QUANTIFYING THE INFLUENCE OF CROWN SIZE ON MECHANICAL WOOD PROPERTIES IN WHITE SPRUCE (PICEA GLAUCA)

by

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A thesis submitted in conformity with the requirements for the degree of Master of Science in Forestry
Graduate Faculty of Forestry
University of Toronto

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I. Abstract

Conceptual models of wood formation suggest that trees with large crowns produce low quality wood, but few studies have explicitly examined the relationship between crown size and wood quality. In this study, I examine how crown size influences the strength and stiffness of wood, as measured by Modulus of Elasticity (MOE) and Modulus of Rupture (MOR), using 42- and 72-old year plantation white spruce (*Picea glauca*) from Ontario, Canada. Mechanical properties were determined from 10x10x140 mm mini-clear samples (*n*=657), selected from a radial gradient at three heights within the stems. Non-linear mixed-effects models showed that strength and stiffness significantly decreased with crown size, and that MOE and MOR were best predicted by cambial age and crown ratio. The results suggest that the models could be used in conjunction with remotely sensed data to identify high quality timber prior to harvest.
II. Acknowledgements

I would like to first thank my supervisor John Caspersen for allowing me the opportunity to undertake and complete this research. I would like to also extend gratitude to my committee, Alexis Achim, Darwin Burgess, and Paul Cooper for their guidance, insight, and support through the many hours spent in the field, workshop, and office. In addition to my academic advisors, I would like to thank Adam Martin for his advice and support throughout all stages of my thesis, and especially in the editing of this manuscript.

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Chapter 1: Wood Properties and their Origins

1.1 Introduction

Wood is one of the most ubiquitous natural resources available to mankind. Wood has been harnessed for its wide array of qualities, whether it is aesthetic charm, thermal, or mechanical attributes. From building primitive weaponry and tools, to being the basis for advanced architectural feats, the physical strength of wood has been fundamental to development of humanity. It is the purpose of this chapter to identify what exactly attributes wood its exceptional mechanical properties by reviewing literature regarding the chemical substance of wood, its cell ultrastructure and hygroscopic nature, as well as the greatest contributing factors influencing its strength and stiffness, specifically density and microfibril angle.

Subsequently, this chapter will focus on the origins of wood properties. This will entail a review of wood formation theory, the definition of juvenile wood and its relation to the crown, as well as the indirect effect of spacing on wood properties through the crown. The purpose of this review is to illustrate how and why the size of a tree’s crown can influence the formation of target wood properties.

1.2 Wood Substance

Wood is formed by binding cellulose, hemicellulose, lignin, extractives, and inorganic ash, in a complex manner that forms its cell structure (Panshin and de Zeeuw, 1980). The formation and delineation of these substances is not very well understood due to the high variability within the tree stem, as well as the difficulty (and therefore variability) in physically accounting for them (Panshin and de Zeeuw, 1980; Ruel et al., 2006). However, these chemical components have been attributed an approximate percentage range in regards to overall dry weight of cell wall substance, placing cellulose at 40-50%, hemicellulose at 20-35%, and lignin
at 15-35% (Panshin and de Zeeuw, 1980). Generally, extractives carry less of a role in the overall cellular structure, comprising only a few percent of the total weight (Panshin and de Zeeuw, 1980; Tsoumis, 1991); however, there are instances where extractives can reach high levels such as in incense-cedar [*Calocedrus decurrens* (Torr.) Florin] and in the heartwood of European larch species (*Larix* sp.) where total extractives can reach upwards to 20% of total dry wood weight (Anderson and Zavarin, 1965; Gierlinger and Wimmer, 2004).

In order to understand the mechanical properties of wood, one must understand the physical, as well as chemical composition of wood cells. As the largest proportion found in wood, cellulose is responsible for forming the crystalline microfibrils that are found in the secondary cell layer. These microfibrils are subsequently encased in a matrix of hemicellulose material and further encrusted with lignin, bonding the cell together (Mark, 1967; Panshin and de Zeeuw, 1980; Bergander and SalmÈn, 2002). Whistler and Chen (1991) suggest that the hemicellulose and lignin are covalently bonded into a matrix, and that the crystalline cellulose microfibrils are either intermixed or bonded with the hemicellulose casing. Regardless of the bonding process, it is the difference between these substances that provide wood its mechanical properties. Specifically, the difference between lignin’s plasticity and cellulose and hemicellulose’s elasticity creates a unique bond that is flexible yet incredibly strong, and is similar to the visco-elastic steel rod construction in reinforced concrete (Panshin and de Zeeuw, 1980).

Despite the dynamics between these chemical substances, the lignin-hemicellulose matrix only contributes significantly to the mechanical properties of the cell wall when the cellulose microfibril angle is higher than 40 degrees (Wardrop, 1951; Cave, 1968). Otherwise, at low
angles (0 < 15-20 degrees) theoretical analysis (Cave, 1968; Mark and Gillis, 1973) reveals that the S₂ cellulose microfibrils primarily determine axial stiffness.

1.3 Cell Architecture

The wood of gymnosperms is comprised primarily (90-94% of total wood volume (Mark, 1967)) of elongated, longitudinally oriented tracheid cells, which are differentiated at the cambium and concentrically layered in the form of growth rings from pith to bark. The architecture and form of these cells change with their position within the stem, be it vertically or horizontally, which also characterizes earlywood and latewood, as well as juvenile and mature wood. However, before defining these terms, the cell structure must first be explored.

The physical structure of the cell consists of primary and secondary walls, which surround an inner lumen; each cell is also separated by the true middle lamella. Both the primary and secondary walls, including the middle lamella, consist of physically aggregated polysaccharides that are known as microfibrils (Panshin and de Zeeuw, 1980). As previously described, these crystalline cellulose microfibrils are encased in an elastic hemicellulose matrix, and further encrusted with amorphous lignin and extractives (Mark, 1967; Thomas, 1979; Panshin and de Zeeuw, 1980). These layers provide the cell with physical rigidity and are helically layered in sheets known as lamellae (Panshin and de Zeeuw, 1980). However, the layering of these different substances creates an intricate fabric that leaves a minute network of microcapillary voids that enable water permeation between non-living tracheids (Panshin and de Zeeuw, 1980).

Moreover, in a mature tracheid, the middle lamella and the primary wall are difficult to distinguish due to the similarity in their chemical composition, which is high in lignin content, and are therefore known together as the compound middle lamella (Thomas, 1979). The
secondary wall has three layers that can be distinguished on the basis of their chemical composition, thickness, and microfibril orientation, and have been labeled the S₁, S₂, and S₃ layers by Kerr and Bailey (1934). The inner S₃ layer, which adjoins the lumen, is the thinnest layer, followed by the outer S₁ layer; the S₂ layer is the most robust of the three and also determines the overall cell width (Mark, 1967; Thomas, 1979). The S₁ and S₃ layers have a microfibril orientation in a helical pattern that is nearly horizontal, whereas the S₂ layer’s microfibril orientation is normally nearly parallel to the cell axis. It is the microfibril orientation that is responsible for determining the stiffness of wood (Barber and Meylan, 1964; Harris and Meylan, 1965; Cave, 1968; Barnett and Bonham, 2004); however, the angles of these microfibrils vary depending on a multitude of factors, such as position within the stem (Preston, 1934; Bendtsen and Senft, 1986; Bonham and Barnett, 2001). Averages of microfibril angles for each layer of the cell are given in Table 1-1.

### Table 1-1. Thickness of Various Cell Wall Layers and Microfibril Angle within the Layers (Thomas, 1979)

<table>
<thead>
<tr>
<th>Wall Layer</th>
<th>Relative Thickness (%)</th>
<th>Average Angle of Microfibrils</th>
</tr>
</thead>
<tbody>
<tr>
<td>PW</td>
<td>+/- 1</td>
<td>Random</td>
</tr>
<tr>
<td>S₁</td>
<td>10-22</td>
<td>50-70°</td>
</tr>
<tr>
<td>S₂</td>
<td>70-90</td>
<td>10-30°</td>
</tr>
<tr>
<td>S₃</td>
<td>2-8</td>
<td>60-90°</td>
</tr>
</tbody>
</table>

### 1.4 Wood Formation

The cell architecture described above is a general description for gymnosperm cell form. However, variations in cell wall thickness and microfibril angle have great implications for the
physical behaviour of wood. Thus it is important to be familiar with these variations as they occur throughout the stem of a tree.

A tree grows by differentiating cells and concentrically layering tracheids from its core (the pith) upwards and outwards. Upward growth is characterized as apical meristematic enlargement where cell differentiation occurs in a spherical manner, whereas outward growth is known as lateral meristematic enlargement where cell differentiation occurs in flat uniform sheets parallel to the pith (Panshin and de Zeeuw, 1980). The apical meristem is responsible for increasing the height of the tree, and the lateral meristem is responsible for adding girth to the stem of the tree (Panshin and de Zeeuw, 1980).

