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IS WOOD CHARACTERISTICS MAPPING AN OPPORTUNITY TO OPTIMIZE THE VALUE CHAIN IN NORTHWESTERN ONTARIO? A CASE STUDY CONSIDERING EASTERN LARCH (LARIX LARICINA (Du ROI) K. KOCH) GROWN IN THE THUNDER BAY DISTRICT.

by

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Partial Fulfillment of the Requirements for the
Degree of Master of Forest Science Degree

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ABSTRACT

Miller, S.T. 2010. Is wood characteristics mapping an opportunity to optimize the value chain in northwestern Ontario? A case study considering eastern larch (*Larix laricina* (Du Roi) K. Koch) grown in the Thunder Bay district. 241 pp.

Keywords: eastern larch, northwestern Ontario tree species, value chain optimization, wood characteristics mapping, wood morphology, wood products.

Wood characteristic mapping was considered as a means for optimizing the value chain of northwestern Ontario tree species. A literature review was completed which investigated the relationship of wood morphology to wood characteristics and end use as related to potential opportunities for northwestern Ontario. It was found that there was insufficient study on the area of interest to make any definitive conclusions; save that research is needed. The literature did, however, provide a general understanding on issues being assessed.

Based on the findings of the literature review, a case study on mapping wood characteristics of eastern larch (*Larix laricina* (Du Roi) K. Koch) grown in the Thunder Bay district was completed. It was found that the greatest variability displayed by eastern larch wood grown in Thunder Bay district was between sites and radial position within trees. In all cases of statistical analysis, variance between sites was significant. Radial variability was significant for all the selected wood properties tested except for MOE perpendicular to the grain. Longitudinal or axial variability was significant in all the selected wood properties tested except for wood density.

Breast height sampling was found to be unsuitable for wood characteristics mapping since it only provides a general understanding of the grand means for the selected wood properties. The findings indicated that breast height sampling becomes less useful in second growth and small diameter trees, which would have a higher proportion of reaction wood than old growth stands at that axial position.

It was found that eastern larch is unique in that it has the morphology of a softwood but displays wood properties variance patterns which are more consistent with hardwoods. The results of the eastern larch case study indicate that eastern larch has fairly homogeneous wood properties within the stem with respect to end use design criteria and that a predictive model for the species is possible.

Wood characteristics mapping of eastern larch grown in the Thunder Bay district was found to be possible. It was found that mapping of wood characteristics of eastern larch would allow the forest sector of northwestern Ontario to optimize the value and increase the overall value of eastern larch by as much as 31%.

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I credit the completion of this report to my supervisor who ensured that I stayed motivated and focused on the task at hand. I am sincerely grateful.

1.0 Introduction

The demand for forest products traditionally produced in Canada has levelled off in recent years as a result of a variety of offshore issues, while over the last 10 years the overall demand for wood products throughout the world has increased. According to the literature, Canada's wood products exports have been diminishing since 2000 (Figure 1) (Statistics Canada, 2010), while world wide demand for wood products has increased steadily in areas including bio-fuels, engineered wood products, wood composite products and value-added products (Roberts, 2007). The problem seems to stem from the approach the Canadian forest sector uses to develop their product lines, and how they deal with their clients.

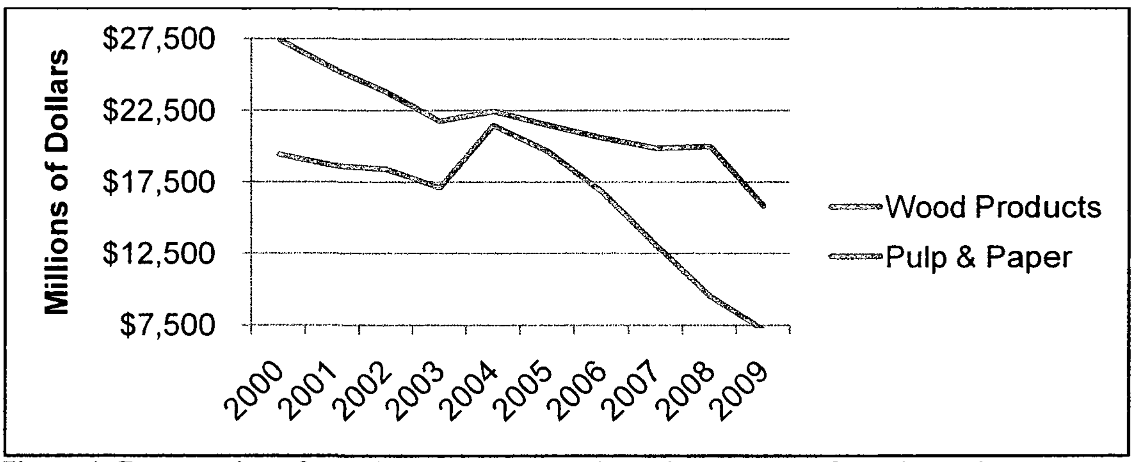


Figure 1. Export value of wood products and pulp and paper manufacturing subsectors (Statistics Canada 2010).

The forest sector in Canada has traditionally used a product push versus pull approach in developing products for sale. They identify a product that can be produced cost effectively, and maximize efforts to produce a low cost product for massive sales. However, this approach does not seem to be working in the changing global market place due to the emergence of many low cost products. A more responsive Canadian forest sector must identify which products are in demand, and what are the best tree species and manufacturing processes needed to supply the products that customers require. This market-response approach requires a research-based understanding of the useful characteristics and limitations of the harvestable wood.

1.1 Forestry – economic engine

Today, the forest sector continues to be an integral part of the Canadian economy and is the largest natural resource based sector. The Canadian forest sector has two main manufacturing subsectors: wood products manufacturing, which includes value-added wood products; and pulp and paper manufacturing. Between 1999 and 2005 the wood products manufacturing subsector had a steadily increasing Gross Domestic Product (GDP) (Figure 2) (Statistic Canada, 2010). By 2004 the Canadian forest sector was impressive by any measure of economic activity (Pricewaterhouse Coopers, 2004):

- $50.7 billion total sales, with exports contributing $39.5 billion
- $1.4 billion net earnings; making $7.2 billion in payments to various levels of government
- 10.4% of total Canadian exports, adding $32.8 billion to Canada's trade balance
- 895,000 jobs, through direct and indirect employment.

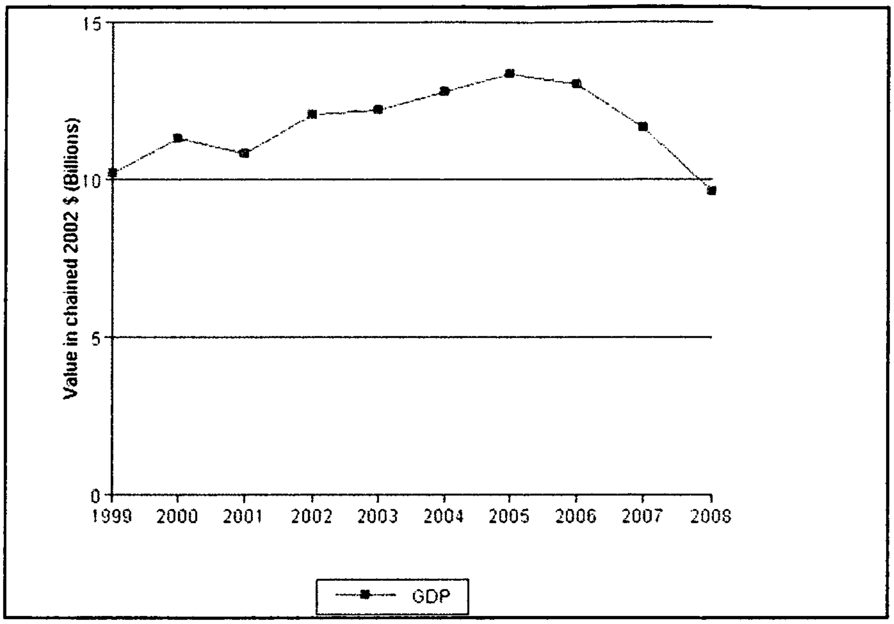


Figure 2. GDP of wood products manufacturing subsector (Statistics Canada 2010).

In contrast to the wood products subsector, the pulp and paper subsector has had a relatively flat GDP growth between 2000 and 2005, and has negative growth in GDP for the last 5 years (Figure 3) (Statistic Canada, 2010). However, despite these problems the forest sector ranks second only to the automotive industry in terms of national economic impact, and is the largest source of employment in many regions of Canada, such as northwestern Ontario (Service Ontario, 2008; Natural Resources Canada, 2009). Ontario's forest industry is the major employer in more than 50 northern communities. Prior to the recent global recession, Ontario's forest sector employed almost 90,000 people, producing over $15 billion a year in wood products and exporting over $9 billion. The forest sector is clearly one of Ontario's largest industries (Pricewaterhouse Coopers, 2004; Rosehart, 2008; Service Ontario, 2008).

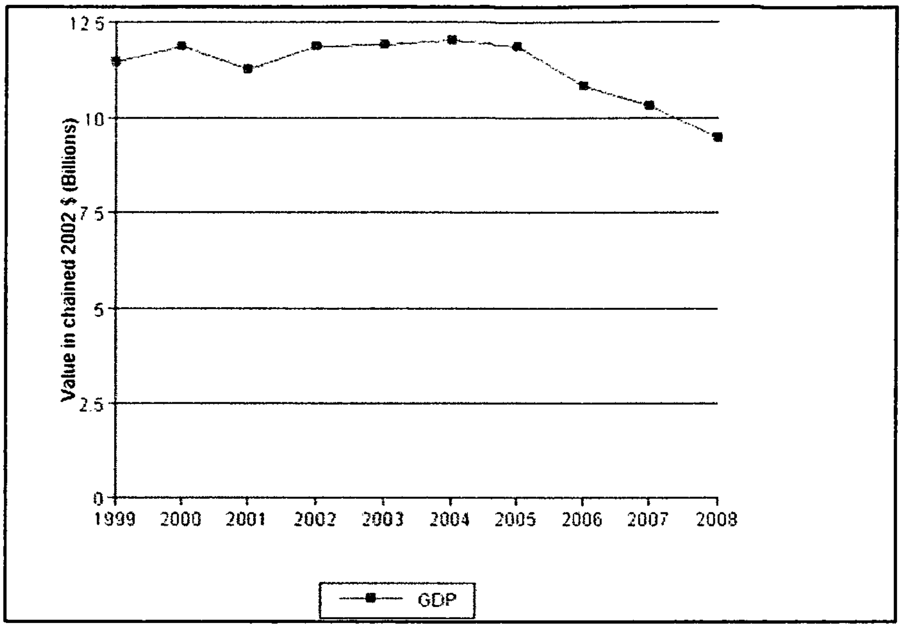


Figure 3. GDP of the pulp and paper manufacturing subsector (Statistics Canada 2010).

Unfortunately, 88.8% of these exports were to the United States, a market which has been in decline since 2006 (Table 1). Such a heavy dependence on a single market has placed the forest industry in northwestern Ontario on the verge of collapse.

Table 1. Wood products manufacturing – top 3 export markets (Statistics Canada 2010).

Country	2005	2006	2007	2008	2009
United States	88.8%	86.4%	82.1%	77.4%	74.3%
China	6.0%	6.9%	7.1%	9.1%	9.4%
Japan	0.5%	0.6%	1.2%	2.2%	4.8%

The Ontario Government understood the significance of the forest industry when it created the Minister's Council on Forest Sector Competitiveness. The purpose of the council was to remove barriers to maintain a sustainable industry which “is the economic bedrock of Northern Ontario." The report stated that more than 40 communities rely on the forest industry for jobs and revenue; and for some, "the industry is the only major employer." The

Council has made a number of recommendations to close the competitiveness gap with global markets (Millard, 2005).

1.1.1 Objectives

The broad goal of this thesis is to review the current state of knowledge regarding the wood characteristics of northwestern Ontario tree species and identify new market opportunities for the region's forest sector using wood characteristics mapping. The purpose of this thesis is to assess whether wood characteristics mapping of northwestern Ontario tree species will increase the understanding of the available wood resources in the region to match end use characteristics with the wood characteristics at harvest.

To accomplish the objectives of this thesis, the paper is divided into two broad sections of research:

1. investigation of the relationship between wood morphology and wood quality, using secondary information on northwestern Ontario tree species; and
2. mapping the wood characteristics of eastern larch *(Larix laricina* (Du Roi) K. Koch), which encompasses destructive testing of wood specimens to determine the physical and mechanical wood properties for the species.

It is anticipated that by understanding these key areas, we will assist the forest sector in determining which products can be made from wood grown in northwestern Ontario, allowing the forest sector to exploit its competitive advantages and overcome market risks.

1.1.1.1 Research questions

To ensure the objectives of this thesis are met the following research questions were considered:

1. Is research needed on the wood characteristics of northwestern Ontario tree species?
2. Does the wood characteristics of eastern larch display axial and radial variability?
3. Does the procedure of breast height sampling provide a reliable prediction of the overall wood properties of eastern larch?
4. Is there significant correlation between relative density and mechanical properties of eastern larch to develop a predictive model?

The scope of research question 1 was limited to the following commercial tree species, identified as important to northwestern Ontario by the Ontario Ministry of Natural Resources (Figure 4):

- black spruce *(Picea mariana* (Mill.) B.S.P.);
- trembling aspen *(Populus tremuloides* Michx.);
- jack pine *(Pinus banksiana* Lamb.);
- white birch *(Betula papyrifera* Marsh.);
- balsam fir *(Abies balsamea* (L.) Mill.);
- eastern white cedar *(Thuja occidentalis* L.);
- eastern larch *(Larix laricina* (Du Roi) K. Koch);
- white spruce *Picea glauca* (Moench) Voss;
- red pine *(Pinus resinosa* Ait.);
- eastern white pine *(Pinus strobus* L.);
- black ash *(Fraxinus nigra* Marsh.);
- red maple *(Acer rubrum* L.).

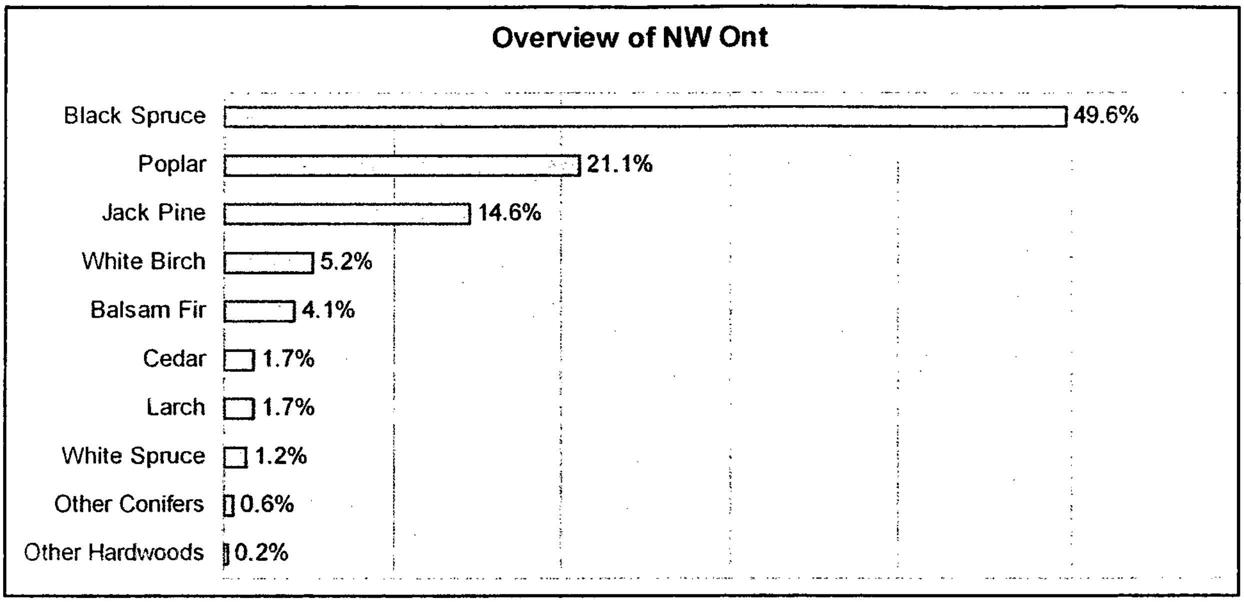


Figure 4. An overview of northwestern Ontario's forests (Service Ontario 2008).

The remaining research questions are limited in scope to eastern larch grown in the Thunder Bay District. These questions comprise a case study, using eastern larch, which contemplates the importance of wood characteristics mapping to the forest sector, while considering the relevance and validity of the available research on northwestern Ontario tree species.

2.0 Literature review

2.1 Relationship of wood morphology to wood quality

2.1.1 Tree growth

Trees grow by converting sugars, manufactured in the leaves through the process of photosynthesis, into organic compounds, which support new cell growth. In the presence of chlorophyll, captured sunlight in the green leaves is combined with water from the soil and carbon dioxide from the air to form glucose and other five and six carbon sugars. The by-product of the manufacture of the sugar is oxygen (Wilson, 1984; Walker, 1989; Bowyer and Smith, 2000; Bowyer *et al.*., 2003).

Tree growth is dictated through genetic programming, which controls tree species responses to environmental conditions, thereby determining the range of growth. In northwestern Ontario, for example, each species has evolved to avoid mortality or damage due to frost and drought by initiating and terminating annual growth by responding to increased moisture and average air temperature between 6 to 8° C (Rossi *et al.*, 2007; Thibeault-Martel, 2008; Rossi *et al.*, 2008; Gruber *et al.*, 2009). In the spring, once the minimum air temperature and moisture levels are present for a species, the roots transport water and stored nutrients to the crown of the tree to initiate bud burst. Wood growth begins after leaves are produced:

1. Height growth; to expand the crown, and
2. Diameter growth; to support the crown.

Research completed on cambial activity and wood growth, in the different parts of the tree, has produced contradictory results. What seems clear is that cambial activity and wood growth are highly variable within a tree, within a 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).

2.1.1.1 Growth in height

Height growth initiation closely follows the emergence of new leaves. Height growth is a result of repeated cell division of specialized reproducing cells in the tip of the main stem, the tips of the branches and the roots. These growth zones are areas of intense activity called apical meristems. As new cells are formed at the apical meristems, the specialized reproducing cells are pushed outward, leaving new tissue behind. The new cells, like bricks in a wall, are added to the top of an existing column of tissue, resulting in height growth (Panshin and de Zeeuw, 1980; Walker. 1989; Bowyer and Smith. 2000).
As illustrated by Table 2, different species grow to different heights. The literature indicates that not much is known about the mechanism that controls total height growth, other than heredity. However, site conditions are always a factor in all cell growth (Probine, 1963; Burns and Honkala, 1990; Harlow *et al.*, 1996; Powell, 2009). For example, white spruce grown in the Hudson Bay Lowland is shorter than is typical for the species (Jozsa, 2004).

Table 2. Variation of tree height within northwestern tree species (Zhang and Koubaa, 2008; Burns and Honkala, 1990a; Burns and Honkala, 1990b).

Tree Species of NWO.	Percent Volume of NWO Forests	Average Height (m)	Maximum Height (m)
black spruce (*Picea mariana* (Mill.) B.S.P.)	49.6	15.5	33.5
trembling aspen (*Populus tremuloides* Michx.)	21.1	26.5	48.0
jack pine (*Pinus banksiana* Lamb.)	14.6	20.0	30.5
white birch (*Betula papyrifera* Marsh.)	5.2	21.0	26.5
balsam fir (*Abies balsamea* (L.) Mill.)	4.1	18.0	27.4
eastern white cedar (*Thuja occidentalis* L.)	1.7	15.2	24.4
eastern larch (*Larix laricina* (Du Roi) K. Koch,)	1.7	20.0	35.1
white spruce (*Picea glauca* (Moench) Voss)	1.2	30.0	55.0
Other Conifers (incl. eastern white pine (*Pinus strobus* L.) and red pine (*Pinus resinosa* Ait.))	0.6	26.8	61.0
Other Hardwoods (Incl. red maple (*Acer rubrum* L.) and black ash (*Fraxinus nigra* Marsh.))	0.2	28.0	26.5

Trees in northwestern Ontario have not been studied to any great extent, however, the literature indicates that there is considerable variation between tree species and within species with regards to height of mature trees. Tree height is an important consideration when assessing the economic viability of harvesting and manufacturing wood products (British Columbia Forest Service, 2002).

2.1.1.2 Growth in diameter

Diameter growth takes place in the vascular cambium, a lateral meristem zone, composed of a tangential band of one to several cells thick located just beneath the inner bark. This very thin cambium layer completely sheaths the stem and branches (Figure 5) (Panshin and de Zeeuw, 1980; Walker, 1989; Bowyer *et al.*, 2003).

Figure 5. Illustration of cambium growth (Bowyer *et al.*, 2003).

The cambium cells have the capacity to divide repeatedly. These intensive activity cells may divide in one of two ways (Wilson, 1984; Walker, 1989; Bowyer and Smith, 2000; Bowyer *et al.*, 2003). The first type of cambium division results in two new cells:

- the first new cell remains in the cambium to further divide and produce of new cells; and
- the second cell becomes either a xylem (wood cell) or phloem cell (bark cell).

The second type of cambium cell division results in two new cambium cells in a tangential direction, both of which can divide and produce new cells. It is the dual role of the cambium cells that allows the cambium to increase in diameter as the tree diameter increases from new wood and bark cells (Figure 6) (Wilson, 1984; Walker, 1989; Bowyer and Smith, 2000).

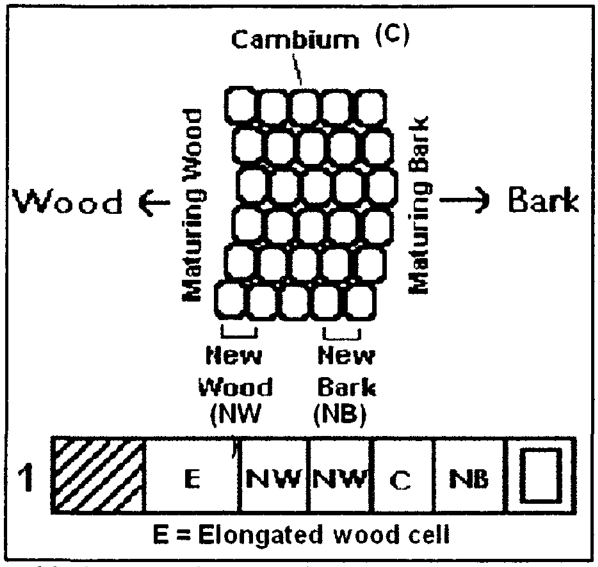


Figure 6. Cell division with the vascular cambium meristem (Bowyer and Smith 2000).

Figure 7 shows the process of development from new cambial cell to wood cell. All the cells (cambium, wood, and bark) were formed by cell division within the vascular cambium meristem. This process of cell division and development causes the cambium cell to expand the diameter of the tree by pushing outward (Wilson, 1984; Walker, 1989; Bowyer and Smith, 2000).

This process continues throughout the growing season, with the cambium producing new wood and new bark cells. However, the literature states that variation in diameter growth within a tree and a stand can vary greatly. The factors effecting growth are age, environmental conditions, and heredity. Heredity is thought to be the main cause for variation in diameter growth (Wilson, 1984; Walker, 1989; Bowyer and Smith, 2000; Bowyer *et al.*, 2003).

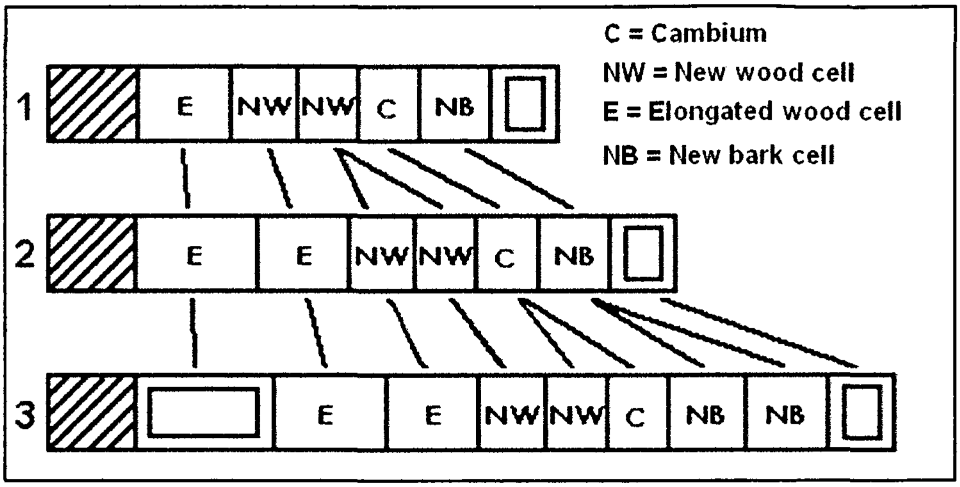


Figure 7. Growth in diameter – from cambium to wood and bark (Bowyer and Smith 2000).

The role of the cambium sheath in diameter growth allows the tree to cover up branch stubs and other wounds during diameter growth. This also produces wood with different characteristics within a stem. As the tree ages the bole becomes free of branches and the tree produces wood with higher strength properties (Panshin and de Zeeuw, 1980; Walker, 1989; Bowyer *et al.*, 2003). As Figure 5 showed, diameter and height growth collectively constitute expansion of the cambium sheath. Thus, diameter growth, like height growth, is an important consideration when assessing the economic viability of harvesting and manufacturing wood products (British Columbia Forest Service, 2002). Heredity seems to be the primary mechanism affecting diameter growth; therefore, variation in diameter growth between species and within a species is considerable (Table 3) (Bowyer and Smith, 2000).

Table 3. Available data of variation of average ring width and percent of latewood for northwestern Ontario commercial species (Zhang and Koubaa 2008).

Species	Average Ring Width (mm)
black spruce (*Picea mariana* (Mill.) B.S.P.)	2.51 to 4.05
white spruce (*Picea glauca* (Moench) Voss)	1.66 to 4.03
jack pine (*Pinus banksiana* Lamb.)	1.10 to 3.97
red pine (*Pinus resinosa* Ait.)	No data
eastern white pine (*Pinus strobus* L.)	No data
eastern white cedar (*Thuja occidentalis* L.)	No data
eastern larch (*Larix laricina* (Du Roi) K. Koch,)	1.2
balsam fir (*Abies balsamea* (L.) Mill.)	1.5
trembling aspen (*Populus tremuloides* Michx.)	No data
black ash (*Fraxinus nigra* Marsh.)	No data
red maple (*Acer rubrum* L.)	No data
white birch (*Betula papyrifera* Marsh.)	No data

2.1.2 Wood anatomy

Wood anatomy is important in defining the wood characteristics of a species. Features commonly identified in wood include: annual growth rings, consisting of alternating bands of earlywood and latewood; straight and spiral grain; microfibril angle; and tight and intergrown knots. It is important to understand why these features are formed in wood, as they affect the characteristics of the wood and the potential end uses of the wood.

2.1.2.1 Formation of wood

After cell division, a newly created wood cell lies just inside the cambium. This cell increases in diameter and length, and begins to develop a secondary wall layer. The cell has started the process of lignification, or hardening of tissue through the deposition of lignin during development of the secondary cell wall (Panshin and de Zeeuw, 1980; Bowyer and Smith, 2000; Bowyer *et al.*, 2003).

Rays (Figure 8) provide radial transport of the sap, which contains the basic building blocks for the creation of cellulose, hemicellulose, and lignin, to the newly formed wood cells (Wilson, 1984; Walker, 1989; Bowyer and Smith, 2000; Bowyer *et al.*, 2003; Panshin and de Zeeuw, 1980).

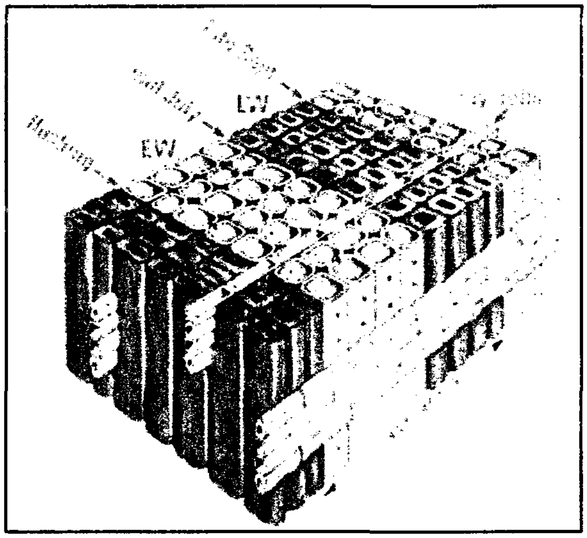


Figure 8. One years' growth (Jozsa and Middleton 1994).

Figure 9 shows the start of the development of the secondary cell wall, which forms as three distinct layers; S1, S2, and S3 (Bowyer and Smith, 2000; Bowyer *et al.*, 2003; Panshin and de Zeeuw, 1980).

The S1 layer forms with the coating of the ultra-thin inner surface of the primary wall. While S1 thickens, about four to six layers of microfibrils are deposited. Microfibril deposition within the S1 layer is oriented almost perpendicular to the long axis of the cell (Bowyer and Smith, 2000; Bowyer *et al.*, 2003; Panshin and de Zeeuw, 1980).

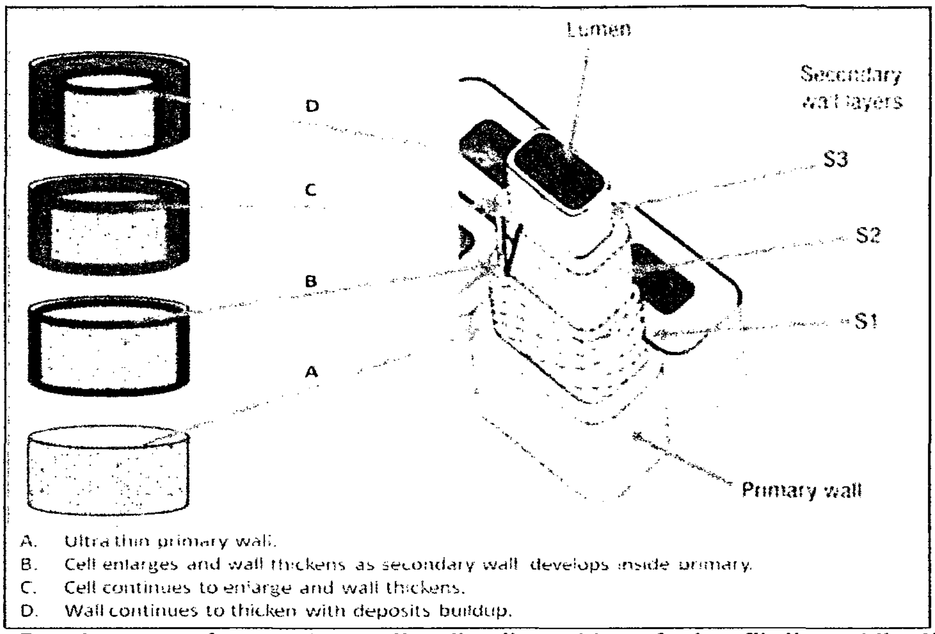


Figure 9. Development of secondary cell wall – disposition of microfibrils and lignification (Bowyer and Smith 2000).

The S2 layer forms just to the inside of S1, but is 8 to 30 times thicker. Microfibril layering within the S2 layer ranges from 30 microfibril layers in earlywood (EW) to 120+ layers in latewood (LW). The heavy layering of latewood accounts for the dense wood cells. Microfibril deposition within the S2 layer is oriented almost parallel to the long axis of the cell (or at no more than a 15° to 30° angle from parallel) (Bowyer and Smith, 2000; Bowyer *et al.*, 2003; Panshin and de Zeeuw, 1980).

The S3 layer forms just to the inside of S2, and is the same thickness as the S1. Similar to S1, S3 displays four to six layers of microfibrils. Microfibril deposition within the S3 layer, like within S1, is oriented almost perpendicular to the long axis of the cell (Bowyer and Smith, 2000; Bowyer *et al.*, 2003; Panshin and de Zeeuw, 1980).

Development of the S2 layer has the primary effect over wood quality due to its substantial volume relative to the S1 and S3 Layers. Changes to the S2 layer will affect wood quality greater than S1 and S3 layers combined. As the literature indicates, there is significant variation in S2 development within a stem and between species (Panshin and de Zeeuw, 1980). However, there has not been any direct research on the variability of S2 development within northwestern Ontario species.

2.1.2.2 Sapwood and heartwood

As growth slows in the fall, a surplus of photosynthate or sap starts to accumulate in the cambium. Most of the surplus sap is stored in the root system to support bud burst in the spring. Surplus sap, which has been delivered to the rays from the cambium, continues along the rays towards the pith, to the limit of radial movement associated with pit aspiration. Accumulated sugar-rich photosynthate begins to break down overtime and produce a variety of new compounds called extractives (Panshin and de Zeeuw, 1980; Mullins and McKnight, 1981; Jozsa and Middleton, 1994).

Heartwood development creates unique properties that are directly related to the death of parenchyma cells and the character and quantity of extractives present. The accumulation of extractives generally causes the wood at the heart of the tree to become dark compared to the outer wood, thus making heartwood distinguishable from sapwood (Figure 10) (Panshin and de Zeeuw, 1980; Jozsa and Middleton, 1994; Hoadley, 2000).

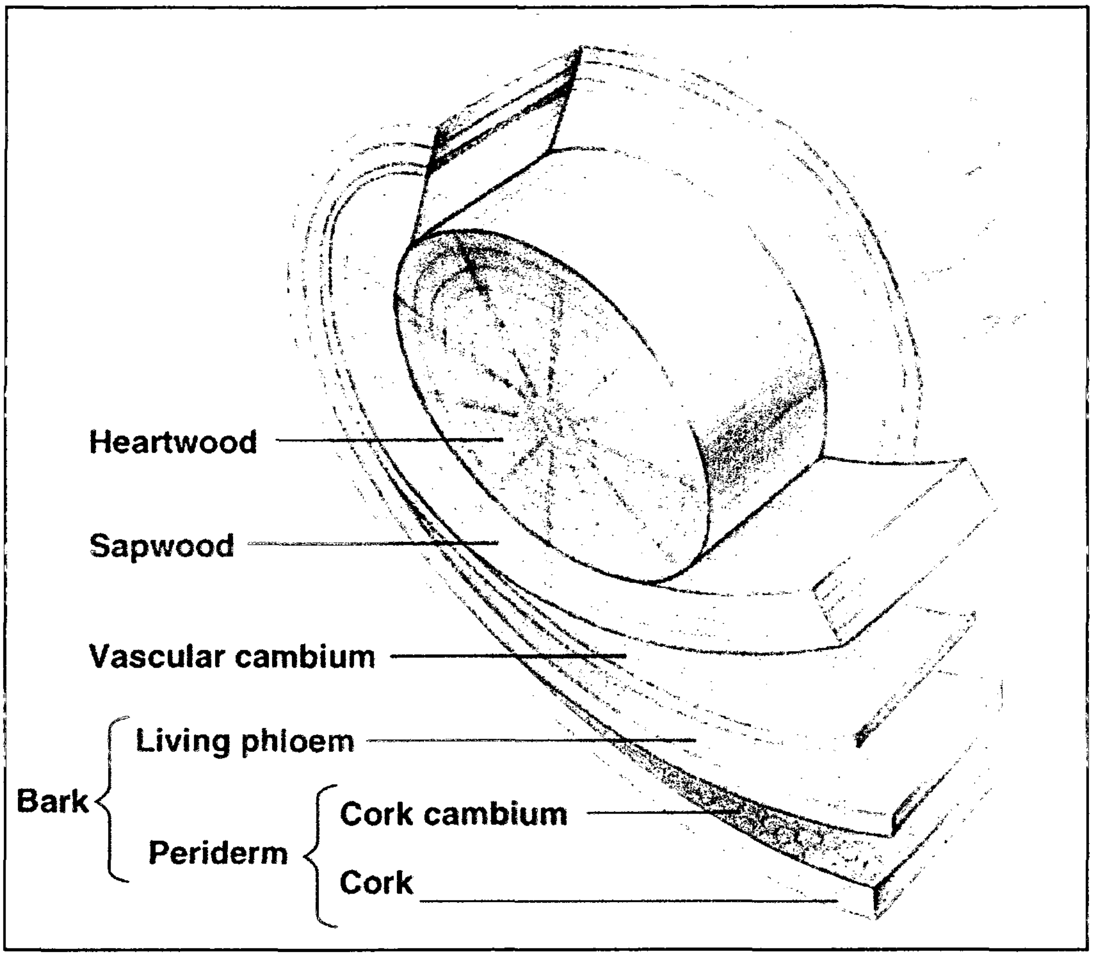


Figure 10. Cross section showing the living and dead parts of the stem (Wilson 2003).

Extractable compounds include waxes, oils, resins, fats, and tannins, along with aromatic and colouring materials. These compounds plug up the intricate structure of cell lumens and pits. The result is that cells near the centre of the tree are rendered non-functional as the extractives accumulate (Panshin and de Zeeuw, 1980; Jozsa and Middleton, 1994; Bowyer *et al.*, 2003).

The development of heartwood does not change the thickness or structure of the wood's cell walls. The wood cells are just impregnated with a variety of compounds, resulting in a large area in which all of the cells are non-functional (Panshin and de Zeeuw, 1980; Jozsa and Middleton, 1994; Hoadley, 2000; Bowyer *et al.*, 2003).

The formation of heartwood also disrupts the movement of water between cells because all cell lumens and pits become plugged. Thus, there is generally no difference in the strength of sapwood and extracted heartwood (heartwood where the extractives are removed) at equal moisture content. However, heartwood tends to have lower moisture content than sapwood, which affects how the two regions of wood should be dried when processed. The plugged cell lumens and pits tend to make heartwood more difficult to impregnate with chemical treatments that prevent decay compared to sapwood (Panshin and de Zeeuw, 1980; Jozsa and Middleton, 1994; Bowyer *et al.*, 2003).

As stated earlier, the unique properties of heartwood can be associated with the character and quantity of the extractives present. These properties could be a change in odour, as you would find in the heartwood of cedars (*Thuja*), or an increased resistance to decay and increased durability found in eastern larch (*Larix laricina* (Du Roi) K. Koch). Some extractives are toxic to or retard decay fungi. If one or more of these extractives is present in sufficient quantity, the heartwood may have increased durability. Thus, while the heartwood would have increased durability there would be no change in durability to the sapwood of the same tree (Table 4) (Bowyer and Smith, 2000; Bowyer *et al.*, 2003; Jozsa and Middleton. 1994).

The proportion of heartwood to sapwood can be highly variable between species and within species. Age, growth rate and site conditions all affect the proportion of heartwood to sapwood. Eastern larch sapwood is whitish, while heartwood ranges in colour from yellowish brown to russet brown, and the heartwood of fast growing eastern larch can have a reddish brown colour. Small saplings and young fast growing trees are void of heartwood as the entire stem is involved in sap conduction (Wang and DeGroot, 1996; Burns and Honkala, 1990a; Burns and Honkala, 1990b; Zhang and Koubaa, 2008).

Table 4. Grouping of some northwestern Ontario tree species by natural durability of heartwood (Zhang and Koubaa, 2008; Burns and Honkala, 1990a; Burns and Honkala, 1990b; Wang and DeGroot, 1996).

Highly Durable	Moderately Durable	Slightly or Non Durable
eastern white cedar	eastern larch eastern white pine	black ash balsam fir white birch red maple pines (other than eastern white pine) poplars spruces

2.1.2.3 Growth rings

As discussed, earlywood cells have thinner secondary walls and large lumens than the latewood cells. These differences in latewood and earlywood are particularly pronounced in softwoods, where the density of latewood is higher than that of earlywood (Panshin and de Zeeuw, 1980; Jozsa and Middleton, 1994; Bowyer and Smith, 2000; Bowyer *et al.*, 2003).

Growth rings are formed as a result of seasonal growth displaying difference in density between earlywood and latewood, which creates rings of dark and light wood (Figure 11). When the stem is viewed in cross section, a ring of the lighter earlywood plus the ring of the darker latewood forms one growth ring.

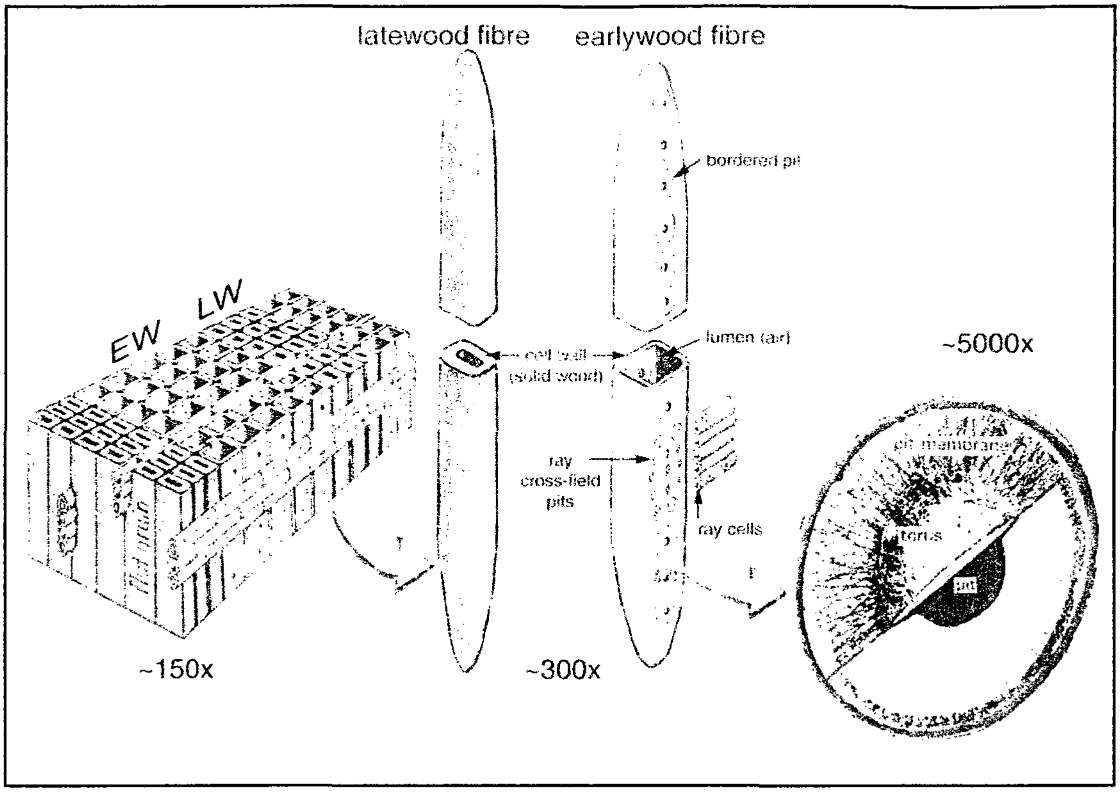


Figure 11. Growth rings are the latewood and earlywood growth within a single year (Jozsa and Middleton 1994).

