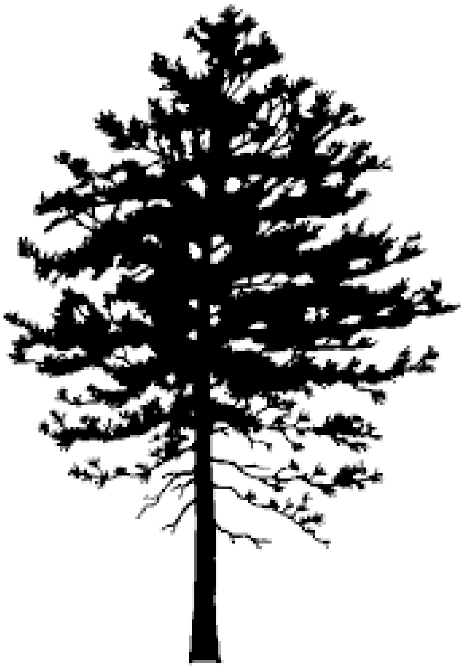
THE EFFECTS OF PLANTATION SPACING ON *PINUS RESINOSA* WOOD DENSITY VARIATION AND MANAGING FOR INCREASED CARBON SEQUESTRATION

By

Shanagh Hore



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THE EFFECTS OF PLANTATION SPACING ON *PINUS RESINOSA* WOOD DENSITY VARIATION AND MANAGING FOR INCREASED CARBON SEQUESTRATION

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Shanagh Hore

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Faculty of Natural Resources Management

Lakehead University

April 2020

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Major Advisor	Second Reader

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ABSTRACT

Hore, S. 2019. The Effects of Plantation Spacing on *Pinus resinosa* Wood Density Variation and Managing for Increased Carbon Sequestration. 59 pp.

Keywords: carbon sequestration, density, *Pinus resinosa*, red pine, growth, silviculture

Pinus resinosa is found throughout a large portion of eastern North America. Dating back to the early settlement era, wood utilization has varied from solely infrastructure to bioenergy and carbon sequestration. Although today's *Pinus resinosa* wood volume has increased, research shows that wood quality has decreased and the potential for increased carbon sequestration has gone largely unnoticed. This can be explained by the current silvicultural management of *Pinus resinosa* which encourages quick growth and shorter harvest rotations. Wood density is not only important for loadbearing, infrastructural purposes, but a higher density in wood is the basis for increased carbon storage. The methodology for this thesis involved extracting ten individual wood core samples: five from open-grown conditions in Pembroke, Ontario and five from tightly-spaced conditions in L'Isle-aux-Allumettes, Quebec; however, the trees at each site originated from the same seed source prior to being planted. Each core was separated into juvenile and mature wood sections and were then weighed in green and dry conditions. They were tested for wood density and with the use of the Thermogravimetric Analyzer, the carbon content for each juvenile and mature sample was recovered. It was found that although each tree was genetically alike, the stand spacing at each location resulted in the respective trees having significantly different wood densities. The results showed that the trees with increased wood densities also had a higher percent carbon sequestered. These results show the importance of strategically managing the plantation spacing of *Pinus resinosa* and how something as simple as increasing the stand density will increase both wood density and carbon sequestration levels, while improving the structural integrity of the wood at both the stem and stand scale. These findings could be used further by forest professionals to assist in reaching Canada's Greenhouse Gas emission targets, and producing higher-value wood products to meet market demand.

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1.0 INTRODUCTION

The vital role that forests play in the process of carbon sequestration has urged landowners and forest managers to strategize and implement plans that improve carbon storage in forests whilst mitigating the rise in atmospheric carbon levels. With increased atmospheric carbon concentrations contributing to the rise in global temperatures, it is important to acknowledge natural climate solutions such as the benefits of sustainable forest management to counteract carbon emissions and subsequently meet the environmental, social and economic objectives originally outlined in the Crown Forest Sustainability Act of 1994, as well as the 2030 and 2050 emission targets set by the Paris Agreement in 2016.

Wood is considered to be one of the most important natural, renewable resources and represents the best mode of carbon absorption for excess atmospheric carbon dioxide. For centuries, *Pinus resinosa* or red pine, wood has been harvested to provide logs for homes and buildings, railway ties, mining timber, pulpwood, fuel wood and sawn timber for lumber. The native range of *Pinus resinosa* extends from Manitoba to New Brunswick and throughout the Lake States of the USA (Figure 1).

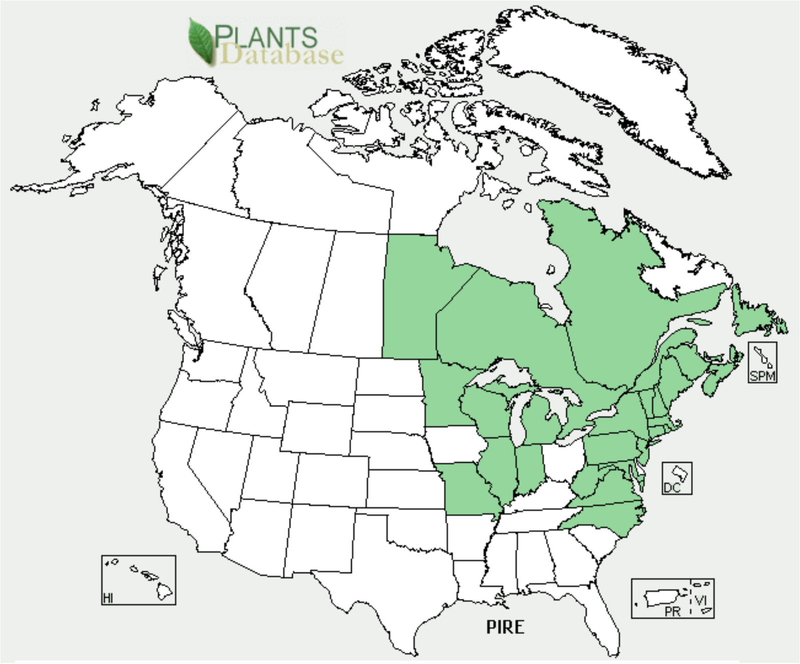


Figure 1. Native Pinus resinosa range, USDA 2019.

Today, it is one of the most frequently planted species in Canada and northern United States, not only for wood production but also for areas like in southern Ontario, where abandoned farmlands have looked to *Pinus resinosa* as the best candidate for land reclamation and watershed protection. This is due to the site and soil compatibility between what is typically found throughout fields and pastures and where *Pinus resinosa* are most suited to thrive, typically sandy or loamy soils. The uniformity of *Pinus resinosa*, as well as a lack of insect and pathogen infestation, which raised concern when Eastern white pine (*Pinus strobus*) was considered, made for a clear choice when deciding a reclamation species in the early 20th century.

Until recently, there was no strategic planning for regeneration of *Pinus resinosa,* and the common harvest system was high grading. Today, *Pinus resinosa* forests are managed with productive intentions and use silvicultural systems such as the Seed Tree or Clear-cut system, which are intended to promote successful natural and artificial regeneration and steady growth, with adequate spacing and low competition levels.

In plantations, stands are managed with varying stand densities to promote increased wood yield and quality while maintaining forest health (Yang et al. 1986; Maeglin 1967; Ballard and Long 1988; Janas and Brand 1988). When trees develop under varying site conditions and competition levels, there is a change in wood properties (Zobel et al. 1989). Treatments such as spacing, thinning and fertilization all impact the earlywood and latewood ratios which both aid in determining the wood density within a tree (Zobel et al. 1989). Throughout this thesis, it will be discussed how wood density plays a key role in determining carbon content within the wood and how carbon sequestration is dependent on wood density development and variation.

Studies show that lumber made from wood that was harvested prior to the current silviculture practices is stronger than the second-growth timber we are producing in forests today (Pretzsch *et al*. 2018). As this thesis investigates the variations in *Pinus resinosa* wood density and carbon content developed under two spatially-varied plantation densities, the results will display the reasoning for variance in wood density and the potential for increased carbon storage. In consideration of the planet's current climate crisis, determining whether a forest is referred to as a carbon source or sink depends on whether there is more carbon being sequestered or released, also commonly referred to as carbon stock balance (Natural Resources Canada 2016). The question to be answered within this thesis is whether wood density is directly influenced by manipulating the plantation spacing; and if so, in what way can forest managers alter the plantation density of *Pinus resinosa* stands to produce increased yields of high-density wood, sequester more carbon and maintain mechanical strength all while promoting timely, continuous regeneration?

In this paper, it is envisioned that the full potential of Ontario's *Pinus resinosa* will be discovered and the likelihood of growing strong timber once again with increased carbon sequestration will be achieved using specialized, sustainable forest management for the purpose of satisfying economic demands and diminishing Ontario's carbon footprint.

1.1 OBJECTIVE

This thesis will be determining how plantation spacing can cause variation in *Pinus resinosa* wood density and carbon sequestration potential by obtaining core samples from trees of the same seed source, but grown at different field spacings. Wet and dry density, as well as carbon content will be calculated to gain a better understanding of the effects that forest managers can have on resulting wood quality and market value. With the results found from density and carbon testing, carbon storage potential will be determined in relation to wood density with the intent of discovering which management style best increases carbon sequestration and higher timber value at the stem, stand and landscape scale.

1.2 HYPOTHESES

1. Wood density is strongly influenced by plantation spacing.
2. Plantation spacing can be managed to produce wood with increased densities that improve both carbon sequestration and the structural integrity of the wood.

2.0 LITERATURE REVIEW

2.1 WOOD DENSITY

Wood density is viewed as one of the most important wood characteristics in relation to log quality and structural integrity of the product. It has a direct impact on the structural performance of timber, and is often associated with modulus of elasticity (MOE), modulus of rupture (MOR), shrinkage and pulp yields (Joza & Middleton, 1994).

A 2007 study researched the utilization of ring width in quantifying the effects of plantation spacing on *Pinus resinosa* wood density and tracheid properties (Zhu *et al.* 2007). After analyzing discs from ten *Pinus resinosa* trees from each of the five different plantations spaced at 220, 320, 420, 620 and 820 stems per acre, it was determined that the average ring width had a direct correlation with wood density and tracheid anatomical properties (Zhu *et al.* 2007). As the stand densities increased, the ring widths narrowed and the latewood increased, which due to the flattened nature of tracheids within latewood, caused a reduced total tracheid surface area in the sample (Zhu *et al.* 2007). The data not only displayed increased density in the latewood as compared to earlywood, but also that the latewood was more dependent on the ring width than the earlywood was (Zhu *et al.* 2007). It was also found within high density stands, that lignin content decreased and glucan, as well as xylan increased, which according to Zhu ad Myers (2006), signifies improved pulp yield in chemical pulping.

Understanding how plantation spacing effects ring width and its correlation with wood density, among other wood properties, aids in the best silvicultural management for the structural integrity of *Pinus resinosa* and challenges forest professionals to manage for high-strength timber stands, whilst maintaining good forest health and production.

2.2 INFLUENCE OF SILVICULTURE ON WOOD DENSITY

Tree development is dependent on both genetic and environmental factors but is also heavily influenced by the type of silviculture it is managed under. The goal of silvicultural management is to adjust a forest's composition, growth and environment and may include treatments such as, but not limited to, spacing, thinning, pruning and fertilizing (Hart 2010).

Wood density is commonly viewed as a key indicator when determining how valuable the wood is regarding its mechanical properties, where a higher wood density is directly related to increased wood strength (Hart 2010). With the positive relationship between wood density and the wood's value, forest managers would find it useful to know the ways in which they could manage for higher density wood.

Tree spacing is commonly applied with the goal of altering a tree's development to improve form and vigour, as well as crown size (Hart 2010). These treatments will usually affect growth rate, which also has an impact on the overall form and characteristics of the tree (Hart 2010).

