Stand density management implications on the wood quality of yellow birch (*Betula alleghaniensis* Britton*)* in Northeastern Ontario

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Abstract

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Keywords: Fiber quality, Hardwood Lumber, Hardwood Management, Mechanical properties, Northeastern Ontario, Silviculture, Spacing, Thinning, Thinning Trial, Tolerant Hardwood, Veneer, Wood Properties, yellow birch (*Betula alleghaniensis* Britton*)*.

Creating quality tolerant hardwood stands through intensive silviculture and mapping their properties is considered a means for optimizing the value chain in Northeastern Ontario. A comprehensive literature review was conducted concerning the growth, morphology and factors influencing end merchantability of diffuse porous hardwoods, which commonly grow in Northeastern Canada and North America. It was seen that there was a gap in the literature concerning the effects varying degrees of density management have on the internal properties of the growing stock occurring on site. The literature did, however, provide a knowledge base from which to evolve. Based on the current gaps in the literature, mapping of the internal properties associated with density management of yellow birch was conducted from a research site 30 kilometers Northwest of Thessalon, Ontario in the Algoma Forest District. Density management associated with the specific research site reflect releasing trees to 10%, 20%, 30% and 40% of tree height at time of treatment, since the trees were on average 10m high the treatments consist of releasing plus trees to one, two, three and four m, respectively. Destructive testing was performed on 15 yellow birch *(Betula alleghaniensis* Britton*)* trees from the thinning trial located in the Northern regions of the Great Lakes St Lawrence forest zone. The results showed that the thinning treatments applied had a significant effect on the internal wood properties of the yellow birch growing on site. The greatest variability was not between treatments but axially throughout the trees. Janka Ball side hardness values attained from the test specimens were on average 24% higher than published values. Modulus of Elasticity (MOE) and Modulus of Rupture (MOR) values attained were 15% and 15% lower than the published values, respectively. The average ring width values across all treatments analysed were found to be 80% higher than the published values. The values for the microscopic attributes (fibers and vessels) displayed no difference between treatments and followed published trends associated with morphological changes in the trees. It was observed that the properties do not follow any discernable pattern associated with the intensity of crop tree thinning intensity. It was determined that thinning treatments do have a significant effect on the internal mechanical properties of the yellow birch growing on site and is suggested that thinning can increase stem merchantability and decrease rotation ages.

Contents

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1.0 Introduction

To create high quality veneer and lumber yellow birch (*Betula alleghaniensis* Britton) crop trees, elite forest management is necessary to maximize the value on private and crown lands in Northeastern and central Ontario. Determining the affect density management and thinning regimes have on yellow birch tree form, wood quality has currently been under-reported. Destructive testing of 15 pole sized yellow birch trees from the Algoma district in Northeastern Ontario will provide detailed information regarding strength qualities, stem characteristics, tree form and morphological response to varying degrees of density management. It is anticipated that this information will provide insight as how to maximize the return on investment of a tract of land and furthermore be woven into the guidelines for managing high quality tolerant northern hardwood species. This information will be used by private and Crown timber managers alike, to further promote superior wood production in northern tolerant hardwoods, specifically, yellow birch. The carrying capacity of a site is only enough to support an amount of trees of a certain size; usually as the size of the tree increases the less abundant they are to be found. Thinning is defined by many, as the removal of stems in a given space in order to allocate more resources to the remaining trees for improved growth (Ontario Ministry of Natural Resources (OMNR) 1988). The trees, which remain in the stand after a partial cutting or a thinning occurs, are allocated the resources from the previous inhabitants of the site. Commonly additional sunlight, water, nutrients, crown expansion space and root expansion space are associated with a thinning (British Columbia Ministry of Forests (BCMF) 2001).

1.1 Research Question

How does thinning northern tolerant hardwood stands, specifically yellow birch, affect wood properties, tree form, and potential merchantability?

1.1.1 Purpose:

To look for opportunities to improve the yellow birch growing stock to potentially revitalize the hardwood veneer and lumber market in Northeastern Ontario.

1.1.2 Goal:

The goal of this research is to create high quality veneer yellow birch crop trees through elite forest management.

1.1.3 Hypothesis

H_1 – Potential wood utilization increases with an increasing intensity of crop tree release in yellow birch stands of the Algoma District in Ontario.

And:

H_2 - Morphological changes in yellow birch are due to site effect accompanied by crop tree release intensity.

1.1.4 Objectives:

Through destructive testing the response of yellow birch crop trees to various thinning regimes was determined. The following objectives were addressed in order to meet the goal of this research:

Characterize and model yellow birch wood properties and characteristics related to various thinning treatments, and

Investigate how change in diameter with height related to a specific thinning treatment affects wood characteristics within a stem.

The tests, which will be performed on the sample trees to achieve some of the objectives of this research are:

MOE: reported in mega pascals (MPa) utilizing the three point flexure test procedure with a maximum span of 24 centimetres,

MOR: reported in MPa, based on the maximum load (Newtons) reported during MOE testing,

Side hardness, reported in Newtons (N) using the Janka Ball tool,

Relative density measurements reported in Kg/m^3,

Ring analysis,

Fiber analysis,

Vessel element analysis, and

Taper analysis.

Definitions:

Modulus of Elasticity (MOE): Elasticity implies that deformations produced by low stress are completely recoverable after loads are removed. When loaded to higher stress levels, plastic deformation or failure occurs (Simpson and TenWolde 1999).

Modulus of Rupture (MOR): reflects the maximum load carrying of a member in bending and is proportional to maximum moment borne by the specimen (Simpson and TenWolde 1999).

1.1.5 Short and long term Objectives

In the short term it is expected that through various analyses the response of varying crop tree thinning in yellow birch for a specific ecosite (ES29.1) is observed and mapped. Moreover this information should be put to use concerning the management of yellow birch for veneer quality and lumber quality logs for an increased return on investment (ROI). Specifically the recommendations found as a consequence of this research should be woven into the fabric of our current silvicultural guide for the management of the northern tolerant hardwood species in Ontario, specifically yellow birch. The use of this discovered knowledge can be used in various applications such as best management practices. Best management practices can be amended to further promote superior quality in yellow birch veneer and lumber growing stock by private landowners and by crown timber managers. Furthermore timber managers can use this knowledge to gain a better understanding of their future and current growing stock's attributes and value. With this information we will be potentially, one silvicultural step closer to the management of yellow birch and achieving desired industrial outcomes.

1.1.6 Context

The importance of determining the effects of thinning on wood quality is pertinent to creating end products of high quality and value. It has been well documented by many that the manipulation of a site can affect the growing stock (Panshin and de Zeeuw 1980, Zobel and van Buijtenen 1989, Hoadley 2000). Various silvicultural activities are designed to achieve desired outcomes from a tract of land. Depending on the objective various interventions may be applied to growing stock to achieve them.

There has been much work on the response of yellow birch and specifically sugar maple to crop tree thinning. Much of the previous work on yellow birch and thinning deals with the effect thinning has on the production of biomass and the five-year growth increment (diameter class). Previous work has shown that the dependent variable for thinning is basal area. There is little work completed and available concerning the affect crop tree thinning has on internal wood properties and potential end uses. Furthermore there is little published data concerning the dependent variable for thinning being a percentage of total tree height of the crop trees. Minor descriptions of tree form attributes regarding crop tree thinning of yellow birch have been reported. It has been noted that with increasing intensity of crop tree thinning yellow birch responds negatively in height growth and positively in diameter growth. The increased taper from releasing yellow birch potentially will yield less high value veneer crop trees.

The results from this research can be incorporated into current practices of crop tree thinning to better understand the effects on wood quality and potential end uses.

Land base managers can better market their growing stock in order to achieve maximum value from yellow birch veneer and lumber quality crop trees.

2.0 Literature Review

2.1 Growth

Tree growth occurs by the conversion of sugars into organic compounds. Photosynthesis is the process in which a tree or plant is able to create these sugars (Wilson 1984, Walker 1989). Sunlight is converted into glucose and oxygen from water and carbon dioxide by the chlorophyll and other structures present in the leaf or stem (Bowyer and Smith 2000, Bowyer *et al.* 2003). Figure 1 is an overview of how a tree grows and stores food, main growth components are also briefly explained in the Figure.

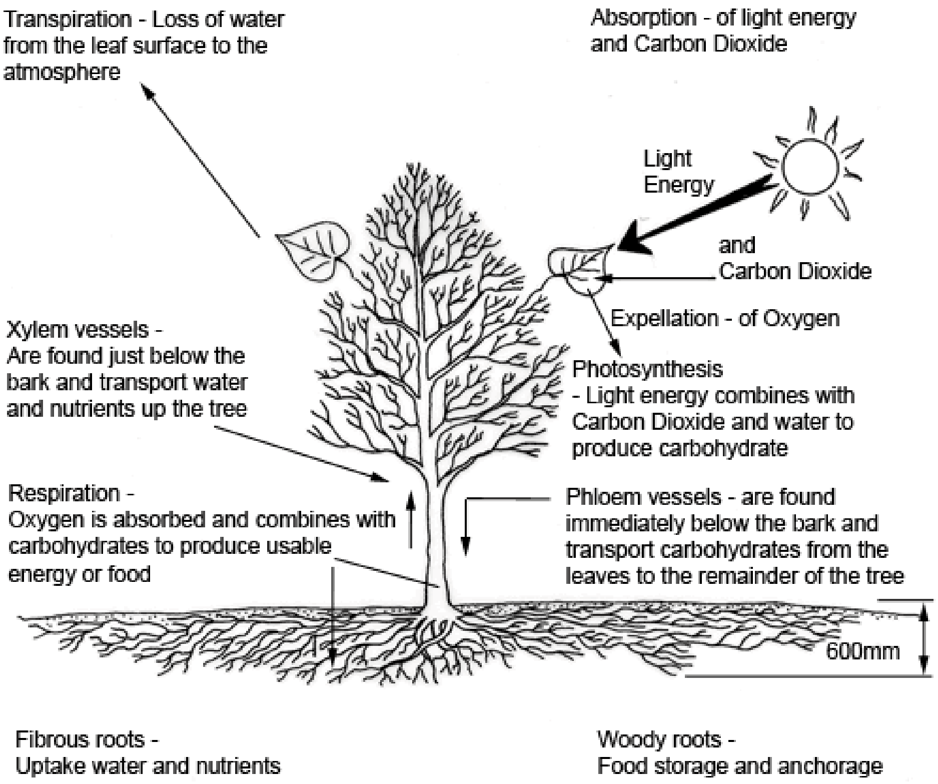


Figure 1. Tree growth activities and general form (Source - leics.gov.uk, 2013).

The growth of a tree is mainly dictated through its genetic inheritance, which is responsible for controlling the trees response to various environmental conditions. Species in Northwestern Ontario have developed a defense against certain aspects of the environment. Cold and drought are combatted by the trees ability to recognize acceptable growing conditions. A tree will terminate or initiate annual growth by responding to increases or decreases in the average air temperature, which occurs between six and eight degrees Celsius, and moisture of the environment (Rossi *et al.* 2007, Thibeault-Martel et al 2008, Rossi *et al.* 2008, Gruber *et al.* 2009). In the spring with minimum moisture and temperature levels present, a tree will begin to move stored sugars and starches in its roots up the tree to the crown to aid in “bud burst”, while wood growth begins, via internal reserves, just before the leaves of the tree are produced and are functioning (Wilson 1984) (Figure 2).

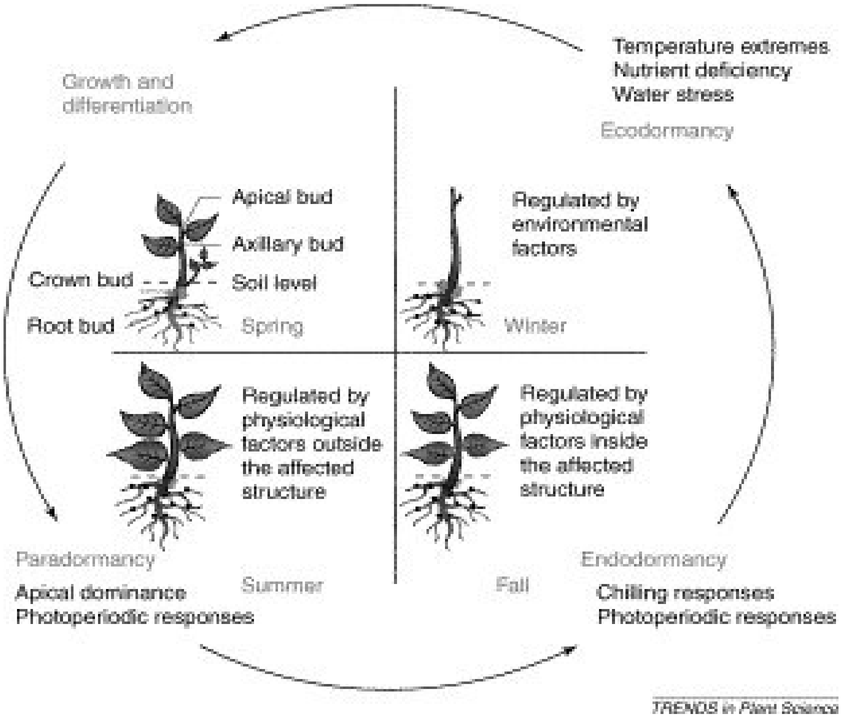


Figure 2. Growth activities (Source – Sciencedirect.com, 1973).

The two types of growth occurring in a tree are height growth to expand the crown and stem diameter growth to support the expanding crown. Current literature on wood growth and cambial activity has brought to light conflicting results, what is clear is that cambial activity and wood growth are highly variable within a tree, within species and between species (Panshin and de Zeeuw 1980, Wilson 1984, Walker 1989, Bowyer and Smith 2000, Bowyer *et al.* 2003, Rossi *et al.* 2007, Thibeault-Martel 2008, Rossi *et al.* 2008, Gruber *et al.* 2009).

2.1.2 Height Growth

Height growth follows the emergence of new leaves where the growth in height is accomplished through the division of specialized cells in the apices of the main stem, branches and roots. These areas are zones of intense meristematic activity and are referred to as apical meristems (Figure 3)(Jane 1956).

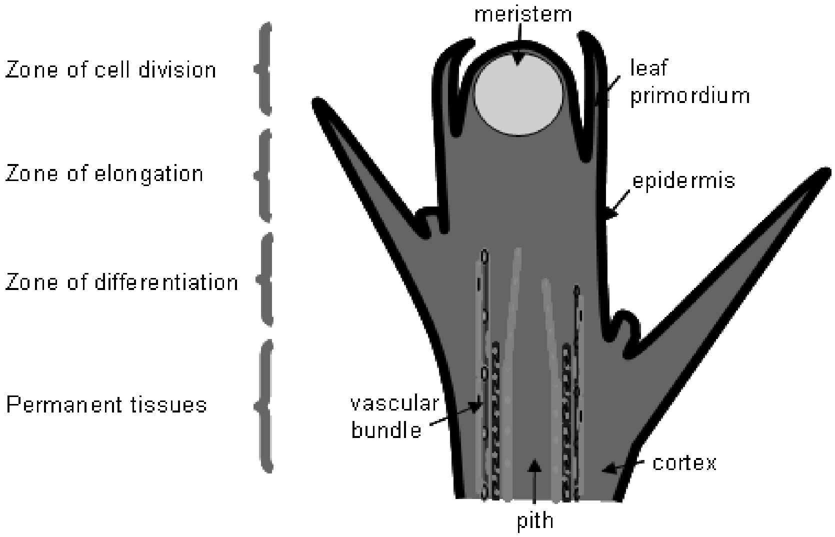


Figure 3. Typical zones in the apical meristem region (Source - Hamal 2010).

As the cells of the apical meristem divide, they leave cells behind the meristem as it is pushed upward, with cells being added to the old ones similar to bricks on a wall creating the extension in height (Panshin and de Zeeuw 1980, Walker 1989, Bowyer and Smith 2000). Different tree species will grow to different heights depending on geographic location, site conditions, among various other interacting factors. Little is known about the mechanism which controls total height growth, what is known is that total height growth is strongly influenced by heredity (Probine 1963, Burns and Honkala 1990, Harlow *et al.* 1996, Powell 2009). Current literature suggests that there is a great deal of variation between tree species and within a tree species when it comes to mature tree height (BCMF 2002).

2.1.3 Diameter Growth

Diameter growth of a tree takes place in an area known as the vascular cambium, which is a lateral meristem, composed of a tangential band of one to many cells thick located directly beneath the inner bark (i.e. live functioning phloem). This layer known as the vascular cambium sheaths the entire living portion of the tree (Panshin and de Zeeuw 1980, Walker 1989, Bowyer *et al.* 2003). The cells which are present in the cambium, have the ability to divide repeatedly, these cells may divide in one of two ways. The first type of division in the cambium, referred to as a periclinal division, results in two new cells:

The first new cell remains in the cambium and will further divide to produce new cells, and

The second cell will become either a xylem cell (wood cell) or a phloem cell (bark cell). The second type of division found in the cambium, referred to as an anticlinal division, results in two new cells in a tangential direction, both of which can divide and create new cells (Panshin and de Zeeuw 1980). It is this dual action of division in the cambium, which allows the cambium to increase in diameter as the tree diameter/circumference increases (Wilson 1984, Walker 1989, Bowyer and Smith 2000). The process of cell division in the cambium occurs throughout the first half of the growing season typically, with the cambium creating new xylem and phloem cells. Current literature states that diameter growth within a tree and within a stand may vary greatly. Factors, which may affect diameter growth include, stems per hectare (SPH), age, growth rate, site class of an ecosite, and moisture regime among various other interacting environmental factors (See Figure 4) (Jane 1956, Forest Products Laboratory 1999).

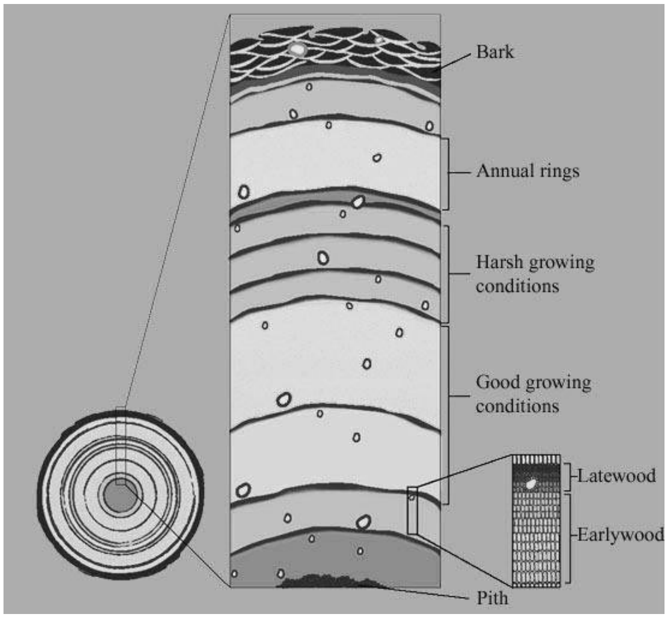


Figure 4. Example of factors affecting radial expansion and wood production (Source - Yukon Government 2003).

Heredity is said to contribute the most to the diameter growth of a tree, it is for this reason that diameter growth varies greatly within species and between species (Wilson 1984, Walker 1989, Bowyer and Smith 2000, Bowyer *et al.* 2003). One of the roles of the cambial sheath is to cover over wounds and branch stubs during diameter growth. This wound / branch covering ability of the cambium produces various types of wood as the tree ages. With age the tree will (depending on species) loose its lower branches, due to their inability to photosynthesize, the cambium will envelop these old branch sites until they cease to exist. After the branch stubs and wounds are covered, this is the point where the tree is producing its most desirable tracheid or fiber for dimensional lumber creating a stronger and clearer grained wood as time progresses and new growth rings are laid over previous growth rings (Panshin and de Zeeuw 1980, Walker 1989, Bowyer *et al.* 2003).

Juvenile wood VS Mature wood:

As trees mature, the wood, which is produced by the vascular cambium begins to change slightly. The coined term for the wood that a tree produces at a certain age or once growing conditions are met is called “mature wood” or “normal wood”. The wood produced prior to this point is called “juvenile wood” (Panshin and de Zeeuw 1980, Jozsa and Middleton 1994, Bowyer *et al.* 2003). McMillin (1969) stated that juvenile wood from a slow grown stem has the same specific gravity of that of a fast grown stem, therefore, growth rate has little effect on juvenile wood properties. It is important to distinguish the wide ringed juvenile wood with relatively short tracheids or fibers from narrow ringed mature wood with long tracheids or fibers in the same stem for purposes of utilization and understanding wood properties. Hoadley (1990) states that juvenile wood is atypical wood formed around the pith of a tree and in the crown as the tree grows in height. The transition from juvenile wood to mature wood is abrupt in some species and gradual in others (Hoadley 1990). Juvenile wood in hardwoods and softwoods typically exhibits lower density than mature wood, although is more pronounced in softwoods. Wood in the juvenile core is almost always drastically different relative to the mature wood produced as the tree ages, irrespective of growth rate (Zobel and van Buijtenen, 1989). It is also important to realize the fact that juvenile wood is not necessarily poor wood, it has excellent use in thermo-mechanical pulp (TMP) and chemical-thermo-mechanical pulp (CTMP) where it is useful for newsprint, tissue paper, high quality printing and writing papers (Zobel 1984, Zobel and van Buijtenen 1989).

Maturing trees put on mature wood at the same time as they put on juvenile wood. Consider the tree broken into two sections, the bole and the crown, the crown has the ability to expand radially tangentially and longitudinally while the bole of the tree is restricted to only radial and tangential growth (Panshin and de Zeeuw 1980, Bowyer *et al.* 2003). It is because of this dynamic nature of the tree that it produces both mature and juvenile wood at the same time when looked at from the base to the crown for strength in one location and flexibility in the other, respectively. It has been stated that the development of mature wood goes hand in hand with the initiation of "self-pruning" (Panshin and de Zeeuw 1980, Bowyer *et al.* 2003, Leitch 2008).

There is a correlation between the percentage of live crown and associated juvenile wood, height referred to as “crown wood”, and the development of mature wood. It has been seen that open grown trees with little competition possess a much lower percentage of mature wood than that of a tightly crowded forest of the same species (Zobel 1992, Willocks and Bell 1995, Burdon *et al.* 2004). There are many factors influencing the development and amount of mature wood a tree will grow, some of those factors with the greatest influence on the development and amount of mature wood are heredity, age, competition, and site regime (Zobel 1992, Willocks and Bell 1995, Burdon *et al.* 2004, Leitch 2008). Changes in cell structure and wood quality are exhibited as a trees growth transfers from juvenile wood to mature wood. Some of the changes are, longer tracheids in softwoods and longer fibers in hardwoods, thicker cell walls, higher percentage of latewood, straighter fibril angle, less spiral grain, less longitudinal shrinkage, greater volume of cellulose, lower volume of lignin, greater density (by 10% to 15%), greater wood strength (by 15% to 30%) and superior wood for pulping (Panshin and de Zeeuw 1980, Mullins and McKnight 1981, Zobel 1992 and 1989, Willcocks and Bell 1994, Bowyer *et al.* 2003, Burdon *et al.* 2004, Leitch 2008). Mature wood is seen to have more “life” than that of the juvenile wood of the same tree. Juvenile wood is characterized as being lifeless due to its low light reflect-ability and flat fibril orientation (Mullins and McKnight 1981). The transition from juvenile wood to mature wood is hard to predict due to the variability in species genetics along with the ever-changing complexity of the environment in which the tree is grown (Mullins and McKnight 1981, Jozsa and Middleton 1994, Bowyer *et al.* 2003). The differences in the inherent quality and properties of the mature wood and juvenile wood affect their potential end utilization. (Panshin and de Zeeuw 1980, Bowyer and Smith 2000, Bowyer *et al.* 2003). The change from juvenile wood to mature wood is usually difficult to see, due to most of the changes occurring at the microscopic level. The literature states that various methods have been employed to determine the transition zone (Panshin and de Zeeuw 1980, Bowyer and Smith 2000, Bowyer *et al.* 2003). Some of the methods used were to measure changes in specific gravity, measurement of mechanical properties, measurement of tracheid and fiber length and measurement of ring width. For example Balatinecz (1983) states ,

> "The *period of juvenile wood formation, as judged by the proportion of short tracheids (i.e. less than 2.0 mm), is relatively short (10 years or less)"*.

The literature also states that the transition of juvenile wood to mature wood occurs when the length of the tracheid or fibers is increased and maintains this length for subsequent years after without great fluctuation, followed by a thickening of the secondary cell wall, mainly the S2 layer (Bowyer *et al.* 2003). Micro-fibril angle also changes, the S2 fibril angle becomes nearly perpendicular to the S1 and S3 layers, Figure 5 shows the difference between compression wood, juvenile wood and mature wood micro-fibril angle of the S2 layer.

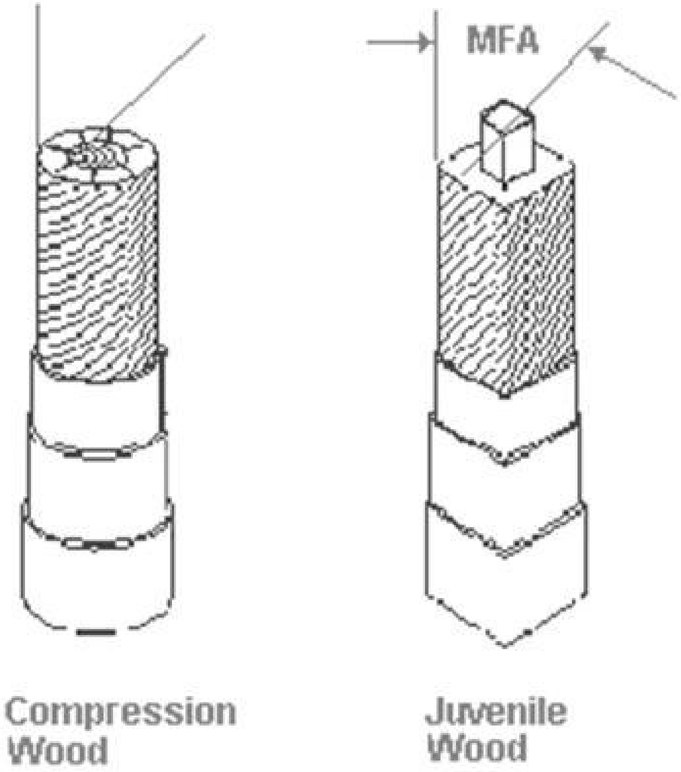


Figure 5. Fibril angle change in compression wood, juvenile wood & Mature wood, (Source - James D. Logan 2013).

More specifically Desch (1981), states and Figure 6 depicts that the cell wall is made up of millions of tiny micro fibrils. The cell wall can be divided into different sections depending on the fibril arrangement and angle. The original wall, or the primary wall is laid down first during cambial division, it is very thin and has a more or less random arrangement of micro fibrils.

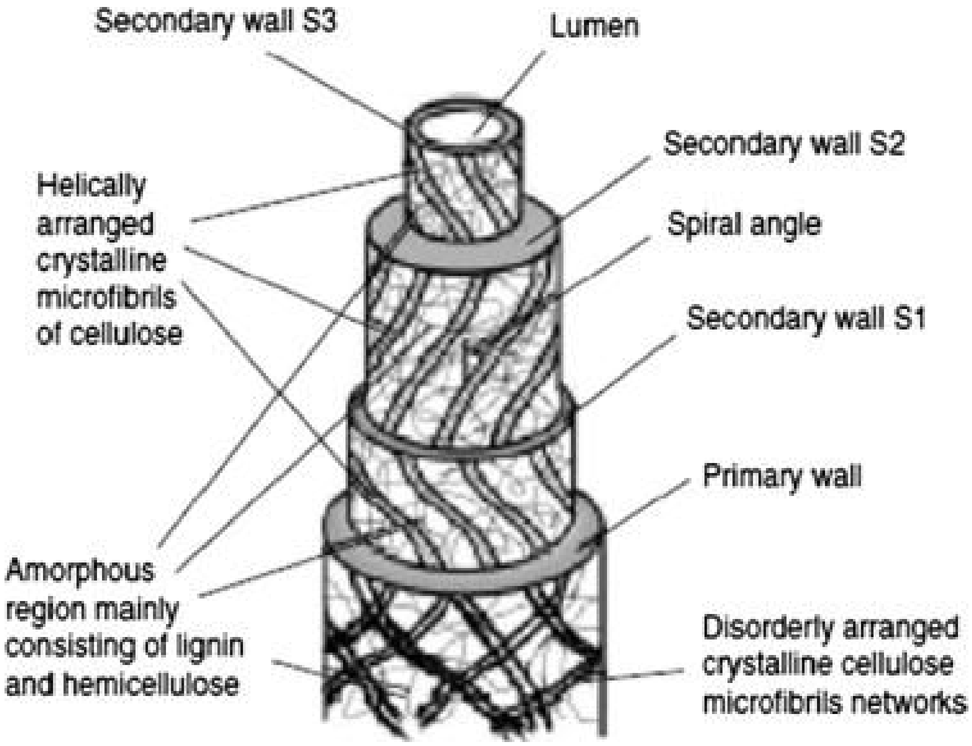


Figure 6. S1, S2, S3, & Primary cell wall diagram, (Source – H.M. Akil 1999).

The secondary cell wall is laid down after division and can be separated into three distinct sections, according to thickness and fibril angle. The outermost layer of the secondary cell wall is called S1 as stated previously. The S1 layer is thin and accounts for roughly 10% of cell wall thickness and has micro-fibrils aligned parallel to each other in two distinct spirals with an angle between 60-90 degrees. The next layer, S2, is the thickest of the three layers, accounting for the majority of the secondary cell wall structure. The S2 layer has its fibrils lying perpendicular to each other in a spiral with a pitch of roughly 10 – 30 degrees. The innermost layer, S3, is the thinnest of the three secondary cell wall layers and has a similar arrangement of micro-fibrils as that of the S1 layer (Desch and Dinwoodie 1981, Hoadley 1990). The structural performance is linked to the fibril angle in the S2 layer. Fibril angle directly affects wood quality and is of great concern when kiln drying a product. The dynamic of juvenile wood and mature wood results in secondary cell wall angles with a great deal of variation throughout the stem (Panshin and de Zeeuw 1980, Jozsa and Middleton 1994, Bowyer *et al.* 2003).

Chemistry of Wood:

Wood is essentially composed of three main components, cellulose, hemicellulose, and lignin with several species having a component of extractives. Cellulose is the main component in the cell wall of cells. Cellulose accounts for roughly 40 – 45% of the woods dry weight (Panshin and de Zeeuw 1980, Bowyer *et al.* 2003). Hemicelluloses are present in smaller amounts, making up on average about 20 – 25% of the woods dry weight, than cellulose and are comprised of fewer sugars. The main hemicelluloses in hardwoods it is glucuronoxylan (Panshin and de Zeeuw 1980). Lignin is a polymer that essentially glues the wood cells together, making up on average about 25 to 30% of the dry weight of wood, in hardwoods is guaiacyl-syringy lignin (Panshin and de Zeeuw 1980, Bowyer *et al.* 2003). Most of the extractives present in a stem are found in the heartwood of the tree. The main extractives, which are found in the heartwood of a tree are of a heterogeneous group of chemical compounds, including terpenoids, tropolones, flavonoids, stilbenes, and other aromatic compounds (Bowyer *et al.* 2003). Table one summarizes the amounts of cellulose, hemicelluloses, lignin and extractives in a few species (Scheffer and Cowling 1966).

Table 1. Chemical Composition of Some Wood Species (Panshin & de Zeeuw 1980).

Species	Cellulose	Lignin	Hemi-cellulose	Ash
Abies balsamea	42.2%	30.0%	27.5%	0.3%
Larix laricina	42.2%	27.0%	30.5%	0.3%
Picea glauca	40.4%	28.6%	30.6%	0.4%
Pinus elliottii	39.0%	30.5%	30.1%	0.4%
Pinus strobus	41.0%	29.0%	29.6%	0.4%
Pseudotsuga menziesii	42.8%	26.4%	30.4%	0.4%
Acer saccharum	40.2%	23.1%	36.4%	0.3%
Betula alleghaniensis	43.5%	23.8%	32.1%	0.6%
Fagus grandifolia	39.5%	23.5%	36.4%	0.6%
Populus tremuloidies	42.6%	20.9%	36.1%	0.4%
Robinia pseudoacacia	40.9%	30.1%	28.5%	0.5%

2. 2 Heartwood and Sapwood

In most species of trees two types of wood are easily distinguishable by eye. Figure 7 depicts that the secondary phloem lies just under the bark next to the vascular cambium, immediately after there is a light band of wood just under the cambium, this wood is referred to as the sapwood, which is where all longitudinal transport up the tree takes place (Jane 1956, Forest Products Laboratory 1999, Hoadley 2000). The second type of wood easily distinguishable is the heartwood. The heartwood lies between the sapwood and the pith of the tree and generally appears to be a darker color in most species (Hoadley 2000). Because of its susceptibility to insects and pathogens along with its light color, sapwood durability of a tree in some cases is considered to be inferior to that of the heartwood, which typically contains many extractives increasing its durability (Panshin and de Zeeuw 1980, Hoadley 2000). By utilizing appropriate preservatives the sapwood of a tree can be made to be equal to, or superior to the durability of the heartwood of the same species (Bamber 1961, Plomion *et al.* 2001*).*

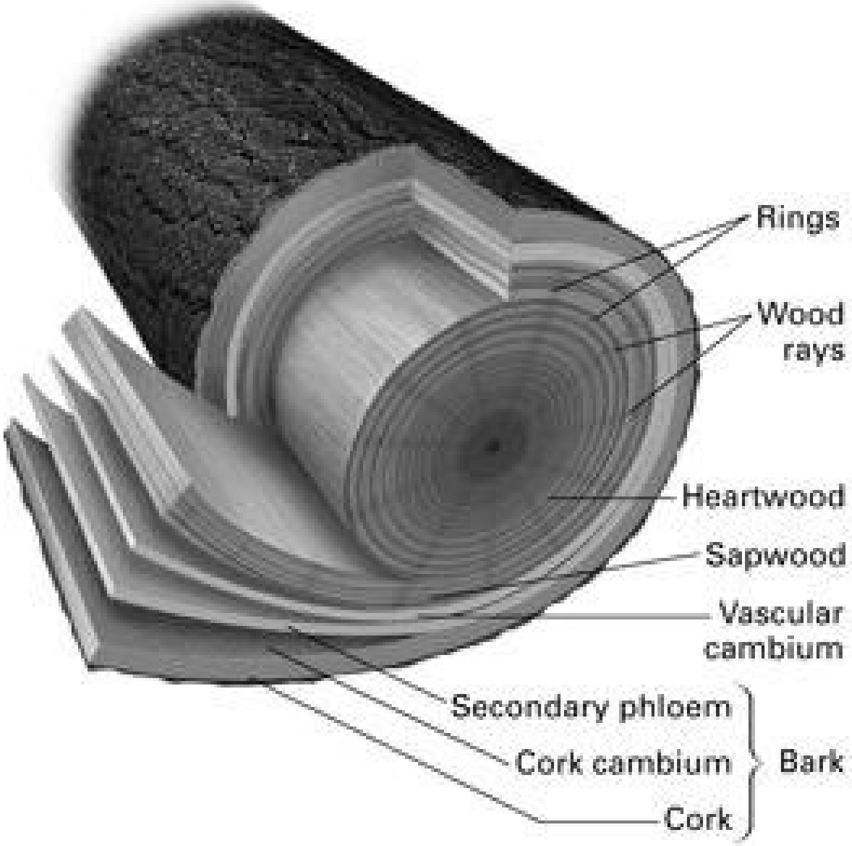


Figure 7. Cross-section revealing the different layers of tissues making up a tree (Source - biologytb.net).

Function of Heartwood and Sapwood:

In a living tree the sapwood has three main functions, conduction, storage and support. The support varies depending on species, in hardwoods the support comes from the fibers and in softwoods the support comes primarily from the latewood tracheids. The sapwood conducts solutes up the tree as well as storing food in the form of starch in parenchyma cells (Zobel and van Buijtenen 1989, Hoadley 2000). Starch is produced during photosynthesis in the leaves as photosynthate initially (Wagaard 1981, Bowyer *et al.* 2003). Photosynthate travels down the stem through the phloem, then radially into the tree via the rays (Bowyer *et al.* 2003). The photosynthate is then transformed into starch grains in the axial and ray parenchyma cells (Bowyer *et al.* 2003). The sapwood is so well developed for transportation, that saw cuts can be made past the center of a tree on opposite sides at different levels, and there will be little to no disruption of water flow to the leaves (Bamber 1961, Plomion *et al.* 2001).

The heartwood of a tree when compared to the sapwood has no living cells. The heartwood development creates unique properties, which are directly related to the death of the parenchyma cells and quantity of the extractives present in the heartwood, this is one of the main reasons for the differentiation of color between heart and sapwood (Panshin and de Zeeuw 1980, Jozsa and Middleton 1994, Hoadley 2000). The Heartwood does not serve as a conduit for transportation or storage in the tree. Bamber (1961) states that heartwood is not essential to the survival of a tree, if the sapwood were to remain, without transition to heartwood, the tree will still grow. Bamber (1961) also states it is likely that the formation of heartwood in a tree is due to optimization of the trees resources and energy, the heartwood forms to keep the sapwood at an optimum, therefore conserving the nutrition balance in the living sapwood of a tree. The sapwood resorbs essential nutrients for growth during its conversion to heartwood, elements that are not resorbed remain locked in the tree until it dies and decomposes (Bamber 1961). The size of the tree determines how much of these elements are locked up until decomposition.

Heartwood Creation:

During the late summer months an accumulation of sap or photosynthate accumulates in the cambial zone. The surplus of sap is either stored in the root system to support bud burst in the spring or it may be transported towards the pith once it enters the rays of the tree. Radial movement of the photosynthate is only hindered by pit aspirations, which occur in conjunction with the formation of heartwood in softwood species. The accumulation of surplus photosynthate in the rays begins to break down over time into various other chemical compounds called extractives (Panshin and de Zeeuw 1980, Mullins and Mcknight 1981, Jozsa and Middleton 1994). The extractive compounds are comprised of waxes, oils, resins, fats and tannins along with aromatic and coloring materials (Panshin and de Zeeuw 1980). The extractives plug the structure of the cell lumens and pits, resulting in an area where cells near the center of the tree are rendered non-functional due to the accumulation of extractives (Panshin and de Zeeuw 1980, Jozsa and Middleton 1994, Bowyer *et al.* 2003). The formation of the heartwood disrupts the flow of water due to all of the cell lumens and pits being plugged in softwoods particularly and in many hardwoods the vessels plug with tylosis. Heartwood once extracted generally has the same strength properties as sapwood, at the same moisture content (Bowyer *et al.* 2003). The pits of heartwood make it very difficult if at all to impregnate the fibers with chemical treatments, which are to resist decay when compared to the sapwood of the same tree (Panshin and de Zeeuw 1980, Jozsa and Middleton 1994, Bowyer *et al.* 2003). Similarly the tyloses in vessels prevent moisture from moving in or out of these plugged vessels.