The percentage of earlywood and latewood produced during cambial development can be highly variable between species, within species and within the stem. The proportion of earlywood to latewood is a genetic response to factors which include age, growth rate and site conditions, and therefore may be predictable. In some species, such as southern yellow pine (*Pinus elliotti* Engelm.), a large percentage of each growth ring is typically latewood, while in other species, such as eastern white pine (*Pinus strobus* L.), the percent of latewood is very small (Panshin and de Zeeuw, 1980; Mullins and McKnight, 1981; Jozsa and Middleton, 1994; Bowyer *et al.*, 2003). Table 5 illustrates the variation in average percentage of latewood within northwestern Ontario tree species.

Table 5. Variation of average percentage of latewood within northwestern Ontario tree species (Zhang and Koubaa 2008).

Species	Percent of Latewood (%)
black spruce (*Picea mariana* (Mill.) B.S.P.)	13.3 to 27.0
white spruce (*Picea glauca* (Moench) Voss)	12.0 to 26.2
jack pine (*Pinus banksiana* Lamb.)	20.7 to 42.1
eastern larch (*Larix laricina* (Du Roi) K. Koch,)	30.0 to 40.0
balsam fir (*Abies balsamea* (L.) Mill.)	17.5

The percentage and variability of earlywood and latewood within a stem affects the wood characteristics and its end uses. The density and shrinkage properties of wood are directly correlated to the ratio of earlywood to latewood. A higher proportion of earlywood to latewood within a stem produces lower density and a higher rate of shrinkage within the wood (Panshin and de Zeeuw, 1980; Isenberg *et al.*, 1980a; Isenberg *et al.*, 1980b; Mullins and McKnight, 1981; Jozsa and Middleton, 1994; Bowyer and Smith, 2000; Bowyer *et al.*, 2003).

For example, the literature indicates that the earlywood of eastern larch usually makes up two thirds of a growth ring with an abrupt transition to a highly dense latewood band, however, the width of growth rings of eastern larch are reported to be highly variable from year to year. Thus, the physical wood properties of eastern larch are highly variable and we would expect the wood of this species to be difficult to work with; a conclusion supported by the literature (Isenberg *et al.*, 1980a; Panshin and de Zeeuw, 1980; Zhang and Koubaa, 2008).

2.1.2.4 Softwood anatomy

Softwoods have a relatively simple cellular composition; longitudinal tracheids and wood rays (Figure 11) (Bowyer and Smith, 2000; Bowyer *et al.*, 2003; Panshin and de Zeeuw, 1980).

Longitudinal tracheids, or wood fibres make up between 94% to 96% of the volume of all softwoods. Softwood fibres are 3 to 8 mm long, hollow, and pitted. Longitudinal tracheids are long wood fibres with tapered ends. The overall proportions are very similar to a soda straw; this gives softwood a uniform honeycomb-like appearance. Rays are radially aligned strips of short brick-shaped parenchyma cells (Panshin and de Zeeuw, 1980; Isenberg *et al.*, 1980a; Mullins and McKnight, 1981; Jozsa and Middleton, 1994).

1.2.2.5 Hardwood anatomy

Hardwoods' structures, by contrast, are more complex than softwoods with considerable variability between species (Figure 12). Hardwoods have four major cell types: fibres, vessels, parenchyma and ray cells. For example, black ash (*Fraxinus nigra* Marsh.) has a percent of wood volume comprised of 69.4% fibres, 11.6% vessels, 12.0% rays and 7.0% parenchyma. While American sycamore (*Platanus occidentalis* L.) has a percent wood volume comprised of 28.9% fibres, 51.9% vessels and 19.2% rays. (Panshin and de Zeeuw, 1980; Isenberg *et al.*, 1980b; Mullins and McKnight, 1981; Jozsa and Middleton, 1994; Leitch. 2008).

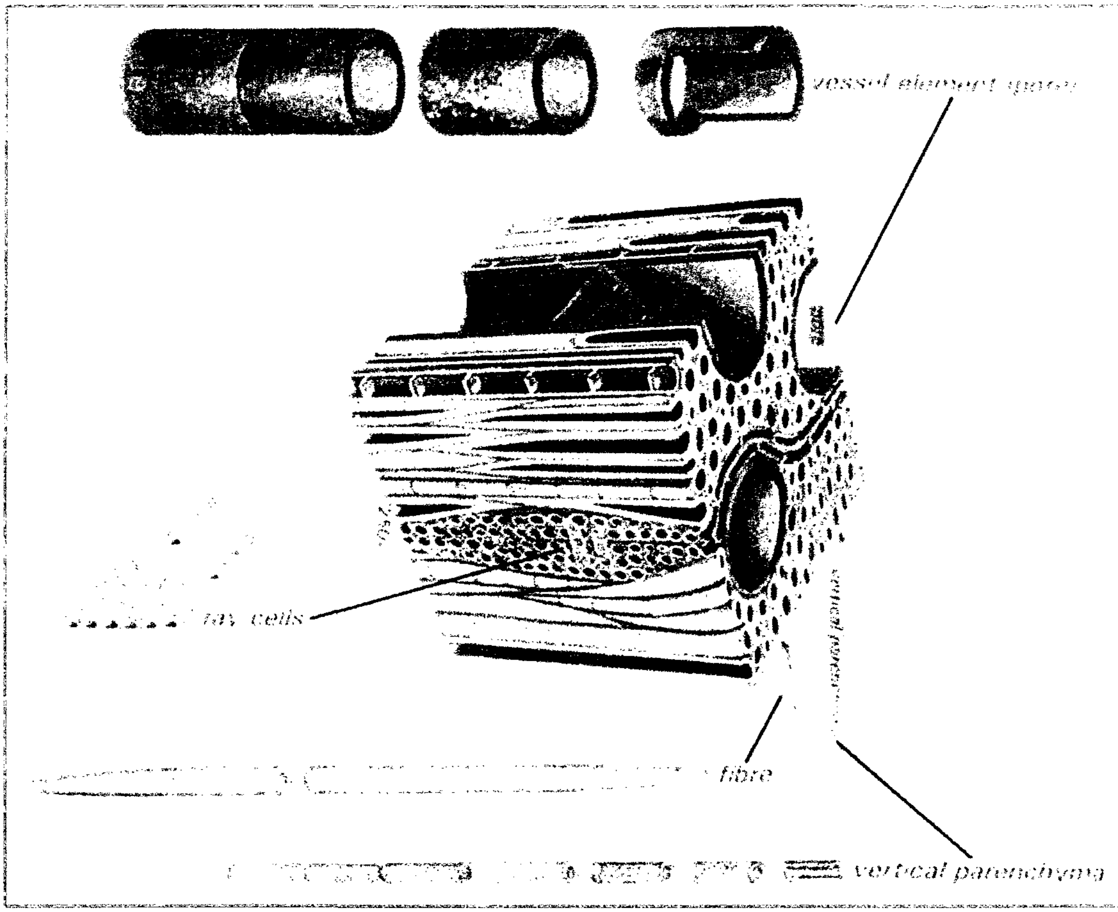


Figure 12. hardwood – wood structure (Jozsa 2004).

2.1.3 Juvenile wood versus mature wood

As the tree starts to mature, the structure of the wood cells produced in the stem change slightly. We refer to the wood produced by a maturing tree as mature wood, and wood produced by an immature tree as juvenile wood (Panshin and de Zeeuw, 1980; Jozsa and Middleton, 1994; Bowyer *et al.*, 2003).

When we consider the anisotropic nature of trees, we should understand that a maturing tree will produce both juvenile and mature wood. If we separate the maturing tree into two areas of growth, the bole and crown, it is easy to contemplate how this may occur (Isenberg *et al.*, 1980a; Isenberg *et al.*, 1980b; Mullins and McKnight, 1981; Bowyer and Smith, 2000).

Wood growth in the bole of a maturing tree is restricted to tangential and radial growth, while the crown also grows in the longitudinal direction. Thus, a maturing tree will produce juvenile wood in the crown and mature wood on the bole (Figure 13). It seems evident, that the development of mature wood may be associated with the mechanism of self pruning (Panshin and de Zeeuw, 1980; Bowyer *et al.*, 2003; Leitch, 2008).

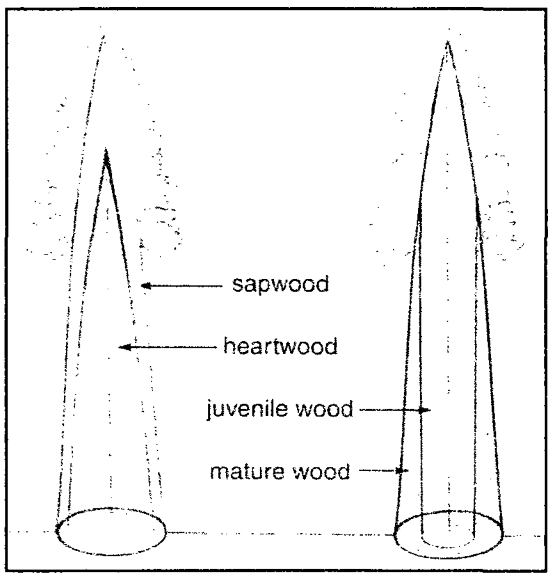


Figure 13. Stem juvenile wood – mature wood distribution (Jozsa and Middleton 1994).

There seems to be a correlation between the percent live crown and the development of mature wood. Thus, juvenile wood is commonly referred to as crown wood; which provides a more accurate description. Therefore, an open grown tree with a 100% live crown would produce significantly less mature wood than a tree grown in a closed canopy with 35% live crown. Other factors that influence mature wood development are:

- heredity,
- time (age),
- competition, and
- site regime.

The greatest influences on mature wood development are time and heredity (Zobel, 1992; Willcocks and Bell, 1995; Burdon *et al.*, 2004; Leitch, 2008).

Changes in wood cell structure from juvenile wood to mature wood are significant in relation to wood characteristics and wood quality. Mature wood has (Panshin and de Zeeuw, 1980; Mullins and McKnight, 1981; Zobel, 1992; Willcocks and Bell, 1995; Bowyer *et al.*, 2003; Burdon *et al.*, 2004; Leitch, 2008):

- longer cell fibres,
- thicker cell walls,
- higher percentage of latewood,
- straighter fibril angle,
- less spiral grain,
- less longitudinal shrinkage,
- less compression wood,
- higher volume of cellulose,
- lower volume of lignin,
- higher density; by 10 to 15%,
- higher strength; by 15 to 30%, and
- superior wood for pulping.

Mature wood development seems to occur between 10 to 30 years after initial growth at the pith, depending on tree spacing. Once mature wood development has occurred within the stem, transition from juvenile wood to mature wood seems to occur 10 years after initial terminal growth within the crown. However, according to the literature, transition between juvenile wood and mature wood is difficult to predict due to the variability in species genetics, and the dynamic nature of stand development (Mullins and McKnight, 1981; Jozsa and Middleton, 1994; Bowyer *et al.*, 2003).

The distinctive differences between mature wood and juvenile wood affect their potential end use. Figure 14 shows changes in relative density over time in nine softwood species grown in Canada. We can see that there is a definite change in wood properties over time, which is highly variable between species, within species and between forests stands (Panshin and de Zeeuw, 1980; Bowyer and Smith, 2000; Bowyer *et al.*, 2003).

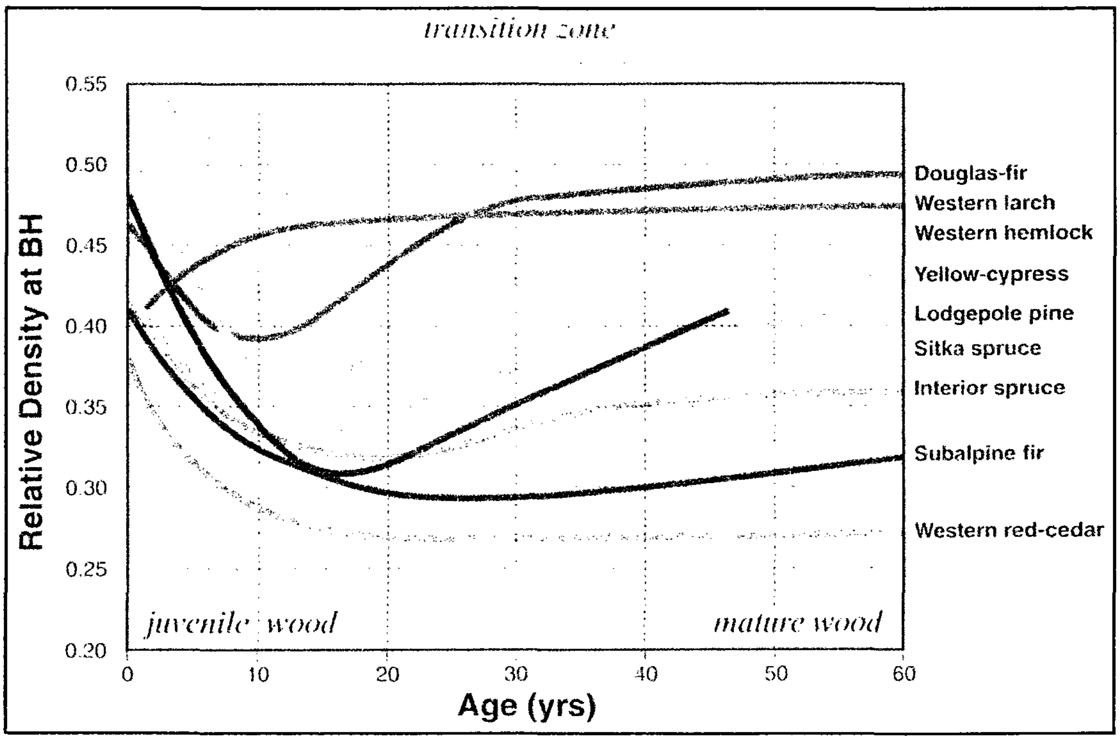


Figure 14. Average ring density trend from pith to bark at breast height (Jozsa and Middleton 1994).

The main difficulty in determining the transition point between mature wood and juvenile wood is that the changes in wood structure occur at the microscopic level, thus the macroscopic features of the wood remain unchanged. According to the literature, the transition between juvenile wood to mature wood occurs when the S2 layer of the wood cell thickens, fibre length increases, and fibril angle of the S2 layer of the wood cell decreases. It is believed that once mature wood develops, the wood cell structure becomes stable. The mature wood zone within a stem has been identified by the appearance of an increase in relative density or fibre length that remained stable to the bark. This procedure assumes that mature wood can be identified using a single factor, which has yet to be proven and produces conflicting reports (Panshin and de Zeeuw, 1980; Mullins and McKnight, 1981; Bowyer *et al.*, 2003; Leitch, 2008).

For example, eastern larch (*Larix laricina* (Du Roi) K. Koch) fibre length increases from pith to bark, however, the greatest change in fibre length occurs within the first 10 years of cambial growth, followed by stable growth to the bark (Zhang and Koubaa, 2008; Yang *et al.*. 1987; Wang *et al.*. 1985; Balatinecz. 1983). Thus, the literature reports that mature wood seems to occur within eastern larch after 10 years of juvenile growth (Zhang and Koubaa, 2008). However, relative density radial profiles, for eastern larch, are highly variable from pith to bark. Further, Beaudoin *et al.* (1989) reported that most of the physical and mechanical properties of eastern larch are higher in the juvenile wood than the mature wood, which contradicts the improved and stable properties, that the literature indicates should be in mature wood (Zhang and Koubaa, 2008; Yang *et al.*. 1987; Wang *et al.*. 1985; Balatinecz. 1983).

When we consider general wood characteristics, distinct structural and morphological differences exist between softwoods and hardwoods. According to the literature, both softwoods and hardwoods develop mature wood over time. However, the differences between mature and juvenile wood are more pronounced in softwoods than in hardwoods. Further, in ring porous hardwoods the improvements to wood characteristics seem to fade over time (Figure 15) (Panshin and de Zeeuw, 1980; Mullins and McKnight, 1981; Jozsa and Middleton, 1994; Bowyer *et al.*, 2003).

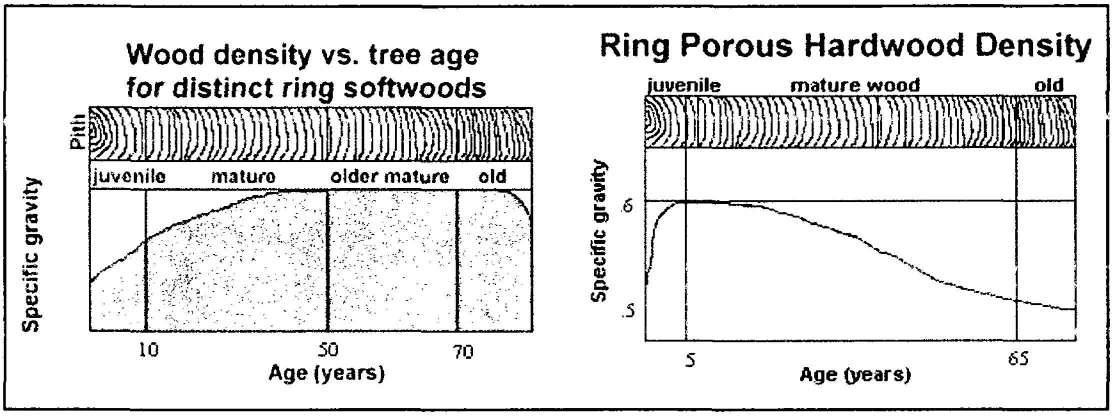


Figure 15. Improvements to wood characteristics due to mature development over time (Bowyer and Smith 2000).

2.1.4 Fibres

Hardwood and softwood fibres have several differences. Where softwood fibres, called tracheids, are long and rectangular shaped, hardwood fibres tend to be round in shape and shorter. This is why softwood tracheids are preferred, especially black spruce (*Picea mariana* (Mill.) B.S.P.) tracheids, for use in making strong paper. The proportion of wood volume comprised of fibres is lower and highly variable in hardwoods; ranging from 15 to 60%. In contrast, softwoods tracheids make up between 94% to 96% of the wood volume. Figure 16 shows a comparison, in a cross sectional view, of the hardwood black ash

(*Fraxinus nigra* Marsh.) and the softwood eastern white pine (*Pinus strobus* L.) fibres (Panshin and de Zeeuw, 1980; Mullins and McKnight, 1981; Bowyer *et al.*, 2003; Leitch, 2008).

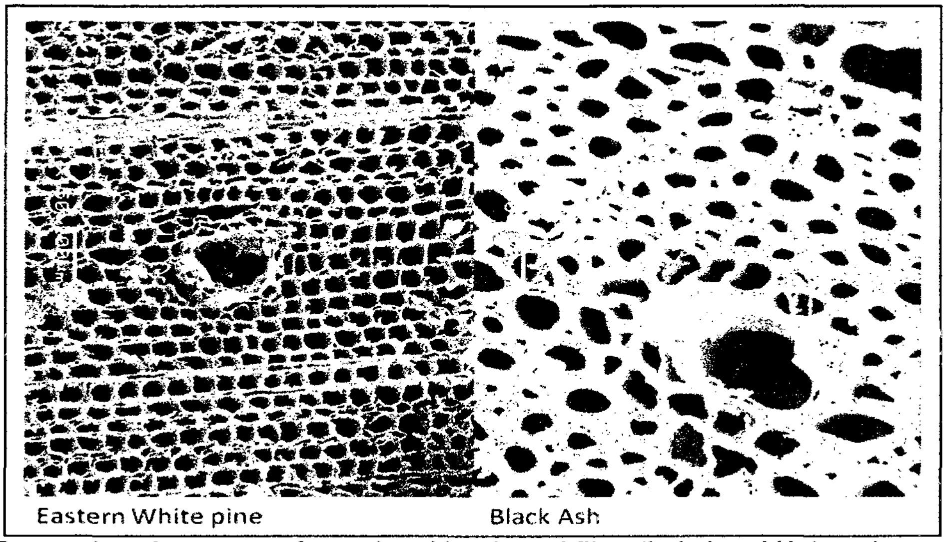


Figure 16. Comparison between softwood and hardwood fibre (Lakehead University Wood Science Testing Facility 2010).

2.1.4.1 Fibre length

Fibre length varies greatly between softwoods and hardwoods, and between juvenile wood and mature wood. There are direct relationships between fibre length and age, radial position in the stem, and species. In Figure 17 clearly illustrates how fibre length are directly related to age (Panshin and de Zeeuw, 1980; Mullins and McKnight, 1981; Jozsa and Middleton, 1994).

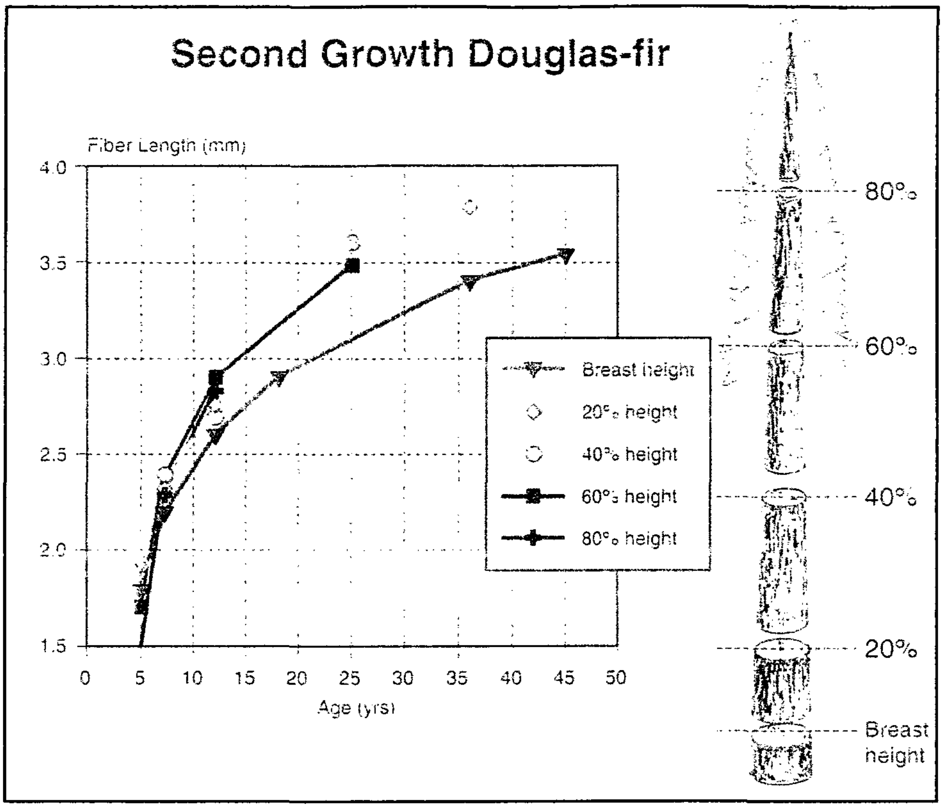


Figure 17. Fibre length as a function of age (Jozsa and Middleton 1994).

Although it appears that fibre length may be related to the improved wood characteristics in mature wood, there is no direct evidence that fibre length improves strength properties of solid wood. However, fibre length is extremely important to sheet strength and finish in paper production (Figure 18). Thus, fibre length is considered less important in the manufacturing of solid wood products than in pulp and paper manufacturing (Panshin and de Zeeuw, 1980; Mullins and McKnight, 1981; Horn and Setterholm, 1990; Jozsa and Middleton, 1994).

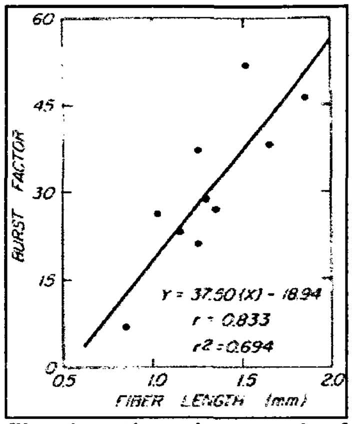


Figure 18. Correlation between fibre length and strength of paper (Horn and Setterholm 1990).

2.1.4.2 Fibril angle

Fibril angle directly affects wood quality and is of extreme concern when drying wood. As discussed, maturing trees produce mature wood over time starting at the bottom of the tree bole moving up in longitudinal position. If we consider these factors collectively, we can see that fibril angle varies throughout the tree as a factor of age and longitudinal position (Figure 19) (Panshin and de Zeeuw, 1980; Jozsa and Middleton, 1994; Bowyer *et al.*. 2003).

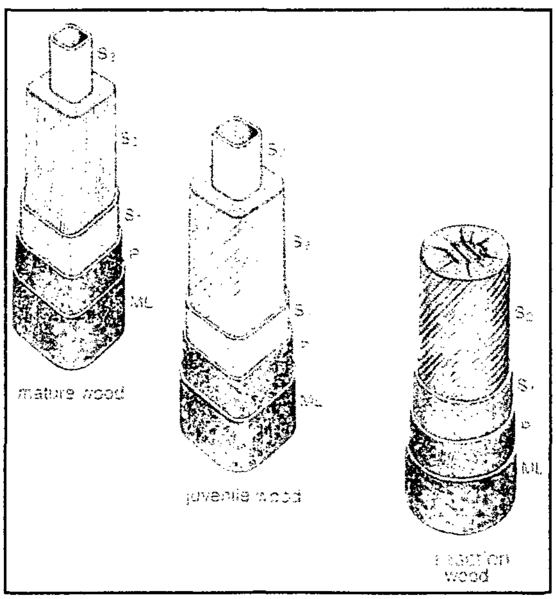


Figure 19. Fibril orientation in normal, juvenile and reaction wood (source Jozsa and Middleton 1994).

Panshin and de Zeeuw (1980) reported that fibril angle generally varies between cell wall layers as follows:

- S1 layer; 50 to 70 degrees to the cell axis,
- S2 layer; 10 to 30 degrees to the cell axis,
- S3 layer; 60 to 90 degrees to the cell axis.

However, these ranges in fibril angle can only be used as indication of the variability between cell wall layers. Donaldson and Xu (2005) found that radiata pine fibril angle varied considerably within the species as follows:

- S1 layer (radiata pine); 79 to 113 degrees to the cell axis,
- S2 layer (radiata pine); 1 to 59 degrees to the cell axis,
- S3 layer (radiata pine); 50 to 113 degrees to the cell axis.

Further, fibril angle changes with age and increase in the length of cambial initials (Panshin and de Zeeuw, 1980; Jozsa and Middleton, 1994; Bowyer *et al.*. 2003). Liese and Dadswell (1959) reported that fibril angle generally increased from juvenile to mature wood as follows:

- S2 layer (softwoods); from 55 to 20 degrees to the cell axis,
- S2 layer (hardwoods); from 28 to 10 degrees to the cell axis.

2.1.5 Reaction wood

When trees are grown on an angle other than vertical, such as trees growing on creeping or windy slopes, abnormal wood is formed called reaction wood. Reaction wood occurs in both hardwood and softwood stems as well as branches, as a genetic response to stem inclination angle. Reaction wood forms as compression wood in softwoods and tension wood in hardwoods. As shown in Figure 20, tension and compression forces causes the stem to react in different ways (Table 6) (Leitch, 2008; Wiemann and Williamson, 2010).

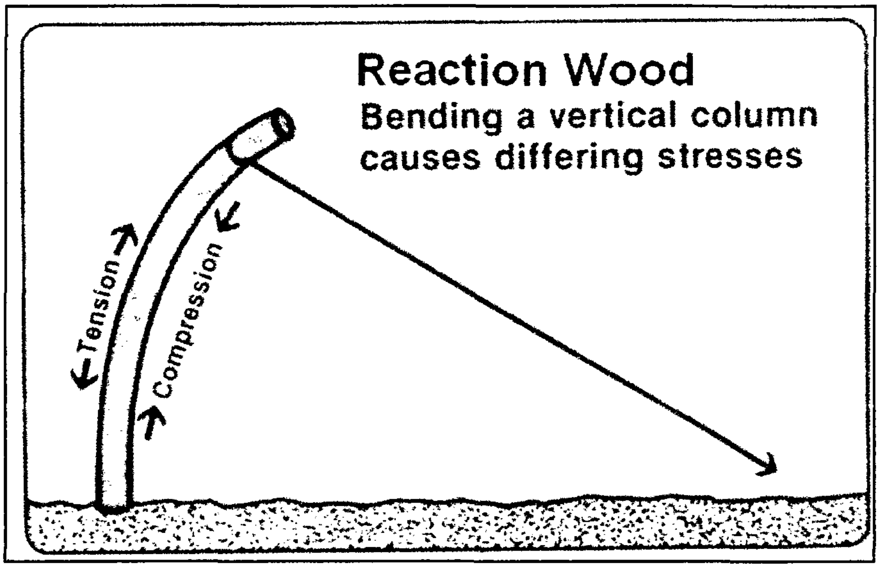


Figure 20. Bending from the vertical causes reaction wood (Laks 2010).

Table 6. Influence of reaction wood on softwoods and hardwoods (Leitch, 2008; Wiemann and Williamson, 2010).

Compression wood	Tension wood
softwoods	hardwoods
underside of branches or leaning stem	top of branches or leaning stem
commonly in juvenile wood elliptical appearance is similar in most species	commonly in juvenile wood elliptical appearance is less consistenet between species

Reaction wood results in increased fibril angle and causes the cells to shrink along the grain during drying. Thus, reaction wood is difficult to process for both solid wood and pulp wood manufacturing (Panshin and de Zeeuw, 1980; Jozsa and Middleton, 1994; Bowyer and Smith, 2000; Bowyer *et al.*, 2003).

When there is a high percentage of reaction wood present, it can be easily identified because it typically has an eccentric shape. However, reaction wood forms at different degrees depending on the stem or branch angle and can be very difficult to detect. Yamashita *et al.* (2006) reported that the degree of reaction wood development increases with an increase in stem inclination angle to a maximum of 30 degrees in gymnosperms. Thus, the influence of reaction wood on wood development is highly variable and is often not recognized until processing, usually during drying. In addition to affecting shrinkage, reaction wood reduces strength properties. Unidentified reaction wood in weight bearing members has led to failures in wood structures (Panshin and de Zeeuw, 1980; Jozsa and Middleton, 1994; Bowyer and Smith, 2000; Bowyer *et al.*, 2003).

Due to the inherent nature of reaction wood, its percent volume is variable between species, within species and within a tree. For example, eastern larch (*Larix laricina* (Du Roi) K. Koch) is known to have a high component of reaction wood even during normal growth, as earlywood cells go through spiral thickening. The percent volume of reaction wood increases in eastern larch, with an increase in tree spacing, which promotes wind interception and increased growth (Zhang and Koubaa. 2008; Panshin and de Zeeuw. 1980; Isenberg *et al.*. 1980a; Isenberg *et al.*, 1980b;).

2.1.5.1 Knots

As a tree increases in height, the crown rises vertically away from the base, and the leaves on the lower branches become less efficient at photosynthesis than those of higher branches. Over time, the photosynthesis rate of these leaves falls below the energy required to support the growth needed, therefore the tree terminates leaf production on the branch. Eventually, the branch dies and falls off and the tree overgrows the branch stub through diameter growth forming a knot (Wangaard, 1981; Forest Products Laboratory, 1999; Rowell, 2005). It is common for knots to be referred to as live and dead knots. Live knots, or red knots, are intergrown with the surrounding wood, whereas dead knots, or black knots, have lost their connection with the surrounding wood and can easily loosen and fall out (NLGA, 2003a).

Knots can affect wood in a number of ways. Until branch stubs are completely overgrown, knots are an avenue for pathogens and insects to attack the tree and degrade the wood. Knots can cause other defects to form within the stem and reduce the strength properties of wood (Wangaard, 1981; Forest Products Laboratory, 1999; Rowell, 2005).

Essentially, knots are holes in the wood which affect the slope of the grain in the surrounding wood. The increase in fibre angle in the wood surrounding the knot causes a reduction in strength parallel to the grain of the wood surrounding the knot. The direct affect of the knots on strength in terms of disruption of clear wood is dependent on the size, frequency and location. In solid wood manufacturing, knots affect wood strength subject to size, number, and orientation within the wood.

Figure 21 shows the effect of size and location of knots on the reduction of bending strength as a percentage of knot-free wood. For example, a 3 inch knot in a 2 X 10, located on the edge of the board, referred to as the tension edge, will reduce the strength of the beam by 50% of that of clear wood (Bowyer and Smith, 2000). However, if the same knot is located in the centre of the board, or on the neutral axis, it will reduce the strength by only 30% of that of clear wood (Wangaard, 1981; Forest Products Laboratory, 1999; Bowyer and Smith, 2000; Rowell, 2005).

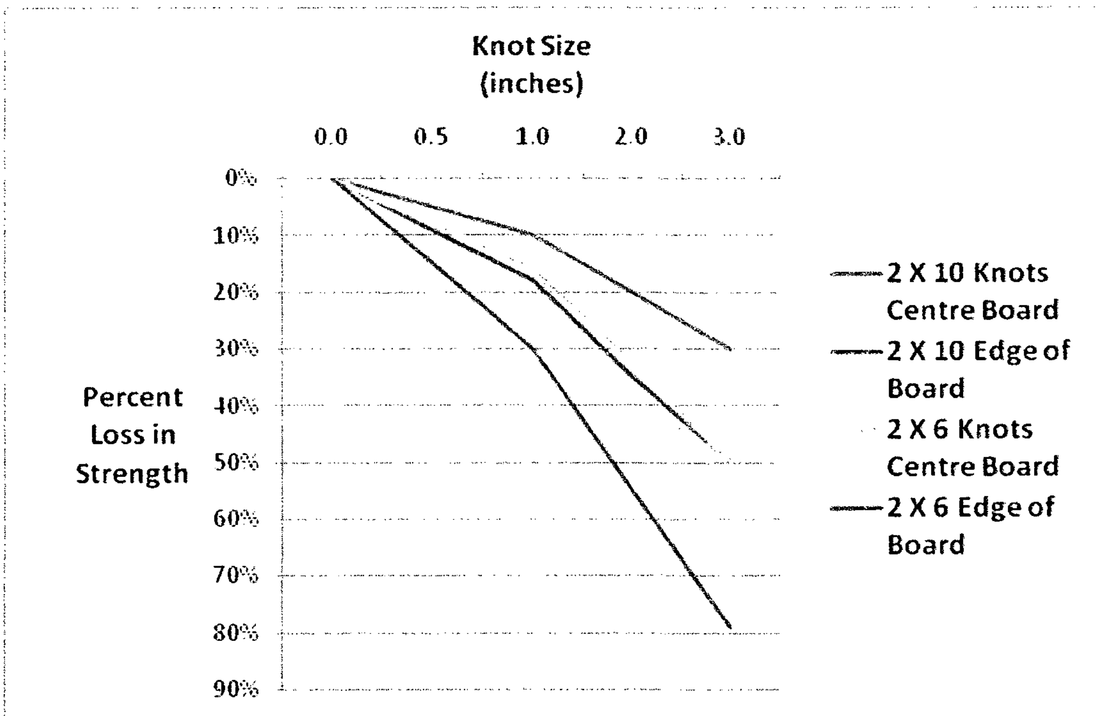


Figure 21. Percent loss in strength as related to size and location of knot.

Canada's forest industry is currently in a transition from old growth forests to the smaller diameter second growth and plantation forests. This transition to younger smaller diameter trees makes knots a real concern for both solid wood and pulp wood manufacturers. Wood from the old natural grown forests had a high percentage of clear wood, which is not present in the second growth. (Panshin and de Zeeuw, 1980; Jozsa and Middleton, 1994; Bowyer and Smith, 2000; Bowyer *et al.*, 2003).

2.1.6 Wood chemistry

Wood chemistry may provide northwestern Ontario the greatest opportunity for new products. Bio-product development is one of the fast growing areas of research in the world, as we try to change from a hydrocarbon based economy to a carbohydrate economy. (Jaworski and St-Louis, 2001; Industry Canada, 2003; de la Roche, 2008; Soderholm and Lundmark, 2009).

2.1.6.1 Components of wood

Wood is hydroscopic, thus, it not surprising that the major chemical component of a living tree is water. However, a wood cell is an interconnected network of cellulose, hemicelluloses and lignin, with minor amounts of extractives and inorganics, which form a three-dimensional biopolymer composite (Figure 22) (Wilson, 1984; Walker, 1989; Rowell, 2005). There is significant variability between hardwoods and softwoods with regards to the percent volume of these chemical components (Table 7) (Bowyer *et al.*, 2003; Rowell, 2005; Leitch, 2008).

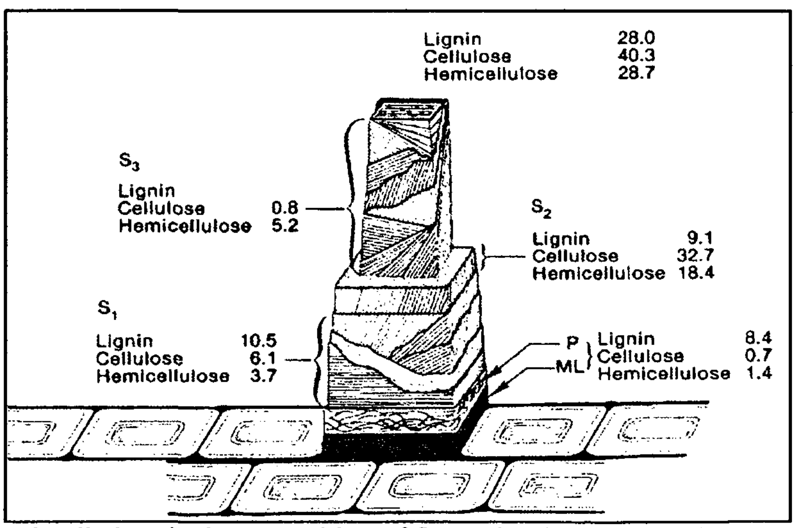


Figure 22. Wood cell chemical composition of Scot pine (Rowell 2005).

Table 7. Organic makeup of wood (% of oven-dry weight) (Leitch, 2008; Rowell, 2005; Bowyer and Smith, 2000).

	Cellulose	Hemicellulose	Lignin
Hardwoods	38 to 49	15 to 35	18 to 30
Softwoods	40 to 45	20 to 32	25 to 35

The chemical structure of wood is more homogenous throughout the stem than fibres. Yeh (2005) states, "differences in chemical structure between the various wood specimens are less significant." Therefore, assessing end use potential of the chemical elements of wood, may be less costly than experienced with wood fibres. However, there is significant variability between species with regards to the amounts of these chemical components (Table 8).

Table 8. Typical chemical properties (Zhang and Koubaa, 2008; Leitch, 2008; Rowell, 2005).

Species	Lignin (%)	Cellulose (%)	Hemicellulose (%)	Ash (%)	Extractives (%)
black spruce *(Picea mariana* (Mill.) B.S.P.)	25 - 28	43 - 46	15 - 28	0.2	2.0 – 3.5
trembling aspen *(Populus tremuloides* Michx.)	25.3	33.5	-	2.8	3.6
jack pine *(Pinus banksiana* Lamb.)	27 - 29	45.2	16.2	0.2	3.2 - 4
white birch *(Betula papyrifera* Marsh.)	21.2	49.4	-	2.9	2.6
balsam fir *(Abies balsamea* (L.) Mill.)	27 - 30	42.2	15 - 26	0.2 – 0.4	3.6
eastern white cedar *(Thuja occidentalis* L.)	30 - 34	43 - 49	-	0.2 – 0.6	1.3 – 1.4
eastern larch *(Larix laricina* (Du Roi) K. Koch)	22 - 29	43 - 45	-	0.2 - 0.5	-
white spruce *(Picea glauca* (Moench) Voss).	26 - 30	39.5	16 - 28	0.2 – 0.3	2.1 – 2.3
eastern white pine *(Pinus strobus* L.)	25 - 28	40 - 60	14.1	0.2 – 0.4	8.3
red pine *(Pinus resinosa* Ait.)	23 - 28	46 - 49	15.1	0.2	-
red maple *(Acer rubrum L.)*	22.8	44.5	-	5.2	2.5
black ash *(Fraxinus nigra* Marsh.)	26	40	-	-	-

Cellulose, the major component of wood, is a straight long-chain polymer which gives wood its strength. Cellulose is formed when glucose anhydride units polymerize or link end-to-end to form the long-chain polymer (Figure 23). Glucose anhydride is composed of tens of thousands of individual glucose molecules which are linked together when glucose ($C_6H_{12}O_6$) loses water (Panshin and de Zeeuw, 1980; Bowyer and Smith, 2000; Bowyer *et al.*, 2003; Rowell, 2005).

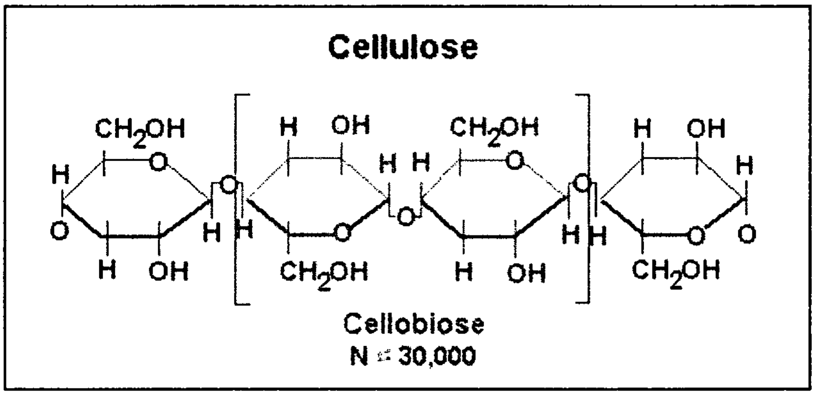


Figure 23. Long-chain cellulose polymer (Bowyer and Smith 2000).