In a recent study on the effects of tree spacing on growth and wood density of Cariniana legalis trees in Brazil (Oliveira *et al*. 2017), it was found that when spaced at 3m x 1.5m, 3m x 2m and 3m x 2.5m, the wood density increased with wider spacing. This was not only found at the base of the tree where higher wood densities are typically observed, but throughout the length of the bole up to 15m. These results contrast with the results of a 1995 study based on the relationship between wood density and initial spacing of *Pinus resinosa*, where the study concluded that closer spacing brought forth increased wood density and decreased the percentage of earlywood (Larocque *et al.* 1995). This contradiction between studies is likely due to the physiological nature of fast growing hardwood species, which typically produce more thick-walled fibres within the growth ring, presenting higher wood densities, as compared to that of softwoods where quicker growth compromises the latewood fraction within the growth ring, causing lower wood density.

A 2003 study looked at the effects of early intensive silviculture treatments on the juvenile and mature wood transition age in loblolly pine in eastern United States (Mora *et al*. 2003). The treatments used were 1. Intensive site preparation, 2. Intensive site preparation and fertilization, 3. Intensive site preparation and weed control, 4. Intensive site preparation, fertilization, and weed control and 5. Control (Mora *et al.* 2003). When the trees were aged 22 and 23 years old, it was found that there were significant increases in individual tree volume growth of 29-33% (Mora *et al*. 2003). It was discovered that in sites which were managed using any of the first four intensive treatments resulted in an average of 57% juvenile wood as compared to the control site with 41% juvenile wood. This suggests that when sites are intensively managed at a young age and volume growth per tree is increased, the proportion of juvenile wood is also increased (Mora *et al*. 2003). Although there were substantial effects of intensive silviculture on tree volume, wood density was not significantly affected when comparing any of the intensive treatments to the control site.

2.3 SILVICULTURE EFFECTING JUVENILE AND MATURE WOOD RATIOS

A 2011 study on the effects of juvenile wood proportions on Laminated Veneer Lumber (LVL) outlined the significance of the amounts of juvenile wood as compared with mature wood and how they affect the mechanical and physical properties of lumber (Nazerian et al. 2011). It was stated that in conifers, such as the studied species' Southern pine and Douglas fir, juvenile wood is found to have lower wood density, influencing lower strength values; thinner cell walls, lower cellulose content and increased longitudinal shrinkage and S2 microfibril angle (Nazerian *et al*. 2011). Thus, higher proportions of juvenile wood will risk the structural integrity of the end-use product, most commonly lumber.

Prior to the early 1900s, most timber being harvested came from old-growth forests. These trees consisted of little juvenile wood as they were grown in competitive environments which, contrary to the 2017 study by Oliveira *et al*., caused the competition for nutrients to speed up the maturation process (Kretschmann et al. 1993). In this era, forests were often high-graded, meaning only the biggest trees were cut. Thus, large diameter trees with low proportions of juvenile wood made for superior lumber due to higher proportions of mature, dense wood which contributed to increased MOE and MOR values and an overall higher quality of wood.

In recent years, intensive forest management has allowed trees to grow to adequate diameters with shorter rotation periods for economic efficiency. Trees are being harvested at younger ages and are experiencing rapid growth with increased juvenile wood proportions, resulting in the decline in both wood quality and market value.

2.4 OLD GROWTH WOOD DENSITY VS. SECOND GROWTH WOOD DENSITY

In a 2018 study conducted in central Europe, the dominant tree species, Norway Spruce, Scots Pine, European Beech and Sessile Oak were tested and presented to all have increased volume growth; however, an 8-12% decrease in wood density since 1900 (Pretzsch *et al*. 2018). The stands in question were fully stocked and had not received any intensive management more than moderate thinnings (Pretzsch *et al*. 2018). This excludes any reasoning, aside from environmental factors, for the increased volume growth and decreased wood density. During the 20th century, there was an increase in mean annual temperature of 1.0 degree Celsius or 9% (Matyssek and Sandermann 2003), as well as a Nitrogen-deposition increase from 2.5 kg ha/year in 1900 to over 9 kg ha/year in the early 2000s (Churkina *et al*. 2010). Over the duration of 110 years, the increase in temperature was consistent with an extended growing season throughout central Europe of 22 days (Pretzsch *et al*. 2018). The longer growing season paired with increased nitrogen levels account for the accelerated volume growth of the trees (Pretzsch *et al*. 2018). The decrease in wood density is described as a result of the increased volume growth due to the nitrogen supply (Pretzsch *et al*. 2018). This is consistent with other trials depicting the effects of fertilization on wood properties, such as a study conducted by Jozsa and Brix (1989) where Douglas fir was tested for growth and wood density response to thinning and nitrogen fertilization in British Columbia. The results displayed reduced earlywood and latewood density (thus, ring density) which only occurred after the nitrogen fertilization treatments took place. The initial decrease in ring density was related to increased nitrogen concentrated in the foliage, causing the carbohydrate supply to restrict secondary cell wall formation, leading to the decline in ring density (Jozsa and Brix 1989). Thinning caused a small gain in ring density in the lower portion of the bole and a small reduction in the upper portion. Ring density lessened as bole height increased, which is consistent with the typical bole structure, mainly consisting of juvenile wood as it reaches closer in proximity to the live crown (Jozsa and Brix 1989). Both thinning and fertilization treatments were causes for the resulting increased diameter growth (Jozsa and Brix 1989). Although the fertilization treatment had a more significant impact on ring density, the results are similar to the findings of Nazerian *et al*. (2011) and conclude that wider spacing at the time of planting and thinning at a young age causes rapid diameter growth of juvenile wood and could cause higher proportions of low-density wood, thus jeopardizing the log quality (Jozsa and Brix 1989).

2.5 SPACING AND THINNING EFFECTS ON RED PINE GROWTH AND YIELD

Established in 1953, The Forest Research Partnership (FRP), Petawawa Research Forest (PRF) and Tembec aimed to study the growth and yield results of several spacing and thinning treatments on two plantations near Chalk River, ON. Results were expected to give researchers a better understanding on how specific treatments could improve wood quality and produce higher-quality products (Canadian Ecology Centre 2006).

Trees were planted at spacings of 1.2m, 1.5m, 1.8m, 2.1m, 2.4m, 3.0m, 4.3m and 6.1m and paired with up to three thinning intensities (Canadian Ecology Centre 2006). In 1962, permanent samples plots were established and re-measured every 5 years with more in-depth measurements, focusing on various wood properties, on 187 trees throughout all the treatment areas.

At 50 years since planting, a significant level of mortality was recorded in the higher plantation-density treatments and in the lower plantation-density treatments, volume production was not meeting expectations (Canadian Ecology Centre 2006). It was evident that the 2.1m spacing treatment had the best overall basal area and volume results. It was found that although the thinning treatments improved overall diameter, it negatively impacted the volume and basal area of the stand. In Figure 2 below, the stem density and gross total volume for each spacing treatment over a 50-year period is displayed.

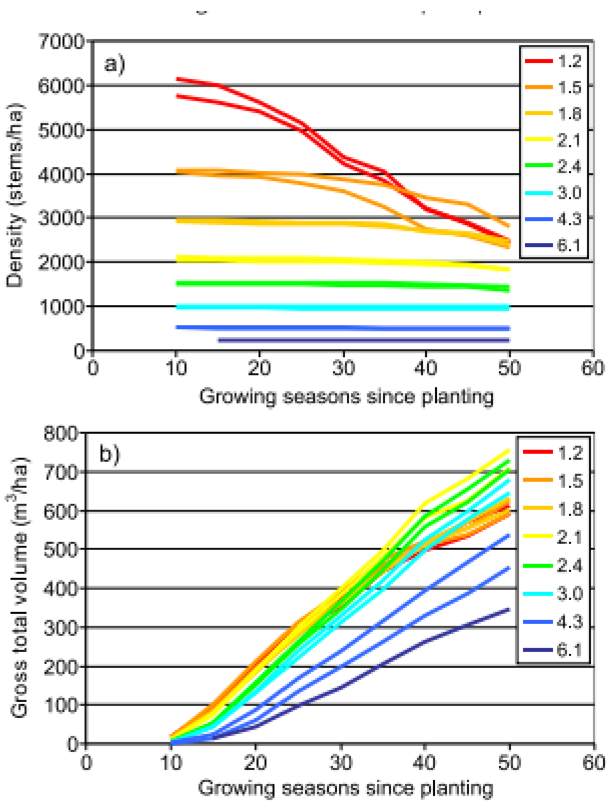


Figure 2 Stem density and gross total volume over time, Canadian Ecology Centre 2006.

The top figure displays the plantation densities of the 1.2m, 1.5m, and 1.8m spacing treatments steadily declining throughout the 50-year trial, representing a high mortality rate. Although the densities for the 6.1m, 4.3m, 3.0m and 2.4m spacing treatments remain fairly consistent and with low mortality rates, the 2.1m treatment is consistent throughout the 50-years, and also allows the highest plantation density possible without losing productive forest to mortality. Thus, making the 2.1m spacing treatment the most optimal treatment in this case scenario.

The bottom figure displays the gross total volume of 6.1m and 4.3m spacing treatments as increasing the least overtime. This is likely due to lack of competition, resulting in quick growth, branchiness and knot content. The 1.2m and 1.5m treatments display slightly more volume. The high plantation density likely caused the stems to grow more so in height rather than diameter, thus stunting the volume growth. The 3.0m, 2.4m and 2.1m treatments were close in total volume production; however, the 2.1m treatment resulted in the most volume production at year 50, and reinstates the conclusion that in this study, the 2.1m spacing treatment yielded the most optimized and productive stand.

2.6 CARBON SEQUESTRATION POTENTIAL

With the target of managing a forest for maximum carbon storing potential, the ability to estimate carbon mass would contribute to the planning process when deciding how to manage a stand. In order to make an appropriate estimation of stand-level carbon mass, forest managers need to determine how carbon is sequestered within a stand and how a given silvicultural treatment may affect it. Before understanding how carbon may be allocated throughout the stand, managers need to know how it is weighted within individual trees and how the carbon content may vary between trees and within wood properties.

In a 2015 study on the amount of carbon in juvenile and mature wood in a 103-year-old Scot's pine based in Northwestern Poland, it was found that the juvenile wood had significantly higher carbon content than mature wood (Bembenek *et al*. 2015). The 2.58% difference in carbon content was likely a result of there being more carbon within earlywood than latewood, and juvenile wood is comprised of higher proportions of earlywood within the annual rings (Bembenek *et al*. 2015). It was observed that as the Scots pine ages, the juvenile wood content decreases and transitions into mature wood content which then increases. In this study, it can be assumed that with less juvenile wood, there is less earlywood content and less carbon content. Thus, older Scots pine will have less carbon content within the wood than that of younger Scots pine (Bembenek *et al.* 2015).

This conclusion was further researched in a study conducted in 2003, where 41 North American species were harvested and tested for carbon contents. Due to many species displaying narrow ring widths, the early and latewood of only 7 of the 41 species were tested. It was observed that there were increased carbon contents in the tested conifers, ranging from 47.21% to 55.2%, as compared to hardwoods, in which carbon contents ranged from 46.27% to 49.97% (Lamlom and Savidge 2003). This result is likely due to softwood species having approximately 10% higher lignin content than in hardwoods and lignin is known to hold the most carbon out of all macromolecules (Savidge 2000). This was further suggested when samples taken from the earlywood and latewood of 7 of the 41 species and tested for carbon. The earlywood displayed higher carbon content than that of the latewood, again corresponding with increased lignin content, as earlywood has increased lignin proportions when compared to latewood, as latewood is generally higher in cellulose (Lamlom and Savidge 2003). However, Lamlom and Savidge (2003) suggested that although increased carbon is found in softwoods due to a lignin advantage, the assumption cannot be made that softwoods therefore store more carbon. It was argued that due to their generally higher wood density, hardwoods will normally still sequester more carbon than softwoods per unit volume (Lamlom and Savidge 2003), meaning that with higher wood density, there will be more carbon stored within the wood.