2.3 Hardwood Trees: Growth Rings

Unlike many softwood species, hardwoods tend to have a wider variety of distinguishing features, which makes them easily recognisable to the trained eye. There are many features in hardwood trees that can be seen with the un-aided eye and the aided eye (10 X lens), which make identification simple. Extreme variability in cell type and structure and the arrangement of these cells produce unique combinations of features easily distinguishable from each other (Hoadley 1990). When dealing with hardwoods, macroscopic features tend to be enough information for one to identify many different woods. Microscopic features tend to be used on woods, which are not as easily distinguishable from others (Hoadley 1990). Hardwoods are mainly comprised of five different basic cell types: vessels (pores), fibers, ray cells, longitudinal parenchyma and tracheids (Figure 8) (Panshin and de Zeeuw 1980).

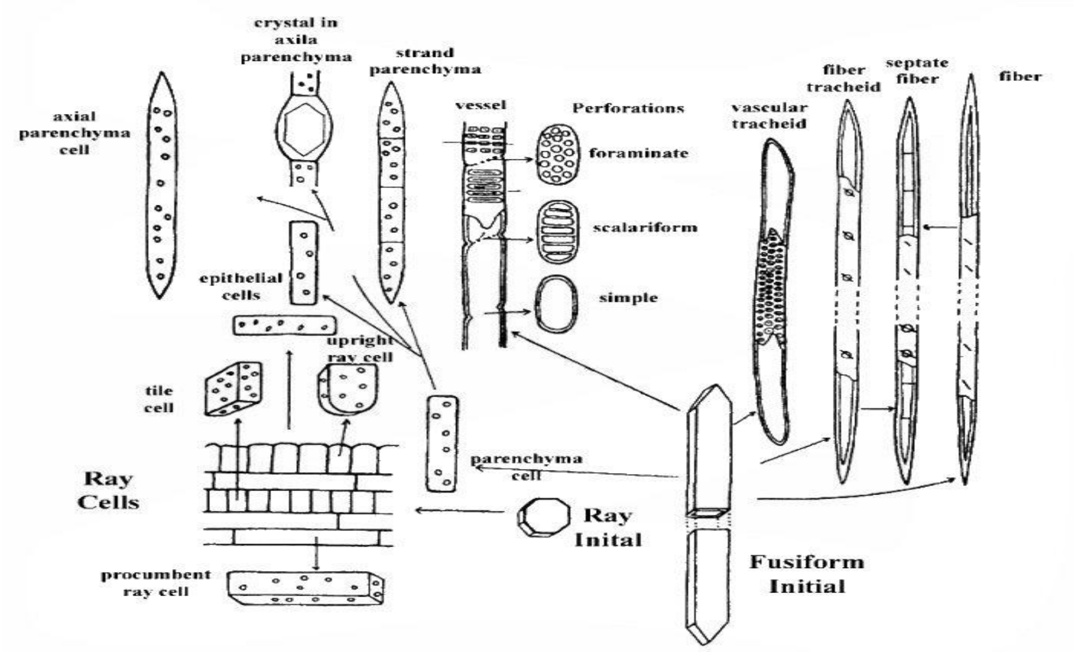


Figure 8. Hardwood cell types produced from ray and fusiform cambial initials (Source-Alden 2009).

Yellow birch contains vessels, which are moderate in abundance, small to medium in size. Yellow birch vessels occur solitarily or on radial multiples of two or more. The inter-vessel pits in yellow birch are arranged in an alternate pattern ranging from two to four micrometers in diameter, are orbicular to broad-oval or angular with confluent apertures. The perforation plates between the vessel elements are scalariform. Fiber tracheids are moderately thick-walled and medium to coarse in texture. The rays of yellow birch are un-storied, homocellular, and range from one to five seriate. The ray ends found in yellow birch are indistinct. Apotracheal parenchyma occurring in small tangential segments is often called “diffuse-in-aggregates parenchyma” this is the type of parenchyma is commonly found in yellow birch (Panshin and de Zeeuw 1980, Hoadley 1990)

Diffuse porous:

A diffuse porous situation occurs when the vessel size from earlywood to latewood does not appreciably vary in size throughout one single growth ring (Hoadley 1990). Yellow birch is a diffuse porous hardwood species. In a diffuse porous situation spiral thickening of the vessel elements throughout the ring may occur, this can be an important diagnostic feature. Although yellow birch possesses a diffuse porous situation it is lacking spiral thickening of the vessel elements (Panshin and de Zeeuw 1980, Hoadley 1990). Hoadley (1990) defines diffuse porous woods as:

“Diffuse Porous Wood - A hardwood in which the pores (vessels) are of approximately the same size and distributed fairly even throughout the growth ring.”

Fibers:

Fibers in a hardwood tree are among the smallest cell types, with the thickest cell walls. When looking at fibers on a tangential surface, they appear as a dense mass of cells. The mass of fibers tends to appear darker than the rest of the cell types and structures within the same specimen (Hoadley 1990). Fibers are typically long slender straight cells whose ends taper to a point (Panshin and de Zeeuw 1980) and range in length from 3.6 mm in loblolly pine to 1.5mm in yellow birch. Fiber cells are among the smallest diameter cells in wood. High magnification is needed to see the fibers as more than a background to the pores. Table two presents various characteristics of softwood and hardwood fibers. The fiber characteristics of yellow birch are, thin to thick walled fibers 0.0197 – 0.036 mm in diameter and commonly possessing a length of 1.5 millimeters (Isenberg 1980).

The definition of a hardwood fiber given by Hoadley (1990) states:

"An elongated hardwood cell with pointed ends and thickened walls that contributes greatly to the strength of the wood".

Table 2. various characteristics of softwood and hardwood fibers (Source - Finebar.com / Isenberg 1980*).

Wood Species	Average Fiber Length (mm)	Average Fiber Diameter (um)	Average Cell Wall Thickness (um)
Loblolly Pine	3.6	35-45	4-11
Douglas Fir	3.9	35-45	3-8
W. Hemlock	4.2	30-40	2-5
White Spruce	3.3	25-35	2-3
Sweetgum	1.7	20-40	5-7
White Oak	1.4	14-22	5-6
White Birch	1.8	19-30	2-4
Yellow Birch*	1.5	20-36	3-3.6
Sugar Maple*	0.8	14-30	-
Red Alder	1.2	16-40	-

2.4 Yellow Birch

Yellow birch, *Betula alleghaniensis (Britt)* can be a fast growing, short-lived species of birch, but can be found to live for upwards of three hundred years in some situations (Hosie 1969). The average longevity of yellow birch is roughly one hundred sixty years old. The average height, which a yellow birch is capable of attaining is roughly 20 m with an average mature diameter ranging from sixty centimeters up to, and over ninety centimeters (Hosie 1969, Sullivan 1994). Common alternate names for yellow birch are, gray birch, swamp birch, and silver birch. Yellow birch has many potential end uses, from lumber products to toothpicks, toys, furniture and veneer (Eardmann and Peterson 1981, Sullivan 1994, Wiemann *et al*. 2004). There is a wide variety of options for economic gain when working with yellow birch, which will be discussed further in “uses” section.

2.4.1 Range

Yellow birch can be found in a variety of locations, although it is mainly constricted to areas reaching from Newfoundland, Cape Breton Island, Nova Scotia, New Brunswick, Anticosti Island, the Gaspe Peninsula, and Maine (Eardmann and Peterson 1981, Sullivan 1994). Yellow birch can also be found west to southern and Southwestern Ontario and Minnesota, south to northern New Jersey, northern Ohio and extreme northern Indiana and Illinois. The southern most regions yellow birch can be found is in the area of South Carolina, extreme Northeastern Georgia and eastern Tennessee (Sullivan 1994, Chambers *et al*. 1997, OMNR 1998). In the southernmost extremes where yellow birch will grow it tends to be restricted to higher elevations (over 900 meters) and is increasingly sporadic. For the most part, throughout its growing range yellow birch can be found in higher abundance on upland, hilly terrain (Sullivan 1994). The largest concentrations of yellow birch are found in Ontario, Quebec, Maine, upper Michigan, New York and New Brunswick (Quigley and Babcock 1969, OMNR 1998, Ross 2010).

General Botanical Characteristics:

Yellow birch is a deciduous tree native to North America. When open grown, yellow birch crowns are irregular shaped and much longer and wider spread than that found in a higher stand density of yellow birch (Sullivan 1994). High stand density yellow birch forests lead to the crown having an irregular “short rounded” shape (Sullivan 1994). The trunk can split into two or more main stems with the main stem usually being free of branches due to heavy lateral branching in the crowns above, allowing for only a marginal amount of light penetration. In dense forest stands of yellow birch the main stem maintains its apical dominance and is relatively straight throughout the tree, to the top with little to no branching existing on the lower half of the stem. The bark of yellow birch is somewhat shimmering with its yellow to gold appearance, it tends to exfoliate in much smaller strips than that of white birch (*Betula papyrifera* Marshall) (Eardmann and Peterson 1972, 2001, Sullivan 1994). Due to the strips of bark exfoliating radially, the tree stems tends to have a shaggy appearance when it is at its average growing age in average conditions. Veteran yellow birch trees have deeply furrowed bark, without the presence of exfoliating strips near the base of the tree (Eardmann and Peterson 1972, Sullivan 1994). Yellow birch has an extensive lateral root system reaching much further outward than downward although roots can extend five feet or more down into growing substrate (Eardmann and Peterson 1972, Sullivan 1994). Yellow birch is a monoecious hardwood, which possesses a fruit classified as a "winged nutlet" (Eardmann and Peterson 1972, 2001, Sullivan 1994, Chambers *et al*. 1997,OMNR 1998).

2.4.2 Soils and Topography

Yellow birch is found to grow over a large area of diverse geology in a wide variety of soil conditions and moisture regimes. Typically yellow birch is found on outwash sands, glacial tills, lacustrine deposits, shallow loess deposits, and sands derived from sandstone, limestone, and igneous and metamorphic rock (Burns and Honkala 1990). Yellow birch can also be found on soils derived from schists and shales. The growth of yellow birch is affected by the growing substrates stone content, rooting zone depth, soil texture, moisture regime, elevation, aspect and fertility (Burns and Honkala 1990). Yellow birch tends to grow better on a northern aspect than it does on a southern aspect and is found to grow best on well-drained fertile loams and moderately well-drained sandy loams of uplands and mountain ravines. In places where drainage is poor, yellow birch can be found abundantly because competition from other species is inhibited, although growth of yellow birch on these types of sites is poor (Post *et al.* 1969). Yellow birch is sensitive to phosphorous in the soil, droughts can also affect yellow birch growth where its rooting is shallow. Yellow birch has also been described as a sensitive species, which doesn't adapt well to change. A study conducted in the Bartlett Experimental Forest in New Hampshire concerning the growth of yellow birch in a podzol soil by Merrill (1965) resulted in poor growth and high mortality in the yellow birch growing stock. Upon examining various environmental aspects the soils were found to be of particular interest. One of the contributing factors to the successful growth of yellow birch is the rooting depth. Yellow birch tends to develop a much shallower root system in the northeast due to the impermeable substrates such as hard pans, bed rock and, glacial till. High water tables can also have an effect on the depth yellow birch will root. Redmond (1954) and Tubbs (1963) conducted studies using yellow birch seedlings in pots to see their response to various rooting substrates. These studies displayed that the rooting of yellow birch was heavily influenced by the substrate it was grown in. Loamy humic substrates displayed prolific rooting while a sandy substrate exhibited poor root expansion. The explanation given for this was that the loamy substrates had higher nutrient contents. Upon further testing into the nutrition of the soil it was found that the nutrients were not the only factor controlling the rooting of the yellow birch seedlings as adding commercial fertilizer (7-6-19) to the sandy soil did not induce rooting (Tubbs 1963). Another study conducted by Merrill (1965) concerning the growth of yellow birch in a podzol soil investigated the effect of texture on root growth. There was a dual purpose of this study, first to better understand the influence of physical properties themselves and second, to be able to make some allowance for physical effects when evaluating the effects of chemical and micro-organism factors. The soil for this particular study was taken from the Bartlett Experimental Forest in New Hampshire and separated into the various horizons found in the substrate profile. The soil was classified as a well-drained deep podzol, developed on loose late Wisconsin glacial till derived from granite and gneiss (Merrill 1965). Some of the soil samples were treated with commercial vermiculite to alter the bulk density while others were watered with a solution of hydrogen peroxide (H_2O_2) to oxygenate the roots. The results of the study show that the growth of yellow birch seedlings was best in the humic horizon, fair in the A2 horizon, poor in the B22 horizon and practically nil in the remaining B and C horizons (Merrill 1965). Treatments to alter the bulk density and aeration did not generally produce better growth than the untreated soils. The conclusion of this study was that the humic layer in the forest is likely the “nutrient bank” for yellow birch growing on the site and all silvicultural activities should aim towards the mitigation of degrading this humic layer (Merrill 1965). Practices to prevent intense wildfire from depleting the humic layer are also promoted in stands where yellow birch is present (Sullivan 1994). Yellow birch will also benefit from crop tree thinning, lowering the amount of root and resource competition in the uppermost soil horizons, which will adequately provide the remaining trees with the nutrients required for increased growth (Merrill 1965, OMNR 1998).

2.4.3 Growth and Yield

Yellow birch requires sufficient overhead light, crown expansion space along with the correct soil moisture and nutrients to compete with its faster growing associated species. Crop tree thinning studies have been completed on saplings, poles and small saw log sized trees in the northeast and the lake states (Hannah 1974 and 1975, Erdmann *et al.* 1975, Erdmann *et al.* 1981, OMNR 1998). These studies reveal that yellow birch when aged sixteen to sixty-five, respond well to thinning and can maintain their crown position throughout their lives. It was also found that the growth rates also decrease in time as the tree ages. In the sapling stage the diameter growth increase by thinning can be up to 7.6 cm per decade by releasing dominant and co-dominant crop tree crowns from all trees whose crowns are within six to eight feet of the crop tree crowns perimeter (Eardmann and Peterson 1992). The diameter growth increase, which is attained by a pole size log given the same thinning treatment as the sapling, can be up to seventy five to seventy eight percent (Eardmann and Peterson 1992). Dominant and co-dominant trees or plus trees with well-established crowns respond the best to thinning treatments. Complete crown thinning provides adequate growing space for optimizing growth rate and quality development in yellow birch (Erdmann *et al.* 1972, 1975). Another study conducted by the Northern Forest Experiment Station shows that by releasing crowns early the amount of future veneer and saw logs are increased, and rotations can be reduced to almost half of a normal rotation (Eardmann and Peterson 1992). The same study provided contradictory results from the previous discussed studies where saplings responded best to crown thinning with the pole size trees responding nearly as well. The volume increase attained in this particular study was roughly two to three square feet in basal area per year (Eardmann and Peterson 1981). The trees, which are left after thinning or crown thinning, should always be the trees of highest potential. Yellow birch self-prunes well if crown closure occurs within five to six years of thinning (Solomon and Shigo 1976). Clear stems can be achieved through pruning, pruning a single stem up to fifty percent of its total height can be done without negatively affecting growth (Solomon and Shigo 1976). Pruning is to be done on small, fast growing trees with knotty cores. Branches up to five centimeters in diameter can be pruned flush with the stem without causing any lumber defects (Solomon and Shigo 1976). Pruning may also have negative implications associated with it. Heavy exposure following crown thinning can induce epicormic branching from two different sources, suppressed lateral buds on the stem and adventitious buds (Erdmann *et al.* 1972). The difference between a suppressed bud and an adventitious bud is a suppressed bud may persist on the stem of a tree for many years as a bud trace and only after a disturbance such as a crown thinning or damage to the stem does the suppressed bud begin to grow into a branch (Erdmann *et al.* 1972). An epicormic branch from a suppressed bud is usually small and dies soon after they are formed. After the epicormic branch dies and eventually falls off of the tree the bud trace may remain active in the cambial zone of the tree, this bud trace can sometimes from into a new epicormic branch, which will be fast growing and die soon after initiating (Rast *et al.* 1982). Additionally a suppressed bud may sometimes form only one branch, which soon dies followed by the bud trace ceasing all activity in the active cambial zone leaving no evidence of it (Rast *et al.* 1982). An adventitious bud forms from the cambium of the tree usually following injury to the stem (Rast *et al.* 1982). Identification for both bud types are marked by a slight break in the bark pattern with a small protrusion located in the center (Rast *et al.* 1982). Epicormic branching severity increases as the severity of the crown release increases, these branches are usually not an issue in managed stands which practice pruning after crown release (Rast *et al.* 1982).

2.5 Silviculture

Silviculture can be defined as:

> "The art and science of controlling the establishment, growth, competition, health, and quality of forests and woodlands to meet the diverse needs and values of landowners and society on a sustainable basis" (Helms 1998).

Silviculture systems are specific to the type of forest, being regenerated. In Ontario there are two main types of silviculture systems practiced, even-aged and un-even aged stand management (Chambers *et al*. 1997, OMNR 1998). Even-aged management consists of a population of trees that are similar in age class grown as a single entity from germination to harvest on a specific rotation (Chambers *et al*. 1997, OMNR 1998). These forest types are typically managed in terms of the areas and volumes occupied by a specific age class. The maximum of the mean annual increment is often used to determine the rotation age when maximum timber production is the main objective, use of a rotation age not attained by this method will result in a lower than average rate of production (Clutter *et al.* 1983, OMNR 1998). Other objectives dictate a shorter or longer rotation age, for example various product rotations may be as short as 50 years for fiber products and as long as 200 years where aesthetics or strength is the prime concerns. In hard maple and yellow birch stands, rotations are frequently set at 90 to 120 years, depending on site and intensity of management (Tubbs 1977). The typical species, which even aged management is commonly associated with is the boreal forest species *Populous* spp., *Picea* spp., *Pinus* spp. and some of the *Betula* spp. These species have adapted over time to a disturbance or fire driven ecosystem with recurring fires, insect outbreaks and disease, which in a sense hits the reset button on the ecosystem allowing for intense competition between shade intolerant species (OMNR 1998). If these ecosites are without stand replacing disturbances, the site can succeed into slower growing mid-shade to shade tolerant species such as is found in the *Picea* spp. (OMNR 1998). Un-even aged management strategy tends to be applied in the tolerant hardwood forests of Ontario. An un-even management strategy consists of a forest stand on a productive site, with multiple age and diameter classes that fully occupy the growing space available (OMNR 1998). The multitude of age and diameter classes ensures that there is always a supply of growing trees maturing into harvestable products (OMNR 1998). In the majority of the forest stands designated to be accompanied by an un-even aged management system, two or more cuts are require to achieve the recommended structure and stocking level of high quality trees described in the Tolerant Hardwood Forests of Ontario by Rowe (1972) for the Great Lakes St. Lawrence and the Deciduous Forest Regions. Research into natural forest dynamics proves that sugar maple saplings, which are shade tolerant, tend to regenerate successively in complete shade under the canopy or in small openings created by falling veteran trees. Major stand replacing disturbances are infrequent in the hardwood stands of Ontario, furthermore the disturbances associated with these types of stands tend to be on a smaller scale than that of a forest fire or an insect epidemic (MRNFP 2003). Some of the most frequent disturbances in Ontario and Quebec's hardwood forests are ice storms, wind shear, dieback and disease (MRNFP 2003). These disturbances allow for small gaps to be created in an otherwise closed canopy situation. These small gaps in the forest canopy are pivotal to the regeneration success of some mid-shade tolerant species as light intensity is one of the determining factors for the formation and growth of regeneration. In a closed canopy situation one can expect to see shade tolerant species such as sugar maple and American beech while the intermediate shade tolerate species such as yellow birch are mainly found in small openings (MRNFP 2003). Table three contrasts the difference in age structure, diameter distribution, basal area and height for even aged and un-even aged managed forests.

Table 3. Stand factors affecting determination of growth and yield in hardwoods (Source: Schlaegel, 1978).

Even-Aged	**Uneven-Aged**
Age Structure	
All trees essentially the same age	Continuous age distribution
Stand age indicates phisiological maturity	Stand age does not exist
Age used to determine parameters such as dimeter, height, basal area, volume and site index	Conventional yield tables and growth equations do not work
	Number of years since treatment is usefull for prediction
Diameter Distribution	
Normal or skewed-normal distribution	Reversed-J-shaped distribution
Most trees are grouped about the mean	Average stand diameter cannot be interpreted
Can use average diameter, range and standard deviation for comparisons	Can use exponential or weibull probability density function
Can use normal probability density function to predict diameter distribution	Growth rates are predictable by stand table projection by diameter class from permanent sample plots
Basal Area	
Basal area increases to an asymptote	Basal area nearly constant except for minor fluctuations due to mortality or selective harvesting followed by ingrowth
Growth pattern is sigmoid, starting slowly, accelerating, then slowing to a constant	
Height	
Average height development is sigmoid, increasing to an asymptote	Average height of tallest trees to be constant over time
Site index is calculated from dominant trees	Growth potential of individual trees related to crown vigor and position in canopy
Suppressed trees contribute little	Suppressed trees may be future growing stock

2.5.1 Silviculture Effects on Wood Quality

The overall quality of wood for a site can be influenced by the silvicultural activities prescribed to it. It is well known that the activities carried out on a tract of land influence the dynamics of the growing stock, in turn, affecting the intrinsic properties of the tree and trees within a stand (Larson 1969, Eardmann and Peterson 1972, Eardmann *et al.* 1980, Zhang and Tong 2005, Bowyer *et al.* 2007, Nova Scotia Department of Natural Resources (NSDNR) 2010). Silvicultural activities alter wood directly through physiological changes within the stem or manipulation of the tree form (Larson 1969). Less is known about the future wood quality implications and the overall affect silviculture has on stand value. Larson (1969) suggests that the crown of a tree is the source of materials that dictate growth and wood development, to change the foliage on the tree would result in an altered cell size, cell wall thickness and perhaps chemistry. Stocking is one tool most commonly used by the silviculturalist to manipulate growth and yield. Stocking is defined by the OMNR (1998) as:

"A measure of the proportion of the area in a stand actually occupied by trees expressed in terms of stocked quadrants or percent of canopy closure. Usually expressed as trees per hectare or some relative measure (well stocked, fully stocked, overstocked, understocked). It is a qualitative expression of the adequacy of tree cover on an area, in terms of crown closure, number of trees, basal area or volume, in relation to a pre-established norm."

Based on this the OMNR (1998) defines stocking levels as:

"Fully stocked*: Productive forest land stocked with trees of a merchantable species. These trees by number and distribution or by average DBH, basal area, or volume are such that at rotation age they will produce a timber stand that occupies the potentially productive ground. The stocking, number of trees and distribution required to achieve this will usually be determined from yield curves. Sometimes called normally stocked.*
Over stocked*: Productive forest land stocked with more trees of merchantable species than normal or full stocking would require. Growth is in some respect retarded and the*

full number of trees will not reach rotation age according to an appropriate yield and stock tables for the particular site and species."

Larson (1969) mentioned that stand density has a tremendous influence on the quality of the wood formed. Stocking and thinning influence branching patterns and growth rate and both affect wood properties (Bamber and Burley 1983). Stocking of a forest can be manipulated in many ways, most commonly through initial planting or thinning treatments. The different types of density management will result in differing wood properties (Desch and Dinwoodie 1981, Zobel and van Buijtenen 1989). A stocking difference in a forest stand can not only affect the wood properties through crown manipulation, wood properties can also be manipulated through the increase in resources available for growth. An example of altering the biotic factors on a site to influence the abiotic factors, is described by Savinia (1956), where he found that by thinning a plantation the soil moisture content increased. To determine the effect of silvicultural activities on a tract of land, lumber conversion studies and strength evaluations have been and are currently being carried out on various species (Jozsa and Middleton 1994). The quality or traits desired in wood is relative to its destined end use, although several key factors can play an important role in determining the quality of wood. One of the most common relationships in a specimen of wood is that as the density of the wood increases the strength properties of that piece of wood increase as well (Zobel and van Buijtenen 1989, Jozsa and Middleton 1994), as will be explained further in this thesis. Methods of mapping the properties, within a log, affected by silvicultural practices have been described by Jozsa and Middleton (1994) as "Log diagramming" explained as being the practice of characterizing a log for future product potential. The information recorded for log diagramming is as follows: bottom and top diameter, length, visible surface defects (knot size and distribution), live/dead classification, knot indicators, scars, spiral grain, shakes, stain and decay (Jozsa and Middleton 1994). Lumber from various trees and parts within a tree are color coded with dies and analysed using various methods making it possible to relate subsequent drying degrades and strength properties to various characteristics found in a tree (Jozsa and Middleton 1994). Many silviculture treatments can affect the growth increments of a tree species, if these treatments increase the density along with biomass, they are treatments, which are improving or maintaining wood quality. Inversely if a treatment to a stand of trees increases growth increments but lowers wood density, then the treatment is promoting poor wood quality in terms of strength. Treatments can affect trees in different ways, some treatments increase only the earlywood portion of a growth ring while others will increase the earlywood and latewood at the same increment and finally some will increase only the latewood portion of the tree (Bowyer *et al.* 2007). Earlywood and latewood can be increased by the amount of available water to the stems on site. Panshin and de Zeeuw (1980) state that:

> *"Available water either as rainfall or ground water has been shown to influence the percentage of latewood. Studies conducted on softwoods indicate in all but a few, optimum available moisture throughout the growing season promotes wide incremental growth in both earlywood and latewood, maximum percentage of latewood and high specific gravity"*

2.5.2 Growth rate and wood properties

In most solid wood products strength plays an integral role, therefore and important question is how and does accelerated growth affect wood quality? The effect of growth rate on wood properties has long been a topic of discussion in wood quality research and has been evaluated by many investigators. Concerns have been raised previously in wood science research as Paul (1927) stated his concerns regarding the accelerated growth of several southern pine species and the associated wood quality from these trees where it was found that free and fast growth would produce wood with undesirable characteristics for quality products. Often fast grown trees from naturally productive sites are readily accepted, whereas the quality of similar wood produced by enhancing the growth conditions is questioned, this especially holds true when one or more abiotic factors in the site are changed (Larson 1967). Controversy relating to accelerated growth, and wood quality, has also been reported by Larson (1967) regarding issues in the grading system concerning rapidly grown wood. Larson (1967) stated the following:

> *"Wood from rapidly grown trees may be completely acceptable under one standard but may be rejected under another standard".*

Due to the constraints on some lumber grading rules fast grown timber may be rejected when held to the standard that a minimum amount of growth rings be found per inch of lumber (Koch 1972). Zobel (1980) and Bingham (1983) emphasized the fact that natural rotation ages of our hardwood and softwood forests cannot keep up with our current forestry activities. The need for faster growing younger trees is imminent and the younger trees, which we are harvesting from plantations, will have to be accepted. Zobel (1980) also stated that the proportion of fast grown conifer and hardwood plantation trees will continue to increase until it will predominate in the next quarter century, therefore, the industry must learn to use it efficiently. Trees produced in fast grown plantations are not necessarily carriers of bad wood, although, the wood is much different from that of a natural grown forest stand. Manipulation of a forest stand to accelerate growth can change the density of the wood produced on that site, in turn affecting the intrinsic qualities associated with it (Zobel *et al.* 1971). An example of this is seen when a site is so perfectly suited for a pine tree and the tree has no competition so it can grow uninterrupted and this wood created by the pine tree would be of low density (Zobel *et al.* 1971).

2.5.3 Release/thinning

For the purposes of this research document the terms “thinning” and “release” may be used interchangeably. The carrying capacity of a site is only enough to support an amount of trees of a certain size, usually as the size of the tree increases the stand density decreases through natural thinning. Thinning, is defined by many as being the removal of stems in a given space in order to allocate more resources to the remaining trees for improved growth. The definition given by OMNR (1998) is as follows:

> “*Full expression of a trees genetic potential is realized when the tree is growing in favourable conditions. An effective thinning program can control spacing and competition, providing better growing conditions for crop trees. In addition, thinning facilitates the selection of individual trees* of greater potential for the residual stand”.

The trees, which remain in the stand after a partial cutting or a thinning takes place are allocated the resources from the previous inhabitants of the site. Commonly additional sunlight, water, nutrients, crown expansion space and root expansion space are associated with a thinning (BCMF 2001). Thinning operations often occur in natural forests or plantations. Thinning is usually a process occurring naturally in forest stands as crown closure occurs and the site enters the “zone of imminent competition mortality” (ZICM), this is when the forest stand is said to be “overstocked” and the strongest trees survive and the weak perish (Archibald and Bowling 1995). Many density management diagrams for various Boreal species have been created which depict the -3/2 power rule, or the law of “self-thinning” where these diagrams relate changes in mean plant size to stand density using logarithmically transformed axes (Archibald and Bowling 1995, Smith 1997, Swift *et al.* 2007).

It is important to note that thinning can have a major effect on wood quality by increasing the number of potential saw logs or logs suitable for veneer (Zobel and van Buijtenen 1989). The actual and relative growth responses of a tree and stand of trees to a thinning treatment can be defined as the difference and ratio between the actual growth and the corresponding assumed growth if unaffected by thinning (Peltola *et al.* 2002). Many studies have shown that there is a diameter increase following thinning, these studies have been carried out on many softwood and hardwood species (Eardmann and Peterson 1992, Althen *et al.* 1994 and 1995, (NSDNR) 2010). Another benefit of thinning a forest stand is the recovery of merchantable timber or biomass, which would have otherwise been lost due to natural mortality (Bowyer *et al.* 2003).

Larson (1972) mentioned the importance of distinguishing between young trees and older stunted trees as each age class will respond different to the same thinning treatment. An example of this, was found by Phelps and Chen (1991) when the same thinning regime was applied to juvenile and co-dominant white oak (*Quercus alba* Linnaeus) with the juvenile trees displaying a significantly higher diameter increase than that of the co-dominant stems in the same stand. Cutter *et al.* (1991) found a similar response to thinning treatments with scarlet oak (*Quercus coccinea* Muench.) and black oak (*Quercus velutina* Lam.), but also noted that after a period of subsequent growth, thinning primarily increased the yield of the lowest grades of lumber. Crown and McConchie (1982) stated the relationship between wood properties and age as:

> *"The change in raw material supply from un-tended old crop trees to the thinning and final harvest from intensively managed forests of radiate pine will be accompanied by age-related differences in wood properties, to which industry will have to adjust"*

Since most trees are harvested at a given size rather than a given age, thinned stands will be inevitably harvested at an earlier age than that of a natural forest stand harbouring trees of the same diameter. The trees harvested from the thinned site commonly have a higher content of juvenile wood, therefore the improved growth of the thinned stands and the added value from a thinning is offset by a higher proportion of juvenile wood from younger thinned stands (Zobel and van Buijtenen 1989).

Thinning treatments applied in Quebec, Canada, have been carried out on young yellow birch stands and sugar maple stands. In many of these thinning studies the deciding factor to be thinned was basal area, the treatments include removing 20% up to 40% basal area in trees 9 cm DBH and greater (MRNFP 2003). These basal area removals have mainly resulted in favourable outcomes. In these treatments the thinned trees were cut, girdled or poisoned. Much less documented, due to the possible damages posed by falling dead trees, felling and removal of the stems seems to be the best method for protecting the remaining crop trees (Meyer 1952, Eyre and Zillgitt 1953, Curry and Rushmore 1955, Church 1955, Aborgast 1957, Gilbert and Jensen 1958, Trimble 1968, Smith and Gibbs 1970). Studies carried out on sugar maple stands by Church (1955), Roberge (1957), Skilling (1959), Drinkwater (1960), Marquis (1960), and McCauley and Marquis (1972) displayed an increase in production and quality is possible by thinning sugar maple stands. Much less work has been done on yellow birch, although, the evidence at hand in related species would imply that thinning treatments could be advantageous for this species.

A study completed specifically on yellow birch growth following crop tree thinning by Hannah (1978) was completed on trees with a DBH of two to 6 inches. The study involved a stand, which was even aged and a stand, which was comprised of two age classes. It was found that the growth differences associated with the degree of thinning became evident after the first growing season, although, the even aged stand responded better to the treatment. Another study conducted by Erdmann and Peterson (1972) found that two – three years following a thinning treatment on co-dominant and dominant yellow birch poles resulted in a diameter increase of nearly two times that found on an un-treated site. The general response found in this study was that the heavier the thinning, the greater the increase in diameter. The growth rates of the thinned trees were also related to the associated foliage density of the thinned crop trees. The increase in adventitious or suppressed buds sprouting was found to be restricted to the second log following thinning treatment, furthermore, it was noted that thinning could severely affect stem quality, therefore reducing the value of the crop trees. As the thinning treatments were applied it was seen that the branch free section of the stem decreased from 24 feet to 21 feet three years following treatment. A study by Roberge (1988) found that the yield from the thinned plots greatly exceeded that of the un-treated plots and the success of yellow birch regeneration was best in patch clear-cutting where more suitable conditions were found for yellow birch seedlings. A branching and diameter response of pre-commercially thinned hardwood stands in Nova Scotia by the Nova Scotia Department of Natural Resources (NSDNR) (2010) found various associated diameter gains when thinning treatments were applied at various intensities to yellow birch. The Higgins Mountain site, which was thinned when it was 5 meters tall consisted of a 36% of height thinning treatment, a 44% of height thinning treatment and a 60% of height thinning treatment resulting in 26%, 44% and 55% diameter gains, respectively (NSDNR 2010). On the McQuarrie Lake thinning trial the resulting diameter gain was 100% from a 75% of height thinning treatment (NSDNR 2010). The effect of different intensities of yellow birch and sugar maple crop tree thinning, has been previously reported by von Althen *et al.* (1994 and 1995). This study was conducted on 20-year-old yellow birch and sugar maple near Thessalon, Ontario where treatments consisted of a control, and thinning treatments freeing crop trees from competition one-meter, two-meters and 3-meters from the bole of the sugar maple crop trees and one, two, three and 4-meters from the bole of the yellow birch crop trees. The findings were that crop tree thinning of both species under investigation resulted in an increased 5-year diameter increment and crown size (von Althen *et al.* 1994 and 1995). It was also found that the greater the crop tree thinning, the greater the physiological response. The height increment of the thinned yellow birch trees decreased as the thinning treatment increased, inversely, the sugar maple crop trees responded with positive height growth in all thinning treatments. The amount of adventitious or suppressed buds, which formed into branches along the bole of the tree was low for both species when considering the one, two and 3-meter thinning, although, the 4-meter thinning applied to the yellow birch crop trees resulted in an increased number of these sprouts and a significant increase in their size. Furthermore it was noted that the 4-meter thinning degraded the stem quality of the yellow birch crop trees and the one-meter thinning wasn't enough to allow for adequate crown expansion. Five-years following the one and two-meter thinning treatments yellow birch crown expansion space was diminished substantially (von Althen *et al.* 1994 and 1995). Much of the previous work did not capture or report on the associated wood qualities related to the thinning treatments.

2.6 Uses

The wood of a yellow birch tree is ideal for many products as it is hard, strong, and heavy with good shock resisting ability and a fine and uniform texture (Hosie 1969, Ross 2010). It is desired for its creamy color, hardness, texture and workability. Yellow birch has many current and historical uses and is one of the most popular hardwood lumbers used for furniture in the United States (Sullivan 1994). Yellow birch can also be used as railroad ties, cooperage, and hardwood distillation (Panshin and de Zeeuw 1980). The most prominent use for yellow birch, however, is veneer for furniture and internal panelling, doors, hardwood flooring and aircraft. Radio, television and stereo cabinets, boxes, crates, wood ware, novelties, toys, flooring, sashes and doors, shuttles, spools, bobbins, wide variety of lathed objects, butchers blocks, musical and scientific instruments, agricultural implementations, toothpicks, shoe pegs and pulpwood are also commonly crafted from yellow birch (Panshin and de Zeeuw 1980, OMNR 1998, Ross 2010). Although yellow birch is, for the most part, without pronounced grain feature a coarse curl can sometimes be found. Applications where a showy grain pattern is not desired are perfect for yellow birch, on the other hand the contrast from heart to sap wood can be quite pronounced if desired (Cassens 2007). The hardwood forest types that yellow birch is commonly associated with also help to purify the air in big cities (MRNFP 2003). These forests, if easily accessible, offer hiking, hunting and fishing and are visually attractive to many due to their aesthetic color changing and diversity in the fall. In Quebec the hardwood forests where yellow birch is commonly found contain great natural wealth with many lakes and water courses leading to indisputable value due to the diversity of flora and fauna as outlined by the (MRNFP 2003) in their “Silviculture research in Quebec’s hardwood forests” report (MRNFP 2003).

2.7 Hardwood Veneer

Veneer is simply thin sections of a log or flitch, which have been peeled or sliced (Hoadley 2000). The difference between a peeled veneer log and a sliced veneer log is peeling involves the log being mounted and rotated while a blade cuts a continuous sheet as wide as the log as the log spins, while sliced veneers involve a flitch being mounted and run up and down over a blade to create slices of veneer that are the length and width of the flitch. This will be described in more detail below. Veneer is commonly mistaken as a modern invention, when in reality it has been in use for thousands of years. Evidence of veneer has been found in many ancient Egyptian sarcophagi's, most famous, King Tutankhamun's foot stools (Mercker & Hopper 2004). Veneer quality logs, in today's market, seem to be the highest valued logs to come out of the Eastern North American forests. Furthermore appearance-grade veneer logs are valued even higher than veneer used in hidden applications (Wiemann *et al*. 2004, Canadian Wood Fiber Center (CWFC) 2009). Processing hardwood logs into veneer products rather than simply turning them into dimensional lumber has various positive attributes associated with it. The resource is greatly extended by creating veneer which ranges from 1/36 – 1/50 of an inch thick in comparison to dimensional boards (Cassens 2004). Veneering also allows for the production of inlays, matched grain patterns, and various other artistic designs. With the increasing ability of the world's veneer procurement facilities to process thinner sheets of veneer, resources are extending even further (Cassens 2004). According to Peter Hamilton of FP Innovations (CWFC Facts – 006, 2009), if tolerant northern hardwood managers are not differentiating between lumber grade and veneer grade logs, they are potentially undervaluing a single log by 1.5 up to 10 times (CWFC 2009). Due to the exceptionally high prices paid for premium veneer logs, frequently the majority of a large forests value will come from only a small portion of the stems. Couple this with the increasing demand for products such as laminated veneer lumber, birch plywood and new laminated veneer products the worldwide demand for North American veneer is increasing, which will inevitably lead to the inflation of veneer prices. This increased potential for revenue should provide landowners and land managers with incentive to enhance the production and retrieval of high quality veneer logs (Wiemann *et al*. 2004). In many instances the quantity of veneer quality logs is lacking in natural forests, therefore, managers often do not find it worthwhile and do not take the time to segregate various logs from lumber production to an appropriate veneer production facility. To complicate the log separation even further, strict log form and quality requirements must be met for a log to qualify as "veneer quality" (Weimann *et al.* 2004). Common defects which constrain veneer buyers from purchasing logs for veneer and veneer products include, heart stain, mineral streaks, heart rot, less than acceptable log form, knots and excessive amounts of abnormal wood (Hansbrough *et al*. 1943, CWFC 2009).