Nanocrystalline cellulose is the smallest physical sub-unit of cellulose, measuring 200 nm long and 10 nm wide (de la Roche, 2008). Strength properties increase as particle size is reduced, and load sharing between broken and intact particles has less effect on strength than with fibres (Simonsen, 2005). Nanocrystalline cellulose is said to be stronger than steel (de la Roche, 2008) and 25% to 30% of the strength of carbon nanotubes (Wegner, 2007). Defects in the substance are also reduced as particle size is reduced (Simonsen, 2005).

Unlike cellulose, only about 150 individual sugar molecules polymerize to produce hemicelluloses. Hemicelluloses are a polymers that are branched, have low molecular weight, and are composed of five or six carbon sugars (Figure 24) (Bowyer and Smith. 2000; Rowell, 2005).

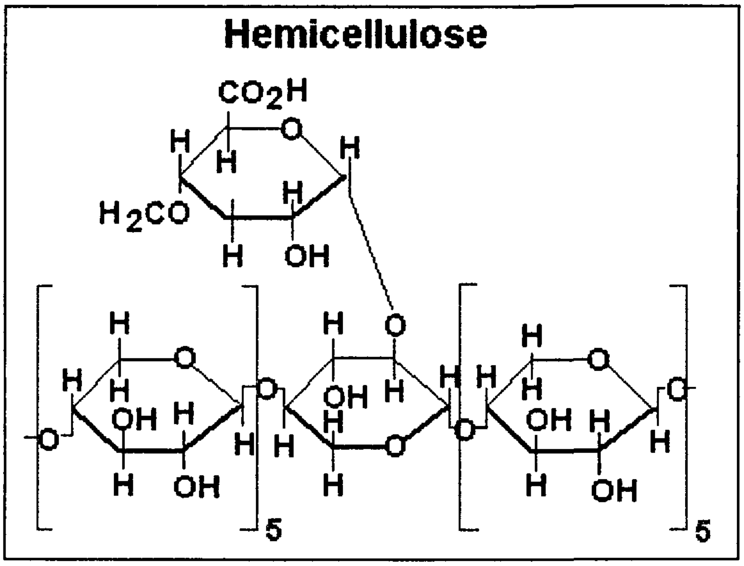


Figure 24. Sugar molecules combine (polymerize) to produce hemicellulose (Bowyer and Smith 2000).

The role of hemicelluloses in the cell wall has received little attention. According to Atalla (2005), the popular view is that hemicelluloses assist in "coupling cellulose and lignin to enhance the mechanical properties of the walls". There are different types of hemicellulose. In softwoods, the main hemicelluloses are galactoglucomannan and arabinoglucuronoxylan, while in hardwoods glucuronoxylan is the main hemicellulose (Rowell, 2005).

The base chemical unit of lignin is phenylpropane. Lignin is a random three dimensional polymer (Figure 25); having a very high molecular weight. The lignin has a number of functions in wood (Rowell, 2005):

- binding and stiffening plant fibres,
- decreases water permeation through the cell walls of the xylem, and
- impedes penetration of destructive enzymes increasing natural defence of tree against degradation.

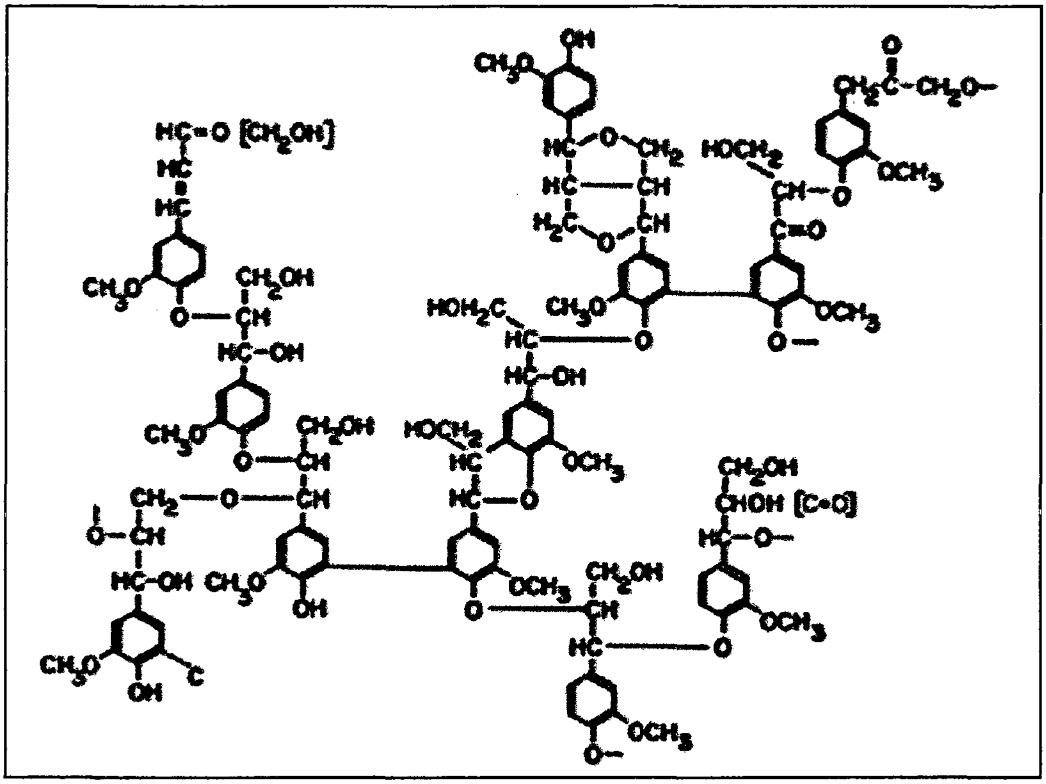


Figure 25. Structure of lignin (Bowyer and Smith 2000).

Sugar-rich photosynthate which has accumulated in the centre of the tree, begins to break down overtime and produces a variety of new compounds called extractives. Extractable compounds include waxes, oils, resins, fats, and tannins, along with aromatic and colouring materials (Rowell, 2005; Cole, 2006). Extractives can be removed using a solvent (Rowell, 2005; Cole, 2006). Some extractives can be removed by simply soaking wood in cold water (Bowyer and Smith, 2000; Rowell, 2005). Others require solvents like ether, acetone, ethanol, or hot water to be removed (Bowyer and Smith, 2000; Rowell, 2005; Cole, 2006).

Extractives are chemicals with relatively small molecules, which comprise on average 1 to 5% of wood volume. The extractives found in wood are species specific and vary greatly within species, between species and within trees (Rowell, 2005; Cole, 2006). Table 9 lists the common extractive components found in wood. According to the literature, hardwoods do not accumulate resin acids or monoterpenes extractives. In softwoods, resin acids account for 40 to 45% of extractive volume and fatty acids account for 40 to 60% of extractive volume. In hardwoods, extractives are dominated by fatty acids, which make up 60 to 90% of extractive volume (Rowell, 2005; Cole, 2006).

Table 9. Common extractive components found in softwoods and hardwoods.

Softwoods	Hardwoods
Resin acids, Fatty acids, Monoterpenes, Phenolics	Fatty acids Phenolics

Extractives can be very valuable once removed. For example, extractive components can be used in turpentine, flavour and fragrance chemicals, and rosin and sizing agents. Phenolic extractive components can be used in tanning agents, adhesives, and as an antioxidant (Rowell, 2005; Cole, 2006).

2.2 Wood quality

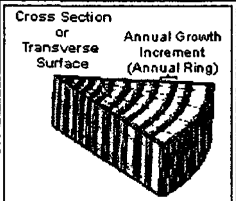
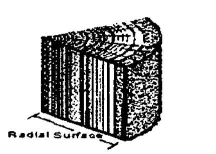
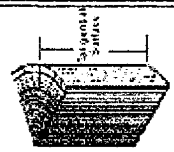
Wood quality is one of the most difficult attributes to define since it is subject to the interpretation of the user. What quality means to one user group does not mean quality to another. For example, forest managers seem to define quality in relation to growth and yield; focusing on producing fast growing trees that produce a large volume of wood by harvest age. Lumber manufacturers may see quality as logs with top diameter ranging between 25 to 35 cm, with minimal taper and free of knots. Pulp manufacturers may define quality wood as having long fibres with a high cellulose and low lignin content. Other stakeholders, may look at the aesthetic qualities of the forest along with the carbon sequestering properties of wood. Home owners may see wood quality in the thermal attributes of wood, which they need to heat their homes. (Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Zhang, 2003).

Perhaps the difficulty in defining wood quality lies in the bias each group uses to value wood. If we considered just the word "quality" generically, we can define it as a distinctive attribute or characteristic considered important or beneficial. The must commonly used definition is "wood quality is the resultant of physical and chemical characteristics possessed by a tree or a part of a tree that enable it to meet the property requirements for different end products" (Zhang, 2003).

According to the literature, most people agree that a definition of wood quality must consider specific end uses (Zhang, 2003). In his paper Wood Quality Attributes and Their Impacts on Wood Utilization, Zhang states that "as wood properties affect various aspects of the manufacturing process, wood quality must be defined in terms of the value recovery chain". He defines wood quality as "all wood characteristics that affect the value recovery chain and the serviceability of end products" (Zhang, 2003).

When studying wood, forest managers and researchers view wood by three surfaces; transverse surface or cross section, radial surface and tangential surface. When wood is viewed in these three surfaces, it assists us to better identify tree species, cell characteristics, and wood properties (Table 10) (Bowyer and Smith, 2000).

Table 10. The different surfaces viewed when studying wood. (Bowyer and Smith 2000).

	**Cross Section or Transverse Surface** The surface that is viewed when looking at the end of a log or the top of a stump is known as a cross section. This surface is sometimes also referred to as a transverse surface. Heartwood and sapwood zones, annual growth rings, and rays can be seen on this surface.
	**Radial Surface** The surface created by cutting along a radius of a round cross section is known as the radial surface.
	**Tangential Surface** The surface created by cutting at a tangent to the growth rings, or the surface you would see if you were to view the outside of a log with the bark removed, is called the tangential surface.

2.2.1 Mechanical properties

Mechanical properties are observed when a material is subjected to an applied external force. These are important properties to understand as they are directly related to end use characteristics and manufacturing processes (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005).

Mechanical properties recorded in Canada are generally reported as an average with respect to a species, they “attempt to give a fair estimate” for the species throughout the growth range and are limited to species of commercial importance (Jessome, 2000). Therefore, knowledge of mechanical properties at the regional and stand level represents a fundamental gap in the knowledge of wood characteristics within Canada, especially in northwestern Ontario.

As discussed, mechanical property testing of various species are standardized tests of small, clear (defect free) specimens at set moisture conditions for comparison. Large specimens of various species are also tested with respect to standard grades of lumber, so that strength data can be derived based on number of defects (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005).

From Table 11, we can make the general observation that moisture content reduces the strength properties of wood at varying degrees specific to species (Rowell, 2005). Further, there is a direct correlation between density of mature wood and strength properties. Finally, wood is 7 to 10 times stronger longitudinally than radially (Panshin and de Zeeuw. 1980; Mullins and McKinight, 1981; Bowyer and Smith, 2000).

It may be helpful in understanding how property values reported in the literature are derived. Let us consider two of the commonly reported strength values for wood; modulus of elasticity (MOE) and modulus of rupture (MOR) from static bending. MOE is a measure of resistance to bending; or a measure of rigidity. MOR is a measure of absolute strength; or a measure of the ultimate load-carrying capacity of a beam. MOE and MOR values are determined through the static bending test (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005).

Table 11. Physical and mechanical properties of northwestern Ontario tree species. (Jessome 2000).

Tree Species of NWO.	Moisture Content	Density (kg/m³)	Shrinkage			Static Bending		Impact Bending		Compression Parallel		Compression Perpend.	Hardness	Shear Parallel	Tension Perpend.	Cleavage
			Radial (%)	Tangential (%)	Volumetric (%)	MOE (Mpa)	MOR (Mpa)	MOE (Mpa)	Hammer Drop (mm)	MOE (Mpa)	Max. Crushing Stress Mpa)	Stress at Prop. Limit (Mpa)	Side (N)	Max. Shear Stress (Mpa)	Max. Tensile Stress (Mpa)	Splitting Strength (N/mm width)
lack spruce 49.6%	Green	406	3.8	7.5	11.1	9100	40.5	10500	640	10100	19	2.07	1680	5.49	2.34	31.5
	12%	428	1.7	4	6.5	10400	78.3	13000	660	12300	41.5	4.25	2430	8.65	3.43	49.2
rembling aspen 21.1%	Green	374	3.6	6.6	11.8	9030	37.6	10400	660	8620	16.2	1.37	1440	4.95	3.04	32
	12%	408	2.7	5.7	8.3	11200	67.6	13500	710	12700	36.3	3.52	2140	6.76	4.19	45.5
ack pine 14.6%	Green	421	4	5.9	9.6	8070	43.5	10300	690	8200	20.3	2.31	1750	5.67	2.44	32.9
	12%	444	2.1	3.8	5.7	10200	48.8	13600	640	10500	40.5	5.7	2560	8.23	3.65	46.2
vhite birch 5.2%	Green	506	5.2	7.2	13.8	10000	47.2	13300	1070	10300	18.5	2.47	2760	6.51	4.26	51.1
	12%	571	4.4	6.6	10.5	12900	94.8	17200	1190	13400	44.7	6.87	4320	11.27	7.17	84.9
alsam fir 4.1%	Green	335	2.7	7.5	10.7	7790	36.5	9100	430	8550	16.8	1.68	1280	4.68	2.02	25.7
	12%	350	1.2	4.3	5.7	9650	58.3	11900	480	9720	34.3	3.14	1820	6.25	2.08	27.3
vhite cedar 1.7%	Green	299	1.7	3.6	6.4	3550	26.6	5890	510	3760	13	1.35	1200	4.55	2.26	28
	12%	302	-	-	3.8	4380	42.3	6140	530	4920	24.8	2.68	1360	6.93	2.63	33.8
astern larch 1.7%	Green	485	2.8	6.2	11.2	8550	47	9450	910	8890	21.6	2.85	1890	6.34	2.76	37.5
	12%	506	-	-	7.1	9380	76	12600	380	10500	44.8	6.15	3220	9	3.47	39.4
vhite spruce 1.2%	Green	354	3.2	6.9	11.3	7930	35.2	9450	580	9030	17	1.69	1240	4.62	2.12	27.3
	12%	372	1.4	4	6.8	9930	62.7	13800	610	11400	36.9	3.45	1880	6.79	3.28	38.7
astern white pine 0.6%	Green	364	2.5	6.3	8.2	8140	35.4	9450	580	9030	17	1.69	1240	4.62	2.12	27.3
	12%	368	-	-	4.5	9380	65	13800	610	11400	36.9	3.45	1880	6.79	3.28	38.7
ed pine	Green	392	3.7	6.3	9.6	7380	34.5	9510	710	7860	16.3	1.94	1490	4.9	2.41	32.2
	12%	401	1.9	4.1	6.5	9450	69.7	13400	640	9380	37.9	4.96	2120	7.5	3.54	41.3
ed maple 0.2%	Green	516	3.6	6	12.4	11000	58.9	15900	910	11700	24.9	3.79	3380	8.36	5.07	67.9
	12%	545	-	-	8.2	11100	97.6	-	-	13300	46.9	7.14	4380	10.51	6.26	74.6
lack ash	Green	468	4.3	8.2	13.8	8550	43.9	8140	1520	9930	16.7	2.61	3270	5.76	4.47	60.9
	12%	494	-	-	7.9	13500	84	12700	1420	13900	40.8	5.84	4220	12.12	4.92	75.7

In a 3 point flexure static bending test, an increasing load is applied to the centre of a specimen (usually 2 cm X 2 cm X 30 cm or 2.5 cm X 2.5 cm X 30 cm), which is supported near the two ends. As a specimen is tested, a record is produced of the specimen's deflection (bending) in response to the load being applied. Initially, the load deflection curve is linear; each increment of load results in an equal increment of deflection. This means that at any point along the linear portion of the load deflection curve, the specimen would return to its previous condition; if the load is removed as shown in green in Figure 26 (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005).

Once the specimen is loaded beyond a certain point, deflection increases at a greater rate than the rate of loading and the line of the graph arches; this point is known as the proportional or elastic limit (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005).

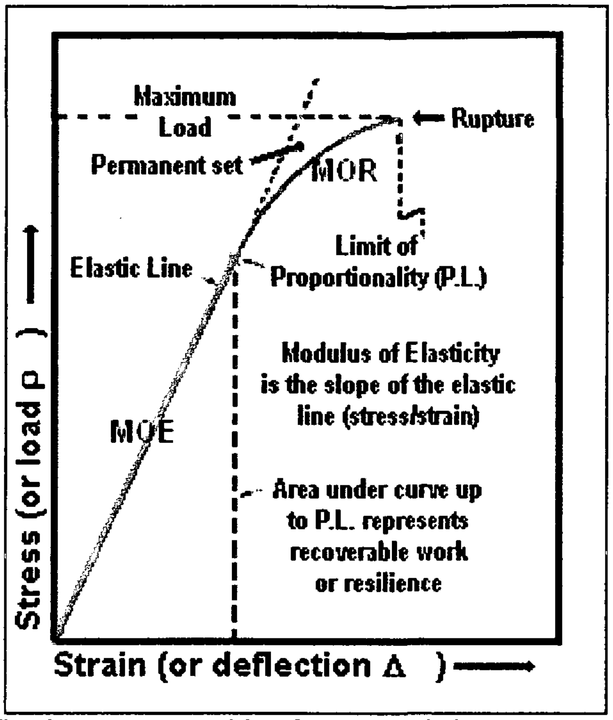


Figure 26. A load deflection curve resulting from a static bending test (Bowyer and Smith 2000).

Once the load applied to the specimen exceeds the proportional limit, it is then loaded beyond its elastic limit, and even if the load were removed it would no longer be able to return to its original shape; rather it is now permanently set. MOE is determined from the slope of the linear portion of the load deflection curve. Load is applied to the specimen until it breaks, thus deflection continues to accelerate to the point of specimen failure (Wangaard, 1981; Forest Products Laboratory, 1999; Rowell, 2005). MOR is calculated from the maximum load value reported by the testing equipment software using (Equation 1) for 3 point loading (Panshin and de Zeeuw. 1980; Mullins and McKinight, 1981; Bowyer and Smith, 2000; Hoadley, 2000):

$$MOR = \frac{1.5PL}{bh^2}$$ **Equation (1)**

Where:
P = maximum load (N)
L = distance between supports (m)
b = is the width of the specimen (m)
h = is the depth of the specimen (m)

Since MOE is related to the slope of the linear section of the load deflection curve, then we can say that the smaller the deflection the larger or higher the MOE will be; since deflection is the denominator.

Further, if we know the MOE, we can determine the dimensions of the beam needed to prevent rupture using (Equation (2) (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005):

$$MOE = \frac{PL^3}{48((b*h^3)/12)*D}$$ **Equation (2)**

Where:
P = maximum load (N)
L = distance between supports (m)
b = is the width of the specimen (m)
h = is the depth of the specimen (m)
D = is the deflection at mid span (m) resulting from P

2.2.2 Moisture content

In wood cells, water is found in the cell walls and the lumen. The water held in the lumen, referred to as free water varies from season to season. The water in the cell walls, referred to as bound water, is held by surface absorption. Surface absorption is the attraction of water molecules to hydrogen-bonding sites present in cellulose, hemicellulose and lignin. The amount of water present within wood, free water plus bound water, is referred to as the moisture content of wood; expressed as percent of wood weight (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005).

The moisture content of wood is constantly changing in response to the atmospheric conditions surrounding the wood. Even if the wood has been kiln dried, it will readily regain moisture if placed in a humid environment (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005).

Wood dries by the movement of free water through lumens, bound water through cell walls, and water vapour through void spaces. As wood dries, it loses the free water first; which depending on atmospheric humidity can occur quite rapidly. However, the cell walls stay saturated with water until all the free water has been lost. The point at which the lumen contains no water, but the cell walls remain saturated, is referred to as the fibre saturation point (FSP); occurring between 25 to 30% moisture content. The characteristics of wood do not change significantly due to the loss of free water, however below FSP wood begins to shrink or swell (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005).

Moisture content (MC) is expressed as a percentage of the dry weight of wood and is determined using (Equation (3) (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005):

$$MC\% = \frac{\text{Green Weight} - \text{Oven Dry Weight}}{\text{Oven Dry Weight}} \times 100\% \qquad \textbf{Equation (3)}$$

Oven dry weight is the weight of wood after all the water has been removed; which is considered a constant (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005).

Wood is constantly losing and gaining water as a result of changes in atmospheric humidity. When the moisture of wood is at a level, that is in a state of equilibrium relative to the atmospheric humidity, it is said to have reached the equilibrium moisture content (EMC). However, if the wood loses more water than it gains, evaporation or drying takes place. If the converse occurs and the wood gains more water than it loses, then wetting takes place and the wood increases in moisture content (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005).

Moisture content affects the properties of wood. When moisture content is reduced in wood, the strength properties of the wood increase (Figure 27). The degree moisture affects wood properties varies between tree species, within species and within trees (Panshin and de Zeeuw, 1980).

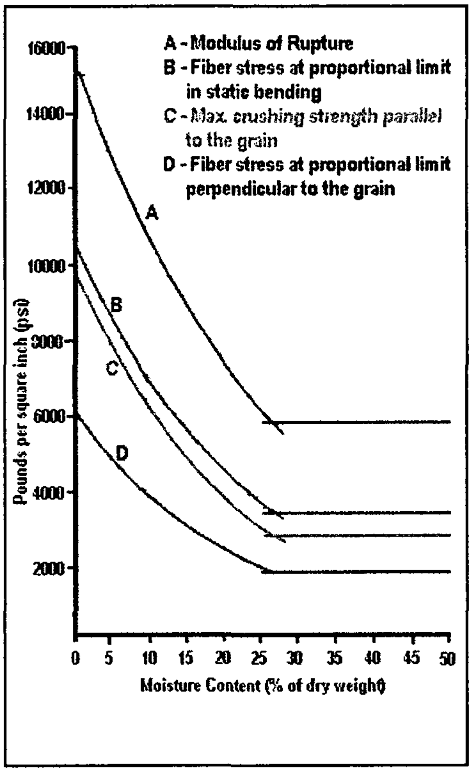


Figure 27. Affect of moisture on wood properties (Bowyer and Smith 2000).

When we state that strength properties improve with reduced moisture content, we mean in general terms, that strength increases 1% to 6% per 1% reduction in moisture content dry weight basis below FSP. For example, Figure 27 shows that the strength values at 10% MC dry weight basis are about double the values at 25% MC dry weight basis. This is just one reason that controlling moisture in wood through proper drying is the primary method of controlling defects in wood (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005).

2.2.3 Shrinking and swelling

When the moisture content of wood drops below the fibre saturation point changes in the wood structure occur; shrinkage being the most notable. Wood shrinks as a result of bound water being removed from the microfibrils in the cell walls. Shrinking begins when the moisture content of wood drops below the FSP; which in general terms is about 30% MC dry weight basis. When wood gains moisture, bound water returns to the cell walls first until they are once again saturated, then free water returns to the lumens. During the period of bound water attraction wood swells and continues to swell until the fibre saturation point is reached (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005).

The S-2 layer is the thickest layer within the wood cell and microfibril orientation in the S-2 layer of mature wood is almost parallel to the long axis of the wood cells. As a result, the S-2 layer has the greatest influence on how wood responds to shrinking and swelling. When bound water leaves the cell walls, microfibrils move closer together resulting in shrinkage occurring tangentially and radially (Figure 28). Conversely, when bound water returns to cell walls, microfibrils move farther apart, causing swelling in the radial and tangential directions (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984;

Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005).

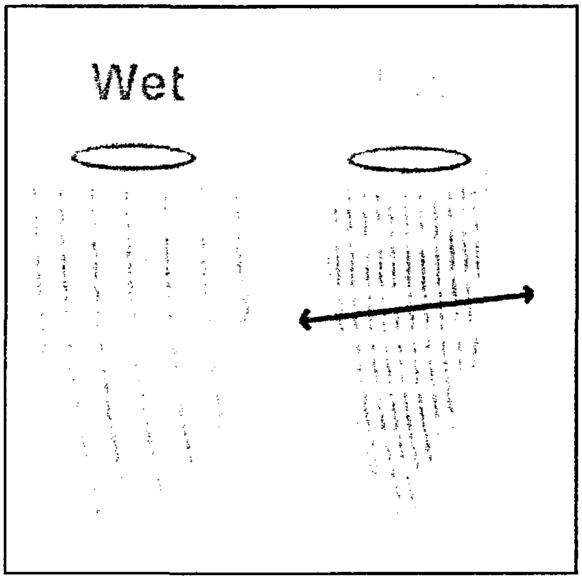


Figure 28. Normal dimensional change of wood due to drying (Bowyer and Smith 2000).

At this point, it should be understood, that some woods will shrink and swell more than others (Table 11). To accommodate the variation in shrinkage between species, the forest sector has developed drying schedules for species groups with similar classification of wood shrinkage and dimensional stability. For example, the most common kiln-drying schedule used in northwestern Ontario is pine spruce; developed for stable wood with low shrinkage. The pine spruce kiln-drying schedule can accommodate 70% of the harvestable volume of wood produced within the region. However, major defects are produced in eastern larch (*Larix laricina* (Du Roi) K. Koch) wood when this schedule is employed during drying. Eastern larch is classified as having moderate stability and low to medium shrinkage, with a high percent of reaction wood, thus eastern larch has its own kiln-drying schedule (Peck, 1957; Cech and Pfaff, 1980; Boone *et al.*, 1993; Jessome, 2000; NLGA, 2003a; Leitch, 2008).

In juvenile wood and reaction wood, the microfibrils in the S-2 layer may be oriented at a considerable angle from the direction of the grain. This causes warping as the cells to shrink along the grain (Figure 29). The degree of shrinkage in wood is based on a number of factors including (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Bowyer *et al.*, 2003; Zhang, 2003; Rowell, 2005):

- amount of cell wall material (density),
- microfibril angle,
- extractive content,
- lignification,
- presence of ray tissue, and
- ratio of earlywood to latewood.

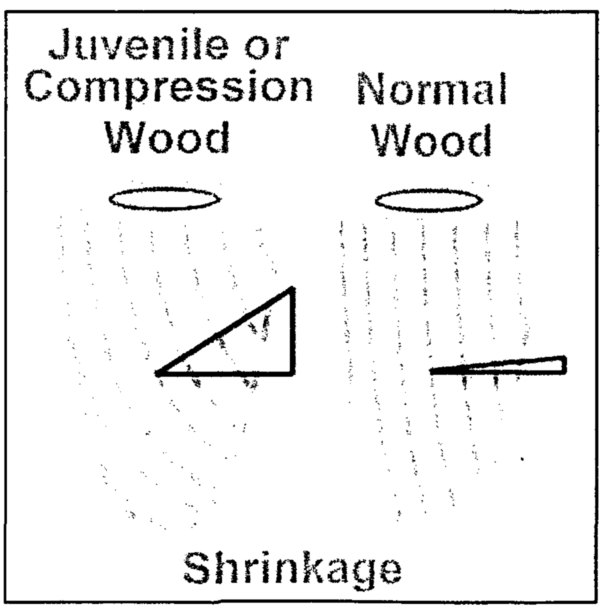


Figure 29. Abnormal dimensional change of wood due to drying (Bowyer and Smith 2000).

Since wood is anisotropic, having properties that differ according to the direction of measurement, it is not surprising that wood shrinks differently in each direction (Table 11). Tangential and radial shrinkage are greatest at 4.7% to 12.7% and 2.1% to 7.9% respectively; longitudinal shrinkage is relatively insignificant at 0.1% to 0.3%, thus it is not generally listed. Tangential shrinkage is generally 1.5 to 2 times greater than radial shrinkage (Bowyer and Smith. 2000). The anisotropic manner in which wood dries is the chief cause of defects in wood products; longitudinal, radial, tangential shrinkage occurs at a ratio of 1:50:100 respectively (Figure 30) (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005).

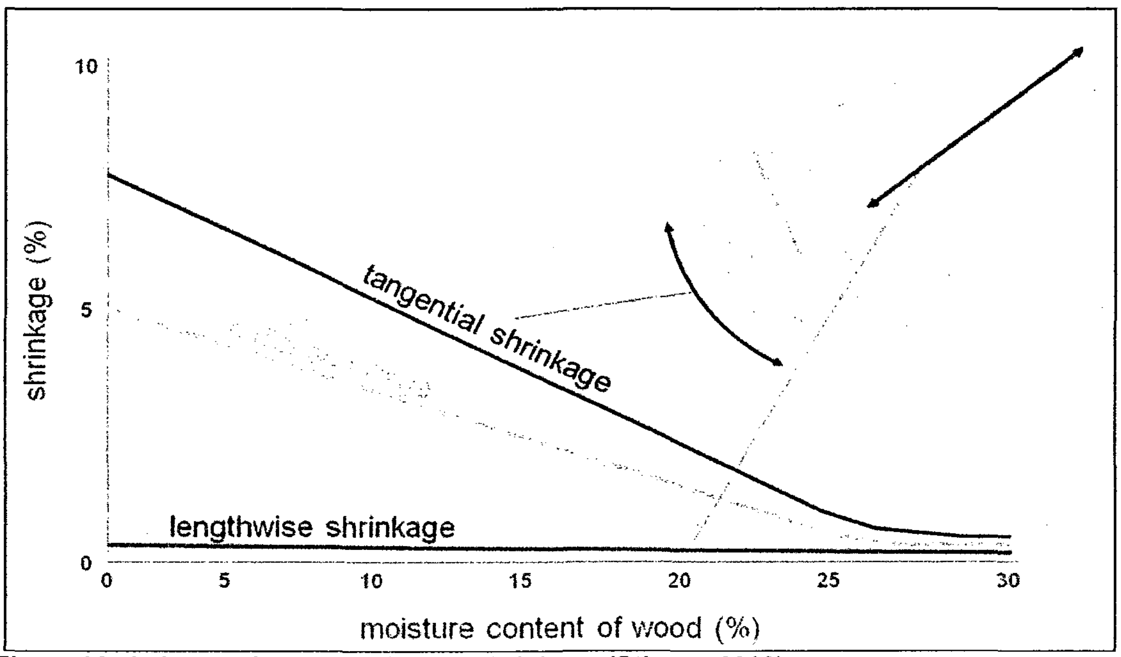


Figure 30. Anisotropic nature of wood shrinkage (Stiemer 2010).

2.2.4 Relative density (specific gravity)

Density is the mass (or weight) per unit volume of a material; expressed as either grams per cubic centimetre (g/cm3) or kilograms per cubic metre (kg/m3). Relative density at an oven-dry state (relative density$_{OD}$), which is also called specific gravity, is the ratio of the density of oven-dry wood to the density of an equal volume of water at 4 degrees Celsius; since it's a ratio it has no units (Equation (4 and Equation (5).

$$\text{Relative Density}_{OD}\ (\text{Specific Gravity}) = \frac{\text{Density of oven-dry wood}}{\text{Density of equal volume of water}} \qquad \textbf{Equation (4)}$$

$$\text{Relative Density}_{MC} = \frac{\text{Mass of oven-dry wood}}{\text{Volume of wood at Moisture Content}} \qquad \textbf{Equation (5)}$$

The relative density of wood is closely correlated to most mechanical properties of wood. For example, there is correlation between relative density and strength, where the higher the relative density observed the higher the strength of mature wood (Figure 31). Other properties that are generally correlated to specific density include (Panshin and de Zeeuw. 1980; Mullins and McKinight, 1981; Bowyer and Smith, 2000; Hoadley, 2000):

- yield of pulp per unit volume,
- heat transmission,
- heat release in combustion, and
- shrinking and swelling of wood.

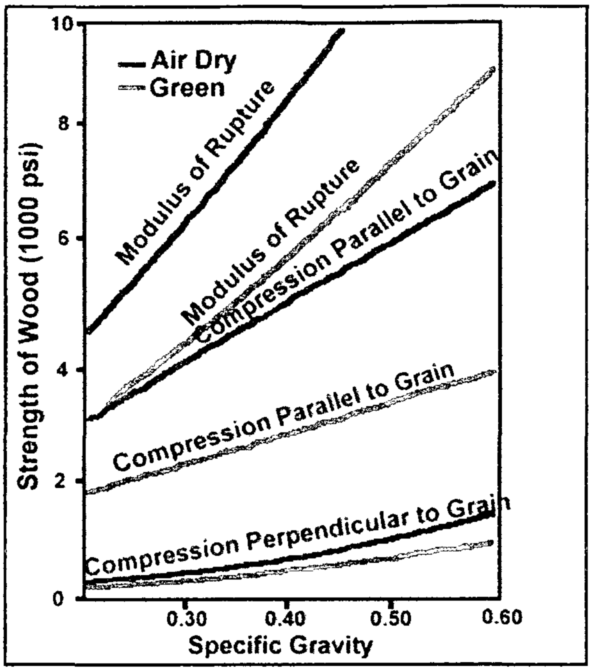


Figure 31. Correlation between specific gravity / relative density$_{OD}$ and strength in wood at different moisture levels (Bowyer and Smith 2000).

Knowing the density and relative density are essential to proper management of the value-chain. While relative density is a good indicator of wood properties for end use considerations, density is an indicator of operational considerations, including identifying appropriate logging and milling equipment (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005). There are standard moisture contents used for the comparison of wood characteristics, these are oven-dry (OD), nominal or air-dry (12% MC) and basic (30% MC) (Table 12).

Table 12. Standard moisture contents used in the comparison of wood characteristics.

Standard Moisture Content (MC)	Relative Density		Density	
	MC of Mass	MC of Volume	MC of Mass	MC of Volume
Oven-Dry (OD)	OD	OD	OD	OD
Nominal or Air-dry	OD	12%	12%	12%
Basic	OD	30%	30%	30%

Relative density is the most common wood property used for comparison in wood science research, and provides us with a means for measuring variation between species, within species and within a tree: e.g.,

- balsa wood (*Ochroma pyramidale*) known to be extremely soft and light-weight has a wood $density_{OD}$ of 0.16 g/cm^3, and
- lignum-vitae (*Guaiacum sanctum*) known to be hard heavy and very strong has a wood $density_{OD}$ of 1.4 g/cm^3.

These seem to be very different woods, yet when we consider these same two species with respect to relative density, they are surprisingly similar. These woods are similar because the relative density of solid matter in their wood cells is equal. In other words, if we remove all the void spaces, such as, the lumens, pit openings, and pit cavities, and measure the relative density of what's left, it will be the same for all wood and every species of tree; just under 1.5 g/cm^3 (Panshin and de Zeeuw. 1980; Mullins and McKinight, 1981; Bowyer and Smith, 2000). Therefore, we can conclude that (Brown, 2008):

- the variance in cellulose between species, within species and within trees is insignificant, especially in the S2 layer of the cell wall; as the relative $density_{OD}$ of the cell material is approximately 1.5 (g/cm^3),
- the configuration of void space elements within a wood cell determines the wood characteristic of a tree species and individual trees within a species,
- the highest possible relative $density_{OD}$ for any wood must be under 1.5, and
- the percentage void spaces for any wood can be predicted by dividing the oven-dry relative density of the wood by 1.5.

2.3 Influencing wood quality

The challenge for the forest sector is to manage Canada's forests so that the wood produced is of the quality required to meet the projected end use. How do we influence wood quality through forest management?

As discussed, trees produce wood to support the vertical growth of the crown; either by transporting material between the roots and the crown, or by supporting the structure of the crown. This allows the tree to maintain vertical position over shorter competing vegetation to capture more sunlight. Thus, a trees interaction with the surrounding environment will be with respect to maintaining a dominant vertical position over competing vegetation (Ruddick, 1982).

According to Zobel (1992) forest management is concerned with understanding what "causes a change in the (normal) growth pattern or form of a tree that may result in differing wood properties." Therefore, it is important to understand what affects wood growth in natural grown stands before considering silvicultural treatments.

2.3.1 Genetics

According to Eriksson and Ekberg (2001) heredity or tree genetics has the greatest influence on how a tree will respond to its surrounding environment, dictating the growth pattern and form of the tree. Although our understanding of tree gene functions is limited, the literature clearly indicates that genetics, not environment, has a greater effect on wood characteristics (Eriksson and Ekberg, 2001; Beaulieu *et al.*, 2005; Leitch, 2008). For example, phenotypic variation within a tree species can account for substantial variation in physical and mechanical properties (Beaulieu *et al.*, 2005; Leitch, 2008); a conclusion based primarily on studies of wood density variation (Leitch, 2008; Zhang and Koubaa, 2008). Thus, genetics offers us the greatest potential to influence wood quality.

Genetic research of northwestern Ontario tree species has been centered on tree improvement initiatives driven by a national or provincial perspective. Direct research within the region is very limited and focused on a few species. Black spruce (*Picea mariana* (Mill.) B.S.P.) is the most economically important species in Canada (Peng *et al.*, 2004), and has received the most attention in this area (King,1967; Zhang and Koubaa. 2008). Table 13 summarizes the research completed on improving wood quality of northwestern Ontario commercial species through forest genetics.

Northwestern Ontario has a long history of tree improvement initiatives dating back to 1953 (Thompson, 2005), through:

- identifying trees which exhibit superior growth and form,
- collecting seeds from these superior trees, and
- producing seedlings with the superior characteristics in a nursery (Forest Genetics Ontario, 2009).

In other parts of the world, genetic modification of tree species has been employed to produce clones that are fast growing trees which will produce wood of normal to higher than normal volume (Leitch, 2008).

Table 13. Research summary of primary findings on genetic variation of northwestern Ontario commercial tree species.

Species	Primary Findings
black spruce (*Picea mariana* (Mill.) B.S.P.)	• Wood characteristics associated with pulp quality can be improved through tree improvement programs except for fibre wall thickness, • Most variation within a provenance is between trees, • Knot properties, although highly variable between trees, is predictable, and • Growth rate has less effect on wood density with an increase in age. (Zhang and Koubaa, 2008; Lemieux *et al.*, 2001; Zhang, 1998; Zhang *et al.*, 1996; Villeneuve *et al.*, 1987; Zhang and Morgenstern, 1995; Khalil, 1985)
jack pine (*Pinus banksiana* Lamb.)	• Attempts to improve wood quality and growth rate, • Variance observed to be greatest between sites, • Improving wood quality and yield simultaneously proved to be the best strategy. (Zhang and Koubaa, 2008; Zhang and Chui, 1996; Morris and Parker, 1992; Magnussen and Keith, 1990; Keith, 1986; Grigal and Sucroff, 1966)
white spruce (*Picea glauca* (Moench) Voss)	• Tree improvement programs focused on tree form, growth rate, and hardness, • Studies on wood quality are limited, and • Genetic response to environmental factors highly variable. (Zhang and Koubaa, 2008; Beaulieu *et al.*, 2007; Knudson *et al.*, 2006; Magnussen, 1993; Yanchuk and Kiss, 1993; Corriveau *et al.*, 1991; Kiss and Yanchuk, 1991; Corriveau *et al.*, 1990; Kiss and Yeh, 1988; Merril and Mohn, 1985; Beaulieu and Corriveau, 1985; Taylor *et al.*, 1982; Holst, 1960)
eastern white cedar (*Thuja occidentalis* L.)	• Relatively no information on the genetics of this species, and • Variance between trees is significant. (Zhang and Koubaa, 2008; Zobel and van Buijtenen, 1989; Maejlin, 1973)
eastern larch (*Larix laricina* (Du Roi) K. Koch)	• Limited studies on the genetics of this species, • Genetic response to environmental factors highly variable, • Greatest variance within the tree, and • Wood density does not vary significantly between sites and trees. (Zhang and Koubaa, 2008; Yang and Hazenberg, 1987; Balatinecz, 1983; Vallee and Stipanicic, 1983)
red pine (*Pinus resinosa* Ait.)	• Known to have uniformed wood properties with limited genetic variation, • Limited variance compared to other pine species, • Significant variance observed to be between sites, and • Variance between trees accounts for as much as 12% of total variance. (Zhang and Koubaa, 2008; Larocque, 1997; Mosseler *et al.*, 1992; Lee and Wahlgren, 1979; Fowler and Morris, 1977; Fowler and Lester, 1970; Gilmore, 1968; Rees and Brown, 1954)
eastern white pine (*Pinus strobus* L.)	• Limited studies on the genetics of this species, • Significant variance observed to be between sites, and • Variance between trees accounts for at least 80% of total variance. (Zhang and Koubaa, 2008; Beaulieu *et al.*, 1990)
balsam fir (*Abies balsamea* (L.) Mill.)	• Limited studies on the genetics of this species, and • Significant variance observed to be between sites . (Zhang and Koubaa, 2008; Li *et al.*. 1997; Zobel and van Buijtenen, 1989; Gilmore, 1968)

According to the literature, it may be possible to produce genetically modified trees to produce wood with:

- long fibers,
- uniform density,
- heartwood extractives,
- low proportions of lignin and juvenile wood,
- resistant to climate fluctuations or plant hardiness, and
- minimal branch development.

However, there are pitfalls to genetic modification (Bowyer and Smith, 2000; Bowyer *et al.*. 2003; Leitch, 2008).

According to Koehler (1939) first generation hybrid clones tend to display vigorous growth that may not be duplicated in the second generation (Koehler, 1939). Trees have a longer rotation age than other genetically modified plant species, and the literature states that assessing the relative success or failure of genetic modification cannot be undertaken until trees are at least 25 years of age (Koehler, 1939; Eriksson and Ekberg, 2001). Further, genetic modification may cause a change in how the tree may respond to the surrounding environment. Storm events, climate change or response to competition may trigger dormant genes which could change the normal growth pattern or form of the tree, causing undesirable results. Finally, interbreeding between plantation clones and natural species could have disastrous results (Leitch, 2008; Eriksson and Ekberg, 2001; Koehler, 1939).