Cell differentiation only occurs during active photosynthesis, which leads to the formation of growth rings in seasonal climates where photosynthesis ceases. Growth rates change periodically throughout the season, and this influences cell wall thickness and wood density and is characterized by the formation of earlywood and latewood (Hoadley, 2000). Both of these terms refer to the cross-sectional variation in size of the diameter of the lumen and the width of the cell wall. Earlywood occurs at the onset of growth during the spring and is characterized with large lumens and thin walls (Panshin and de Zeeuw, 1980). Latewood occurs as the growing season slows or nears completion and is physically defined by narrow lumens and thick cell walls. Furthermore, the progression throughout the growing season from large lumens and thin cell walls towards narrow lumens and thick walls is a fluid process; however it can differ in intensity according to species, ranging from sudden to gradual transitions (Zobel and Buijtenen, 1989). This variation within a growth ring is also a key factor in discerning juvenile wood from mature wood.
Juvenile wood is associated with a high ratio of earlywood to latewood formation, but is also distinguished by other features such as shorter longitudinal cell length, larger $S_2$ microfibril angles, more compression wood, higher lignin content, and lower cellulose content; (Zobel and Buijtenen, 1989; Zobel and Sprague, 1998; Kretschmann, 2008). These key differentiating factors have distinct implications on the mechanical properties and physical behaviour of wood, such that mature wood produces stronger and stiffer wood than juvenile wood (Ivkovic et al, 2008).

### 1.5 Hygroscopicity of Wood: Cell Form & Moisture Interaction

Hygroscopicity refers to the ability of wood to absorb water from the surrounding atmosphere either in vapour or liquid form (Ahlgren, 1972). This feature is due to the nature of the chemical composition of wood, as cellulose, hemicellulose, lignin, and certain extractives are all water-permeable substances (Tsoumis, 1991). In non-living wood, moisture either enters (adsorption) or withdraws (desorption) from wood cells due to variation between the moisture content of the wood cells and the atmosphere. Cellulose is the primary attractor of water molecules, which then dissipates moisture through the minute capillary voids found in the cell wall’s fabric of chemical substances (Panshin and de Zeeuw, 1980; Tsoumis, 1991). The term ‘free water’ refers to water held in the cell cavities, whereas ‘bound water’ refers to water held in the cell wall (Tsoumis, 1991). The fibre saturation point occurs when the cell wall reaches full moisture content yet the cell cavity remains empty (Tiemann, 1906).

The hygroscopic nature of wood carries great significance when referring to wood quality due to its ramifications for altering physical wood properties, principally dimensional change. Deformation such as shrinkage and swelling are instances of such change, which also ultimately influences its physical behaviour, specifically its mechanical properties. For example, Wangaard
(1950) noted that below FSP moisture content, for every 1% decrease in moisture content there is a corresponding 5% increase in bending strength and a 2% increase in bending stiffness. This result occurs because the removal of water from the cell wall strengthens the attractive forces between the cellulose chain molecules and compacts the microfibril ultrastructure (Stamm, 1964).

1.6 Measures of the Mechanical Properties of Wood

Wood is a highly anisotropic substance that requires different techniques to measure its many different mechanical properties. Microscopic properties such as chemical composition, as well as cell form and architecture, lend an understanding to the observer for generic wood quality characteristics, yet are not the most appropriate measure for the mechanical properties of wood at the human scale. Therefore, specific metrics that link cell attributes to wood quality are necessary to fully understand how wood interacts with external forces. Such gauges include: modulus of elasticity (MOE), modulus of rupture (MOR), microfibril angle (MFA), and specific gravity (SG). The primary factors affecting the effectiveness of these gauges are the presence of juvenile, mature, and compression wood. Because wood is an orthotropic material (Panshin and de Zeeuw, 1980; USDA, 1999), meaning that its mechanical properties vary according to each of its axes, all mechanical attributes referred to hereafter refer specifically to the longitudinal axis, unless otherwise noted.

1.6.1 Strength & Stiffness

Strength and stiffness in wood is defined by its ability to deter and incur deformation due to applied external forces (Garratt, 1931). Stiffness measures the elasticity of wood and is represented by modulus of elasticity (MOE) by specifically determining the ability of a piece of wood to return to its original shape after being subject to an external force (Tsoumis, 1991).
Stress (force applied) and strain (deformation incurred) are directly proportional until a point where each additional unit of stress records a greater unit of deformation; this point is known as the proportional limit and is characterized by Hooke’s Law (Hoadley, 2000). MOE is obtained by calculating the slope of the plotted stress/strain curve up to the point of deformation (i.e. the proportional limit). Moreover, when a specimen records a higher MOE value, it indicates greater stiffness; a lower MOE value corresponds with greater flexibility (Desch and Dinwoodie, 1981).

Strength is measured by applying an external force until the point of failure; in bending tests this point is known as the modulus of rupture, otherwise it is referred to as ultimate strength (USDA, 1999). Measurement of both the modulus of elasticity and modulus of rupture are the standard procedures for testing mechanical strength of wood as they closely mimic real world bending strength situations applied to normal sized lumber.

MOE and MOR are tested by static bending tests. These tests are executed using small clear samples or full-sized lumber, which can vary in size according to the selected testing procedure and scope of the particular study. Several testing procedures exist such as the American Society for Testing and Materials (ASTM) which uses 2.5 x 2.5 cm (width and depth) by a variable length; the International Organization for Standardization uses a 2 x 2 x 40 cm standard; while even smaller small clear samples 1 x 1 x 15 cm samples have been employed on smaller diameter trees (Alteyrac et al., 2006; Schneider et al., 2008).

To complete the bending tests, these small clear samples are subjected to external pressure tests that may apply forces in various designs, such as three-point and four-point load testing. In a standard three-point test, a small clear specimen rests on two fixed points, and the third point applies the external force downward onto the specimen; a four-point test introduces a second downward force.
Moreover, there are three primary stresses incurred when testing the mechanical properties of wood, those are: tensile, compressive, and shear. These stresses can be isolated and tested individually or they act together as they do in bending tests (Garratt, 1931). These dynamic stresses work simultaneously by distributing the applied force within the specimen and affecting different parts of the bending timber. Specifically, when bending occurs, the fibres on the concave part of the specimen are compressed; the fibres on the convex part elongate (and therefore are put under tension); and the longitudinal fibres are under stress to slide past one another (shearing force), which is greatest at mid-depth (Garratt, 1931).

There are many factors that affect the mechanical strength and stiffness of wood. It is interesting to compare the strength of wood at varying physical scales, as it exemplifies how the molecular and anatomical strength of wood sets the foundation for mechanical properties at the human scale. For instance, as a broad generalization for temperate wood species, strength in axial tension at the human scale (testing on small clears) ranges from 50-160 MPa (Tsoumis, 1991). On an anatomical level, single axial tracheid strength for conifers ranges from 200-1300 MPa (Kollmann and Cote, 1968), while on the molecular level, the strength of cellulose chains is theoretically estimated at 7.5 GPa (Giordano, 1971; Tsoumis, 1991). In order to explain this successive reduction of mechanical strength from the molecular to the whole wood level, one must seek the fundamental factors affecting mechanical properties of wood, two of which are microfibril angle and specific gravity.

1.6.2 The Influence of Microfibril Angle

Numerous studies have demonstrated the curvilinear relationship between MFA and mechanical properties of wood, generally indicating that as MFA decreases, strength and stiffness increase (Kraemer, 1950; Harris and Meylan, 1965; Cowdrey and Preston, 1966; Cave,
1969; Mark and Gillis, 1973; Bendtsen and Senft, 1986; Cave and Walker, 1994; Booker et al., 1998; Tsehaye et al., 1998; Yamashita et al., 2000; Deresse et al., 2003; Xu et al., 2004). Kraemer (1950) found that in examining strength and stiffness in red pine there was a considerable negative correlation between MFA and MOR and MOE with respective coefficients of $r^2 = -0.782$ and $r^2 = -0.783$. Cave (1969) measured earlywood cell wall stiffness against mean microfibril angle in radiata pine and found a five-fold increase in stiffness with a decreasing MFA. Similarly, Tsehaye et al (1998) recorded a strong negative correlation between MFA and MOE for radiata pine with an $r^2$-value of -0.913. Xu et al (2004) studied the effect of MFA and density in the butt log of radiata pine and found that MFA was the main determinant of MOE variation with height. This plethora of evidence illustrates the certainty to which MFA is associated with the mechanical properties of wood.