It is important to note that many studies use a global generic conversion factor of 0.5 when calculating carbon content in wood, based on the assumption that carbon makes up for 50% of the total volume (Birdsey 1992). Although there are studies which prove this to be an accurate estimate, this assumption fails to consider variations in intraspecific wood density; intra and interspecific variation in carbon fraction; variation in carbon fraction amongst wood properties; variation in age nor size and regional variation (Jones and O’Hara 2018). The results from Lamlom and Savidge’s 2003 study, as previously discussed, prove that the generic 50% value for carbon content is an inaccurate representation of carbon content which, in further studies, should be re-evaluated and should not be a widely used factor for any future calculations.

If forest managers can interpret the wood properties and characteristics which sequester more carbon, the next step is to determine whether intensively managing a stand will contribute to or risk the carbon balance as opposed to minimal management or leaving it to become old-growth. In a 2016 study based in central Finland, the objective was to distinguish whether managing a forest improves its carbon balance. It was discovered that for the first several decades, the unmanaged forest had a positive carbon balance (Pukkala 2016). Mature, unharvested forests aged 80-100 years old displayed significantly higher carbon balance values than old growth forests, implying that old growth forests, although positive in carbon balance, are very weak carbon sinks. The results showed that an unmanaged stand's carbon balance values will begin to decrease once its biomass production becomes limited and its soil carbon reaches a steady state (Pukkala 2016). This decline continues until the carbon balance reaches zero at approximately the 200-year mark (Pukkala 2016). The results of carbon balance in a managed forest mainly depends on whether the substitution value of cement, metals and fossil fuels is greater than the release of carbon during the harvesting, transport and processing procedures; thus, more material use of wood products will improve carbon balance in managed forests (Pukkala 2016). It was documented that after approximately 120 years, managed forests which had undergone partial harvests had better carbon balance values than those of unmanaged forests (Pukkala 2016). This study concluded that when attempting to prove whether managed versus unmanaged forests have better carbon balances, it is important to take into consideration 1. the timeline in question, as on a short-term basis the unmanaged forests will have a better carbon balance and in a long-term basis the managed forests will have a better carbon balance, and 2. The substitution value in relation to the release value. If there is a low rate of substitution compared to amount of carbon being released, the carbon balance will be better in an unmanaged forest. This means that forest managers cannot make assumptions which presume every stand should be treated equally when the target is to sequester carbon. Factors such as forest structure, age, health, time since last thinning or disturbance, live and downed-biomass are all influences contributing to whether or not further management of a stand will add to or take away from the carbon balance of a given forest stand.

To summarize, results from the discussed studies show that 1. Spacing, thinning and fertilization treatments typically cause rapid diameter and volume growth; 2. Tighter spacing causes less diameter growth, narrow ring widths, increased latewood fraction, higher density and earlier transition from juvenile to mature wood; 3. Rapid volume growth is generally indicative of higher proportions of earlywood and juvenile wood; 4. Softwoods tend to have higher carbon contents per unit mass than hardwoods due to higher lignin proportions; 5. Although juvenile wood is less dense than mature wood, it can store more carbon per unit mass, also due to higher lignin proportions; 6. High-density wood will still retain more carbon per unit volume when compared to lower-density wood; 7. Improving forest carbon balance is dependent on both time horizon and carbon substitution and release values; 8. It should be recognized that a generic carbon content value of 50% is not always accurate and is not representative of many of the variations observed at both tree and stand levels.

3.0 MATERIALS & METHODS

To properly analyze the variation of wood densities and carbon contents within *Pinus resinosa* wood, core samples of 5 wide-spaced trees and 5 tight-spaced trees were extracted (Figure 3). A wood density analysis and a carbon extraction procedure were conducted on the 10 *Pinus resinosa* cores. Each sample was broken down into juvenile and mature wood sections before testing.

Figure 3 Pinus resinosa core extraction using an increment borer (left). Extracted core in spoon (right).

3.1 MATERIALS

3.1.1 Wood Density

To obtain wood density data, the following materials were used: 1 Increment borer, 10 pith to bark cores, 10 cylindrical containers, 1 chisel, 1 hammer, 1 scale, 1 volume indicator scale, 1 beaker of water, 1 diameter tape and 1 measuring tape.

3.1.2 Carbon Content

To obtain the amount of carbon content, the following materials were used: 10 juvenile wood samples, 10 mature wood samples, 10 porcelain crucibles and 1 thermogeoanalyzer (TGA).

3.2 METHODOLOGY

3.2.1 Wood Density

To determine the wood density in grams per cubic centimeter of wood, there are four main steps which were conducted: extraction of the sample, determining the sample volume, determining the mass of the sample and the density calculation. To obtain the *Pinus resinosa* core samples, 5 tightly spaced *Pinus resinosa* trees were located on L'Isle-aux-Allumettes, QC and 5 widely spaced *Pinus resinosa* trees were located in Pembroke, ON. The diameter at breast height was recorded and the tree was marked with pink flagging tape (Figure 4).

Figure 4 Pinus resinosa samples flagged for coring.

An increment borer was used to extract core samples from each tree and each sample was carefully inserted into a plastic core container to prevent damage to the samples. Cores were then brought to Dr. Leitch's wood science lab and were separated into juvenile and mature sections, using a chisel and hammer. The sample sections were then tested for wood density. As wood density was calculated using an equation of mass divided by volume (water displacement method), each sample section was weighed on a

4-point scale to determine the mass value and then submerged into water, in which the volume indicator scale produced a volume value. These two values were then substituted into the previously mentioned density equation and thus, the densities of the juvenile and mature wood of 5 wide-spaced trees and 5 tight-spaced trees were calculated. This was done while the wood was green, and again after being dried for 24-hours following ASTM standards methodology for determining wood density. There was a total of 40 density values calculated; however, throughout this thesis, only the dry densities are discussed.

3.2.2 Carbon Content

Juvenile and mature sections of each of the 10 wood samples were brought to the wood science lab at Lakehead University. The main function of the Thermpgravimetric Analyzer-601 (TGA) is to assess the composition of organic, inorganics, and synthetic materials (Symonds 2011). The analyzer controlled the furnace regulation and data compilation (Symonds 2011). Mass reduction was measured as a function of temperature in a controlled setting (Symonds 2011). After designating an analysis procedure (ASTM Wood Procedure in the case of this thesis), empty crucibles were loaded into the furnace carousel. The TGA first weighed empty crucibles and zeroed-out their weight before placing 1g from each juvenile and mature section of each sample into individual crucibles. The filled crucibles were then placed in the TGA for 160 minutes at a temperature of up to 950°C. Once complete, the TGA was paired with a windows application which records all analyzed data into a digital format. The data included the initial weight, moisture content removed, ash content, and fixed carbon content.

All data was then transferred and analyzed in Excel and can be found in the Appendices of this thesis.

4.0 RESULTS

A two-factor Analysis of Variation (Anova) with replication was used to analyze the statistical significance of the wood density and carbon sequestration data for the Ontario site and the Quebec site. This type of Anova was required for each set of data due to there being two groups (Ontario and Quebec) and each group required two tests (juvenile and mature wood).

The null hypothesis A for the wood density analysis is that there are no significant differences between the effectiveness of the sample location for juvenile and mature wood density. The null hypothesis B for this analysis is that the locations are not statistically different. The alpha value for significance determination is 0.05. Table 1 below displays the results of the two-factor Density Anova with replication. Table 2 presents the critical values derived from the density Anova.

Table 1. Dry Density Anova between Quebec (QC) and Ontario (ON)

Density Anova: Two-Factor with Replication

SUMMARY	Juvenile	Mature	Total
QC			
Count	5	5	10
Sum	1.771917	2.806611	4.578528347
Average	0.354383	0.561322	0.457852835
Variance	0.000781	0.000532	0.012479003
ON			
Count	5	5	10
Sum	1.97545	2.28469	4.260139678
Average	0.39509	0.456938	0.426013968
Variance	0.001432	0.001593	0.002407062
Total			
Count	10	10	
Sum	3.747367	5.091301	
Average	0.374737	0.50913	
Variance	0.001444	0.003971	

Table 2 Critical values derived from the Density Anova.

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	0.005069	1	0.005068567	4.673498	0.046129	4.493998
Columns	0.090308	1	0.090307874	83.26883	9.66E-08	4.493998
Interaction	0.026314	1	0.026314175	24.26312	0.000152	4.493998
Within	0.017353	16	0.001084534			
Total	0.139043	19				0

The results of the dry density Anova display a higher average mature density and a lower average juvenile density in the Quebec location compared to the Ontario location. Variance is consistently lower in the Quebec location when compared to the Ontario location.

Since the p-value for the columns (juvenile and mature wood) is 9.66E-08 (0.0000000966), which is < 0.05, the null hypothesis A is rejected and therefore there are significant differences between the effectiveness of the sample location for juvenile and mature wood density.

Similarly, since the p-value for samples (locations) is 0.046129, which is < 0.05, the null hypothesis B is rejected and therefore the sample locations are statistically different. It can also be observed that the p-value for interaction is 0.000152, which is < 0.05, again, concluding that there are significant differences in the interaction between sample location and juvenile/mature wood.

The F-values for column (83.26882853), sample (4.6735) and interaction (24.2631) all exceed the F-crit value of 4.494, indicating the rejection of the null hypotheses.

The null hypothesis A for the carbon sequestration analysis is that there are no significant differences between the effectiveness of the sample location for juvenile and mature wood carbon content. The null hypothesis B for this analysis is that the locations are not statistically different. The alpha value for significance determination is 0.05. Table 3 below displays the results of the two-factor Carbon Anova with replication. Table 4 presents the critical values derived from the Carbon Anova.

Table 3. Carbon content Anova between Quebec (QC) and Ontario (ON)

Carbon Anova: Two-Factor with Replication

SUMMARY	Juvenile	Mature	Total
QC			
Count	5	5	10
Sum	58.583	77.62	136.203
Average	11.7166	15.524	13.6203
Variance	4.235703	0.53198	6.145719
ON			
Count	5	5	10
Sum	50.558	64.706	115.264
Average	10.1116	12.9412	11.5264
Variance	2.77813	5.526847	5.915167
Total			
Count	10	10	
Sum	109.141	142.326	
Average	10.9141	14.2326	
Variance	3.832822	4.545828	

Table 4 Critical values derived from the Carbon Anova.

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Sample	21.92209	1	21.92209	6.707766	0.01974	4.493998
Columns	55.06221	1	55.06221	16.84805	0.000828	4.493998
Interaction	1.195116	1	1.195116	0.365684	0.553846	4.493998
Within	52.29064	16	3.268165			
Total	130.4701	19				

The results of the carbon Anova display a higher average carbon content in the mature and juvenile wood in the Quebec location when compared to the Ontario location. The samples from the Quebec location show increased variance in the juvenile wood and the Ontario samples show increased variance in the mature wood; however, the Ontario location has the higher overall variance.

Since the p-value for columns is 0.00083 and < 0.05, the null hypothesis A is rejected; thus, there are significant differences between the effectiveness of the sample location for juvenile and mature carbon content. Likewise, the p-value for sample (locations) is 0.01974 which is also < 0.05 and the null hypothesis B is rejected; thus, the sample locations are statistically different.

However, the p-value for interaction is 0.55385, which is > 0.05, concluding that, in terms of carbon content, there are no significant differences in the interaction between sample location and juvenile and mature wood.

The F-values for column (16.8481) and sample (6.70777) both exceed the F-crit value of 4.494, indicating the rejection of the null hypotheses A and B; however, the interaction (0.36568) is < 4.494, indicating the failure to reject the null hypotheses.