2.3.2 Silviculture

The word silviculture comes from the Latin words silva, meaning a wood, and cultura, meaning cultivate (Hawkins and Allen, 1991). Thus, silviculture literally means to cultivate a wood. Today, this definition could be expressed as the management of tree growth for wood production. However, there are a number of different definitions for silviculture. According to the British Columbia Forest Service, the most common definition for silviculture is, "the art and science of controlling the establishment, growth, composition, and quality of forest vegetation for the full range of forest resource objectives" (Zielke and Bancroft, 1999). In other words, it is managing a forest to meet a set of shared attitudes, values, goals and practices that are characterized by a stakeholder group (Calfee and White, 2008). Thus, cultivating wood is just one of many management goals.

In the discussion on wood morphology, we have been trying to understand the factors associated with cultivating wood which provide opportunities for development of woods products in Northwestern Ontario. We have identified wood quality as the principle factor which affects the potential for product development. Further, we know that any factor which changes the normal "growth pattern or form of a tree may result in differing wood properties" (Zobel, 1992) and ultimately influence wood quality. We also have identified a number of gaps in the knowledge and understanding of wood morphology, especially in northwestern Ontario.

Given what we have discussed thus far, this new and broader definition of silviculture presents us with a number of challenges in understanding how silviculture may influence wood quality, and what are the future opportunities for northwestern Ontario with respect to new product development. Zobel (1992) states, "the crux of the problem is the 'may'. Sometimes wood is affected by forest practices, and sometimes it is not" (Zobel, 1992). Zobel (1992) points out that because of phenotypic variation trees growing next to each other can respond differently to the same silviculture treatment. Therefore, it is difficult or even impossible to make generalizations on how silvicultural practices may influence wood quality (Zobel, 1992). It is not surprising then that the literature on the effects of silviculture on wood quality is contradictory (Zobel, 1992; Zielke and Bancroft, 1999; B.C Forest Service, 2002; Gartner, 2005).

Silviculture uses management techniques to maximize the wood volume yielded and wood quality at harvest which include:

- site preparation,
- planting,
- genetically improved,
- tree spacing,
- selective or commercial thinning, and
- harvesting systems.

For the purposes of the discussion, we will focus on the silviculture practices commonly used in northwestern Ontario.

In Ontario, silviculture treatments are not legislated, as in other jurisdictions. The Forest Operations and Silviculture Manual states:

> "Rather than give forest managers a set of strict rules that must be followed, Ontario relies on the professional judgment, within a set of broad guidelines and principles, of the people given the responsibility to manage the forest resource" (OMNR, 2000).

It is generally understood, that silviculture practices which increase growth rate result in degrading the mechanical properties of the wood. However, there is little or no information available on the relationship between changes in growth rate and the mechanical properties of the northwestern Ontario commercial tree species.

Table 14 summaries the research completed on improving wood quality of northwestern Ontario commercial species through silvicultural practices. No studies were available on eastern white cedar (*Thuja occidentalis* L.)

Rotation age may be one of the best ways for a silviculturist to influence wood quality. Harvesting trees too early, reduces the percent of mature wood per volume available, and reduces the amount of clearwood, thus, reduces the overall quality of wood harvested. Harvesting trees too late creates over mature trees with declining wood production and high susceptibility to pest attack and disease (Zobel, 1984: Zobel, 1992; Zielke and Bancroft, 1999; B.C Forest Service, 2002; Gartner, 2005).

Table 14. Research summary of primary findings on the influence of silvicultue on the wood quality of northwestern Ontario commercial tree species.

Species	Primary Findings
black spruce (*Picea mariana* (Mill.) B.S.P.)	• Increased spacing results in a corresponding increase in growth rate and a decrease in wood density and the percentage of mature wood, • Small to moderate spacing results in longer fibers with no significant change in wood density or the percentage of mature wood, • Increase in thinning intensity results in corresponding increase in growth rate and a decrease in wood density, and • Trenching, to manage drainage, results in an increase growth rate with a decrease in wood density and fibre length. (Zhang and Koubaa, 2008; Yang and Hazenberg, 1994; Yang, 1994; Yang and Hazenberg, 1992; Wang *et al.*, 1985)
jack pine (*Pinus banksiana* Lamb.)	• Spacing is the most effective method of influencing the wood quality of jack pine, • Increase in spacing results in an increase in growth, knot size, branch angle, stem taper, and decrease in wood density, MOE, MOR, and pulping properties, and • Thinning resulted in reduced knot size with relatively no change in the lumber bending properties or tree height. (Zhang and Koubaa, 2008; Zhang *et al.*, 2005; Morris *et al.*, 1994; Morris and Parker, 1992; Bell *et al.*, 1990; Magnussen and Yeatman, 1987)
white spruce (*Picea glauca* (Moench) Voss)	• Increase spacing results in a corresponding increase in the growth rate and a decrease in the percentage of mature wood, • Thinning – no information available, • Trenching, to manage drainage, results in an increased growth rate with decreases in wood density and fibre length, and • Pruning beneficial but not cost effective. (Zhang and Koubaa, 2008; Yang and Hazenberg, 1994; Yang, 1994; Yang and Hazenberg, 1992; Berry, 1964)
eastern larch (*Larix laricina* (Du Roi) K. Koch)	• Few studies available, • Thinning results in increased growth rate with a decrease in wood density and fibre length, and • Trenching, to manage drainage, results in increased growth rate with a decrease in wood density and fibre length. (Zhang and Koubaa, 2008; Koga *et al.*, 1996; Wang *et al.*, 1985)
red pine (*Pinus resinosa* Ait.)	• Spacing and thinning results in minor changes in wood quality. (Zhang and Koubaa, 2008; Chauret and Zhang, 2004; Laroque and Marshall, 1995; Jayne, 1958)
eastern white pine (*Pinus strobus* L.)	• Thinning and pruning results in increase growth rate without degrading the lumber properties during processing and drying activities. (Zhang and Koubaa, 2008; Page and Smith, 1994)
balsam fir (*Abies balsamea* (L.) Mill.)	• Increases in thinning intensity results in corresponding increase in the growth rate and a decrease in wood density. (Zhang and Koubaa, 2008; Koga *et al.*, 2002)

For example, the lumber bending properties of jack pine (*Pinus banksiana* Lamb.) were significantly degraded, 36.1% lower, using a 50 year old rotation age. However, using a 70 year old rotation age showed no difference in lumber bending properties from 90 year old stands (Duchesne, 2006). Table 15, shows the average rotation age and average maximum age of Northwestern Ontario tree species.

Table 15. Average rotation age and average maximum age of northwestern Ontario tree species.

Species	Max Average Age (years)	Average Rotation Age of Second Growth (years)
black spruce (*Picea mariana* (Mill.) B.S.P.)	280	70 to 100
white spruce (*Picea glauca* (Moench) Voss)	250 - 300	75 to 125
jack pine (*Pinus banksiana* Lamb.)	160	60 to 100
red pine (*Pinus resinosa* Ait.)	300	60 to 100
eastern white pine (*Pinus strobus* L.)	300	60 to 120
eastern white cedar (*Thuja occidentalis* L.)	400 to 500	70 to 160
eastern larch (*Larix laricina* (Du Roi) K. Koch)	150 to 180	30 to 120
balsam fir (*Abies balsamea* (L.) Mill.)	150	60 to 90
trembling aspen (*Populus tremuloides* Michx.)	120 to 200	15 to 90
black ash (*Fraxinus nigra* Marsh.)	250 to 300	70+
red maple (*Acer rubrum* L.)	150	70 to 100
white birch (*Betula papyrifera* Marsh.)	140	30 to 70
Note: This table presents the range of averages reported by the literature (Burns and Honkala, 1990a; Burns and Honkala, 1990b; Archibald and Arnup, 1993; OMNR, 1997; Kevan and Murphy, 2007; Zhang and Koubaa, 2008; OMNR, 2010).		

Site preparation increases plantable spots by either physical, mechanical or chemical disturbance to the forest floor, thus, increasing site productivity. There are very few studies investigating the influence of site preparation on wood quality (Zobel, 1984; Zobel, 1992; Zielke and Bancroft, 1999; B.C Forest Service. 2002). There is conflicting evidence that site preparation can influence wood quality, however, trenching can improve plantable spots, and drain excess water off a site. The responses to trenching are increased wood yield on a site, and improved growth in some species (Hillman and Roberts, 2006). However, studies show that improved growth from trenching, results in a decrease in wood density in some species (Berry, 1964; Wang *et al.*. 1985; Hillman and Roberts, 2006). Site preparation, in combination with proper regeneration and stand tending, may play a key role in developing high quality uniform wood in northwestern Ontario. However, further study is required before this could be said with any certainty.

Renewal of forest stands in northwestern Ontario are either through artificial regeneration or natural regeneration. Artificial regeneration includes planting seedlings and direct seeding (OMNR, 1997). Under the Ministry of Natural Resources Directive FOR 06 02 01, seed used in renewal must be from "climatically-based seed zones to ensure that tree seed and stock used in artificial regeneration activities are adapted to local climatic conditions" (OMNR, 2001). There are 13 seed zones in northwestern Ontario (Figure 32) (OMNR, 2001).

As discussed, tree genetics has the greatest influence on how a tree responds to its surrounding environment, thus, dictates growth pattern and form of the tree. The seed zone directive of the Province of Ontario will promote phenotypic variation within tree species of northwestern Ontario and will influence variation in wood quality for a given species from one seed zone to another (Zobel, 1992; Lei *et al.*, 2004; Beaulieu *et al.*, 2005). Many jurisdictions throughout the world, have developed similar seed zone policies (OMNR, 2001). This may affect the relevance of data when comparing studies between different jurisdictions.

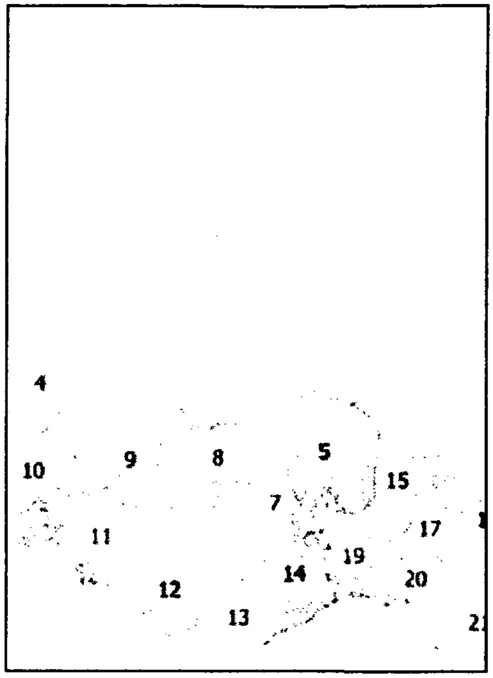


Figure 32. Provincially designated seed zones located in northwestern Ontario (OMNR 2001).

The intensity of regeneration or stocking levels has been shown to influence wood quality. As discussed, when trees are open grown or widely spaced, mature wood development is delayed, thus reducing wood quality (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005). Therefore, under stocking during renewal can significantly influence wood quality. Planting trees too close can suppress height growth in some species (Zobel, 1984; Zobel, 1992; Zielke and Bancroft, 1999; B.C Forest Service. 2002). The literature shows that stocking levels or spacing can affect relative density, fibre length, wood volume yield, and percentage of mature wood. Higher stocking (decreased spacing between trees) can increase fibre length, wood density, and the percentage of mature wood (Jayne, 1958; Magnussen and Yeatman, 1987; Yang and Hazenberg, 1987; Bell *et al.*, 1990; Morris and

Parker, 1992; Yang and Hazenberg, 1992; Barbour *et al.*, 1994; Yang and Hazenberg, 1994; Yang, 1994; Larocque and Marshall, 1995; Yang, 1995; Zhang and Chauret, 2000; Zhang *et al.*, 2002; Chauret and Zhang, 2004; Zhang *et al.*, 2005; Leitch, 2008; Zhang and Koubaa, 2008).

Generally speaking, when stocking levels are under 2000 stems per hectare, relative density is significantly reduced. While stocking levels over 3000 stems per hectare, seem to have little or no effect on relative density (Zobel, 1984; Zobel, 1992; Willcocks and Bell, 1995; Zielke and Bancroft, 1999; B.C Forest Service, 2002; Zhang *et al.*, 2001). Having said this, the literature indicates, that optimum stocking levels are site specific. For example, on less dense wetter sites, spacing between stems can be greater, resulting in lower stocking levels (Willcocks and Bell, 1995; B.C Forest Service, 2002).

Stand tending in Northwestern Ontario appears to be limited to promoting tree growth and increasing volume by the removal of competing vegetation (Willcocks and Bell, 1995; OMNR, 2000). Tending can influence wood quality primarily by affecting stocking levels within the stand (Willcocks and Bell, 1995; OMNR, 2000). Reducing competition within a stand (Shepard, 1980; Smith, 1984; Yang and Hazenberg, 1994; Barbour *et al.*, 1994; Morris *et al.*, 1994; Willcocks and Bell, 1995; Koga *et al.*, 1997; Zielke. and Bancroft, 1999; B.C Forest Service, 2002; Chauret and Zhang, 2004):

- Increased volume,
- Decreased density, and
- Reduced vertical growth on some sites.

2.3.3 Environment

As discussed, genetics not environment has a greater effect on wood characteristics (Eriksson and Ekberg, 2001; Zobel, 1984; Beaulieu *et al.*, 2005; Leitch, 2008). However, this does not mean that environmental conditions do not influence wood quality. Rainfall, length of growing season and soil factors clearly affect tree growth and may influence wood quality (Eriksson and Ekberg, 2001; Zobel, 1984; Beaulieu *et al.*, 2005). Environmental factors may be mitigated through silviculture treatments such as delaying harvesting, irrigation or fertilization (Zobel, 1984; Beaulieu *et al.*, 2005). These treatments are site specific and may require a prescription of a number of treatments to achieve the desired effect (Zobel, 1992; Willcocks and Bell, 1995; Zielke and Bancroft, 1999; B.C Forest Service, 2002). For example, Table 16 illustrates how variable the growth environment can be for the commercial species of northwestern Ontario within their growth range (Burns and Honkala, 1990a; Burns and Honkala, 1990b; OMNR, 1997; Zhang and Koubaa, 2008).

When reviewing Table 16, we must keep in mind the vast differences in growth ranges between nothwestern Ontario tree species. The growth range for red pine, red maple, eastern white cedar, eastern white pine, and black ash are limited to eastern North America. While the remaining commercial species of northwestern Ontario have growth ranges stretching across Canada and the northern United States (Burns and Honkala, 1990a; Burns and Honkala, 1990b; OMNR, 1997; Zhang and Koubaa, 2008).

Table 16. Environmental variation, requirements, and tolerance to environmental stress of northwestern Ontario tree species (Zhang and Koubaa, 2008; OMNR, 1997; Burns and Honkala, 1990a; Burns and Honkala, 1990b).

Species	Environmental Variation in Growth Range			Environmental Requirements				Tolerance to Environmental Stress				
	Range in Temperature	Range in Precipitation	Frost Free Days	Water	Nutrients	Shade	Zone of Rooting	Drought	Prolonged Flooding	Frost	High Temp	Wind
Black Spruce	-62 to 41° C.	150 to 1520 mm	60 to 140 days less near tree line.	Low to Moderate	Low	Intermediate to Tolerant	Organic / Mineral	Low to Moderate	Low	Low	-	Low to Moderate
White Spruce	-54 to 43° C	250 to 1270 mm	20 to 180 days 20 days near tree line.	Moderate	Moderate	Intermediate to Tolerant	Mineral	Low to Moderate	Low to Moderate	Low to Moderate	-	Low to Moderate
Jack Pine	-46 to 38° C	250 to 1400 mm	50 to 173 days	Low	Low	Very Intolerant	Mineral	High	Low	Moderate	-	Moderate to High
Red Pine	-40 to 38° C	510 to 1520 mm	40 to 160 days	Low	Low to Moderate	Intolerant	Mineral	Moderate to High	Low	Moderate	-	High
Eastern White Pine	July Daily Average 18 to 23° C	510 to 2030 mm	90 to 180 days	Moderate	Moderate	Intermediate	Mineral	Moderate	Low to Moderate	Moderate to High	-	Moderate to High
Eastern White Cedar	-12 to 22° C	510 to 1400 mm	80 to 200 days	Moderate	Low to Moderate	Tolerant	Organic / Mineral	Moderate	Moderate to High	Moderate to High	-	Low to Moderate
Eastern Larch	-62 to 43° C	180 to 1400 mm	75 to 180 days	Low to Moderate	Low to Moderate	Very Intolerant	Organic / Mineral	Low to Moderate	Moderate	Moderate	-	Low to Moderate
Balsam Fir	-18 and -18° C	150 to 1400 mm	80 to 180 days	Moderate	Moderate	Very Tolerant	Organic / Mineral	Low	Moderate	Low to Moderate	-	Low
Trembling Poplar	-57 to 41° C	180 to 1020 mm	30 to 160 days	Moderate to High	Moderate to High	Very Intolerant	Mineral	Low to Moderate	Low to Moderate	Low	Low	Moderate
Black Ash	-12 to 22° C	510 to 1400 mm	80 to 180 days	High	Moderate	Intolerant	Organic / Mineral	Low	Moderate to High	Moderate to High	-	Low
Red Maple	Widest tolerance to climatic conditions of all the Maples	Extreme moisture conditions very wet or quite dry.	80 to 240 days	Low to Moderate	Low to Moderate	Tolerant	Mineral	Moderate	Moderate to High	Low	-	Moderate
White Birch	July Daily Average 13 to 21° C	300 to 1520 mm	80 to 140 days	Moderate	Moderate	Very Intolerant	Mineral	Moderate	Low	Low	Low	Moderate

Figure 33 illustrates the environmental variation of four northwestern Ontario tree species. We cannot assume wood characteristics for these species will be unchanged throughout their growth range. Site specific forest management for these species is recommended by the literature, and this paradigm should carry forward along the value chain for all northwestern Ontario species (Burns and Honkala, 1990a; Burns and Honkala, 1990b; Zobel, 1992; Willcocks and Bel, 1995; OMNR, 1997; Zielke and Bancroft, 1999; B.C Forest Service, 2002).

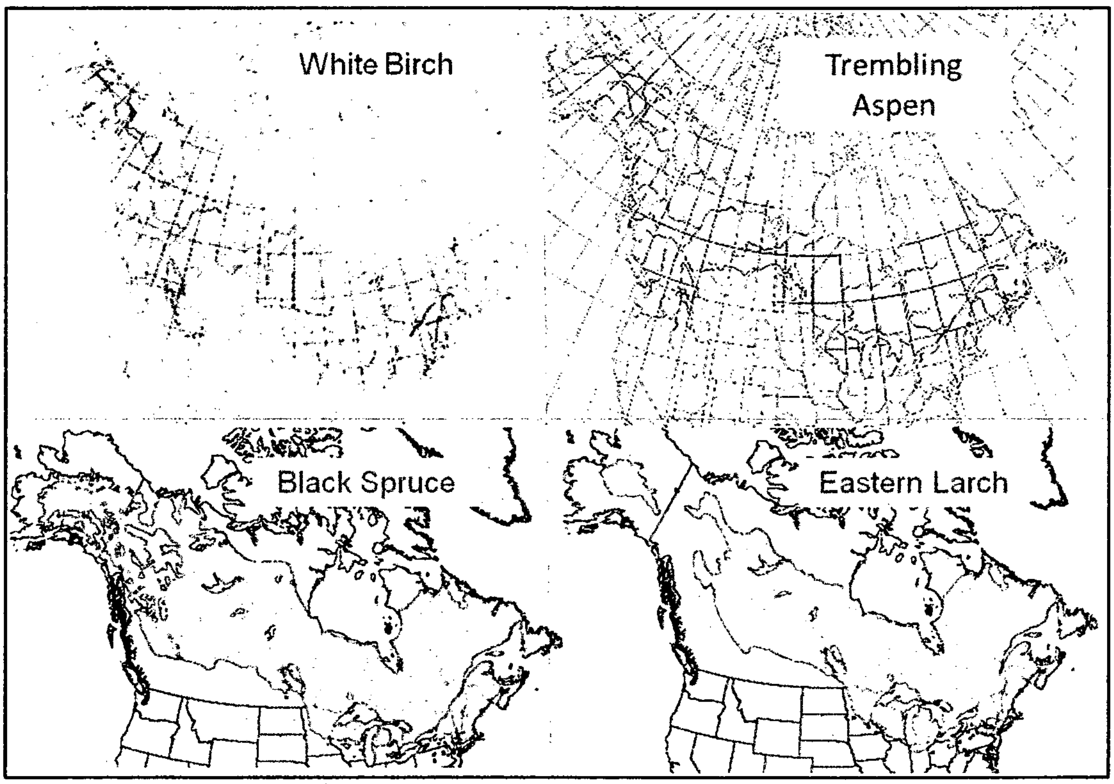


Figure 33. Growth range of trembling aspen, white birch, black spruce, and eastern larch (Burns and Honkala, 1990a; Burns and Honkala, 1990b).

We have not always understood how environmental conditions influence wood quality. Only through research, have foresters and wood scientists increased their knowledge on wood morphology over the last century. For example, in the 1930s it was postulated that "environment has a very pronounced influence on wood quality and therefore may mask lesser hereditary differences" (Koehler, 1939). It was felt, that environment was the driving factor on wood quality and almost any wood element was attributed to environmental factors (Koehler, 1939). Today the literature pertaining to influences on wood quality clearly indicates that genetics and environment are key factors (Eriksson and Ekberg, 2001; Zobel, 1984; Beaulieu *et al.*, 2005; Leitch. 2008).

No studies were found on investigating the influence of environment on the wood quality of the tree species of northwestern Ontario specifically. However, studies were found for these species growing in other regions. These studies showed significant difference in wood density between geographic locations that may be attributed to climatic differences between sites (Alemdag, 1984; Singh, 1986).

2.4 Wood uses

As discussed, very little research has been completed on the wood characteristics of northwestern Ontario tree species. The challenge is to identify what products can be made from northwestern Ontario tree species without having certainty as to their actual wood characteristics.

A number of studies have been completed comparing regional variation of wood characteristics to published baseline data such as Jessome's (2000). Singh (1986) observed that there were regional variations in reported wood density of -10.0% to +18.2% between the Jessome (2000) study and the same tree species study in three other areas of Canada. Further, he reported that Alemdag (1984) experienced similar results when comparing 28 Ontario tree species.

According to the literature, the best way to maximize the value chain of the forest industry is to match end use characteristics with the wood properties of available tree species (Gartner, 2005; de la Roche, 2008). As we do not have regional data on wood properties for northwestern Ontario tree species Table 17 lists wood characteristics, working properties and uses as report by Mullins and McKnight (1981), Henderson (1981), Burns and Honkala (1990). Table 17 shows that knowing the characteristics is just one part of the equation to matching choice of tree species to end use; processing properties of wood are also important.

In northwestern Ontario wood products manufacturing has been limited to (Moazzami, 2006):

- Pulp and Paper,
- Lumber, Panels,
- Engineered Wood Products,
- Chemical Extractives, and
- Value-added; although only minorly.

Table 17. Wood characteristics of northwestern Ontario tree species (Zhang and Koubaa, 2008; Burns and Honkala, 1990; Mullins and McKnight, 1981; Henderson, 1981).

Tree Species of northwestern Ontario.	Wood Characteristics	Working Properties	Uses
black spruce	Wood mechanically is not very resistant to bending or end-wise compression, is moderately strong (stronger than white spruce) with above average stiffness. Dries easily with moderately high shrinkage. Is straight, even grained, medium to fine textured, and soft.	Wood is easily worked and finishes with a satin-like surface. It glues well, average in paint-holding ability, but rates low in nail-holding capacity.	Wood use primarily pulpwood for paper and composites, and lumber products. Secondary products primarily millworks. Also food containers, boxes, ladders, canoe paddles and oars, scaffolding, wood siding, and crates.
Trembling Aspen	Wood mechanically is moderately strong with above average stiffness comparable to white spruce. Is straight grained, light and soft with uniform texture. Has good dimensional stability and low to moderate shrinkage.	Wood machines easily however care most be given to prevent a slightly fuzzy surface. It holds nails poorly to fairly well and does not split when nailed. It turns, bores, sands, and holds paint well. It is moderate to easy to glue.	Used mainly as pulpwood and fuelwood. Secondary products include structural lumber, wood composite, veneer, millworks, furniture parts, match sticks, tongue depressors, paneling, and milled house logs.
Jack Pine	Wood mechanically is moderately strong in bending and moderate to low in compressive strength, moderately resistant to impact, and moderately low in stiffness. Is coarse textured and resinous, moderately light in weight, and low to moderate shrinkage.	Wood is generally knotty average workability with tools. It has fair nail-holding capacity and glues well, however is liable to split when nailed.	Mainly pulpwood (70% in Ontario) for paper and composites, and lumber. Secondary products include timber, post and pole products, pilings, railway ties, slack cooperage, veneer, form work, joinery, packing cases, panelling,.

Table 18 continued			
White Birch	Wood mechanically is weak and not resistant to impact. Wood is fine with uniform texture and has high shrinkage.	Wood is difficult to work with hand tools, moderately easy to glue, but easily machined.	Used mainly as pulpwood and fuelwood. Secondary products include lumber, veneer, plywood, furniture, and wood flooring. Can be tapped in the spring to obtain sap from which syrup, wine, beer, or medicinal tonics can be made.
Balsam Fir	Wood mechanically has low bending and compressive strengthen in stiffness and resistance to impact and shear. Better strength properties than white spruce but less than black spruce. Wood is light weight, soft, and has moderate shrinkage.	Wood works easily with both hand tools and machine operations, low nail holding capacity, but good splitting resistance. Finishes well, and takes paint, varnish, and polish well.	Wood use primarily pulpwood for paper and composites and lumber. Secondary products include paneling, timbers, boxes, creates, ladders, oars, canoe paddles, and wood siding. Extractives, oleoresin used in microscopy, medicinal compounds, and spirit varnishes.
Eastern White Cedar	Wood mechanically has the lowest density of any commercial domestic wood, thus bending and compressive strength, hardness, stiffness, and resistance to impact and splitting are all low. It soft with an even grain and fine texture. It dries easily with very little shrinkage and no warping.	Wood machines easy to average works with using hand tools easily. It glues well, holds paint well, and does not hold nails or screws well..	Used mainly for its superior durabilty and strength features. Lumber, primarily boards for secondary manufacturing. Secondary products: best wood for use in outdoor furniture or any products that come into to contact with the ground or water. Boats, canoes, posts, fencing, wood siding, poles, pilings, roof acsent, wood shingles, and pulpwood for specialty composites.

Table 18, continued

Eastern Larch	Wood mechanically is intermediate to high in strength, stiffness, and hardness, but low resistance to impact. The wood is fairly coarse to medium in texture and spiral grain is common. Drying is difficult with moderate shrinkage with a tendency to warp.	The wood is not simple to work with, however works well in most instances when great care is taken. It is the best wood for outdoor applications	Depending on the region, either pulpwood or lumber are the main products produced. Historically, tamarack was the preferred species for rail ties. Secondary products include wood composites, wood flooring, outdoor furniture, wood siding, paneling, doors and door frames, window and frame parts, house logs, poles, pilings, fencing, and engineered wood products. Superior to most other NWO species for bio-fuel and bio-chemical products
White Spruce	Wood mechanically is moderately strong with above average stiffness. Dries easily with moderate shrinkage. Is moderately light, soft, with straight even grained.	Wood is easily worked and finishes with a satin-like surface.	Wood use primarily pulpwood for paper and composites, and lumber products. Secondary products include plywood, veneer products, millworks, food containers, musical instruments, transmission poles, furniture parts, match sticks, tongue depressors, and paneling..
Eastern White Pine	Wood mechanically has low to medium strength, stiffness, and resistance to impact; the weakest eastern pine. Is light weight, soft, straight grained with uniform texture, is dimensionally stable and shrinkage is low.	Wood is machined and worked with tools easily. It stains, glues, and finishes well, with good nail and screw holding ability. It is a highly regarded wood in the United States.	Wood used in lumber and secondary products. Secondary products include house logs, siding, millwork, doors, furniture, caskets and burial boxes, toys, and woodware. Extractives produce white pine tar, an antiseptic and expectorant.

Table 18, continued			
Red Pine	Wood mechanically is intermediate in density, moderately strong, moderately stiffness, resistant to impact, bending, and compression. Is moderately heavy, with straight even grain, and medium texture. Dries easily with little shrinkage.	Wood is machined and worked with tools easily. It glues, finishes well, with good nail and screw holding ability.	Primarily lumber and roundwood; including transmission poles, pilings, house logs, posts and columns. Secondary products include pulpwood for paper and composites; from chips and low grade logs. Wood toys, carving, woodenware, novelties, and outdoor furniture. Extractives used in tanning, and for turpentine and rosin production.
Red Maple	Wood mechanically is low in strength, stiffness, and impact. The wood is resistant to abrasion and has high shrinkage. Wood is fine, soft, and straight grained with uniform texture.	Wood is harder to work than softer woods, turns well, stains and polishes well, intermediate in gluing, and has high nail-holding ability.	Primarily fuelwood and lumber. Wood use in lumber, veneer, timber, pulp, and secondary products. Secondary products include veneer, timbers, pulpwood, wood flooring, furniture, woodware, and novelties. Sap from for maple syrup.
Black Ash	Wood mechanically is moderate in strength, stiffness, and resistant to impact. Wood is straight grained, heavy, hard, it wears smooth, and moderate shrinkage.	It has high nail-holding ability, moderately difficult to glue, above average machining characteristics, but tends to split in nailing.	Wood is used exclusively used in secondary products. Fuelwood, wood floors, furniture, millwork, baseball and cricket bats, paddles, bows, musical instruments, joinery, veneer, woodware, and novelties.

2.4.4 Value-added products

Value-added wood products, or secondary wood products, add value to other wood products along the value chain through further manufacturing or specialty processing (Industry Canada, 2000). Value-added wood products include (Industry Canada, 2000):

- remanufactured products (lumber specialties, fencing, etc.),
- engineered wood products (MSR lumber, laminated beams, trusses, wood I-beams, etc.),
- millwork (doors, windows, architectural woodwork, turnings, etc.),
- cabinets (kitchen and vanity cabinets, cabinet doors, countertops, etc.),
- furniture (household furniture, ready-to-assemble furniture, commercial and institutional furniture,patio furniture, etc.), and
- pallets and containers.

In addition to finished and pre-finished wood products, custom services like specialty milling (cut to customer specification) and custom drying are also value-added products (Industry Canada, 2000).

Northwestern Ontario has a minor value-added wood products sector compared to southern Ontario (Manson and Rose, 2005). According to Shahi (2008) there is only one computer numerical control (CNC) machine in all of northwestern Ontario. This is one area that northwestern Ontario's forest industry could diversify.

According to Manson and Rose (2005), the value-added sector is one area the north could readily expand their lumber market. Currently, the majority of the wood supplying southern Ontario's $2.2 billion value-added sector is from

Quebec. Quebec supplies 41.5% of southern Ontario's value-added sector, while United States supplies 15%. Ontario, all regions, supplies only 38.1% of its own value-added wood products sector's needs (Manson and Rose, 2005).

2.4.5 Pulp and paper products

Pulp is produced by one of two ways (Cohen *et al.*, 1996; Shahi, 2008.):

1. Mechanical Pulp; produced using mechanical force with heat to separate fibres from the other components of wood.
2. Chemical Pulp; produced by using chemical reagents with heat to separate fibres from other components of wood.

Pulp is used to make various materials, including paper, paperboard, hardboard, insulation board and a variety of moulded fibre products (Bowyer *et al.*, 2003).

Pulp and paper production has been the stable but cyclical flagship of northwestern Ontario's forest industry. However, in 2003, while world demand for pulp was increasing, demand for northwestern Ontario pulp was declining (Figure 34) (Thornton, 2008). The reason for the decline was the cost of northwestern Ontario's higher quality and more expensive pulp (Moazzami, 2006; Leitch, 2008). The pulp mills of northwestern Ontario are struggling to compete with the low cost pulp coming from Chile and other southern hemisphere countries made from fast growing clone plantations (Leitch, 2008; Shahi, 2008). This illustrates that wood characteristics alone are not a guarantee to product success.

Northwestern Ontario needs to identify new premium wood products in demand within the global market place. According to the literature, areas it should be researching are value-added wood products, bioproducts and nanotechnologies.

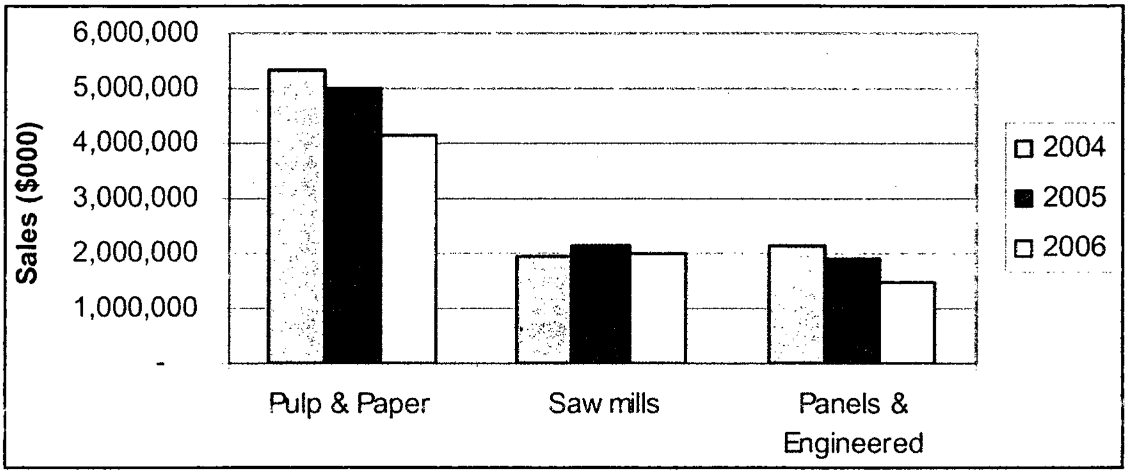


Figure 34. Sales trend for NWO's major wood products (Thornton 2008).

1.5.6 Future products

Bioproducts are produced wholly or in part from renewable resources. There are three categories of bioproducts (Jaworski and St-Louis, 2001):

1. biofuels
2. biochemicals, and
3. biomaterials.

Bioproducts present northwestern Ontario with a potential growth market that integrates well with the regions pulp and paper manufacturing infrastructure (Winandy *et al.*, 2008). For example, underutilized tree species such as eastern larch and trembling aspen, are suitable for pulpwood for composite wood products, biofuels, and biochemicals (Table 17). Integrating these fast growing Boreal tree species into the existing pulp and paper manufacturing infrastructure may provide the region the competitive advantage necessary to make the products from these tree species economically viable.

Nanotechnology is another avenue to develop nnew product suited well for northwestern Ontario's pulp and paper producers. For the forest industry, nanotechnology can be considered in two ways; as a wood product and as an additive to make a specialized wood product. Biomaterial includes nanotechnology substances such as nanocrystalline cellulose, the smallest physical sub-unit of cellulose (de la Roche, 2008; Winandy *et al.*, 2008). Also, other nanotechnologies can be incorporated into value-added wood products to make such things as smart papers and self-cleaning counter tops (de la Roche, 2008; Winandy *et al.*, 2008).

Integration with existing manufacturing operations is key to these new products viability. As Figure 35 illustrates, bioproducts will rely on residual products from other manufacturing processes and extensive research (de la Roche, 2008; Winandy *et al.*, 2008).

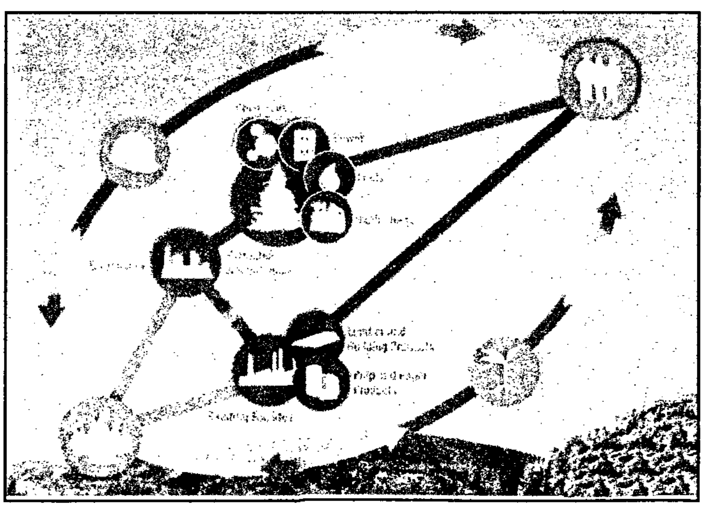


Figure 35. Integration of existing manufacturing with bioproducts and nanotechnology (Winandy *et al.* 2008).

Life cycle research and development seems to be another gap, which impedes successful product development and diversification of northwestern Ontario's Forest Industry. Figure 36 shows the lifecycle of wood products within the global market place (Thornton, 2008). Note, that the majority of the products northwestern Ontario produces are nearing maturity (which represents stagnant growth in demand) or are already in decline (Shahi, 2008; Thornton, 2008).

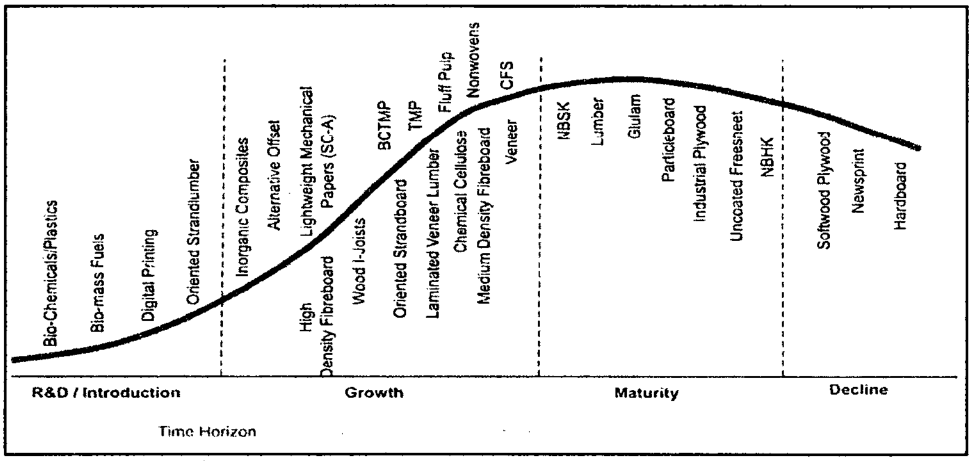


Figure 36. Life cycle of certain forest products (Thornton 2008).

2.5 Opportunities for northwestern Ontario

We have identified a number of opportunities for Northwestern Ontario's forest industry and a number of constraints associated primarily with gaps in the knowledge with respect to forest inventory wood characteristics and trends in the global market place. Before the forest industry can capitalize on opportunities in the global market place and exploit any competitive advantages they may have, they must first shift their management philosophy from a production to a market paradigm.

1.6.1 Production paradigm

In his presentation, "Forest: Building Blocks of the New Bio-Economy at the conference Growing Forest Value: Opportunities in Northern Ontario," Ian de la Roche, former President and CEO of FP Innovations, pointed out that the forest industry has become single minded in their manufacturing of wood products (de la Roche, 2008). In the lumber sector, for example, industry focused their efforts on being the most efficient at producing a cheap product. "We became so good at being efficient, that only those mills that could produce the cheapest products survived" (de la Roche, 2008). While, we were becoming the most efficient at producing a single commodity, the global market place changed and producing a cheap product no longer guaranteed survival (de la Roche, 2008).

De la Roche was describing the classic production marketing paradigm (Webster, 1992; Almeder, 2007; Shahi, 2008). The production paradigm is a marketing system that is (Webster, 1992; Almeder, 2007; Shahi, 2008):

- a production driven system,
- a cost efficient production being the main goal,
- defined by high quality standardized goods,
- indifferent to the market (taken as a given).

According to the literature, the global forest industry began shifting from the traditional commodity production paradigm to a customer based market paradigm during the recession of the 1980s (Almeder, 2007; Shahi, 2008). The change in marketing philosophy was in response to a changing market. A market that had (Webster, 1992; Almeder, 2007; Shahi, 2008):

- more sophisticated consumers,
- short product life cycles,
- increased product variety and direct product alternatives, and
- global competition in a heterogeneous market.

The increase in global competition can be directly attributed to the economic growth in the developing world, which has been the driving force in growth in international markets (Shahi, 2008).

According to de la Roche (2008), the forest sector needs to change its approach to product development. In order to compete successfully, the forest sector needs to optimize the value chain for its customers when developing products (Webster, 1992; Almeder, 2007; de la roche. 2008; Shahi).

2.5.2 Market paradigm

What de la Roche (2008) is describing is the market paradigm. The market paradigm is not just a philosophy it is a management system, affecting every aspect of the business (Shahi, 2008; Almeder, 2007; Webster, 1992). The market paradigm means (Shahi, 2008; Almeder, 2007; Webster, 1992):

- customers are thought of as individual rather than average,
- quickly responding to rapidly changing expectations,
- do not expect customer loyalty,
- operations are centred on the customer; creating 'internal customers.'

Webster (1992) explains that marketing can no longer be the sole responsibility of a few specialists. Rather, everyone in the firm must be charged with responsibility for understanding customers and contributing to developing and delivering value for them (Webster, 1992; Shahi, 2008; Almeder, 2007). For example, if a customer calls the janitor, the janitor must know how to transfer the call to the 'right' person (Webster, 1992). Thus, the market paradigm is a market management system (Webster, 1992; Shahi, 2008; Almeder, 2007).