### 1.6.3 Specific Gravity and Wood Density

Specific gravity is the ratio of dry wood density to water density, and is often expressed in grams per cubic centimetre (Hoadley, 2000). By measuring the density of wood, one is essentially measuring the amount of solid cell wall which is related to the void space within a given piece of wood. Considering that there is little variation in the density of cell wall layers, specific gravity is ultimately providing a ratio between cell wall thickness and lumen diameter (Zink-Sharp, 2003). Due to the nature of moisture interaction with cells (increased moisture content results in both cell wall expansion and cavity filling), specific gravity is determined using three common measures: basic, nominal, and oven-dry. Basic specific gravity uses oven-dry weight and green volume; nominal uses oven-dry weight and air-dry volume (12% moisture content); oven-dry uses oven-dry specimens for both weight and volume (Porter, 1981). Variations in specific gravity for common Canadian coniferous species are presented in Table 1-2.
Table 1-2. Basic, nominal, and oven-dry specific gravity values for various Canadian conifer tree species (Adapted from (Porter, 1981))

<table>
<thead>
<tr>
<th>Species</th>
<th>Basic</th>
<th>Nominal</th>
<th>Oven-dry</th>
</tr>
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<tbody>
<tr>
<td>Eastern white cedar</td>
<td>0.30</td>
<td>0.30</td>
<td>0.31</td>
</tr>
<tr>
<td>Balsam fir</td>
<td>0.34</td>
<td>0.35</td>
<td>0.37</td>
</tr>
<tr>
<td>White spruce</td>
<td>0.35</td>
<td>0.37</td>
<td>0.39</td>
</tr>
<tr>
<td>Eastern white pine</td>
<td>0.36</td>
<td>0.37</td>
<td>0.38</td>
</tr>
<tr>
<td>Red pine</td>
<td>0.39</td>
<td>0.40</td>
<td>0.42</td>
</tr>
<tr>
<td>Lodgepole pine</td>
<td>0.40</td>
<td>0.41</td>
<td>0.46</td>
</tr>
<tr>
<td>Black spruce</td>
<td>0.41</td>
<td>0.43</td>
<td>0.44</td>
</tr>
<tr>
<td>Jack pine</td>
<td>0.42</td>
<td>0.44</td>
<td>0.45</td>
</tr>
<tr>
<td>Tamarack</td>
<td>0.48</td>
<td>0.51</td>
<td>0.54</td>
</tr>
</tbody>
</table>

The measurement of specific gravity is often considered the best method for gauging mechanical strength of wood (Garratt, 1931; Haygreen and Bowyer, 1996; Zink-Sharp, 2003). Panshin and de Zeeuw (1980) created a general equation relating specific gravity and mechanical properties in the form \( S = K G^n \) where \( S \) is the strength property, \( K \) is a constant, \( G \) is specific gravity and as the exponent, \( n \) defines the resulting curve. Many others have investigated the relationship between SG and mechanical properties in a linear method (Pearson and Gilmore, 1971; Bendtsen and Senft, 1986; Deresse et al., 2003; Mackes et al., 2005; Ivkovic et al., 2008). Supporting this, Polge and Keller (1970) found a positive correlation for oak between wood density and mechanical strength. Deresse et al (2003) also found positive correlations between
SG and MOE and MOR, while Ivkovic et al (2008) found higher correlations between SG and MOR than MOE.

In addition, there is a long-standing belief that SG is directly associated with both mechanical properties and wood quality in general. Illustrating this, Lewark (1981) stated that strength was determined by specific gravity and knottiness, while Wilson and Ifju (1965) concluded that specific gravity is the single most important factor influencing tensile strength. Zobel and van Buijtenen (1989, p15) support this by stating: “specific gravity largely determines the value and utility of wood and overshadows the importance of other wood properties.”

Despite such strong beliefs in the correlation of strength and specific gravity, Walker and Woollons (1998) make a compelling argument that specific gravity should not be used as the single determining factor of wood quality and strength, but rather it should be determined by looking at the fundamental characteristics of the cell wall (i.e. microfibril angle). They did this by critiquing the seminal paper by Wardrop (1951) and proving the importance of the microfibril angle over specific gravity by reinterpreting Wardrop’s data. This reinterpretation focused on the fact that the cell wall is comprised mainly (80%) of the S2 layer, and that because the S2 layer is the primary contributor to axial strength and stiffness (USDA, 1999) its property must be attributed more of a role during analysis. When this was done, Walker and Woollons illustrated that the MFA was more of a determinant for breaking load (MOR) than density. Other authors also concur that MFA is more of a determinant factor of mechanical strength than density (Cave and Walker, 1994; Tsehaye et al., 1998). Furthermore, Walker and Woollons go on to state:

“The point of this review is not to dismiss the value of wood density studies, but to appreciate the interactions of density, as measured at a particular point in the tree (ring number and height in tree), with the underlying, fundamental characteristics of the cell wall. Changes in density do not directly determine
wood properties in some way although this remains a popular misperception within the forest products industry” (Walker and Woollons, 1998, p25).

It is evident that a sort of schism exists as to whether density or MFA is a greater indicator of the mechanical properties of wood. Donaldson’s (2008) comprehensive literature review on the influence of microfibril angle bridges this schism by noting that MFA determines the stiffness of the cell wall, which is consequently linked to the MOE of wood by the amount of cell wall material per unit volume (density). Therefore, MFA and density are both associated with stiffness either theoretically or experimentally (Cave, 1969; Tang and Hsu, 1973; Armstrong et al., 1977; Cave and Walker, 1994; Hirakawa et al., 1998; Cown et al., 1999; Xu et al., 2004).

The rationale behind this debate can be largely attributed to the variability of specific gravity throughout the stem. This variation occurs due to the change in cell wall thickness and lumen diameter from pith to bark and stump to treetop. As such, greater amounts of earlywood over latewood lead to a reduction in specific gravity (Zobel and van Buijtenen, 1989; Zobel and Sprague, 1998), and as juvenile wood has a high proportion of earlywood, the specific gravity is lower near the pith than it is close to the bark. Also, because juvenile wood is thought to be formed within the crown (Bannan, 1966; Larson, 1969; Barbour et al., 2003), specific gravity decreases with increasing height as a result of a greater earlywood presence (Kellison, 1981; Zobel and Sprague, 1998). Furthermore, the difficulty in defining these transitory zones between higher and lower values of specific gravity throughout the stem, as well as the natural differences between juvenile and mature wood, has led to considerable debate.
1.6.4 Variability in MOE and MOR: The Role of Juvenile, Mature, and Compression Wood

Due to the variation in cell structure between juvenile and mature wood, there are natural variations in strength and stiffness properties within these two wood types. As expected, MOE and MOR are lower in juvenile wood than in mature wood. Bendtsen and Senft (1986) recorded ratios for juvenile to mature wood of 2:3 for MOR and 3:5 for MOE. McAlister and Clark (1991) also found similar results for loblolly pine where MOE (million psi) in juvenile wood was 0.60 and mature wood was 1.50; MOR (thousand psi) for juvenile was 4.90 and for mature wood was 9.10. In a study of fast grown 28-year old loblolly pine plantation, Kretschmann and Bendtsen (1992) recorded lower strength and stiffness in juvenile compared to mature wood; specifically, they found juvenile MOE values were 51-63% of mature wood MOE values, depending on lumber grade.

These findings are consistent with the definition of juvenile wood having a higher proportion of earlywood, which results in lower specific gravity due to larger lumen diameter as well as higher microfibril angles. Cramer et al. (2005) solidifies this in a study examining MOE, MFA, and SG values on earlywood and latewood in various radial and vertical positions within the stem. Latewood had a higher MOE than earlywood, and latewood MOE also increased with ring number and height. Stiffness improves with a greater proportion of latewood, which increases with older stems that have a greater amount of mature wood.

Compression wood is yet another factor that can affect the mechanical attributes of wood. Compression wood is formed underneath the leaning part of a coniferous tree; this ‘reaction’ wood has distinctly different characteristics than normal wood and can therefore affect its mechanical attributes (Zobel & van Buijtenen, 1989). Panshin and de Zeeuw (1980) note that the strength of compression wood (in bending, compression, and toughness) is greater than
normal wood in green conditions, yet lower when dry. These unique features of compression wood are due to the increase in cell wall thickness and resultant SG, which likely benefits strength when living; however when dried, high MFA, reduced cellulose content, increased lignin content, and spiral checking result in reduced mechanical properties (Jackson, 2008).

Supporting this, Dhubhain et al. (1988) tested the influence of compression wood on structurally sized planks of sitka spruce and found that increased compression wood content led to a reduction in MOE, but did not affect MOR. The only note regarding the influence of compression wood on MOR was that in 70% of planks containing more than 10% compression wood, failure occurred in a brash manner. Moreover, compression wood generally results in a degradation of wood quality and strength due to several irregular characteristics, including: extreme hardness, brash rupture, extensive longitudinal shrinkage, and an inability to increase strength with a reduction in moisture content (Timell, 1986). Therefore it is important to distinguish the presence and control for the presence of compression, juvenile, and mature wood when evaluating mechanical properties in wood.

1.7 The Influence of Crown Structure on Wood Formation

1.7.1 Wood Formation Theories

There have been several theories presented throughout the past 150 years that attempt to fundamentally define why wood is formed; each of these theories attribute the tree crown the primary role in influencing stem cambial activity, tree growth allocation, and wood structure. A comprehensive literature review by Lindstrom (1996) outlined the mechanical, nutritional, water conduction, and hormonal theories of wood formation. As these works were completed in various languages, the following citations were sourced from the Lindstrom (1996) review.
The mechanical theory was first presented by Schwendener (1874) and later developed by Metzger (Metzger, 1893, 1908) and attempted to correlate stem taper as a function of wind-load. Metzger hypothesized that a tree’s crown acted as a sail in harnessing wind-load, thereby transferring that load into bending stress absorbed by the branch-free bole below the crown. The nutritional theory was presented and developed by Hartig (Hartig, 1891, 1892, 1901), and expressed wood formation as a function of the transpiration and assimilation requirements set by the tree’s crown (Lindstrom, 1996). Hartig believed that cambial growth was determined by nutrient availability, which was itself determined by the need for water conduction. The water conduction theory was presented by Jaccard (Jaccard, 1913, 1915) and attempted to explain wood formation occurring purely as a result of the transpiration needs of the crown. He hypothesized that water flow decreases proportionally towards the crown top, which occurs in unison with a reduction in living transpiring branches. Therefore, his theory stated that stem cross-sectional area is proportional to the actively transpiring foliage above the given cross-section (Lindstrom, 1996).