When comparing the dry densities of the juvenile and mature wood samples from the Quebec location, the results displayed a consistent pattern of mature wood having higher dry density than the juvenile wood for all five samples. The mature wood densities ranged from 0.525-0.580 g/cm^3, whereas the juvenile wood densities ranged from 0.328-0.398 g/cm^3 (Figure 5).

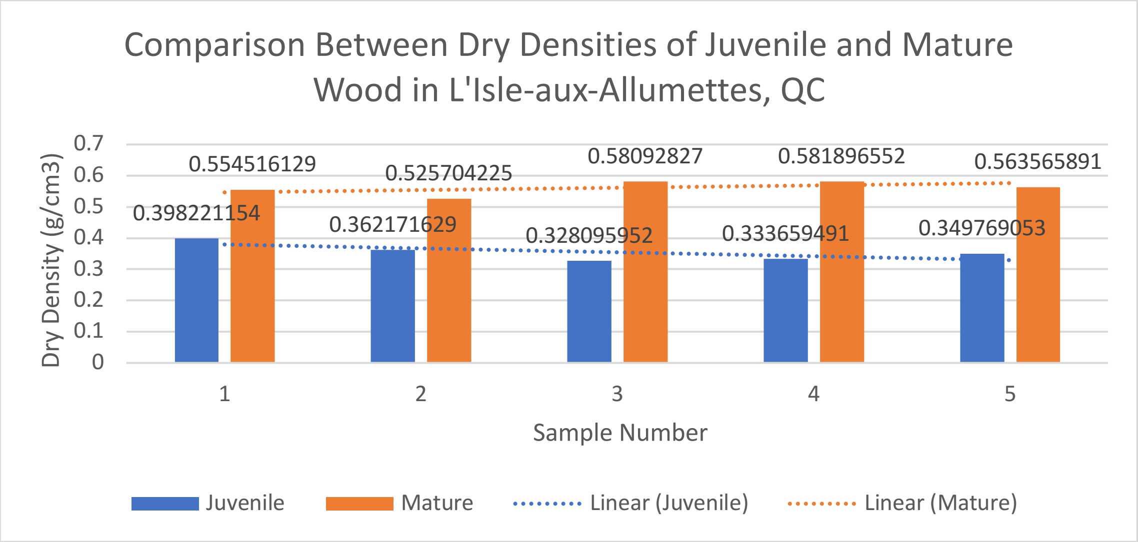


Figure 5 Comparison between dry densities from juvenile and mature wood samples from the Quebec location

When comparing the dry densities between the mature and juvenile wood samples from the Ontario location, the results displayed higher densities within the mature wood. The mature wood densities ranged from 0.389-0.486 g/cm^3, whereas the juvenile wood ranged from 0.348-442 g/cm^3 (Figure 6). It is noted that the variances between the juvenile and mature wood for each sample from the Ontario location are less consistent than the variances between the juvenile and mature wood for each sample from the Quebec location.

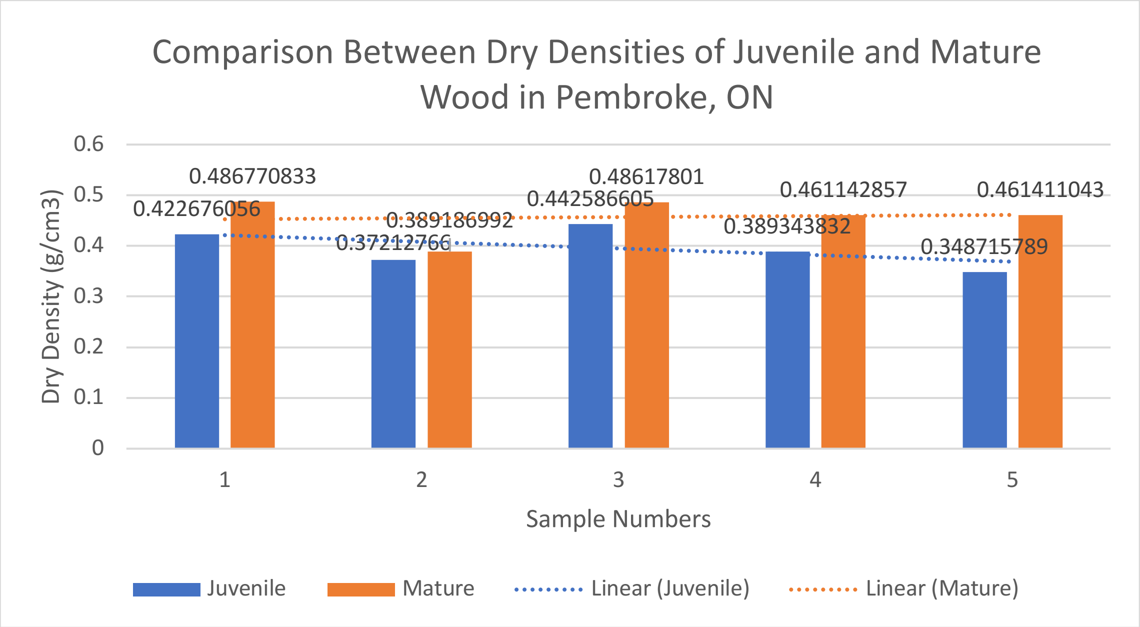


Figure 6 Comparison between dry densities from juvenile and mature wood samples from the Ontario location.

When comparing the dry densities of juvenile wood from both the Quebec and Ontario locations, the samples from Ontario displayed a higher dry density in all samples except for sample 5, where the Quebec sample had slightly higher density. The Ontario juvenile wood sample densities range from 0.348-0.442 g/cm^3, while the Quebec juvenile wood sample densities range from 0.328-0.398 g/cm^3 (Figure 7).

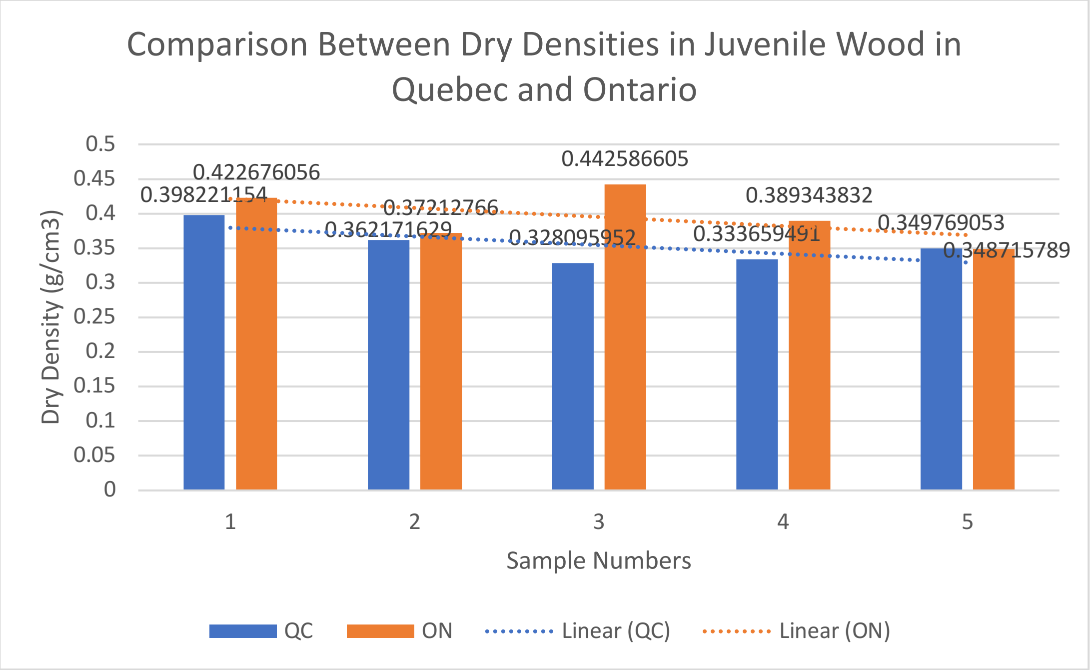


Figure 7 Comparison between dry densities of juvenile wood within the Quebec and Ontario locations.

When comparing the dry densities of mature wood from both the Quebec and Ontario locations, the samples from Quebec displayed a higher dry density in all samples. The Ontario Mature wood sample densities range from 0.389-0.486 g/cm^3, while the Quebec juvenile wood sample densities range from 0.525-0.581 g/cm^3 (Figure 8).

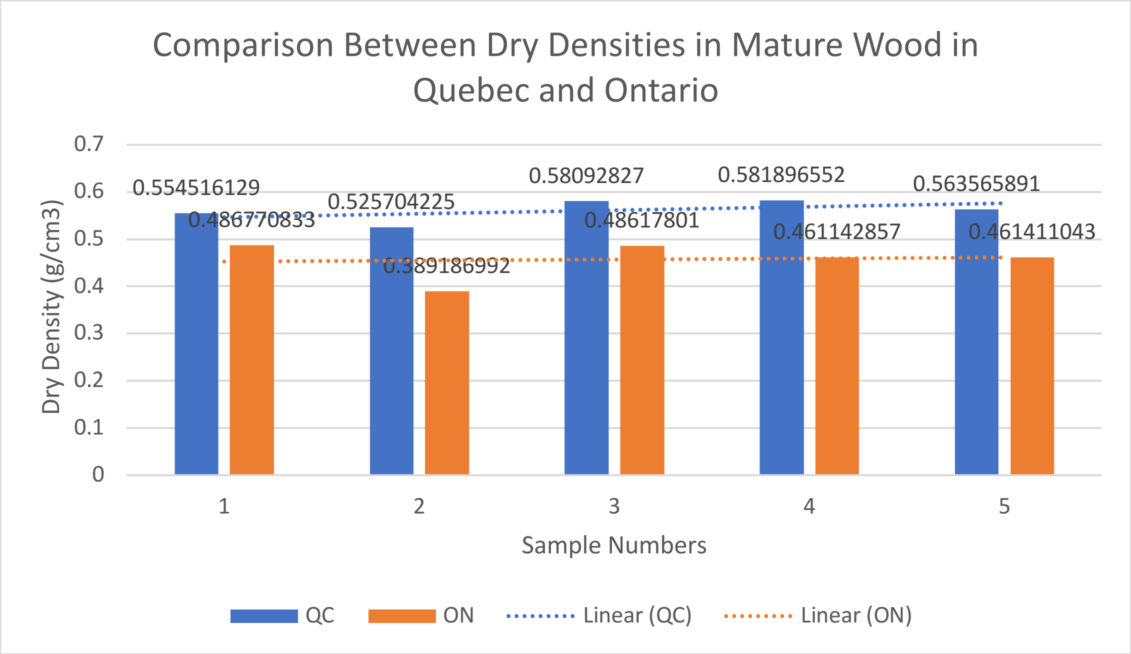


Figure 8 Comparison between dry densities of the mature wood within the Quebec and Ontario locations.

When comparing the average dry densities of juvenile and mature wood in Quebec and Ontario, the results show that in both locations, the mature wood had a higher average density than the juvenile wood. It was also presented that the mature wood from the Quebec location (0.5613 g/cm^3) had 18.8% higher average density than that of the mature wood from the Ontario location (0.4569 g/cm^3); however, the juvenile wood from the Ontario location (0.3951 g/cm^3) had higher average density of 10.4% than that of the juvenile wood from the Quebec location (0.3543 g/cm^3) (Figure 9).