The market management system, centred on the customer, optimizes the value chain for its customers as one of its execution strategies. The changing role of marketing in a corporation, requires the marketer to manage three sets of relationships; customers, suppliers, and re-sellers. To do this, the corporation must develop sector clusters to deliver products and services to its customers. Figure 37 shows the forest sector cluster for northwestern Ontario and was developed by Moazzami (2006) for the northwestern Ontario forest council in 2006. The cluster diagram clearly shows the potential strengths of the northwestern Ontario forest sector, however, we can see gaps in the cluster (Moazzami, 2006). The gaps are (Moazzami, 2006; Shahi. 2008):

- millwork,
- prefabricated wood building systems manufacturing; requires CNC equipment,
- bioproducts,
- nanotechnology,
- asphalt roofing industry

- value-added manufacturing in office furniture, or other furniture requiring CNC equipment, and
- Underdeveloped forestry service industry

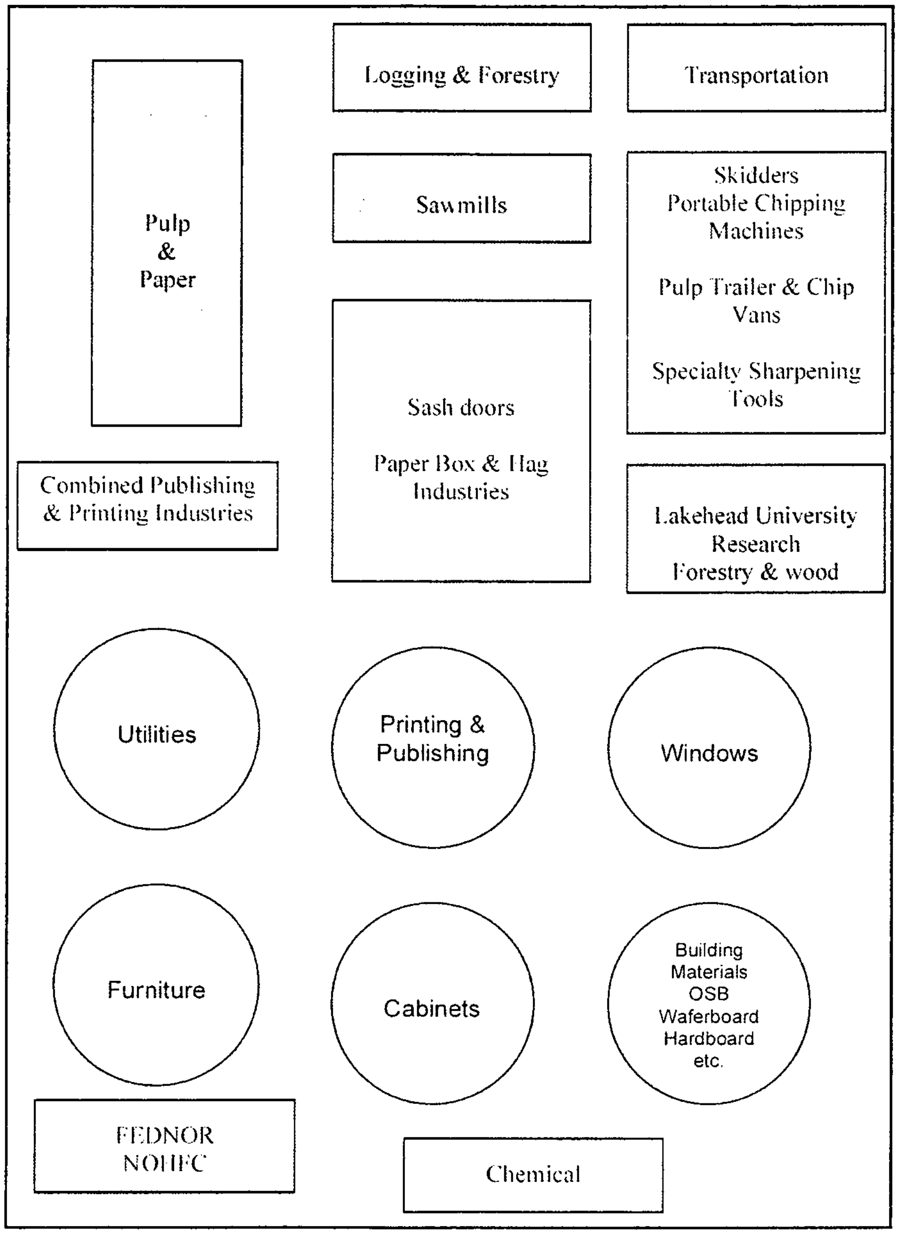


Figure 37. NWO forest sector cluster (Moazzami 2006).

Thus, we can say with certainty, that northwestern Ontario's forest sector has a number of the key direct and indirect manufacturing and support services necessary to operate successfully under a market management system (Moazzami, 2006; Shahi. 2008).

2.5.3 Characteristics of end use products

Under a market management system research and development are key to competitiveness. It is crucial that a corporation have a diverse basket of products and services that are constantly changing to meet the needs of their customers. This has been one of the failings of northwestern Ontario's forest sector.

What is key is that the business will be defined by its customers, not its forest tenures or factories or offices (Webster, 1992; Almeder, 2007; Shahi, 2008). Thus, product development is driven (Figure 38) and executed (Table 18) by customer value chain optimization (de la Roche, 2008; Leitch, 2008; Shahi, 2008).

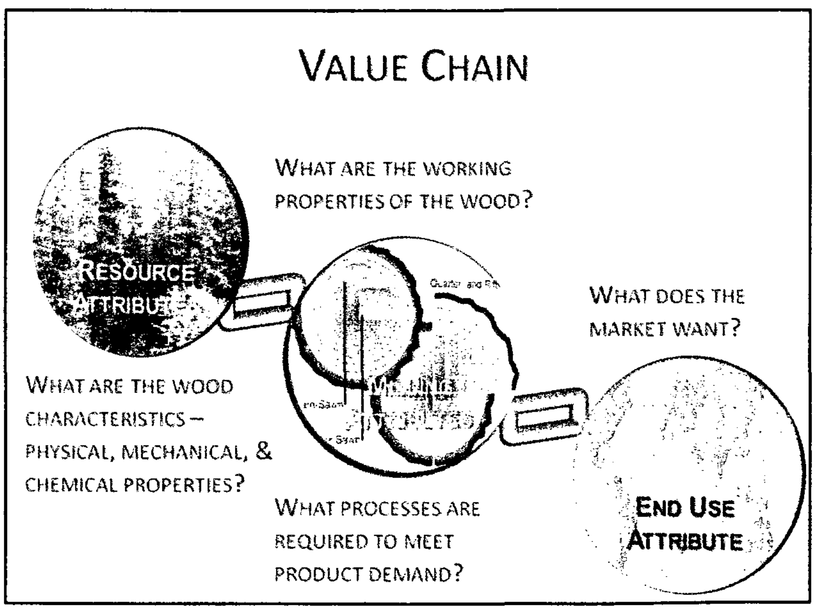


Figure 38. Value chain optimization (de la Roche 2008).

Table 18. Knowledge base gaps / barriers with respect to value chain attributes.

Value chain attribute	Knowledge base gap / barrier
Market demand	Lack of research and development based on customer needs. Majority of wood products are at zero or negative growth within their life cycle. Shift to market based management system at initial stages.
Processing	Unknown if current manufacturing capacity is able to produce new products, such as smart products using nanotechnology, and bioproducts. Minor underdeveloped value-added sector, only one CNC in NWO.
Raw materials	Few studies completed on wood characteristics of NWO Forest Inventory. Those completed were primarily on black spruce and Jack Pine. No data on NWO's second growth forests managed under government silvicultural policy. Level of genetic variance due to artificial regeneration is unknown. Effect on stocking standards on second growth wood characteristics is unknown. Inventory of chemical extractives is unknown.

2.6 Validating the literature reviewed

The need for further forest research has been identified for some time now. For example, between 1959 and 1968, during a series of symposia on wood quality, it was identified in Ladell *et al.* (1968), "that there was a serious lack of information regarding the structure and variability of wood of commercially important species of Ontario." Since the pulp and paper industry dominated the provincial economy, it was decided to study the characteristics of black spruce as they related to the desired paper properties (Ladell *et al.*, 1965). "It was hoped that the results (would) be useful in the management of existing stands as well as furnish information that will assist in the selection of superior trees for breeding purposes" (Ladell *et al.*, 1968).

It is clear from the literature reviewed, that some species have been more thoroughly sampled than others (Jessome, 2000); with few studies being completed within northwestern Ontario. Properties vary from tree to tree and from location to location within a species, but Jessome (2000) believed that the data reported on the northwestern Ontario species are fair estimates of their properties throughout the growth range (Jessome, 2000).

If you consider the range of eastern larch (Figure 33) and the species variability in height and diameter growth, it is important to understand what is meant by "a fair estimate" of the properties "throughout the growth range" (Jessome, 2000). For example, Jessome's research on eastern larch (tamarack), was limited to a total of 11 trees over two sites across its growth range, which is insufficient to develop design criteria for end use products for this species, under the National Lumber Grades Authority's (NLGA) procedures, outlined in the Wood Reference Handbook, and the Lumber Properties Project Report (CWC, 1994; CWC, 1997). The sampling procedures for the NLGA requires that:

> sampling be conducted throughout the full growth region for each commercial species group...and each growth region (be) subdivided into homogeneous sampling regions...for the species (CWC, 1994; CWC, 1997).

The NLGA procedure refers to each species size, grade and property combination as a sample "cell", and requires a minimum target sample for a given property of 360 specimens per cell across the growth region. For the major commercial species of Canada, 27 main cells were used to develop their internationally accepted grades; 3 specimen sizes, 3 properties tested, and 3 visual grades (CWC, 1994; CWC, 1997). The species group Spruce-Pine-Fir (SPF) is Canada's most important commercial species groups. All other species groups in northwestern Ontario are referred to as northern species, since they have not undergone the same intensive wood properties testing as the SPF species group. Further, within northwestern Ontario, most of the species within the SPF species group, are considered a northern species when graded as a single species (Table 19).

Table 19. Northwestern Ontario tree species listed by individual and species group grade stamp (NLGA, 2003a).

Species	Individual Species NLGA Grade Stamp	Species Group NLGA Grade Stamp
black spruce (*Picea mariana* (Mill.) B.S.P.)	B.Spr (N)	S-P-F
white spruce (*Picea glauca* (Moench) Voss)	W.Spr (N)	S-P-F
jack pine (*Pinus banksiana* Lamb.)	J.Pine (N)	S-P-F
eastern white pine (*Pinus strobus* L.)	EW.Pine (N)	S-P-F
red pine (*Pinus resinosa* Ait.)	R.Pine	S-P-F
balsam fir (*Abies balsamea* (L.) Mill.)	B.Fir (N)	S-P-F
eastern larch (*Larix laricina* (Du Roi) K. Koch)	Tam (N)	Hem-Tam (N)
eastern white cedar (*Thuja occidentalis* L.)	EW.Cedar (N)	N.Species
white birch (*Betula papyrifera* Marsh.)	W.Birch	N.Species
trembling aspen (*Populus tremuloides* Michx.)	Aspen (N)	N.Aspen
black ash (*Fraxinus nigra* Marsh.)	N.Species	N.Species
red maple (*Acer rubrum* L.)	N.Species	N.Species

Most of the findings on wood characteristics reported for species found in northwestern Ontario, are from trees studied in eastern Ontario, other provinces, or the United States. For example, only 5 of the 12 commercial tree species of northwestern Ontario studied by Jessome (2000) included test samples from trees grown in the Province of Ontario. Thus, we can conclude, that the wood properties, or raw resource attributes, reported in the literature, for northwestern Ontario's species, must be validated in order to support proper forest management and new wood products development. A reliable knowledge base of raw resource attributes are essential to maximizing the value chain (NLGA. 2003a).

2.6.1. Prioritizing the validation research

We must keep in mind that the goal for validating the reported wood characteristics of northwestern Ontario's commercial tree species, is to identify new market opportunities for the region for these species. The purpose for validating the reported wood characteristics of the commercial species is to identify gaps within the knowledge base of these species with respect to maximizing the value chain of northwestern Ontario's forest sector. Validating the wood characteristics is a costly and labour intensive process. Thus, it would be helpful to prioritize which species should undergo validation research based on:

- level of previous study,
- potential market opportunity,
- potential to increase utilization, and
- available volume.

Using these four criteria, we can prioritize the validation research methodically (Table 20), ensuring the research completed is economically beneficial to the region, the province and the rest of Canada.

Table 20. Northwestern Ontario tree species priority of research.

Species	Validation Research Priority for Northwestern Ontario
eastern white cedar	Very few studies completed on species, underutilized, high potential for value-added and specialty products, superior wood characteristics for outdoor use; especially outdoor furniture.
eastern larch	Few studies completed on species, underutilized within region high potential for pulpwood, value-added, and specialty products, fast growing species and well suited for intensive silviculture, suited for outdoor use.
black ash	Few studies completed on species, although some were done in Ontario, underutilized, high potential for value-added and specialty products.
trembling aspen	Few studies completed on species, underutilized within region, high potential for pulpwood, value-added, and specialty products, fast growing species and well suited for intensive silviculture, accounts for 21% of the region's harvestable volume.
white birch	Few studies completed on species, underutilized within region, high potential for value-added, and specialty products, accounts for 5% of the region's harvestable volume.
black spruce	Most important economic species in Canada and the region, accounts for 50% of the regions harvestable volume, majority of the studies focused on pulpwood properties.
balsam fir	Few studies completed on species, although some were done in Ontario high potential for value-added products, accounts for only 4% of the region's harvestable volume.
eastern white spruce	Few studies completed on species, well suited for value-added products, accounts for only 1.2% of the region's harvestable volume.
red maple	Few studies completed on species, although some were done in Ontario well suited for value-added, accounts for less than 0.1% of the region's harvestable volume,
eastern white pine	Few studies completed on species, although some were done in Ontario, well suited for value-added products, accounts for less than 0.3% of the region's harvestable volume.
jack pine	Some studies were done in Ontario and within the region well suited for value-added products, accounts for less than 15% of the region's harvestable volume.
red pine	Least variable species within the region, studies on this species have been completed in Ontario; although very few within the region, well suited for value-added products, accounts for less than 0.3% of the region's harvestable volume.

2.6.2 Eastern larch wood characteristics mapping

The purpose of mapping the wood properties of eastern Larch is to validate previously reported wood characteristics for the northwestern Ontario region, and identify whether sections or zones of unique wood characteristics can be found which will:

- identify value-added market potential, and
- increase utilization of the species.

According to the literature reviewed, eastern larch, which grows throughout the province, is an underutilized tree species, which accounts for 1.7% of the available harvestable volume for the region (OMNR, 2008). Eastern larch is a deciduous conifer, which has a strong association with black spruce in mixed stands, and shares similar habitat requirements; growing on moderate to well drained wet to moist organic soils (Burns and Honkala, 1990a; OMNR, 1997; Zhang and Koubaa, 2008). Eastern larch is extremely shade intolerant, can grow on sites with extreme fluctuation in weather, however, cannot survive prolonged exposure to flooding or drought (Burns and Honkala, 1990a; OMNR, 1997; Zhang and Koubaa, 2008). Eastern larch is a highly adaptable, or plastic species, it is one of the earliest species, along with white spruce, to populate areas following glaciations (Burns and Honkala, 1990a). Eastern larch is generally considered to be a medium size tree, however, tree growth varies greatly within its growth range due to local environmental factors (Burns and Honkala, 1990a; OMNR, 1997; Zhang and Koubaa, 2008). Eastern larch is best described as (Alemdag, 1984; Wang *et al.*, 1985; Yang *et al.*, 1986; Burns and Honkala, 1990; Koga *et al.*, 1996; Zhang and Koubaa, 2008):

- range in height 3 to 35 m,
- range in diameter 7 to 60 cm,
- highest variability is within a tree,
- significant variability between sites, and
- ratio of earlywood to latewood accounts for most wood density variability.

The literature indicates that some patterns exist for within tree variation, however, no significant variations in wood density between sites are reported (Balatinecz, 1983; Singh, 1984; Singh, 1986; Yang and Hazenberg, 1987; Zhang and Koubaa, 2008). Radial wood density decreases initially to a minimum followed by a slight increase, however, it is reported that heartwood density is higher than sapwood density (Balatinecz, 1983; Doucet *et al.*, 1983; Yang and Hazenberg, 1987; Zhang and Koubaa, 2008). Patterns in radial variation appear to be more stable with an increase in height (Balatinecz, 1983; Doucet *et al.*, 1983; Yang and Hazenberg, 1987; Zhang and Koubaa, 2008). Longitudinal variation for density is reported to show a general pattern of decreasing with an increase in stem height, however, tracheid length appears to increase from the base of the tree to a maximum at mid-height then decreases upward to the crown (Balatinecz, 1983; Yang *et al.*, 1986; Zhang and Koubaa, 2008). Generally the physical and mechanical properties of eastern larch decrease from juvenile wood to mature wood (Beaudoin *et al.*, 1989, Zhang and

Koubaa, 2008). Thus, eastern larch seems to exhibit wood morphology more consistent with hardwoods than softwoods.

A large variety of products can be produced from eastern larch, however, in northwestern Ontario the species was historically used to produce rail ties, lumber and pulpwood (Mullins and McKnight, 1981; Henderson, 1981; Burns and Honkala, 1990; Zhang and Koubaa, 2008). A number of bio-products can be produced from eastern larch, including holistic medicines, resins, tannins and bio-fuels (Mullins and McKnight, 1981; Henderson. 1981; Burns and Honkala, 1990; Zhang and Koubaa. 2008).

The wood of eastern larch has a medium to fine texture, with intermediate strength, stiffness, and hardness (Mullins and McKnight, 1981; Henderson, 1981; Burns and Honkala, 1990; Zhang and Koubaa, 2008). The wood is heavy, durable and moderately decay-resistant, and generally works or machines well, however, it is difficult to penetrate with coatings (Mullins and McKnight, 1981; Henderson, 1981; Burns and Honkala, 1990; Zhang and Koubaa, 2008).

3.0 Methodology

3.1 Experimental design

The wood characteristics mapping of eastern larch involved mapping the radial and longitudinal changes in physical and mechanical proprieties of twelve eastern larch trees from four sites grown within the Thunder Bay District (Figure 39).

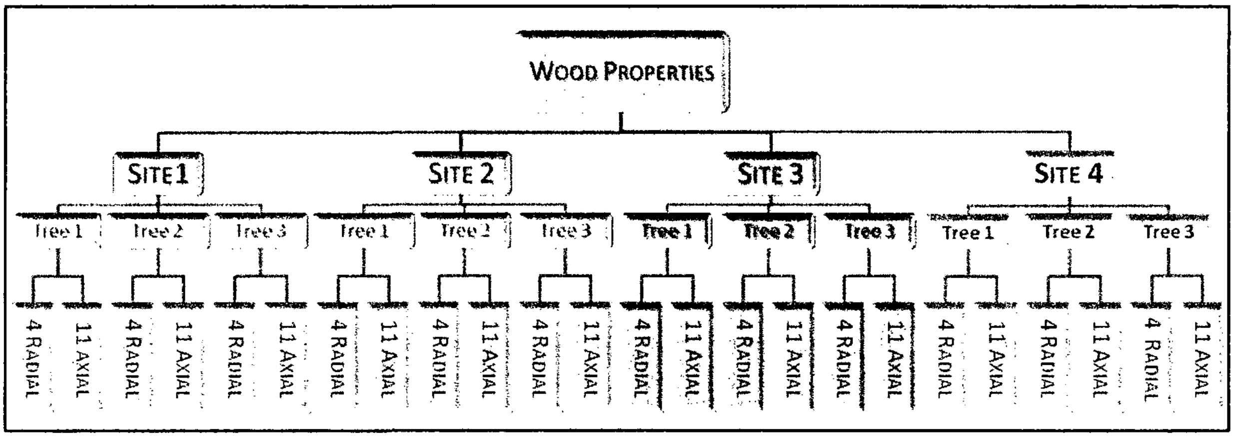


Figure 39. Experimental design for the wood characteristics.

Wood properties for each tree were tested from specimens collected from 11 bolts and 4 radial positions of each bolt, from pith to bark. The bolts represented 10 longitudinal or axial positions set every 10% of total height from the butt to a 10 cm minimum diameter at the top of the tree, and from the pith of the bolt set at 25% intervals of total diameter of the bolt. An 11th one metre bolt was set at breast height. The 4 radial sections of the bolts represented the juvenile core (0 to 25% zone), outer heartwood (25% to 50% zone), inner sapwood (50% to 75% zone), and the zone of outer sapwood and cambial activity, (at 75% to 100% of bolt diameter). The experimental design of the study was simple, balanced, with an inference space limited to the Thunder Bay District.

As shown in Figure 40, the wood properties examined were:

- relative density, density, and ring density; at oven-dry and 12% MC,
- shrinkage (tangential, radial, longitudinal, and volumetric),
- MOE / MOR,
- compression parallel to grain, and
- Janka ball side hardness.

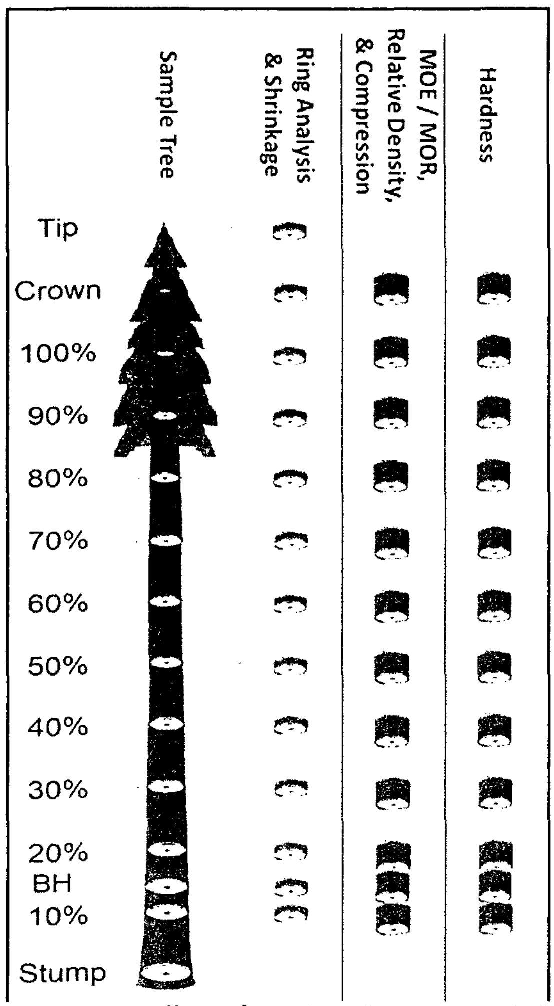


Figure 40. Diagram of specimens collected per tree for the wood characteristics.

3.2 Field Procedures

3.2.1 Site Selection

Working with staff of the Ontario Ministry of Natural Resources' (OMNR) Thunder Bay District, four sites were randomly selected within the Dog River Matawa SFL (Figure 41). The chosen sites were then provided to the forestry staff of AbitiBowater, who helped identify and finalize one sample stand within each site.

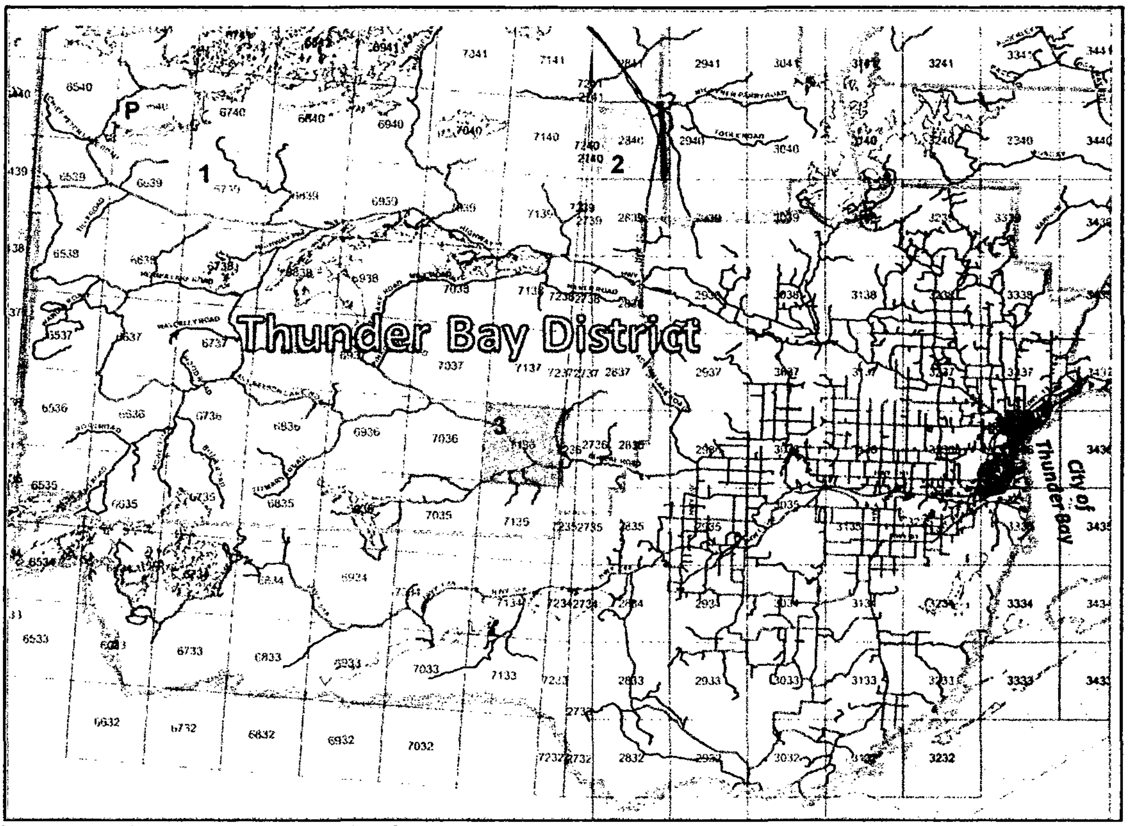


Figure 41. Location map of the four sample sites for the wood characteristics mapping of eastern larch grown in the Thunder Bay District.

3.2.2 Sample Tree Selection and Collection

Selected stands within sample sites were located in the field by using map sheets provided by AbitibiBowater and satellite images. Once stands were located, two mature dominant eastern larch trees and one juvenile tree were selected for destructive testing; all trees were free of defects. The literature indicates that mature wood development begins between 25 to 30 years of age, and mechanical properties should not be tested on trees less than 10 years of age; because of the high proportion of reaction wood and knots. Thus, trees over 30 years of age were considered mature, and trees 10 to 30 years of age were considered juvenile (Bowyer *et al.,* 2003; Jozsa and Middleton, 1994; Panshin and de Zeeuw, 1980; Mullins and McKinight, 1981).

Sample trees were felled using a chain saw then measured for total height, height to 10 cm diameter and height of lowest live branch. Once the sample trees were felled, 10 equal sections, from the butt to a 10 cm diameter minimum, were marked onto logs using logger's paint. The sections had a 1 m bolt marked at the bottom of each section using logger's paint, and then a 1 m bolt was marked at breast height (Figure 42). All 11 bolts, from each of three trees, were bucked and labelled on site, and returned to the LUWSTF for processing into test specimens.

Figure 42. Picture of bolt processing of an eastern larch sample tree on site 1.

3.3 Laboratory procedures

3.3.1 Processing specimens

Once the samples were transported to the LUWSTF, each bolt had a 7.5 cm disk bucked off the butt end for processing into X-ray densitometry specimens. Bolts were then cut into 3 cm thick waney boards using the LUWSTF's Woodmizer LT40 Hydraulic Portable Band Saw. The boards were then trimmed to produce two 40 cm lengths; the bottom lengths produced MOE, MOR, compression, and relative density specimens, and the top lengths produced hardness specimens. As the bolts were processed, they were further labelled to ensure sample continuity and left to air dry down to 30% moisture content.

3.3.1.1 Processing of relative density, MOE, MOR, and compression specimens

Once at the target moisture content, the bolts' bottom lengths were cut into 2.5 X 2.5 X 40 cm test specimens for MOE, MOR, compression, and relative density testing, using a conventional table saw in the LUWSTF workshop. These specimens were referred to as MOE sticks. As the MOE sticks were processed into specimens, they were further labelled to ensure sample continuity and left to air dry down to 14% moisture content.

Once at the target 14% moisture content, the MOE sticks were further cut down to 2.0 X 2.0 X 40 cm, then all specimens were placed into the Thermo Scientific Forma Environmental Chamber (conditioning chamber), where they were left to stabilize to 12% moisture content, within an environment of 20 degrees Celsius and 60% relative humidity. Once the 2.0 X 2.0 cm test specimens were stabilized, they were further trimmed into 2.0 X 2.0 X 30 cm Modulus of Elasticity (MOE) test sticks, 2.0 X 2.0 X 6.0 cm compression test sticks, and 2.0 X 2.0 X 3.0 cm relative density cubes. During trimming the specimens were labelled and sorted to remove cull specimens, to ensure only clear samples were returned to the conditioning chamber until testing. Figure 43 illustrates cull features removed during sorting of speciemens for MOE / MOR perpendicular to the grain.

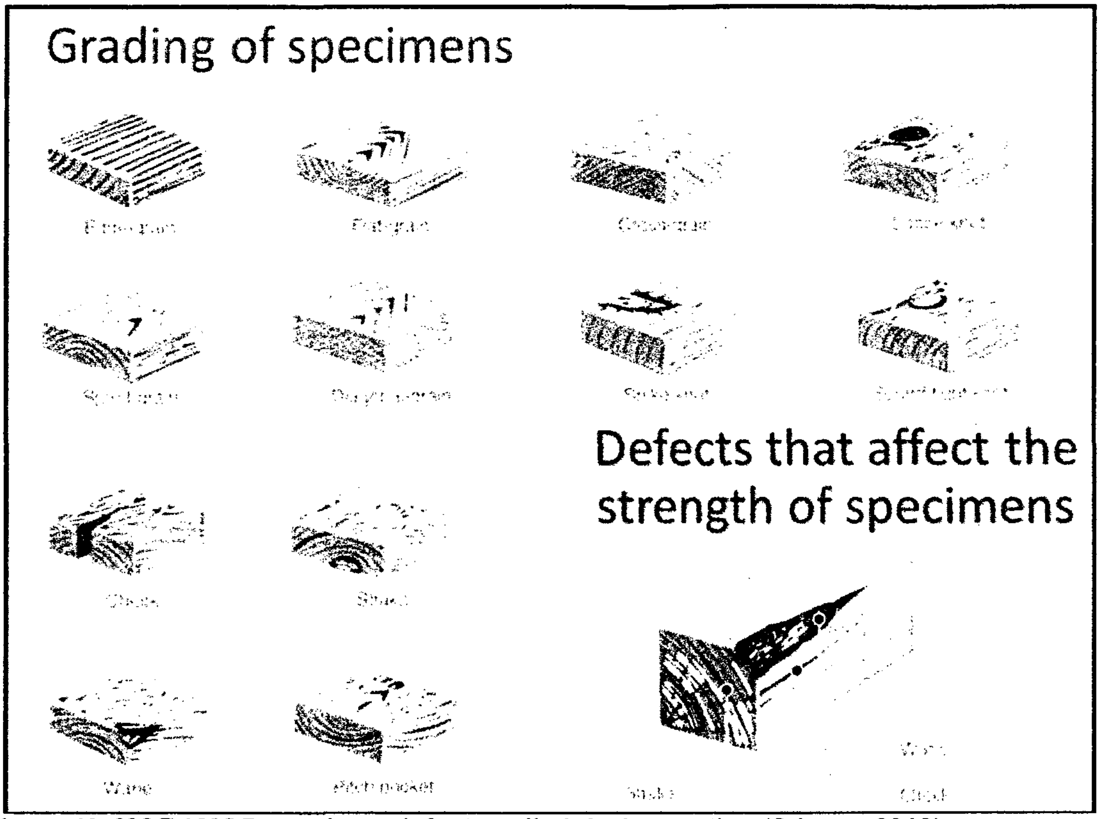
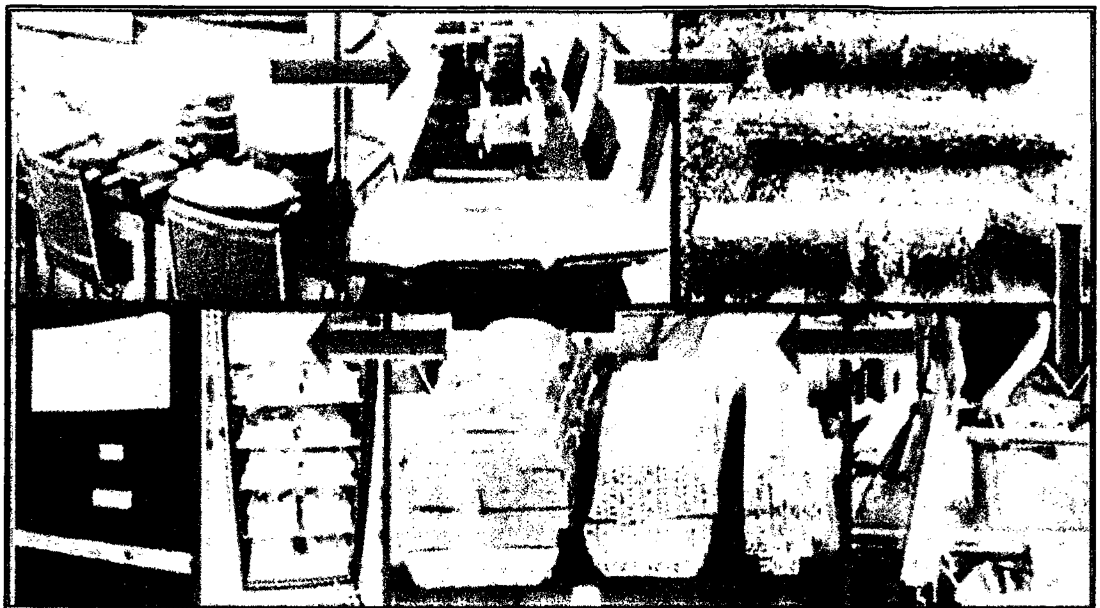


Figure 43. MOE / MOR specimen defects culled during sorting (Stiemer 2010).

3.3.1.2 Processing of hardness specimens

The bolts' top sections were further trimmed to a length of 25 cm to produce Janka Ball hardness specimens. As the hardness specimens were processed, they were further labelled to ensure sample continuity and left to air dry down to 14% moisture content. Once the target 14% moisture content was reached, the specimens were placed into the conditioning chamber, where they were left to stabilize to 12% moisture content for testing (Figure 44).



A. Disks cut from the bottom of each bolt air drying. B. Bolts cut into 3 cm boards, air drying.
C. (Top) Whole bolt cut from sample tree. (Middle) Bolt cut into 3 cm boards. (Bottom, from left to right) Bolt's bottom lengths trimmed to 40 cm, 7.5 cm disk, bolt's top lengths trimmed to 25 cm ; the trim ends were stored for a thermal testing at a later date.
D. Bolt's bottom lengths being cut into MOE/MOR, Compression, and wood density specimens using a table saw.
E. (From left to right) Bolt's bottom lengths: trimmed to 40 cm , with specimen labels, and cut then culled MOE/ MOR specimens.
F. Specimens stabilizing in the Conditioning Chamber.
G. Test specimens (From top to bottom) 25 cm Janka Ball Hardness, 2 X 2 X 3 cm wood density, 2 X 2 X 6 cm Compression parallel to grain, and MOE/MOR perpendicular grain.

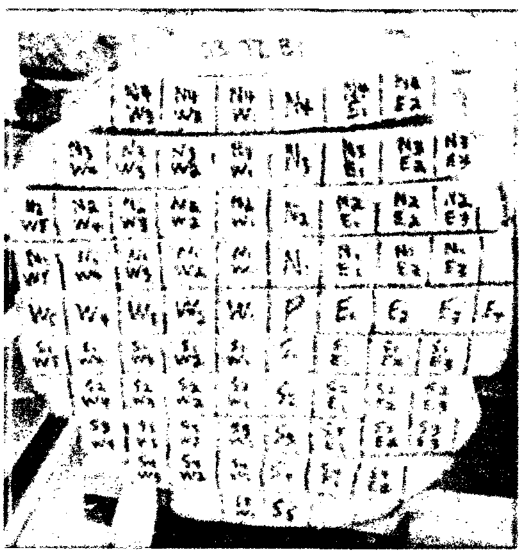
Figure 44. Picture of specimen processing for the wood characteristics mapping.

3.3.1.3 Processing of shrinkage specimens

One mature tree from each site was randomly chosen to produce shrinkage samples. A 10 cm board was cut from the top of the breast height bolt of each of the four chosen trees. The shrinkage samples were immediately processed into clear specimens of 25 millimetres (mm) (longitudinal) x 25 mm (tangential) x 100 mm (radial), Once processed, the specimens' dimensions were measured and then placed into the conditioning chamber to stabilize to 12% moisture content. Once at 12% moisture content, their dimensions were again measured and they were placed into the laboratory's oven to stabilize to an oven dry 0% moisture content. The oven dry specimens were further measured one last time. The measurements were used to produce shrinkage values.

2.3.1.4 Labelling convention

Specimen labels indicate the site number, tree number, bolt number, radial position relative to the pith, and radial direction; north, south, east, or west. For example, a specimen with the label S1T2B3N4W3, came from site 1, tree 2, bolt 3, 4 radial positions from the pith oriented to the north by 3 radial positions from the pith oriented to the west. Figure 45, illustrates how labels relate to specimen position in the bolt. Labelled specimens were graded so that only specimens containing clear wood were tested.



Bolt 1 from Tree 2 Site 3
with specimen labels

N5 W5	N5 W4	N5 W3	N5 W2	N5 W1	N5	N5 E1	N5 E2	N5 E3	N5 E4	N5 E5
N4 W5	N4 W4	N4 W3	N4 W2	N4 W1	N4	N4 E1	N4 E2	N4 E3	N4 E4	N4 E5
N3 W5	N3 W4	N3 W3	N3 W2	N3 W1	N3	N3 E1	N3 E2	N3 E3	N3 E4	N3 E5
N2 W5	N2 W4	N2 W3	N2 W2	N2 W1	N2	N2 E1	N2 E2	N2 E3	N2 E4	N2 E5
N1 W5	N1 W4	N1 W3	N1 W2	N1 W1	N1	N1 E1	N1 E2	N1 E3	N1 E4	N1 E5
W5	W4	W3	W2	W1		E1	E2	E3	E4	E5
S1 W5	S1 W4	S1 W3	S1 W2	S1 W1	S1	S1 E1	S1 E2	S1 E3	S1 E4	S1 E5
S2 W5	S2 W4	S2 W3	S2 W2	S2 W1	S2	S2 E1	S2 E2	S2 E3	S2 E4	S2 E5
S3 W5	S3 W4	S3 W3	S3 W2	S3 W1	S3	S3 E1	S3 E2	S3 E3	S3 E4	S3 E5
S4 W5	S4 W4	S4 W3	S4 W2	S4 W1	S4	S4 E1	S4 E2	S4 E3	S4 E4	S4 E5
S5 W5	S5 W4	S5 W3	S5 W2	S5 W1	S5	S5 E1	S5 E2	S5 E3	S5 E4	S5 E5

LUWSTF Quadrant Testing
labeling grid

Figure 45. Specimen labelling used in the wood characteristics mapping of eastern larch.

3.3.2 Testing of wood properties

The American Society for Testing and Materials (ASTM) standard D143 – 09 Standard Test Methods for Small Clear Specimens of Timber, D4442 Standard Test Methods for Direct Moisture Content Measurement of Wood and Wood-Based Materials, and D2395 – 07a Standard Test Methods for Specific Gravity of Wood and Wood-Based Materials procedures were followed to determine eastern larch wood properties.

ASTM D5536-94 Standard Practice for Sampling Forest Trees for Determination of Clear Wood Properties dictates that standard procedures are followed when processing multiple bolts. The ASTM procedure for producing test specimens (Figure 46), creates a bias by including the pith. In the ASTM procedure, the bolt pith was included in processing test specimens, and only eight specimens per radial position are processed. However, culling of clear wood specimens of northwestern Ontario species can create a case where there are insufficient specimens per radial position to be statistically viable. Thus, LUWSTF has developed quadrant testing procedures, for wood density and MOE testing, to ensure specimen viability for statistical analysis of test bolts.

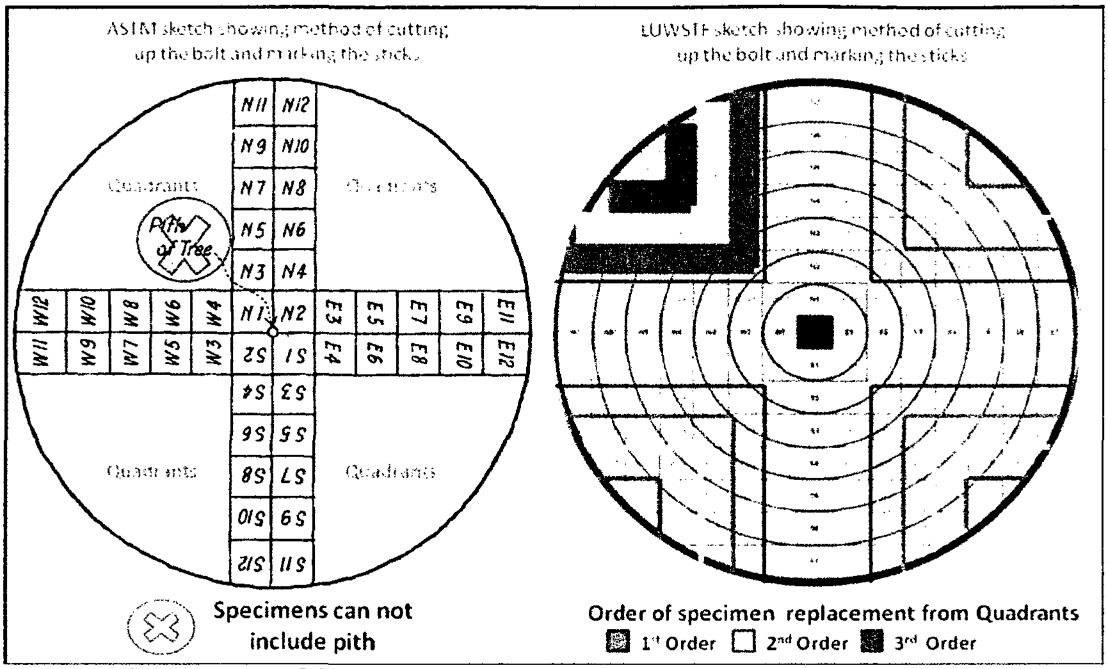


Figure 46. Comparison of ASTM bolt labelling procedure and LUWSTF labelling procedure (ASTM D5536, 2004; Leitch, 2008).