Larson (1962) solidified the hormonal theory of wood formation when he explained the link between physiological crown growth and cambial activity through auxin availability. Although he was not the first to suggest the presence of growth regulating stimuli, Larson hypothesized that growth promoters (auxin) produced in new foliage (shoots and buds) flowed basipetally and activated wood formation in the cambial layer of the stem.

Auxin is thought to be responsible for plasticizing the primary cell wall, thereby making it more reactive to increased turgor pressure during periods of rapid growth and transpiration (Thornqvist, 1993). The reduction of crown growth results in a reduction in auxin production, consequently leading to cell wall thickening that fixes the lumen diameter, and characterizes
latewood formation (Thornquist, 1993). Auxins have also been linked to other functions in the cambium, including: division rate of cambium initials, direction of cell expansion, changes to individual cell genetic expression, and microfibril orientation (Roberts et al., 1988; Raven et al., 1992) all of which can affect wood quality.

Moreover, Larson consolidated the hormonal theory in 1969 by stating that the distance between the hormone producing crown and the wood forming vascular cambium determined tracheid differentiation. In addition, further research has been conducted since Larson’s findings in exploring the auxin gradients within trees (Sundberg et al., 2000; Kramer, 2002; Barnett and Jeronimidis, 2003), indicating the general acceptance of the hormonal influence of wood formation.

1.7.2 Juvenile Wood and the Role of the Crown

The true significance of these theories is that although they provide differing approaches as to why wood is formed, they all acknowledge the primary role of the crown. The importance associated with understanding why wood is formed is directly associated with improving the ability of man to harness the growth power of trees to produce wood of desired quality and quantity. Wood is not only a highly variable material between species, but also within species, and even within an individual tree stem.

The variations within a stem are characterized by the formation of earlywood and latewood within a single growing season, and the juvenile and mature wood categorizations that occur between pith and bark. Juvenile wood has a high percentage of earlywood formation, which is correlated with high growth rate and is thought to form within the crown; mature wood is thought to form in the branch-free bole, and has a greater amount of latewood, often correlating with a slower growth rate. Although there may be slight ambiguities in the exact
partitioning of these two areas, such generalizations have largely been accepted (Zobel and Buijtenen, 1989; Kennedy, 1995; Zobel and Sprague, 1998). This categorization occurs because the nature of these two areas differs significantly in both their micro and macroscopic features, having much different values for strength, density, hygroscopicity, microfibril angle, etc (Zobel and Buijtenen, 1989; Tsoumis, 1991; Josza and Middleton, 1994; Hoadley, 2000). Therefore, in addition to being the fundamental factor behind why wood is formed, the crown is also critical in influencing how wood is formed.

Furthermore, physiological crown growth is stimulated by several key factors that relate to the basic photosynthetic processes responsible for such growth. These factors include above ground process in the form of light and temperature, and below ground in the form nutrient and moisture availability as well as soil type (Zobel and van Buijtenen, 1989; Tsoumis, 1991). The practice of silviculture aims to manipulate these factors in order to achieve desired results in terms of wood-quality. However, of these factors, only light and nutrient availability can be directly manipulated; water may be somewhat influenced through thinning by making water more available to fewer trees (Barbour et al, 1994); and temperature control is only possible by changing the physical location of sites to different climatic conditions (Bergh et al, 2005).

Nutrient management is achieved through fertilization and has proven to affect growth rate, wood formation, and wood characteristics by increasing earlywood properties (Posey, 1965; Lindstrom, 1996; Jyske et al., 2008). The manipulation of light availability is achieved through stem density and spacing, whereby high stem density restricts crown growth and total photosynthetic area, consequently affecting wood formation as noted by the aforementioned theories. As presented by Lindstrom (1996), Gevorkiantz and Hosley (1929) created the first model illustrating competition influenced by growing space in the form $S=\frac{L}{C}$, where $S=$
growing space, \( L \) = branch-free stem portion, and \( C \) = crown width. Although it is not entirely definitive, this model formally recognizes the influence of stand spacing and crown growth. McClain et al. (1994) supported this model by examining the effect of stocking density on crown size (width, depth) in white and black spruce provenances in northern Ontario, and finding a significant relationship (\( P<0.001 \)). More recently, Peracca and O’Hara (2008) found a significant positive relationship between growing space and percentage of live-crown for ponderosa pine, Douglas-fir, and giant sequoia.

Moreover, although stand density and spacing indirectly influence wood formation through the crown, it is still a useful indicator. However, as previously mentioned, there is much variation between species as well as within species; therefore it is often difficult to accurately measure the effects of such broad parameters while accounting for other influences such as site variability and genetic discrepancies (Beaulieu et al., 2006). Nonetheless, many attempts have been made to identify variables responsible for governing wood quality in many commercial species, with mixed results.

### 1.8 The Influence of Stand Structure on Wood Properties

There are many ways to measure wood characteristics, but this review will examine wood attributes as characterized by specific gravity and mechanical strength and stiffness. Silviculture determines stand density by employing either initial spacing regimes or by thinning to a predetermined density as measured by basal area (square metres per hectare). For coniferous and diffuse porous hardwoods, specific gravity generally declines with increasing spacing; Willcocks and Bell (1994) presented a table from Sjolte-Jorgensen (1967) for Norway spruce (\textit{Picea abies}) that illustrates this reduction over five different spacings (Table 1-3). Yang and Hazenberg (1994a) analyzed specific gravity in black spruce (\textit{Picea mariana}) and found similar results,
recording 8\% lower values for specific gravity at the largest spacing (3.6m x 3.6 m) when compared with the tightest spacing (1.8 m x 1.8 m). A study examining the oldest initial spacing trial in jack pine (\textit{Pinus banksiana}) by Kang \textit{et al} (2004a) remarked that there was a clear negative relationship between spacing and specific gravity, using spacings ranging from 1.5 m to 2.7 m.

Despite such strong examples correlating spacing and specific gravity, other studies recorded no correlation. For example, Maeglin (1967) recorded no variation in specific gravity at different spacings. Similarly, in a review of coastal western hemlock (\textit{Tsuga heterophylla}), Watson \textit{et al} (2003b) found that wood density was not related to spacing. The disparity is most likely due to the fact that Maeglin selected young trees of 15 years in age; this is likely because another study by Larocque and Marshall (1995) on red pine indicated that differences in specific gravity were only recognizable after 20 years. On the other hand, Watson’s findings may be a result of the genetic disposition of coastal hemlock, or the unique coastal climate, and may not be as useful to use in comparison with other species.

\begin{table}[h]
\centering
\begin{tabular}{llllll}
\hline
Spacing (m) & Mean Diameter (cm) & Taper Whole Stem (cm/m) & Percentage of Knots & Specific Gravity & Total Production (tonnes/ha) \\
\hline
1.25 x 1.40 & 20.1 & 0.98 & 0.191 & 0.415 & 261 \\
1.40 x 1.65 & 20.5 & 1.02 & 0.236 & 0.423 & 240 \\
2.00 x 2.00 & 24.1 & 1.04 & 0.260 & 0.419 & 218 \\
3.00 x 3.00 & 26.0 & 1.13 & 0.340 & 0.385 & 218 \\
3.50 x 3.50 & 28.3 & 1.26 & 0.335 & 0.384 & 166 \\
\hline
\end{tabular}
\caption{Stand characteristics of 47-year-old \textit{Picea abies} as affected by initial spacing (from Sjolte-Jorgensen, 1967 as presented in Willcocks and Bell, 1995).}
\end{table}
Moreover, similar controversial findings were reported for the effects of thinning experiments on specific gravity. For example, Tasissa and Burkhart (1998) recorded no effect of thinning on earlywood and latewood formation of loblolly pine, and thus no effect on ring density. Pape (1999) however noted that although they did not observe variations of density between thinning regimes for Norway spruce, they concluded that variations in ring density were a result of fluctuations within annual growth rings. Therefore they acknowledged that thinning does affect wood density. Further studies suggest no relationship between thinning and density; Morling (2002) stated no significant relationship between either fertilization or thinning on density of Scots pine, while Jaakkola et al (2005) experimented on mature Norway spruce and also found no correlation between thinning and specific gravity.

The logic behind wood formation as presented by Larson suggests that thinning should have a negative relationship with wood density. Perhaps one of the more novel approaches to solving this controversy in the literature was an approach taken by Dutilleul et al (1998), where they attempted to bridge the gap in the literature by explaining it as a result of incorrect statistical analysis. They claimed that much of the previous analysis had utilized the classical ‘student’s’ t-test to verify their results, without properly incorporating a time-factor into their regression analysis. In their study they analyzed 20 fast-grown and 20 slow-grown Norway spruce trees that incurred multiple thinnings, and looked at among-tree variations in ring-width and density. They observed that the slow-grown trees recorded a strong negative correlation between ring-width and density before and after the thinning, whereas such a relationship was absent in the fast-grown trees. These results suggest that faster-growing trees may be the source of the
controversy in the literature regarding the relationship between thinning, growth-rate, and wood density.