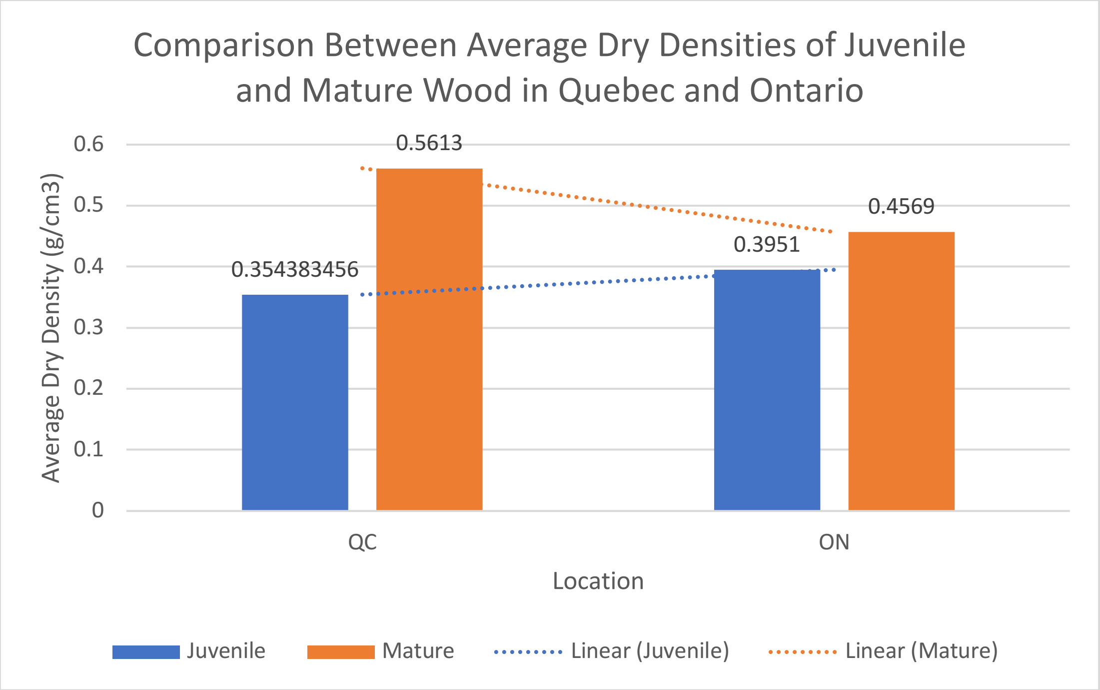


Figure 9 Comparison between average dry densities of the juvenile and mature wood within the Quebec and Ontario locations.

When comparing the carbon content between juvenile and mature wood from the Quebec location, the results displayed the mature wood samples as having consistently higher amounts of carbon content than the juvenile wood samples. The Juvenile wood samples’ carbon content ranged from 8.53-14.00%, whereas the mature wood samples’ carbon content ranged from 14.87-16.70% (Figure 10).

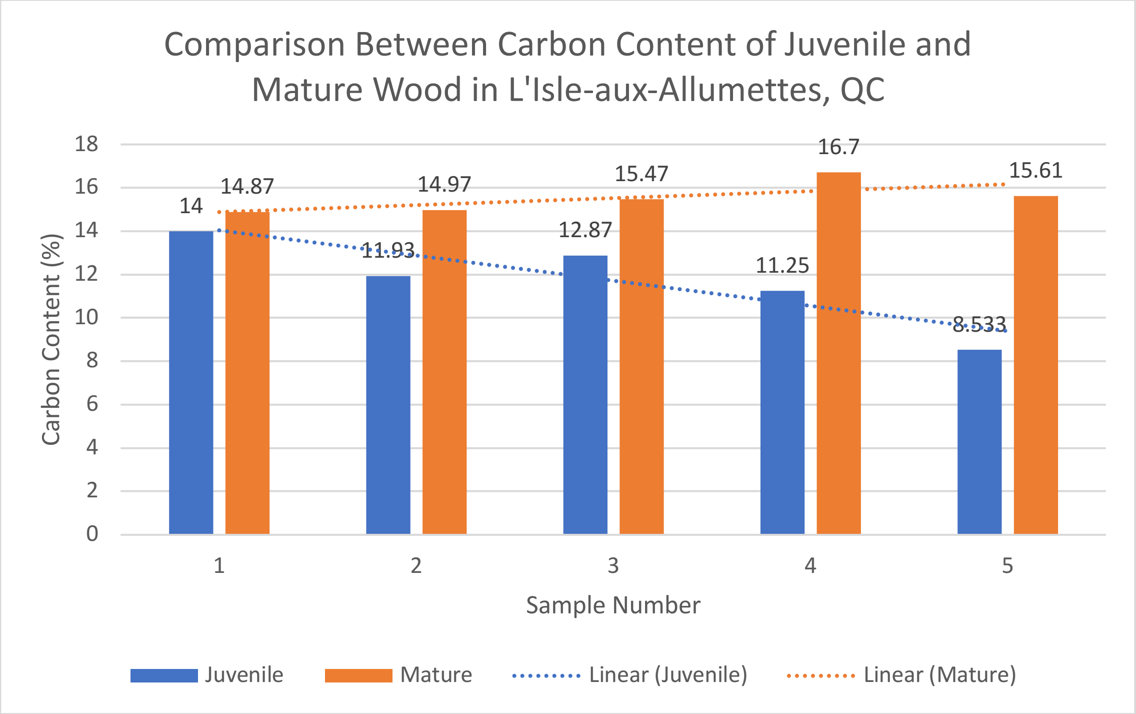


Figure 10 Comparison between carbon content of the juvenile and mature wood within the Quebec location.

When comparing the carbon content between juvenile and mature wood from the Ontario location, the results displayed the mature wood samples as having consistently higher amounts of carbon content in all except one of the juvenile wood samples. In sample 2, the juvenile carbon content is slightly higher than that of the mature wood carbon content. The Juvenile wood samples' carbon content ranged from 8.47-12.84%, whereas the mature wood samples' carbon content ranged from 9.47-15.60 (Figure 11).

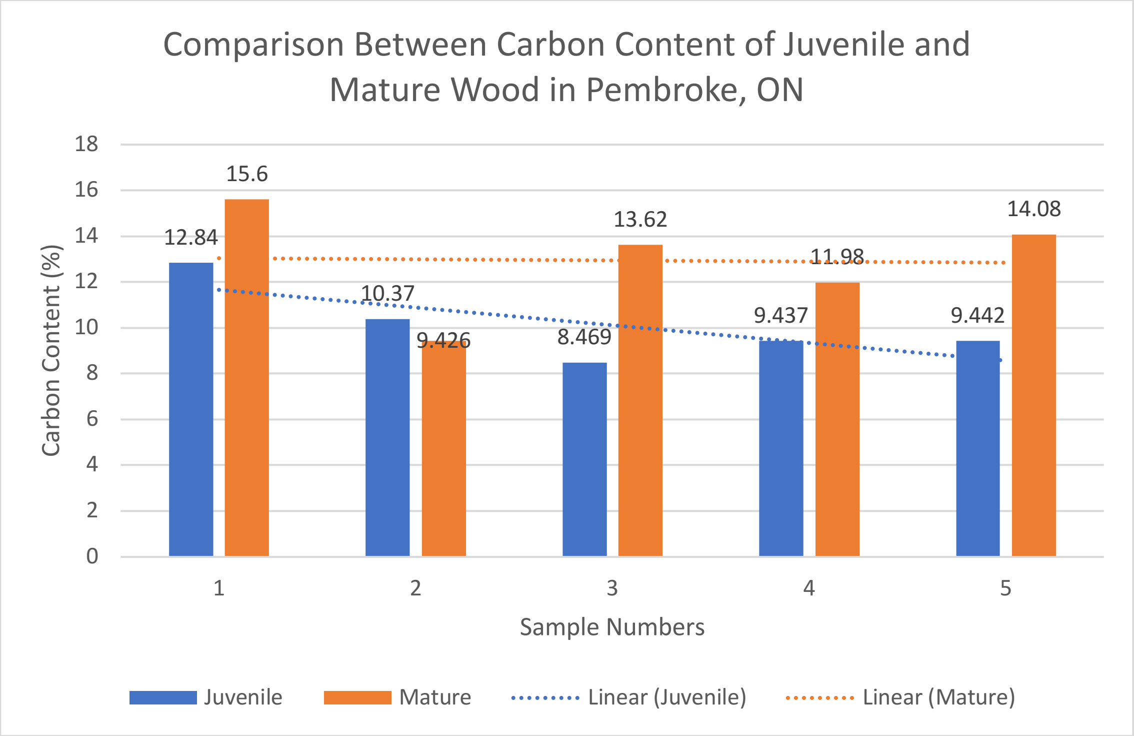


Figure 11 Comparison between the carbon contents of the juvenile and mature wood within the Ontario location.

When comparing the carbon content in the mature wood samples from both Quebec and Ontario, the results displayed the samples from the Quebec location as having higher carbon content in all but one sample (sample 1) than the Ontario samples.

Ontario's carbon content within the mature wood ranged from 9.42-15.6%, whereas the Quebec carbon content ranged from 14.87-16.70% (Figure 12).

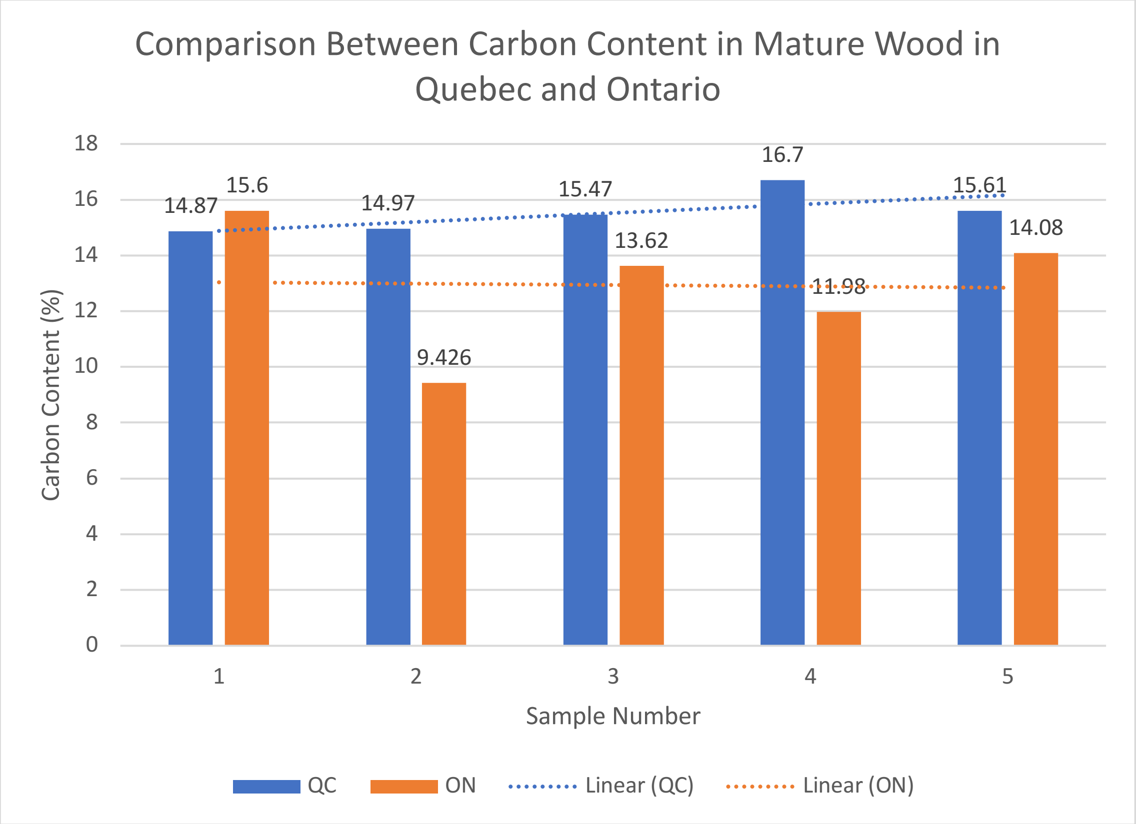


Figure 12 Comparison between carbon contents of the mature wood within the Quebec and Ontario locations.