Wood density specimens were trimmed to a 2 cm X 2 cm X 3 cm dimension then sorted for cull. Due to their small size, culling of wood density specimens was not problematic to statistical viability, one of the main reasons why wood density dominates wood science research. However, wood density specimens had to be processed from the same sample stick as MOE specimens to accommodate property modeling; discussed later. Thus, limitation on wood density specimen viability was limited to MOE specimen viability.

MOE testing, using 2 cm X 2 cm X 30 cm specimens, had a target of eight specimens for each radial position; as per ASTM procedures discussed earlier. If the pith was included in specimen processing, as ASTM procedures require, the resulting effect would have been zero specimens from the centre of the bolt, thus biasing the MOE test results. Pith wood had the highest proportion of reaction wood relative to other radial positions. You will recall that pith wood was originally apical growth at the top of the crown. Thus, to ensure specimen viability throughout the bolt, LUWSTF developed a modified processing procedure for specimen processing.

The quadrant testing procedure required that if there were not the target 8 MOE test specimens within the modified standard's cross section, then replacement specimens would be recovered from the quadrant in order, from next available specimen closest to the standard's cross section outward.

3.3.2.1 Mechanical testing

A Tinius Olsen H10KT and H50KT Universal Wood Testing Machines, with Test Navigator software, were used to determine:

- MOE; reported in mega pascal (MPa) using the 3 point flexure tool,
- side hardness; reported in Newtons (N) using the Janka Ball tool, and
- compression parallel to the grain; reported in mega pascal (MPa) using the compression parallel to the grain tool.

Using the maximum load (Newton) reported by the Universal Wood Testing Machines during MOE testing, MOR was calculated using Equation 1 (Panshin and de Zeeuw. 1980; Mullins and McKinight, 1981; Bowyer *et al.*, 2003).

3.3.2.2 Physical properties

Relative density cubes were first weighed to establish their mass at 12% moisture content and then volume was determined using a water displacement test. The cubes were then placed into the oven until their mass stabilized. Once the samples were stabilized, mass and volume were measured to determine relative density at Oven Dry moisture (Figure 47).

A. Establish mass of specimens.
B. Press probe into earlywood of specimen.
C. Dunk specimen into a breaker filled with distilled water and record displacement (volume).

Wood density = Mass/Volume

Figure 47. Water displace method for determining wood density and moisture content.

The dimensions of each shrinkage specimen were measured at the green volume (wood having a Moisture Content >30%), once stabilized at 12% moisture content in the conditioning chamber, and after being stabilized in the oven. Radial and tangential shrinkage values were calculated based on the dimensional changes from the green to 12% to oven-dry conditions. Volumetric shrinkage was calculated based on the results of radial and tangential shrinkage.

3.3.3 Processing and testing x-ray densitometry specimens

The sample disks, bucked during initial bolt processing, were air dried down to 30% moisture content. Once at the target moisture content, x-ray densitometry disks were processed using a standard table saw, to produce 2 mm X 25 mm specimen. As shown in Figure 48, disks were cut to intersect the pith, so that the specimen was centered on the pith. The processed specimens were then placed in the conditioning chamber to stabilize before testing.

A. Using the LUWSTF's Densitometry Table Saw, put an incision on the outside of the bolt disk,
B. Leaving a 2 X 25 mm slice on the outside of the disk,
C. Cutoff the X-Ray Densitometry specimen using a straight edge.

Figure 48. Processing of x-ray densitometry specimen for site 4 tree 1 bolt 3.

Once specimens were stabilized, they were placed into the Quintek X-ray Densitometer for scanning. Since relative density was measured for each bolt, the corresponding relative density value for a bolts' x-ray densitometry specimen were entered as the target density, or calibration density. This procedure provided us with the best possible result when determining ring width and latewood to earlywood ratios.

3.4 Statistical analysis

Our analysis of variance (ANOVA) model allowed us to attribute a level of significance to an observed variation within eastern larch to a given factor within the statistical model. Our ANOVA model is based on three main assumptions;

- groups are independent, both within and between samples,
- groups are homogenous, and
- errors are normally distributed (DeVeaux *et al.*, 2008; Shahi, 2009).

3.4.1 Statistical design

Test results underwent a statistical analysis using the following design:

$$Y_{ijklm} = \mu + S_i + T_{(i)j} + H_k + R_l + SH_{ik} + SR_{il} + TH_{(i)jk} + TR_{(i)jl} + SHR_{ikl} + THR_{(i)jkl} + \varepsilon_{(ijkl)m}$$

i = 1, 2, 3, 4; j = 1, 2, 3; k = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11; l = 1, 2, 3, 4; m = 1;

Where:

Y_{ijklm} = the measured response.
μ = the overall mean.
S_i = the random effect of the 4 sites.
$T_{(i)j}$ = the fixed effect of the 3 trees per site, which is nested in the site effect.
H_k = the fixed effect of the 11 longitudinal positions.
R_l = the fixed effect of the 4 radial positions.
SH_{ik} = the mixed effect of the site factor with the longitudinal position factor.
SR_{il} = the mixed effect of the site factor with the radial position factor.
$TH_{(i)jk}$ = the mixed effect of the tree factor with the longitudinal position factor.
$TR_{(i)jl}$ = the mixed effect of the tree factor with the radial position factor.
SHR_{ikl} = the mixed effect of the site factor with the longitudinal position factor and the radial position factor.
$THR_{(i)jkl}$ = the mixed effect of the tree factor with the longitudinal position factor and the radial position factor.
$\varepsilon_{(ijkl)m}$ = the random effect of l^{th} radial positions from k^{th} longitudinal positions from j^{th} trees from i^{th} sites.

The null hypothesis stated that there would be no significant difference in wood properties with changes in radial, longitudinal, and geographic (site) positions. In order for the null hypothesis to be accepted, all of the following conditions had to occur:

1. radial position within the tree had no effect on wood properties,
2. axial position within the tree had no effect on wood properties, and
3. geographic position (site) of a tree had no effect on wood properties.

The wood properties' test results were compiled and then analysed using SPSS 18 software. An ANOVA was carried out using a general linear model and a Duncan's post hoc test at 95% probability. Variance was determined using averages of each test ring from the pith out to bark for each bolt.

During the statistical analysis, interactions were pooled when no significance was found. Based on the literature reviewed, it was anticipated that variance due to longitudinal position would be insignificant, while radial position and sites would be significant.

To determine the variance of the wood characteristics of eastern larch grown within the Thunder Bay District, over 15,700 test specimens were analysed for relative density, modulus of elasticity perpendicular to the grain (MOE), modulus of rupture perpendicular to the grain (MOR), compression parallel to the grain, Janka ball side hardness, and ring analysis.

4.0 Results and discussion

Using the Sims *et al.* (1997) and Racey *et al.* (1996) the ecosystem classifications for the four sites were found to be as follows:

Site 1: ES20 Spruce-Pine / Feathermoss: Fresh, Sandy-Course Loamy Soil; a dry fast growing site with eastern larch dominance;

Site 2: ES34 Treed Bog: black spruce / Sphagnum: Organic Soil; a poorly drained wet site with eastern larch / black spruce mix,

Site 3: ES19, Hardwood-Fir-Spruce Mixedwood: Fresh, Sandy-Course Loamy Soil; a well drained site with high competition from mixture of hardwoods and softwoods, and

Site 4: ES36 Intermediate Swamp: black spruce (Tamarack): Organic Soil; a very wet site with black spruce dominance.

Ecosystem classifications were consistent with the forest resource inventory data provided by the OMNR and AbitibiBowater. Figure 49 summarizes the ecological data of the four sample sites and shows that we were successful in sampling a range of environmental conditions representative of eastern larch's growth range within the Thunder Bay District. Sites 2 and 4 are ecosystems where eastern larch is more commonly found within its growth range. Sites 1 and 3 are more atypical of environments where eastern larch is expected to be found, however, the literature confirmed that the species can perform well on these sites until over taken by competition (Johnston and Carpenter, 1985; Burns and Honkala, 1990a; Bell, 1991).

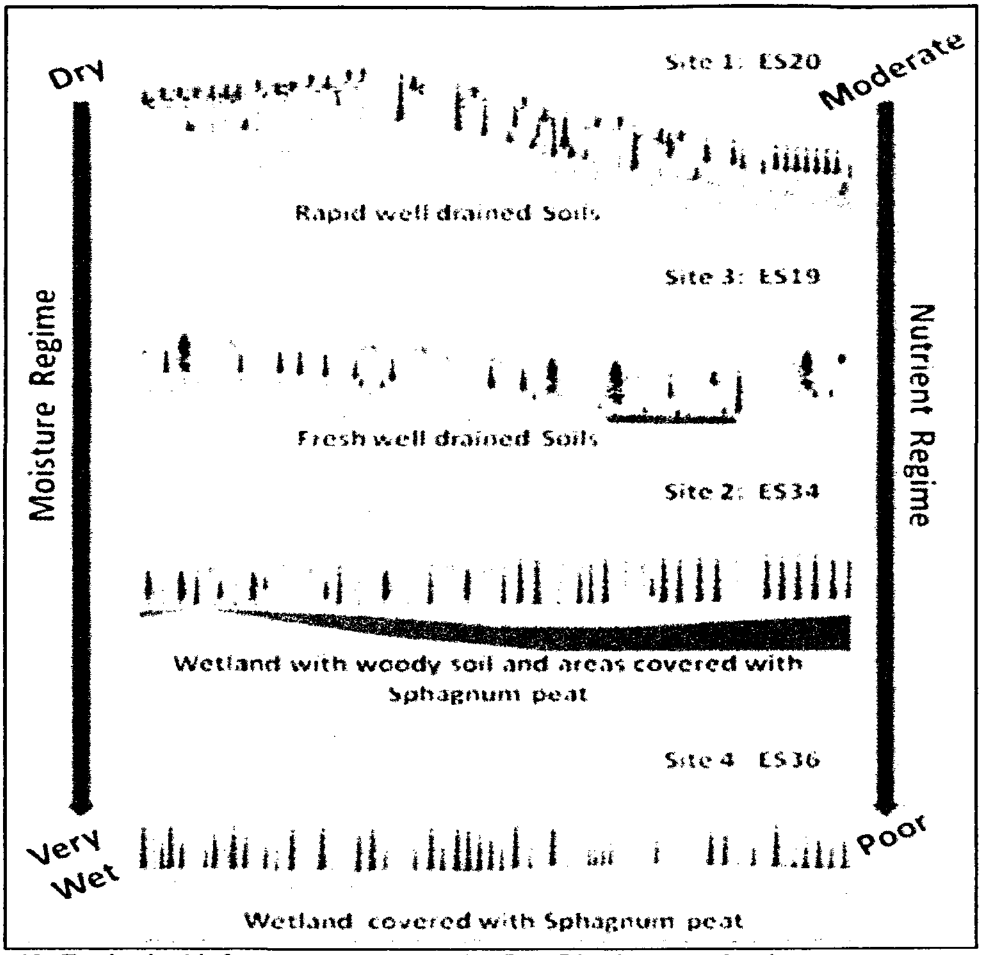


Figure 49. Ecological information on Thunder Bay District sample sites.

Table 21 presents the mean wood properties for each sample site, grand means for the study, and reported values from the literature for discussion. Trees grown on the dry fast growing site with eastern larch dominance, site 1, exhibited accelerated growth (using growth ring width) resulting in reduced relative density and mechanical properties, and increased shrinkage. While, the well drained site with high competition, site 3, exhibited good growth while effects on wood properties were mixed. Site 3's relative density means were lower than all the sample sites, however, MOE was found to be highest on this site. The very wet site with black spruce dominance, site 4, produced the best wood characteristics. Finally, site 2, the poorly drained wet site with eastern larch / black spruce mix, was the site most representative of the grand mean values.

Table 21. Summary of findings on the wood characteristics mapping of eastern larch grown in the Thunder Bay District (Zhang and Koubaa, 2008; Forest Products Laboratory, 1999; Jessome, 2000; *Panshin and de Zeeuw, 1980).

Sample Site	$Density_{12\%}$ (kg/m^3)	$Relative\ density_{12\%}$	$Relative\ density_{OD}$	Shrinkage			Average Ring Width at BH (mm)	MOE (MPa)	MORn (MPa)	Compressive strength parallel to grains (MPa)	Hardness - Side (N)
				Radial at BH	Tangential at BH	Volumetric at BH					
1	664	514	539	4.8%	9.4%	13.9%	3.64	7305	67	42	3452
2	681	528	553	4.3%	8.1%	12.5%	1.30	8401	82	49	3534
3	670	520	544	4.7%	8.9%	13.6%	2.74	8935	80	47	3834
4	715	554	580	4.4%	8.5%	12.8%	2.20	8765	88	No Data	3940
All	683	530	554	4.6%	8.7%	13.2%	2.47	8351	79	46	3690
BH	691	536	561	4.6%	8.7%	13.2%	2.28	8620	83	48	3867
Jessome		506	544	2.8%	6.2%	11.4%	1.20	9380	76	44.8	3220
Forest Products Laboratory		530	570	3.7%	7.4%	13.6%		11300	80	49.4	2600
Zhang and Koubaa			415					5890	34.9		

4.1 Validating findings

When the findings are compared to published values from Forest Products Laboratory (1999) and Jessome (2000) there are differences. For comparison of the values published by Jessome (2000) and Thunder Bay District (TBD) findings, the observed differences were within +/- 10%; an acceptable range of variance according to the literature (Bowyer *et al.*, 2003; Singh, 1986; Alemdag, 1984). The average value for side hardness at breast height was 15% higher than the values reported by Jessome (2000). This difference can be accounted for by the variability in side hardness observed between sample sites.

Comparison between values reported by the Forest Products Laboratory (1999) and the TBD findings showed a higher range of variability. Eastern larch from the TBD had 26% lower average MOE, 42% higher average side hardness, an equal average relative $density_{12}$ and 3% lower relative $density_{OD}$ than the Forest Products Laboratory (1999) published values. There are many factors that could account for this variation. Within the TBD study, variation between MOE sites means was as much as 31%. The Jessome (2000) values also had a relatively high percent difference to the Forest Products Laboratory (1999) values; confirming that eastern larch is variable between sites.

4.2 Variance in wood properties

4.2.1 Variance in ring data

4.2.1.1 Variance in ring width

X-ray densitometry analysis on disks cut from the bottom of each bolt, showed variable ring width from pith to bark. Further, when densitometry results of different bolts are compared by cambial age, differences in growth are very apparent. Figure 50 compares the annual ring width, at three axial heights (bolt 1, breast height bolt, and bolt 10), of a 101 year old eastern larch tree grown on site 4. Figure 50 presents the annual ring width of the selected axial positions plotted on a single graph on the left, and graphed separately on the right; to clearly illustrate the radial variance observed.

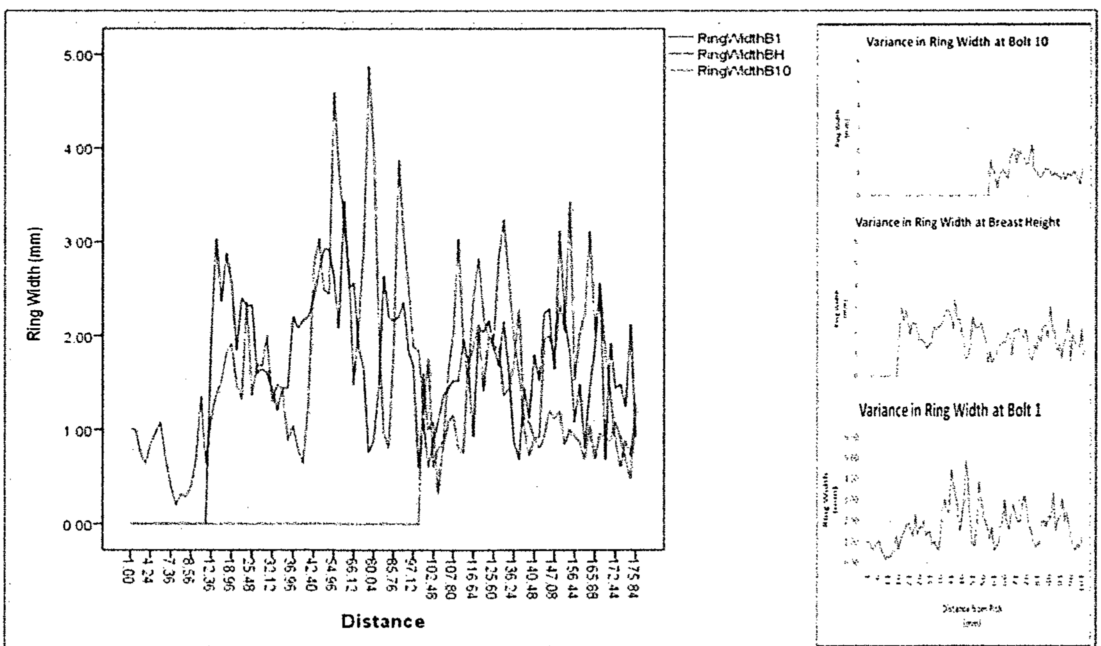


Figure 50. Comparison of annual ring width, at select bolt heights, of an eastern larch tree.

4.2.1.2 Variance in ring density

In addition to annual growth, x-ray densitometry analysis allowed us to study ring density. We observed significant variation in ring density from pith to bark, however, unlike the radial variance observed for ring width (Figure 50), ring density displayed a distinct pattern of variance similar to that of the relative density and density specimens (Figure 51). This indicated that age, rather than annual growth, had more influence on ring density or relative density in general.

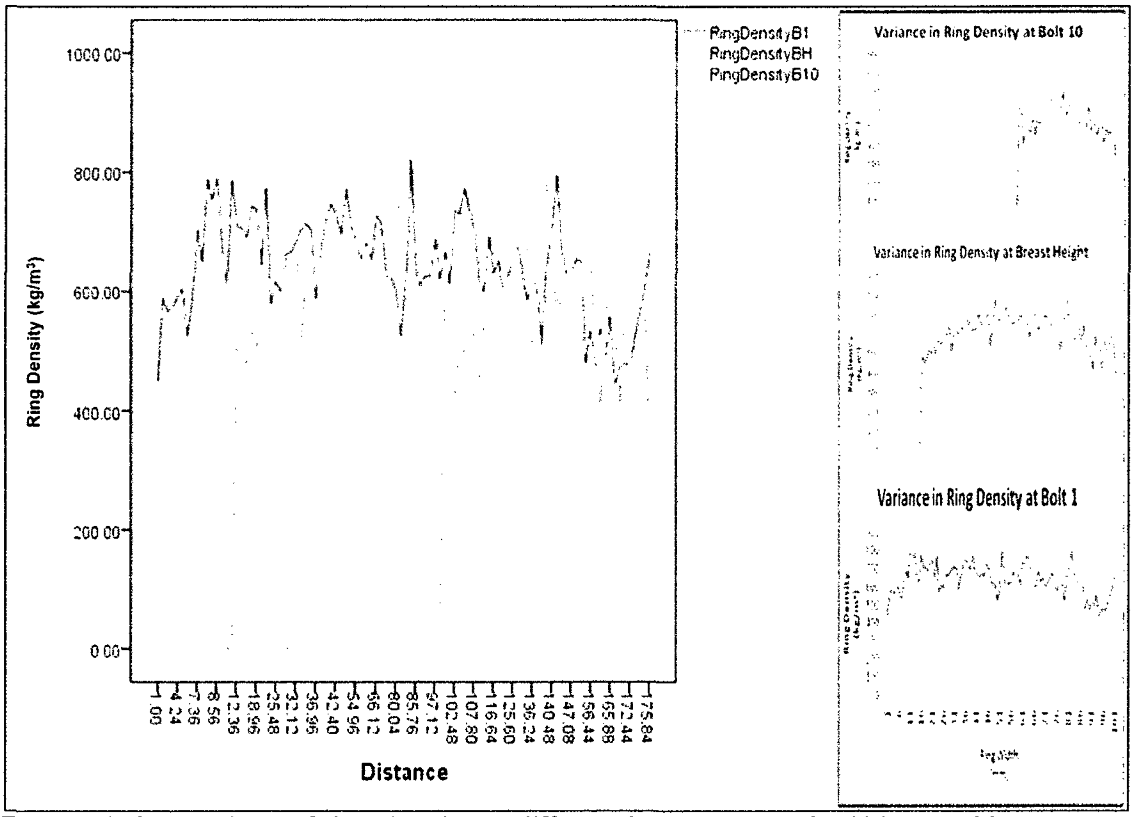


Figure 51. Comparison of ring density, at different bolt heights, of a 101 year old eastern larch tree grown in the TBD.

In Figure 52 we compared box plots of ring width variance, on the left, and ring density variance, on the right. The direct comparison of site data showed that ring width is more variable between sites than ring density, while ring density is more variable within sites than ring width. This pattern of ring density variance was consistent with relative density and density observations and was supported by the results reported by Doucet *et al.* (1983).

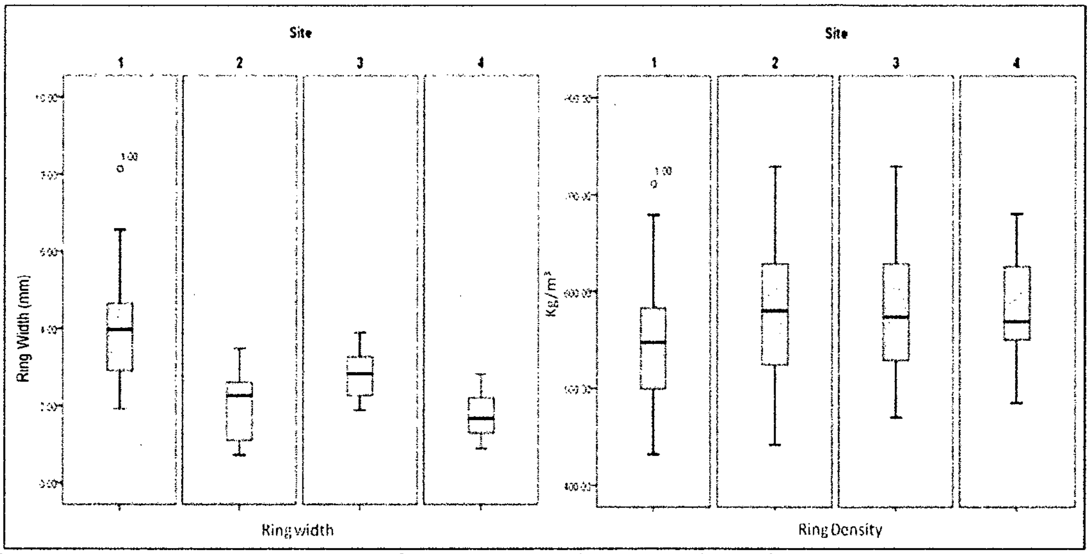


Figure 52. Box plot comparison of site variance between ring width and ring density.

The x-ray densitometry results indicated that the ring density of eastern larch varied between a low of 202 kg/m^3 on site 2 and a high of 849 kg/m^3 on site 1, with a grand mean in the TBD of 562 kg/m^3 (Table 22). Ring width varied between a low of 0.23 mm on site 2 and a high of 6.86 mm on site 1, with a grand mean in the of 2.47 mm. The grand mean for percent latewood in the TBD was 39.0%.

Table 22. Results from x-ray densitometry analysis.

Site	Ring Width (mm)			Earlywood density (Kg/m3)	Latewood density (Kg/m3)	Density (Kg/m3)		
	Minimum	Maximum	Mean	Mean	Mean	Minimum	Maximum	Mean
1	0.59	6.86	3.64	324	682	366	849	511
2	0.23	3.61	1.30	358	820	202	870	573
3	0.84	4.96	2.74	348	722	312	853	583
4	0.36	5.93	2.20	354	798	347	813	582
Study	0.23	6.86	2.47	346	755	202	849	562

Comparison of the ring analysis grand means to published values (Table 23) showed that eastern larch grown in TBD had 20% higher ring density and latewood proportion than published values, consistent with differences in relative density to Forest Products Laboratory (1999) values, which were discussed.

Table 23. Results from x-ray densitometry analysis.

Study	Ring density (Kg/m3)	Earlywood density (Kg/m3)	Latewood density (Kg/m3)	Minimum density (Kg/m3)	Maximum density (Kg/m3)	Latewoood proportion (%)
TBD. (2010)	562	346	755	202	849	39.0
Zhang and Koubaa. (2008)	471	351	707	268	845	32.7

Ring density data was analyzed using SPSS 18 software. The ANOVA results indicated that the variation patterns for ring density were similar to wood density. The ANOVA showed a significant variance existed between ring density means for sites and radial position, however, no significance between axial positions or interactions between factors were found, at 95% probability. Based on the ANOVA results the null hypothesis, no variance in ring density, was rejected.

A Duncan's post hoc test was performed on the ring density means for radial position indicating three subsets of significance. Figure 53 shows that the three subsets were:

subset 1; included the juvenile core,

subset 2; included the outer heartwood and inner sapwood zones,

subset 3; included the zone of outer sapwood and cambial activity.

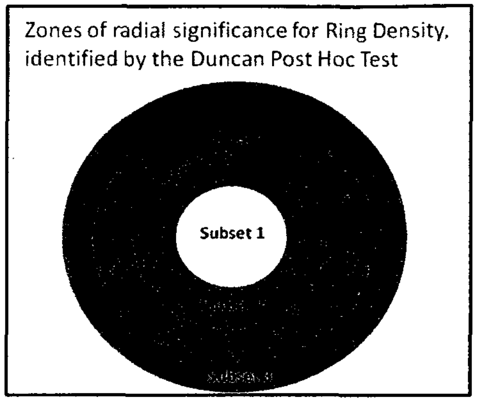


Figure 53. Diagram of Duncan's post hoc test subsets for radial position of ring density means.

The Duncan's post hoc test results on sites indicated two subsets:

subset 1; included site 1 the dry fast growing site with eastern larch dominance,

subset 2; included site 2 the poorly drained wet site with eastern larch / black spruce mix, site 3 the well drained site with high competition, and site 4 the very wet site with black spruce dominance.

The findings indicated that, increased growth rate did affect the density of eastern larch at the extreme of its growth range within the TBD; similar observations were made by Yang and Hazenberg (1987) and Dong (1996). These findings are consistent with Zhang and Koubaa (2008), which reported that plantation eastern larch, grown to produce maximum biomass within 30 years, had reported wood density values, 22% lower than natural grown trees.

4.2.2 Variance in relative density (specific gravity) and density

Relative density$_{OD\ and\ 12}$ / density$_{12}$ data were analyzed using SPSS 18 software. The ANOVA results (Table 24) indicated that the variation between site and radial means for the dependant variables was significant, however, axial variance and interactions between factors were insignificant at 95% probability.

The ANOVA results indicated that the variation patterns for relative density$_{OD\ and\ 12}$ and density$_{12}$ were very similar. Relative density$_{OD}$ values were higher than relative density$_{12}$, while density$_{12}$ had the highest values. This relationship is an important principle in wood science, where increased percent moisture content resulted in higher density values and lower relative density values (Panshin and de Zeeuw, 1980; Mullins and McKnight, 1981; Bowyer *et al.*, 2003).

Table 24. ANOVA results for relative density$_{OD\ and\ 12}$ / density$_{OD}$.

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	RD0	114818.297[a]	15	7654.553	4.869	.000
	D12	174234.484[b]	15	11615.632	4.867	.000
	RD12	104790.797[c]	15	6986.053	4.863	.000
Intercept	RD0	9.815E7	1	9.815E7	62429.256	.000
	D12	1.490E8	1	1.490E8	62410.542	.000
	RD12	8.966E7	1	8.966E7	62412.318	.000
Site	RD0	81102.934	3	27034.311	17.195	.000
	D12	123152.609	3	41050.870	17.199	.000
	RD12	74131.009	3	24710.336	17.200	.000
Bolt	RD0	15013.953	9	1668.217	1.061	.392
	D12	22747.091	9	2527.455	1.059	.393
	RD12	13647.628	9	1516.403	1.056	.396
Radial	RD0	18701.409	3	6233.803	3.965	.009
	D12	28334.784	3	9444.928	3.957	.009
	RD12	17012.159	3	5670.720	3.947	.009
Error	RD0	477953.250	304	1572.215		
	D12	725598.637	304	2386.838		
	RD12	436730.425	304	1436.613		
Total	RD0	9.874E7	320			
	D12	1.499E8	320			
	RD12	9.020E7	320			
Corrected Total	RD0	592771.547	319			
	D12	899833.122	319			
	RD12	541521.222	319			

a., b. and c. R Squared = .194 (Adjusted R Squared = .154)

The ANOVA results indicated that relative density$_{OD}$ of eastern larch varied between 458 and 658 kg/m^3, with a grand mean in the TBD of 554 kg/m^3 (Figure 54). The ANOVA showed that a significant variance existed between relative density$_{OD}$ means for radial position and sites, however, no significance in axial position or interactions between factors at 95% probability was found.

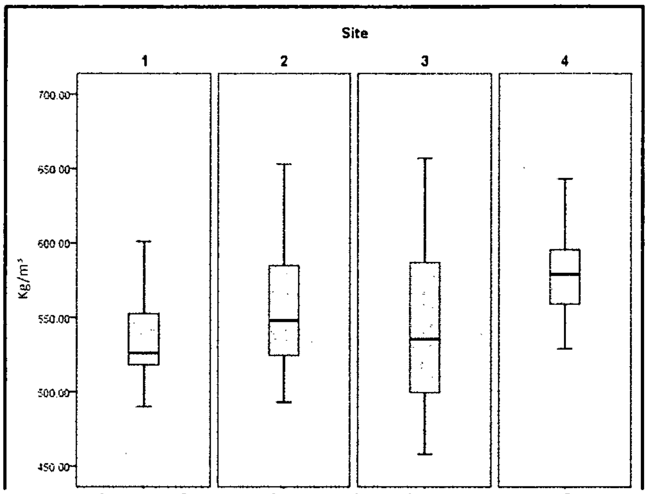


Figure 54. Box plot comparison of site relative density$_{OD}$ means for eastern larch sites.

The ANOVA results indicated that relative density$_{12}$ of eastern larch varied between 437 and 629 kg/m^3, with a grand mean in the TBD of 530 kg/m^3 (Figure 55). The ANOVA showed that a significant variance existed between relative density$_{12}$ means for radial position and sites, however, no significance in longitudinal position or interactions between factors at 95% probability was found.

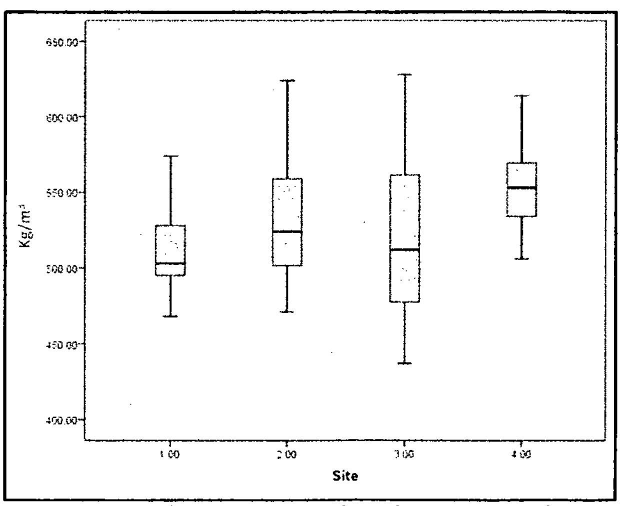


Figure 55. Box plot comparison of site relative density$_{12}$ means for eastern larch sites.

The ANOVA results indicated that $density_{12}$ of eastern larch varied between 564 and 811 kg/m^3, with a grand mean in the TBD of 683 kg/m^3 (Figure 56): comparison of site $density_{12}$ means. The ANOVA showed a significant variance existed between $density_{12}$ means for radial position and sites, however, no significance in axial position or interactions between factors at 95% probability was found.

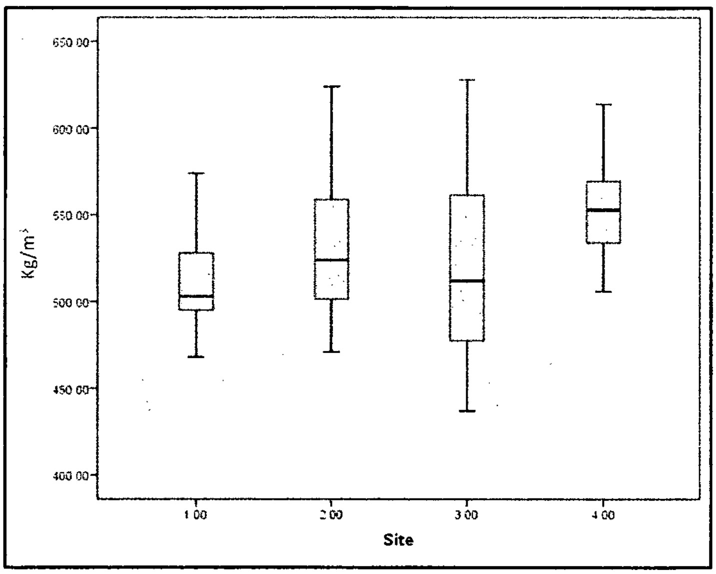


Figure 56. Box plot comparison of site $density_{12}$ means for eastern larch sites.

Site 4, the wettest site, had the highest wood density values and the least variance. Site 3, the well drained site, exhibited the highest variance, however, average wood density values were similar to site 2, the poor drained wet site, which exhibited the second highest variance. Finally, site 1, the dry site, had the lowest wood density values, which were expected for this fast growing site. Variance for site 4, however, was similar to site 1.

Radial variance of relative density$_{OD\ and\ 12}$ and density$_{12}$ means were very consistent between sites and bolts, (Figure 57 and Figure 58). Doucet *et al.* (1983) reported that the general radial wood density patterns for eastern larch, decreased to minimum from the pith, then increased to the bark (Doucet *et al.*, 1983; Zhang and Koubaa, 2008). Eastern larch in the TBD consistently displayed the opposite pattern reported by Doucet *et al.* (1983), increasing from the pith to a maximize at the heartwood / sapwood transition, then decreasing to the bark. However, Balatinecz (1983) reported that heartwood has a higher wood density than sapwood (Balatinecz, 1983; Zhang and Koubaa, 2008), which was observed on all four sites. Due the consistency of TBD's radial variance patterns the contradictory results with Doucet *et al.* (1983) may be attributed to different processing and calculation methods (Alemdag,1984).

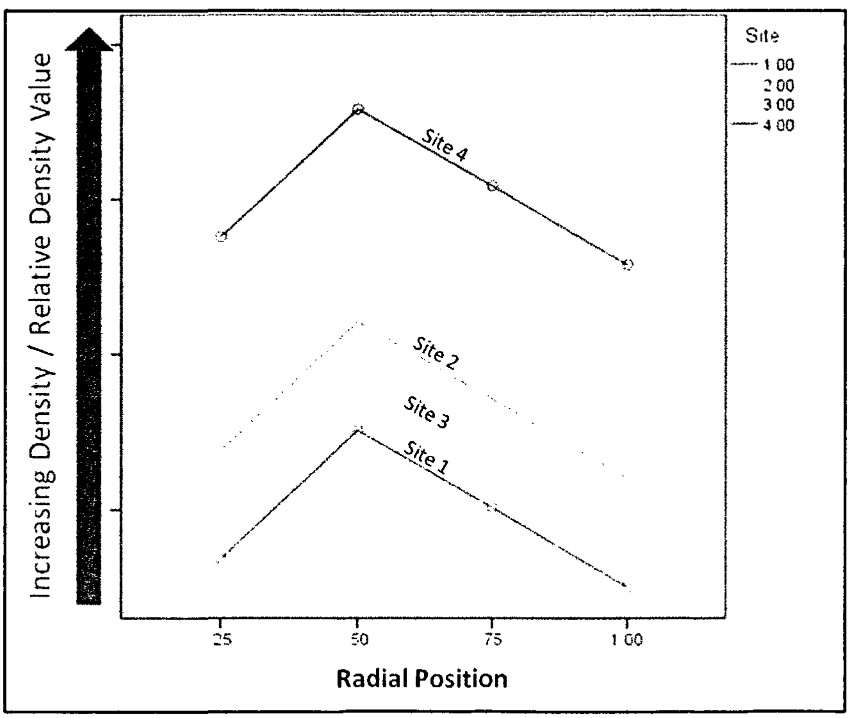


Figure 57. Line graph comparison of sites' radial variance of wood density means.

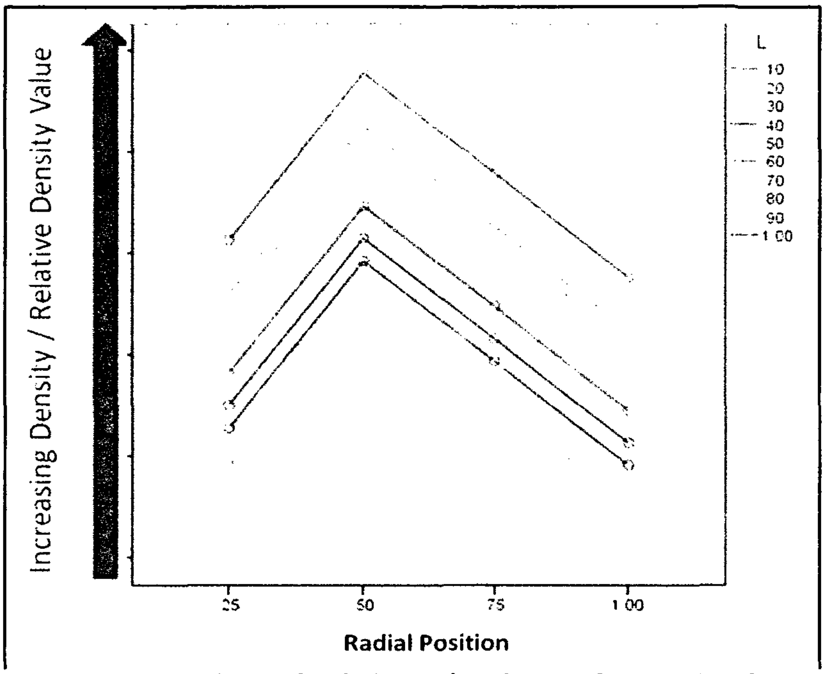


Figure 58. Line graph comparison of bolts' radial variance of wood density means.

Based on the ANOVA results the null hypothesis, no variance between wood density means, was rejected at 95% probability. There was significant variance observed in eastern larch between sites and radial positions within stems, while variance between axial means was insignificant; this was also supported by the literature (Balatinecz, 1983; Singh, 1984; Singh, 1986; Yang and Hazenberg, 1987; Zhang and Koubaa, 2008).

A Duncan's post hoc test was performed on the relative density$_{OD \text{ and } 12}$ and density$_{12}$ means for sites and radial position. For sites, the post hoc test indicated three subsets of similarity:

subset 1; included site 1 the dry fast growing site with eastern larch dominance and site 3 the well drained site with high competition,

subset 2; included site 2 the poorly drained wet site with eastern larch / black spruce mix and site 3, and

subset 3; included site 4 the very wet site with black spruce dominance.

However, given the level of variance between means observed, subset 1 was corrected to exclude site 3. Thus, based on similarities exhibited within site variance, and the Duncan's post hoc test of wood density means, sites 2 and 3 had the greatest similarity between sites (Figure 59).

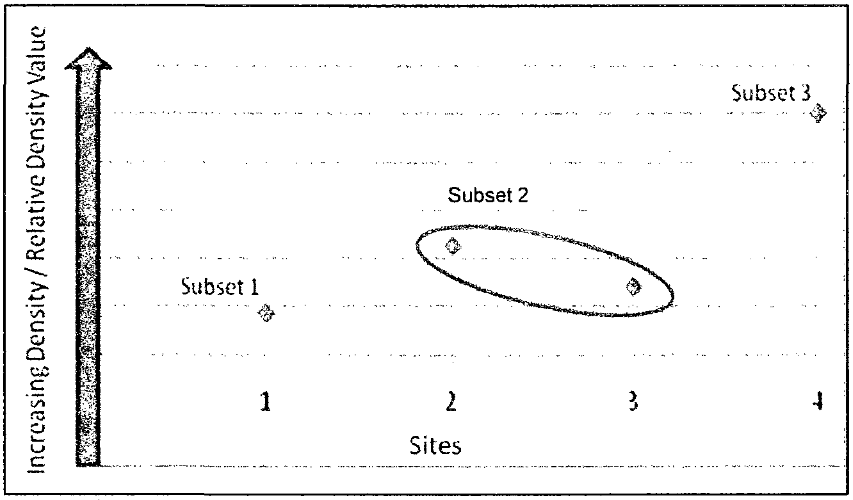


Figure 59. Graph of corrected Duncan's post hoc test subsets for sites' wood density means.

The Duncan's post hoc test on radial variance of wood density means identified two subsets of similarity (Figure 60):

subset 1; included the juvenile core and zone of sapwood and cambial activity,

subset 2; included the zones of outer heartwood and inner sapwood.

These subsets consistently displayed recurring radial pattern of variance exhibited in all bolts, and was supported by the literature reports of higher relative density and density in the heartwood than sapwood in eastern larch.

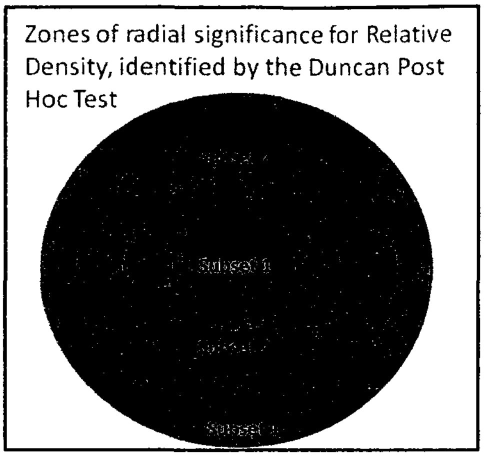


Figure 60. Diagram of Duncan's post hoc test subsets for radial position of wood density means.