As previously discussed, despite being much relied upon, considerable debate has ensued whether wood density should be relied upon as an umbrella measure of wood quality. Consequently, the use of direct measures such as mechanical properties (i.e. MOE and MOR) is more fitting, even though wood density and mechanical properties are closely related. Nonetheless, MOE and MOR are influenced by juvenile/mature wood prevalence, similar to wood density (Zobel and Sprague, 1998). Increasing proportions of juvenile wood and consequent decreases in wood density result in reductions in MOE and MOR values. As previously indicated, less dense stands are thought to have reduced specific gravity and therefore should also have reduced MOE and MOR (Willcocks and Bell, 1994; McAlister et al., 1997; Zhang et al., 2002; Zhang et al., 2005; Duchesne, 2006; Eriksson et al., 2006; Zhang et al., 2006; Schneider et al., 2008).

Illustrating the effects of stand spacing, McAlister et al (1997) conducted a study on plantation slash pine (Pinus elliottii Engelm.) and tested for mechanical strength and stiffness on dimensional timber for lumber grades. They recorded a significant decrease (p=0.05) in mechanical strength and stiffness for only one grade in 2 by 4s. Zhang et al (2002) looked at four densities (3,086, 2 500, 2,066, 1,372 trees/ha) of 48-year-old black spruce (Picea mariana) in eastern Canada and observed a decrease in strength and stiffness in dimensional lumber with decreasing density (Table 1-4). The table also denotes a general trend indicating a reduction in strength and stiffness with increasing height.

As for the effects of thinning, Zhang et al (2006) studied three thinning intensities (1.22 m x 1.22 m, 1.52 m x 1.52 m. and 2.13 m x 2.13 m) in a naturally regenerated jack pine stand
and recorded a decrease in strength and stiffness for dimensional lumber with increasing thinning intensity.

**Table 1-4. Influence of spacing on strength and stiffness in dimensional lumber of black spruce (Zhang et al, 2005)**

<table>
<thead>
<tr>
<th>Log Height (ft)</th>
<th>Modulus of Rupture (MPa)</th>
<th>Modulus of Elasticity (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5x5 feet</td>
<td>7x7 feet</td>
</tr>
<tr>
<td>0-8</td>
<td>47.0</td>
<td>41.4</td>
</tr>
<tr>
<td>8-16</td>
<td>42.6</td>
<td>35.6</td>
</tr>
<tr>
<td>16-24</td>
<td>39.6</td>
<td>37.6</td>
</tr>
<tr>
<td>24-32</td>
<td>43.1</td>
<td>34.4</td>
</tr>
<tr>
<td>32-40</td>
<td>40.6</td>
<td>36.6</td>
</tr>
<tr>
<td>40-48</td>
<td></td>
<td>20.8</td>
</tr>
</tbody>
</table>

Eriksson et al (2006) evaluated two silvicultural regimes, a densely seeded 85-year-old site and a 56-year-old widely spaced planted site of Scots pine. They tested for mechanical strength and stiffness using small clear samples (120.5 mm long, 6.3 mm high, 3 annual growth rings wide) at two heights within each selected tree (stump and intermediate top height), and categorized the samples into two sections, heartwood and sapwood. They observed that the densely seeded site had much higher MOE and MOR values than the larger spaced site, by respective values of 150 and 70%. Vertical and horizontal location of the samples also influenced strength and stiffness, with stem base and sapwood values being greater than intermediate top height and heartwood, respectively. They further suggest that these results are indicative of the influence of juvenile wood on the mechanical attributes of wood.
Finally, Duchesne (2006) looked at three naturally regenerated stands of jack pine in northern Ontario, Canada, with three ages (50, 73, and 93-year old). The study showed that the MOE and MOR values for the 50-year-old stand were roughly 16% lower and 16-19% lower than the values for the 73 and 90-year-old stands; however, there was no significant difference between the 73 and 90-year-old stands. They ascribed this variation to the presence of juvenile wood in the younger stand, yet natural thinning could also have been a factor in advancing mature wood. In any case, all of the above listed examples of mechanical strength and stiffness testing illustrate that as stand density increases, mechanical strength and stiffness in wood also increases, whether they are naturally regenerated, planted at specific spacings, or incur periodic thinnings.

1.9 The Complex Nature of Wood and its Origin in the Crown

Wood is a complex substance that has many contributing factors towards its mechanical properties. From its chemical composition, crystalline cellulose in the S2 layer is the major contributor of strength and stiffness to the cell wall, yet the dynamic lignin-hemicellulose matrix also contributes additional rigidity. MFA is arguably the most predominant indicator of strength and stiffness at both the anatomical and human (i.e. lumber) scales, while specific gravity can also provide insight for mechanical attributes as a general proxy. Overarching variables affecting MOE and MOR in wood are caused primarily by changes in growth rate throughout the tree, both vertically and horizontally, but also include growth deviations such as compression wood. Understanding these variations is pivotal when attempting to model wood properties in relation to stand and stem characteristics.

Moreover, exploring the relationship between stand dynamics and wood quality is essential in determining the most efficient and effective silvicultural method that can produce
exceptional wood quality attributes such as strength and stiffness. It is important to note that all existing wood formation theories implicate the crown as the pivotal factor in influencing cambial activity in trees. Larson’s seminal 1969 work solidified the role of the crown as the key factor in regulating wood formation; in addition, much research has been conducted since then to correlate simple stand level variables to wood quality attributes indirectly through the crown. All of these findings suggest that larger crowns, often governed through the management of stand density, can negatively influence wood quality. Moreover, recent advancements in remote sensing technologies such as Light Detection and Ranging Systems (LiDAR) have increased the need to directly quantify this hitherto conceptual link between the crown and wood properties. As such, the following research is not only warranted, but long overdue.
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Chapter 2: Quantifying the Influence of Crown Size on Mechanical Wood Properties in White Spruce (*Picea glauca*)

2.1 Abstract

Conceptual models of wood formation suggest that trees with large crowns produce low quality wood because they produce more auxin and hence more earlywood, characterized by large cell diameters with thinner cell walls. Thus, it is often assumed that crown size is inversely related to both wood strength and wood stiffness. However, this relationship remains largely theoretical, and few studies have explicitly linked crown size metrics with wood quality. In this study, I examine the relationship between crown size and mechanical wood properties, as measured by Modulus of Elasticity (MOE) and Modulus of Rupture (MOR), in 42- and 72-old year plantation white spruce (*Picea glauca*) from the Petawawa Federal Research Forest (Ontario, Canada). A total of 48 trees were destructively sampled across four plantation spacings (1.2, 1.8, 4.3, and 6.1 m), and four plantation densities, in which the stands were thinned to residual basal areas of 18, 25, and 32 m$^2$ ha$^{-1}$ (plus control). MOE and MOR were determined from 10x10x140 mm mini-clear samples (n=657), taken across a radial (pith-to-bark) gradient, at three heights within the stem. At the stand level, I found that trees had larger crowns in stands that were widely spaced or well thinned, while at the tree level I found that strength and stiffness significantly decreased with crown size. Non-linear mixed-effects models showed that MOE and MOR was best predicted by cambial age and crown ratio, demonstrating that crown size influences the strength and stiffness of wood. The results suggest that the models could be used in conjunction with remotely sensed data to identify high quality timber prior to harvest.
2.2 Introduction

There is an urgent need to optimize the value of wood products manufactured in northern regions with low growth rates and high labor costs (Nilsson and Bull, 2005). The value of the timber used to manufacture wood products could be increased by using forest inventory data to identify high quality timber prior to harvest. However, this will require new methods to predict wood quality using either ground-based inventory data or remotely-sensed inventory data. Advances in remote sensing technology such as Light Detection and Ranging (LiDAR) have increased our ability to inventory forests at large spatial scales (Lutz et al., 2008; Wulder et al., 2008), while also providing accurate information on individual trees, such as crown size (Naesset and Okland, 2002; Lim et al., 2003). Thus, predicting wood quality from crown size promises to be the most effective way to increase the value of harvested timber.

Conceptual models of wood formation suggest that trees with large crowns produce low quality wood because they produce more auxin (Larson, 1962; Larson, 1969; Lindstrom, 1996; Sundberg et al., 2000). Auxins produced in the stem apices, such as indolic-3-acetic acid (IAA), have been linked to the type (size and thickness) of wood cells formed (Little and Pharis, 1995), such that higher concentrations of IAA result in larger cell diameters with thinner cell walls, which is known as earlywood (Larson, 1962; Sundberg et al, 2000).

Auxin concentrations gradually decrease from the stem apices toward the stem base as the distance from the auxin-producing crown increases, corresponding to slower growth rates at lower stem heights (Cato et al., 2006). Consequently, a vertical distribution of earlywood and latewood ratios exists within the tree stem, such that wood produced further from the crown has more latewood than earlywood. Assuming that this distribution is not only influenced by crown location, but also by size, an increase in crown width and depth should result in the production of
more auxin and thus more earlywood, and less latewood. This is important because latewood has more favourable mechanical properties as measured by Modulus of Elasticity (MOE) and Modulus of Rupture (MOR), due to superior microscopic wood properties such as lower microfibril angle, higher wood density, and greater fibre length (Thornqvist, 1993; Josza and Middleton, 1994; Yang, 1994; Yang and Hazenberg, 1994b; Zobel and Sprague, 1998; Kramer, 2002; Ivkovic, 2008). Disregarding defects such as knots, wood that contains large proportions of latewood is consequently of higher commercial value due to these superior structural attributes (Kennedy, 1995; Zobel and Sprague, 1998).