When comparing the carbon content in the juvenile wood samples from both Quebec and Ontario, the results displayed the samples from the Quebec location as having higher carbon content in all but one sample (sample 5) than the Ontario samples.

Ontario's carbon content within the juvenile wood ranged from 8.47-12.84%, whereas the Quebec carbon content ranged from 8.53-14.00% (Figure 13).

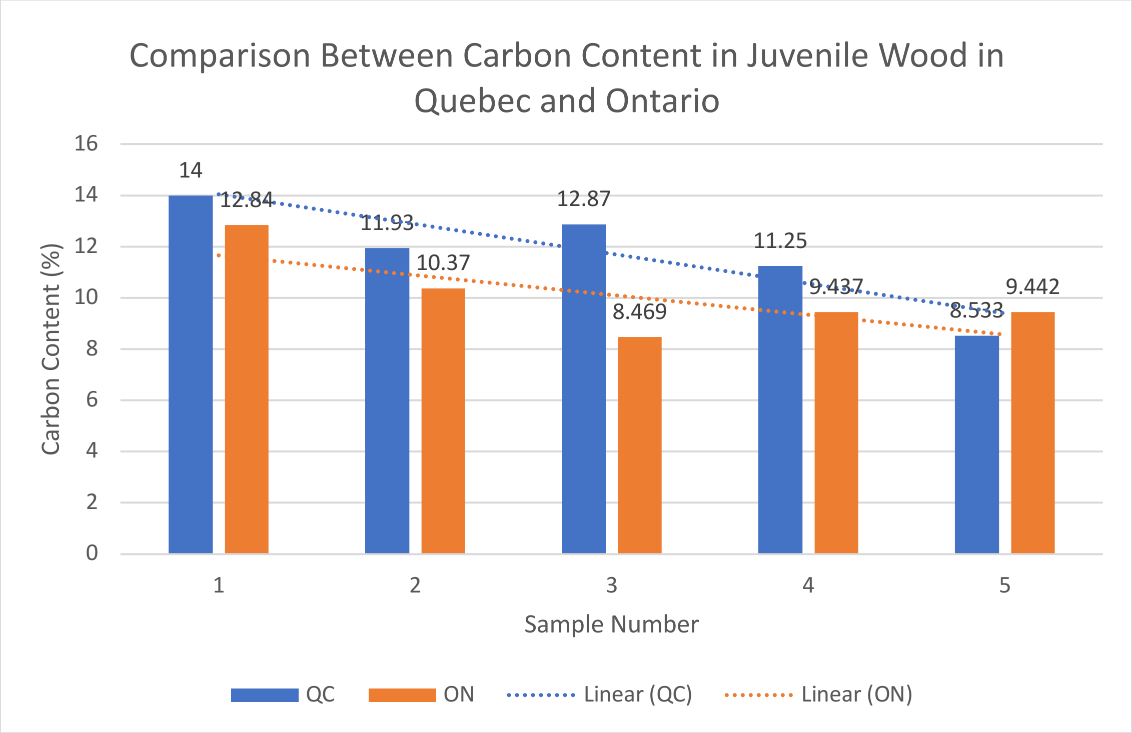


Figure 13 Comparison between carbon contents of the juvenile wood within the Quebec and Ontario locations.

When comparing the average carbon contents of juvenile and mature wood in Quebec and Ontario, the results show that in both locations, the mature wood had a higher amount of carbon content than the juvenile wood. It was also presented that both the juvenile and mature wood from the Quebec location had increased carbon contents than that of the juvenile and mature wood from the Ontario location. The mature wood from the Quebec location had 16.67% higher carbon content than the Ontario mature wood and the juvenile wood from the Quebec location had 13.70% higher carbon content than the juvenile wood in the Ontario location (Figure 14).

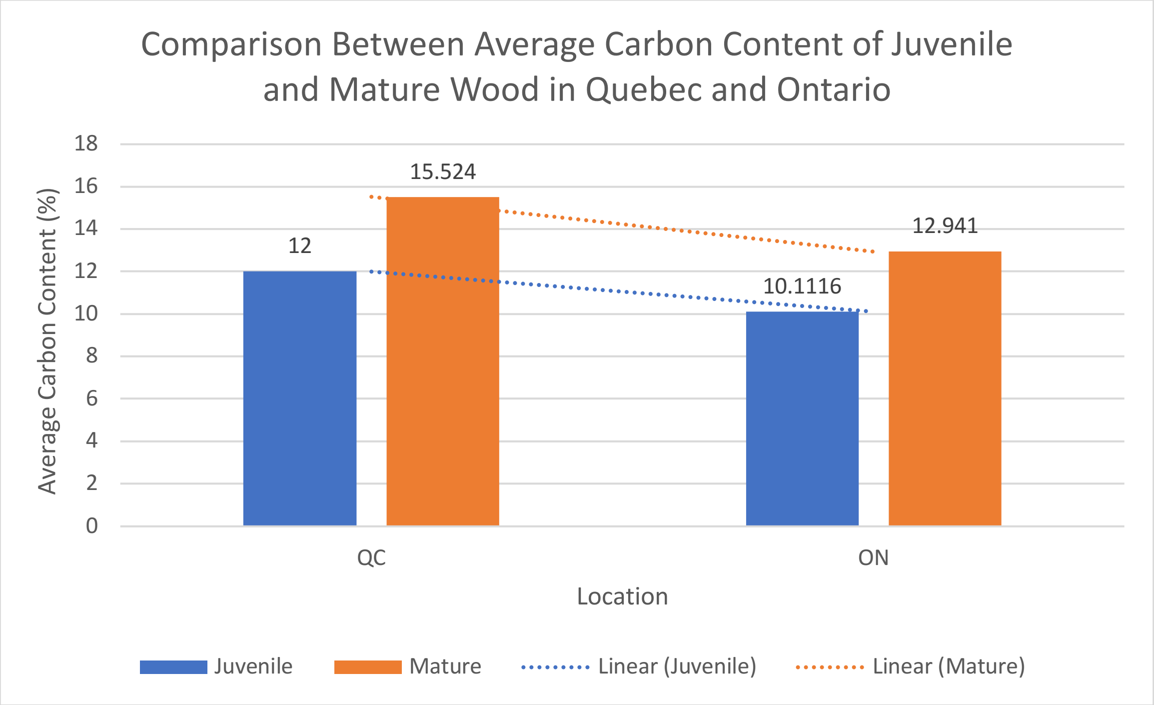


Figure 14 Comparison between average carbon contents of the juvenile and mature wood within the Quebec and Ontario locations.

A hypothetical experiment was conducted to analyze the potential weight of carbon dioxide (CO_2) that would be sequestered in the mature wood of a single tree at each of the study sites, given the different spacings, which resulted in varying wood density and percent carbon content.

To do so, the initial weight of the trees was required. This was done by multiplying the density (Quebec: 0.561 g/cm^3, Ontario: 0.457 g/cm^3) by the volume. The volume consisted of a squared value of the diameter at breast height (Quebec: 13.57 inches, Ontario: 16.25 inches) which was multiplied by an average hypothetical height of 60 ft for both Quebec and Ontario trees. The Quebec tree had a weight of 6198.32 lbs (2,811,507.16 g) and the weight of the Ontario tree was 7240.59 lbs (3,284,275.4 g). The TGA recorded an initial average sample weight of 0.94 g for the Quebec site and 0.87 g for the Ontario site. By dividing the tree weight by the sample weight, an expansion factor for each location was determined (Quebec: 2,990,965.06; Ontario: 3,775,029.20). These expansion factors were utilized to calculate the weight of the carbon in each tree. The average weight of carbon in each sample was determined by the TGA (Quebec: 0.146 g; Ontario: 0.109 g) and was multiplied by the expansion factor, resulting in 436,345.91 g (961.98 lbs) of carbon in the Quebec tree and 411,848.14 g (907.97 lbs) of carbon in the Ontario tree (Figure 15).

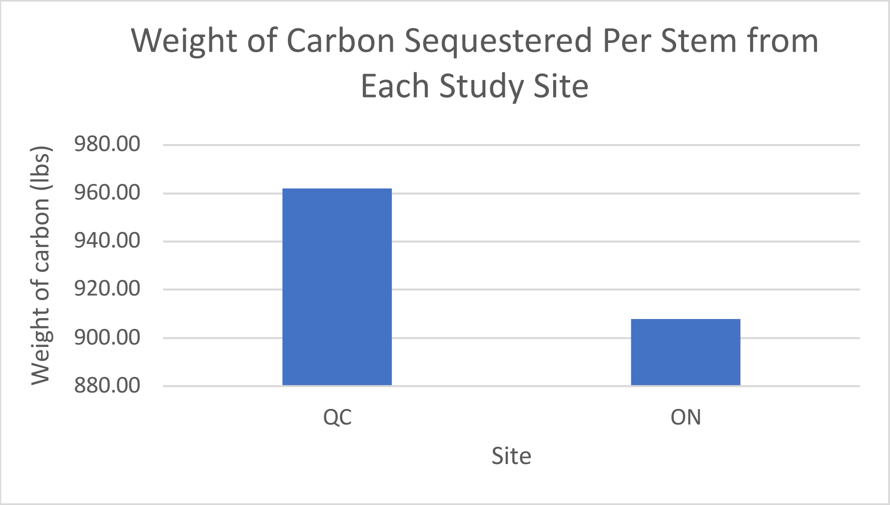


Figure 15 Weight of carbon sequestered per tree in the Quebec and Ontario sites.

To determine the weight of CO_2 within each tree, as opposed to solely carbon (C), the atomic mass of CO_2 (43.999915) was divided by the atomic mass of C (12.001115), resulting in a quotient of 3.6663. The quotient then acted as a coefficient to be multiplied by the weight of carbon in each tree, which resulted in the Quebec tree as sequestering 1,599,775.01 g of (3526.9 lbs) CO_2 and the Ontario tree sequestering 1,509,958.82 g (3328.89 lbs) of CO_2 (Figure 16).

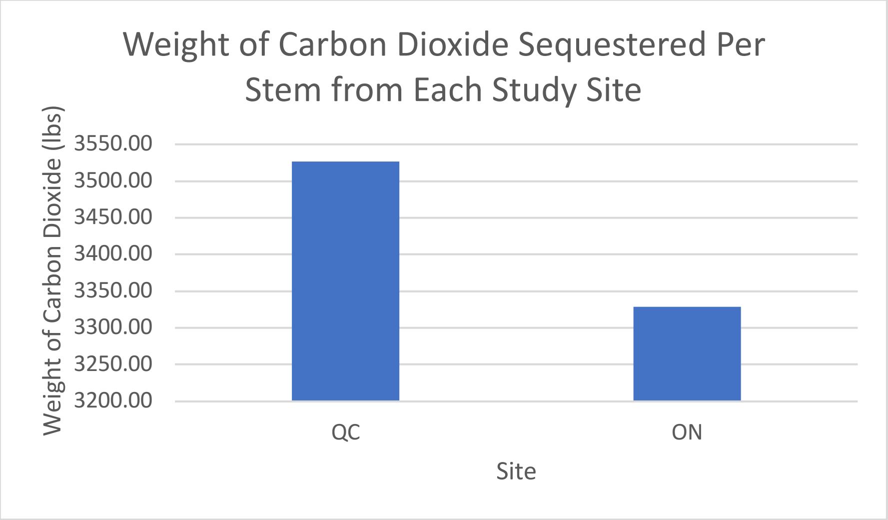


Figure 16 Weight of carbon Dioxide sequestered per stem at each study location.