2.7.1 Peeling / slicing methods

The highest quality veneer logs are commonly worth less if they are not cut with the appropriate pattern that displays certain grain features (Wiemann *et al*. 2004). Various cutting and slicing methods create veneer with varying properties in turn increasing or decreasing its value. The highest quality veneers come from "slicing" methods rather than "rotary-peeling" methods (Wiemann *et al*. 2004, Mercker and Hopper 2004).

Vertical / Stay-log:

The two most common veneer-slicing methods are the “vertical” or “stay-log” slicing methods. Vertical slicing is completed by mounting (chucking) a log half (flitch) on a moveable mount, the log is then passed in front of a stationary blade and veneer sheets of varying thickness can be created. The veneer patterns created by vertical slicing are the flat and quarter-sliced veneer pattern, the flat sliced veneer knife is oriented so that it runs at a right angle to the wood rays, the pattern produced is called a “cathedral” grain pattern while the quarter-sliced veneer displays the growth rings as vertical lines. Figure 9 left and right, display two methods of vertical slicing producing the cathedral and vertical line appearance, respectively (Wiemann *et al*. 2004, Mercker and Hopper 2004, Ross 2010).

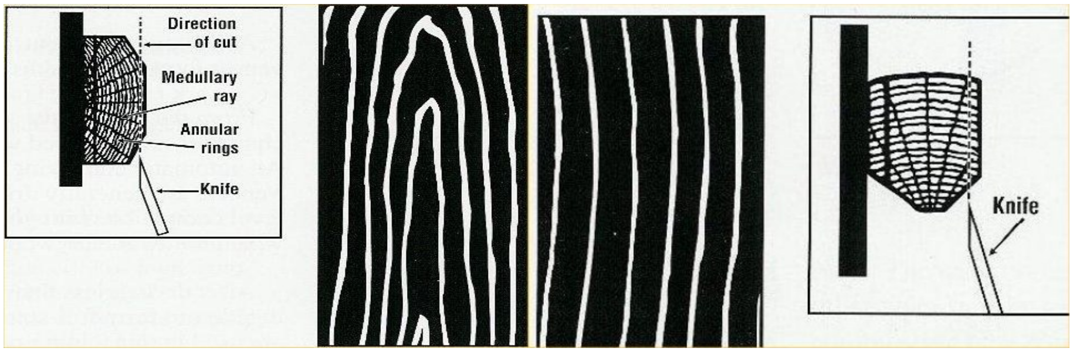


Figure 9. Vertical veneer slicing methods (Source: NGWoodSupplies, Inc. 2013).

Stay log slicing methods are completed by attached a flitch to the chuck on a circular rotating mount and passing it against a stationary knife in an arced motion, or “half-round” motion (Wiemann *et al*. 2004and 2010, Mercker and Hopper 2004).

Rift / Half Round:

Figure 10, left and right, display this method and the production of straight vertical line and cathedral appearance, respectively. Commonly the side of the blade will create minor checks in the veneer, inversely the surface which is on top of the knife is free from blade checks and is considered to be the finishing face. This checked side is commonly called the “loose” side (Wiemann *et al*. 2004and 2010). The surface with blade checks is commonly mounted to a backing of veneer, which is of lower visual appeal.

Sawing:

Sawing veneer is done from long narrow flitches, both surfaces of sawn veneer are free from blade checks and are both suitable for face veneer products (Wiemann *et al*. 2004, Mercker and Hopper 2004, Ross 2010). Half round, quarter and rift sliced veneer are preferred for many face veneer applications as their grain pattern is more visually appealing than that of the rotary peeled veneer, in addition pattern or book matching is accomplished with more ease utilizing this method (Wiemann *et al*. 2004).

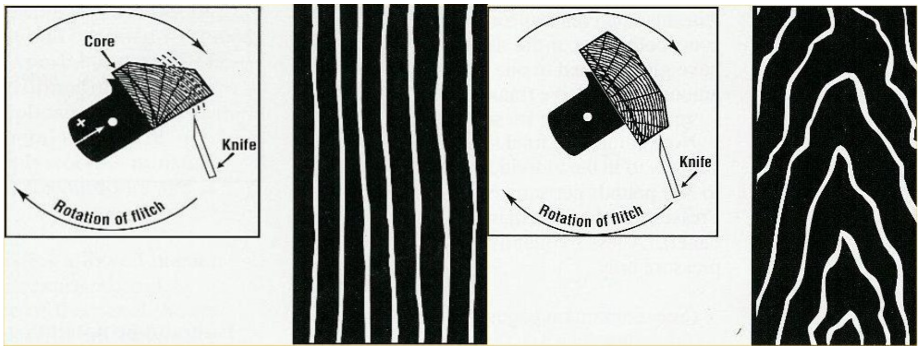


Figure 10. Stay log veneer slicing methods (Source: NGWoodSupplies, Inc. 2013).

Rotary cut:

Rotary cut veneer is produced by attaching a log to the chuck at both ends and rotating it against a stationary knife (Figure 11). The veneer processed by the rotary cutting method is a long continuous sheet. Commonly the lowest quality veneers are produced by this peeling method, although, this veneering method also results in the highest quality visual appearance for “birds-eye” featured wood (Wiemann *et al*. 2004) and high quality veneer for basket weaving (Wiemann *et al*. 2004, Mercker and Hopper 2004). Lower quality veneers are used for lower quality products or as backing for high quality face veneers for the use in flooring, cabinetry or furniture. The rotary peeling method is the fastest method, which produces the least amount of waste, although the grain pattern is commonly less appealing than produced by other slicing methods (Wiemann *et al*. 2004). Rotary cut veneer opens the tangential surface of the wood, this face is often plain with wide sections of “featureless” wood depending on the tightness of the growth rings. Rotary cut veneer is the hardest veneer pattern to match than veneer produced via other slicing methods (Wiemann *et al*. 2004, Mercker and Hopper 2004, Ross 2010) and is the standard method for producing softwood plywood.

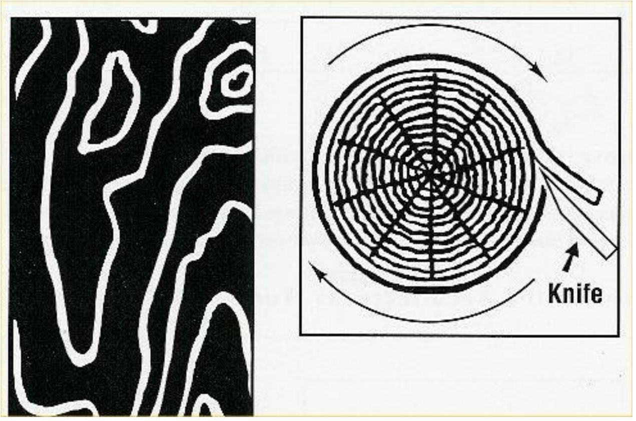


Figure 11. Rotary veneer cutting method (Source: NGWoodSupplies, Inc. 2013).

2.7.2 Yellow birch Veneer

In the 1950’s yellow birch was considered one of the most favourable species from which hardwood veneer was derived (Hansbrough *et al*. 1943). Its mechanical properties and the associated abundance in the Lake States and eastern Canada led to its acceptance as one of the most widely used woods for furniture and veneer in North America. Several factors have led to the decline of yellow birch as a prominent veneer species in North America since the mid 1900’s. Birch die back along with heavy harvesting and the associated damage to the standing trees left the yellow birch acceptable growing stock in a state of decline (Clausen and Godman 1967, Eardmann *et al.* 1980), furthermore the regeneration efforts of quality birch have been hindered by animals browsing on juvenile stands (Harkonen 2009). Much of the yellow birch veneer-quality logs are now being acquired from Canada rather than the northern Lake States (Hansbrough *et al*. 1943, Ohman 1970, Ross 2010). Yellow birch and sweet birch are commonly interchangeable when processed as veneer and are both commonly called “yellow birch” as they have similar characteristics (Cassens 2007). The logs from yellow and sweet birch commonly have a good straight form and are absent of any ring shakes (Cassens 2007). Logs, which possess rough bark typically have a characteristic grain pattern which is not desirable by many veneer processing facilities. The logs with smooth bark tend to have a straighter grain and are more valuable to veneer processing facilities (Cassens 1992 and 2007, Wiemann *et al*. 2004). All of the birches which are of commercial importance and grow in North America are diffuse porous, have white to creamy yellow sapwood and light brown to dark reddish brown heartwood (Cassens

1992and 2007). The vessels of birch are medium in size and may or may not be filled for finishing. Yellow birch wood has similar properties to that of sugar maple (Merrill 1965 and 1999, Panshin and de Zeeuw 1980, Zerbe 1988). In North America there are 12 species of birch, which can be found on various ecosites. Of the 12 species, three are currently considered to be merchantable for veneer production and lumber production: yellow and sweet birch (*Betula lenta.* Linnaeus) and paper birch (B*etula papyrifera.* Marsh). Sweet birch and yellow birch are marginally heavier and stronger than white birch and the other nine species. It is difficult for the untrained individual to distinguish between the three merchantable birch species once processed into lumber or veneer (). According to the Cassens (2007) about three quarters of the birch veneer cut in North America was from yellow birch. Traditionally yellow birch has been the baseline for comparison for other hardwood veneers.

2.7.3 Factors influencing veneer and lumber price

The desired properties of wood veneer are similar to that of the desired properties for dimensional lumber. The manufacturing process of veneer including cutting, drying and laminating can drastically change the physical and chemical surface properties of the veneer (Ross 2010). As previously stated prices fluctuate between lumber grade and veneer grade logs, furthermore the price of a single veneer quality log can vary greatly as well. For most appearance grade veneer logs the primary quality criterion is attractiveness or observational appeal. Attractiveness is in the eye of the beholder, for this reason the common traits associated with attractiveness are wood color, grain pattern and blemish or defect content (Wiemann *et al*. 2004, Cassens 2004). The effect a defect has on appearance depends on the size, type and location of the defect. Defects in logs are commonly, spotted by a veneer log buyer and rejected prior to purchase. Defects, which may not have been identified by external appearance, unfortunately, only become visible upon slicing or peeling. The defect logs, which make it into the veneer processing facility are commonly worthless, these logs represent a loss for the veneer manufacture (Wiemann *et al*. 2004, Cassens 2004). Value of a forest stand can be diminished in many ways, un-timely harvest (if the veneer quality logs are harvested prior to reaching sufficient diameter), skidder damage, moose damage, sapsucker damage, mechanical and non-mechanical damage during thinning operations, crowded stands (poor between tree spacing), insect damage, presence of rot and overgrown branch stubs (Erdmann and Oberg 1974, Cassens 2004, Wiemann *et al*. 2004, Harkonen 2009). Commonly moose damage is restricted to juvenile stands as young birch species are considered to be medium-preferred browse for the large ungulates (Harkonen 2009). The feeding habits of the moose can therefore hinder regeneration efforts of straight single stemmed trees (Harkonen 2009). Sapsucker damage seems to be concentrated to saw-log and pole-sized logs although can be found on trees of various age and size. The sapsucker will often make a distinct pattern while feeding on the sap and phloem tissue of the tree. The holes are roughly ¼ inch in diameter with squared edges, the holes penetrate through the bark into the cambium layer of the tree (Erdmann and Oberg 1974). The heavier the tree is fed upon the more damage is done. Mortality, wood quality degradation, discoloration and slowed growth are common after sapsucker feeding and subsequent damage occurs (Erdmann and Oberg 1974). Wood is commonly downgraded due to the discoloration associated with the feeding holes. Sapsucker feeding holes become grade defects when more than four bird pecks per square foot are present in clear-cuttings of factory grade one and grade two logs (Erdmann and Oberg 1974). Silvicultural operations commonly carried out on the northern tolerant hardwood stands such as thinning, selection cutting, and regenerations cuts often result in mechanical and non-mechanical damage to the residual standing trees (Ohman 1970). To further compound this issue, equipment and loads continue to increase in size leading to larger and more severe wounds on the standing residual timber, as well as soil compaction issues, which can restrict root growth. Skidding wounds offer a path of entry for pathogens and insects ultimately leading to discoloration and decay causing an inevitable downgrade in the final product (Ohman 1970). Cassens (2004) suggests that ring uniformity is imperative to a high quality veneer log, thus, ring width is an important aspect of a high quality veneer logs, and the wavering ring widths associated with a crop tree thinning are undesirable. If one is to wait too long for crop tree thinning, there will be an increase in the ring width soon following thinning, upon crown closure the ring width will diminish almost to the previous state prior to thinning (Wiemann *et al*. 2004). The sudden thinning of crop trees can also induce bole sprouts or braches from adventitious buds (Mercker and Hopper 2004, Wiemann *et al*. 2004). The acceptable amount of growth rings per inch ranges from six to nine (Mercker and Hopper 2004, Wiemann *et al*. 2004, Cassens

2004). Ring width homogeneity is imperative to veneer, which is not to be cut across rings. Tighter growth rings are required for veneer markets in Europe, veneer with wider rings is commonly used in the domestic market (Wiemann *et al*. 2004). Japan has the capability to use veneer sheets 1/100 – 1/128 of an inch thick, this veneer also requires tight growth rings (Wiemann *et al*. 2004).

2.8 Hardwood Lumber

One of the most important aspects of a successful hardwood lumber operation, is understanding the available resource and its associated quality and quantity (Foreward and Russell 2003). As previously stated, the properties associated with high quality lumber are roughly the same properties sought after for the production of high quality veneer. The amount of lumber recovered from a log during the sawing of dimensional lumber is determined by various factors, furthermore each scaling method provides a different result (USDA 1979). Each different sawmill has its own components, which effect the amount of lumber recovered, and seldom two sawmills are alike. Understanding the variables, which control the recovery amount can increase the ability of the operator to maximize potential product (Briggs 1994) Table four summarizes the main factors to consider when determining lumber recovery.

Table 4. Factors determining lumber recovery (Source: Briggs 1994).

Factors determining lumber recovery
Species
Log diameter, length, taper, and quality.
Kerf width.
Sawing variation, rough green-lumber size, and size of dry-dressed lumber
Product mix.
Decision making by sawmill personnel.
Condition and maintenance of mill equipment.
Sawing method.
Drying Method

There are several methods for determining the amount of recovery from a log. Two of the most common methods are: 1.) Cubic volume of lumber as a percentage of total log volume, and 2.) Board feet of lumber from a given cubic volume of logs commonly known as lumber recovery factor (Steele 1984). Because both the lumber volume and the log volume are measured in cubic meters, cubic recovery percent gives the most accurate representation of the lumber volume to log volume relationship (Fahey and Snellgrove 1982). During sawmilling the size of the log really does matter for the products, which are to be produced from the log. The larger the logs, which are being run through the sawmill, the higher the production per hour and recovery percentage (Briggs 1994). As the diameter of the log increases the recovery increases dramatically as well. Although an increased recovery is expected with larger diameter logs, it may not occur in some instances with certain species. Large logs for some species mean that they could possibly be over mature and have the presence of decay and an abundance of unsound wood. Grading can also affect the amount of lumber recovered, if a large diameter log has certain defects which must be cut out to increase aesthetics and structural integrity, the recovery will not increase with diameter (Steele 1984, Briggs 1994). For example if a log is rotten near the core it may not be suitable for rotary peeling as it will not mount to the chucks, however the same log may be able to be sliced into veneer, as a flitch from the log could be mounted to the chuck and sliced in an appropriate manner. Similarly a log with a large frost crack will not produce rotary cut veneer as it will break into pieces at the frost crack, however, the log could be cut into flitches that could be mounted to a chuck for slice veneers (Steele 1984, Wiemann *et al*. 2004)

Flat Sawing (Plain Sawing):

Plain sawn (or flat-sawn or through and through-sawn) lumber has the growth rings of the tree parallel to the board's broad face (Bowyer *et al.* 2003). Plain sawn wood highlights the grain typically in a cathedral appearance. “Flat sawn” or “live sawn” lumber is one of the most commonly produced products due to its ease and the fact that it creates less waste in most instances (see Figure 12). This method of sawing is very useful when dealing with high tensioned logs. The grain of the log will be running parallel with the wide faces of the board, this will cause the boards to bow upwards and also cup due to differences in how the upper and lower faces dry. These flat sawn boards have a great deal of flex associated with them, and can therefore be straightened through correct stacking and stickering combined with weights on top of the load during the kiln / drying process (Peterson 2006). Flat sawn boards are excellent for nailing directly through as they tend to hold together well and do not split. Although flat sawn boards are easy to create and have less waste associated with them, there are certain disadvantages to this saw pattern. Because of their inherent ability to flex and bend when under pressure, the flat sawn boards are not ideal for many uses. Treads on a staircase is a perfect example where flat sawn board would not be appropriate (Petersons 2006).

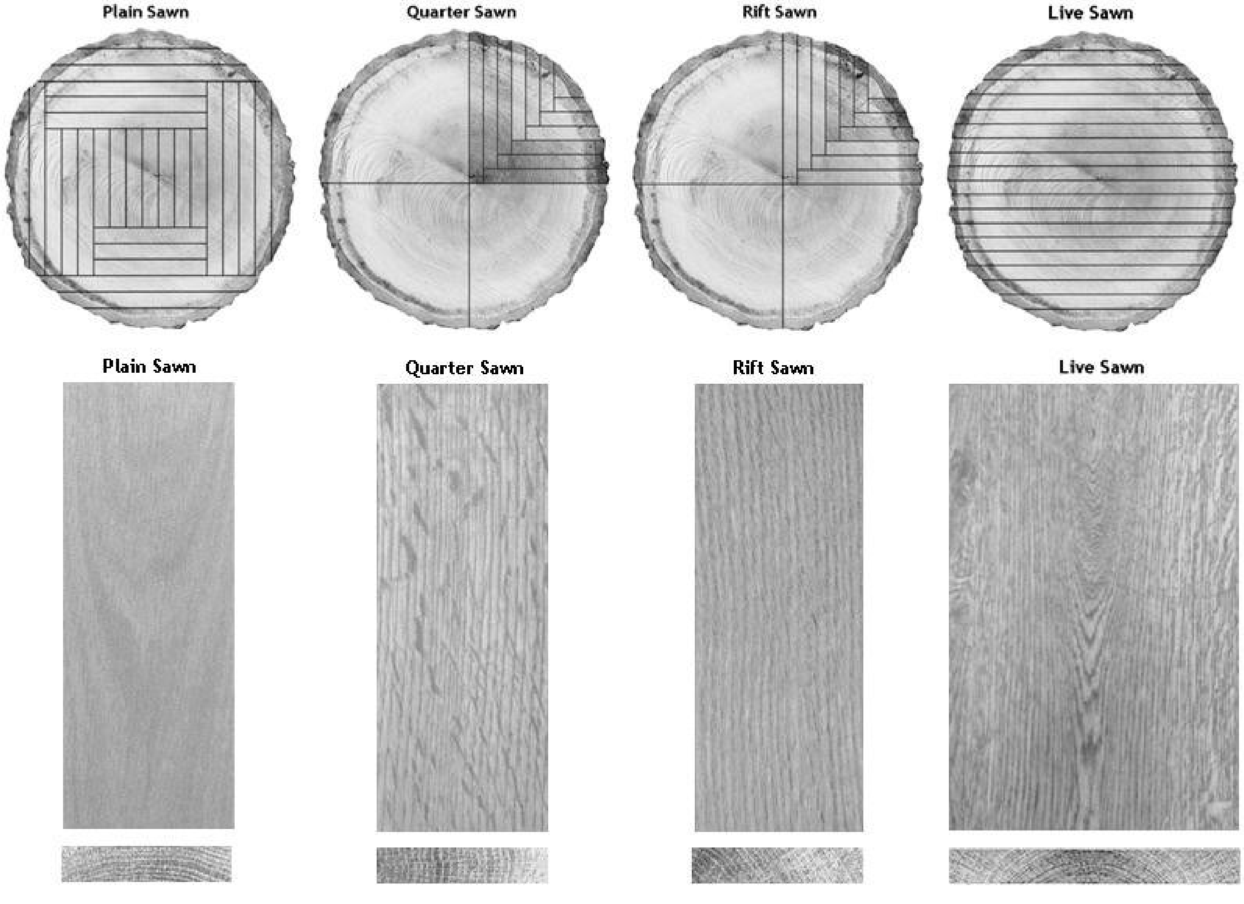


Figure 12. Sawing techniques and resulting appearance of board surfaces and ends (Source - http://alleghenymountainhardwoodflooring.com/).

Quarter Saw:

Quarter sawn has the growth rings of the tree approximately perpendicular to the board's surface (Bowyer *et al.* 2003). Quarter sawn wood has the straightest grain, and is used for our premium floors to add a sleek, streamlined look to any room. This style of cutting is considered to be to most ideal style of cut for strength although its grain feature is attractive in that it has the organized vertical lines along the boards length although many find the cathedral grain pattern of flat sawn lumber is attractive to many (Ross 2010). Some species, when quarter sawn, reveal hidden beauties such as the wide rays of oak and the beautiful ray fleck produced on the quarter cut surface (Hoadley 2000). These boards are sought after among wood workers and increase the overall value of the end product. Quarter sawn boards are also much easier to match the grain during a lamination process than that of the flat sawn boards (Petersons 2005). Some drawbacks to choosing a quarter-sawn pattern is that the recovery is decreased as the waste is increased (Bowyer *et al.* 2003). Quarter sawn boards are very stable and very strong, and are therefore ideal for use in load-bearing applications (Petersons 2005).

Rift Saw:

Rift Sawing is specified when a uniform straight grain appearance is desired. The annual rings of a Rift sawn board will lie at an angle of 30-70 degrees, optimally 45 degrees, to the face of the board (Ross 2010). The grain, which is produced from this cutting pattern, is explained by Hoadley (2000) as:

> *“Rift Grain: the surface or Figure produced by a longitudinal plane of cut which is approximately 45 degrees to both rays and growth rings. The term is used especially for white oak with its large rays”*.

The rift cut produces narrow boards with accentuated vertical or "straight" grain patterns. The technique of rift sawing is very similar to that of the quarter-sawn pattern. While rift sawing, the quartered log section must be turned slightly off perpendicular prior to cutting as to not expose the medullary rays. This is to minimize the amount of “flake” on the face of the board (Hood Distribution 2011). Rift sawing lumber produces a virtually straight grain appearance on the face of the board with little to no visible “flake”. The rift sawing technique also produces more waste and yields narrower boards when compared to flat sawn lumber (Hood Distribution 2011).

Rift sawn boards are stable boards produced from a log during sawing, quarter cut boards are among the strongest and stable cut from a cant, while flat sawn boards are the weakest. Rift sawn boards are also among the most wasteful boards to produce, as much of the log is wasted in order to attain the specific pattern. Large triangles of waste produced from the sawing of the rift pattern may be turned into another useful product, through processing and ingenuity (Northern Hardwoods 2010).

2.8.1 Maximizing value from lumber

One of the main objectives to any sawmill operation or portable sawmill operation is some sort of economic gain. With the increased price and scarceness of raw materials, if the price of the lumber being sawn does not increase, sawmilling would not be a profitable industry. It has been found that lumber volume recovery can be accurately attained by using the DBH of a tree and applying a second-order polynomial equation (Zhang and Tong 2005). Three possible ways to increase the value of a product being sawn are: 1) make the product more valuable, 2) reduce the cost of the raw materials, or 3) reduce the cost of processing. A simple equation named “the PROFIT equation” may be used to determine the amount of economic gain one is to expect from sawing lumber (Constantino 1988).

PROFIT = [Product value when sold] - [Raw material cost] - [Processing cost]

In today’s industry it is common for the price of the raw material to be as high as three times that of the processing cost (Wengert 2012). If a mill/sawyer could achieve more end product out of the sawn raw product the value will expectedly increase. Wengert (2012) states:

> *“This increased importance of raw material costs results in a new emphasis in the mill on quality and on waste reduction. No longer are production rates or production costs the keys for mill profitability, yield is the key. This shift means that sawmills’ using narrow-kerf blades are becoming more the favoured technology for high-profit sawing operations”.*

Recognizing attributes such as Spalting, curly wood grain, ray flecks and other grain or wood features during the sawing process is important to adding value to your product. Knowing how to market your product is also an important way to increase the value of any end product. Specific wood traits are sought after by many wood woodworkers and are of great value to them so recognizing this when sawing will result in added value of the product.

2.9 Mechanical Properties Testing

The definition of the mechanical properties of wood given by Panshin & de Zeeuw (1980) is as follows,

“The mechanical properties of wood are an expression of its behaviour under applied forces”

Two of the most common reported values regarding wood strength properties are modulus of elasticity (MOE) and modulus of rupture (MOR) the values are attained from static bending tests. MOE is a measure of the test specimens’ rigidity, or its resistance to bending, while MOR is a measure of the test specimens absolute strength / load carrying capacity. As stated by many the MOE and MOR values are determined through static bending tests in the form of three-point flexure (Wangaard 1981, Zobel 1984, Kellogg 1989, Rowell 2005). Three point flexure testing consists of applying a load to the middle of a specimen which is held / supported at both ends. During the application of the load, the computer software tracks the force applied, creating a visual record of the process flexure (Wangaard 1981, Zobel 1984, Kellogg 1989, Rowell 2005). The strain present in a test specimen during testing is proportional to the stress applied by testing, when the strain is small. Dimensional wood has the ability to revert back to its original shape if the stress, which is applied is light and of short duration. Every test specimen will exhibit various stages during testing. When looking at the visual representation of three-point flexure testing one can see that, initially, a straight line is produced extending on a horizontal acute angle. This straight-line portion of the curve for load and deformation is illustrates the elastic behaviour of wood. The angle of the “elastic behaviour line” is a measure of the magnitude of the elastic modulus. The greater the angles present in the curve for load and deformation, the greater the modulus (Panshin & de Zeeuw 1980, Bowyer *et al.* 2003). For all test specimens subject to stress, the curve for load and deformation reaches a proportional limit. The proportional limit is the point at which the test specimen can no longer recover completely to its original form once the stress is removed, at this time often, a permanent set occurs in the wood. Beyond the proportional limit, plastic deformations of the test specimens occur. Plastic deformations increase as accumulative stress is applied until the test specimen breaks of fails on some style. Figure 13 is an idealized load deformation diagram for static bending to failure. MOE is determined by the “straight-line’ portion of the curve for load and deformation, and calculated using the following equation, (Panshin & de Zeeuw, 1980, Bowyer *et al.* 2003)

$$\textbf{M.O.E.} = \frac{PL^{3}}{48\ ((b*h^{3})/12*D}$$

Where:

P = Maximum Load
L = Distance between supports (m)
b = Width of the specimen (m)
h = Depth of the specimen (m)
D = Deflection at mid-span (m) resulting from "P"

MOR is calculated from the maximum load data reported by the testing equipment software for three point flexure loading the following equation is how we can derive MOR

$$\textbf{M.O.R.} = \frac{1.5\ PL}{bh^{2}}$$

Where:

P = Maximum Load
L = Distance between supports (m)
b = Width of the specimen (m)
h = Depth of the specimen (m)

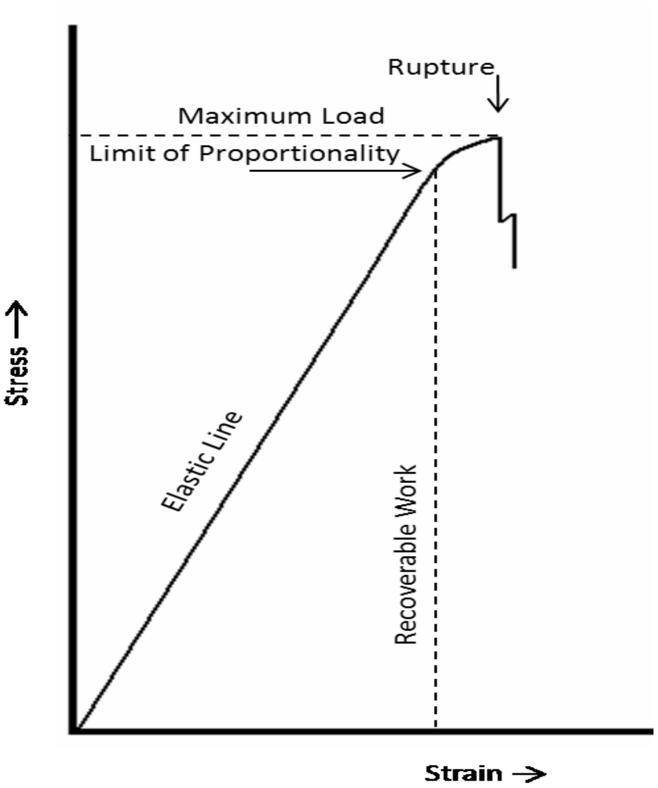


Figure 13. Idealized load deformation diagram for static bending to failure (Source – Panshin and de Zeeuw 1980).

According to the USDA's wood handbook (2010) elastic properties encompass 12 constants, nine of which are independent, which are needed to describe the elastic behaviour of wood. Three of these constants are moduli of elasticity, three moduli of rigidity, and six Poisson's ratios. The moduli of elasticity and Poisson's ratios are related by expressions of the form,

$$\frac{\mu_{ij}}{E_i} = \frac{\mu_{ji}}{E_j} \quad ,i \neq j,\ I,j = L,R,T$$

Where L = the longitudinal axis, R = the radial axis and T = the tangential axis.

The Poisson's ratio defined by the wood handbook (Ross 2010) as being, *"When a member is loaded axially, the deformation perpendicular to the direction of the load is proportional to the deformation parallel to the direction of the load. The ratio of the transverse to axial strain is called Poisson's ratio."*

2.10 Wood Density

Wood density is an integrated measure of different aspects of the wood itself and is usually reported as specific gravity (Bowyer *et al.* 2003). Specific gravity is measured as being the weight of a volume in wood relative to the same volume of water (Panshin and de Zeeuw 1980, Jozsa and Middleton 1994, Hoadley 2000). Volume measurements are commonly attained using the volume displacement method. The volume displacement method involves immersing a dry weighed sample of wood into a beaker of water that is placed on a balance, and the value displayed as weight in grams is the cm^3 volume of the sample (Bowyer *et al.* 2003). A simple grams/cm^3 is then calculated, which can easily be converted to kg/m^3. Relative density is one of the most important measures of wood quality (Bowyer *et al.* 2003). The importance of specific gravity stems from its use as an indicator of the products final end use. Cell wall thickness, lumen diameter, proportion of cell types, and latewood percentage among many other variables when measured together create wood density (Panshin and de Zeeuw 1980). Wood density varies tremendously within a single tree, between trees of the same species, between species and among a stand of trees (Panshin and de Zeeuw 1980). For most materials density is defined as the mass per unit volume at the same specific conditions, wood density is usually measured at the oven-dried moisture content or weight (Bowyer *et al.* 2003). Table five presents a list of the densities one can expect to encounter when dealing with certain species (Wangaard 1979, Grabner *et al.* 2005). As can be seen yellow birch displays a relatively high density for Canadian woods at 670kg/m^3 (Forest Products Laboratory 1999).

Table 5. Tree Densities of various species (Source - Conceptual Reference Database for Building Envelope 2009).

Wood	Density (kg/m^3)	Density (lbs/ft^3)
Ash,black	540	33.7
Ash,white	670	41.8
Aspen	420	26.2
Balsa	170	10.6
Bamboo	300-400	18.7
Birch, white	571	35.6
Birch, yellow	670	41.8
Cedar,red	380	23.7
Cypress	510	31.8
DouglasFir	530	33.1
Ebony	960-1120	59.9
Larch	590	36.8
Lignum Vitae	1280-1370	79.9
Mahogany(Honduras)	545	34
Maple, sugar	755	47.1
Maple, red	624-753	39-47
Oak	590-930	36.8
Pine(Parana)	560	34.9
Pine(Canadian)	350-560	22-35
Pine(Red)	370-660	23.1
Redwood(American)	450	> 28.1
Redwood(European)	510	31.8
Spruce(Canadian)	450	28.1
Spruce(Sitka)	450	28.1
Sycamore	590	36.8
Teak	630-720	39.3

Density and Strength:

Wood is highly anisotropic, therefore it is highly variable in its strength properties (Zobel and van Buijtenen 1989, Forest Products Laboratory 1999, Bowyer and Smith 2000, Hoadley 2000). Each stem will have different strength properties in both its longitudinal and radial directions. The existence of a linear relationship between wood density and strength, has been demonstrated by several investigators (Wangaard 1979, Panshin and de Zeeuw 1980, Grabner *et al.* 2005). A similar relationship exists among specific gravity and wood strength properties (Grabner *et al.* 2005). Density has not been reported to be an accurate indicator of cell wall stiffness (Wangaard 1979).

Moisture & Specific Gravity

As stated earlier, relative density for wood products is reported at the oven dry moisture content (Panshin and de Zeeuw 1980). Wood moisture may vary greatly when in service, from high moisture content (i.e. >20% MC) to low moisture content (i.e. <10% MC). Moisture content has a great effect on the relative density of a wood product. As moisture increases from the oven dry condition to the fiber saturation point, the weight increases and as a result of the swelling so does the volume (Wangaard 1979). These factors counteract each other during a measurement of density and water weight must be included. One major factor to consider when measuring wood, when it has a moisture content above the fiber saturation point, is that the fibers do not swell past this point, therefore an increase in water would contribute to weight and relative density without an increase in volume (Wangaard 1979).

2.11 Fiber Analysis

Fiber analysis has long been an integral part of quality control in the pulp and paper industry. There are many methods for determining fiber characteristics, Image analysis, fiber length, densitometry, UV microscopy, molecular beam, mass spectroscopy, confocal microscopy, near infrared spectroscopy, high resolution computed tomography, atomic-force microscopy and nano-indentation (Wimmer, 1997). The physical dimensions of the fiber are among the most important factors in pulping and other industries (Han *et al.* 1999). The size of tracheids in conifers has been a subject of investigation for nearly 80 years. Foresters have been interested in wood cell dimensions because of the real or assumed correlation between this and the strength properties of wood and paper (Spurr and Hyvärinen 1954). Many companies such as Integrated Paper services Inc. (IPS) have been working with fiber analysis. IPS has created an optic fiber-analysis system that provides size and shape data on fibers in dilute pulp suspensions (Wimmer 1997). Optic analysis of fibers requires the wood to be macerated into a pulp and the fibers suspended in solution so they can be optically measured. Attributes such as fiber length, width, curl, and coarseness can be measured (Wimmer 1997). Through optic fiber analysis of more than 60 pulp samples, Watson and Bradley (2003) found that Canadian pulps exhibit clear superiority to that of other countries pulp stock. The system employed for the purposes of this thesis was the HiRes FQA, FP Innovations (2009) states that:

> *"The Hi Resolution Fiber Quality Analyzer (HiRes FQA), developed jointly by Paprican, the University of British Columbia and OpTest Equipment Inc., is a commercial instrument that rapidly, accurately, and automatically determines length, shape (curl and kink),*

shive content, vessel elements, and average coarseness. The HiRes FQA can measure fiber width simultaneously with all other parameters with great accuracy and precision, on fibers up to 10 mm long. Fiber width information and fiber coarseness measurements provide valuable fiber morphology data."

Table 6. Fiber characteristics of various hardwood species in North America (Source - USDA, Forest Products Laboratory, 2010).

Species	Specific Gravity	Fiber Length (mm)	Pulp Fiber Coarseness (mg/100 m)	Fibers / Gram (10^{5})
Red alder	0.38	1.25	12.38	81.6
Aspen	0.391	1.05	8.59	118.9
Sweetgum	0.454	1.65	24.6	24.2
American elm	0.5	1.35	9.53	108.3
Blackgum	0.507	1.85	25.4	22.35
Yellow birch	0.55	1.5	11.4	40
Paper birch	0.531	1.51	13.08	76.12
American beech	0.579	1.16	13.1	75.96
Shagbark hickory	0.582	1.29	10.59	97.5
Sugar maple	0.588	0.85	7.86	127.9
White oak	0.627	1.25	14.08	68.91

2.12 Gap in literature

To create high quality veneer and lumber yellow birch crop trees through elite forest management is necessary to maximize the value on private and crown lands in northeastern and central Ontario. Determining the affect density management and thinning regimes has on yellow birch tree form, wood quality and end merchantability has currently been under reported. Destructive testing of 15 pole sized yellow birch trees from the Algoma forest unit in Ontario will provide detailed information regarding strength qualities, stem characteristics, tree form and morphological response to varying degrees of stand density management. It is anticipated that this information will provide insight into how to maximize the return on investment of a tract of land and furthermore be woven into the guidelines for managing high quality tolerant northern hardwood species. This information can be used by private and crown timber managers alike to further promote superiority in northern tolerant hardwoods, specifically, yellow birch. Currently the effects of thinning yellow birch stands, furthermore diffuse porous hardwood stands in Northeastern Ontario and their association with mechanical properties have been underreported. The reported trends in diffuse porous hardwoods are conflicting, one can find literature to support virtually any point of view (Zobel and van Buijtenen 1989). This has been previously reported by Wangaard 1981, Zobel and van Buijtenen 1989 and Zhang 1995, as it was found that no discernable correlation between growth rate and relative density has been found in diffuse porous hardwood species, while other investigators such as Kellison (1967), Mutibaric (1967), Bhat and Bhat (1983) and Keiding et al (1986) have found there is either a negative correlation between growth rate and specific gravity or a positive correlation for diffuse porous hardwoods.

2.13 Detailed Site Description

Currently in Thessalon Ontario research concerning the response of thinning on yellow birch is taking place as part of a silvicultural step forward towards the management of yellow birch for greater economic value, specifically its veneer and lumber qualities. In Northern and central Ontario there are few opportunities to profit from extremely valuable hardwood species, there simply is not the acceptable growing stock to sustain an industry specializing in hardwood veneer and lumber (Clausen and Godman 1967, Eardmann *et al.* 1980).

In 1960 a research plot near Axe Lake, located in the Sault Ste. Marie (Algoma) district was harvested of its standing timber, only veteran yellow birch “seed trees” were left standing on the site. The site was then mechanically site prepped with a D9 bulldozer, windrows were created to promote the regeneration of the target species, yellow birch. The site was left to regenerate until 1987, when it was treated with various thinning regimes. On this research site, two versions of the same thinning trial were going to be applied. One version would be thinned to a desired percentage of the tree’s height only once, while the second version will be thinned twice. The thinning treatments consist of releasing “plus trees” to 10%, 20%, 30% and 40% of their total height at the time of treatment. Figure 14 shows the block divided into nine different sections to accommodate for the different treatments and one control site.