We have considered the statistical analysis of wood density of eastern larch, and identified subsets of similarity amongst wood density means. However, when end use classifications of wood density are considered, the variance observed during the statistical analysis becomes extremely limited. Density, at 12% (air-dry) moisture content, classifications are typically (Gardiner, 2010):

1. exceptionally light — under 300 kg/m³
2. light — 300 to 450 kg/m³
3. medium — 450 to 650 kg/m³
4. heavy — 650 to 800 kg/m³
5. very heavy — 800 to 1000+ kg/m³.

The five $density_{12}$ classifications were assigned a numeric value 1 to 5; 1, being exceptionally light, and 5 being, very heavy, and analysed using SPSS 18 software. The resulting ANOVA table and Duncan's post hoc test indicated that bolts had two subsets of significance (Figure 61):

subset 1; included bolt 90% to bolt 100%,

subset 2; included bolt 10% to bolt 80%.

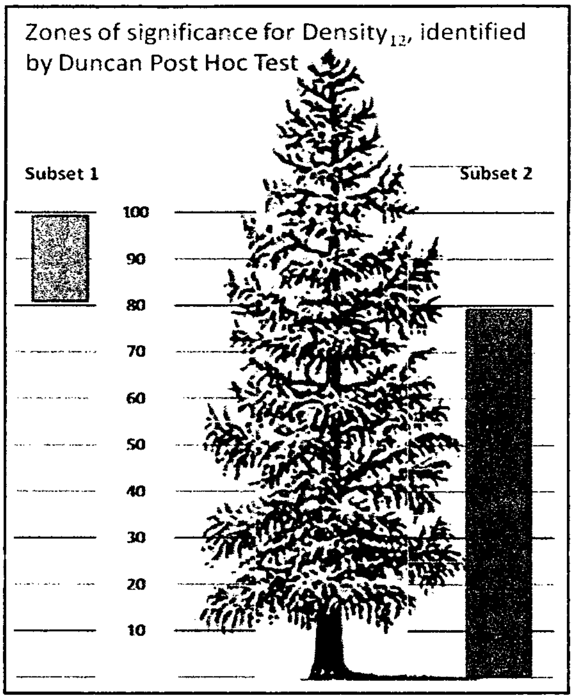


Figure 61. Diagram of Duncan's post hoc test subsets for density$_{12}$ classification means.

Although the variability of wood density axial means was insignificant it was also inconsistent between trees; which was supported by Wahlgren et al (1966). By using density classifications, two subsets of significance could be identified, which will assist in developing a wood characteristics map.

It has been generally accepted that for softwoods increased wood density resulted in increased mechanical properties. We must keep in mind that eastern larch contains a high proportion of reaction wood and spiral grain, therefore, the medium wood density observed would not necessarily result in corresponding mechanical properties (Balatinecz, 1983; Zhang and Koubaa, 2008). However, for pulpwood end use products increased wood density was directly related to increased pulp yield, and directly affected pulp properties (Balatinecz, 1983; Zhang and Koubaa, 2008). It was found that wood density of eastern larch in the TBD was very consistent between sites, with significant variance limited to the juvenile core and crown wood. The wood density findings suggest that eastern larch was well suited to produce pulpwood products.

4.2.3 Variance in MOE

MOE data was analyzed using SPSS 18 software, the ANOVA results (Table 25) indicated that MOE of eastern larch varied between 5,130 and 11,273 MPa, with a grand mean in the TBD of 8,355 Mpa (Figure 62). The ANOVA showed a significant variance existed between MOE means for sites and axial position, however, no significance in radial position and interactions between factors at 95% probability was found.

Table 25. ANOVA results for MOE.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.647E8	15	1.098E7	8.211	.000
Intercept	2.232E10	1	2.232E10	16685.439	.000
Site	1.286E8	3	4.288E7	32.058	.000
Bolt	2.765E7	9	3072634.776	2.297	.017
Radial	8451983.175	3	2817327.725	2.106	.099
Error	4.066E8	304	1337554.292		
Total	2.289E10	320			
Corrected Total	5.714E8	319			

a. R Squared = .288 (Adjusted R Squared = .253)

Figure 63 showed that site 3, the well drained site, had the highest average MOE at 8,935 MPa and high variance similar to site 4. Site 4, the very wet site, exhibited the highest variance, however, average MOE was similar to site 3 at 8,765 MPa. Site 2, the poorly drained wet site, had the lowest variance in MOE with average a value of 8,145 MPa; close to the grand mean. Finally, site 1, the dry fast growing site, had the lowest MOE average at 7,306 MPa and moderate variance.

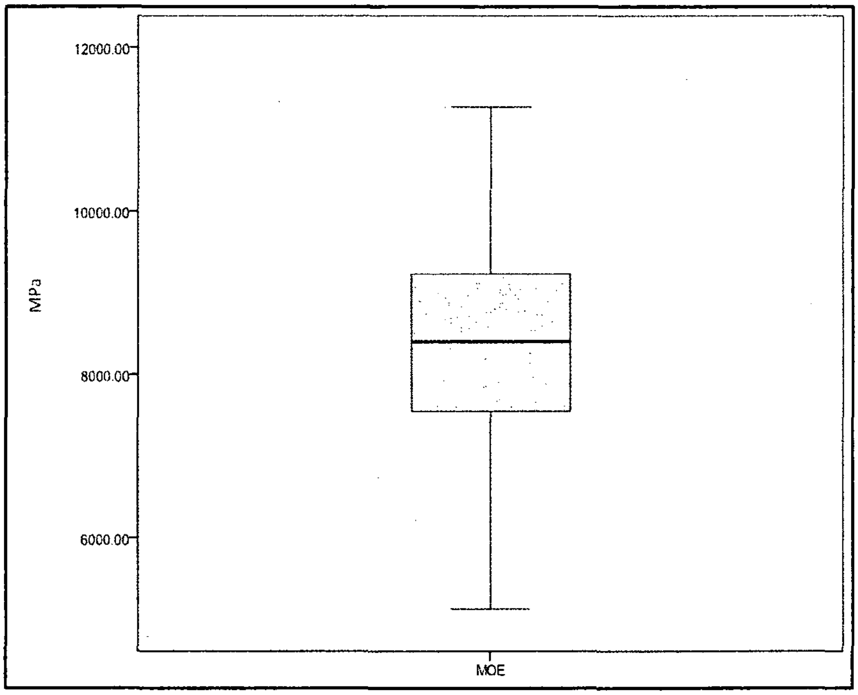


Figure 62. Box plot of MOE means.

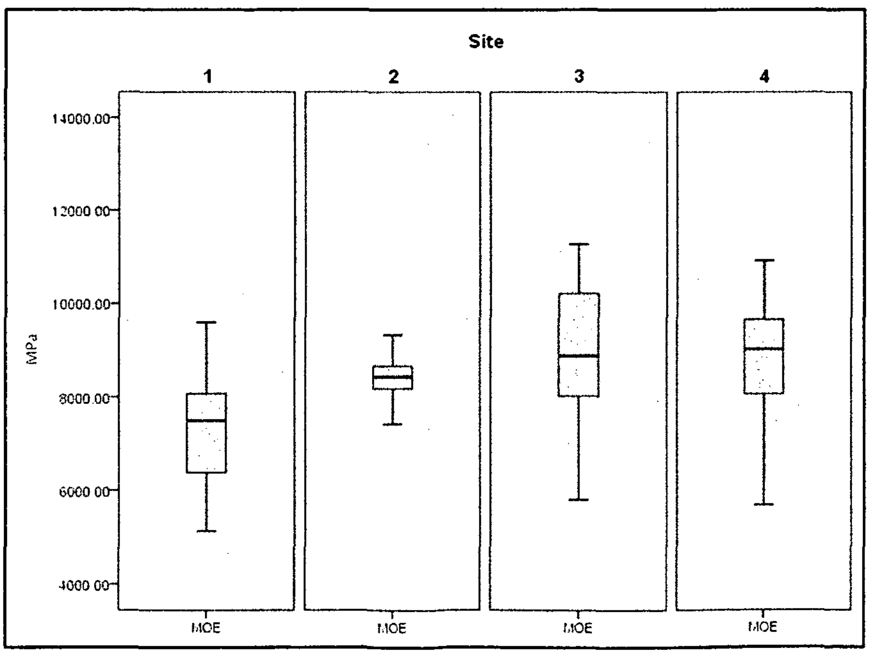


Figure 63. Box plot comparison of site MOE means.

Axial variance of MOE means were very consistent between sites and within bolts. Balatinecz (1983) reported that the general axial patterns for mechanical properties were variable, however, generally decreased in value from base to crown (Balatinecz, 1983; Yang *et al.*, 1986; Zhang and Koubaa, 2008). Eastern larch in the TBD consistently displayed an axial variance pattern, which had a sharp increase from bolt 1 to 2, then proceeding up the stem, although fluctuating, generally increasing to a maximum around the mid stem, followed by a pronounced decrease in MOE to the crown (Figure 64).

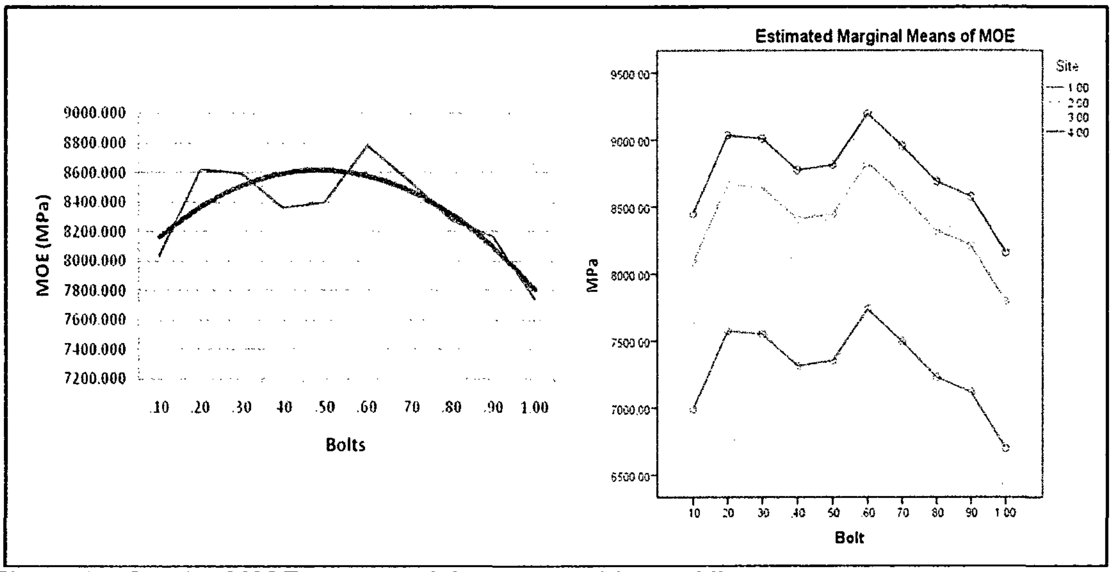


Figure 64. Graph of MOE means axial variance with trend line.

Radial variance of MOE means were insignificant according to the ANOVA results, however, it did display a pattern of variance, which was consistent on all sites. Yang *et al.* (1986) reported that the juvenile wood had higher mechanical properties than mature wood. Radial variance patterns in MOE for eastern larch grown in the TBD, were consistent with Yang *et al.* (1986) findings, increasing from pith to a maximum in the heartwood/sapwood transition zone, then decreasing in value proceeding to the bark (Figure 65). Radial variance patterns of MOE for eastern larch are more consistent with hardwoods than softwoods.

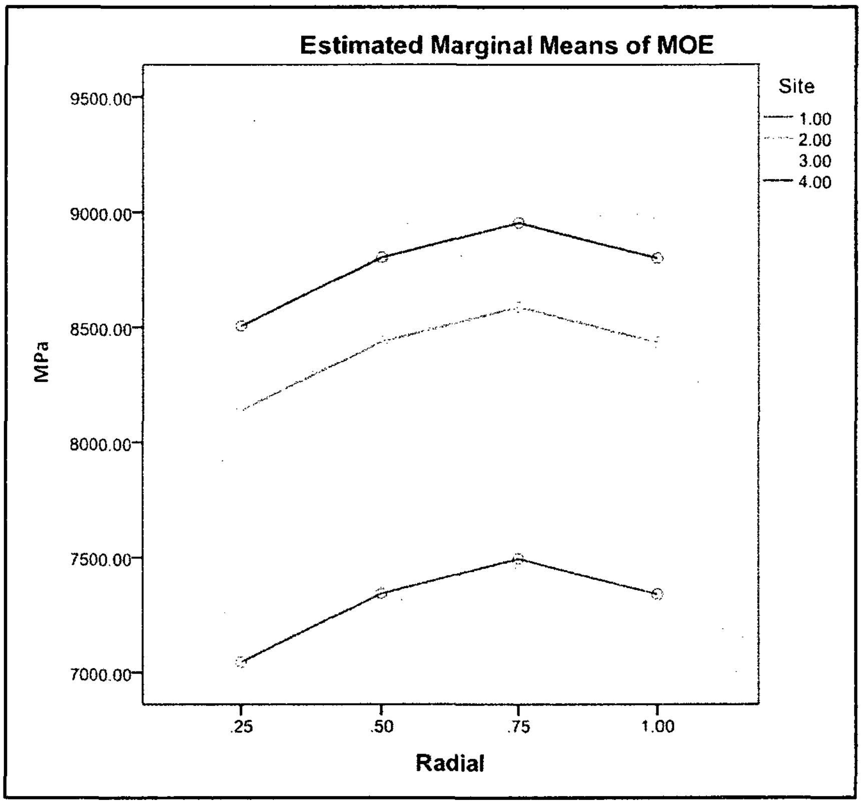


Figure 65. Graph of MOE means radial variance with Trend line.

Based on the ANOVA results the null hypothesis, that there is no variance in MOE, was rejected at 95% probability. There is significant variance in eastern larch sites and axial position within stems, while interaction affects and radial means are insignificant; which was consistent with other studies (Balatinecz, 1983; Yang *et al.*, 1986; Zhang and Koubaa, 2008).

A Duncan's post hoc test was performed on the MOE means for sites and axial positions. For sites, Figure 66 shows that the post hoc test indicated three subsets of similarities:

subset 1; included site 1 the dry fast growing site with eastern larch dominance,

subset 2; included site 2 the poorly drained wet site with eastern larch / black spruce mix,

subset 3; included site 3 the well drained site with high competition from mixed species and site 4 the very wet site with black spruce dominance.

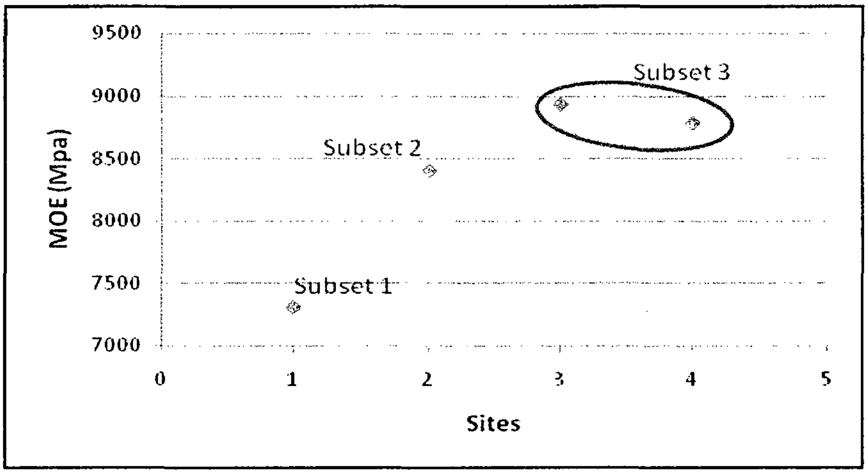


Figure 66. Graph of Duncan's post hoc test subsets for site MOE means.

As Figure 67 shows, the Duncan's post hoc test of MOE means indicated two axial subsets of similarity:

subset 1; included bolt 2 to bolt 9, the main stem,

subset 2; included bolt 1 and bolt 10, areas of high compression wood.

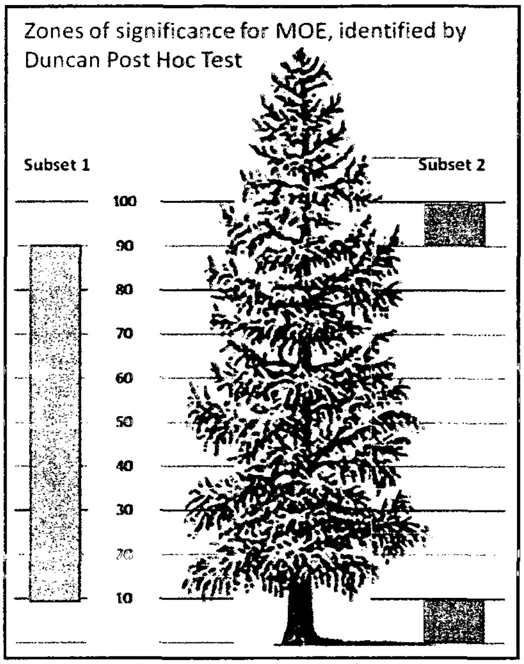


Figure 67. Graph of Duncan's post hoc test subsets for axial MOE means.

Although the radial variances of MOE means were not significant, A Duncan's post hoc test was performed to identify zones of similarity, which would be used in wood characteristics mapping. Two zones of similarity were identified for MOE radial position (Figure 68):

subset 1; included the juvenile core and the zone of outer sapwood and cambial activity,

subset 2; included the outer heartwood and inner sapwood zones.

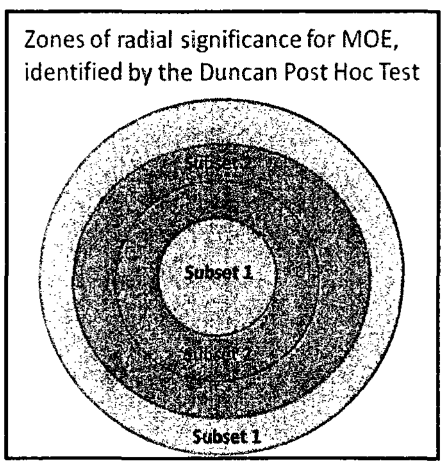


Figure 68. Graph of Duncan's post hoc test subsets for radial MOE means.

The juvenile core consistently had the highest number of cull specimens, and the least number of test specimens, compared to the other radial positions. While the zone of outer sapwood and cambial activity had the highest moisture content, which led to high levels of culled specimens due to warping and pitch pockets. Compression wood, knots, pith eccentricity, pitch pockets, and warping were the main causes of specimen cull.

The relative consistency of moderate MOE means observed within stems and between sites suggests that eastern larch would be suitable for a variety of solid wood and pulpwood products. Further, the similarity between wood density radial variance and MOE suggests there may be a correlation between the two properties.

4.2.4 Variance in MOR

MOR data was analyzed using SPSS 18 software, the ANOVA results (Table 26) indicated that MOR of eastern larch varied between 51 and 107 MPa, with a grand mean in the TBD of 79 MPa (Figure 69). The ANOVA showed a significant variance existed between MOR means for sites, and radial and axial positions, however, no significant interactions between factors at 95% probability were found.

Figure 70 shows that site 4, the very wet site, had the highest average MOR at 88 MPa and a high variance similar to site 1. Site 1, the dry site, exhibited a high variance, however, average MOR was the lowest at 68 MPa.

Site 2, the poorly drained wet site, had moderate variance in MOR, similar to site 3, with an average MOR of 82 MPa. Finally, the well drained site, site 3's average MOR at 80 MPa was closest to the grand mean and the site had moderate variance.

Table 26. ANOVA results for MOR.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	20532.375[a]	15	1368.825	22.533	.000
Intercept	2018030.450	1	2018030.450	33220.092	.000
Radial	638.375	3	212.792	3.503	.016
Bolt	1686.175	9	187.353	3.084	.001
Site	18207.825	3	6069.275	99.910	.000
Error	18467.175	304	60.747		
Total	2057030.000	320			
Corrected Total	38999.550	319			

a. R Squared = .526 (Adjusted R Squared = .503)

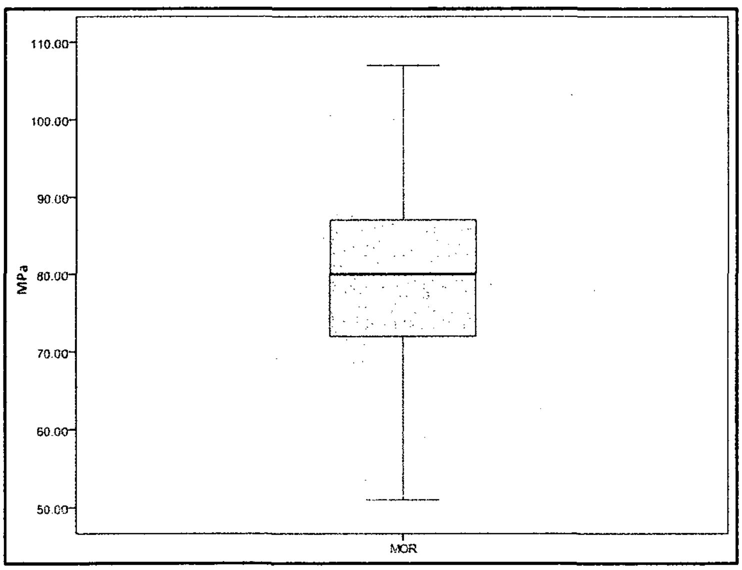


Figure 69. Box plot of MOR means.

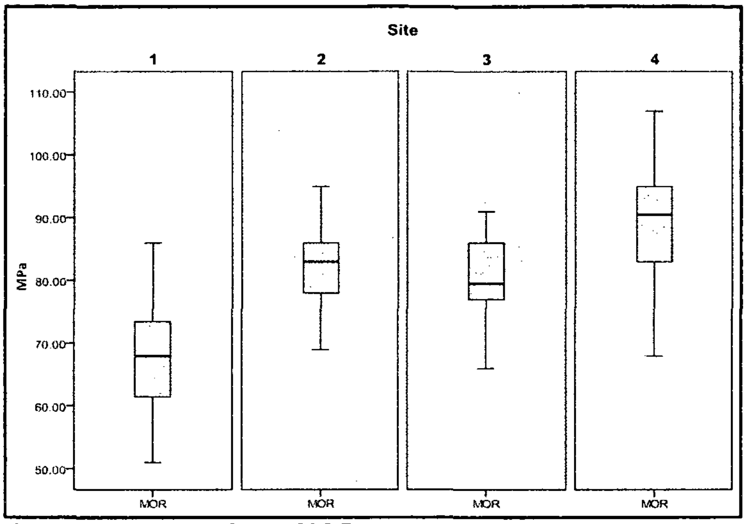


Figure 70. Box plot comparison of site MOR means.

Axial variances of MOR means were very consistent between sites and within trees. The literature reported that the general axial patterns for mechanical properties were variable, however, generally decreased in value from base to crown (Balatinecz, 1983; Yang *et al.*, 1986; Zhang and Koubaa, 2008). Eastern larch grown in the TBD, consistently displayed the variable axial pattern for MOR reported by the literature, with a general decrease from base to tip (Balatinecz, 1983; Yang *et al.*, 1986; Zhang and Koubaa, 2008) (Figure 71).

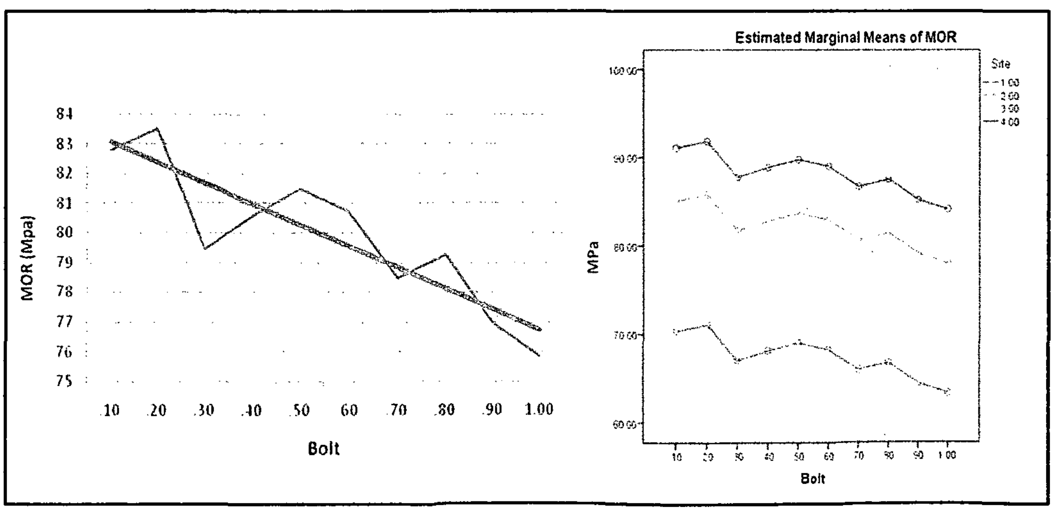


Figure 71. Graph of MOR means axial variance with trend line.

Radial variance of MOR means displayed a pattern of variance, which was consistent on all sites. Radial MOR values increased from pith to a maximum in the heartwood/sapwood transition zone, and then decreasing in value proceeding to the bark (Figure 72).

Based on the ANOVA results the null hypothesis, no variance in MOR, was rejected at 95% probability. There was significant differences in eastern larch MOR between sites, radial and axial position within stems, while interaction affects were insignificant.

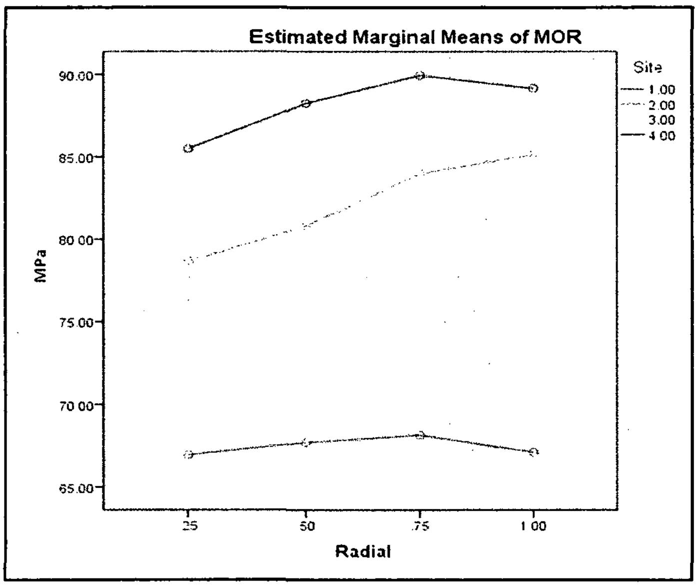


Figure 72. Graph of MOR means radial variance with trend line.

A Duncan's post hoc test was performed on the MOR means for sites, radial and axial positions. For sites, Figure 73 shows that the post hoc test indicated three subsets of similarity:

subset 1; included site 1 the dry fast growing site with eastern larch dominance,

subset 2; included site 2 the poorly drained wet site with eastern larch / black spruce mix and site 3 the well drained site with high competition from mixed species, subset 3; included site 4 the very wet site with black spruce dominance.

These findings suggested that eastern larch MOR can be affected by tree spacing and trenching silvicultural treatments, as observed for MOE.

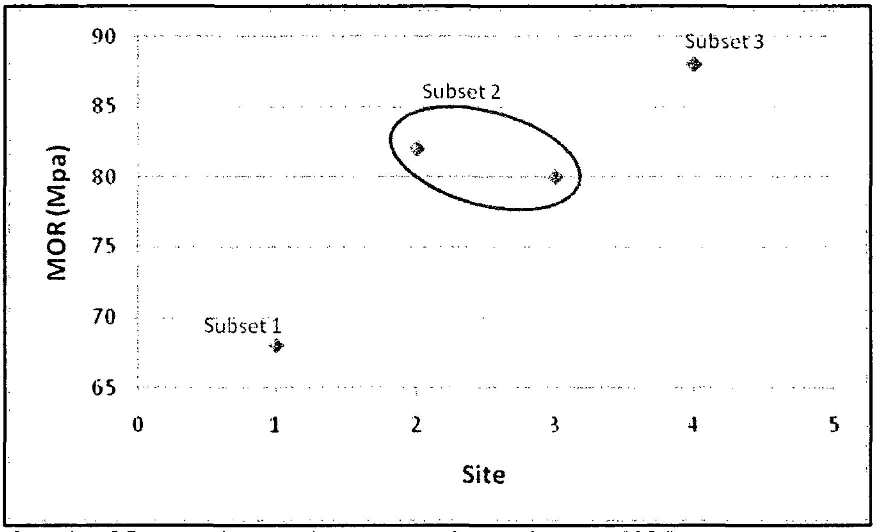


Figure 73. Graph of Duncan's post hoc test subsets for site MOR means.

As Figure 74 shows, the Duncan's post hoc test of MOR means indicated two axial subsets of similarity for axial position:

subset 1; included bolt 7 to bolt 10, high proportion of compression wood and large knots,

subset 2; included bolt 1 to bolt 7, small knots in whorls with sections of clearwood.

A Duncan's post hoc test identified two subsets of similarity for MOR means' radial position (Figure 75):

subset 1; included the juvenile core and outer heartwood,

subset 2; included the inner sapwood and zone of outer sapwood and cambial activity.

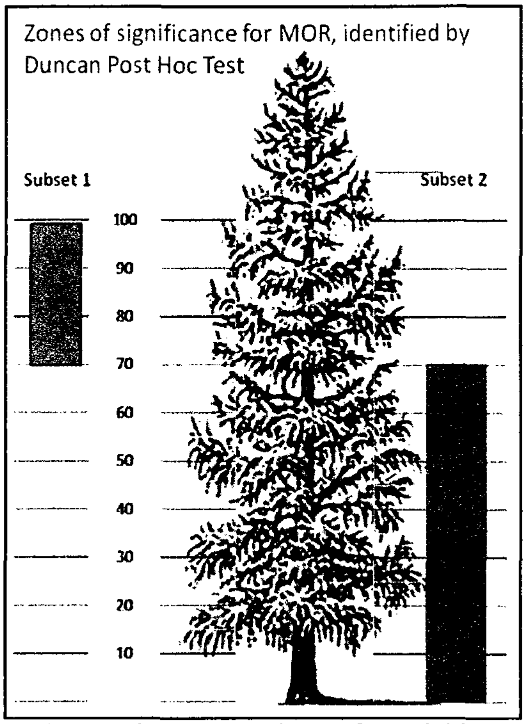


Figure 74. Graph of Duncan's post hoc test subsets for axial MOR means.

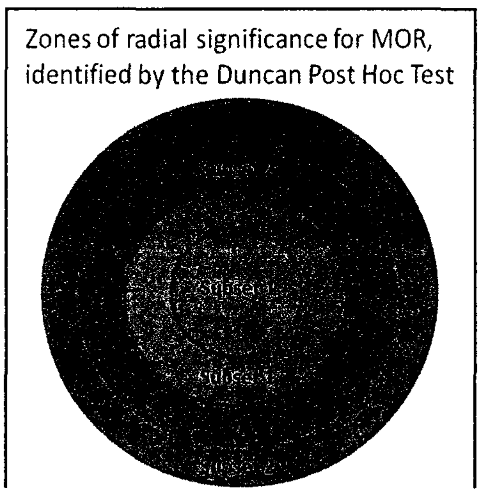


Figure 75. Graph of Duncan's post hoc test subsets for radial MOR means.

4.2.5 Variance in compression parallel to grain

Compression specimens were limited to the first 3 sites, as samples were unavailable for site 4. Compression data was analyzed using SPSS 18 software, the ANOVA results (Table 27) indicated that compression of eastern larch varied between 33 and 59 MPa, with a grand mean in the TBD of 46 MPa (Figure 76). The ANOVA showed a significant difference existed between compression strength means for sites, and radial and axial positions, however, no significant interactions between factors at 95% probability were found.

Table 27. ANOVA results for compression.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	3114.100[a]	14	222.436	11.966	.000
Intercept	504808.538	1	504808.538	27157.359	.000
Site	2096.400	2	1048.200	56.390	.000
Bolt	584.754	9	64.973	3.495	.000
Radial	432.946	3	144.315	7.764	.000
Error	4182.363	225	18.588		
Total	512105.000	240			
Corrected Total	7296.462	239			

a. R Squared = .427 (Adjusted R Squared = .391)

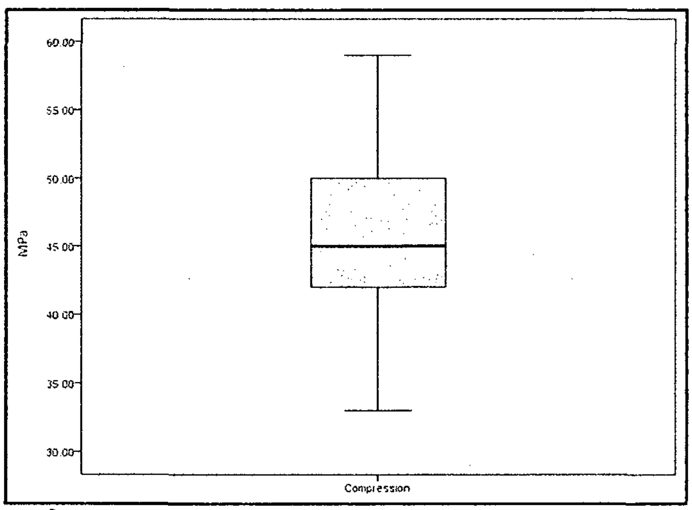


Figure 76. Box plot of compression means.

Figure 77 shows that site 2, the poorly drained wet site, had the highest average compression strength at 49 MPa and highest variance between means. Site 1, the dry site, exhibited the least variance between means, however, the average compression was the lowest at 41 MPa. Site 3, the well drained site, had moderate variance in compression, with an average value of 47 MPa, which was closest to the grand mean.

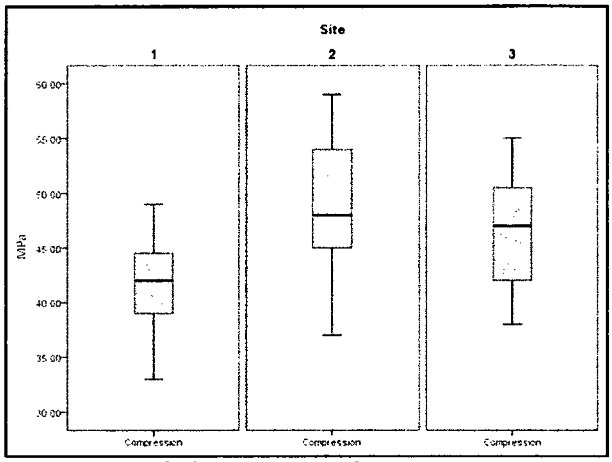


Figure 77. Box plot comparison of site compression means.

Axial differences of compression means were very consistent among sites with fluctuations in the bottom 1/3rd of the stem, with a minor increase in values proceeding up the stem through the middle 1/3rd, followed by a minor decrease in values in the top 1/3rd of the stem (Figure 78). However, a similar pattern of variance was reported by Balatinecz (1983) for axial variance in mature wood tracheid lengths.

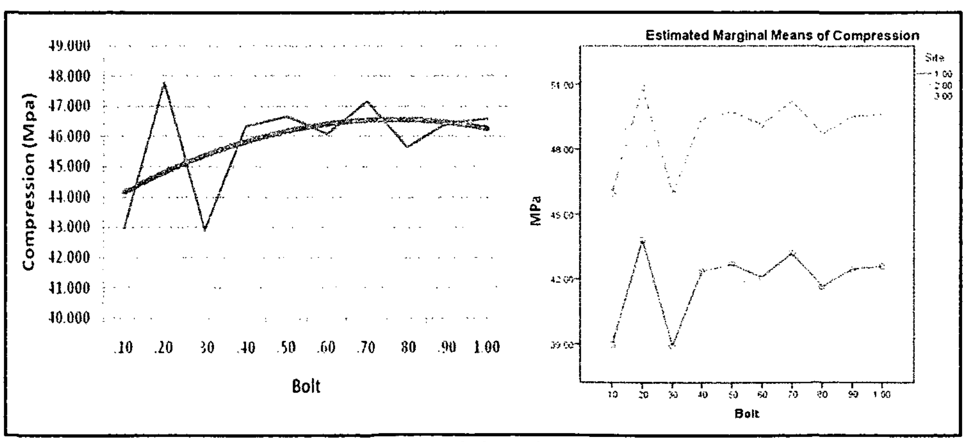


Figure 78. Graph of compression means axial variance with trend line.

Radial compression strength means displayed consistent variance patterns on all sites, increased from pith to a maximum in the heartwood/sapwood transition zone, and then decreasing in value proceeding to the bark (Figure 79).

Based on the ANOVA results the null hypothesis, no variance in compression, was rejected at 95% probability. There is significant variance in eastern larch sites, radial and axial position within stems, while interaction affects are insignificant.

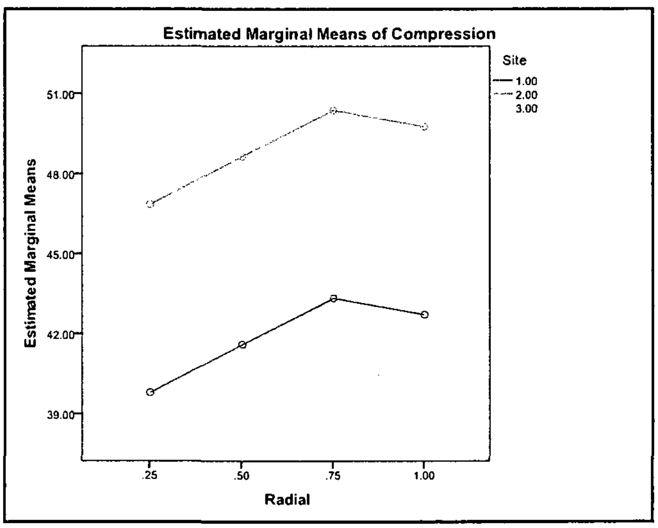


Figure 79. Graph of compression radial variance means.

A Duncan's post hoc test was performed on the compression means for sites, and radial and axial positions. For sites, Figure 80 shows that the post hoc test indicated three subsets of similarity:

subset 1; included site 1 the dry fast growing site with eastern larch dominance,

subset 2; included site 3 the well drained site with high competition from mixed species,

subset 3; included site 2 the poorly drained wet site with eastern larch /

black spruce mix.

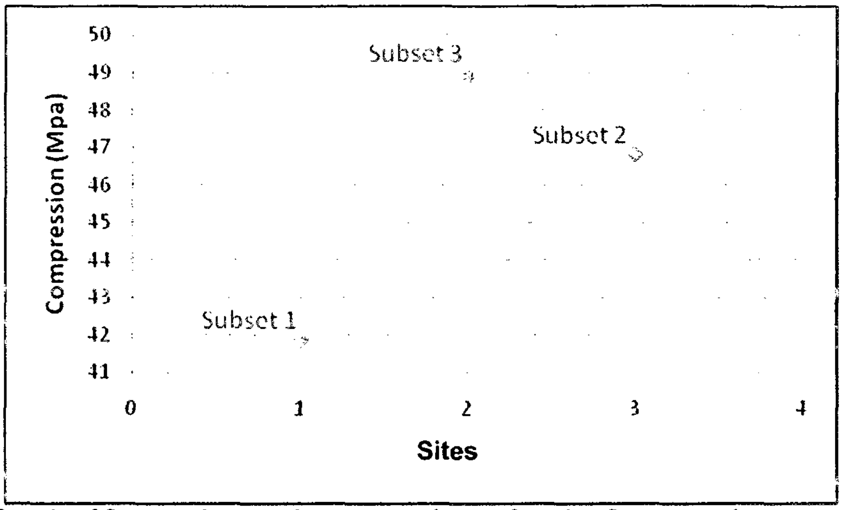


Figure 80. Graph of Duncan's post hoc test subsets for site Compression means.

As Figure 81 shows, the Duncan's post hoc test of compression means indicated two axial subsets of similarity for axial position:

subset 1; included bolt 1 to bolt 3,

subset 2; included bolt 4 to bolt 10.

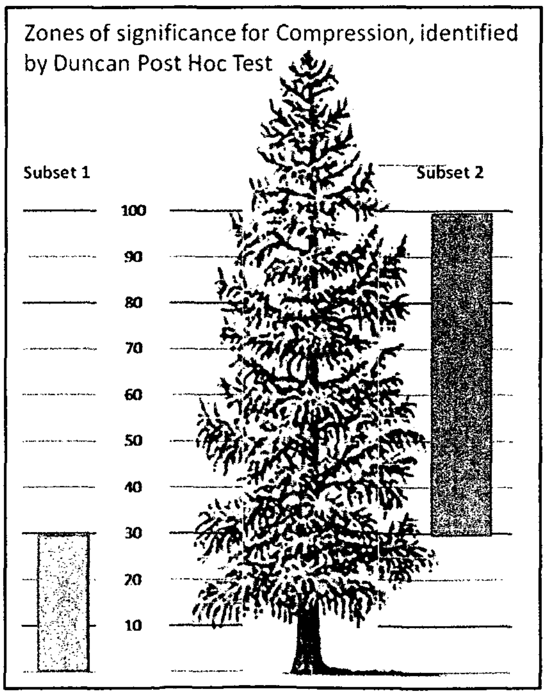


Figure 81. Graph of Duncan's post hoc test subsets for axial Compression means.

A Duncan's post hoc test identified three subsets of similarity for compression means' radial position (Figure 82):

subset 1; included the juvenile core,

subset 2; included the outer heartwood and zone of outer sapwood and cambial activity,

subset 3; included the inner sapwood and zone of outer sapwood and cambial activity.