Numerous studies have examined the relationship between wood quality and standard inventory metrics, including stand density and tree diameter (Willcocks and Bell, 1995; Zhang et al., 2002; Kang et al., 2004b; Jaakkola et al., 2005; Lei et al., 2005). However, few studies have examined the relationship between crown size and wood properties. Lei et al. (2005) reported a weak correlation between crown size metrics (length and width) and the mechanical properties (MOE and MOR) of dimensional lumber, while Lui et al. (2007) found that crown width was negatively related to MOE and MOR in black spruce (Picea mariana). Studies of European temperate species have yielded similar results. In a study of Corsican pine (Pinus nigra var. maritima) crown size was negatively correlated to specific gravity (SG), MOE and MOR (Amarasekara and Denne, 2002). However, because Amarasekara and Denne (2002) examined a small number of trees (n=9), that were only 23 years of age, their results cannot be extrapolated to represent harvest-age stems that would comprise of a greater proportion of mature wood.

From a commercial perspective, additional uncertainties regarding the influence of crown size on wood quality also exist, due to intra-stem variation in wood quality: an important consideration few studies have taken into account. Although several studies have observed
significant variation in wood quality along both radial and longitudinal stem axes, virtually no generalities emerge from current literature. For instance, in mature black spruce, ring density has been found to increase with height (Alteyrac et al., 2005). Conversely, SG did not vary with height in commercially viable Douglas-fir trees (Pseudotsuga menziesii (Mirb.) Franco) (Gartner et al., 2002), or Norway spruce (Picea abies (L.) Karst.) (Jyske et al., 2008). In terms of radial variation, SG has been found to increase from pit to bark in Scots pine (Pinus sylvestris), and MOE and MOR to increase with cambial age (Auty and Achim, 2008). Strength and stiffness typically increase with age through the juvenile period, then reach a plateau known as the mature wood zone (Zobel, 1989; Zobel and Sprague, 1998). Thus, the rate of maturation can be modeled by predicting MOE and MOR as asymptotic functions of cambial age (Auty and Achim, 2008).

In this study, I examine the relationship between crown size and wood quality in plantation white spruce. The study was designed to test the following questions: (1) Do trees with large crowns produce low quality wood? (2) How does crown size influence the rate of wood maturation? (3) How does crown size influence the asymptotic strength and stiffness of mature wood? Ultimately, addressing these questions will provide theoretical insights into the process of wood formation, assess our ability to gauge wood quality directly from tree crown data, and inform future decisions regarding forest management prescriptions.

2.3 Materials and Methods

2.3.1 Experimental Site

This study was conducted in two white spruce plantations located in the Petawawa Federal Research Forest, central Ontario, Canada (latitude 460 00' N, longitude 77' 25' W). Mill Lake plantation was established in 1966 by the Canadian Forest Service (CFS), and was initiated as a 4.6 ha spacing study with trees planted at 1.2, 1.8, 4.3, and 6.1 m, in a randomized block design.
The plantation has been managed to maintain the initial tree spacings. Lost plantation is a 4.6 ha thinning experiment established in 1936 by the CFS, initially designed as a growth and yield study. Initially planted at 1.8 m spacings, Lost plantation was thinned to three residual basal areas, with 18, 25, and 32 m$^2$ ha$^{-1}$ of standing timber removed, in 1962, 1972, and 1982. Two controls were employed retaining approximate basal areas of 42 m$^2$/ha, and each of the four site classes had a replicate for a total of 8 plots.

2.3.2 Tree Selection and Wood Sample Testing

In the summer of 2008, 16 trees were destructively sampled in the Mill Lake plantation, including 4 trees from each spacing treatment. At the Lost plantation, 36 trees were destructively sampled, with four trees being taken from each individual plot. The four trees were selecting to include one intermediate tree, two co-dominants trees, and one dominant tree, using diameter at breast height measurements and crown size in relation to neighbouring trees as selection criterion.

From each tree, 40 cm long sections of tree stem (referred to here as a bolt) were taken at three heights: breast height (1.3 m), crown base, and at mid stem - half way between breast height and crown base. Bolts were taken between branch whorls to reduce the chance of encountering internal knots and focus on clear wood. The bolts were then processed into a 2.5 cm length plank with a band saw. All wood samples were cut from the northern aspect of the plank, to eliminate reaction wood. Planks were conditioned to 12% moisture content in a convection kiln, and then cut into mini-clear samples (10x10x140 mm), with the long axis of the sample oriented along the radius of the tree (pith to bark). In total, our dataset consisted of 657 mini-clear samples. Mini-clears were chosen instead of standardized ASTM small clear samples to avoid macro defects such as knots, and focus testing on specific cambial ages. More
specifically, by having such small specimens, any changes to wood cell ultrastructure associated with different cambial ages would be much more apparent than having a larger sample that covered a larger radial area.

For each mini-clear sample, we measured MOR and MOE using three-point bending tests, conducted in accordance with protocols D 143-94 of the ASTM manual (2005). Bending tests were performed with an MTS-QTEST/5 testing machine (MTS Systems Corporation, Eden Prairie, MN USA). Cambial age (A) was determined by counting outwards from the pith; each mini-clear was assigned the cambial age of the annual ring located closest to the middle of the sample. Growth rate was determined by measuring the width of all visible annual growth rings and dividing it by the number of rings within this distance, thereby calculating a mean growth rate per specimen.

2.3.3 Tree Crown Measurements

Prior to felling, crown size was determined by taking 8 radial measurements taken at 45° intervals from the stem, using a TriPulse Professional Laser Range Finder (Laser Technology Inc., Centennial, CO, USA) following Cole (1995). Crown base height (B) and total tree height (H) were recorded with a tape measure once the tree was felled: crown base was defined by the lowest continuous whorl of branches displaying live foliar tissues. Crown ratio (CR) was calculated as (T-B)/T.

2.3.4 Data Analysis and Modeling

We used non-linear mixed-effects models to quantify the relationship between crown size and wood quality (Pinheiro and Bates, 2000). MOE and MOR were treated as the dependent variables, while cambial age (A) and crown ratio (CR) were treated as independent fixed effects. Other possible explanatory variables such as stand spacing/density and growth rate were highly
correlated to crown size, and were therefore excluded from the model.

Random effects were also included to account for correlations between non-independent observations. The random effects were estimated by grouping observations into four nested categories, including bolt \((B)\), tree \((T)\), plot \((P)\), and site \((S)\). The unexplained variation was assumed to be normally distributed about the mean value predicted by the mixed-effects model.

We used an exponential asymptotic function to quantify the rate of wood maturation:

\[
\text{Model 1a(b): } \text{MOE (or MOR)} = \beta_1 * (1 - e^{(-\beta_2 * A)}) + \beta_3
\]

where \(A\) is cambial age, and \(\beta_1, \beta_2, \text{ and } \beta_3\) are asymptote, slope, and intercept, respectively.

To examine the effect of crown size, we then fit two alternative models that included crown ratio as a predictor of wood quality. In Model 2, the slope of the asymptotic function varies with crown ratio:

\[
\text{Model 2a(b): } \text{MOE}_{ij} \text{ (or MOR}_{ij} = \beta_1 * (1 - e^{(-\beta_2 * A - \beta_3 * A * CR)}) + \beta_4
\]

such that the rate of maturation varies with crown size, but not the strength or stiffness of mature wood.

In Model 3, the asymptote of the function varies with crown ratio:
Model 3a(b): \( \text{MOE}_i \) (or \( \text{MOR}_i \)) = \((\beta_1 + \beta_2 \times CR) \times (1 - e^{(-\beta_3 \times A)}) + \beta_4 \)

such that the strength and stiffness of mature wood varies with crown size, but not the rate of maturation (i.e. the asymptote is reached at the same age, regardless of crown size).

In these models, the fixed effects (\( \beta_1 \), \( \beta_2 \), \( \beta_3 \), and \( \beta_4 \)) were fit using maximum likelihood. Akaike's information criterion (AIC) values were used to evaluate the three competing models, with the lowest AIC value indicating the most parsimonious model fit. Additionally, linear regression between observed and predicted values was used to determine goodness-of-fit for each model. Alternative measures of crown size were also considered as predictors of wood quality, but crown ratio was the most effective predictor as indicated by AIC, so the alternative predictors are not presented here.

2.4 Results

2.4.1 Variation in crown size and wood properties across treatments

Average crown radius, crown ratio, and DBH varied two-fold (1.65-3.28 m, 0.35-0.73, and 16.04-31.48 cm respectively) across spacings at the Mill lake plantation (Table 2-1, Figure 2-1). For wood properties, MOE, MOR, and SG generally declined as spacing increased, while growth rate and DBH increased nearly two-fold between the 1.2 and 6.1 m spacings.
Figure 2-1 Average crown ratio (error bars indicate 95% confidence intervals) at different spacings in the Mill Lake plantation (a) and different residual basal areas in the Lost plantation (b).