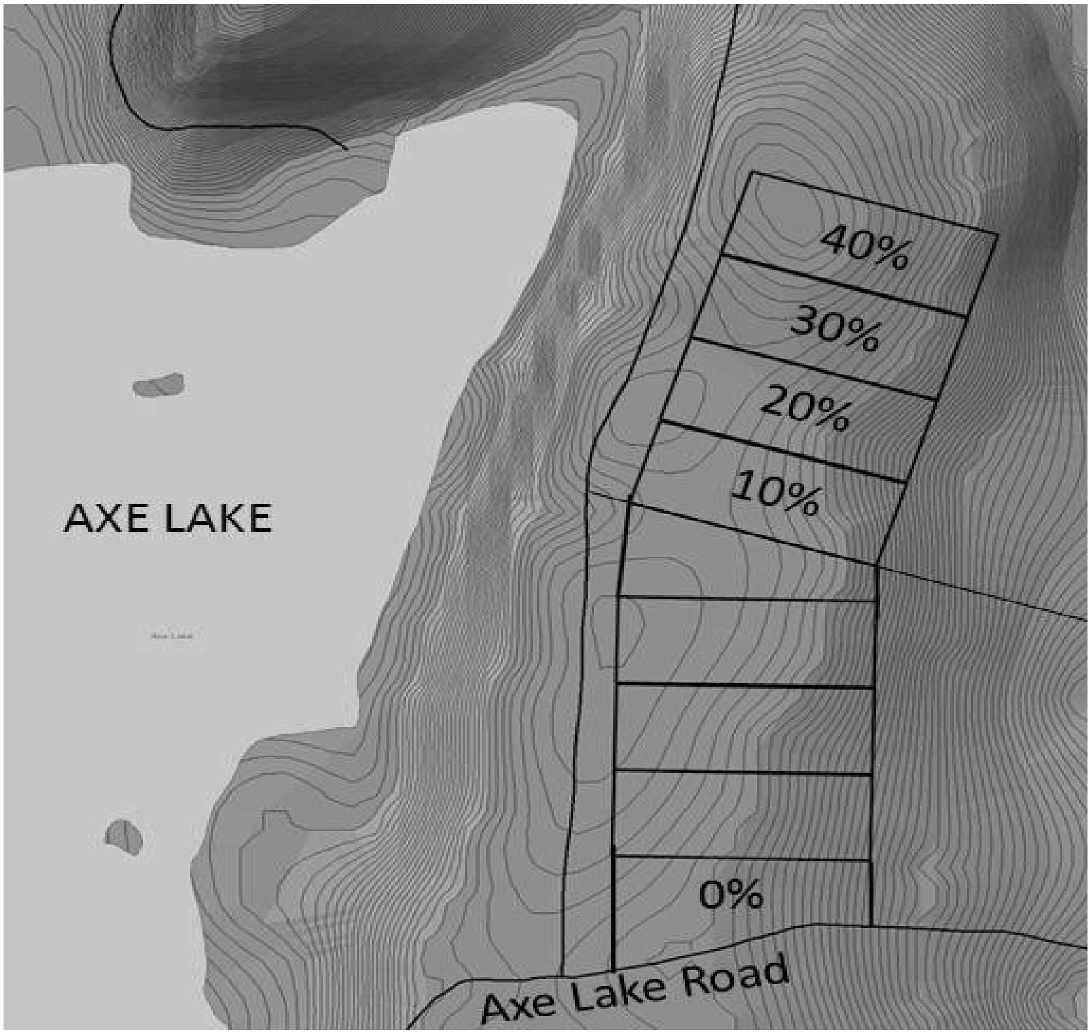


Figure 1. Research Area Block Design (Source: LUWSTF, 2014)

The ecosite information surrounding the Axe lake research forest described by the Field Guide to Forest Ecosystems of Central Ontario (1997) is as follows, **ES29.1** – General Description: ***Sugar Maple – Yellow Birch dry to moderately fresh***. Sugar maple – yellow birch dominated stands on dry to fresh to moderately fresh soils. Understory with moderate levels of hardwood and conifer regeneration and tall hardwood shrubs. Ground hemlock is often a component of the shrub layer. Found on this site are a moderate number of herbs. The soils are sandy to coarse loamy, with high coarse fragments, usually on upper slopes or level sites. An analysis of the soil sampled in July 1993 is presented in Table seven.

Table 7. Soil analysis of research area conducted in 1993. Source - von Althen. *Et al.,* 1994

Horizon	Sample Depth (cm)	pH	Sand (%)	Silt (%)	Clay (%)	N (%)	P (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)
LFH	3	4.5	-	-	-	0.635	17.61	190.88	1068.4	102.68
Ah	15	4.9	64	36	0	0.285	7.54	89.97	134.66	13.81
Bhf	40	5	70.5	22.5	7	0.083	10.46	62.78	46.37	4.59
C1	56	5.2	72.5	19.5	8	0.024	21.79	61.6	38.75	4.72
C2	60	5.3	65.5	30.5	4	0.017	24.93	60.48	34.19	4.09

Originally the forest research area consisted of mature sugar maple and yellow birch with a minor component of red oak and white elm. The initial cutting of this stand occurred from 1938 – 1939, and a second cut in 1961 – 1963 both times the stand was high-graded. In the winter of 1965 – 1966, alternate strips were cut roughly 20m wide in a North to South orientation and leave strips were partially harvested to ensure there was an adequate seed source for regeneration. After clear-cutting the 20m strips the site was then mechanically site prepped with a D9 bulldozer to mix the soil horizons and further promote the regeneration of the target species, yellow birch. After 20 years the clear-cut strips were densely populated with roughly 8800 stems per hectare (SPH) of mainly yellow birch, sugar maple, and a light component of red oak, pin cherry, trembling aspen, iron wood and white elm. The site was left to regenerate until 1987, when it was treated with various release / thinning regimes. Table eight summarizes the species composition and relative abundance. On this research site, two versions of the same release / thinning trial were going to be applied. Table nine summarizes the mean number and stump diameter of the competing trees cut around the individual yellow birch crop trees. One version would be thinned to a desired percentage of the stands overall mean height only once, while the second version will be thinned twice. Figure 14 represents the treatments where test specimens were collected from. The thinning treatments consist of releasing "plus trees" to a certain percentage of the stands overall mean height, the percentages are: 10%, 20%, and 30%, which will be represented in both versions of the thinning trial along with a 40% of total height thinning, which will only be represented in the "thinned-once" version. Figure 15 below depicts the block design, which the sample trees for this study were harvested from. Elevation changes can be clearly seen across the treatments. Since at the time of thinning the mean height of the crop trees was 10m, the thinning, which took place were one, two, three, and 4 meters. Furthermore there is one control plot (0%) where no thinning has occurred. The block was divided into eight different sections to accommodate the different treatments and one control site.

Table 8 species composition and relative abundance on research site. (Source - von Althen *et al*. 1994).

Treatment	Sugar Maple no.	Yellow Birch no.	Other spp. No.	total no.
Control	2158	6120	177	8455
10%	1344	6756	71	8171
20%	1381	6407	71	7859
30%	1770	6160	177	8107
40%	1440	6426	248	8114

Table 9. Mean number and stump diameter of the competing trees cut around the individual yellow birch crop trees (Source - von Althen. *Et al.* 1994).

	Sugar Maple		Yellow Birch		Other spp.			
Treatment	no.	Diameter (cm)	no.	Diameter (cm)	no.	Diameter (cm)	Total no.	Mean diameter (cm)
Control	-	-	-	-	-	-	-	-
10%	0.50	3.70	3.10	4.10	0.00	0.00	3.60	4.00
20%	1.50	4.80	7.40	4.20	0.10	3.30	9.00	4.30
30%	5.00	4.70	17.40	4.60	0.50	6.00	22.90	4.70
40%	5.20	4.10	23.40	4.10	0.70	6.20	29.30	4.10

3.0 Methodology

3.1 Experimental Design

Wood properties in varying radial and axial positions were measured and recorded for 15 pole sized yellow birch trees grown in the Algoma district from the Axe Lake Research Forest. Axial positions reflect the total merchantable height divided by four, extending for 1 m each. Radial positions reflect the juvenile core (pre-treatment) and mature wood (response to treatment). Sampling from the research area will consisted of harvesting three trees from each thinning treatment (thinned once) and three trees from the control. The trees were run through various analyses to detect any morphological changes, which occurred in the trees due to the various thinning treatments. The analyses, which were completed on the 15 trees are as follows: MOE / MOR, Janka Ball hardness, ring analysis, fiber analysis, vessel element analysis, taper analysis and relative density analysis. The experimental design is presented in Figure 15.

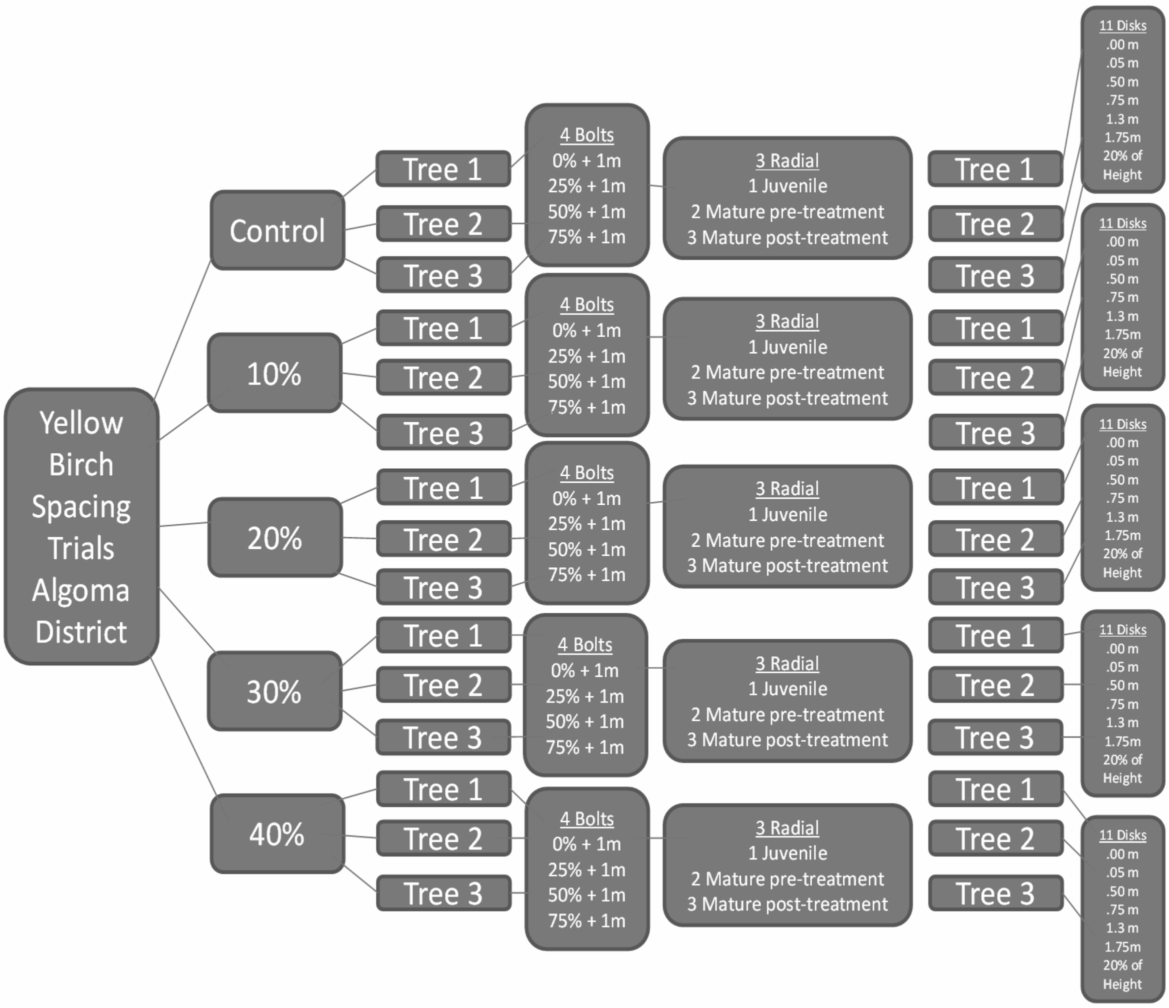


Figure 15. Experimental Design for 15 yellow birch trees growing in the Axe Lake Research Forest.

3.2 Field Procedures

3.2.1 Site Location

The site composed of pole sized yellow birch trees is located in the Gould Township in the District of Algoma (Figure 16), approximately 30 km north of the town of Thessalon, Ontario across from Axe lake (Lot eight, Concession four, Lot seven, Concession four, Lot eight, Concession three, Lot seven, Concession three) (Lat. 46°30'N, Long. 83Q25'W).

Figure 16. Axe Lake yellow birch research forest (Source: google earth, 2013).

3.2.2 Sample tree selection and collection

Three pole sized trees from each treatment (thinned once) and three pole-sized trees from the control were selected for destructive sampling based on a number of criteria to ensure quality, quantity and reliability of sample data. Co-dominant crop trees were examined from the ground for external defects, crown deformities, scars and disease, which could potentially affect sample quality. The selected trees had to meet the criteria of the thinning as well. Trees meeting the above criteria were felled (diameter and height recorded), bucked into the 1m sections (0%, 25%, 50%, 75% of total height from base) and labeled accordingly (tree, thinning treatment, bolt height, North Direction), returned to the LUWSTF and processed for mechanical and physical property testing. The measurements and characteristics were recorded for each tree as per the American Society for Testing and Materials (ASTM) Standard Practice for Sampling Forest Trees for Determination of Clear Wood Properties (ASTM D5536-94, 2010) along with the Ontario Forest Growth and Yield Program Field Manual for Establishing and Measuring Permanent Sample Plots (Hayden *et al.* 1995). The location of the sample bolts was dictated by the total merchantable height of the stem according to the 2013 Scaling Manual for yellow birch, which is measured to a 14-centimeter log diameter top. Figure 17 depicts the process in which the selected trees underwent prior to sample preparation, Figure 18 is a visual representation of the bolt sampling methodology.

Figure 17. Field collection crew (Tyler Power) felling trees and processing specimens. 1.) Assessing standing crop tree (North direction on tree as red vertical line), 2.) Felling crop tree, 3.) Labelling crop tree in field, 4.) Labeled disks / cookies, 5.) Bolts and disks / cookies in field, 6.) Sample extraction via Quad Runner and wagon provided by Mr. Keith Hobak and LUWSTF.

The total length of the merchantable pole was divided into four, 1-meter sections were extracted representing 0, 25, 50 and 75% of total height to a 14cm stem diameter (Figure 19). The bolts were carefully labelled in the field and returned to the LUWSTF for analysis. The location of the sample disks was based on the total height of the tree. As seen in Figure 16 the disks represent 0.0, 0.05, 0.5, 0.75, 1.3, 1.75 meters, and the remaining height of the tree in 20% height increments. The disks were carefully labelled in the field and returned to the LUWSTF for processing and analysis.

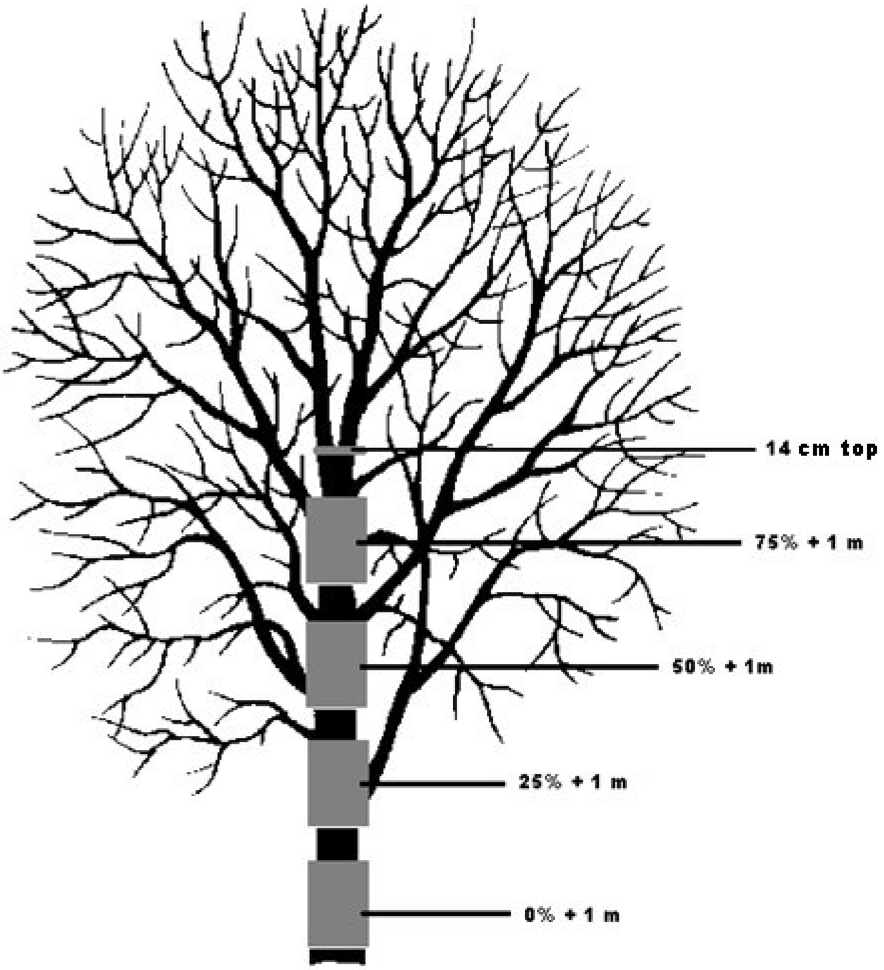


Figure 18. Bolt sampling methodology employed for yellow birch thinning study.

3.3 Laboratory Procedures

3.3.1 Processing Mechanical testing specimens

The collected sample bolts were processed to meet the requirements specific to LUWSTF's variation of the secondary method of clear wood testing (ASTM D5536-94, 2010). The sample bolts were first processed into 3 cm thick slabs in a North to South orientation using a Woodmizer LT-40 portable hydraulic band sawmill as seen in Figure 19. The slabs were then visually analysed for defects, 50 cm sections of clear wood were extracted from the meter long slabs. The samples were then stacked with stickers and dried to =<30% Moisture Content as determined using a GE Protimeter Timbermaster moisture meter in a temperature controlled room.

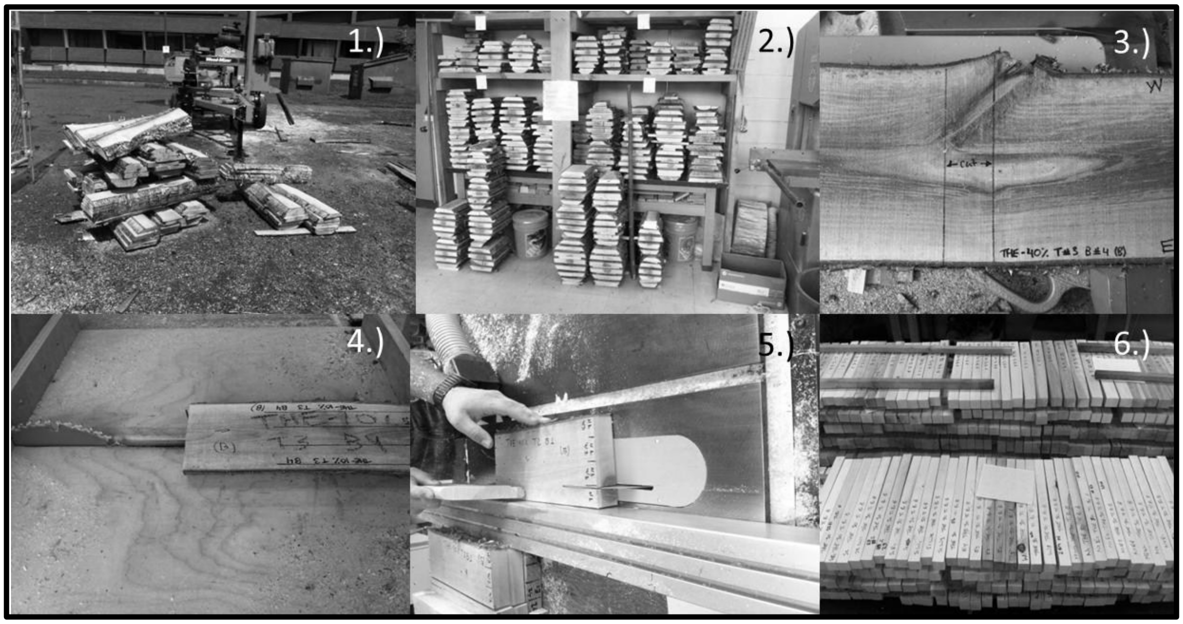


Figure 19. Mechanical and Physical Properties Specimen Preparation. 1.) Coarse refinement of bolts on Woodmizer-LT-40. 2.) Samples reducing in moisture content. 3.) Extraction of defects. 4.) Cutting slab in half on LUWSTF jig. 5.) Extracting radial positions from slabs. 6.) Stacked MOE / MOR samples in LUWSTF.

Figure 20 shows LUWSTF's variation of the ASTM secondary method of clear wood testing that was applied to the stacked slabs following milling (see Figure 20.2and.5).

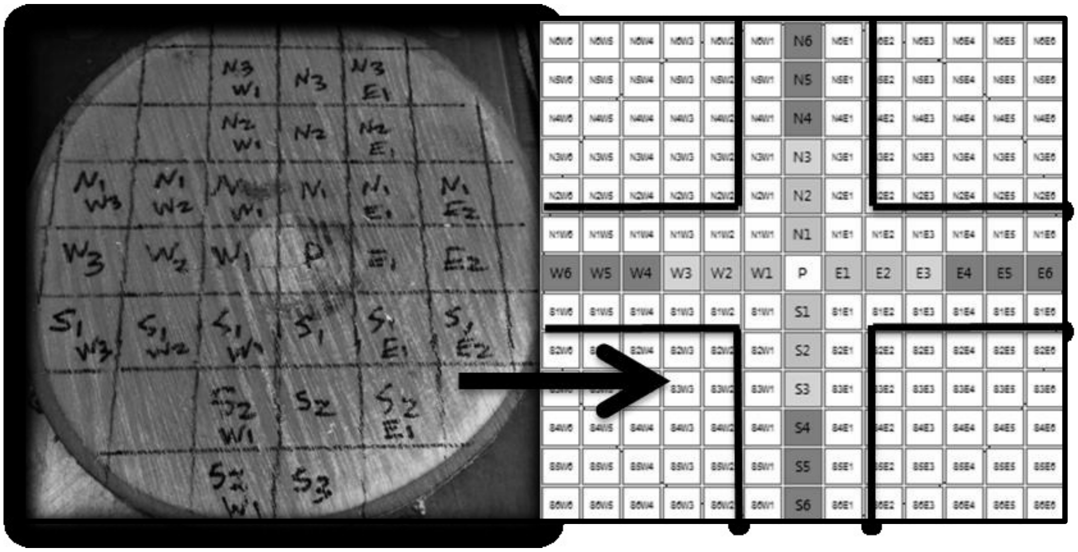


Figure 20. LUWSTF modified test procedure.

3.3.2 Processing MOE /MOR Specimens

Figure 20 depicts the processes, which took place in order to achieve the finial dimensions of the test specimens. Once the samples were at the appropriate moisture content the slabs were further divided into 30 cm and 30 cm samples for MOE / MOR, and side hardness tests, respectively. Relative density analysis would come from the MOE / MOR samples following MOE tests. Figure 22 depicts the process in which the information regarding relative density was gained. The MOE / MOR samples were then sawn from the slabs into 2.5 x 2.5 cm clear wood test samples, all samples were then further dried to 15% moisture content in the Thermo-scientific Environmental Conditioning Chamber set at 65% RH and 20°C to achieve a final MC% of 12% (see Figure 20.6). When the samples reached 15% MC they were processed into 20 mm x 20 mm x

300 mm MOR / MOR test samples and placed back into in the Thermo-scientific Environmental Conditioning Chamber. The test samples were left in the conditioning chamber until the desired 12% moisture content was achieved in the test specimens. Once the samples were at 12% moisture content they were ready for destructive testing on a Tinius Olsen Universal Wood Testing Machine. During the sample refining process any test specimens with excessive sweep or defects were culled out to avoid the analysis of defective samples to satisfy ASTM standard D-143-09.

3.3.3 Processing of side Hardness samples

The processing of the hardness specimens began at the same time as the MOE and MOR specimens. The bolts processed on the Woodmizer LT-40 to create the 3 cm thick slabs are the same samples to be used for hardness testing. All labels applied to the slabs at that point were carried over to the hardness samples identifying the North direction as well as the radial position as described in Figure 20 to maintain continuity. Figure 21 depicts the process of side hardness sample processing after the slabs have been cut on the portable sawmill. The slabs were then visually analysed for defects, 30 cm sections of clear wood were extracted from the meter long slabs. The samples were then stacked with stickers and dried to =<30% Moisture Content as determined using a GE Protimeter Timbermaster moisture meter in a temperature controlled room. Figure 21.1 depicts processing the 30 cm slabs into a manageable and appropriate size for side hardness tests according to ASTM standard D143 – 09 (Standard test methods for small clear specimens of timber). After the specimens were of an appropriate size, they were placed in the Thermo-scientific Environmental Conditioning Chamber to reduce the moisture content down to 12% and to wait for testing on the Tinius Olsen Universal Wood Testing Machine.

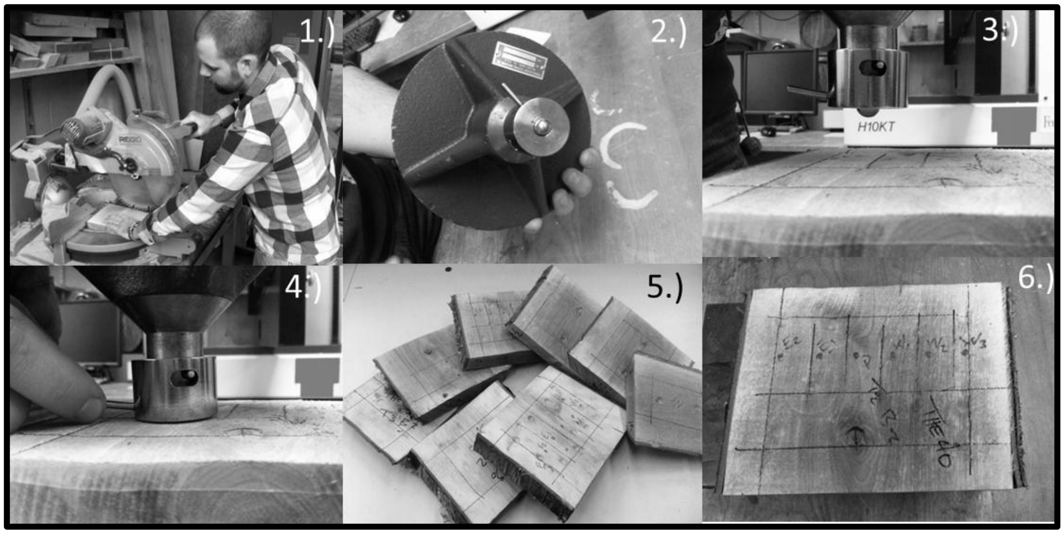


Figure 21. Processing of side yellow birch hardness samples: 1.) working 33 cm slabs down to manageable size, 2.) Janka ball testing tool, 3.) Side hardness testing in progress, 4.) Side hardness test reaching end result, 5.) Bolt # 1 of tree # 2 , 10% thinning, hardness competed, 6.) Visual representation of used hardness specimen.

3.4 Processing physical specimens

3.4.1 Taper and Fiber analysis specimen preparation

Taper disks had to be measured at green or live moisture content, measurements were taken soon after the tree was felled, in the field, in order to reduce the effect of shrinkage due to drying. Eleven taper disks were extracted from the merchantable bole length of the tree (D-00 to D-10), the first five taper disks came from the bottom section of the tree up to 1.75 m, as this is the area with the most exaggerated taper, the remainder of the merchantable bole was broken into 20% increments until the 11th disk was obtained. Disks “04” and “08” were further processed at the LUWSTF for fiber and vessel element analysis on the FQA fiber analyser, representing the diameter at breast height and base of live crown respectively. The first step in preparing the samples for the high-Res fiber quality analyzer was working the samples down to a manageable size for maceration to take place. This was completed by gathering samples from the original taper disks and can be seen in Figure 22. A 2 cm wide section extending through the pith in a North to South orientation was extracted (Figure 22.2). These samples were individually cut into 5-year increments using a microtone blade and a cutting block (Figure 22.3). The samples were then placed into test tubes with the appropriate corresponding labels (Figure 23.4). The samples were macerated in a solution of 1:1 acetic acid and hydrogen peroxide (30%) with the maceration taking place over 48 hours at 75° Celsius in a TR- 125 Reactor by “Orbeco, Hellinge” following ISO standard 7213 (1981). After 24 hours of maceration, mixing the samples was required and achieved using a Vortex agitator.

Figure 22.2 F.Q.A. Sample Preparation. 1.) Extracting 2 cm “swath” extending through the pith from bark to bark on band saw, 2.) “Cookie” processed into fiber specimen, 3.) Microtone and mallet processing station, 4.) Test tubes and processing station for FQA.

The samples were fully macerated after 48 hours. The samples were then collectively stored in a fridge awaiting analysis. Prior to analysis the samples had to be mixed one final time to ensure the fibers were suspended in solution. The samples were then taken out of the fridge three hours prior to testing to allow them to reach room temperature, when testing could begin. Running the samples through the High-Res fiber quality analyzer was done according to ISO standard 16065-1 (1981). The results, which are reported during F.Q.A. testing are:

Percent fines
Mean Length
Mean Curl Index
Mean Kink Index
Mean Width
Average Vessel Area
Mean Vessel Effective Length
Mean Vessel Effective Width
Vessels per m
Vessels per g
Coarseness (mg/m)

For the FQA to work properly air quality regulation must be followed, and a clean dust free environment is required. Each radial position was tested three times for all of the microscopic attributes.

3.4.2 Relative Density Specimen Preparation and analysis

Relative Density samples were gathered from the used MOE / MOR test specimens at 12% moisture content. A block roughly 3cm long by 2 cm high and 2 cm wide was used as a “tracing template” to ensure the size of the samples extracted was relatively similar. Once the outline was traced on the used MOE / MOR test specimens, as near to the break as possible, it was extracted using a band saw in the LUWSTF wood working shop and labelled. The samples were then analysed and measurements were recorded. The relative density measurements were attained in accordance with Method B - Volume by Water Immersion methodology found in the ASTM Standard Test Methods for Specific Gravity of Wood and Wood-Based Materials (D 2395 – 07a) (2007). The relative density measurements, reported, were taken at 12% moisture (air dry) and oven dry moisture content. Figure 23 depicts the process of attaining the density measurements.

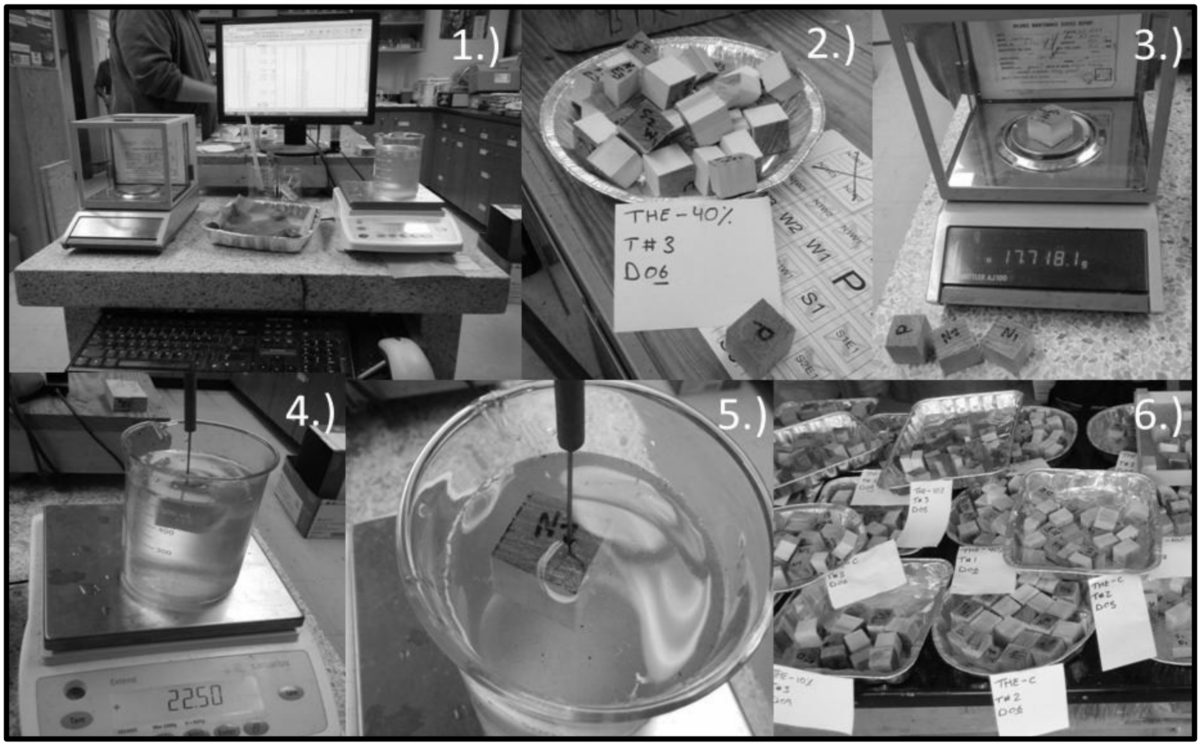


Figure 23. Relative Density measurements being acquired. 1.) Relative density station, 2.) Samples cut for relative density measurements, 3.) Mass measurements being attained, 4.) Volume measurements being attained, 5.) Relative density sample immersed in 4 degree H_20, 6.) Relative density samples after completion.

3.4.3 Ring Width Specimen Preparation and analysis

Ring width analysis was performed on disks 00, 04 and 08, which represent the axial positions point of germination, diameter at breast height and base of live crown, respectively. Figure 24 depicts sections of the disks being cut using a jig created by LUWSTF for X-Ray densitometry analysis. The jig effectively removes a 2 mm thick x 25.4 mm high section, pith to bark, which can be placed into a carriage for analysis on the X-Ray densitometer by "Quinteck Measuring System Inc" (QMS) Model number QTRS – 01X.The process described above for ring width analysis and preparation can be seen in Figure 24. The section, which is removed from the parent material is 2 mm thick and the length is determined by the radius of the disk being processed.

Figure 24. Ring width analysis sample preparation and analysis. 1.) "Swath" extracted from Disk – 00 for scanning, 2.) Sample being ran through LUWST X-Ray "jig", 3.) Measuring thickness of sample prior to scanning, 4.) Ring width analysis specimen on scanner.

3.5 Mechanical and Physical Testing

Tinius Olsen H10KT and H50KT Universal Wood Testing Machines, with Test Navigator Software (year), were used to determine mechanical properties, including:

MOE - reported in mega pascals (MPa) utilizing the three point flexure test procedure with a maximum span of 24 centimetres,

MOR - reported in MPa, based on the maximum load (Newtons) reported during MOE testing,

Side hardness - reported in Newtons (N) using the Janka Ball tool.

The MOE, MOR and Side hardness tests were performed according to ASTM Standard Test Methods for Small Clear Specimens of Timber (D143 – 09) (2009) . The Microscopic attributes were macerated and measured in accordance with ISO standard 7213 (1981). All microscopic attributes were analysed on the fiber quality analyser (FQA) model number LDA02 by “Op Test Equipment Inc”. The direct moisture content measurement measurements were completed according to the standard test methods for direct moisture content measurement of wood and wood-based materials (D4442 – 07) (2007). Relative density measurements were attained in accordance with Method B - Volume by Water Immersion methodology found in the ASTM Standard Test Methods for Specific Gravity of Wood and Wood-Based Materials (D 2395 – 07a) (2007). The relative density measurements were taken at 12% moisture (air dry) and oven dry moisture content. Ring width analysis was completed by placing specimen on a scanner for image analysis via “Windendro”. All data was compiled and sorted using Microsoft

Excel, and the LUWSTF app while processing as completed using “R” version 3.0.2. - 2014 – Statistical software.

4.0 Statistical Analysis

The objective of this study was to determine whether or not varying degrees of density management had an effect on the internal properties of the yellow birch growing on site and if the potential wood utilization would increase as a consequence of thinning treatments applied.

The null hypotheses states that:

H_1 – Potential wood utilization increases with an increasing intensity of crop tree release in yellow birch stands of the Algoma District in Ontario.

And:

H_2 - Morphological changes in yellow birch are due to site effect accompanied by crop tree release intensity.

To effectively address the objectives set out by this study and test the null hypotheses, analysis of variance (ANOVA) tests were performed on the selected test properties with a general linear model at 99% confidence using “R” statistical software. The linear model which was used and associated expected mean squares table is as follows;

$$Y_{ijkl} = \mu + B_i + A_j + BA_{ij} + \varepsilon_{(ij)k}$$

Where:

$Y_{ijkl}=$	Measured response
μ +	Overall mean
B_i +	Fixed effect of the treatment blocks
A_j +	Fixed effect of the axial positions
BA_{ij} +	Mixed effect of the treatment block factor with the axial position factor
$\varepsilon_{(ij)k}$	Random effect of the i^{th} treatment block from the j^{th} axial position

Pooling rules were applied where necessary. One of the first steps in conducting conventional statistical analysis is to ensure the data is normally distributed and homogenous. To discern weather or not the data was normally distributed homogenous, the “Shapiro-Wilk’s” test of normality was completed along with a “Bartletts” test of normality.

5.0 Results and Discussion

To satisfy two of the major assumptions of statistical analysis, normality and homogeneity of the data must be proven, presented below are the relative density results for the “Bartlets” test for Homogeneity of Variances along with the “Shapiro – Wilk” test of normality results (Figure 25). All selected test properties exhibited similar results of normality and homogeneity. The results from the tests are as follows, Shapiro-Wilk normality test W = 0.9954, p-value = 0.2339 and Bartlett's K-squared = 0.0638, df = 1, p-value = 0.8006 (Figure 26).