Next, the weight of CO_2 sequestered per tree was divided by the average tree age at each site (Quebec: 43-years, Ontario: 41-years) which produced the average weight of CO_2 sequestered per year, resulting in 82.02 lbs for the Quebec tree and 81.19 lbs for the Ontario tree. Although these numbers may not seem substantial at stem scale, when converted to stand and landscape scale, there would be a significant difference in CO_2 sequestered between sites with difference spacings, which will be further explained in the Discussion section of this thesis.

5.0 DISCUSSION

This study used two locations, Ontario and Quebec, with significantly different plantation densities. The trees grown on the Ontario site were open-grown in a low competition, residential environment. The trees grown on the Quebec site were tightly-spaced, with a high level of competition for light, space and nutrients, as seen in Figure 17.

Figure 17 Charlie in front of sample trees at the Quebec location.

All trees originated from the same seed source and were within 6 years of age. These sites were chosen to deliberately eliminate as many variables as possible when determining wood density and carbon contents to ensure genetic erraticism did not interfere with the main purpose of the thesis, which is to analyze the effect of plantation density on *Pinus resinosa* wood density and carbon content. With the sample trees originating from the same seed source and grown in different environments, the results can be exclusively dependent on stand and environmental conditions.

The results of the dry density Anova's show that the average mature wood density is higher than that of juvenile wood density in both Ontario and Quebec locations, insinuating that the mature wood has higher latewood percentage which results in an increased density as latewood typically has thicker cell walls and smaller lumens than earlywood. These findings are consistent with those of Larocque *et al*. and Zhu *et al.* where both studies determined that closer spacing between trees resulted in decreased earlywood fraction and higher wood density; as well as the 2011 study by Nazerian *et al*. where southern pine and douglas fir were researched and it was found that juvenile wood had consistently lower wood density due to thinner cell walls, less cellulose content and increased longitudinal shrinkage.

The density of the mature wood in Quebec (0.561322 g/cm^3) is higher than the density of the mature wood in Ontario (0.456938 g/cm), and the density of juvenile wood in Ontario (0.39509 g/cm^3) is higher than the density of the juvenile wood in Quebec (0.354383 g/cm^3). These results are indicative of the tighter spacing at the Quebec location causing more competition, slower growth and thus, higher latewood to earlywood ratio, comparable with Kretschmann *et al*. 1993, which suggests a higher wood density in the tightly-spaced conditions when compared to the open-grown conditions of the Ontario location. The reasoning behind the higher juvenile wood densities at the Ontario site could be due to slightly slower growth caused by increased competition for nutrients at the juvenile stage, which could be due to the Ontario seedlings experiencing more difficulty adjusting to environmental conditions of a less versatile, residential area as opposed to the forest environment in which the Quebec seedlings were planted. Once grown to maturity, the Ontario trees became fully adjusted to their environment, with minimal competition; although the Quebec trees became more crowded and competitive with one another, which serves as explanation for the change in the wood density dynamic; however, this theory would need to be further studied.

The calculated variances within the Quebec samples (juvenile: 0.000781 g/cm^3 and mature: 0.000532 g/cm^3) were less than those within the Ontario samples (juvenile: 0.001432 g/cm^3 and mature: 0.001593 g/cm^3) which is consistent with the density findings displayed in the results. With the Ontario juvenile samples presenting an irregularity in the wood density as previously discussed, this would cause more variance to occur than it would in the samples taken from the Quebec site which displayed more uniform results.

The carbon Anova's displayed that the average percent carbon content within both the juvenile (11.71%) and mature (15.52%) samples from the Quebec site were consistently higher than the average juvenile (10.11%) and mature (12.94%) samples from Ontario. It was also determined that in both locations, the mature wood samples contained higher carbon content than the juvenile wood samples in all but one case. The one outlying case (Ontario #2 sample) had slightly more carbon sequestered in the juvenile wood (10.37%) than the mature wood (9.43%); these results are perceived to be due to higher parenchyma content within the mature wood which would result in significantly higher ash content, and thus less carbon sequestered in the mature wood than the juvenile wood. Aside from the one outlying case, the results go along with the studies conducted by Lamlom and Savidge (2003) where it was determined that carbon is often sequestered per unit volume, indicating that with increased wood density (as seen in the mature wood at both sites, as well as the Quebec samples as compared to the Ontario samples) one can expect more carbon to be stored within the wood, which was concluded in this analysis as the mature wood from the higher-density Quebec location had 16.67% higher carbon content than the Ontario mature wood, as well as the juvenile wood from the Quebec location had 13.70% higher carbon content than the juvenile wood in the Ontario location.

The variances calculated within the Quebec samples showed more variance within the juvenile wood (4.23570) than within the mature wood (0.53198). This is typical and can be explained, as stated in the 2011 study by Nazerian *et al*., as juvenile wood often displays increased microfibril angle, longitudinal shrinkage and thinner cell walls, making the young tree more prone to being affected by different environmental conditions, such as high winds, floods or drought. Once the tree begins to produce mature wood, it becomes hardier and less susceptible to those same conditions.

The Ontario samples showed more carbon variance in the mature wood (5.52684) than within the juvenile wood (2.77813). Although abnormal, this is likely due to the fact that the #2 sample from the Ontario site was smaller in diameter, younger and was the only sample which presented as having higher carbon content within the juvenile wood than the mature wood. This sample is considered an outlier, and is likely what caused the higher average variability in the mature wood. Overall, the Ontario samples once again displayed more variance than the Quebec samples.

Since the demand for timber has grown over the years, forest managers have responded by using intensive management to ensure maximum volume growth with minimum rotation durations. As discussed, rapid growth guarantees disproportionate juvenile and early wood ratios, which consequently results in lower wood quality and the missed opportunity to sequester more carbon.

In the hypothetical experiment to determine the pounds of CO_2 sequestered per year as described in the Results section, the slightly larger DBH's at the Ontario site caused the average tree volume to increase and thus the mass of wood material on each site was unequal; however, because of the increased wood density at the Quebec site, the hypothetical pounds of CO_2 sequestered per year was still slightly higher at the stem scale (Quebec: 82.02 lbs/tree/year; Ontario: 81.19 lbs/tree/year). This difference, although small, would become significant when extrapolated over an entire stand or landscape. In the future, a similar study could be led to determine the difference in pounds of CO_2 sequestered at each site. There would realistically need to be more samples taken from each site to obtain an equally balanced mass of wood at each location, as well as actual tree heights to obtain an accurate and representative difference in CO_2 sequestered at each site, per stem, per year.

Based on the results of this thesis, manipulating the management styles of plantations to initiate tighter spacing and higher stand densities can have a significant effect on both wood density and carbon sequestration. With the knowledge of how to improve wood density without the need to drastically increase the rotation age, it will allow forest managers to produce mechanically stronger wood with high quality and high grade of lumber, which not only improves the structural integrity of the wood product, but also meets market demand while ensuring social and economic growth, without risking the environmental values at both stand and landscape scales.

Moreover, the increased wood density causing increased carbon sequestration is an extremely valuable outcome in a time where global atmospheric carbon dioxide levels are at an all-time high. Forest managers should consider increasing the planting densities in Ontario's current *Pinus resinosa* silviculture system, typically following a clear-cut or seed-tree cut (which may or may not include planting in addition to natural regeneration). Although this would result in slightly higher regeneration costs, it would be a major step for the forest industry in meeting provincial sustainability targets and only a minor financial burden when compared to the potential increased wood quality and carbon sequestration achieved if forest managers agree to make this shift, both in the planning process and on the ground.

6.0 CONCLUSION

The understanding of how plantation spacing affects wood density and carbon content are two very important factors in forest management.

Pinus resinosa is one of the most commonly planted species in Ontario and is located in almost half of Canada and the entire northeastern portion of the United States. Knowing the most optimal ways to manage such a vast species, whilst subsequently maximizing its structural potential, and increasing the amount of carbon sequestered at stand and landscape scales, will not only encourage economic and social prosperity, but also initiate the achievement of environmental sustainability and climate change mitigation objectives.

The original question that this thesis sought out to answer, was whether different silvicultural management, in terms of spacing densities, would cause a significant change in wood density, and if so, how would that affect carbon sequestration potential?

It was determined that both of the stated hypotheses (1. Wood density is strongly influenced by silvicultural management and 2. Plantation densities can be managed to produce wood with increased densities that improve both carbon sequestration and the structural integrity of the wood) were correct. Although the samples from both locations originated from the same seed source and were of similar ages and diameter class, the site with closer spacing, L'Isle-aux-Allumettes, Quebec, presented samples with higher average wood densities when compared to the site with wider spacing, Pembroke, Ontario. The increased wood densities coincided with increased carbon sequestration levels; thus reinforcing the supposition that with the ability to improve *Pinus resinosa* wood density and concurrently, carbon sequestration, forest managers can further promote productive forests as a means of climate change mitigation, while maintaining the ability to produce high-quality wood in a time-efficient manner which meets the demands of both the global market and the environment.

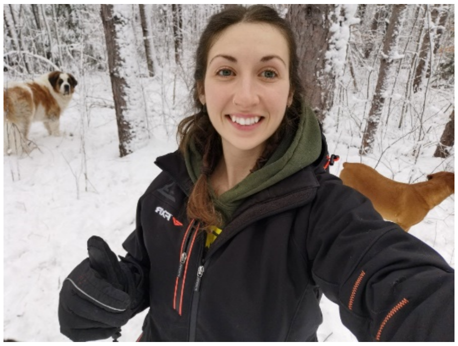


Figure 18 Oscar (left), Shanagh (center) and Daisy (right) in front of sample trees at the Quebec location.

7.0 LITERATURE CITED

Ballard l., and Long, J. 1988. Influence of Stand Density on Log Quality of Lodgepole Pine. *Canadian Journl of Forest Research*. 18:911 –916.

Bembenek, M., Giefing, D.F., Jelonek, T., Karaszewski, Z., Kruszyk, R., Tomezak, A., Woszezyk, M., Mederski, P.S. 2015. Carbon Content in Juvenile and Mature Wood of Scots Pine *(Pinus sylvestris L.). Baltic Forestry* 21 (2): 279-284.

Birdsey, R.A. 1992. Carbon Storage and Accumulation in United States Forest Ecosystems. *United States Department of Agriculture Forest Service*. Northeastern Forest Experiment Station, Radnor, PA.

Browning, B.L. 1963. The Chemistry of Wood. London, New York: Interscience.

Canadian Ecology Centre. 2006. AECL Red Pine Spacing and Thinning Trial. *Forestry Research Partnership Project No. 130-211.*

Churkina, G., Zaehle, S., Hughes, J., Viovy, N., Chen, Y., Jung, M., Heumann, B.W., Ramankutty, N., Heimann, N., Jones, C. 2010. Interactions Between Nitrogen Deposition, Land Cover Conversion, and Climate Change to Determine the Contemporary Carbon Balance of Europe. *Biogeosciences*. pp. 2749-2764.

Hart, J.F. 2010. A Review of the Effects of Silviculture on Wood Quality.

Janas, P., and Brand, D. 1988. Comparative Growth and Development of Planted and Natural Stands of Jack Pine. *Forest Chronicles* 64(4):320–328.

Jones, D., & O'Hara, K. 2018. Variation in Carbon Fraction, Density, and Carbon Density in Conifer Tree Tissues. *Forests*, *9*(7), 430.

Jozsa, L.A., Brix, H. 1989. The Effects of Fertilization and Thinning on Wood Quality of a 24-year-old Douglas-fir Stand. *Canadian Journal of Forest Research*. pp. 1137-1145

Kretschmann, D.E., Moody, R.C., Pellerin, R.F., Bendtsen, B.A., Cahill, J.M., McAlister, R.H., Sharp, D.W. 1993. Effect of Various Proportions of Juvenile Wood on Laminated Veneer Lumber. Res. Pap. FPL– RP–521. Madison, WI. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 31p.

