3.2W3A	8020	74.5	41.1	0.491	0.443
Lt	P20T4	4.1E1C	5490	56.3	29.4	0.444	0.408

Treatment	Sample ID	Sample No.	MOE (MPa)	MOR(MPa)	Max Stress (MPa) (Compression)	Density (12% MC) (g/cm3)	Density (Dry) (g/cm3)
Lt	P20T4	4.1E2B	5540	53.9	31.9	0.424	0.391
Lt	P20T4	4.1E3A	8180	64.6	41.8	0.495	0.448
Lt	P20T4	4.1W1C	5420	55.1	31	0.453	0.413
Lt	P20T4	4.1W2B	7380	59.9	35.1	0.450	0.409
Lt	P20T4	4.1W3A	8450	70.9	43.4	0.511	0.472
Lt	P20T4	4.2E1C	6650	54.3	32.8	0.428	0.387
Lt	P20T4	4.2E2A	7950	64.2	43.2	0.478	0.443
Lt	P20T4	4.2W1C	5130	55.5	30.7	0.438	0.398
Lt	P20T4	4.2W2B	6790	55.7	29.4	0.439	0.403
Lt	P20T4	4.2W3A	8080	71.9	42.2	0.496	0.463
Lt	P20T4	5.1E1A	6460	58.3	35.2	0.439	0.399
Lt	P20T4	5.1E2A	8260	70.1	44.4	0.487	0.446
Lt	P20T4	5.1W1A	6840	64.3	42.6	0.488	0.437
Lt	P20T4	5.2E1B	6650	65.3	38.5	0.456	0.421
Lt	P20T4	5.2E2A	7490	70.1	46.2	0.510	0.466
Lt	P20T4	5.2W1C	6800	64.4	35.8	0.446	0.407
Lt	P20T4	5.2W2B	6590	64.4	37.9	0.463	0.421
Lt	P20T4	5.2W3A	7720	70.5	46.6	0.495	0.466
C	P21T11	1.1E1A	6340	66.7	40.2	0.479	0.437
C	P21T11	1.1W1A	7670	74.6	43.4	0.491	0.454
C	P21T11	1.2W1A	7340	76.7	46.1	0.497	0.456
C	P21T11	2.1E1B	5810	59.4	34.3	0.436	0.399
C	P21T11	2.1E2B	6220	62.4	38.2	0.440	0.414
C	P21T11	2.1E3A	6700	65.4	38.8	0.470	0.433
C	P21T11	2.1W1B	6070	63.8	37.6	0.457	0.417
C	P21T11	2.1W2A	7260	65.8	41.7	0.485	0.443
C	P21T11	2.2E1B	6190	61.7	39.7	0.449	0.412
C	P21T11	2.2E2A	7830	64.7	42	0.462	0.429
C	P21T11	2.2W1B	6230	61.6	39.6	0.446	0.411
C	P21T11	2.2W2A	7120	67.4	45	0.489	0.446
C	P21T11	3.1E1C	5890	53.1	30.8	0.466	0.421
C	P21T11	3.1E2B	6930	62.4	35.3	0.446	0.408
C	P21T11	3.1E3A	7740	69.7	37.6	0.463	0.423
C	P21T11	3.1W1C	5200	51.5	28.7	0.459	0.417
C	P21T11	3.1W2C	6480	58.6	32.8	0.438	0.397
C	P21T11	3.1W3A	8250	74.2	42.3	0.505	0.465
C	P21T11	3.2E1C	5750	52.3	31.2	0.431	0.391
C	P21T11	3.2E2B	7440	62.6	40.3	0.446	0.413