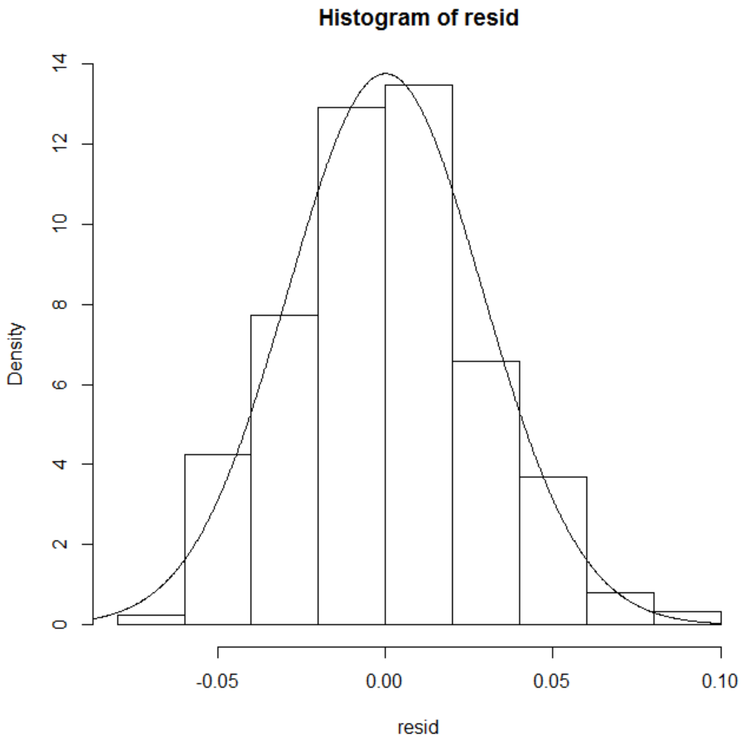


Figure 25. Shapiro-Wilk normality test W = 0.9954, p-value = 0.2339.

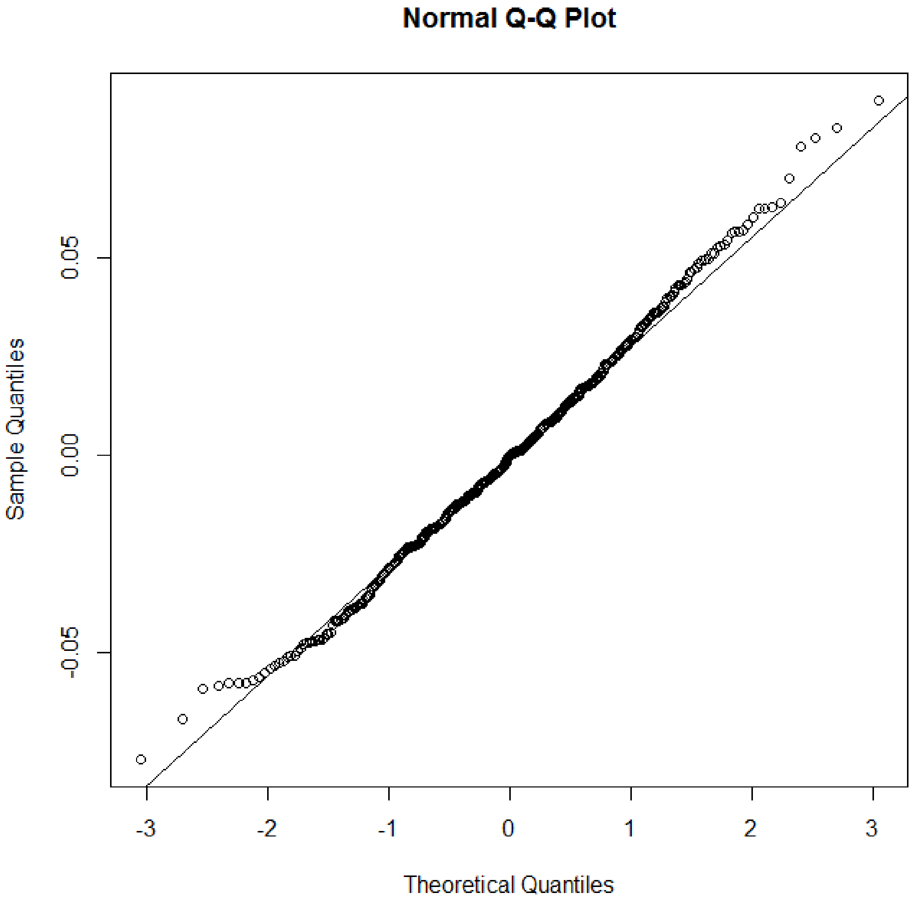


Figure 26. Bartlett's K-squared = 0.0638, df = 1, p-value = 0.8006.

5.1 Stratification

Upon analysing previous works conducted on the research site, an error in the original plot design became evident and was noted by Von Althen *et al.* (1994):

> *“No randomization of treatments was attempted because the cutting was carried out by a crew inexperienced in hardwood thinning, although not suitable for conventional statistical analysis the 30 crop trees evaluated in each treatment block provide a suitable database with which to demonstrate treatment effects”*.

Viewing the 68 ha block on an elevation map, variances in elevation were made obvious (Refer to Figure 13). Elevation changes will affect the rooting depth, drainage and moisture of the microsite contained in ecosites ES29.1, therefore altering the physical and mechanical properties of the growing stock on the individual microsites. To discern weather or not there is a site affect occurring over the 68 ha block, select properties were measured which represented pre-treatment conditions (Germination – Time of Treatment). The select test properties which were measured to discern site effect were microscopic attributes, hardness, MOE / MOR and relative density. The pre-treatment results shown in Figure 27 represent the Janka Ball hardness test results, values for the remaining tests can be found in the appendix, it shows that homogenous growth and properties are not found across the entire treatment area, therefore, the selected wood properties are controlled by varying microsite conditions and the same trend was seen in all select test properties. The trees occurring in the control treatment and the 20% treatment are statistically different from each other and the remaining 10%, 30% and 40% thinning treatments (see Figure 27). Statistic similarity in the pre-treatment scenario is needed across all blocks to ensure we are comparing the same sites (apples with apples and oranges with oranges) and that the mechanical and physical properties are a consequence of the thinning treatment applied and not a reflection of the microsite condition which the block's may occur on within ES 29.1 and the research area.

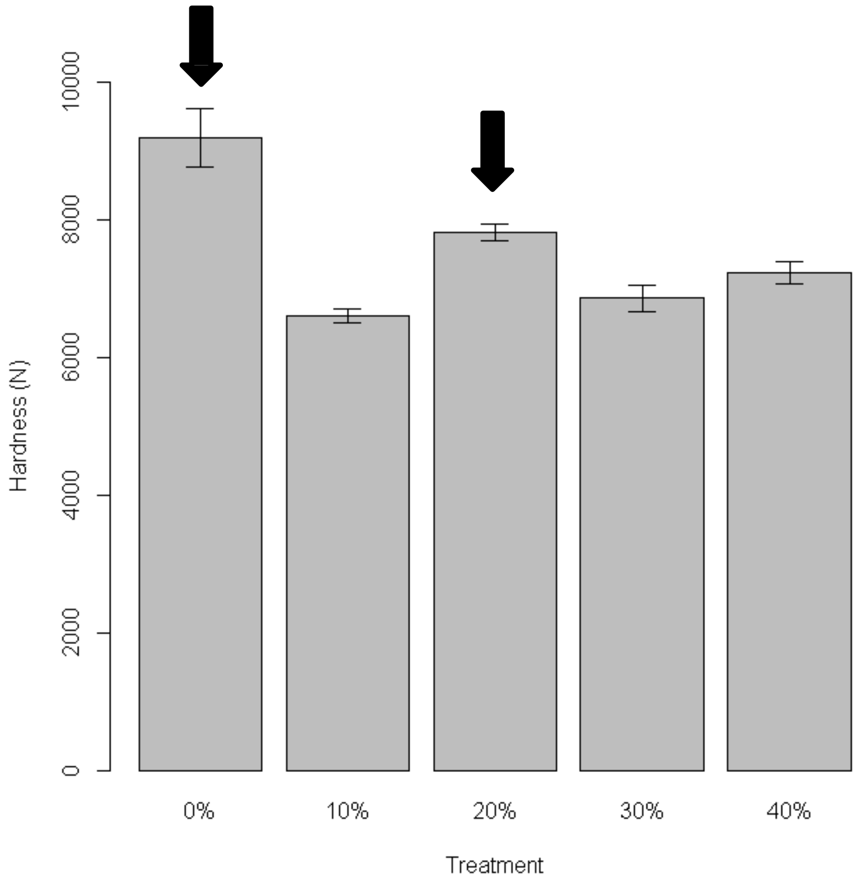


Figure 27. Significant difference in hardness values between sites prior to pooling out control, pre-treatment values, Thessalon yellow birch thinning trials.

Analysis with all of the treatment sites without the control site was then completed. The results show that once the control site was pooled out the 20% treatment is still significantly different from the remaining 10%, 30% and 40% thinning blocks (See Figure 28). Twenty percent trees seem to be growing on a more favourable microsite within ES 29.1, which is enhancing the mechanical properties. Incorporating 20% would therefore skew the results towards 20% being the optimal thinning for increased mechanical properties (as a consequence of thinning) as this site already has the upper hand in mechanical properties (prior to treatment). Therefore three standalone microsites are present on the 68 ha block, the first being the control site, second being the area containing the 20% thinning treatment, and lastly the area containing the 10%, 30% and 40% thinning treatments. For a visual explanation of this the Janka Ball hardness results shown in Figure 28 clearly show that there are significant differences in treatment blocks pre-treatment, after the control has been pooled out, which was consistent for all of the selected test properties (see Appendix 1). To compare the effect the thinning treatment had on the trees pooling rules were applied, the control block and the 20% block were pooled out. The control block and 20% thinning treatment blocks are occurring on microsites, which enhance the mechanical properties to the point where they cannot be used for comparing the remaining treatments to. As this research is to discern the "Release / Thinning Response" of yellow birch and not "Site Response" of yellow birch, if the pre-treatment results showed that the 20% thinning fell into the same homogeneous subset as the 10%, 30% and 40% they would be included in the results. The same explanation holds true for the control site, it is also growing on a micro site which even further enhances the mechanical properties, superseding that of the 20% in the pre-treatment scenario, also following through to the post treatment scenario. The mechanical and ring width and microscopic attribute analysis results will be reported only on the 10%, 30% and 40% treatment sites as they are the only sites suitable for ordinary statistical analysis for this research, while the taper analysis and volume will encompass the control, 10%, 20%, 30% and 40% thinning treatments (all sites).

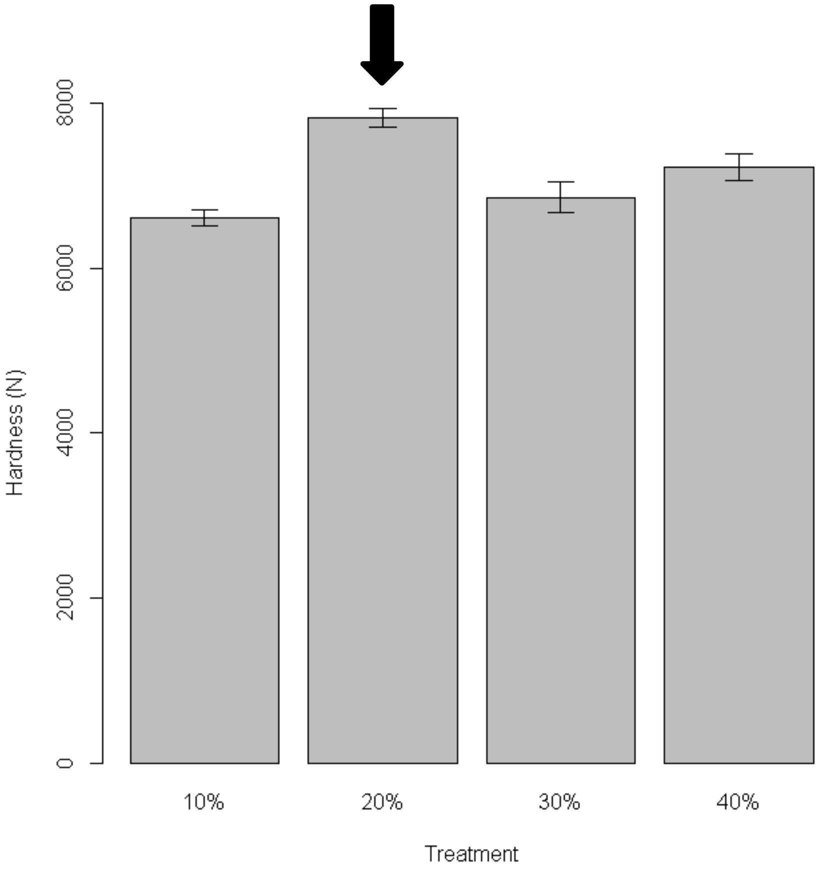


Figure 28. Significant difference in hardness values between sites after using pooling rules on control block, pre-treatment values Thessalon yellow birch thinning trial.

5.2 Validating Findings and Grand means

Upon comparing the results to the published values, from Wangaard (1979), Isenberg (1981), Hoadley (1990), Forest Products Laboratory (1999), and Jessome (2005), clear discrepancies can be seen. The following tables (Tables 10-12) represent the grand means of the select test properties and their percent (%) deviance or change from the published literature by Jessome (2005). Modulus of Elasticity (MOE) and Modulus of Rupture (MOR) values, were both 15% lower than the published values (Table 10). The Janka Ball side hardness values attained from the test specimens were on average 24% higher than published values (Table 10). Relative density values were within +/-10% of the published values (Table 11). The average ring width values across all treatments analysed were found to be 80% higher than the published values (Table 11). The fiber attributes can be seen in table 12, it can be seen that all of the treatments fall well below the published values by the forest products laboratory (2010) and Isenberg (1980). The fiber length values are on average 25% below the published values, the fiber width measurements are 44% lower than what is expected to be seen for yellow birch, and the vessel width values are on average 30% lower than what is expected to be seen.

Table 10. Table of mechanical property means and (%) change from published values. Source – Jessome 2005*

				Deviation From Published (Mechanical)		
	Hardness (N)	MOE (MPa)	MOR (MPa)	Hardness (N) (% Change)	MOE (Mpa) (% Change)	MOR (Mpa) (% Change)
Published *	5930*	14100*	106*	-	-	-
Average for Treatment	7326	11980	90	24%	-15%	-15%
10% Thinning	7233	12398	92	22%	-12%	-13%
30% Thinning	7281	12236	92	23%	-13%	-13%
40% Thinning	7449	11525	86	26%	-18%	-19%
Pre-Treat	7878	10853	84	33%	-23%	-21%
Post-Treat	6797	12022	90	15%	-15%	-15%

Table 11. Table of physical property means and (%) change from published. Source – Jessome 2005*

			Deviation From Published	
	Relative Density 12% (Kg/m^3)	Ring Width (mm)	Relative Density 12% (Kg/m^3) (%Change)	Ring Width (mm) (%Change)
Published *	608*	1.4*	-	-
Average for Treatment	583	2.54	-4%	81%
10% Thinning	573	2.1	-6%	50%
30% Thinning	589	2.8	-3%	100%
40% Thinning	586	2.73	-4%	95%
Pre-Treatment	576	2.23	-5%	59%
Post-Treatment	588	2.7	-3%	93%

Table 12. Microscopic fiber attrbutes and %change from published values. Source – Forest products laboratory 2010*, Isenberg 1980**

				Deviation From Published		
	Fiber Length (mm)	Fiber Width (um)	Vessel Width (um)	Fiber Length (%change)	Fiber Width (%change)	Vessel Width (%change)
Published *	1.5*	36*	160**	-	-	-
Average for Treatment	1.115407	20.19852	111.1461	-26%	-44%	-31%
10% Thinning	1.107	20.22	109.4	-26%	-44%	-32%
30% Thinning	1.129	20.28	111.9	-25%	-44%	-30%
40% Thinning	1.11	20.1	113.2	-26%	-44%	-29%
Pre-Treatment	1.015	20	108	-32%	-44%	-33%
Post-Treatment	1.166	20.3	113	-22%	-44%	-29%

5.3 Modulus of Elasticity - MOE

The MOE results are reported in megapascals (MPa), the results for the treatments for 10%, 30% and 40% are 12398, 12236 and 11525 MPa, respectively. The highest values are found in the 10% thinning treatment followed by the 30% thinning treatment and finally the 40% thinning treatment (Refer to table 10). The published value by Jessome (2005) for MOE related to yellow birch is 14100 MPa leaving all of the treatments below the expected values. The 10%, 30% and 40% thinning treatments are lower by 12%, 13% and 18%, respectively. Since the physical properties are highly correlated with the mechanical properties of a tree we would expect to see a similar trend following the relative density values (Panshin and de Zeeuw 1980, Zhang 1995 and 1997, Evans and Elic 2001, Yang and Evans 2003). Although it has been found that the inherent properties associated with different species groups either cause a stronger relationship between interacting factors or a weaker relationship. An example of this was found by Zhang (1997) as it was reported that:

> *"Among three mechanical properties studied, MOR is most closely and almost linearly related to specific gravity, followed by Cmax, whereas MOE is poorly and least linearly related to specific gravity. In general, the relationship between MOE and specific gravity in a species from the ring-porous category is stronger than in a species from the diffuse-porous category."*

There is no significant difference between the 30% and 10% treatments in MOE. The 40% treatment is statistically significantly different from the 10% and 30% thinning treatments, leaving two subsets. The first subset contains the 10% and 30% thinning treatments and the second subset is the 40% thinning treatment. The ANOVA results can be seen in table 13.

Table 13. ANOVA results for MOE.

MOE (Mpa)	Df	SS	MS	F	p
Treatment	2	38020541	19010271	8.303	3.22E-04
Bolt	3	97314615	32438205	14.168	1.46E-08
Tables of means					
Grand mean	11979				
Treatment	10%	30%	40%		
	12398	12236	11525		

Differences in MOE values cannot be totally attributed to the thinning regime applied due to the morphological status of the trees at the time of thinning, this is further compounded by the lack of a published correlation between growth rate of diffuse porous hardwoods and mechanical properties (Zobel and van Buijtenen 1989). The time of the thinning took place when the trees were in transition between juvenile and mature wood, similar to the microscopic physical attributes, the mechanical properties attributes are a consequence of the morphological status of the tree and its transition from juvenile wood to mature wood (Zobel and van Buijtenen 1989). Table 10 presents the values attained from pre-treatment and post treatment measurements. It shows that the values increased gradually from the pre-treatment scenario to the post-treatment scenario. The highest values ,axially, are found to be in the third bolt when we take into consideration the entire radial variation within the bolt, then decreasing values are found as one moves further up the stem of the tree. The qualities of the mechanical properties are seen to coincide with the proportion of juvenile wood present in the tested axial portions of the tree. (Wangaard 1981, Zhang 1995 Hoadley 2000). The uppermost portions tested represented a great portion of juvenile wood which accounts for the decrease in MOE (Zobel and van Buijtenen 1989). This has been previously reported by Evans et al (2000), juvenile and mature portions of red alder (*Alnus rubra.* Bong) trees were attained to discern the effect that juvenile wood has on MOE, MOR and specific gravity. It was found that MOE and MOR are good indicators of juvenile wood presence in red alder as the radial and axial profiles of all red alder trees tested exhibited a rapid increase in MOE and MOR during the early years of growth, extending from the pith to the bark. This same trend has also been seen in radiata pine and reported on by Ivkovic´ *et al.* (2009). It has been reported by Bao *et al.* (2001) that the relationship between juvenile wood and mechanical properties and mature wood and mechanical properties tends to be species dependent. Bao *et al.* (2001) also found that the relationship between tree morphology and mechanical properties is more pronounced in softwood species. Bhat *et al.* (2001) reported that the MOE and MOR values for juvenile wood of a ring-porous tropical hardwood – teak (*Tectona grandis L. F*) represented 85% and 82% respectively of the mature wood values of the same trees. Figure 29 shows that the highest values are found in the most merchantable portion of the tree (bolt two and three). Bolts two and three occur above the “swell butt” of the tree at a section in the stem which is free of severe taper but maintains size. Log taper is seen as a hindrance on recoverability during the veneer slicing / peeling process due to the loss of fiber by using reducers, also Increased processing is required for logs with a large base or a “buttress flare” so a butt reducer is commonly used on logs with high taper (Wiemann *et al*. 2004). The butt reducer grids down the buttress flare or swollen bases of a log, this process is commonly associated with debarking (Wiemann *et al*. 2004). Figure 29 below show the differences in MOE by treatment and by bolt. The 40% thinning treatment was found to be statistically different from the 10% and 30% thinning treatments as it was the thinning treatment with the lowest MOE values. Reports on softwood species are conflicting with what has been seen in this research, Duchesne *et al.* (2013) reported that that pre commercial thinning to 4 feet, 6 feet and 8 feet did not influence the MOE value of the subject balsam fir (*Abies balsamea* Mill.) on site. This has also been reported by Guller (2007), as it was found that a correlation between thinning and strength properties (MOE, MOR and compression strength parallel to the grain) was not present in heavily thinned, moderately thinned and un-thinned 33-35 year-old plantations of pinus brutia Ten. Although the MOE results for the 2013 Axe Lake study show the 40% thinning treatment is different from the 10% and 30% thinning treatments, bolts two, three and four are not statistically different across treatments.

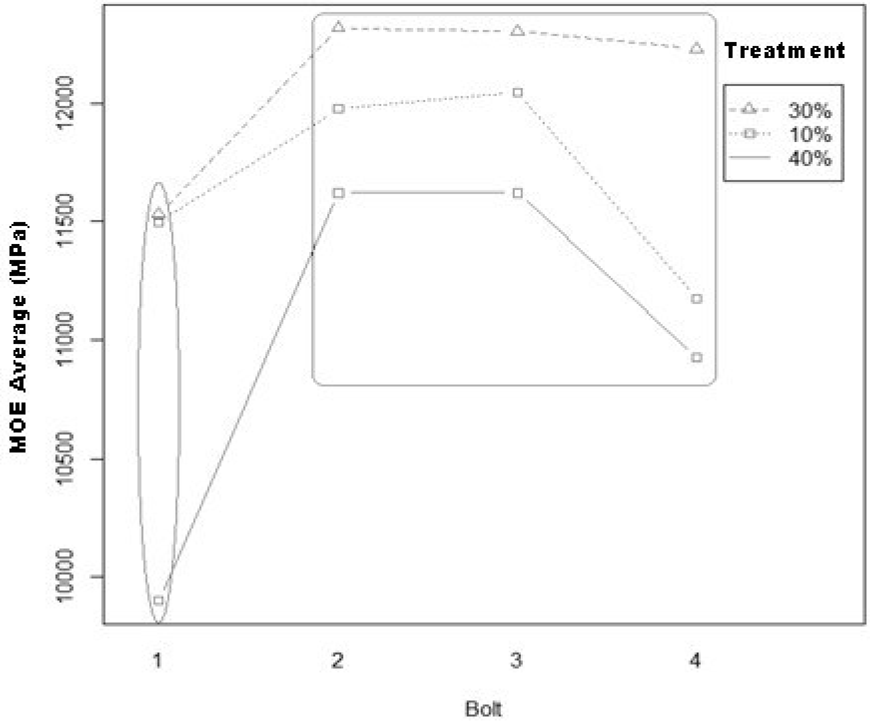


Figure 49. Axial zones of similarity for MOE, Stratified post treatment values from Thessalon yellow birch thinning trial.

The lack of a strong discernable trend in MOE between treatments as a consequence of thinning is consistent with the fact that the correlation between growth rate and relative density of diffuse porous hardwoods is highly controversial and inconsistent, as stated by Wangaard (1981). The Thinning which held the highest MOE values was seen to be the 10%, therefore the beneficial thinning treatment concerning MOE would be the 10%. Once again it should be remembered that there has not been a solid published correlation between growth rate of diffuse porous hardwoods and mechanical properties and would be erroneous to completely attribute the enhanced values found in the 10% to the thinning treatment applied in that specific area.

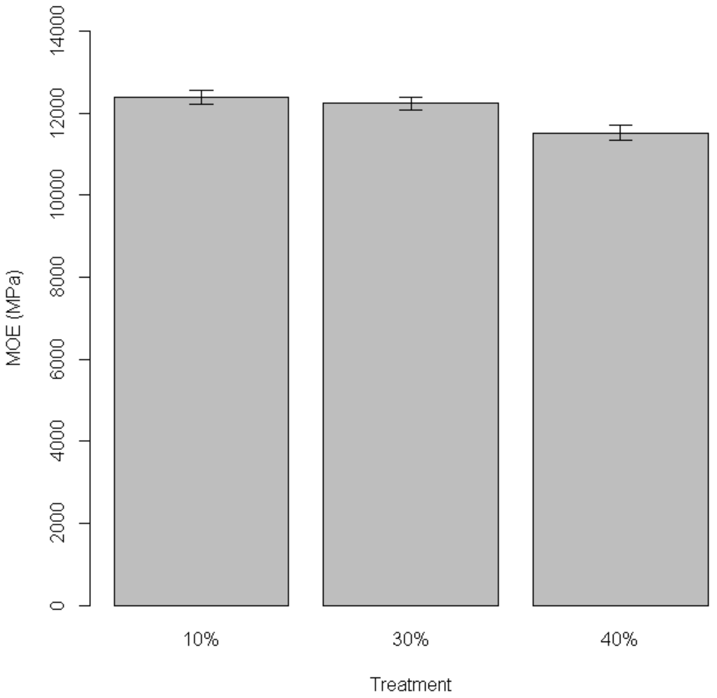


Figure 30. MOE results of stratified post treatment values from Thessalon yellow birch thinning trial.

5.4 Modulus of Rupture - MOR

The MOR results are reported in megapascals (MPa), the results for the 10%, 30% and 40% thinning treatments are 92, 92 and 86 MPa, respectively. The highest values are found in the 10% and 30% thinning treatments (refer to table 10 and Figure 31). The values attained from the 10% and 30% thinning treatments are 13% lower than the published values (Jessome 2005). The values attained from the 40% thinning treatment are 19% lower than the published values for yellow birch (Jessome 2005).

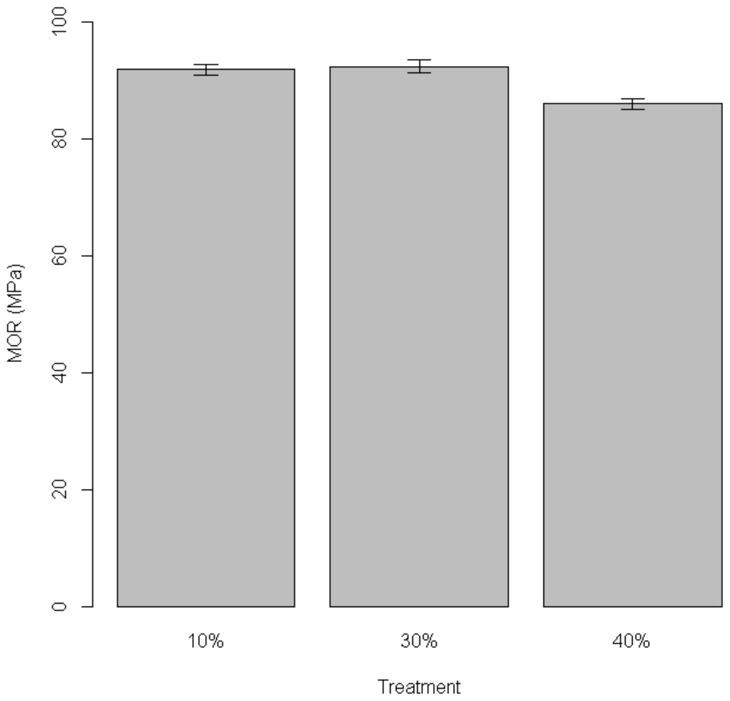


Figure 315. MOR results stratified post treatment values from Thessalon yellow birch thinning trial.

Similarly to the MOE results the MOR results cannot be completely attributed to the thinning regimes applied to the site. Similar to the MOE results, the MOR results are greatly affected by the presence of juvenile or mature wood. This has been seen before in naturally grown fir trees (*Abies cephalonica x* A. alba*, Populus hybridogenous*), as Passialis and Kiriazakos (2004) found that the MOE and MOR values attained from the tested juvenile sections of the tree were found to be lower than the MOE and MOR values attained from the mature wood sections of the same trees. The fact that the site was treated with various thinning regimes during the transition from juvenile to mature wood makes the MOR results a poor expression of the thinning treatments applied due to the morphological changes occurring in the stem at the time of treatment. The explanation for this can be found in the previous results section (MOE) . Similar results have been found in red alder reported by Evans et al (2000) and Ivkovic´ *et al.* (2009). Concerning axial variation the 10% and 40% follow a different trend than that of the 30%, this reinforces what has been published concerning the lack of a relationship for accelerated growth in diffuse porous hardwoods and their associated mechanical properties (Panshin and de Zeeuw 1980). In Figure 32 it can be seen that in the 10% and 40% treatments there is a gradual increase in MOR up to the third bolt, and then a decrease in the fourth bolt. As the mechanical properties are related to the relative density of the trees we would expect to see similar trends (Zhang 1996). Figure 32 depicts the axial variability in the MOR values attained from the three treatment blocks. The ANOVA results can be seen in table 14.

Table 14. ANOVA results for MOR.

MOR (Mpa)	Df	SS	MS	F	p
Treatment	2	2431	1215.3	14.629	9.75E-07
Bolt	3	2109	703.1	8.464	2.23E-05
Tables of means					
Grand mean	89.68605				
Treatment	10%	30%	40%		
	91.89	92.45	86.02		

The 10% and 30% thinning treatments are not statistically different from each other, while the 40% thinning treatment is statistically different from the 10% and 30% treatments, leaving two subsets. The first subset contains the 10% and 30% thinning treatments and the second subset is the 40% thinning treatment. Although the treatments are statistically different bolts two, three, and four are not different throughout treatments. The groupings on the plot below show regions of statistical similarity in the axial positions tested. Bolt one is similar across treatments and bolts two, three and four are similar across treatments. The 40% thinning treatment possesses the lowest values for MOR (see Figure 32).

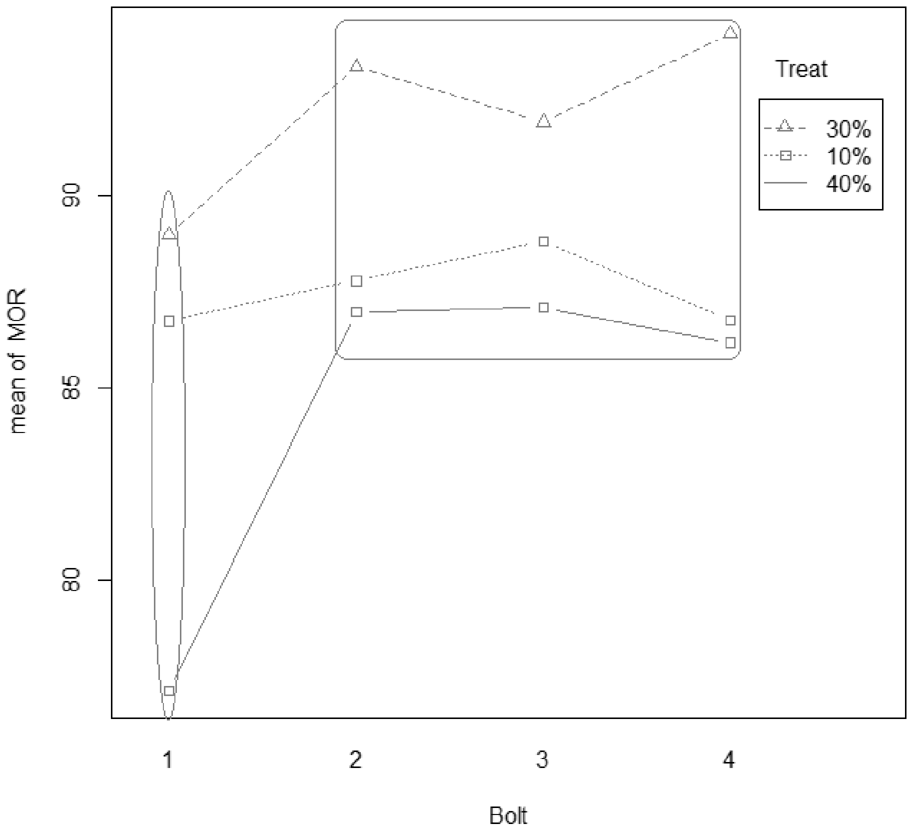


Figure 32. Axial zones of similarity in MOR post-treatment results from Thessalon yellow birch thinning trial.

5.5 Hardness

The harness results are reported in Newtons (N), the results for the treatments 10%, 30% and 40% are 7233, 7281 and 7449 N, respectively, which is an average of bolts two and three for each treatment. The values from the 10% thinning treatment are 22% higher than the published value by Jessome (2005) for yellow birch. The 30% and 40%

thinning treatments are both 23% and 26% higher than the published hardness values. The reported results are for the section of the merchantable bole, which is relatively free of taper and/or other anomalies, they do not encompass the anomalous “swell butt” of the tree or the anomalous base of live crown. The mean values for both bolt two and three across all sites is 6870 N and 7731 N, respectively. The grand mean for the entire study area is 7326.169 N. Upon visually inspecting Figure 33 it can be seen that the greatest variability for hardness is found in the 30% thinning treatment followed by the 10% treatment. The most homogenous values were found in the 40% thinning treatment.

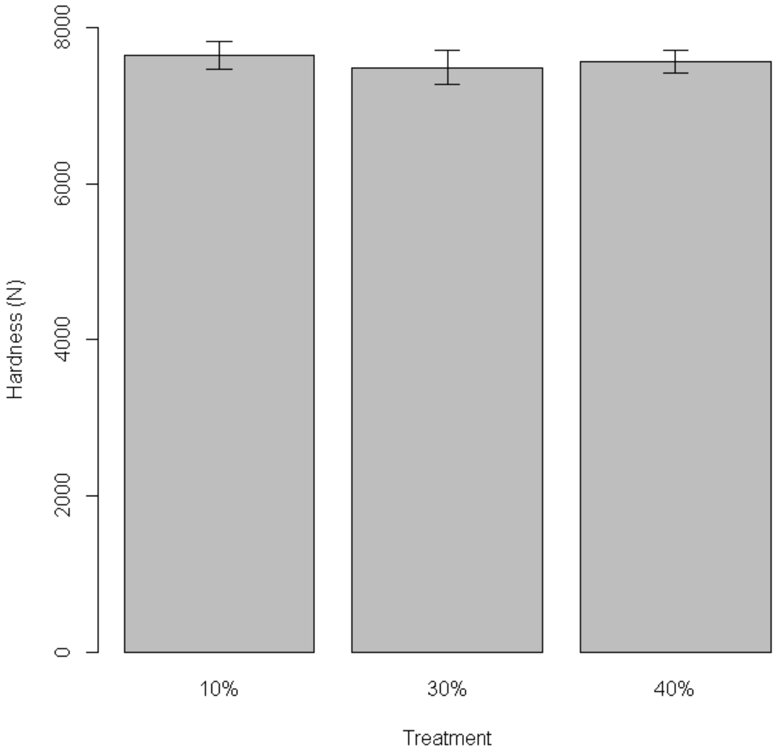


Figure 33. Janka ball hardness results stratified post-treatment values from Thessalon yellow birch thinning trial.

The effect thinning has on hardness seems to be minimal and defying any distinct pattern. As stated by Wangaard (1981), Panshin and de Zeeuw (1980) and Zobel and van Buijtenen (1989) and density is a very strong indicator of hardness, keeping this in mind it is expected that anything affecting the consistency of density will also affect the hardness values recorded. The thinning treatments are not statistically different from each other, concerning hardness, significance seems to be found axially throughout the tree in the bolts tested (Figure 34). The ANOVA results can be seen in table 15.

Table 15. ANOVA results for Janka Ball Hardness.

Hardness (N)	Df	SS	MS	F	p
Treatment	2	1167665	583832	0.813	4.46E-01
Bolt	1	25328763	25328763	35.25	2.42E-08
Tables of means					
Grand mean	7326.169				
Treatment	10%	30%	40%		
	7233	7281	7449		

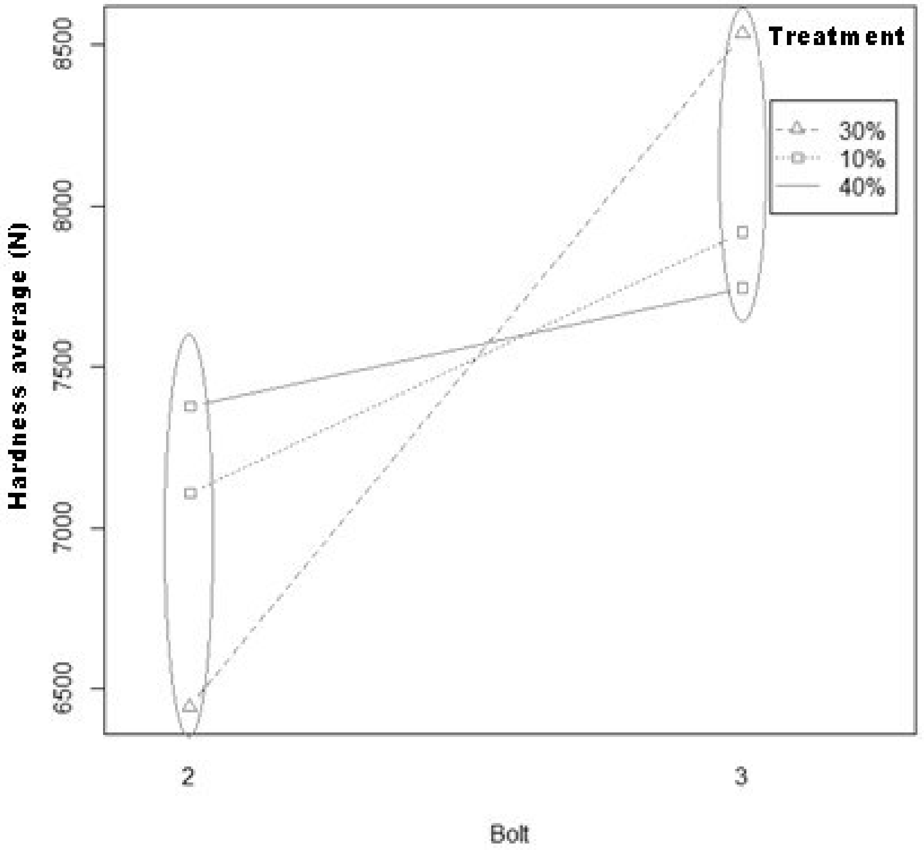


Figure 34. Significant difference between bolts and areas of axial similarity, post-treatment stratification from the Thessalon yellow birch thinning trial.

Figure 34 shows that there is a significant difference in hardness values in between the tested portions of the tree. The trend seen follows published observations for diffuse porous hardwoods of increasing relative density as one move axially up the stem of the tree, although the literature also supports contradictory findings. Hernandez *et al.* (1998) states:

> “Experiments *with trees of the genus Populus have also shown density occasionally to be higher than normal, unaffected, or lower than normal as a result of fast growth.”*

Hardness values for bolt two in Figure 34 represent the base portion of the tree. The bolt two average hardness values are not statistically different between treatments.