Lamlom, S., Savidge, R. 2003. A Reassessment of Carbon Content in Wood: Variation Within and Between 41 North American Species. *Biomass and Bioenergy*, *25*(4), 381–388.

Larocque, G.R., Marshall, P.L. 1995. Wood Relative Density Development in Red Pine (*Pinus Resinosa* Ait.) Stands as Affected by Different Initial Spacings. Forest Science 41: 709–728.

Maeglin, R. 1967. Effect of Tree Spacing on Weight Yields for Red Pine and Jack Pine. *Joural of Forestry*. 65:647–650.

Matyssek, R., Sandermann, H. 2003. Impact of Ozone on Trees: an Ecophysiological Perspective. *Progress in Botany, Springer, Berlin, Heidelberg*. pp. 349-404

Mora, C.R., Allen, H.L., Clark, A., Daniels, R.F. 2003. Effects of Early Intensive Silviculture on the Juvenile-Mature Wood Transition Age and Proportion of Juvenile Wood in Loblolly Pine Trees Using Latewood Specific Gravity. (92) 51-64.

Natural Resources Canada. 2016. Forest Carbon. Retrieved from https://www.nrcan.gc.ca/climate-change/impacts-adaptations/climate-change-impacts-forests/forest-carbon/13085

Nazerian, M., Ghalehno, M., & Kashkooli, A. 2011. Effect of Wood Species, Amount of Juvenile Wood and Heat Treatment on Mechanical and Physical Properties of Laminated Veneer Lumber. *Journal of Applied Sciences*, *11*(6), 980–987.

Nikitin, N.I. 1966. The Chemistry of Cellulose and Wood. Israel Program for Scientific Translations, Jerusalem.

Oliveira, I. R. D., Chagas, M. P., Bouillet, J.-P., Longui, E. L., Lima, I. L. D., Bordron, B., Filho, M. T. 2017. Effect of Tree Spacing on Growth and Wood Density of 38-year-old Cariniana Legalis Trees in Brazil. *Southern Forests: a Journal of Forest Science*, *80*(4), 311–318.

Plomion, C. 2001. Wood Formation in Trees. *Plant Physiology*, *127*(4), 1513–1523.

Pretzsch, H., Biber, P., Schütze, G., Kemmerer, J., Uhl, E. 2018. Wood Density Reduced While Wood Volume Growth Accelerated in Central European Forests Since 1870. *Forest Ecology and Management*, *429*, 589–616.

Pukkala, T. 2016. Does Management Improve the Carbon Balance of Forestry? *International Journal of Forest Research,* 90, 125-135.

Savidge, R.A. 2000. Biochemistry of Seasonal Cambial Growth and Wood Formation - An Overview of the Challenges. *Cell and molecular biology of wood formation*. Bios Scientific Publishers Limited.

Symonds, J. 2011. Thermogravimetric Analyzer. Lakehead University Centre for Analytical Services. Forest Soils Laboratory. Pp. 5.

United States Department of Agriculture. 2019. Plant profile: *Pinus resinosa*. https://plants.usda.gov/core/profile?symbol=PIRE

Yang, J., & Evans, R. 2003. Prediction of MOE of Eucalypt Wood from Microfibril Angle and Density. *Holz als Roh- und Werkstoff, 61*, 449-452.

Yin, W., Yin, M., Zhao, L., & Yang, L. 2012. Research on the Measurement of Carbon Storage in Plantation Tree Trunks Based on the Carbon Storage Dynamic Analysis Method. *International Journal of Forestry Research*, *2012*, 1–10.

Zhu, J., Scott, C., Scallon, K., Myers, G. 2007. Effects of Plantation Density on Wood Density and Anatomical Properties of Red Pine (*Pinus Resinosa*).

Zobel, B. J. 2012. Wood Variation: Its Causes and Control. Place of publication not identified: Springer.

8.0 APPENDICES

8.1 APPENDIX I

ONTARIO AND QUEBEC SAMPLE NUMBERS, DIAMETER AT BREAST HEIGHT (DBH), AVERAGE DBH AND AGE

Location	**Sample #**	**DBH**	**Average DBH**	**Age**
L'Isle aux Allumettes, QC	1	34.1	34.48	46
L'Isle aux Allumettes, QC	2	33.6		40
L'Isle aux Allumettes, QC	3	36.7		42
L'Isle aux Allumettes, QC	4	30.8		45
L'Isle aux Allumettes, QC	5	37.2		42
Pembroke, ON	1	42.4	41.3	44
Pembroke, ON	2	18		33
Pembroke, ON	3	40.8		41
Pembroke, ON	4	43.8		41
Pembroke, ON	5	38.2		44

8.2 APPENDIX II

WOOD DENSITY RESULTS FOR QUEBEC AND ONTARIO

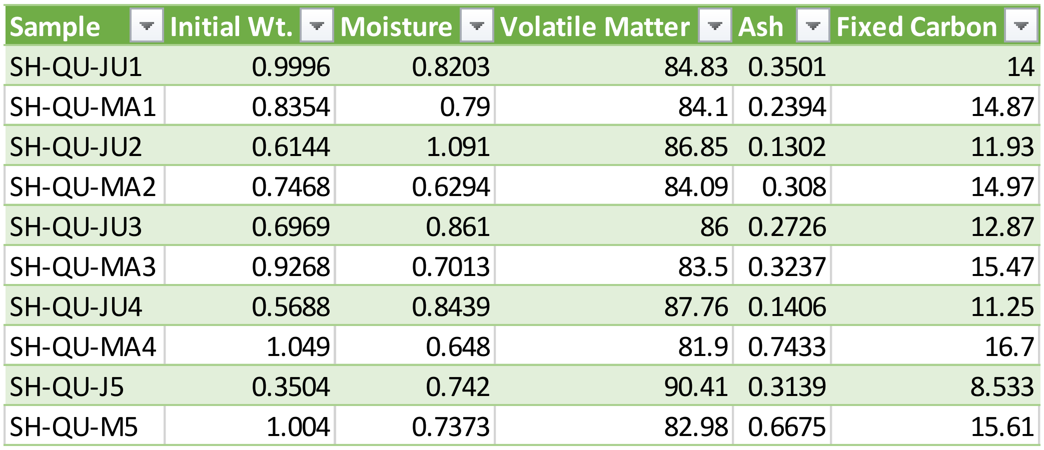
	Dry Weight (g)		Dry Volume (cm3)		Dry Density (g/cm3)		Average Density	
Sample Number	Juvenile	Mature	Juvenile	Mature	Juvenile	Mature	Juvenile	Mature
QC 1	1.6566	0.8595	4.16	1.55	0.398221154	0.554516129	0.354383456	0.561322214
QC 2	2.068	0.7465	5.71	1.42	0.362171629	0.525704225		
QC 3	2.1884	1.3768	6.67	2.37	0.328095952	0.58092827		
QC 4	1.705	1.0125	5.11	1.74	0.333659491	0.581896552		
QC 5	1.5145	0.727	4.33	1.29	0.349769053	0.563565891		
ON 1	1.2004	1.4019	2.84	2.88	0.422676056	0.486770833	0.395089988	0.456937947
ON 2	1.2243	0.4787	3.29	1.23	0.37212766	0.389186992		
ON 3	1.9164	0.9286	4.33	1.91	0.442586605	0.48617801		
ON 4	2.9668	0.807	7.62	1.75	0.389343832	0.461142857		
ON 5	1.6564	0.7521	4.75	1.63	0.348715789	0.461411043		

REMOVED MOISTURE CONTENT AND CARBON CONTENT RESULTS FOR QUEBEC AND ONTARIO

	%Moisture Content Removed		Carbon Content		Average Carbon Content	
Sample Number	Juvenile	Mature	Juvenile	Mature	Juvenile	Mature
QC 1	26.8381	80.58173357	14	14.87	11.7	15.524
QC 2	29.80174	84.96985934	11.93	14.97		
QC 3	29.75233	91.74898315	12.87	15.47		
QC 4	30.88563	72.59259259	11.25	16.7		
QC 5	31.93133	115.4883081	8.533	15.61		
ON 1	27.74908	138.2266923	12.84	15.6	10.1116	12.9412
ON 2	30.65425	149.1330687	10.37	9.426		
ON 3	29.49802	135.9250485	8.469	13.62		
ON 4	28.11447	153.5192069	9.437	11.98		
ON 5	31.07341	110.4241457	9.442	14.08		

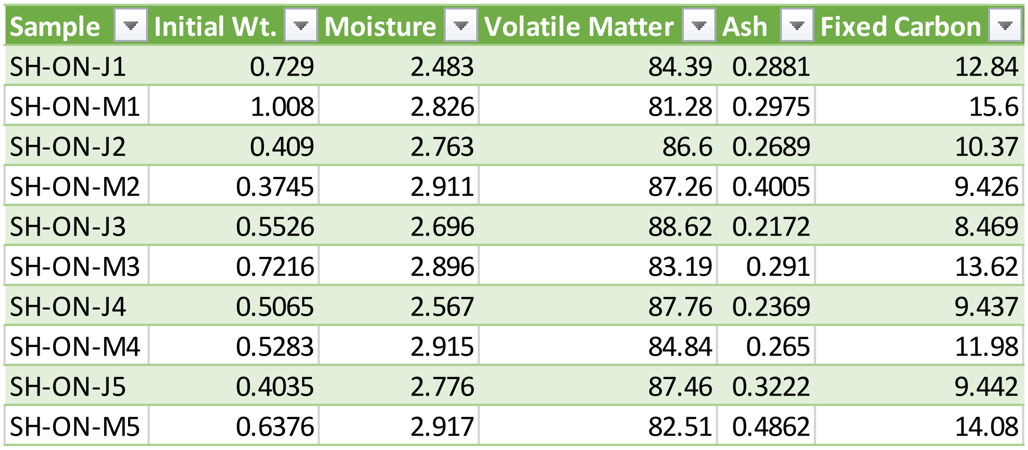
8.3 APPENDIX III

THERMOGRAVIMETRIC ANALYZER RESULTS FOR THE QUEBEC SITE



Sample	Initial Wt.	Moisture	Volatile Matter	Ash	Fixed Carbon
SH-QU-JU1	0.9996	0.8203	84.83	0.3501	14
SH-QU-MA1	0.8354	0.79	84.1	0.2394	14.87
SH-QU-JU2	0.6144	1.091	86.85	0.1302	11.93
SH-QU-MA2	0.7468	0.6294	84.09	0.308	14.97
SH-QU-JU3	0.6969	0.861	86	0.2726	12.87
SH-QU-MA3	0.9268	0.7013	83.5	0.3237	15.47
SH-QU-JU4	0.5688	0.8439	87.76	0.1406	11.25
SH-QU-MA4	1.049	0.648	81.9	0.7433	16.7
SH-QU-J5	0.3504	0.742	90.41	0.3139	8.533
SH-QU-M5	1.004	0.7373	82.98	0.6675	15.61

THERMOGRAVIMETRIC ANALYZER RESULTS FOR THE ONTARIO SITE



Sample	Initial Wt.	Moisture	Volatile Matter	Ash	Fixed Carbon
SH-ON-J1	0.729	2.483	84.39	0.2881	12.84
SH-ON-M1	1.008	2.826	81.28	0.2975	15.6
SH-ON-J2	0.409	2.763	86.6	0.2689	10.37
SH-ON-M2	0.3745	2.911	87.26	0.4005	9.426
SH-ON-J3	0.5526	2.696	88.62	0.2172	8.469
SH-ON-M3	0.7216	2.896	83.19	0.291	13.62
SH-ON-J4	0.5065	2.567	87.76	0.2369	9.437
SH-ON-M4	0.5283	2.915	84.84	0.265	11.98
SH-ON-J5	0.4035	2.776	87.46	0.3222	9.442
SH-ON-M5	0.6376	2.917	82.51	0.4862	14.08