Treatment	Sample ID	Sample No.	MOE (MPa)	MOR(MPa)	Max Stress (MPa) (Compression)	Density (12% MC) (g/cm3)	Density (Dry) (g/cm3)
C	P21T11	3.2E3A	8200	68.4	44.9	0.464	0.431
C	P21T11	3.2W1C	5480	55.2	31.8	0.446	0.406
C	P21T11	3.2W2C	6670	61.9	37.4	0.440	0.404
C	P21T11	3.2W3A	8190	75.3	46.9	0.497	0.457
C	P21T11	4.1E1C	5280	53.7	30.6	0.445	0.404
C	P21T11	4.1E2B	7010	61.1	36.1	0.436	0.399
C	P21T11	4.1E3A	8190	67.2	40.2	0.465	0.424
C	P21T11	4.1W1C	4590	54.1	29.9	0.456	0.413
C	P21T11	4.1W2C	6170	54.2	33.3	0.443	0.404
C	P21T11	4.1W3A	8120	73.5	42.1	0.483	0.442
C	P21T11	4.2E1C	4740	52.3	33	0.434	0.387
C	P21T11	4.2E2B	6460	57.2	36	0.445	0.405
C	P21T11	4.2E3A	6650	63.9	38.9	0.450	0.410
C	P21T11	4.2W1C	4830	53.9	31.4	0.443	0.401
C	P21T11	4.2W2C	6950	61.4	36.3	0.433	0.407
C	P21T11	4.2W3A	7600	71.9	46	0.488	0.448
C	P21T11	5.1E1B	5440	57.7	35.2	0.440	0.398
C	P21T11	5.1E2A	6040	61.7	38.8	0.459	0.418
C	P21T11	5.1W1B	5970	64	39.1	0.436	0.415
C	P21T11	5.1W2A	8250	70.5	45.8	0.484	0.445
C	P21T11	5.2E1B	5770	62.6	38	0.439	0.403
C	P21T11	5.2E2A	5970	57.4	37.2	0.463	0.414
C	P21T11	5.2W1B	5540	61.2	39.8	0.452	0.412
C	P21T11	5.2W2A	7180	68.8	46.5	0.482	0.448
C	P21T11	6.1E1A	6870	68.5	39.8	0.452	0.419
C	P21T11	6.2E1A	8130	78.3	46.4	0.487	0.449
C	P21T13	1.1E1A	6680	75.9	43.3	0.509	0.466
C	P21T13	1.2W1A	7170	77.3	43.6	0.543	0.503
C	P21T13	2.1E1B	5030	57.9	33.9	0.465	0.424
C	P21T13	2.1E2A	6160	61.2	41	0.510	0.467
C	P21T13	2.1W1B	5270	62.7	33.1	0.463	0.419
C	P21T13	2.1W2A	6350	63	44.1	0.516	0.477
C	P21T13	2.2E1B	5220	64	36.2	0.480	0.446
C	P21T13	2.2E2A	6150	62.6	39.4	0.514	0.467
C	P21T13	2.2W1B	5640	69.5	37.4	0.482	0.442
C	P21T13	2.2W2A	6620	69.7	43	0.507	0.466
C	P21T13	3.1E1C	4590	55.6	29.7	0.463	0.427
C	P21T13	3.1E2A	5320	72.3	39.5	0.496	0.448

Treatment	Sample ID	Sample No.	MOE (MPa)	MOR(MPa)	Max Stress (MPa) (Compression)	Density (12% MC) (g/cm3)	Density (Dry) (g/cm3)
C	P21T13	3.1W1C	4710	56.7	32.9	0.501	0.452
C	P21T13	3.1W2C	4710	57.8	32.6	0.462	0.423
C	P21T13	3.1W3A	7270	71.9	41.7	0.498	0.452
C	P21T13	3.2E1C	4790	55.6	32.3	0.490	0.440
C	P21T13	3.2E2A	4670	60.9	38	0.472	0.433
C	P21T13	3.2W1C	4640	57.2	33.1	0.498	0.450
C	P21T13	3.2W2C	5470	56.5	31.6	0.464	0.418
C	P21T13	3.2W3A	7750	76	45.1	0.512	0.477
C	P21T13	4.1E1C	4750	57.2	29.3	0.505	0.456
C	P21T13	4.1E2C	4210	50.8	29.6	0.453	0.416
C	P21T13	4.1E3A	5250	59.1	37.4	0.486	0.442
C	P21T13	4.1W1C	4470	49.8	29.1	0.457	0.414
C	P21T13	4.1W2A	5780	61.3	40.1	0.482	0.441
C	P21T13	4.2E1C	5010	59.3	33.8	0.534	0.480
C	P21T13	4.2E2C	4700	56.7	30.5	0.506	0.464
C	P21T13	4.2E3A	6330	64.6	39.3	0.483	0.452
C	P21T13	4.2W1C	4750	53.3	31.5	0.465	0.432
C	P21T13	4.2W2A	6260	65.2	41.9	0.488	0.444
C	P21T13	5.1E1B	4760	54.6	33.1	0.462	0.421
C	P21T13	5.1E2A	5350	57.9	36.8	0.481	0.433
C	P21T13	5.1W1B	4470	53	31.9	0.449	0.406
C	P21T13	5.1W2A	5260	57.6	37.7	0.470	0.429
C	P21T13	5.2E1B	4870	59.8	32.4	0.461	0.417
C	P21T13	5.2E2A	5520	58.1	39	0.477	0.434
C	P21T13	5.2W1B	4340	62.5	32	0.469	0.430
C	P21T13	5.2W2A	5050	57.2	36.9	0.457	0.421
C	P21T15	1.1E1A	6840	76.4	45.3	0.514	0.475
C	P21T15	1.1E2A	6490	73	47.3	0.536	0.495
C	P21T15	1.1W1A	6920	74.9	47	0.504	0.464
C	P21T15	1.2W1A	7680	76.1	49.9	0.542	0.501
C	P21T15	2.1E1C	6820	60.6	38.8	0.468	0.434
C	P21T15	2.1E2B	8490	71.3	44.4	0.504	0.473
C	P21T15	2.1E3A	9040	67.2	46	0.534	0.494
C	P21T15	2.1W1C	6280	61.9	40.7	0.485	0.447
C	P21T15	2.1W2A	8790	72.2	46.5	0.508	0.472
C	P21T15	2.2E1B	7370	69.3	46.3	0.514	0.478
C	P21T15	2.2E2B	7650	71.3	47.1	0.512	0.479
C	P21T15	2.2E3A	7490	73.4	48.9	0.530	0.487