The bolt two average is 17 % higher than the published value by Jessome (2005), which for yellow birch is 5930 N. The bolt three depicts the upper section of the merchantable bole which was tested. The bolt three values are not statistically different between treatments. The values found in bolt three are 30% higher than the published values for yellow birch by Jessome (2005). The lack of difference in hardness between treatments is likely due to the fact that there is little correlation between growth rate and relative density of diffuse porous hardwoods (Panshin and de Zeeuw 1980,Wangaard 1981). Therefore if the growth rate is increased by releasing trees, the mechanical properties, directly affected by relative density, should not differ greatly between treatments but reflect the relative density present in the test portion of the stem. As mentioned by Desch and Dinwoodie (1981) density is strongly correlated to the mechanical property hardness and varies based on growth rate as well. In addition Desch and Dinwoodie (1981) also state that position in the tree significantly affects mechanical properties as well due to juvenile and mature wood such that strength is at a minimum near the centre of the tree and will increase outwards significantly and slightly as you move upwards as well. This supports the results of bolt three displaying increased hardness values.

5.6 Microscopic properties

The microscopic properties measured were fiber length, fiber width and vessel element width. All of the attained values for this study fall well below the published values by Isenberg (1980) and the forest products laboratory (2010). The fiber length measurements are on average 25% below the published values by the forest products laboratory (2010), across all thinning treatments. The fiber width measurements were on average 44% below the published values for yellow birch while the vessel width measurements show that all of the thinning treatments are on average 30% below the published value by Isenberg (1980) for yellow birch. There is no significant difference between treatments in microscopic properties, significance is found axially within the stems. The reason for the significance is the high percentage of juvenile wood in the uppermost tested portion of the subject trees compared to the juvenile / mature-wood ratio present in the base section tested. Similar results have been reported by Yeh *et al.* (2006), as the microscopic properties of a mature bent loblolly pine were examined. Yeh *et al.* (2006) found that the fiber properties were significantly different in the top from the bottom of the tree examined. The results for the 2013 Axe Lake yellow birch thinning trials show that there is no effect on the select tested microscopic attributes as a consequence of the thinning treatments applied on site. The ANOVA results for fiber length, fiber width and vessel width can be seen in tables 16, 17 and 18 respectively.

Table 16. ANOVA results for Fiber Length.

Fiber Length (mm)	Df	SS	MS	F	p
Treatment	2	0.0126	0.0063	0.616	5.41E-01
Bolt	1	0.3894	0.3894	38.24	7.40E-09
Tables of means					
Grand mean	1.115407				
Treatment	10%	30%	40%		
	1.107	1.129	1.11		

Table 17. ANOVA results for Fiber Width.

Fiber width (um)	Df	SS	MS	F	p
Treatment	2	0.701	0.351	4.939	8.64E-03
Bolt	1	5.152	3.026	42.642	1.55E-09
Tables of means					
Grand mean	20.19852				
Treatment	10%	30%	40%		
	20.22	20.28	20.1		

Table 18. ANOVA results for Vessel Width.

Vessel Width (um)	Df	SS	MS	F	p
Treatment	2	338	169	1.104	3.35E-01
Bolt	1	4897	4897	32.009	1.02E-07
Tables of means					
Grand mean	111.1461				
Treatment	10%	30%	40%		
	109.4	111.9	113.2		

The samples were extracted from two separate disks throughout the axial positions of the merchantable bole, D-04 (DBH) and D-08 (BLC). Each fiber sample contained five growth rings, extending from the pith to the bark in a radial profile. The radial results in Figure 35 show that the test specimens follow trends published in the literature for morphological changes occurring on a natural site (Burdon *et al.* 2004). Following germination the trees grow rapidly until eventual crown closure and are producing juvenile wood as they compete for crown position and dominance (Hoadley 2000). Between 20 – 25-years of age the trees go through morphological changes, which may last five – 10 years, where they transition into mature wood, from their previous juvenile wood stage (Wangaard 1981, Zhang 1995). This entails the fibers reaching their maximum length and diameter with minor fluctuations in subsequent years (Burdon *et al.* 2004). The thinning regimes were applied to the study site in 1987, leaving the response of fiber attributes mainly to the morphological status of the tree, as we see the trees following the same trends published by Zobel and van Buijtenen (1989) concerning the concepts and occurrence of juvenile wood. Upon analysis it was found that there was no significant difference in microscopic fiber properties across treatments (Figure 35). Concerns about growth rate and wood property relationships, studied independent of other factors that affect wood such as age, have been reported by Goggans (1961) and Erickson and Armia (1974). Goggans (1961) and Erickson and Armia (1974) noted that age plays an integral role in the formation and attributes of wood. It was seen that there was a slight delay in the transformation to mature wood as a consequence of the treatments applied, as seen in the fiber attributes. Zobel and van Buijtenen (1989) and Hoadley (2000) state that the transition zone from juvenile wood to mature wood occurs over five – 7 years and is commonly found in young stems which rapidly grow until crown closure is reached in the stand, as a consequence of the treatments applied the stands crown closure status was lost, fierce competition for crown position to the point of crown closure lengthened the transition into mature wood. Wangaard (1981), Zhang (1995), Hoadley (2000), Evans (2000) and Bao (2001) explain that the physical and chemical properties are quite variable in the juvenile core, whereas the mature wood contains more consistent properties. We can see, in Figure 35, that the fibers do not reach homogeneity in size until roughly the 6th radial position (year 35) defying what has been published, meaning that the transition phase lasted for roughly 10 - 15 years as a consequence of the treatment applied. Figure 35 presents the mean fiber length in a radial direction displaying the time lag from juvenile to mature wood.

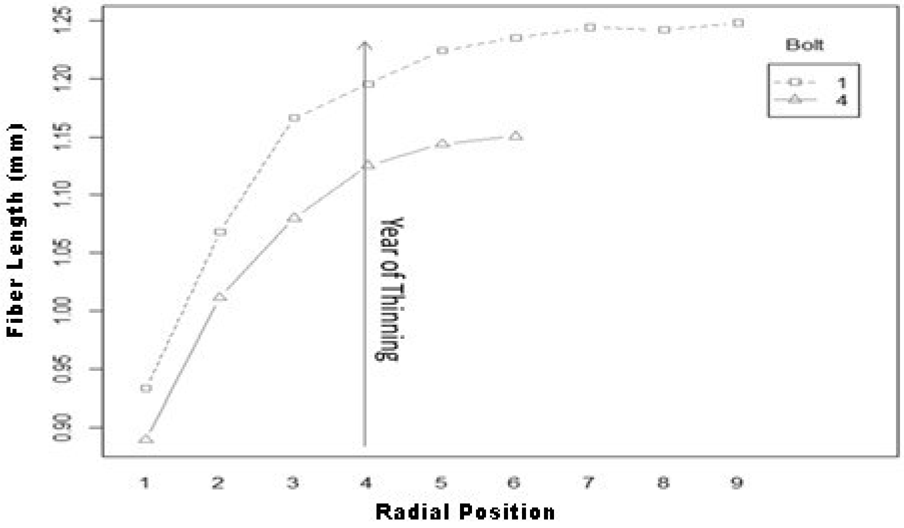


Figure 35. Bolt one and four fiber length morphological response and year of pre-treatment and post-treatment values, Thessalon yellow birch thinning trial.

No statistical significance was found between blocks, the significance found was radially within the stem and axially within the stem. The average values for fiber length are slightly below the published value of 1.5mm (Isenberg 1981), with diameter at breast height values of 1.155 mm and base of live crown values at 1.172 mm. We would expect to see the shortest fibers occurring in the thinning treatment, which allowed for the fastest growth rate, inversely it is expected that the longest fibers occur in the slowest growing trees. Results similar to this have been found in studies conducted on black cotton wood *Populus balsamifera.* (L.) by Kennedey (1957) and *Lonchocarpus sericeus. Poir.* by Morawiec *et al*. (2008). The results of these studies showed that with accelerated growth the fiber length of both species under investigation was decreased. The reasons for the shorter fibers existing explained by Bailey (1954) as the circumference of tree stems within non-storeyed elements increases by transverse anticlinal division of the cambial initials, this is followed by the readjustment and elongation of the resulting cells. Cambial initials in fast grown stems divide in a much quicker time than that of a slow grown stem, this occurs in order to keep pace with the rapid radial and circumferential expansion of the stem (Bannan 1960). Similarly growth rate and how it affects fiber length has been discussed and explained by Ridoutt and Sands (1993, 1994) and Honjo *et al.* (2006) as the rate and duration of cell expansion and secondary wall formation is influential on the overall final size of the cell wall thickness of the elements present in the xylem, furthermore the final size of the fibers is also influenced by the maturation state of various xylem elements (Ridoutt and Sands 1993 and 1994, Honjo *et al.* 2006). We did not see this trend following analysis of the yellow birch data, this reinforces what has been previously explained regarding the lack of a relationship between diffuse porous hardwood properties and growth rate (Panshin and de Zeeuw 1980, Wangaard 1981). The implications of shorter fibers are pronounced through the effect they have on the density or specific gravity of the wood, which is produced. Fiber length, specifically, is of more importance when the wood is to be pulped and made into various pulp products. As mentioned earlier, by Zobel and van Buijtenen (1989) and Jozsa and Middleton (1994) one of the most common relationships in a specimen of wood is that as the density of the wood increases the strength properties of that piece of wood increase as well, solid wood products of lower specific gravity tend to be weaker than that of solid wood products possessing higher specific gravity (Zobel *et al.* 1971, Jozsa and Middleton 1994). Fiber length and width as discussed earlier, directly affect the relative density properties of the wood produced by a tree (Panshin and de Zeeuw 1980). The implications this may have on hardwood lumber production are significant as there is a relationship between MOE/MOR and relative density (Wangaard 1981). Furthermore positive relationships between fiber length and tensile strength of solid wood products have been observed by Zobel and van Buijtenen (1989), shorter fibers produce wood with inferior strength properties when compared to the effect long fibers have on a solid wood piece. Although a significant effect or difference in MOE or MOR values across treatments was not seen in the current study. However, confounding effects of cell dimensions, taper and other growth properties will have effects that are not realized in single property measurements.

5.7 Relative Density

The density results are reported in kg/m^3, the results for the 10%, 30% and 40% treatments are 574, 589 and 586 kg/m^3, respectively. The published value for yellow birch relative density in the wood handbook, by Jessome (2005) is 608 kg/m^3. The values from the 10% treatment are 6% lower than the published value, 30% are 3% lower than the published value, while the 40% value is 4% lower than the published values. The highest values are found in the 30% thinning treatment followed by the 40% thinning and finally the 10% thinning (see Table 12). The averages for bolts one, two, three and four for all treatments are 571, 577, 591 and 600 kg/m^3, respectively. It can be seen in Figure 36 that the greatest variability for density is found in the 40% thinning treatment this is likely due to the higher presence of crown wood and juvenile wood in the upper portion of the crown and the rings closest to the pith, similar results have been reported by Zobel and van Buijtenen (1989) as it was found that juvenile wood has lower relative density values than that of normal mature wood in the same tree. The 10% thinning treatment is significantly different from the remaining 30% and 40% thinning treatments; therefore there are two homogenous subsets. The first homogenous subset of relative density measurements contains only the 10% thinning treatment, the second subset contains both the 30% and 40% thinning treatments. The ANOVA results can be seen in table 19.

Table 19. ANOVA results for Relative Density.

Relative density (Kg/m^3)	Df	SS	MS	F	p
Treatment	2	0.0189	0.009468	11.09	2.01E-05
Bolt	3	0.0559	0.018644	21.84	3.53E-13
Tables of means					
Grand mean	583.4				
Treatment	10%	30%	40%		
	574	589	586		

Although there is significance found between the treatments, no strong trend has been seen. This has been previously reported by Wangaard (1981), Hernandez *et al.* (1998) and Zhang (1994) as it was found that no discernable correlation between growth rate and relative density has been found in diffuse porous hardwood species. Following this simple premises it would be expected to not find a pattern of increasing or decreasing relative density as the subject trees undergo accelerated growth brought on by the thinning treatments applied. The most variable density measurements were found in the 40% thinning, the 10% and the 30% possess relative densities which are low in variation, meaning they do not fluctuate as much as the values found in the 40% thinning treatment and are considered to be homogenous. Further significant differences were found axially within the selected trees (in the chosen bolts). It was seen that there is an increasing density as one moves up the stem, this has been found by investigators such as Wangaard (1981). Inverse relationships have been reported by Repola (2006) as 38 Scots pine (*Pinus sylvestris* L.), 39 Norway spruce (*Picea abies* L. Karst.) and 15 birch (*Betula pendula* R. *and Betula pubescens* E.) stems were sampled to determine the effect height has on wood density. Repola (2006) found that there is a weak trend of decreasing density as one moves axially up the stem of the sampled birch species. There is much controversy, surrounding the effects tree species and growth rate has on relative density, although it is an area of widespread interest literature can be found to support any point of view for diffuse pours hardwoods. Current literature on softwood species, specifically balsam fir (*Abies balsamea.* Mill.*),* by Duchesne *et al.* (2013) states that:

> “PCT had no appreciable effect on sawn lumber wood density ($p \geq 0.26$) or lumber stiffness (MOE; ≤-6.2 %, $p \geq 0.11$), but had a negative effect on lumber strength (MOR; ≤ -13.4 %, $p \leq 0.03$) and wood basic density at stump height (≤- 7%; $p < 0.01$).”

The results for the yellow birch study at Axe Lake in 2013 showed the effect of thinning on the overall density of the wood to be weakly correlated, without any strong trend. This statement can be supported by literature by Hernandez *et al.* (1998), where is was found that hybrid populous clones responded either negatively, positively, or not at all in relative density measurements as a consequence of accelerated growth. The highest density measurements found in the uppermost sections tested is consistent with the findings by Zobel and van Buijtenen (1989), although conflict with published literature by Repola (2006) as previously discussed. The treatment with the highest relative density value is the 30% thinning. Once again there is not a distinguishable pattern for treatment effect on wood density, although the values do increase to a maximum in the 30% and then decrease in the 10%, therefore the most beneficial treatment for relative density associations is the 30%. Conflicting results have been reported in softwood thinning / fertilizing trials. A study conducted in Chapleau, Ontario on Jack pine (*Pinus banksiana,* Lamb.) by Scott *et al.* (1982) found that the portion of the tree which transferred into high density mature wood, from low density juvenile wood the quickest was the portion tested just below the live crown, although overall the highest densities were found in the base sections of the trees tested.

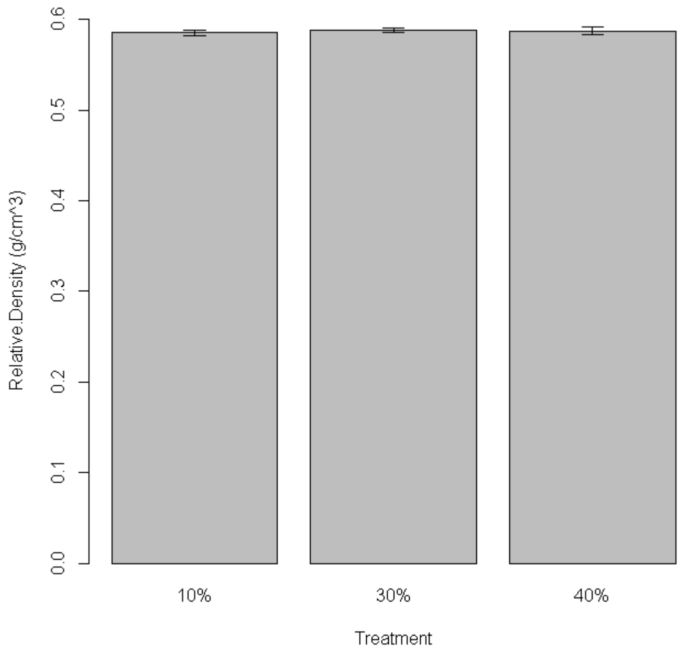


Figure 36. Relative density at 12% moisture content results, stratified post treatment values from Thessalon yellow birch thinning trial.

The above graph displays a comparison of treatments to each other. Shown in the Figure below (Figure 37) are the axial zones of statistic similarity for relative density. There are three separate regions of statistic similarity, the lowest grouping depicts the base of the tree while the middle grouping is the mid-section of the stem and finally uppermost grouping represents the top bolts of the tree.

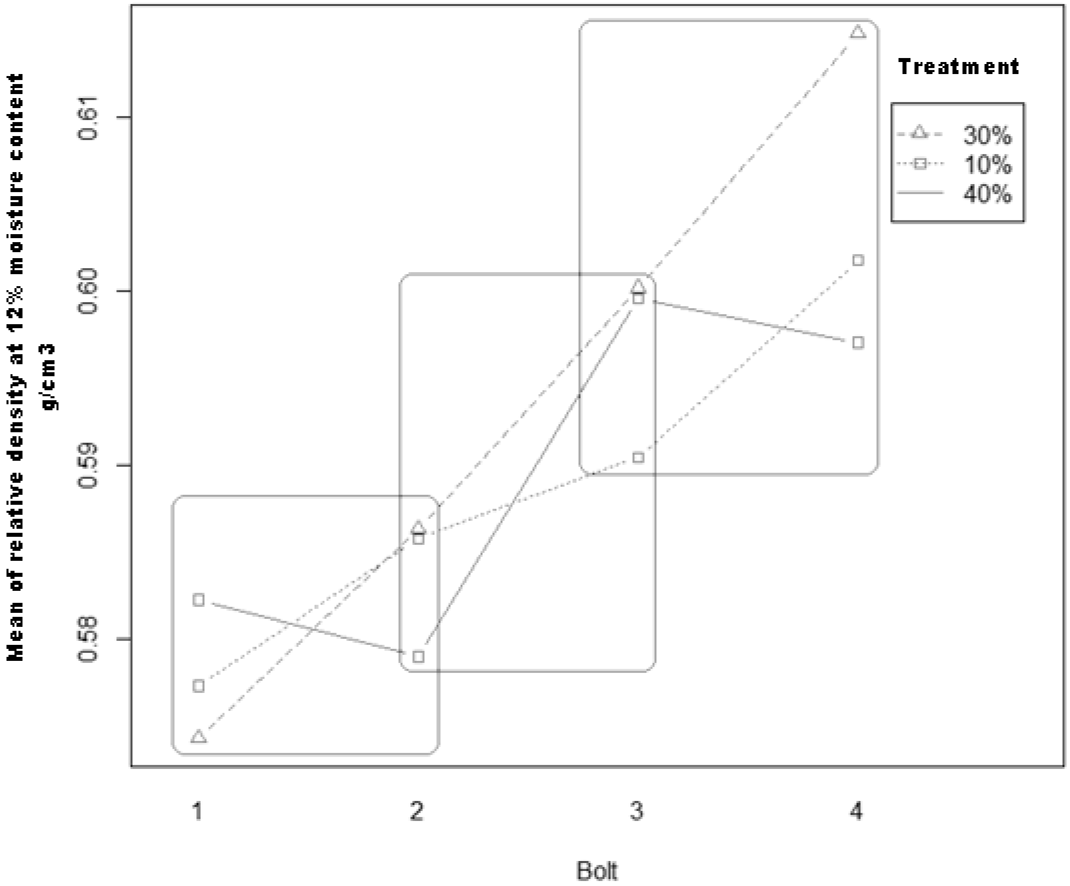


Figure 37. Axial zones of similarity for relative density at 12% moisture content, stratified post treatment values from Thessalon yellow birch thinning trial.

5.8 Ring Width

The ring width results are reported in millimeters (mm), the results for the 10%, 30% and 40% thinning treatments are 2.1 mm, 2.799 mm and 2.728 mm, respectively. The highest values are found in the 30% thinning treatment followed by the 40% thinning and finally the 10% thinning (refer to Table 12). The ring widths present in the 10% thinning are 50% higher than the reported value for yellow birch by Jessome

(2005), the 30% treatments contains trees with growth rings which are 99.9% above the reported value, lastly the 40% thinning treatment possesses ring widths 94.86% higher than the reported value and is similar to the 30% thinning treatment. The ring width pre-treatment average across all treatment blocks was 2.23 mm while the post treatment for the same area is 2.70 mm. The ring widths in both scenarios are above what is found in the published literature. The grand pre-treatment scenario yields ring widths, which are 59% larger than the published value of 1.4 mm, the grand post treatment scenario yields ring widths, which are 93% greater than what is seen in the literature reported by (Jessome 2005). Figure 38 shows the variability in ring width radially between treatments. Each radial position represents five years of annual tree growth. It can be seen that in the first 15 years (pre-treatment radial positions one - three in Figure 38) ring width between treatments follow the same trend across treatments. Upon thinning, when the trees were roughly 20 - 25 years of age, it can be seen that with a heavier intensity of thinning applied the wider the growth rings tend to be. For example at age 30 (radial position six in Figure 38) the 10% thinning is roughly 1.7 mm while the 40% thinning at the same radial position is roughly 3.3 mm. The thinning allows for more sunlight, nutrients, water, crown expansion space and root expansion space to be allocated to the remaining trees, therefore increasing their growth and ring width across the radial profile (Roberge 1975, BCMF 2001).

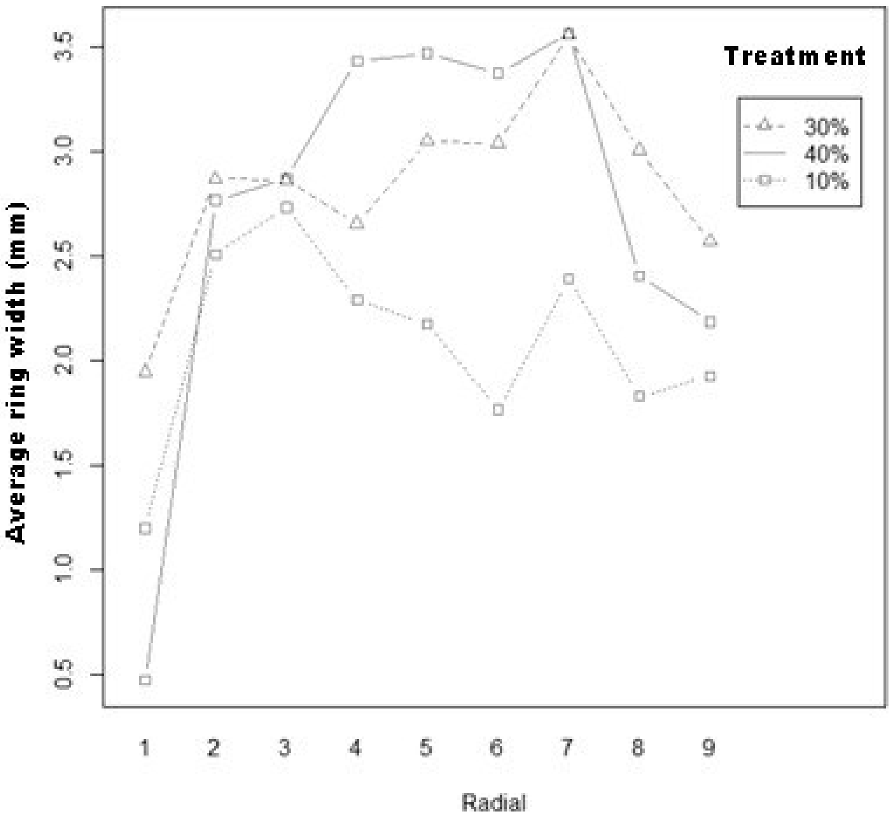


Figure 38. Variability in ring width, radially, between treatments, pre-treatment and post-treatment values, Thessalon yellow birch thinning trail.

Similar results have been seen in previous studies conducted on this site for yellow birch and sugar maple by Von Althen *et al.* (1994, 1995) as both species responded positively in 5 year growth increments after the thinning treatments were applied. Similar studies carried out on sugar maple stands by Church (1955), Roberge (1957), Skilling (1959), Drinkwater (1960), Marquis (1960), and McCauley and Marquis (1972) show that an increase in production and quality can be attained by thinning in sugar maple stands. Similar diameter increase trends have been seen in many other studies which have shown that there is a diameter increase following thinning, these studies have been carried out on many softwood and hardwood species (Von Althen *et al.* 1994, 1995, NSDNR 2010, Eardmann and Peterson 1992). The thinning has a pronounced effect on ring width for five years after it is applied, eventually stabilizing then decreasing towards the most outer radial positions analysed. The effect of the thinning and the additional resources allows for the trees to grow rapidly, once the additional resources and space have been adequately used up by the tree, and crown closure or maximum crown expansion has been achieved, the growth rate begins to slow again, creating a tighter grained stem in the outermost radial positions. Cutter *et al.* (1991) found a similar response to thinning treatments with white oak, but also noted that after a period of subsequent growth, thinning primarily increased the yield of the lowest grades of lumber. Since most trees are harvested at a given size rather than a given age, thinned stands will be inevitably harvested at an earlier age than that of a natural forest stand harbouring trees of the same diameter (Zobel and van Buijtenen 1989). The trees harvested from the thinned site commonly have a higher content of juvenile wood, the improved growth of the thinned stands and the added value from a thinning is offset by a higher proportion of juvenile wood from younger thinned stands (Zobel and van Buijtenen 1989). The reason for the increased amount of juvenile wood as a consequence of a thinning treatment has been explained by Panshin and de Zeeuw (1980) as being a result of the prolonged influence of the apical meristems in the active crown region on wood formation by the cambium. As the thinning treatment increases, there is more room for crown expansion, leading to the increased portion of juvenile wood and results produced. Regarding the log quality attributes previously discussed for a veneer industry and quality veneer growing stock it can be seen that as we increase the growing space of each crop tree the ring width homogeneity fluctuates according to the thinning regime applied. There currently is not an industrial standard specific to ring width for veneer products, although it seems that the tighter grained the product the more value it tends to have. On the other hand the hardwood lumber industry must follow the "growth rings per inch" rules for medium grain (four or more growth rings per inch) or close grain (six or more growth rings per inch). With crown closure and maximum crown expansion we can see the radial growth of the trees slowing down, in turn, creating tighter grained growth. The 10% thinning treatment, once crown closure occurred, exhibited little variation in ring width. In regards to the remaining treatments, all fall within acceptable standards for grain tightness (growth rings per centimeter). Ring with variability is evident in the thinning treatments, therefore decreasing the products value to a veneer industry and lessening the ability of the crop trees to be used as face veneer in various products such as furniture, cabinetry and woven baskets. Ring width homogeneity and the impact it has on hardwood lumber can be a minimal issue in cases, inversely, it can be a cause of concern in specific applications. The thinning treatments cause a fluctuation in homogeneity according to the thinning regime applied. The heavier the thinning the wider the rings tend to be, similar results in a diameter increase likely resulting in ring width increase have been reported by Eardmann *et al.* (1975), McCauley and Marquis (1972), Peterson *et al.* (1997), RNQ (2003), NSDNR (2010). All thinning treatments fall within reasonable "grain tightness" standards for the production of hardwood lumber according to the National Lumber

Grades Authority (NLGA, 2012). The definition given for acceptable growth rate concerning stress grade measurements is as follows (NLGA, 2012):

> *"Medium Grain: means an average of approximately* four *or more annual rings per inch on either one end or the other of a piece".*
>
> *"Close Grain: Means an average of* six*, but no more than 30, annual rings per inch on either one end or the other of a piece".*

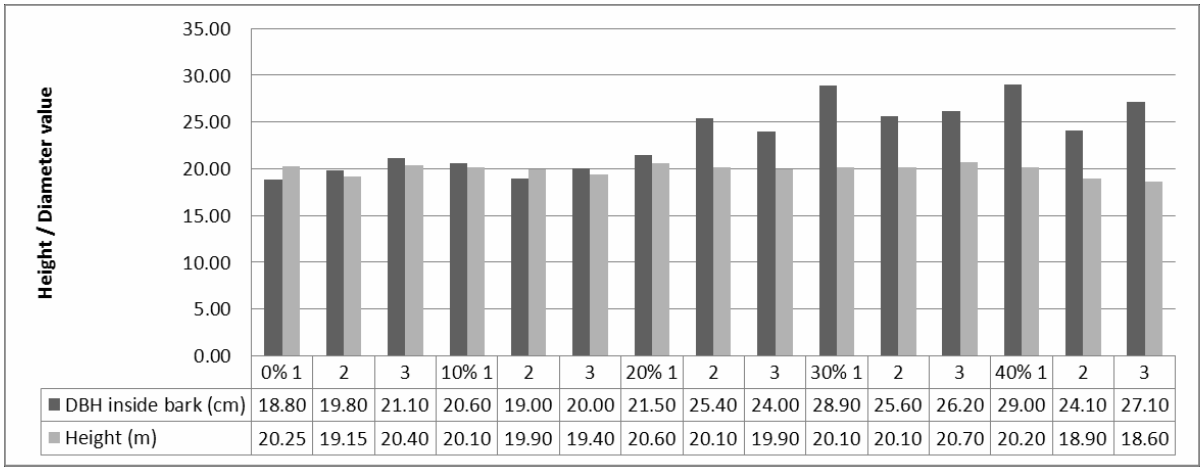
As the thinning intensity increases the growth rings mainly in the base of the tree are exaggerated up to the 30% thinning treatment level due to the formation of an increased "swell butt" to accommodate for the swaying crown (Bowyer *et al.* 2003). This accumulation of wood contains a high percentage of reaction wood or muscle wood, which may be inferior for high quality hardwood lumber when processed due to its reactivity and uneven shrinkage patterns. (Bowyer *et al.* 2003).

5.6 Tree Taper and Recoverable volume

The average diameter at breast height measurements for all three trees in each treatment, inside bark, ranking from smallest to largest are as follows; control, 10%, 20%, 40% and 30% which can be seen in Figure 39 along with the individual DBH measurements for all treatments. There are three significantly different subsets of diameter classes among the five thinning treatments, which are;

1.) Control and 10%
2.) 20%
3.) 30% and 40%

The diameters follow a trend of increasing according to intensity of thinning until the 30% treatment, at which point the average DBH decreases into the 40% thinning treatment. Similar results have been previously observed and reported by von Althen *et* *al.* (1994, 1995) on this same research site for both yellow birch and sugar maple, as 5 year diameter increments were found to increase hand in hand with the thinning intensity.



	0% 1	2	3	10% 1	2	3	20% 1	2	3	30% 1	2	3	40% 1	2	3
■ DBH inside bark (cm)	18.80	19.80	21.10	20.60	19.00	20.00	21.50	25.40	24.00	28.90	25.60	26.20	29.00	24.10	27.10
■ Height (m)	20.25	19.15	20.40	20.10	19.90	19.40	20.60	20.10	19.90	20.10	20.10	20.70	20.20	18.90	18.60

Figure 39. Height and diameter relationship for all five treatment blocks as of July 2013 for the Axe Lake yellow birch thinning trials.

A study conducted by the NSDNR (2010) at “The Higgins mountain site” produced supporting results. The Higgins mountain site was thinned when it was 5 meters tall utilizing a 36% of height thinning treatment, a 44% of height thinning treatment and a 60% of height thinning treatment resulting in 26%, 44% and 55% diameter gains per unit, respectively. A similar study conducted by the NSDNR (2010) on the “McQuarrie Lake thinning trial research area” this resulted in diameter gains of 100% from a 75% of height thinning treatment. Although unit volume is increased, total stand volume was decreased when compared to controls. A positive diameter increase associated with intensity of thinning has also been reported by the RNQ (2003). In this study, forested stands were thinned to a certain percentage of basal area, the remaining trees in the subsequent stands responded by increasing in diameter. The relationship of diameter increase with intensity of treatment was similar to what was found in the Axe Lake trials. Eardmann et al (1975) thinned 16 year old yellow birch saplings with five intensities of crown thinning (control, 75 cm, 150 cm, 300 cm and 450 cm). It was found that crown thinning increased the diameters of all the crop trees. Contradictory results have been reported by Roberge (1974) as it was found that thinning sugar maple and yellow birch stands did not have a pronounced effect on stem form. More work has been conducted on the response of sugar maple to thinning treatments than on yellow birch. Similar increases in single tree productivity have been seen in sugar maple crown releases by Drinkwater (1960). It was found that significantly higher diameters were obtained by the trees in the heavily thinned stands, although recommended thinning to 150-180 cm for best growth and quality development rather than thinning to 240-300 cm. Work on other species such as *Quercus pyrenaica Wild*. by Canellas *et al.* (2003) found that thinning stands to various desired stand basal areas resulted in the production of trees with larger diameters in the heaviest thinned stands and smaller diameters in the lighter thinned stands. Referring to Figure 39 it can also be seen that the height of the trees fluctuates very little between the thinning treatments. The heights of the crop trees do not seem to follow a statistically significant trend, although tend to be slightly shorter in the 40% thinning.This finding is controversial to what has been previously seen on this research site and reported by von Althen *et al.* (1994 and 1995) who reported that the trees in the control, 10% and 20% were found to have a substantial height advantage over the 30% and 40% thinning treatments. The lack of a relationship between thinning intensity and increased height has also been observed previously by Eardmann *et al.* (1975) as crown thinning yellow birch saplings to five different intensities (control, 75 cm, 150 cm, 300 cm and 450 cm) resulted in no relationship between height and thinning intensity. The lack of a relationship between thinning intensity and increased height has also been observed in softwood species such as red pine (*Pinus resinosa.* Ait) as Penner *et al.* (2001) saw that the height increment was not statistically significant between thinning treatments which were based on basal area removals, although a weak negative correlation was found between height and thinning intensity.

The amount of recoverable products from each individual stem for the purposes of this research was dependent on two factors; length and small end diameter. Each of the five thinning treatments were analysed for recoverable veneer logs, recoverable saw-logs and recoverable pulp logs. Figure 40 shows the recoverable products, per tree, for each treatment, which can be found as a consequence of thinning the stands as determined using Buck II.

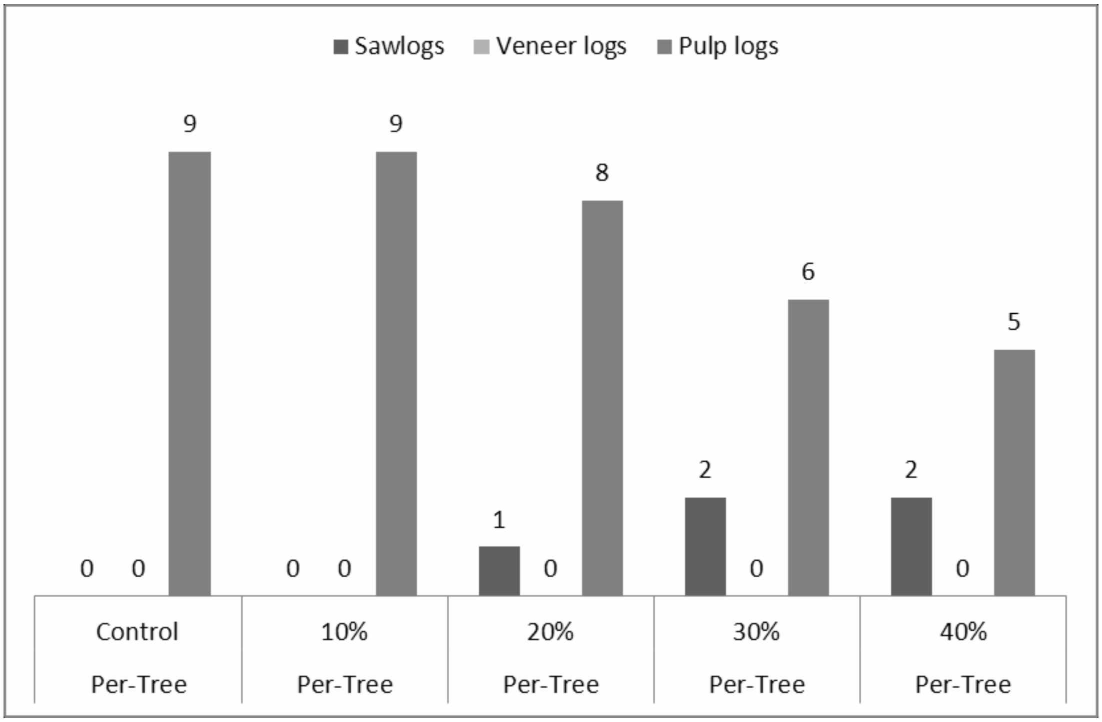


Figure 40. Recoverable products, per tree, for each treatment, which can be found as a consequence of thinning the stands (Saw-logs, Veneer logs and Pulp logs).

It can be seen that the control and the 10% thinning treatment both have roughly the same amount of recoverable product. Currently there are not sufficient diameter / length requirements found in the control and the 10% thinning treatment for either veneer logs or saw-logs of any class to be harvested in 2013. Throughout the entire study area there are not sufficient diameter / length requirements for veneer quality logs presently found as a consequence of thinning. As the individual tree size increases due to the thinning treatments applied, saw-log requirements are seen to be met. Out of the four saw-log classes only class four saw-log requirements are met. It is anticipated that by the age of rotation the quantity and diversity of recoverable products is expected to increase. Table 20 shows the specific size requirements which must have been satisfied for merchantability for the purposes of this research.

Table 20. Specific size requirements for recoverable products found within the five yellow birch thinning treatments in Thessalon Ont. Source (SAPPI* 2012, USDA** 2004).

Timber Product	Product Classes	Log Length (m)	Minimum Top Diameter (cm)	Product Rank
Saw-Log*	4	3.3	17.9	5
	3	3.3	25.9	4
	2	3.3	33.9	3
	1	3.3	34	2
Veneer Logs**	4	2.7	25.4	1
Pulp Logs*	N/A	1.8	5	6

Current technologies in Ontario and the lake states require logs of suitable diameter for “chucking” during the veneering process. Chucking is the process in which the “flitch” is mounted to be peeled / sliced into veneer sheets. The diameter requirements, which were used for this research found in table 20, represent grade four, or the lowest grade veneer log requirements reported by the USDA (2004). The saw-log and pulp log requirements are consistent with Sappi (2012) standards. The calculations preformed on this research site by Buck II for recoverable products did not take into consideration any defects. The results reported would only hold true if the crop trees are 100% free from defects and met hardwood lumber and veneer grading standards. Each treatment was found to also have varying volumes per crop tree, the volume measurements follow the same trend as presented in Figure 39 for height diameter relationships. Figure 41 shows the volume differences present per crop tree for each treatment attained in 2013 as a consequence of thinning treatment, furthermore Figure 41 shows the amount of recoverable volume per merchantable item.