In the Lost plantation, there was less variation in average crown radius and crown ratio across the treatments (2.28-3.10 m, 0.35-0.48, respectively), but crown size generally increased as residual basal area decreased (Table 2-2, Figure 2-1.). MOE, MOR, and SG generally decreased as residual basal decreased (Table 2-2), while growth rate increased.
Table 2-1. Average tree and wood properties for each spacing in the Mill Lake plantation

<table>
<thead>
<tr>
<th></th>
<th>1.2 x 1.2</th>
<th>1.8 x 1.8</th>
<th>4.3 x 4.3</th>
<th>6.1 x 6.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crown Radius (m)</td>
<td>1.65</td>
<td>1.86</td>
<td>2.64</td>
<td>3.28</td>
</tr>
<tr>
<td>Crown Ratio</td>
<td>0.35</td>
<td>0.47</td>
<td>0.64</td>
<td>0.73</td>
</tr>
<tr>
<td>Tree Height (m)</td>
<td>15.7</td>
<td>14.9</td>
<td>14.4</td>
<td>16.0</td>
</tr>
<tr>
<td>DBH (cm)</td>
<td>16.0</td>
<td>18.3</td>
<td>23.9</td>
<td>31.5</td>
</tr>
<tr>
<td>MOE (MPa)</td>
<td>8774</td>
<td>7653</td>
<td>7688</td>
<td>6674</td>
</tr>
<tr>
<td>MOR (MPa)</td>
<td>80.3</td>
<td>72.7</td>
<td>70.0</td>
<td>65.5</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>0.38</td>
<td>0.37</td>
<td>0.36</td>
<td>0.35</td>
</tr>
<tr>
<td>Growth Rate (mm/year)</td>
<td>2.66</td>
<td>3.54</td>
<td>4.47</td>
<td>5.09</td>
</tr>
</tbody>
</table>

Overall, the widest spaced plot of Mill lake (6.1 m) showed the largest average crown radius, crown ratio, and the lowest MOE, and MOR values within the entire study. The least thinned plots at Lost plantation (32 m²/ha) had the highest overall mean values of MOE, MOR, and SG (9283 MPa, 82.4 MPa, 0.40, respectively). In general, we found that for both Lost and Mill Lake, wood quality generally increased with stocking density, reflecting concomitant decreases in crown size.

Table 2-2. Tree and wood properties for each thinning treatment in the Lost plantation

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>32</th>
<th>25</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crown Radius (m)</td>
<td>2.28</td>
<td>2.45</td>
<td>2.25</td>
<td>3.10</td>
</tr>
<tr>
<td>Crown Ratio</td>
<td>0.35</td>
<td>0.39</td>
<td>0.46</td>
<td>0.48</td>
</tr>
<tr>
<td>Tree Height (m)</td>
<td>23.9</td>
<td>21.8</td>
<td>20.8</td>
<td>23.9</td>
</tr>
<tr>
<td>DBH (cm)</td>
<td>30.6</td>
<td>27.8</td>
<td>27.7</td>
<td>35.6</td>
</tr>
<tr>
<td>MOE (MPa)</td>
<td>8727</td>
<td>9283</td>
<td>8390</td>
<td>8107</td>
</tr>
<tr>
<td>MOR (MPa)</td>
<td>76.5</td>
<td>82.3</td>
<td>75.0</td>
<td>74.2</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>0.37</td>
<td>0.40</td>
<td>0.37</td>
<td>0.36</td>
</tr>
<tr>
<td>Growth Rate (mm/year)</td>
<td>2.91</td>
<td>2.68</td>
<td>2.96</td>
<td>3.21</td>
</tr>
</tbody>
</table>
2.4.2 Model Selection and Goodness-of-Fit

Figure 2-2. Predicted and observed wood quality as a function of cambial age: (a) MOE, (b) MOR.

Figure 2-3. Goodness of fit for the (a) MOE and (b) MOR models.
The most parsimonious models (Model, Table 2-3) included both cambial age \((A)\) and crown ratio \((CR)\) as predictors, demonstrating that crown size influences the strength and stiffness of wood (Table 2-3, Figure 2-2). The models provide a good fit to the observed data, with a 1:1 relationship between predicted and observed and symmetrically distributed residuals (Figure 2-3). The models explained 67% and 56% of the variation in the observed data.

As expected, MOE and MOR initially increase with cambial age, then level off as the wood matures, somewhat earlier in the case of MOE (Fig 2-2). Using the boundary delineated by Yang (2002), mature wood (>20 years) was 27% stiffer and 16% stronger than juvenile wood (<8 years). The pattern of maturation was best described by model 3 (Table 2-3), indicating that the strength and stiffness of mature wood varies with crown size (Fig 2-2), but not the rate of maturation (i.e. the asymptote is reached at the same age, regardless of crown size).

Table 2-3. Parameter estimates and goodness-of-fit statistics for the MOE (a) and MOR (b) models.

<table>
<thead>
<tr>
<th>Equation</th>
<th>Measure</th>
<th>(\beta_1)</th>
<th>(\beta_2)</th>
<th>(\beta_3)</th>
<th>(\beta_4)</th>
<th>(r^2)</th>
<th>logLik</th>
<th>AIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>MOE</td>
<td>5.585 (413)</td>
<td>0.147 (0.012)</td>
<td>3806 (350)</td>
<td>-</td>
<td>0.67</td>
<td>-5,454</td>
<td>10,926</td>
</tr>
<tr>
<td>2a</td>
<td>MOE</td>
<td>5.572 (412)</td>
<td>0.153 (0.026)</td>
<td>-0.014* (0.055)</td>
<td>3821 (352)</td>
<td>0.67</td>
<td>-5,454</td>
<td>10,928</td>
</tr>
<tr>
<td>3a</td>
<td>MOE</td>
<td>8.104 (668)</td>
<td>-5441 (1245)</td>
<td>0.148 (0.012)</td>
<td>3774 (353)</td>
<td>0.67</td>
<td>-5,449</td>
<td>10,917</td>
</tr>
<tr>
<td>1b</td>
<td>MOR</td>
<td>18.77 (2.45)</td>
<td>0.096 (0.011)</td>
<td>62.88 (1.37)</td>
<td>-</td>
<td>0.57</td>
<td>-2,176</td>
<td>4,370</td>
</tr>
<tr>
<td>2b</td>
<td>MOR</td>
<td>19.41 (2.14)</td>
<td>0.043* (0.034)</td>
<td>0.150* (0.089)</td>
<td>62.00 (1.55)</td>
<td>0.56</td>
<td>-2,177</td>
<td>4,373</td>
</tr>
<tr>
<td>3b</td>
<td>MOR</td>
<td>39.90 (5.55)</td>
<td>-46.30 (11.47)</td>
<td>0.095 (0.011)</td>
<td>62.96 (1.37)</td>
<td>0.56</td>
<td>-2,170</td>
<td>4,360</td>
</tr>
</tbody>
</table>

Note: \(r^2\), coefficient of determination of observed versus predicted; AIC, Akaike's Information Criterion; logLik, log likelihood; MOE, modulus of elasticity; MOR, modulus of rupture; standard deviation is listed in adjacent parentheses (). *indicates non-significant parameter at the 0.05 level.

2.5 Discussion

Many studies have examined the relationship between stand density and wood quality (Yang, 1994; Yang and Hazenberg, 1994b; McAlister \textit{et al.}, 1997; Zhang \textit{et al.}, 2002; Eriksson \textit{et al.}, 2006; Schneider \textit{et al.}, 2008), but few have attempted to directly quantify the relationship between crown and wood properties (Amarasekara and Denne, 2002; Zhang \textit{et al.}, 2002; Liu \textit{et al.}...
The models presented in this study demonstrate that crown size has an effect on the mechanical properties of wood, showing that trees with larger crowns (represented by large crown ratios) produce low quality wood of low strength and stiffness. These findings support the accepted theory of wood formation (Larson, 1969) and align with recent research (Amarasekara and Denne, 2002; Zhang et al., 2002; Liu et al., 2007; Mansfield et al., 2007), demonstrating that it is possible to predict wood quality from crown size.

The inherent variable nature of wood can make it difficult to link external tree characteristics (DBH, height, stem taper, etc.) to internal wood properties (microfibril angle, wood density, MOE, MOR, etc.). Although this has been the aim of much research to date, few trends have emerged. Forest managers have traditionally relied upon simple forest measurements such as DBH, age, and height to predict standing timber volume; however, such measurements have been poorly linked to internal wood properties. Considering that auxin-production in the crown has been proven as a key driver in wood formation, it is logical to use crown size and location as simple surrogate measures of auxin production to predict internal wood properties. Moreover, advances in LiDAR technology will replace traditional manual methods of crown measurement with rapid automated procedures (Naesset and Okland, 2002; Lim et al., 2003), providing increased incentive to understand the relationship between crown size and wood quality.

2.5.1 How Crown Size Affects Wood Formation

A tree grows by differentiating cells and concentrically layering tracheids from its core (the pith) upwards and outwards. Growth occurs throughout the stem and is driven by the presence of growth hormones like IAA, which can influence cell wall thicknesses and consequent wood quality. Therefore, the proximity of wood formation to the hormone-producing
crown can directly influence wood quality. Old-growth timber has exceptional mechanical wood properties because it is sourced from closed-canopy stands that have experienced crown recession resulting in tall stems with low crown ratios (e.g. 25% crown). This results in a large branch-free bole that is far from the auxin-producing crown, and which adds many years of mature wood growth. Conversely, if an open-grown tree exhibits a crown with a large crown ratio, most wood formed on that tree will be in close proximity to the crown, which would lead to greater amounts of earlywood with poorer mechanical properties. In a plantation, the forest manager has the ability to manipulate conditions to control the type of wood formed through changes in crown size. Hence, I developed a model to explain the influence crown size exerts on mechanical wood properties.