Treatment	Sample ID	Sample No.	MOE (MPa)	MOR(MPa)	Max Stress (MPa) (Compression)	Density (12% MC) (g/cm3)	Density (Dry) (g/cm3)
C	P21T15	2.2W1B	7420	67	47	0.507	0.476
C	P21T15	2.2W2A	8770	67.2	49.2	0.556	0.520
C	P21T15	3.1E1C	7680	60.7	36.8	0.486	0.444
C	P21T15	3.1E2B	8240	67.9	43.6	0.504	0.470
C	P21T15	3.1E3A	8500	76.4	45.7	0.565	0.521
C	P21T15	3.1W1C	7220	57	37	0.486	0.445
C	P21T15	3.1W2B	8670	71.6	42.9	0.505	0.467
C	P21T15	3.1W3A	9690	77.2	46.4	0.530	0.492
C	P21T15	3.2E1C	6810	67.2	39.1	0.482	0.447
C	P21T15	3.2E2B	8090	71.5	46.1	0.504	0.470
C	P21T15	3.2E3A	8370	78	51	0.528	0.491
C	P21T15	3.2W1C	6380	60.6	39.9	0.480	0.443
C	P21T15	3.2W2B	8750	75.7	49.2	0.524	0.490
C	P21T15	3.2W3A	8390	80.8	49.1	0.567	0.526
C	P21T15	4.1E1C	8390	63.2	38.2	0.482	0.442
C	P21T15	4.1E2B	8390	71.7	44	0.511	0.473
C	P21T15	4.1E3A	9710	73.4	46.2	0.543	0.504
C	P21T15	4.1W1C	7450	64.4	39.3	0.502	0.465
C	P21T15	4.1W2C	8190	64.8	42.6	0.488	0.446
C	P21T15	4.1W3A	9320	79.8	50.1	0.535	0.503
C	P21T15	4.2E1C	6660	60.3	39	0.512	0.470
C	P21T15	4.2E2B	8270	71.9	41.1	0.494	0.454
C	P21T15	4.2E3A	9120	76.8	49.3	0.544	0.512
C	P21T15	4.2W1C	4640	46.4	39.4	0.507	0.464
C	P21T15	4.2W2B	6930	54.2	46.4	0.513	0.480
C	P21T15	4.2W3A	8500	51.7	47.4	0.564	0.518
C	P21T15	5.1E1C	7010	77.8	41.9	0.484	0.444
C	P21T15	5.1E2B	6560	69.3	46.1	0.502	0.466
C	P21T15	5.1E3A	7960	68.3	48.9	0.534	0.504
C	P21T15	5.1W1B	6950	70.5	45	0.505	0.464
C	P21T15	5.1W2A	7750	74.5	50	0.538	0.500
C	P21T15	5.2E1C	7440	79.3	44.5	0.498	0.466
C	P21T15	5.2E2B	6870	72.1	47.6	0.515	0.479
C	P21T15	5.2E3A	9130	75.1	51.6	0.551	0.519
C	P21T15	5.2W1C	7080	71.5	49.3	0.524	0.487
C	P21T15	5.2W2A	8410	72.6	51.2	0.540	0.499
C	P21T15	6.1E1A	8720	77.7	50.9	0.532	0.497
C	P21T15	6.1W1A	8150	78.6	50.9	0.544	0.507

Treatment	Sample ID	Sample No.	MOE (MPa)	MOR(MPa)	Max Stress (MPa) (Compression)	Density (12% MC) (g/cm3)	Density (Dry) (g/cm3)
C	P21T15	6.2E1A	9300	83.4	46.9	0.538	0.513
C	P21T15	6.2W1A	9030	81.9	55.8	0.553	0.519