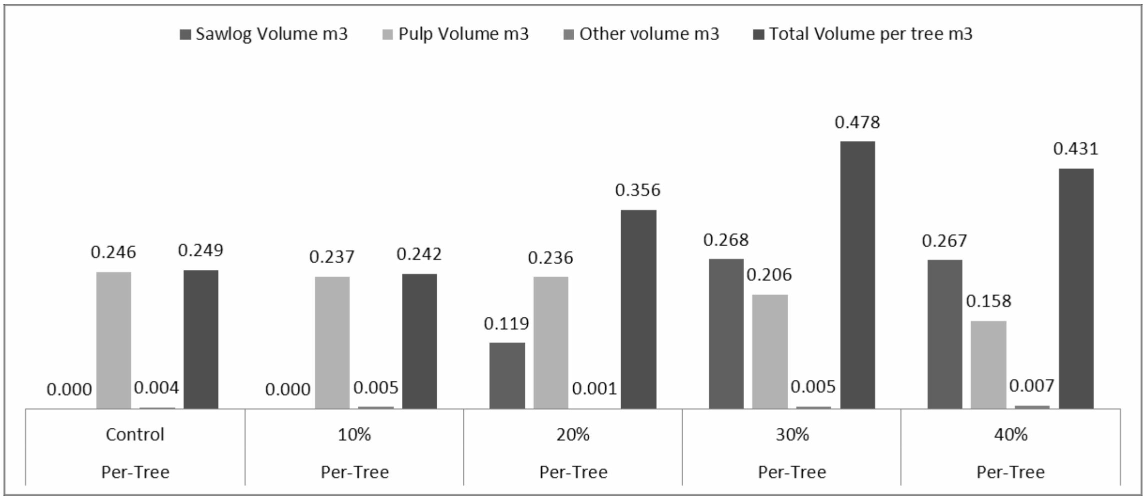


Figure 41. Volume differences present per crop tree for each treatment by recoverable product.

Accelerated growth occurring under natural conditions without anthropogenic intervention generally created logs which are readily accepted, whereas similar wood produced by enhancing the growth conditions is questioned, this especially holds true when one or more abiotic factors in the site are changed (Larson 1967). Controversy relating to accelerated growth and wood quality has also been reported by Larson (1967) regarding issues in the grading system concerning rapidly grown wood. Larson (1967) stated the following:

> *"Wood from rapidly grown trees may be completely acceptable under one standard but may be rejected under another standard'.*

Due to the constraints on some lumber grading rules fast grown timber may be rejected when held to the standard that a minimum amount of growth rings be found per inch of lumber (Koch 1972). The desired properties of wood for the production of veneer are similar to that of the desired properties for the production of dimensional lumber (Cassens 2004, Ross 2010). Trees produced in fast grown plantations or similar altered conditions are not necessarily carriers of bad wood, although, the wood is much different from that of a natural grown forest stand (Larson 1969).

5.10 Predictive Model

Several predictive models were attempted during this study. It was found that the dataset was insufficient to provide for a suitable working base from which to create a predictive model with a strong meaning. The insufficiencies of the data stem from the lack of quantity, if more samples would have been taken across the thinning blocks from Thessalon the dataset would provide for a much more suitable base to accurately analyse and predict dependant values based on independent occurrences. Table 21 summarizes the models attempted and the summarized findings.

Table 21. Predictive models for yellow birch on ES 29.1 in Thessalon Ontario Canada, Equation of the model and model type.

Predictive Model	Equation	Type
lm(formula = RD_12 ~ MOE)	$Y = 0.5 + 0 * x$, $R^2 = .12$, p-value <0.001	Linear
lm(formula = MOR ~ MOE)	$Y = 11.4 + 0.1 * x$, $R^2 = .71$, p-value <0.001	Linear
lm(formula = Disk_Ht ~ Dia)	$Y = 25.514 +-1.006 * x$, $R^2 = .524$, p-value <0.001	Linear
N-lm(formula = Disk_Ht ~ Dia)	$y = 26.028 +-0.053 * x$, $R^2 = .5507$, p-value<0.001	Exponential

The first linear model, seen in Figure 42, was predicting MOE based upon relative density at 12%. The attained strength of the model is low with an r^2 value of 0.12 and Pr <0.001. Although not a strong predictive model the relationship between MOE and relative density is found to be significant. Similar significance has been reported by many investigators.

According to Panshin and de Zeeuw (1980):

> “Specific gravity of wood, because it is a relative measure of the relative amount of solid cell wall material, it is the best index that exists for predicting the strength properties of wood. In general terms, without regard to the type of wood, the relationship between specific gravity and strength can be expressed by the following equation S=K (G) ^{n} where S= is any one of the strength properties, K= the proportionality constant differing for each strength property, G= the specific gravity and ^{n}= an exponent that defines the shape of the curve representing the relationship. ”

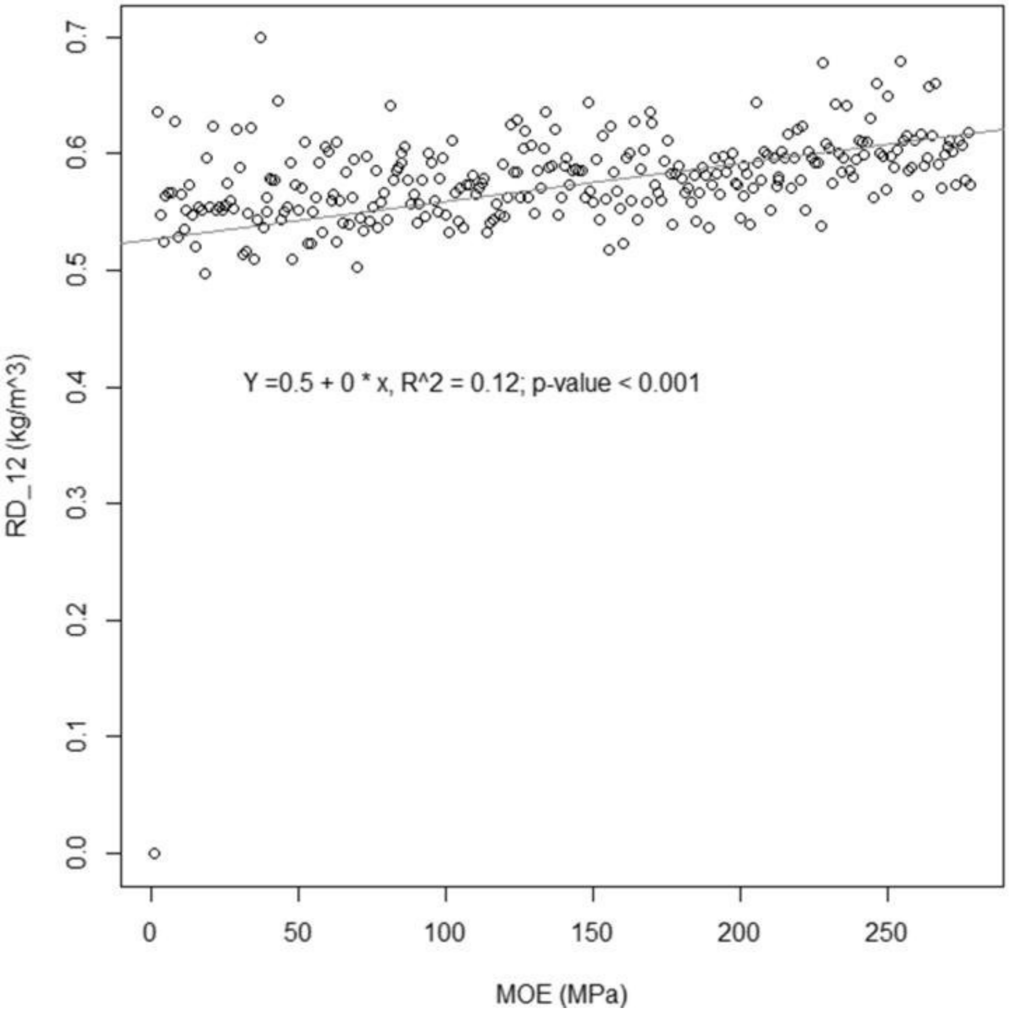


Figure 42. Linear Model predicting MOE from relative density at 12% moisture content, Thessalon yellow birch thinning trial.

A known correlation between MOE and MOR exists in the published literature, Panshin and de Zeeuw (1980) state that in static bending tests MOE is calculated from the slope of the elastic line below the area of permanent set and the limit of proportionality, the greater the slope of the elastic line, the greater the MOE, while MOR is calculated from beyond the limit of proportionality into the area of permanent set and deformation. Wagaard (1981) and Schniewind (1982)state:

> *"The bending strength is expressed as modulus of rupture, which is stress at the extreme fiber of the beam calculated from the maximum bending moment by assuming an ideal stress distribution. Although the actual stress distribution differs, it tends to be basically the same in all wood beams so that the use of an assumed stress can be justified. Also derived from the static bending test is the modulus of elasticity calculated from beam deflection."*

The relationship between MOE and MOR has been further noted by the USDA (2010) in the wood handbook as:

> *"Modulus of rupture: Reflects the maximum load-carrying capacity of a member in bending and is proportional to* maximum moment borne by the specimen. Modulus of rupture is an accepted criterion of strength, although it is not a true stress because the formula by which it is computed is valid only to the elastic limit".

Yang and Evans (2003) found MOE and MOR to be highly correlated in *Eucalyptus globulus L, E. nitens M,* and *E. regnans M,* that were between 15 and 31 years of age. An adjusted r^2 value of 0.79 was attained while modeling the relationship of MOE and MOR attained from static central point-loading bending tests.

Upon modeling the relationship of MOE and MOR based upon the data collected, it was found that there is a moderately strong relationship. Figure 43 represents the second attempted model "lm (formula = MOR ~ MOE)". The attained strength of the model was relatively strong with an r^2 value of 0.71 and subsequent Pr <0. 001.

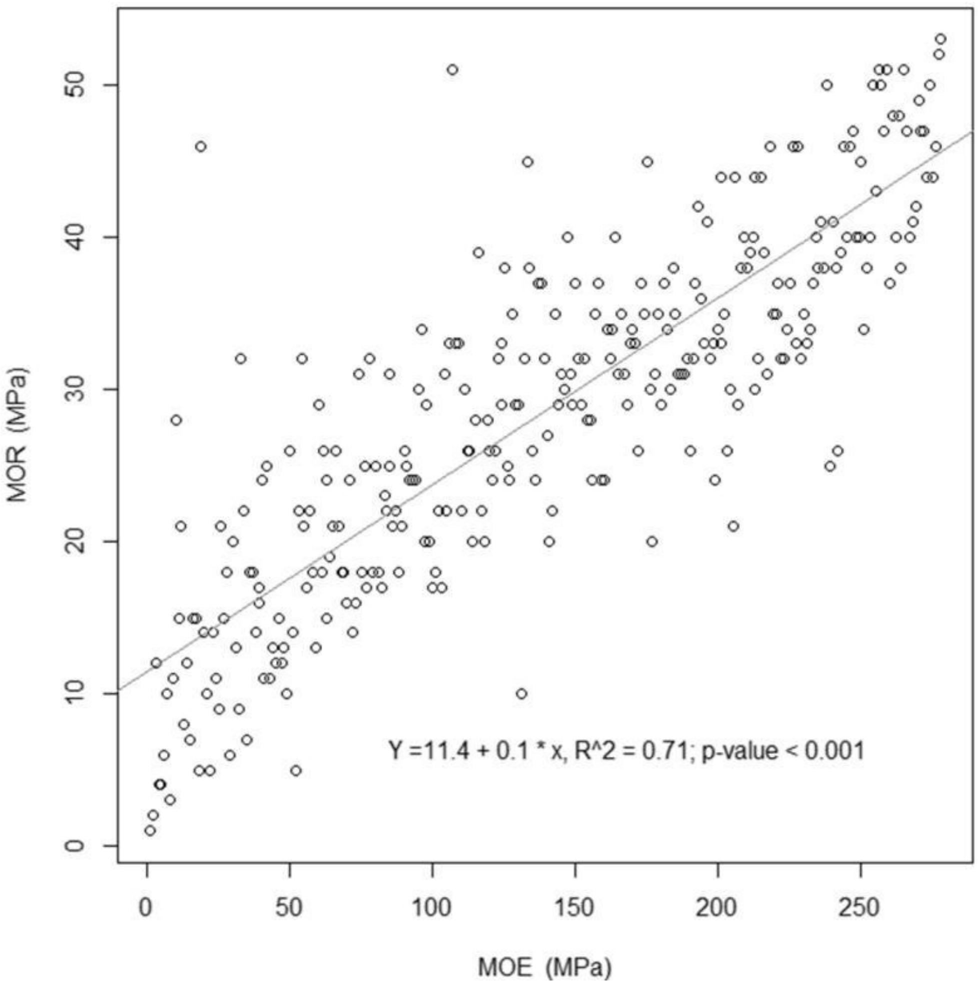


Figure 43. Predictive Linear Model predicting MOE from MOR, Thessalon yellow birch thinning trial.

Seen in Figure 44 is the last predictive model, which attempted to predict diameter with height or taper. Two versions of this model were attempted, one being linear and one being a negative exponential, based on the observations the relationship is non-linear. Upon analysing the linear model a weak prediction was found with an r^2 value of 0.524 and subsequent Pr <0. 001. This means there is a high probability that the height is correlated with diameter, however it is a weak predictor. The second, a non-linear negative exponential model, was found to be a slightly stronger predictor with an r^2 value of 0.5507.

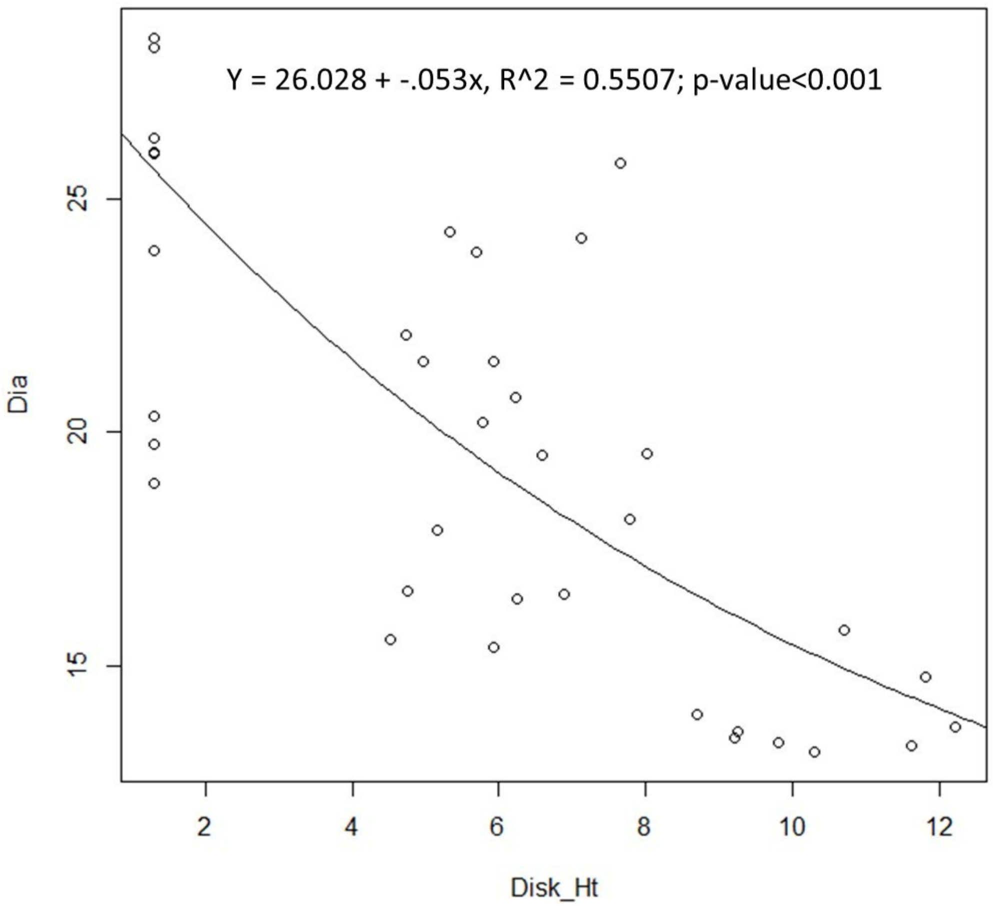


Figure 44**.** Non-Linear Model predicting diameter with disk height, Thessalon yellow birch thinning trial.

To increase the strength of the models a larger sample size is required, the sample size of individuals for this research was 15 pole-sized trees. Sample size has been defined in different ways by many statistical textbooks, De Veaux *et al.* (2011) describes sample size as:,

"Sample Size: The number of individuals in a sample, the sample size determines how well the sample represents the population, not the fraction of the population sampled"

Porkess (2006) provides another definition of sample size as:

“Sample Size: The number of individuals or items in a sample. Samples are often called small if their size is less than 30”

Furthermore the importance of sample size has been explained by De Veaux *et al.* (2011) as:

“How big of a sample size do you need? That depends on what you’re estimating. If you’re just interested in the broth of a pot of soup, then you can just take a sip from a spoon. But to get an idea of what’s really in the soup, you need a large enough taste to be a representative sample from the pot, including a selection of the vegetables. For a survey that tries to find the proportion of the population that fall into a category, you’ll usually need a large enough sample to see several respondents in each category, usually at least several hundred respondents, to say anything precise enough to be useful.”

6.0 Conclusion

Varying select properties and attributes were tested to investigate the potential effects thinning yellow birch crop trees has on the internal properties for the purposes of a potential hardwood lumber and veneer industry. The analyses performed consisted of the following:

MOE: reported in mega pascals (MPa) utilizing the three point flexure test procedure with a maximum span of 24 centimetres.

MOR: reported in MPa, based on the maximum load (Newtons) reported during MOE testing

Side hardness: reported in Newtons (N) using the Janka Ball tool

Relative density measurements reported in Kg/m^3

Ring analysis

Fiber analysis

Vessel element analysis

Taper / Potential Recoverability analysis inherent

It was hypothesized with an increase in thinning treatment, the better the wood properties occurring on site would be, along with an increase in the amount of potential pulp, saw and veneer logs as thinning intensity increased. Upon the analysis of all thinning treatment blocks, the results consistently displayed three subsets of sites, it was realized that not all of the treatment blocks could be compared due to the microsites which they occurred on within ES 29.1 and the inherent wood properties associated with the sites. It was found that the site, not the treatment, contributes a significant amount to the internal properties of the growing stock. The entire 68 hectare block was stratified into three individual sites the first containing the control, the second containing the 20% thinning treatment and the third containing the 10%, 30% and 40% thinning treatments. The third site proved to be the only site suitable for conventional statistical analysis.

It was found that over site three (10%, 30% and 40% thinning treatment) there was a statistically significant difference in the wood properties (mechanical and physical), although, evidence of a discernable trend in the morphology as a consequence of the various thinning treatments was not observed. All select test properties exhibited significant variability in the axial positions tested in the trees. And all but the Janka Ball Side Hardness results displayed significance between treatments. The highest MOE values were seen in the 10% thinning treatment followed by the 30% thinning treatment and lastly the 40% thinning treatment. The highest MOR values were found in the 10% and 30% thinning treatments and lowest in the 40% thinning. The fiber attribute values attained from the FQA showed that all of the treatments fall below the published values for yellow birch. Fiber length, fiber width, and vessel width were 26%, 44%, 31% lower than what was expected to be seen.

Radial variance in some of the selected test properties could not be fully attributed to the thinning treatments applied due to the morphological status of the test specimens at the time of treatment. These tests results include MOE/MOR (mechanical) along with all of the fiber attributes (microscopic). Ring width increases steadily according to the thinning until a maximum in the 30% thinning, then decreases slightly in the 40% thinning treatment. All of the treatments fall within acceptable standards for “grain tightness” for merchantable hardwood lumber and veneer quality logs.

Based on the findings we can Accept the null hypotheses that:

H_1 – Potential wood utilization increases with an increasing intensity of crop tree release in yellow birch stands of the Algoma District in Ontario.

And:

H_2 - Morphological changes in yellow birch are due to site effect accompanied by crop tree release intensity.

Further research is needed to discern the microsite effect on internal wood properties of yellow birch related specifically to ES 29.1 and the effects thinning along with site class and condition have on the internal properties of yellow birch for potential end merchantability. It would also be useful to conduct a similar study as this upon the harvest and rotation age of this particular site to discern whether or not the treatment effect is compounded by a temporal effect.

The effects thinning treatments have on yellow birch internal wood properties are found to heavily affect potential end merchantability of the crop tree growing stock on site. The volume differences present and the potential product recoverability associated with the various thinning treatments, as determined by Buck II, would prove that the 30% thinning treatment would be the optimal thinning treatment to apply to yellow birch on ES 29.1 for the purposes of increasing your merchantability and recoverability while maintaining wood quality. Another reason for thinning is made by taking into consideration rotation age / diameter requirements for harvest. Thinning was seen to increase the size of the crop trees on site, shortening the rotation age potentially for diameter limit cutting to occur.

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APPENDIX I

MECHANICAL PROPERTY SUMMARY PRE-TREATMENT

				Deviation From Published (Mechanical)		
	Hardness (N)	MOE (MPa)	MOR (MPa)	Hardness (N) (% Change)	MOE (Mpa) (% Change)	MOR (Mpa) (% Change)
Published *	5930	14100	106	-	-	-
Average for Treatment	7824	12049	91.5	31.94	-14.55	-13.68
Control	9497	12656	98.3	60.15	-10.24	-7.26
10% Thinning	7233	11694	87.53	21.97	-17.06	-17.42
20% Thinning	8122	12926	102.5	36.96	-8.33	-3.30
30% Thinning	7281	12034	91.76	22.78	-14.65	-13.43
40% Thinning	7449	12191	84.05	25.62	-13.54	-20.71

APPENDIX II

MECHANICAL PROPERTY SUMMARY (HARDNESS)

Block	Bolt	Treat	Rep	Hard
10%	2	1	1	6577
10%	2	1	1	6686
10%	2	1	1	6799
10%	2	1	1	6664
10%	2	1	2	6845
10%	2	1	2	6881
10%	2	1	2	7085
10%	2	1	2	7049
10%	2	2	1	6176
10%	2	2	1	7859
10%	2	2	1	6888
10%	2	2	1	7206
10%	2	2	2	6395
10%	2	2	2	7617
10%	2	2	2	6908
10%	2	2	2	7810
10%	3	1	1	6851
10%	3	1	1	6251
10%	3	1	1	6191
10%	3	1	1	6195
10%	3	1	2	6666
10%	3	1	2	5852
10%	3	1	2	7089
10%	3	1	2	6069
10%	3	2	1	7938
10%	3	2	1	7128
10%	3	2	1	7482
10%	3	2	1	7516
10%	3	2	2	8665
10%	3	2	2	6908
10%	3	2	2	6530
10%	3	2	2	7368
10%	3	3	1	9044
10%	3	3	1	9044
10%	3	3	1	9044
10%	3	3	1	9044
10%	3	3	2	7752
10%	3	3	2	7752
10%	3	3	2	7752
10%	3	3	2	7752
30%	2	1	1	6133
30%	2	1	1	5960

30%	2	1	1	6366
30%	2	1	1	5946
30%	2	1	2	5804
30%	2	1	2	6398
30%	2	1	2	6804
30%	2	1	2	6263
30%	2	2	1	6076
30%	2	2	1	6549
30%	2	2	1	6886
30%	2	2	1	6756
30%	2	2	2	5959
30%	2	2	2	6559
30%	2	2	2	6542
30%	2	2	2	6250
30%	2	3	1	6208
30%	2	3	1	6689
30%	2	3	1	6593
30%	2	3	1	6496
30%	2	3	2	6279
30%	2	3	2	6880
30%	2	3	2	6007
30%	2	3	2	6389
30%	3	1	1	8049
30%	3	1	1	6926
30%	3	1	1	7478
30%	3	1	1	7647
30%	3	1	2	7846
30%	3	1	2	7229
30%	3	1	2	6993
30%	3	1	2	7940
30%	3	2	1	8016
30%	3	2	1	7631
30%	3	2	1	7975
30%	3	2	1	8757
30%	3	2	2	7701
30%	3	2	2	7379
30%	3	2	2	7359
30%	3	2	2	8562
30%	3	3	1	8618
30%	3	3	1	8556
30%	3	3	1	8618
30%	3	3	1	8556
30%	3	3	2	10523

30%	3	3	2	8904
30%	3	3	2	10523
30%	3	3	2	8904
40%	2	1	1	8291
40%	2	1	1	7349
40%	2	1	1	7751
40%	2	1	1	6073
40%	2	1	2	7606
40%	2	1	2	6659
40%	2	1	2	7754
40%	2	1	2	6323
40%	2	2	1	7216
40%	2	2	1	7238
40%	2	2	1	7018
40%	2	2	1	7330
40%	2	2	2	7399
40%	2	2	2	7223
40%	2	2	2	7629
40%	2	2	2	7765
40%	2	3	1	5991
40%	2	3	1	9184
40%	2	3	1	7007
40%	2	3	1	7394
40%	2	3	2	6284
40%	2	3	2	9143
40%	2	3	2	6801
40%	2	3	2	7409
40%	3	1	1	8043
40%	3	1	1	7301
40%	3	1	1	6609
40%	3	1	1	6779
40%	3	1	2	7430
40%	3	1	2	7680
40%	3	1	2	7390
40%	3	1	2	6547
40%	3	2	1	7203
40%	3	2	1	7074
40%	3	2	1	7542
40%	3	2	1	9089
40%	3	2	2	6552
40%	3	2	2	7513
40%	3	2	2	7069
40%	3	2	2	8795

40%	3	3	1	6844
40%	3	3	1	7545
40%	3	3	1	8935
40%	3	3	1	7775
40%	3	3	2	7601
40%	3	3	2	7323
40%	3	3	2	9074
40%	3	3	2	7999

APPENDIX III
MECHANICAL PROPERTY SUMMARY (MOE AND MOR)

Treatment	Tree	Bolt	MOE	MOR
10%	1	1	12914	94
10%	1	1	10831	83
10%	1	1	13737	103
10%	1	1	13562	101
10%	1	1	12780	93
10%	1	1	12816	104
10%	1	2	14484	99
10%	1	2	13867	95
10%	1	2	12982	95
10%	1	2	13111	95
10%	1	2	13157	93
10%	1	3	12436	90
10%	1	3	11270	91
10%	1	3	10893	85
10%	1	3	12676	91
10%	1	3	10396	85
10%	1	4	7453	69
10%	1	4	11608	87
10%	1	4	11300	85
10%	2	1	12284	96
10%	2	1	10728	94
10%	2	1	12443	94
10%	2	1	11851	84
10%	2	1	11447	84
10%	2	1	11664	92
10%	2	1	12633	90
10%	2	1	11855	92
10%	2	1	10704	78
10%	2	1	12075	88
10%	2	2	13262	100
10%	2	2	11549	90
10%	2	2	11849	86
10%	2	2	12095	91
10%	2	2	13195	89
10%	2	2	12214	94
10%	2	2	13073	93
10%	2	2	11953	83
10%	2	3	13502	92
10%	2	3	14643	100
10%	3	1	10144	87
10%	3	1	12677	93
10%	3	1	13205	95
10%	3	1	14341	101

10%	3	1	13575	95
10%	3	2	10949	82
10%	3	2	12833	96
10%	3	2	12328	91
10%	3	2	12878	99
10%	3	2	13537	103
10%	3	2	12224	94
10%	3	3	12624	92
10%	3	3	14341	101
10%	3	3	13155	90
10%	3	3	14187	103
10%	3	4	12478	88
10%	3	4	11545	88
30%	1	1	11795	92
30%	1	1	10188	77
30%	1	1	12398	93
30%	1	1	12256	88
30%	1	1	13167	94
30%	1	1	11372	85
30%	1	1	11919	91
30%	1	1	13175	103
30%	1	1	9799	83
30%	1	1	12609	88
30%	1	1	11969	95
30%	1	1	13048	101
30%	1	1	13271	85
30%	1	1	12613	88
30%	1	2	12864	96
30%	1	2	12093	89
30%	1	2	12105	86
30%	1	2	12513	85
30%	1	2	12699	91
30%	1	2	11325	86
30%	1	2	12376	89
30%	1	2	13174	100
30%	1	2	12333	91
30%	1	3	11653	89
30%	1	3	11433	88
30%	1	3	11961	92
30%	1	3	12563	82
30%	1	3	12218	97
30%	1	3	12078	94
30%	1	3	12884	91
30%	1	3	12547	90

30%	1	3	11918	87
30%	1	4	12376	92
30%	1	4	4209	30
30%	1	4	13530	102
30%	1	4	9695	74
30%	2	1	10630	89
30%	2	1	12705	94
30%	2	1	12093	98
30%	2	1	13324	92
30%	2	1	12133	85
30%	2	1	13602	93
30%	2	1	12510	92
30%	2	1	12420	103
30%	2	1	13391	94
30%	2	1	8311	100
30%	2	2	13760	100
30%	2	2	14619	104
30%	2	2	12887	83
30%	2	2	13338	104
30%	2	2	13730	102
30%	2	2	13660	102
30%	2	2	13384	101
30%	2	3	15001	99
30%	2	3	12298	94
30%	2	3	13697	105
30%	2	3	12307	100
30%	2	3	13955	106
30%	2	3	15371	106
30%	2	3	13408	105
30%	2	4	15017	111
30%	2	4	14762	120
30%	2	4	11682	91
30%	2	4	11188	92
30%	2	4	14471	104
30%	3	1	10787	78
30%	3	1	10287	80
30%	3	1	10573	79
30%	3	1	9476	88
30%	3	1	9695	81
30%	3	1	8986	76
30%	3	1	9909	73
30%	3	1	11563	92
30%	3	1	11950	83
30%	3	1	11818	84

30%	3	1	12495	84
30%	3	1	11913	86
30%	3	1	10859	95
30%	3	1	11967	98
30%	3	2	11352	95
30%	3	2	11816	90
30%	3	2	11479	92
30%	3	2	12693	105
30%	3	2	11844	100
30%	3	2	12864	90
30%	3	2	12489	104
30%	3	2	12747	95
30%	3	2	10591	105
30%	3	3	12143	93
30%	3	3	12240	86
30%	3	3	12643	95
30%	3	3	12227	95
30%	3	3	15603	107
30%	3	4	13099	101
30%	3	4	12539	91
30%	3	4	14268	101
40%	1	1	10158	75
40%	1	1	10090	77
40%	1	1	9994	82
40%	1	1	10463	74
40%	1	1	10123	80
40%	1	1	11804	89
40%	1	1	11613	85
40%	1	1	11462	85
40%	1	1	12124	95
40%	1	1	9371	64
40%	1	1	12526	87
40%	1	2	12410	88
40%	1	2	11543	90
40%	1	2	12544	89
40%	1	2	10893	89
40%	1	2	11476	91
40%	1	2	14699	104
40%	1	2	13203	98
40%	1	2	14764	98
40%	1	2	15399	100
40%	1	2	13857	105
40%	1	2	15022	105
40%	1	3	11353	87

40%	1	3	13895	89
40%	1	3	11630	89
40%	1	3	11557	95
40%	1	3	14587	100
40%	1	3	13693	93
40%	1	3	15653	100
40%	1	3	14542	98
40%	1	3	14837	89
40%	1	3	15754	105
40%	1	3	15525	99
40%	1	4	13010	100
40%	1	4	14227	108
40%	1	4	12462	100
40%	1	4	12568	90
40%	1	4	13744	104
40%	1	4	13214	104
40%	2	1	8390	73
40%	2	1	9766	79
40%	2	1	8789	77
40%	2	1	13884	97
40%	2	1	10042	82
40%	2	1	9898	81
40%	2	1	12453	87
40%	2	1	11007	85
40%	2	1	10029	77
40%	2	1	12186	89
40%	2	1	11662	83
40%	2	2	10686	83
40%	2	2	12364	89
40%	2	2	11428	85
40%	2	2	12936	98
40%	2	2	13172	89
40%	2	2	12085	90
40%	2	2	12714	87
40%	2	2	12134	88
40%	2	2	12476	93
40%	2	2	11902	91
40%	2	3	10177	80
40%	2	3	11028	85
40%	2	3	12825	92
40%	2	3	10203	83
40%	2	3	12196	93
40%	2	4	11231	85
40%	2	4	8705	80

40%	2	4	11232	93
40%	2	4	10029	88
40%	2	4	9975	77
40%	2	4	9567	77
40%	3	1	8155	66
40%	3	1	8124	67
40%	3	1	8438	74
40%	3	1	10140	80
40%	3	1	9401	72
40%	3	1	9992	75
40%	3	1	9735	74
40%	3	1	8324	73
40%	3	1	9739	77
40%	3	2	10558	80
40%	3	2	9225	71
40%	3	2	10001	76
40%	3	2	10668	76
40%	3	2	12502	91
40%	3	2	12530	88
40%	3	2	10439	76
40%	3	2	12391	84
40%	3	2	11317	86
40%	3	2	11998	90
40%	3	2	11536	88
40%	3	3	10777	78
40%	3	3	10151	79
40%	3	3	10710	84
40%	3	3	11717	81
40%	3	3	12581	88
40%	3	3	13027	90
40%	3	3	10494	77
40%	3	4	9826	77
40%	3	4	10033	77
40%	3	4	9198	71
40%	3	4	11181	81
40%	3	4	10322	83
40%	3	4	9032	81
40%	3	4	10695	83
40%	3	4	11778	88

APPENDIX IV RELATIVE DENSITY SUMMARY

Treat	Tree	Bolt	Radial	GR	WD	RD_12	RD_OD
10%	1	1	1	7	0.655	0.552	0.601
10%	1	1	1	9	0.667	0.562	0.614
10%	1	1	1	8	0.675	0.565	0.62
10%	1	1	1	11	0.689	0.573	0.628
10%	1	1	2	7	0.653	0.546	0.61
10%	1	1	2	6	0.692	0.58	0.641
10%	1	1	2	11	0.689	0.585	0.64
10%	1	1	2	15	0.713	0.607	0.663
10%	1	1	2	10	0.71	0.61	0.664
10%	1	2	1	8	0.652	0.544	0.589
10%	1	2	1	9	0.655	0.546	0.6
10%	1	2	1	11	0.658	0.55	0.605
10%	1	2	1	12	0.671	0.562	0.617
10%	1	2	1	10	0.673	0.563	0.622
10%	1	2	1	8	0.686	0.575	0.637
10%	1	2	1	13	0.69	0.579	0.638
10%	1	2	1	11	0.689	0.582	0.637
10%	1	2	2	15	0.673	0.562	0.621
10%	1	2	2	9	0.682	0.569	0.631
10%	1	2	2	11	0.698	0.588	0.649
10%	1	2	2	10	0.703	0.591	0.654
10%	1	2	2	12	0.713	0.593	0.657
10%	1	3	1	6	0.621	0.525	0.56
10%	1	3	1	7	0.641	0.535	0.579
10%	1	3	1	15	0.662	0.554	0.608
10%	1	3	1	12	0.681	0.57	0.626
10%	1	3	1	12	0.685	0.571	0.63
10%	1	3	1	12	0.683	0.577	0.631
10%	1	3	1	13	0.703	0.592	0.654
10%	1	3	1	9	0.7	0.594	0.652
10%	1	3	1	14	0.694	0.594	0.653
10%	1	3	2	11	0.694	0.579	0.644
10%	1	3	2	14	0.696	0.584	0.648
10%	1	3	2	10	0.698	0.585	0.646
10%	1	3	2	11	0.703	0.597	0.656
10%	1	4	1	12	0.653	0.548	0.601
10%	1	4	1	9	0.682	0.564	0.618
10%	1	4	1	8	0.687	0.577	0.637
10%	1	4	1	8	0.702	0.588	0.648
10%	1	4	1	13	0.693	0.591	0.652
10%	1	4	1	8	0.707	0.594	0.651
10%	1	4	1	11	0.717	0.6	0.667

10%	1	4	1	9	0.724	0.605	0.671
10%	1	4	2	13	0.682	0.567	0.628
10%	1	4	2	10	0.7	0.587	0.65
10%	1	4	2	9	0.714	0.603	0.666
10%	2	1	1	8	0.587	0.497	0.524
10%	2	1	1	7	0.616	0.503	0.533
10%	2	1	1	8	0.608	0.51	0.544
10%	2	1	1	8	0.598	0.51	0.539
10%	2	1	1	10	0.627	0.526	0.557
10%	2	1	1	14	0.637	0.532	0.572
10%	2	1	1	7	0.658	0.536	0.568
10%	2	1	1	13	0.647	0.543	0.576
10%	2	1	2	10	0.641	0.533	0.576
10%	2	1	2	11	0.649	0.544	0.584
10%	2	1	2	13	0.67	0.56	0.603
10%	2	1	2	10	0.663	0.56	0.599
10%	2	1	2	9	0.662	0.561	0.602
10%	2	1	2	16	0.669	0.563	0.602
10%	2	1	2	12	0.673	0.568	0.612
10%	2	1	2	13	0.673	0.569	0.607
10%	2	1	2	10	0.669	0.571	0.611
10%	2	1	2	10	0.684	0.579	0.623
10%	2	2	1	8	0.618	0.514	0.554
10%	2	2	1	7	0.629	0.517	0.559
10%	2	2	1	12	0.649	0.537	0.586
10%	2	2	1	11	0.638	0.539	0.585
10%	2	2	1	11	0.647	0.539	0.59
10%	2	2	1	11	0.647	0.545	0.596
10%	2	2	1	16	0.652	0.546	0.6
10%	2	2	1	14	0.654	0.548	0.602
10%	2	2	2	12	0.667	0.559	0.615
10%	2	2	2	10	0.664	0.56	0.61
10%	2	2	2	12	0.682	0.573	0.632
10%	2	2	2	10	0.685	0.576	0.63
10%	2	2	2	14	0.69	0.58	0.637
10%	2	2	2	14	0.684	0.583	0.642
10%	2	3	1	10	0.629	0.523	0.569
10%	2	3	1	8	0.649	0.536	0.574
10%	2	3	1	12	0.653	0.538	0.587
10%	2	3	1	12	0.652	0.552	0.602
10%	2	3	1	10	0.659	0.559	0.608
10%	2	3	1	16	0.667	0.561	0.615
10%	2	3	1	14	0.68	0.569	0.625