I tested numerous alternative model forms to find the best fit. From both my raw data and the literature the rate of wood maturation was expressed by an exponential asymptotic function (Zobel, 1989). The second model made slope a function of crown size, meaning that small crowns would follow the traditional asymptotic cambial age effect, but larger crowns would make that relationship more linear. In this model form, a larger crown simply abbreviates the traditional cambial age effect because the majority of the bole is found in the crown, affecting total mature wood production. However, the problem with this form is that it assumes trees with large crowns reach the mature wood plateau, which our data suggests it does not. Therefore, the final model made the asymptote a function of crown size so that mechanical wood properties begin at the same level at early cambial ages, then as crown growth and development occur with ageing, the maximum values of MOE and MOR separate with crown size (Figure 2-2). This means that the theoretical mature wood plateau that each tree will reach is inversely correlated to crown size, or in this case with crown location as measured by crown ratio.
2.5.2 Stand Structure, Crown Size Metrics, and Wood Properties

Generally, the stand structure data supports previous growth and yield studies in showing that less dense stands result in greater crown size, increased growth rates, and decreased wood quality, as measured by mechanical properties and wood density (McClain et al., 1994; Yang and Hazenberg, 1994b). However, these trends were only statistically significant when comparing the extremes of the spectrum (i.e. 1.2 m and 6.1 m spacings), supporting similar findings with Zhang et al (2002). Nonetheless, the general trends between our stands, crowns, and wood properties support and reflect the accepted biological reasoning behind wood formation through auxin synthesis and regulation (Larson, 1969; Savidge et al., 2000).

2.5.3 Improving the Assessment of Wood Quality

There is notable difficulty in capturing the effect of tree crown size on wood properties due to its dynamic nature through time. Each annual growth ring correlates with a specific crown size unique to that year of growth; therefore in order to fully correlate these two variables one would require crown measurements for each year of growth for the entire life of the tree. This would be particularly important for naturally forested areas; however because our study focused on controlled growing conditions we were more able to attribute a single fixed crown size and ratio to a single tree and its internal mechanical wood properties. From this perspective the spacing trial has the greatest consistency in light availability and crown history. The thinning trial provides more dynamic light conditions due to tree removal with subsequent changes in stand density, however by controlling the rate and volume of removal allows us to capture a full gradient of light conditions. When coupled together the use of these plantations provide a strong surrogate measure of crown history and permits the use of a single fixed measurement of crown size and ratio over the life of a tree.
In addition to sampling across a wide variety of spacings and densities, the robust size of the mini-clear dataset and wide within-stem distribution is rare among similar studies of mechanical properties. Many studies focus on the use of wood density as an umbrella measure for several wood properties, including mechanical properties; however the measurement of wood density itself is often a challenging task and there is controversy over the accuracy of extrapolating other wood properties from it (Walker and Woollons, 1998). Therefore my results are more tangible because I directly tested mechanical properties rather than extrapolate or infer the values from wood density. Also by using mini-clear samples we can more accurately isolate anatomical changes in wood properties that are biologically controlled by the crown, and exclude macroscopic deviation such as found in knot influence. This approach allows greater accuracy in projecting the effect of crown size on mechanical properties by aligning with the biological triggers of wood formation.

2.6 Acknowledgements

I would like to thank the Petawawa Research Forest and the Canadian Wood Fibre Centre for allowing use of the field sites, as well as the NSERC-funded ForValueNet Strategic Network for providing funding and a framework for collaboration that was integral to the completion of all aspects of this project. The impeccable facilities and technicians at Laval University’s Gene H. Kruger pavilion were crucial to completing the challenging task of physically processing the wood samples for this study.
2.7 References


Larson, P.R., 1969. Wood Formation and the Concept of Wood Quality. Yale University School of Forestry Bulletin 74, 54.


Chapter 3: Practical Management Implications and Recommendations for Future Research

3.1 Introduction

Canadian forest management has largely focused on maximizing the production of wood volume, rather than wood quality (Mullins and McKnight, 1981); however, as the North American forestry sector continues to evolve and mature, focus has shifted to the latter. In this chapter, I will focus on how the results of my research could be synthesized and incorporated into practice by forest managers, as well as provide key recommendations and suggestions for future work on this topic.

3.2 Practical Management Implications

The models herein utilize both cambial age and crown size to predict the mechanical properties of wood. Consequently, if forest managers have both of these measurements at their disposal they could estimate what sort of mechanical properties their standing timber may hold. As this study used some of the most unique experimental spruce stands in the nation, both in their age (Lost plantation) and their design (wide spacings at Mill Lake Plantation), correlations to wood properties from both the tree and plot level are very practical to managers looking to both establish initial planting regimes, and develop long-term management plans including thinning. Forest managers may not be looking to adopt such extreme stocking or treatment measures as used in this study, but by revealing the trends related to the effect of spacing on wood properties, this study gives foresters the ability to fit these results into more conservative silvicultural regimes while understanding the context of their prescription.

The results from both Mill Lake and Lost plantation clearly show that trees from tighter spacings or less thinned stands have both smaller crowns and better mechanical wood properties.
These results support findings by (Stiell, 1969) that tree spacing is negatively correlated with crown size. More generally, comprehensive reviews relating silviculture to wood quality have noted similar findings between stand density and wood quality, but their reviews included a much larger array of wood quality measures, including numerous micro and macro-anatomical properties such as knot size and frequency, sloping grain, and microfibril angle (Zobel and Buijtenen, 1989; Zobel, 1992; Thornqvist, 1993; Jozsa and Middleton, 1994; Kennedy, 1995; Zobel and Sprague, 1998; MacDonald and Hubert, 2002). Although my work focuses solely on mechanical properties of white spruce, it is nonetheless it is important to note that my results are confluent with other work.

Forest managers often focus on the production of wood volume, utilizing volume tables such as the metric yield tables for plantation white spruce at the Petawawa Forest Experiment Station (Berry, 1978, 1987). Berry’s (1978) report focused on a range of 1.25 (6400 stems per hectare) to 3.0 m (1111 stems per hectare) spacings in Petawawa, Ontario across four site classes (15, 18, 21, and 24 metres in height at age 50), providing both raw volume and merchantable volume projections for each spacing and site class. An equation was fit to the volume tables to account for tree mortality, providing final timber volume figures. The projections consistently showed that the tightest spacings provided the highest volume of both raw and merchantable timber, despite higher levels of mortality due to increased competition.

In addition to Berry, Stiell (1980) observed growth and yield of three thinning treatments (18, 25, 32 m²/ha) plus a control, as well as consequent changes to crown size following thinning. It is interesting to note that Stiell (1980) used the same Lost plantation which was used in this thesis. Stiell recorded greater timber volume the least thinned stands, while also observing more rigorous crown and stem growth in more heavily thinned stands.
The findings in both of Berry’s reports (Berry, 1978, 1987) and Stiell (1980) reveal that greater stand density produces greater timber volume while reducing individual stem size. This means that while forest managers may increase both volume and quality with increased stocking density, they may sacrifice the quantity of sawmill-sized timber, potentially reducing the overall value of the timber. Despite this, when coupled with my research, more dense stands are shown to produce not only greater volume but also higher grade of timber as measured by the mechanical properties of MOE and MOR on small clear specimens; therefore, it is advisable that forest managers opt for tighter spacings to gain both greater volume and superior mechanical properties of wood despite possibly losing value by reducing stem diameters.

3.3 Recommendations for Further Research

The execution of this research has made apparent what is necessary in future studies of the same topic. My suggestions fall primarily into three categories: (1) site selection, (2) wood quality measurements, and (3) statistical analysis.

The sites employed in this study were selected due to their age and immaculate management history. Having been planted in 1936 and 1966, these sites offered a rare opportunity to conduct work on stands of harvestable age that have been maintained from the time of seedling initiation to final harvest, with scientific intentions in mind. Despite the interesting nature of these study sites, future work should focus on expanding to more northern mixed-wood stands in a natural setting. However, if choosing natural stands the optimal situation would have crown metrics recorded over time so one could account for the size variation through time when dissecting the stem wood properties.

In my analysis of wood property attributes I measured MOE, MOR, SG, and growth rate at three stem heights. Future work would benefit from the observation of microfibril angle (MFA).
This study did not include MFA due to financial restraints, however due to its role as a key indicator of juvenile and mature wood as well as overall mechanical wood properties, it is of great importance. Ideally this would be measured in a radial fashion at various stem heights.

Moreover, the hierarchal nature of sampling wood from within and between trees often makes it challenging to apply proper statistical methodology to find significant results. Not only is it inherently difficult to account for natural variation present in wood, but even more so when samples are taken from different stems within different treatments, and within different site locations. When working with such hierarchal data, standard statistical analysis such as the use of ANOVA often does not lead to significant results. Therefore, experience from this study suggests that the use of mixed-effects models as listed in Pinheiro and Bates (2000) is indispensable in finding meaningful results when dealing with nested data.

Overall, studies exploring the link between stand and stem structure and wood properties face a multitude of inherent difficulties. However, the possibilities of achieving such relationships provide enormous possibilities to both large and small-scale forest managers, and represent what I believe to be the next critical advancement in the forest industry. Therefore, despite such difficulties future research in this field is not only warranted, but is necessary to the survival of the forest industry in Canada.
3.4 References