10%	2	3	1	15	0.672	0.57	0.627
10%	2	3	2	12	0.672	0.564	0.618
10%	2	3	2	11	0.686	0.577	0.634
10%	2	4	1	7	0.65	0.548	0.593
10%	2	4	1	13	0.681	0.549	0.603
10%	2	4	1	9	0.662	0.558	0.602
10%	2	4	1	11	0.664	0.559	0.603
10%	2	4	1	11	0.672	0.565	0.612
10%	2	4	1	8	0.725	0.618	0.671
10%	3	1	1	11	0.705	0.583	0.634
10%	3	1	1	7	0.711	0.584	0.632
10%	3	1	1	9	0.698	0.587	0.633
10%	3	1	1	11	0.749	0.592	0.653
10%	3	1	2	10	0.72	0.59	0.639
10%	3	1	2	10	0.714	0.596	0.634
10%	3	1	2	10	0.718	0.603	0.649
10%	3	1	2	15	0.729	0.607	0.663
10%	3	1	2	16	0.736	0.613	0.662
10%	3	2	1	12	0.704	0.589	0.643
10%	3	2	1	9	0.713	0.595	0.641
10%	3	2	1	14	0.707	0.597	0.644
10%	3	2	1	12	0.725	0.605	0.656
10%	3	2	2	8	0.72	0.597	0.638
10%	3	2	2	11	0.737	0.611	0.666
10%	3	2	2	11	0.733	0.621	0.665
10%	3	2	2	15	0.737	0.623	0.671
10%	3	3	1	20	0.654	0.553	0.654
10%	3	3	1	16	0.702	0.588	0.639
10%	3	3	1	13	0.719	0.595	0.647
10%	3	3	1	9	0.711	0.598	0.646
10%	3	3	1	13	0.718	0.6	0.646
10%	3	3	1	13	0.727	0.602	0.658
10%	3	3	1	16	0.723	0.607	0.657
10%	3	3	2	14	0.712	0.598	0.648
10%	3	3	2	12	0.725	0.602	0.661
10%	3	3	2	15	0.721	0.606	0.655
10%	3	3	2	12	0.731	0.612	0.654
10%	3	4	1	11	0.705	0.588	0.639
10%	3	4	1	10	0.709	0.59	0.645
10%	3	4	1	11	0.711	0.593	0.645
10%	3	4	1	12	0.714	0.594	0.652
10%	3	4	1	17	0.714	0.595	0.657
10%	3	4	1	15	0.711	0.601	0.662

10%	3	4	1	13	0.727	0.606	0.671
10%	3	4	1	13	0.735	0.621	0.685
10%	3	4	2	13	0.72	0.6	0.663
10%	3	4	2	15	0.721	0.602	0.663
10%	3	4	2	13	0.728	0.608	0.67
10%	3	4	2	12	0.779	0.645	0.653
30%	1	1	1	6	0.652	0.544	0.592
30%	1	1	1	8	0.674	0.567	0.62
30%	1	1	1	6	0.688	0.574	0.62
30%	1	1	1	9	0.697	0.584	0.642
30%	1	1	2	7	0.664	0.557	0.602
30%	1	1	2	6	0.674	0.566	0.616
30%	1	1	2	7	0.671	0.567	0.617
30%	1	1	2	8	0.675	0.568	0.62
30%	1	1	2	7	0.664	0.568	0.614
30%	1	1	2	6	0.678	0.571	0.624
30%	1	1	2	6	0.682	0.575	0.623
30%	1	1	2	6	0.681	0.576	0.621
30%	1	1	2	7	0.696	0.582	0.637
30%	1	1	2	6	0.689	0.582	0.632
30%	1	1	2	9	0.709	0.594	0.647
30%	1	1	2	10	0.731	0.617	0.673
30%	1	1	2	6	0.736	0.617	0.673
30%	1	2	1	8	0.679	0.566	0.62
30%	1	2	1	11	0.696	0.574	0.634
30%	1	2	1	7	0.706	0.586	0.642
30%	1	2	2	8	0.683	0.564	0.625
30%	1	2	2	7	0.683	0.57	0.627
30%	1	2	2	8	0.688	0.573	0.636
30%	1	2	2	8	0.694	0.575	0.633
30%	1	2	2	10	0.684	0.577	0.631
30%	1	2	2	8	0.69	0.578	0.633
30%	1	2	2	7	0.701	0.58	0.643
30%	1	2	2	8	0.703	0.582	0.643
30%	1	2	2	8	0.713	0.595	0.65
30%	1	2	2	8	0.719	0.601	0.663
30%	1	3	1	7	0.69	0.571	0.629
30%	1	3	1	8	0.699	0.583	0.634
30%	1	3	1	8	0.704	0.595	0.65
30%	1	3	1	9	0.747	0.615	0.684
30%	1	3	2	6	0.688	0.573	0.631
30%	1	3	2	6	0.7	0.581	0.643
30%	1	3	2	8	0.708	0.583	0.65

30%	1	3	2	11	0.708	0.593	0.653
30%	1	3	2	5	0.725	0.596	0.662
30%	1	3	2	6	0.731	0.607	0.67
30%	1	3	2	8	0.736	0.608	0.673
30%	1	3	2	7	0.735	0.611	0.668
30%	1	4	1	6	0.719	0.601	0.656
30%	1	4	1	7	0.744	0.62	0.684
30%	1	4	1	6	0.752	0.626	0.691
30%	1	4	1	9	0.771	0.636	0.708
30%	1	4	2	8	0.758	0.602	0.665
30%	1	4	2	9	0.73	0.61	0.673
30%	1	4	2	8	0.742	0.617	0.683
30%	1	4	2	9	0.741	0.623	0.686
30%	1	4	2	7	0.749	0.624	0.688
30%	2	1	1	7	0.706	0.593	0.649
30%	2	1	1	7	0.718	0.597	0.642
30%	2	1	1	8	0.709	0.597	0.644
30%	2	1	1	9	0.712	0.599	0.655
30%	2	1	2	6	0.693	0.578	0.634
30%	2	1	2	5	0.687	0.582	0.631
30%	2	1	2	6	0.699	0.586	0.642
30%	2	1	2	5	0.692	0.589	0.638
30%	2	1	2	6	0.712	0.598	0.657
30%	2	1	2	9	0.709	0.599	0.657
30%	2	1	2	8	0.711	0.606	0.654
30%	2	1	2	8	0.714	0.608	0.661
30%	2	1	2	6	0.721	0.617	0.667
30%	2	1	2	7	0.735	0.628	0.683
30%	2	2	1	8	0.681	0.578	0.632
30%	2	2	1	7	0.702	0.593	0.653
30%	2	2	1	9	0.703	0.599	0.656
30%	2	2	1	8	0.702	0.599	0.653
30%	2	2	1	10	0.705	0.601	0.662
30%	2	2	2	6	0.688	0.585	0.646
30%	2	2	2	6	0.689	0.588	0.647
30%	2	2	2	7	0.697	0.596	0.656
30%	2	2	2	10	0.71	0.602	0.668
30%	2	2	2	7	0.711	0.602	0.673
30%	2	2	2	8	0.728	0.62	0.683
30%	2	3	1	8	0.697	0.59	0.651
30%	2	3	1	9	0.7	0.598	0.6477
30%	2	3	1	7	0.708	0.607	0.67
30%	2	3	1	9	0.735	0.617	0.685

30%	2	3	2	6	0.704	0.596	0.662
30%	2	3	2	7	0.718	0.604	0.671
30%	2	3	2	10	0.717	0.612	0.681
30%	2	3	2	10	0.717	0.615	0.679
30%	2	3	2	7	0.718	0.62	0.678
30%	2	3	2	9	0.737	0.629	0.693
30%	2	4	1	6	0.695	0.597	0.641
30%	2	4	1	8	0.71	0.61	0.659
30%	2	4	1	8	0.714	0.616	0.664
30%	2	4	1	9	0.723	0.621	0.677
30%	2	4	1	9	0.733	0.63	0.691
30%	2	4	1	11	0.742	0.64	0.697
30%	2	4	1	10	0.764	0.651	0.715
30%	2	4	2	8	0.696	0.594	0.647
30%	2	4	2	8	0.714	0.611	0.666
30%	2	4	2	8	0.734	0.613	0.666
30%	2	4	2	7	0.718	0.618	0.672
30%	2	4	2	10	0.724	0.627	0.684
30%	2	4	2	9	0.736	0.634	0.692
30%	3	1	1	9	0.611	0.516	0.544
30%	3	1	1	9	0.621	0.523	0.555
30%	3	1	1	7	0.652	0.557	0.59
30%	3	1	1	7	0.658	0.563	0.596
30%	3	1	2	6	0.612	0.523	0.551
30%	3	1	2	4	0.617	0.524	0.554
30%	3	1	2	7	0.632	0.534	0.567
30%	3	1	2	7	0.636	0.539	0.576
30%	3	1	2	5	0.633	0.542	0.576
30%	3	1	2	4	0.637	0.543	0.574
30%	3	1	2	7	0.641	0.545	0.58
30%	3	1	2	6	0.647	0.548	0.584
30%	3	1	2	5	0.646	0.551	0.586
30%	3	1	2	5	0.655	0.557	0.59
30%	3	1	2	9	0.67	0.573	0.609
30%	3	1	2	9	0.669	0.576	0.615
30%	3	1	2	9	0.678	0.581	0.617
30%	3	1	2	13	0.68	0.581	0.617
30%	3	2	1	9	0.623	0.537	0.575
30%	3	2	1	6	0.651	0.562	0.604
30%	3	2	1	7	0.664	0.57	0.613
30%	3	2	1	9	0.674	0.573	0.614
30%	3	2	2	5	0.65	0.562	0.601
30%	3	2	2	6	0.661	0.568	0.611

30%	3	2	2	6	0.663	0.57	0.609
30%	3	2	2	8	0.668	0.577	0.622
30%	3	2	2	10	0.688	0.589	0.64
30%	3	2	2	8	0.691	0.593	0.639
30%	3	2	2	11	0.694	0.599	0.646
30%	3	2	2	9	0.703	0.604	0.649
30%	3	2	2	10	0.711	0.608	0.656
30%	3	3	1	8	0.677	0.579	0.625
30%	3	3	1	7	0.681	0.584	0.628
30%	3	3	1	7	0.684	0.586	0.625
30%	3	3	1	8	0.708	0.602	0.647
30%	3	3	2	7	0.668	0.572	0.617
30%	3	3	2	6	0.678	0.58	0.625
30%	3	3	2	9	0.681	0.584	0.63
30%	3	3	2	9	0.711	0.611	0.659
30%	3	3	2	11	0.735	0.628	0.677
30%	3	4	1	9	0.678	0.581	0.625
30%	3	4	1	8	0.694	0.592	0.636
30%	3	4	1	8	0.694	0.592	0.642
30%	3	4	1	7	0.705	0.6	0.652
30%	3	4	1	12	0.702	0.605	0.657
30%	3	4	1	8	0.726	0.621	0.067
30%	3	4	2	9	0.701	0.601	0.658
30%	3	4	2	13	0.713	0.612	0.664
30%	3	4	2	9	0.772	0.621	0.656
40%	1	1	1	6	0.656	0.554	0.586
40%	1	1	1	6	0.721	0.595	0.641
40%	1	1	1	8	0.723	0.601	0.656
40%	1	1	1	4	0.716	0.606	0.651
40%	1	1	1	6	0.722	0.61	0.663
40%	1	1	2	8	0.695	0.585	0.632
40%	1	1	2	4	0.703	0.588	0.63
40%	1	1	2	4	0.725	0.599	0.648
40%	1	1	2	5	0.717	0.6	0.647
40%	1	1	2	4	0.719	0.607	0.647
40%	1	1	2	6	0.735	0.617	0.67
40%	1	1	2	5	0.731	0.62	0.007
40%	1	1	2	8	0.739	0.621	0.676
40%	1	1	2	5	0.752	0.628	0.686
40%	1	1	2	7	0.763	0.64	0.697
40%	1	1	2	6	0.696	0.641	0.691
40%	1	2	1	8	0.685	0.563	0.62
40%	1	2	1	9	0.706	0.575	0.636

40%	1	2	1	7	0.701	0.579	0.637
40%	1	2	1	8	0.771	0.629	0.704
40%	1	2	2	5	0.709	0.584	0.643
40%	1	2	2	7	0.726	0.596	0.668
40%	1	2	2	6	0.734	0.597	0.662
40%	1	2	2	6	0.73	0.602	0.664
40%	1	2	2	6	0.746	0.611	0.676
40%	1	2	2	9	0.749	0.617	0.687
40%	1	2	2	7	0.747	0.618	0.688
40%	1	2	2	11	0.753	0.625	0.698
40%	1	2	2	11	0.756	0.627	0.694
40%	1	2	2	8	0.778	0.633	0.709
40%	1	2	2	9	0.776	0.637	0.709
40%	1	3	1	6	0.769	0.625	0.693
40%	1	3	1	8	0.786	0.636	0.703
40%	1	3	1	6	0.801	0.644	0.719
40%	1	3	1	7	0.801	0.644	0.721
40%	1	3	2	7	0.764	0.628	0.698
40%	1	3	2	7	0.783	0.636	0.708
40%	1	3	2	7	0.8	0.641	0.72
40%	1	3	2	5	0.801	0.648	0.723
40%	1	3	2	11	0.808	0.653	0.736
40%	1	3	2	7	0.803	0.655	0.726
40%	1	3	2	5	0.794	0.657	0.724
40%	1	3	2	5	0.813	0.659	0.735
40%	1	3	2	9	0.814	0.661	0.736
40%	1	3	2	11	0.81	0.677	0.755
40%	1	4	1	6	0.745	0.63	0.685
40%	1	4	1	5	0.774	0.65	0.709
40%	1	4	1	8	0.78	0.66	0.723
40%	1	4	1	5	0.807	0.678	0.74
40%	1	4	2	7	0.759	0.642	0.704
40%	1	4	2	5	0.779	0.66	0.723
40%	1	4	2	7	0.801	0.679	0.745
40%	1	4	2	7	0.833	0.692	0.769
40%	1	4	2	8	0.832	0.699	0.765
40%	2	1	1	10	0.629	0.537	0.568
40%	2	1	1	7	0.639	0.539	0.578
40%	2	1	1	9	0.64	0.543	0.577
40%	2	1	1	6	0.658	0.555	0.599
40%	2	1	2	7	0.636	0.541	0.573
40%	2	1	2	8	0.634	0.544	0.572
40%	2	1	2	5	0.646	0.545	0.579

40%	2	1	2	5	0.646	0.549	0.583
40%	2	1	2	9	0.653	0.554	0.589
40%	2	1	2	9	0.677	0.571	0.619
40%	2	1	2	7	0.674	0.572	0.611
40%	2	1	2	8	0.695	0.585	0.627
40%	2	1	2	8	0.689	0.585	0.623
40%	2	1	2	9	0.699	0.593	0.635
40%	2	1	2	7	0.732	0.63	0.683
40%	2	2	1	8	0.645	0.542	0.585
40%	2	2	1	8	0.666	0.557	0.604
40%	2	2	1	6	0.675	0.565	0.614
40%	2	2	1	8	0.681	0.575	0.597
40%	2	2	2	6	0.646	0.542	0.578
40%	2	2	2	9	0.644	0.543	0.582
40%	2	2	2	5	0.648	0.545	0.582
40%	2	2	2	11	0.652	0.551	0.594
40%	2	2	2	11	0.656	0.552	0.596
40%	2	2	2	11	0.661	0.556	0.599
40%	2	2	2	9	0.671	0.563	0.601
40%	2	2	2	8	0.666	0.563	0.599
40%	2	2	2	12	0.671	0.566	0.605
40%	2	2	2	8	0.688	0.577	0.619
40%	2	3	1	6	0.653	0.552	0.596
40%	2	3	1	8	0.664	0.56	0.604
40%	2	3	1	8	0.68	0.577	0.628
40%	2	3	2	6	0.637	0.541	0.579
40%	2	3	2	10	0.645	0.549	0.591
40%	2	3	2	5	0.652	0.552	0.595
40%	2	3	2	10	0.668	0.571	0.617
40%	2	3	2	7	0.719	0.608	0.654
40%	2	4	1	12	0.648	0.55	0.577
40%	2	4	1	6	0.662	0.56	0.606
40%	2	4	1	10	0.734	0.622	0.666
40%	2	4	2	12	0.631	0.532	0.569
40%	2	4	2	6	0.656	0.554	0.595
40%	2	4	2	10	0.661	0.558	0.601
40%	2	4	2	6	0.67	0.567	0.61
40%	2	4	2	10	0.697	0.587	0.633
40%	2	4	2	7	0.7	0.591	0.643
40%	3	1	1	10	0.631	0.528	0.567
40%	3	1	1	10	0.663	0.552	0.594
40%	3	1	1	8	0.669	0.556	0.601
40%	3	1	1	5	0.68	0.574	0.617

40%	3	1	2	4	0.627	0.521	0.555
40%	3	1	2	5	0.663	0.552	0.595
40%	3	1	2	5	0.661	0.555	0.591
40%	3	1	2	5	0.667	0.559	0.597
40%	3	1	2	5	0.662	0.56	0.598
40%	3	1	2	7	0.668	0.565	0.598
40%	3	1	2	7	0.672	0.566	0.603
40%	3	1	2	4	0.681	0.573	0.617
40%	3	1	2	6	0.683	0.573	0.616
40%	3	1	2	6	0.716	0.592	0.642
40%	3	2	1	11	0.671	0.553	0.606
40%	3	2	1	6	0.7	0.574	0.633
40%	3	2	1	5	0.688	0.577	0.619
40%	3	2	1	8	0.71	0.592	0.644
40%	3	2	2	5	0.651	0.537	0.579
40%	3	2	2	6	0.66	0.547	0.582
40%	3	2	2	4	0.687	0.565	0.617
40%	3	2	2	7	0.685	0.565	0.613
40%	3	2	2	7	0.678	0.565	0.614
40%	3	2	2	8	0.685	0.566	0.614
40%	3	2	2	9	0.688	0.567	0.617
40%	3	2	2	6	0.676	0.57	0.615
40%	3	2	2	9	0.694	0.575	0.632
40%	3	2	2	10	0.704	0.579	0.63
40%	3	2	2	10	0.699	0.585	0.639
40%	3	3	1	6	0.691	0.575	0.624
40%	3	3	1	7	0.713	0.588	0.65
40%	3	3	1	6	0.721	0.598	0.657
40%	3	3	1	8	0.727	0.606	0.661
40%	3	3	2	5	0.64	0.532	0.57
40%	3	3	2	5	0.651	0.541	0.583
40%	3	3	2	5	0.66	0.548	0.598
40%	3	3	2	11	0.654	0.548	0.587
40%	3	3	2	6	0.668	0.55	0.601
40%	3	3	2	11	0.679	0.563	0.607
40%	3	3	2	9	0.689	0.572	0.627
40%	3	4	1	5	0.651	0.55	0.591
40%	3	4	1	7	0.66	0.56	0.601
40%	3	4	1	7	0.667	0.565	0.602
40%	3	4	1	6	0.689	0.575	0.629
40%	3	4	1	7	0.684	0.579	0.624
40%	3	4	2	5	0.646	0.55	0.587
40%	3	4	2	7	0.667	0.562	0.607

40%	3	4	2	8	0.66	0.562	0.603
40%	3	4	2	4	0.665	0.566	0.609
40%	3	4	2	7	0.673	0.568	0.613
40%	3	4	2	11	0.686	0.582	0.626
40%	3	4	2	11	0.695	0.595	0.639

APPENDIX V

MICROSCOPIC + MACROSCOPIC ATTRIBUTES SUMMARY (RING WIDTH AND FIBER LENGTH)

Treat	Tree	Bolt	Comp	Radial	Age	GR	RW	FL
10%	1	1	1	1	48	5	0.97	0.89
10%	1	1	1	2	48	10	3.19	1.05
10%	1	1	1	3	48	15	3.94	1.15
10%	1	1	1	4	48	20	2.9	1.19
10%	1	1	2	5	48	25	2.98	1.2
10%	1	1	2	6	48	30	2.46	1.22
10%	1	1	2	7	48	35	2.46	1.26
10%	1	1	2	8	48	40	2.03	1.27
10%	1	1	2	9	48	45	1.87	1.27
10%	1	4	1	1	48	5	1.42	0.86
10%	1	4	2	2	48	10	2.34	0.97
10%	1	4	2	3	48	15	2.18	1.05
10%	1	4	2	4	48	20	1.65	1.1
10%	1	4	2	5	48	25	1.5	1.14
10%	1	4	2	6	48	30	1.42	1.13
10%	2	1	1	1	48	5	0	0.9
10%	2	1	1	2	48	10	1.77	1.02
10%	2	1	1	3	48	15	3.53	1.14
10%	2	1	1	4	48	20	2.31	1.15
10%	2	1	2	5	48	25	1.99	1.17
10%	2	1	2	6	48	30	1.59	1.18
10%	2	1	2	7	48	35	2.27	1.2
10%	2	1	2	8	48	40	1.78	1.21
10%	2	1	2	9	48	45	1.83	1.21
10%	2	4	1	1	48	5	0.74	0.86
10%	2	4	2	2	48	10	3.05	0.99
10%	2	4	2	3	48	15	2.84	1.05
10%	2	4	2	4	48	20	2.74	1.1
10%	2	4	2	5	48	25	2.17	1.15
10%	2	4	2	6	48	30	1.27	1.07
10%	3	1	1	1	39	5	1.16	0.88
10%	3	1	1	2	39	10	3.23	1.04
10%	3	1	1	3	39	15	1.96	1.14
10%	3	1	1	4	39	20	2.26	1.14
10%	3	1	2	5	39	25	2.88	1.19
10%	3	1	2	6	39	30	2.36	1.23
10%	3	1	2	7	39	35	2.45	1.25
10%	3	1	2	8	39	40	1.68	1.25
10%	3	1	2	9	39	45	2.08	1.26
10%	3	4	1	1	39	5	2.9	0.86
10%	3	4	2	2	39	10	1.47	0.99
10%	3	4	2	3	39	15	1.94	1.05

10%	3	4	2	4	39	20	1.89	1.1
10%	3	4	2	5	39	25	1.54	1.13
10%	3	4	2	6	39	30	1.5	1.15
30%	1	1	1	1	48	5	2.77	0.94
30%	1	1	1	2	48	10	3.64	1.09
30%	1	1	1	3	48	15	2.9	1.19
30%	1	1	1	4	48	20	2.23	1.22
30%	1	1	2	5	48	25	3.35	1.24
30%	1	1	2	6	48	30	3.28	1.25
30%	1	1	2	7	48	35	3.36	1.23
30%	1	1	2	8	48	40	3.08	1.26
30%	1	1	2	9	48	45	1.8	1.24
30%	1	4	1	1	48	5	2.54	0.88
30%	1	4	2	2	48	10	2.44	1.02
30%	1	4	2	3	48	15	3.51	1.05
30%	1	4	2	4	48	20	3.56	1.07
30%	1	4	2	5	48	25	2.43	1.1
30%	1	4	2	6	48	30	2.57	1.11
30%	2	1	1	1	48	5	0.93	1.01
30%	2	1	1	2	48	10	2.76	1.1
30%	2	1	1	3	48	15	3.38	1.13
30%	2	1	1	4	48	20	3.38	1.22
30%	2	1	2	5	48	25	5.25	1.18
30%	2	1	2	6	48	30	4.71	1.22
30%	2	1	2	7	48	35	3.56	1.2
30%	2	1	2	8	48	40	3.39	1.26
30%	2	1	2	9	48	45	3.33	1.26
30%	2	4	1	1	48	5	2.47	0.89
30%	2	4	2	2	48	10	3.01	1.04
30%	2	4	2	3	48	15	2.39	1.12
30%	2	4	2	4	48	20	2.04	1.16
30%	2	4	2	5	48	25	1.96	1.14
30%	2	4	2	6	48	30	1.56	1.17
30%	3	1	1	1	48	5	0.51	0.99
30%	3	1	1	2	48	10	2.65	1.09
30%	3	1	1	3	48	15	2.82	1.18
30%	3	1	1	4	48	20	2.74	1.17
30%	3	1	2	5	48	25	3.07	1.21
30%	3	1	2	6	48	30	3.84	1.19
30%	3	1	2	7	48	35	3.75	1.19
30%	3	1	2	8	48	40	2.55	1.22
30%	3	1	2	9	48	45	2.59	1.23
30%	3	4	1	1	48	5	2.46	0.91

30%	3	4	2	2	48	10	2.72	1.02
30%	3	4	2	3	48	15	2.17	1.08
30%	3	4	2	4	48	20	1.99	1.13
30%	3	4	2	5	48	25	2.24	1.08
30%	3	4	2	6	48	30	2.29	1.12
40%	1	1	1	1	47	5	0.91	0.91
40%	1	1	1	2	47	10	4.03	1.03
40%	1	1	1	3	47	15	4.61	1.17
40%	1	1	1	4	47	20	3.9	1.21
40%	1	1	2	5	47	25	5.09	1.21
40%	1	1	2	6	47	30	5.12	1.25
40%	1	1	2	7	47	35	3.81	1.26
40%	1	1	2	8	47	40	2.55	1.28
40%	1	1	2	9	47	45	2.3	1.28
40%	1	4	1	1	47	5	0.94	0.9
40%	1	4	2	2	47	10	3.26	1.01
40%	1	4	2	3	47	15	3.2	1.07
40%	1	4	2	4	47	20	3.95	1.12
40%	1	4	2	5	47	25	2.88	1.13
40%	1	4	2	6	47	30	3.19	1.15
40%	2	1	1	1	48	5	0.25	0.92
40%	2	1	1	2	48	10	2.39	1.05
40%	2	1	1	3	48	15	2.57	1.15
40%	2	1	1	4	48	20	2.59	1.15
40%	2	1	2	5	48	25	3.72	1.22
40%	2	1	2	6	48	30	3.01	1.23
40%	2	1	2	7	48	35	2.92	1.25
40%	2	1	2	8	48	40	2.39	1.27
40%	2	1	2	9	48	45	1.85	1.27
40%	2	4	1	1	48	5	0.06	0.9
40%	2	4	2	2	48	10	2	0.99
40%	2	4	2	3	48	15	2.03	1.08
40%	2	4	2	4	48	20	3.34	1.13
40%	2	4	2	5	48	25	2.2	1.17
40%	2	4	2	6	48	30	1.69	1.18
40%	3	1	1	1	47	5	0.38	0.95
40%	3	1	1	2	47	10	2.91	1.04
40%	3	1	1	3	47	15	2.17	1.1
40%	3	1	1	4	47	20	1.89	1.07
40%	3	1	2	5	47	25	4.77	1.16
40%	3	1	2	6	47	30	5.05	1.18
40%	3	1	2	7	47	35	3.96	1.18
40%	3	1	2	8	47	40	2.27	1.17

40%	3	1	2	9	47	45	2.41	1.17
40%	3	4	1	1	47	5	0.29	0.83
40%	3	4	2	2	47	10	2.01	0.93
40%	3	4	2	3	47	15	2.63	0.98
40%	3	4	2	4	47	20	4.93	1.06
40%	3	4	2	5	47	25	2.15	1.09
40%	3	4	2	6	47	30	2.18	1.12

APPENDIX VI

MICROSCOPIC + MACROSCOPIC ATTRIBUTES SUMMARY (FIBER WIDTH, VESSEL WIDTH, VESSEL LENGTH AND VESSELS PER GRAM)

Treat	Tree	FL_STD	FL_COV	FW	FW_STD	FW_COV	VL	VW	V_G
10%	1	0.0074	0.83	20.2	0.294	1.46	0.78	127.5	68.1
10%	1	0.0098	0.93	20.5	0.28	1.36	0.78	127.5	68.1
10%	1	0.0115	1	20.6	0.272	1.32	0.78	127.5	68.1
10%	1	0.0125	1.05	20.6	0.269	1.3	0.78	127.5	68.1
10%	1	0.0127	1.06	20.7	0.264	1.28	0.72	118.6	77.5
10%	1	0.0129	1.06	20.7	0.267	1.29	0.78	0.78	97.8
10%	1	0.0138	1.09	20.6	0.268	1.3	0.75	127	96.4
10%	1	0.0137	1.08	20.6	0.275	1.34	0.71	128	94.3
10%	1	0.0138	1.09	20.4	0.278	1.36	0.7	121.9	83
10%	1	0.0081	0.94	18.9	0.323	1.71	0.658	104.1	32
10%	1	0.0094	0.97	19.2	0.316	1.65	0.658	104.1	32
10%	1	0.0113	1.08	19.9	0.298	1.49	0.658	104.1	32
10%	1	0.0119	1.08	19.8	0.305	1.54	0.658	104.1	32
10%	1	0.013	1.14	20.2	0.292	1.45	0.658	104.1	32
10%	1	0.0132	1.17	20.1	0.295	1.46	0.658	104.1	32
10%	2	0.0078	0.87	19.9	0.305	1.53	0.72	107.3	39.9
10%	2	0.0097	0.95	20.4	0.281	1.38	0.72	107.3	39.9
10%	2	0.0114	1.01	20.5	0.275	1.34	0.72	107.3	39.9
10%	2	0.012	1.05	20.5	0.275	1.34	0.72	112.9	44.9
10%	2	0.0124	1.06	20.6	0.27	1.31	0.69	120.4	44.9
10%	2	0.0126	1.07	20.6	0.267	1.3	0.61	105.7	36.7
10%	2	0.0127	1.06	20.7	0.262	1.26	0.83	129.8	44.5
10%	2	0.0129	1.07	20.5	0.269	1.31	0.8	138.8	23.7
10%	2	0.0129	1.07	20.5	0.269	1.31	0.8	138.8	23.7
10%	2	0.0077	0.89	19.7	0.307	1.55	0.658	104.1	32
10%	2	0.01	1.01	20.2	0.302	1.49	0.658	104.1	32
10%	2	0.0119	1.13	20.5	0.284	1.38	0.658	104.1	32
10%	2	0.0121	1.1	20.5	0.284	1.39	0.658	104.1	32
10%	2	0.0127	1.11	20.1	0.299	1.49	0.658	104.1	32
10%	2	0.0118	1.1	20.4	0.297	1.46	0.658	104.1	32
10%	3	0.0075	0.85	19.6	0.311	1.59	0.59	105.3	51.6
10%	3	0.0095	0.91	20	0.3	1.5	0.59	105.3	51.6
10%	3	0.0109	0.96	20.3	0.279	1.38	0.59	105.3	51.6
10%	3	0.0111	0.97	20.3	0.28	1.38	0.59	105.3	51.6
10%	3	0.0117	0.98	20.3	0.28	1.38	0.72	113.4	59.6
10%	3	0.0129	1.05	20.4	0.279	1.37	0.73	109.2	44
10%	3	0.0129	1.04	20.4	0.279	1.37	0.67	111.3	42
10%	3	0.0133	1.07	20.4	0.28	1.37	0.7	107.6	47.7
10%	3	0.0133	1.06	20.4	0.28	1.37	0.69	110.8	22.8
10%	3	0.008	0.92	19.4	0.313	1.62	0.658	104.1	32

10%	3	0.0098	0.98	19.7	0.31	1.57	0.658	104.1	32
10%	3	0.0108	1.03	20.2	0.298	1.48	0.658	104.1	32
10%	3	0.0115	1.05	20	0.296	1.48	0.658	104.1	32
10%	3	0.0121	1.07	20	0.298	1.49	0.658	104.1	32
10%	3	0.0125	1.09	19.8	0.302	1.52	0.658	104.1	32
30%	1	0.0082	0.88	20.2	0.3	1.49	0.72	116.2	58.1
30%	1	0.0104	0.95	20.5	0.28	1.37	0.72	116.2	58.1
30%	1	0.0124	1.04	20.5	0.275	1.34	0.72	116.2	58.1
30%	1	0.0129	1.07	20.2	0.291	1.44	0.72	116.2	58.1
30%	1	0.0132	1.06	20.6	0.266	1.29	0.72	118.3	63.8
30%	1	0.0135	1.08	20.5	0.279	1.36	0.76	122.1	61.6
30%	1	0.0136	1.11	20.3	0.284	1.4	0.73	125	52.5
30%	1	0.0136	1.08	20.3	0.281	1.39	0.68	124.3	79.5
30%	1	0.0143	1.15	20.1	0.288	1.43	0.68	120.6	66.1
30%	1	0.0087	1	19.4	0.319	1.65	0.658	104.1	32
30%	1	0.0105	1.03	19.5	0.314	1.6	0.658	104.1	32
30%	1	0.0113	1.08	20.2	0.292	1.44	0.658	104.1	32
30%	1	0.0124	1.15	20.4	0.288	1.41	0.658	104.1	32
30%	1	0.0129	1.18	20.4	0.286	1.4	0.658	104.1	32
30%	1	0.0133	1.2	20.4	0.287	1.41	0.658	104.1	32
30%	2	0.0095	0.95	20.4	0.286	1.4	0.62	104	23.2
30%	2	0.0105	0.96	20.2	0.289	1.43	0.62	104	23.2
30%	2	0.0115	1.02	20.1	0.289	1.44	0.62	104	23.2
30%	2	0.0128	1.04	20.6	0.266	1.29	0.69	112.4	47.5
30%	2	0.0122	1.03	20.4	0.275	1.35	0.65	115.8	26.4
30%	2	0.0128	1.05	20.5	0.276	1.35	0.74	112.9	46
30%	2	0.013	1.09	20.5	0.274	1.34	0.72	123.6	42
30%	2	0.0139	1.1	20.4	0.273	1.34	0.67	120.5	68.7
30%	2	0.0139	1.1	20.4	0.273	1.34	0.67	120.5	68.7
30%	2	0.0083	0.93	19.4	0.32	1.65	0.658	104.1	32
30%	2	0.011	1.06	20.2	0.294	1.45	0.658	104.1	32
30%	2	0.0127	1.14	20.4	0.277	1.35	0.658	104.1	32
30%	2	0.0134	1.15	20.4	0.286	1.4	0.658	104.1	32
30%	2	0.0141	1.23	20.6	0.28	1.36	0.658	104.1	32
30%	2	0.0144	1.23	20.4	0.288	1.41	0.658	104.1	32
30%	3	0.0093	0.94	20	0.301	1.5	0.54	101.8	43.2
30%	3	0.0108	0.99	20.3	0.291	1.43	0.69	110.3	43.2
30%	3	0.0126	1.07	20.5	0.273	1.33	0.75	118.4	35.7
30%	3	0.0122	1.04	20.5	0.277	1.35	0.73	118.5	41.4
30%	3	0.0122	1.01	20.7	0.27	1.3	0.73	115.8	44
30%	3	0.0131	1.11	20.6	0.274	1.33	0.76	128.2	53.6
30%	3	0.0129	1.08	20.5	0.28	1.37	0.67	117.8	58.7
30%	3	0.0135	1.11	20.5	0.277	1.35	0.7	123.9	38.5

30%	3	0.0137	1.11	20.4	0.284	1.39	0.76	132.5	55.5
30%	3	0.0087	0.95	19.6	0.316	1.61	0.658	104.1	32
30%	3	0.0105	1.02	20.2	0.299	1.48	0.658	104.1	32
30%	3	0.0119	1.1	20.3	0.296	1.46	0.658	104.1	32
30%	3	0.013	1.15	19.8	0.308	1.56	0.658	104.1	32
30%	3	0.0134	1.23	20	0.304	1.52	0.658	104.1	32
30%	3	0.0136	1.22	20.1	0.302	1.5	0.658	104.1	32
40%	1	0.0078	0.86	20	0.295	1.47	0.64	116.1	71.9
40%	1	0.0098	0.95	20.5	0.279	1.36	0.64	116.1	71.9
40%	1	0.012	1.03	20.6	0.27	1.31	0.64	116.1	71.9
40%	1	0.0125	1.03	20.6	0.264	1.28	0.64	116.1	71.9
40%	1	0.0123	1.02	20.7	0.263	1.27	0.75	131.3	61.8
40%	1	0.0129	1.03	20.6	0.266	1.29	0.74	128.1	64.9
40%	1	0.0141	1.12	20.6	0.267	1.29	0.73	130.1	53.2
40%	1	0.0147	1.14	20.5	0.273	1.33	0.81	148.2	52.7
40%	1	0.0142	1.11	20.5	0.276	1.35	0.75	132.3	63.9
40%	1	0.0087	0.97	19.8	0.311	1.57	0.658	104.1	32
40%	1	0.0103	1.02	20.3	0.291	1.44	0.658	104.1	32
40%	1	0.0116	1.09	20.4	0.28	1.37	0.658	104.1	32
40%	1	0.0127	1.14	20.4	0.283	1.39	0.658	104.1	32
40%	1	0.013	1.16	20.1	0.299	1.48	0.658	104.1	32
40%	1	0.0136	1.19	19.9	0.3	1.51	0.658	104.1	32
40%	2	0.0084	0.92	19.2	0.32	1.66	0.7	116	32.7
40%	2	0.0102	0.97	19.6	0.308	1.57	0.7	116	32.7
40%	2	0.0119	1.03	20.1	0.292	1.45	0.7	116	32.7
40%	2	0.0118	1.03	20.2	0.282	1.39	0.66	119.3	49.9
40%	2	0.013	1.07	20.5	0.27	1.32	0.71	126.4	70.1
40%	2	0.0136	1.11	20.4	0.282	1.38	0.74	130.2	63.1
40%	2	0.0135	1.08	20.4	0.286	1.4	0.59	117.2	78.1
40%	2	0.0138	1.09	20.2	0.284	1.4	0.66	129.1	58.5
40%	2	0.0138	1.09	20.2	0.284	1.4	0.66	129.1	58.5
40%	2	0.0084	0.93	19.5	0.318	1.63	0.658	104.1	32
40%	2	0.0101	1.02	19.7	0.305	1.55	0.658	104.1	32
40%	2	0.0118	1.09	20.1	0.303	1.51	0.658	104.1	32
40%	2	0.0128	1.13	20.1	0.296	1.47	0.658	104.1	32
40%	2	0.0132	1.13	20	0.299	1.5	0.658	104.1	32
40%	2	0.0136	1.15	19.6	0.307	1.57	0.658	104.1	32
40%	3	0.0083	0.88	20	0.301	1.5	0.63	105.3	17.2
40%	3	0.0097	0.94	20.1	0.301	1.5	0.63	105.3	17.2
40%	3	0.0107	0.97	19.8	0.311	1.57	0.63	105.3	17.2
40%	3	0.0103	0.96	20.2	0.295	1.46	0.6	102.6	42
40%	3	0.0116	1	20.5	0.269	1.31	0.65	106.6	40.9
40%	3	0.0122	1.03	20.3	0.284	1.4	0.67	111.9	71.8

40%	3	0.0131	1.11	20.2	0.291	1.44	0.66	121.5	63
40%	3	0.0125	1.07	20.3	0.284	1.4	0.67	113.8	67.2
40%	3	0.0125	1.07	20.3	0.284	1.4	0.67	113.8	67.2
40%	3	0.0078	0.94	19.4	0.325	1.67	0.658	104.1	32
40%	3	0.0092	0.99	19.4	0.318	1.64	0.658	104.1	32
40%	3	0.0114	1.16	19.5	0.313	1.61	0.658	104.1	32
40%	3	0.0121	1.14	19.8	0.304	1.54	0.658	104.1	32
40%	3	0.013	1.2	19.7	0.306	1.55	0.658	104.1	32
40%	3	0.013	1.15	19.8	0.306	1.54	0.658	104.1	32