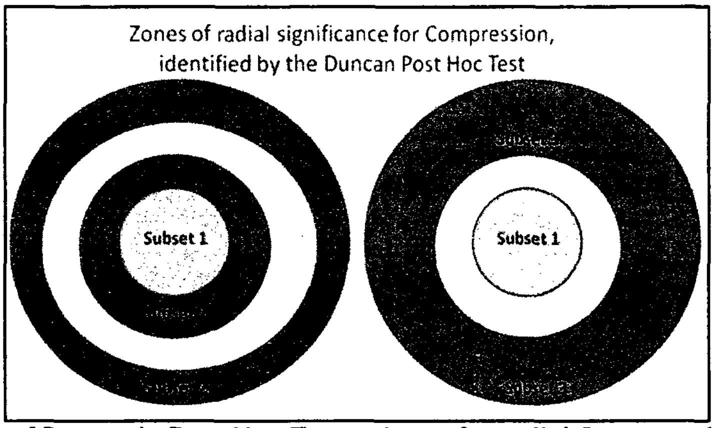


Figure 82. Graph of Duncan's Post Hoc Test subsets for radial Compression means.

4.2.6 Variance in Janka ball side hardness

Hardness data was analyzed using SPSS 18 software, the ANOVA results (Table 28) indicated that hardness of eastern larch varied between 2845 and 4825 Newton (N), with a grand mean in the TBD of 3686 N (Figure 83). The ANOVA showed a significant variance existed between hardness means for sites, and radial and axial positions, however, no significance interactions between factors at 95% probability was found.

Table 28. ANOVA results for hardness.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.872E7	15	1248085.107	11.546	.000
Intercept	4.348E9	1	4.348E9	40221.537	.000
Radial	835880.259	3	278626.753	2.578	.054
Bolt	4675823.066	9	519535.896	4.806	.000
Site	1.321E7	3	4403191.095	40.735	.000
Error	3.286E7	304	108094.646		
Total	4.399E9	320			
Corrected Total	5.158E7	319			

a. R Squared = .363 (Adjusted R Squared = .332)

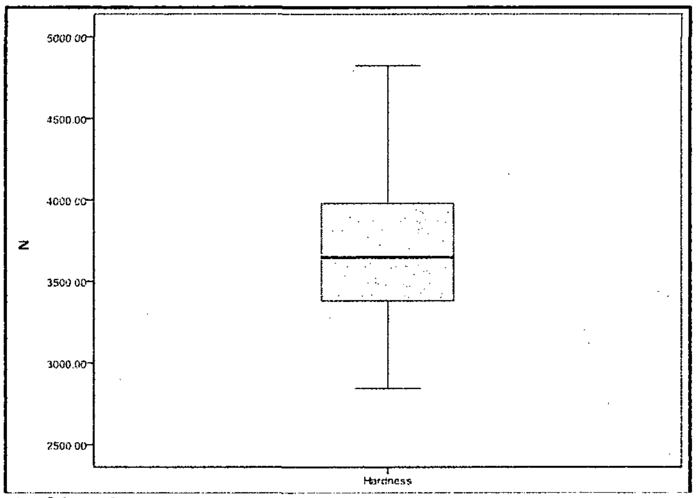


Figure 83. Box plot of hardness means.

Figure 84 shows that site 4, the very wet site, had the highest average hardness at 3935 N and with high variance between means. Site 1, the dry site, exhibited the least variance between means, and average hardness was the lowest at 3451 N. Site 2, the poorly drained wet site, had high variance in hardness, with an average value of 3525 N, which was closest to the grand mean. Finally, site 3, the well drained site, had an average hardness of 3834 N, with high variance.

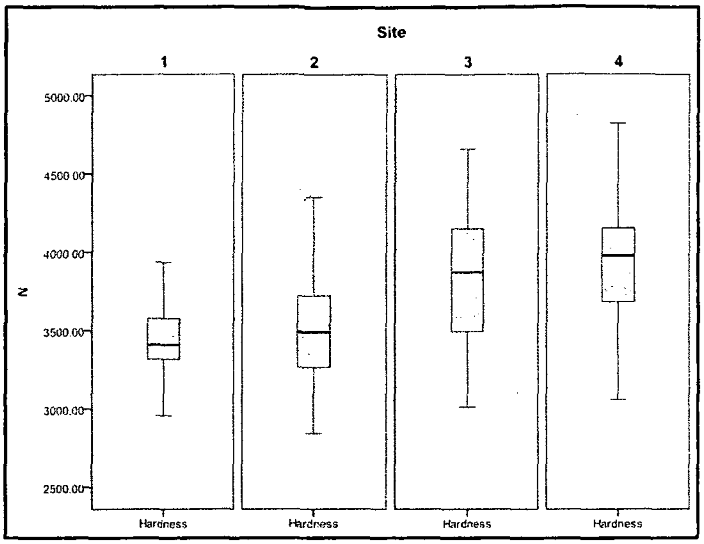


Figure 84. Box plot comparison of site hardness means.

Axial variances between hardness means were very consistent among sites. Within trees average hardness values decreased from the base proceeding up the tree to a minimum at mid stem, between bolts 6 to 7, then increased with axial position to the crown (Figure 85). It has been reported that the mechanical properties of eastern larch generally decrease in value from base to crown (Balatinecz, 1983; Yang *et al.*, 1986; Zhang and Koubaa, 2008). However, the majority the studies completed on the axial changes of mechanical properties of softwoods, are based on four bolt testing; 25%, 50%, 75%, and 100%. Further, under ASTM Test Standard 143D, dimensions of hardness specimens shall be 50 by 50 by 150 mm of clear wood. Due to the percentage of compression wood and knots at the top of the stem, the 100% axial position, viable hardness specimens are limited. Thus, observations on axial variation on mechanical properties may be limited to trends displayed in the lower 75% of the stem.

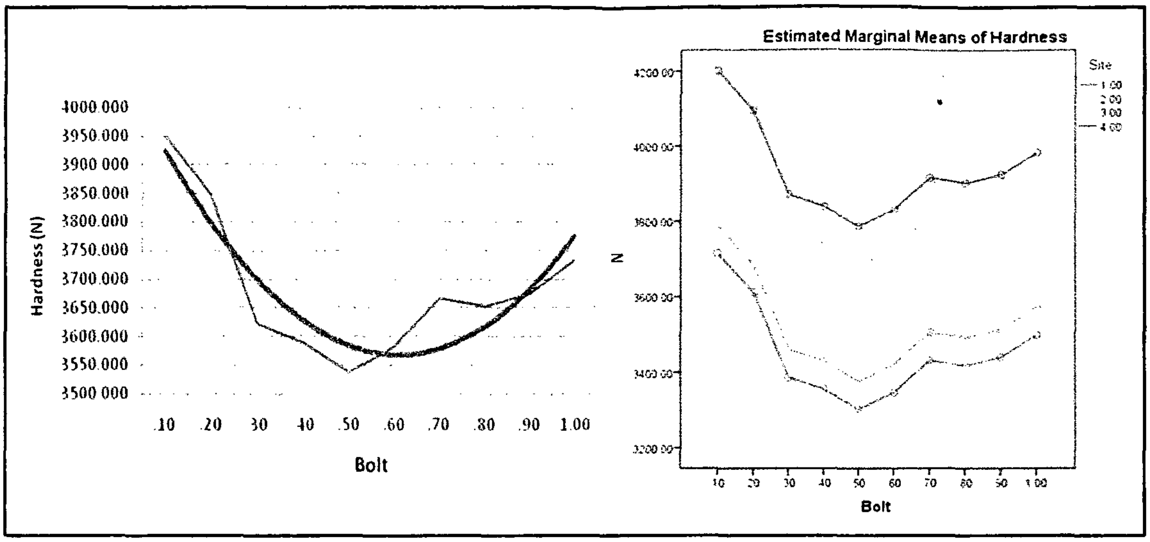


Figure 85. Graph of hardness means axial variance with trend line.

Many of the softwood studies reviewed limited their observations to mature wood or outer wood, to avoid the influence of juvenile and reaction wood. This is problematic for studies on eastern larch, as mature wood has lower mechanical values than juvenille wood (Balatinecz, 1983; Yang *et al.*, 1986; Zhang and Koubaa, 2008). Further, the axial position of mature wood transition is difficult to determine through conventional testing procedures. Therefore, it can be argued that patterns in axial hardness variation displayed by eastern larch grown in the TBD were within the expected range.

Radial variation of hardness means displayed a pattern of variance, which was consistent on all sites. Radial variance patterns in hardness increased from pith to a maximum in the heartwood/sapwood transition zone, and then decreased in value proceeding to the bark (Figure 86).

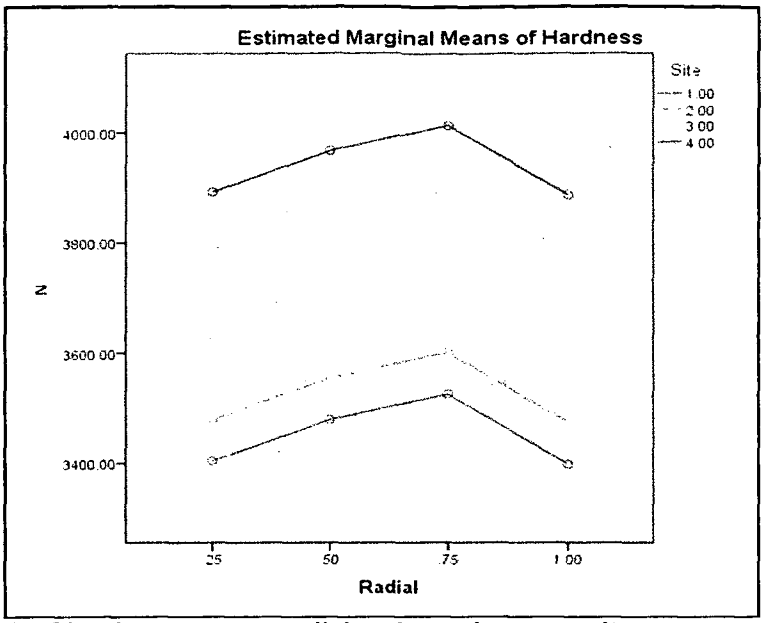


Figure 86. Graph of hardness means radial variance between sites.

Based on the ANOVA results the null hypothesis, no variance in hardness, was rejected at 95% probability. There is significant variance in eastern larch sites, radial and axial position within stems, while interaction effects are insignificant.

A Duncan's post hoc test was performed on the hardness means for sites, and radial and axial positions. For sites, Figure 87 shows that the post hoc test indicated two subsets of similarity:

subset 1; included site 1 the dry fast growing site with eastern larch dominance, and site 2 the poorly drained wet site with Eastern Larch / black spruce,

subset 2; included site 3 the well drained site with high competition from mixed species, and site 4 the very wet site with black spruce dominance.

These findings were supported by Hillman and Roberts (2006), who reported that eastern larch is a species that likes moist and drained sites. While OMNR (1997) report eastern larch had low to moderate tolerance of drought and flooding (Burns and Honkala, 1990a). Extreme changes in moisture seem to reduce the mechanical properties of eastern larch grown in the TBD.

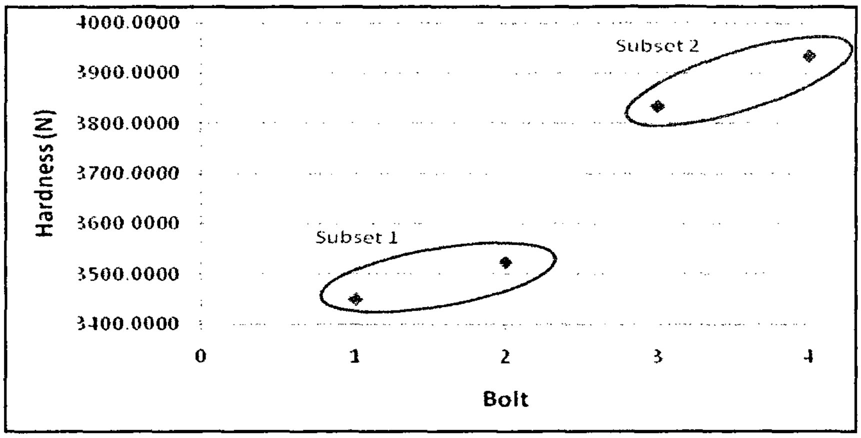


Figure 87. Graph of Duncan's post hoc test subsets for site hardness means.

As Figure 88 shows, the Duncan's post hoc test of hardness means indicated two axial subsets of similarity for axial position:

subset 1; included bolts 1, 2, and 10; highest percentage of reaction wood, and

subset 2; included bolt 3 to bolt 9, juvenile/mature wood mix.

As was found with the other mechanical properties, these findings suggested that eastern larch trees response to competition were uniform among sites once seedlings were established, and free to grow over competition.

A Duncan's post hoc test identified two subsets of similarity for hardness means' radial position (Figure 89):

subset 1; included the juvenile core and zone of sapwood and cambial activity,

subset 2; included outer heartwood and outer sapwood zone.

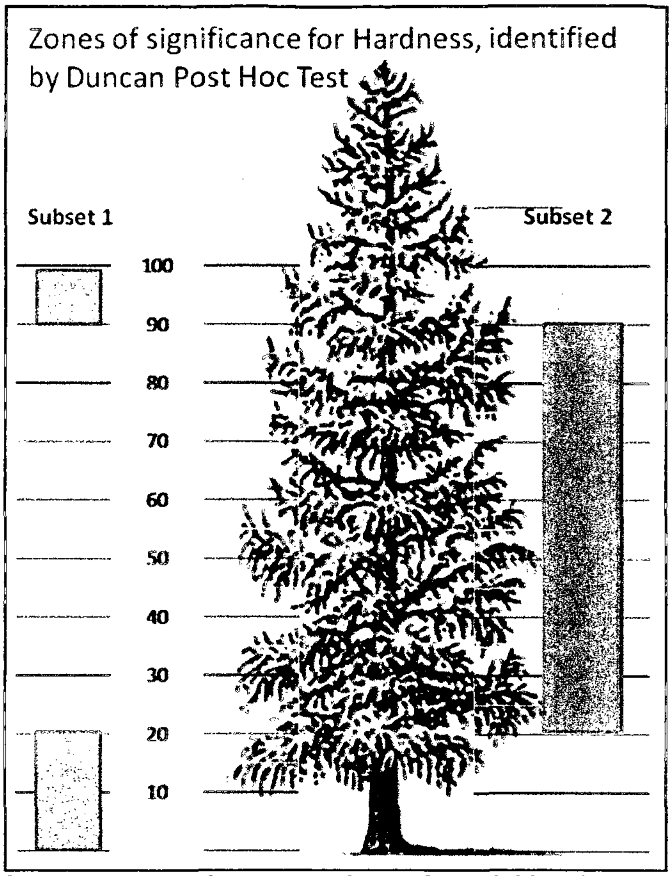


Figure 88. Graph of Duncan's post hoc test subsets for axial hardness means.

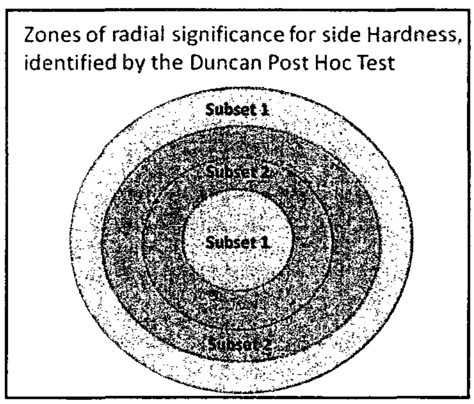


Figure 89. Graph of Duncan's post hoc test subsets for radial hardness means

4.2.7 Variance in juvenile wood

Specimens for the juvenile core wood properties study were obtained from two sources for each site:

- juvenile core of the two mature trees (over 30 years of age), and
- one juvenile tree (under 30 years of age).

The factors studied were the relative density$_{OD}$, MOE, and hardness of the juvenile core, using three trees from 4 sites at 10 axial positions; 10% to 100%.

4.2.7.1 Juvenile core relative density$_{OD}$

Juvenile core relative density$_{OD}$ data was analyzed using SPSS 18 software, the ANOVA results (Table 29) indicated that juvenile core relative density$_{OD}$ of eastern larch varied between 408 and 637 kg/m^3, with a grand mean in the TBD of 541 kg/m^3; (Figure 90). The ANOVA showed a significant variance existed between juvenile core relative density$_{OD}$ means for sites, no significance in axial position or interactions between factors at 95% probability were found.

Table 29. ANOVA results for juvenile core relative density$_{OD}$.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	45888.550[a]	12	3824.046	1.860	.056
Intercept	2.337E7	1	2.337E7	11366.109	.000
Site	22913.000	3	7637.667	3.715	.016
Bolt	22975.550	9	2552.839	1.242	.285
Error	137741.250	67	2055.840		
Total	2.355E7	80			
Corrected Total	183629.800	79			

a. R Squared = .250 (Adjusted R Squared = .116)

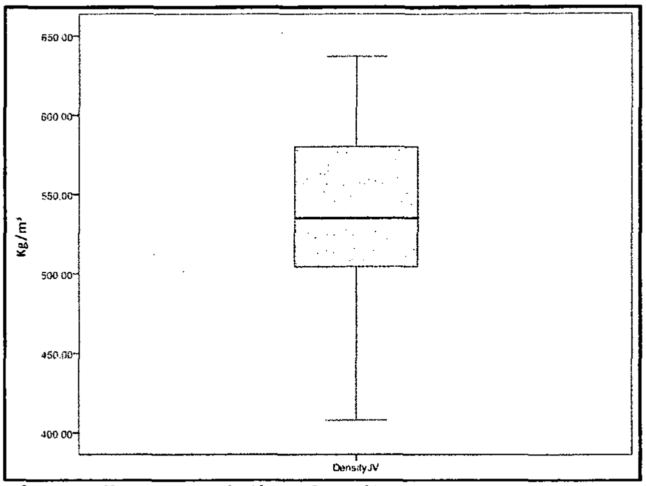


Figure 90. Box plot of juvenile core relative density$_{OD}$ means.

Figure 91 shows that site 4, the very wet site, had the highest average juvenile core relative density$_{OD}$ at 569 kg/m^3, and with moderate variance between means. Site 3, the well drained site, exhibited the highest variance between means, and the average juvenile core relative density$_{OD}$ was the lowest at 526 kg/m^3. Site 2, the poorly drained wet site, had high variability in juvenile core relative density$_{OD}$, with an average value of 533 kg/m^3. Finally, site 1, the dry site, had moderate variance with an average juvenile core relative density$_{OD}$ of 534 kg/m^3, which was closest to the grand mean.

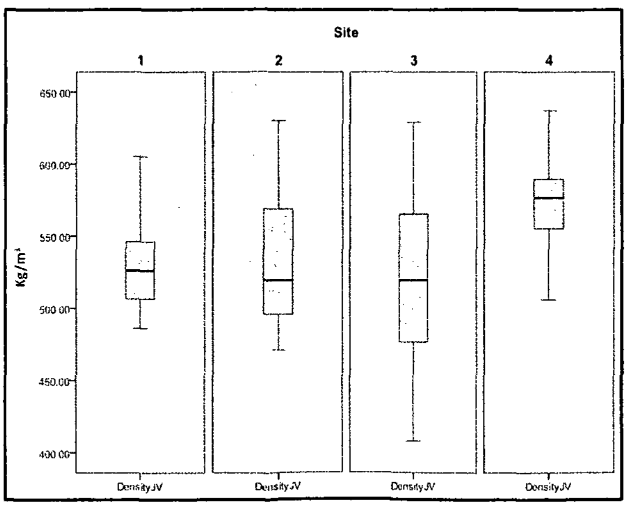


Figure 91. Box plot comparison of site juvenile core relative density$_{OD}$ means for eastern larch tree grown in the TBD.

Based on the ANOVA results the null hypothesis, no variance in relative density$_{OD}$ within the juvenile core, was rejected at 95% probability. There is significant variance in eastern larch between sites, while axial position and interaction affects are insignificant.

A Duncan's post hoc test was performed on the juvenile core relative density$_{OD}$ means for sites. For sites, Figure 92 shows that the post hoc test indicated two subsets of similarity:

subset 1; included site 1 the dry fast growing site with eastern larch dominance, site 2 the poorly drained wet site with eastern larch / black spruce, site 3 the well drained site with high competition from mixed species,

subset 2; included site 4 the very wet site with black spruce dominance.

These findings suggested that site environmental factors, primarily wind and snow load, affect wood density within the TBD. Site 4 was more susceptible to wind exposure and heavy snow load than the other three sites.

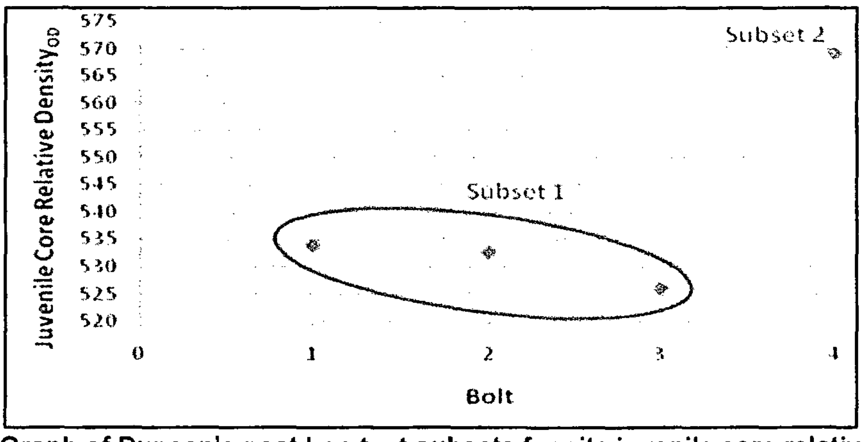


Figure 92. Graph of Duncan's post hoc test subsets for site juvenile core relative density$_{OD}$ means.

Patterns in axial variance of juvenile core relative density$_{OD}$ means, although not significant, are interesting. Axial variance was consistent between sites, however, within trees variance patterns decreased from the base proceeding up the tree to a minimum at mid stem, between bolts 4 to 5, then increased with axial position to the crown (Figure 93).

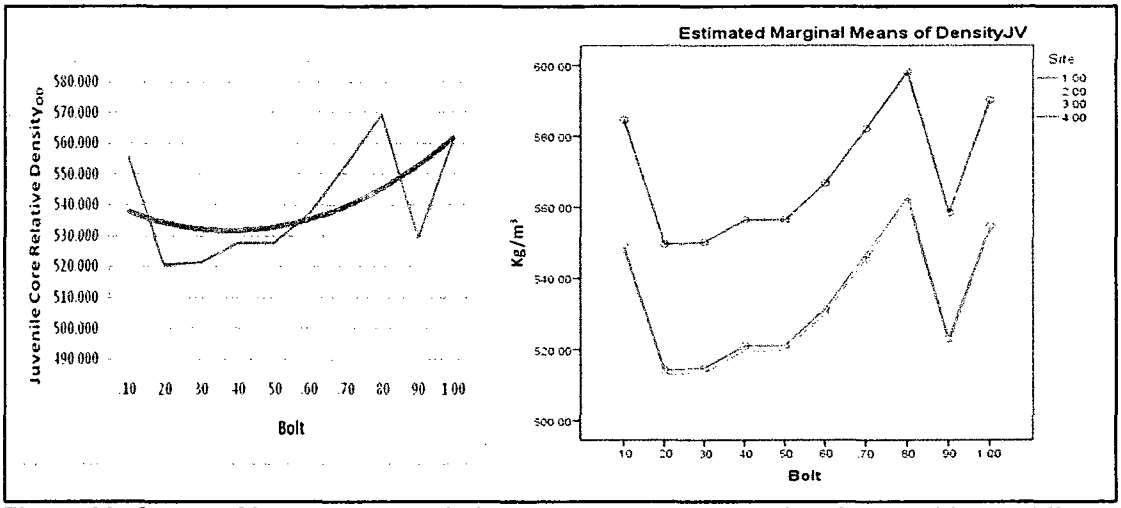


Figure 93. Graph of juvenile core relative density$_{OD}$ means axial variance with trend line.

4.2.7.2 Juvenile core MOE perpendicular to grain

Juvenile core MOE data was analyzed using SPSS 18 software, the ANOVA results (Table 30) indicated that juvenile core MOE of eastern larch varied between 5,130 and 10,950 MPa, with a grand mean in the TBD of 8,091 MPa (Figure 94). The ANOVA showed a significant variance existed between juvenile core MOE means for only sites, no significance in axial position or interactions between factors at 95% probability was found.

Table 30. ANOVA results for MOE juvenile core.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	4.216E7	12	3513328.429	1.887	.052
Intercept	5.237E9	1	5.237E9	2813.250	.000
Bolt	4531889.512	9	503543.279	.270	.981
Site	3.763E7	3	1.254E7	6.738	.000
Error	1.247E8	67	1861615.877		
Total	5.404E9	80			
Corrected Total	1.669E8	79			

a. R Squared = .253 (Adjusted R Squared = .119)

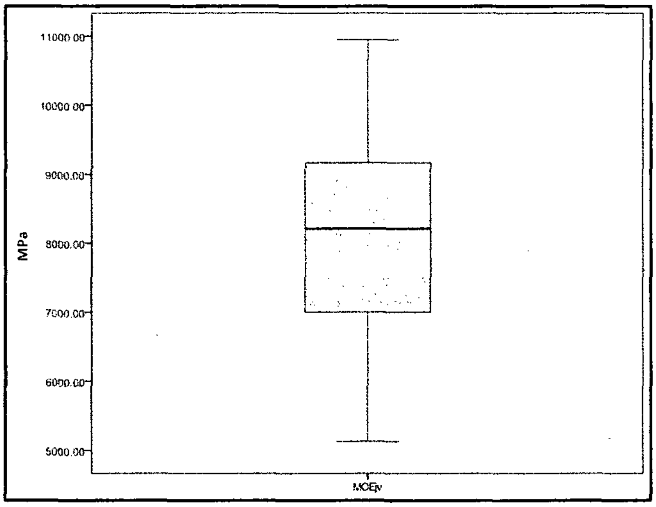


Figure 94. Box plot of juvenile core MOE means.

Figure 95 shows that site 4, the very wet site, had the highest average juvenile core MOE at 8,736 MPa and with high variance between means. Site 1, the dry site, exhibited the moderate variance between means, and average juvenile core MOE was the lowest at 6,954 MPa. Site 2, the poorly drained wet site, had the lowest variance in MOE juvenile core, with an average value of 8,179 MPa, which was closest to the grand mean. Finally, site 3, the well drained site, had the highest variance with an average juvenile core MOE of 8,496 MPa.

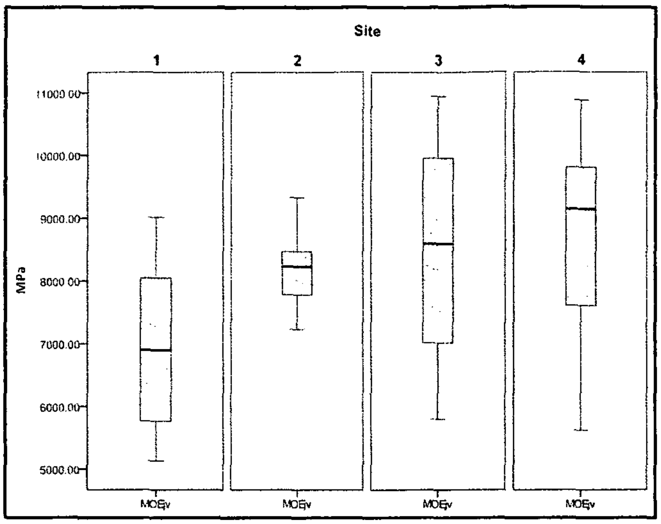


Figure 95. Box plot comparison of site juvenile core MOE means.

Based on the ANOVA results, the null hypothesis, no variance in MOE within the juvenile core, was rejected at 95% probability. There is significant variance in eastern larch between sites, while axial position and interaction affects are insignificant.

A Duncan's post hoc test was performed on the juvenile core MOE means for sites. For sites, Figure 96 shows that the post hoc test indicated two subsets of similarity:

subset 1; included site 1 the dry fast growing site with eastern larch dominance,

subset 2; included site 2 the poorly drained wet site with eastern larch / black spruce, site 3 the well drained site with high competition from mixed species, and site 4 the very wet site with black spruce dominance.

These findings suggested that increased tree growth decreased juvenile core MOE within the TBD.

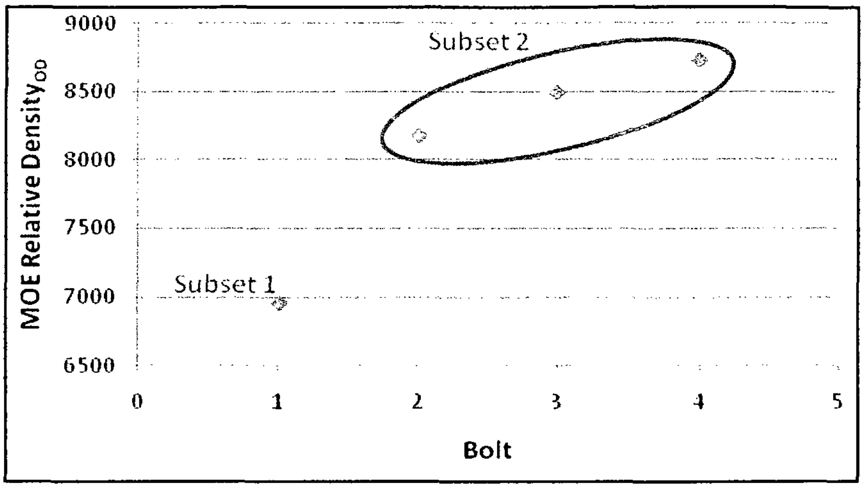


Figure 96. Graph of Duncan's post hoc test subsets for site juvenile core MOE means.

Patterns in axial variance of juvenile core MOE means, although not significant, are interesting. Axial variance was consistent between sites, however, within trees variance patterns increased from the base proceeding up the tree to a maximum at mid stem, between bolts 4 to 5, then decreased with axial position to the crown (Figure 97).

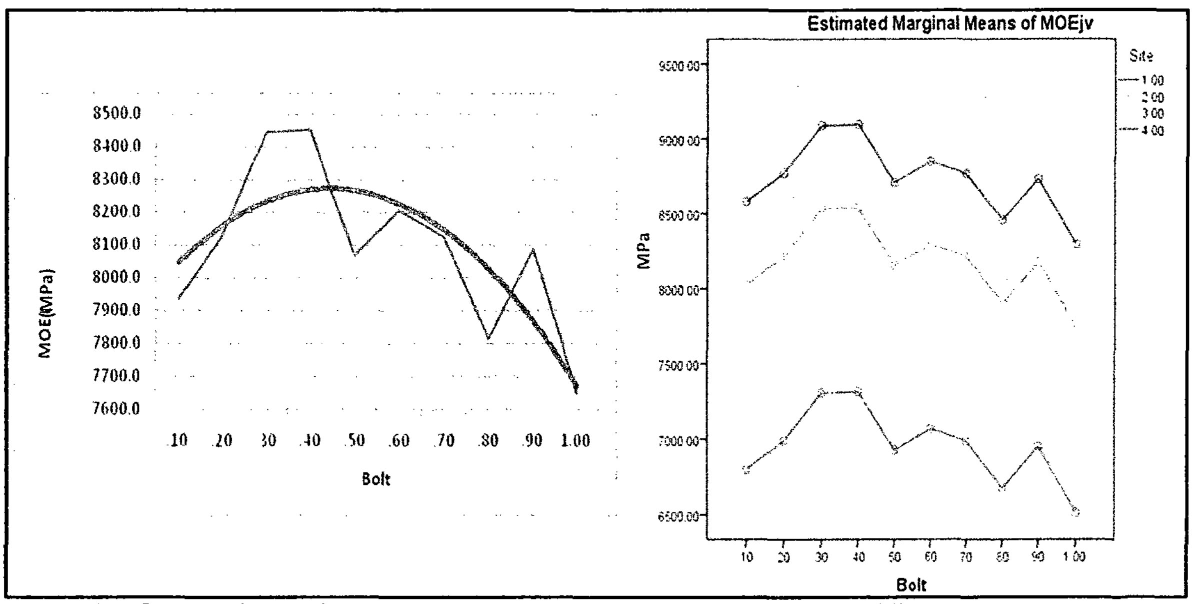


Figure 97. Graph of juvenile core MOE means axial variance with trend line.

3.2.7.3 Juvenile core hardness

Juvenile core hardness data was analyzed using SPSS 18 software, the ANOVA results (Table 31) indicated that juvenile core hardness of eastern larch varied between 2,845 and 4,497 N, with a grand mean in the TBD of 3,617 N (Figure 98). The ANOVA showed a significant variance existed between juvenile core hardness means for sites, no significance in axial position or interactions between factors at 95% probability was found.

Table 31. ANOVA results for juvenile core hardness.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	4.016E6	12	334680.508	3.095	.002
Intercept	1.046E9	1	1.046E9	9674.663	.000
Bolt	1304948.863	9	144994.318	1.341	.233
Site	2711217.238	3	903739.079	8.356	.000
Error	7246075.888	67	108150.386		
Total	1.058E9	80			
Corrected Total	1.126E7	79			

a. R Squared = .357 (Adjusted R Squared = .241)

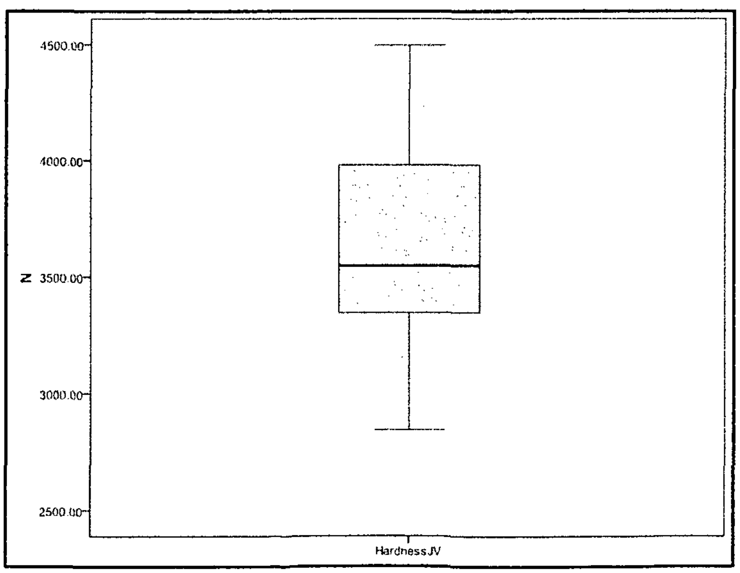


Figure 98. Box plot of juvenile core hardness means.

Figure 99 shows that site 4, the very wet site, had the highest average juvenile core hardness at 3,869 N and with medium variance among means. Site 1, the dry site, exhibited the lowest variance between means, and average juvenile core hardness was the lowest at 3,418 N. Site 2, the poorly drained wet site, had the high variance in MOE juvenile core, with an average value of 3,465 N. Finally, site 3, the well drained site, had the high variance with an average juvenile core hardness of 3,714 N, which was closest to the grand mean.

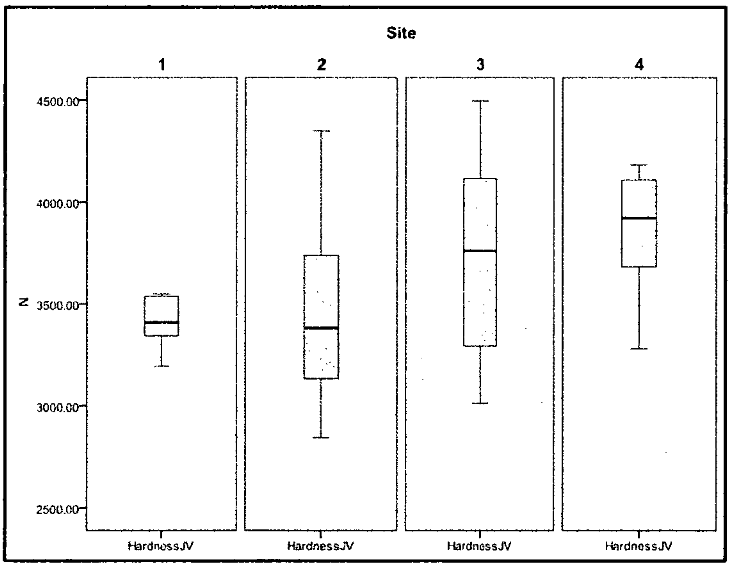


Figure 99. Box plot comparison of site juvenile core hardness means.

Based on the ANOVA results, the null hypothesis, no variance in hardness within the juvenile core, was rejected at 95% probability. There is significant variance in eastern larch between sites, while axial position and interaction affects are insignificant.

A Duncan's post hoc test was performed on the juvenile core hardness means for sites. For sites, Figure 100 shows that the post hoc test indicated two subsets of similarity:

subset 1; included site 1 the dry fast growing site with eastern larch dominance, and site 2 the poorly drained wet site with eastern larch / black spruce,

subset 2; included site 3 the well drained site with high competition from mixed species, and site 4 the very wet site with black spruce dominance.

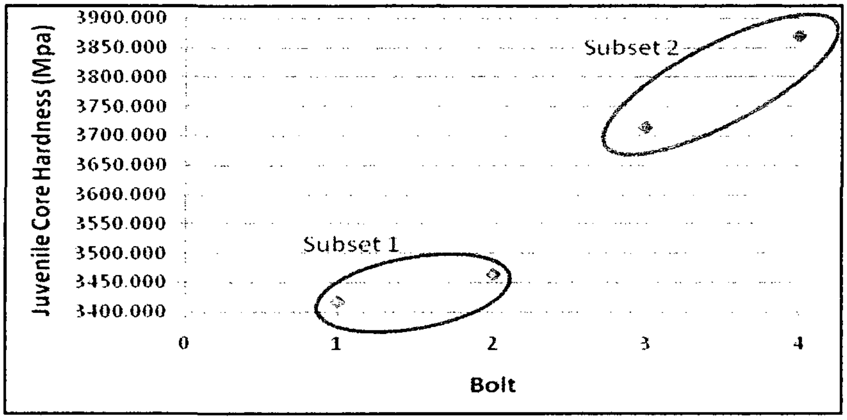


Figure 100. Graph of Duncan's post hoc test subsets for site juvenile core hardness means.

Patterns in axial variance of juvenile core hardness means, although not significant, are interesting. Axial variance was consistent between sites, however, within trees variance patterns decreased from the base proceeding up the tree to a minimum at mid stem, between bolts 6 to 7, then increased with axial position to the crown (Figure 101).

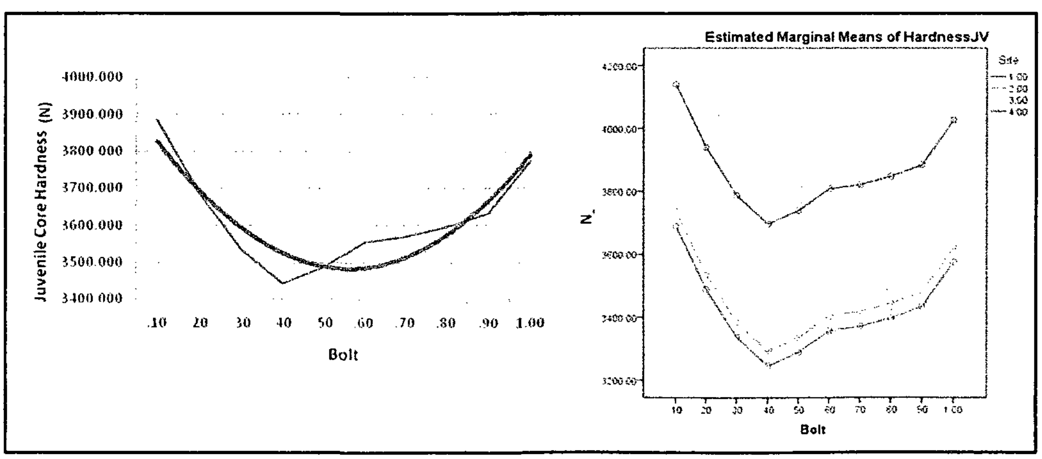


Figure 101. Graph of juvenile core hardness means axial variance with trend line.

4.3 Sampling

As we have discussed, one of the purposes of this section of the thesis was to validate the published physical and mechanical wood properties of northwestern Ontario species, using eastern larch as a case study. We have also identified, that the majority of the research completed on wood properties, primarily wood density, has reported generalized observations based on single height sampling; breast height. Zobel and van Buijtenen (1989) reported that breast height sampling produced statistically valid results when a variety sampling procedures were employed, including:

- comparison of mature wood or outerwood samples only,
- comparison of juvenile wood or innerwood samples only,
- comparison of samples from pith to bark, and
- comparison of samples by cambial age.

However, the results discussed in this report have identified eastern larch as being an anomalous species; a softwood species displaying variation patterns in wood characteristics similar to hardwoods. Thus, it would be prudent to validate the sampling procedures used in obtaining the reported values for this species (Shahi, 2008; Zobel and van Buijtenen, 1989).

Validation of sample procedures focused on determining whether breast height and 10 bolt means differ significantly. Thus, a t-test was used in the comparison of the analytical results obtained from breast height and 10 bolt sampling procedures in order to confirm whether both methods provide similar analytical results or not. The outcome of the t-tests is the acceptance or rejection of the null hypothesis (H_0); both methods provide the same analytical results. (Zar, 1984; McClave and Dietrich, 1994; DeVeaux *et al.*, 2008; Shahi, 2009):

4.3.1 Breast height sampling

4.3.1.1 Comparison of breast height relative density$_{OD}$

The comparison of relative density$_{OD}$ means between 10 bolt sampling and breast height sampling were analyzed using SPSS 18 software, the t-test results (Table 32) indicated that the means for the two sampling methods were not significantly different at 99.9% probability. These findings are consistent with Zobel and van Buijtenen (1989), who reported that wood density means using breast height and multiple bolt sampling of softwood trees were not significantly different. However, (Figure 102) variance between means is greater in breast height sampling than 10 bolt sampling, and breast height sampling had a higher grand mean than 10 bolt sampling.

Table 32. T-test results for breast height and 10 bolt sampling comparison of relative density$_{OD}$ means at $p<0.001$.

		T-test for Equality of Means						
		t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference: Lower	95% Confidence Interval of the Difference: Upper
RD	Equal variances assumed	-.730	62	.468	-7.03125	9.62857	-26.27849	12.21599

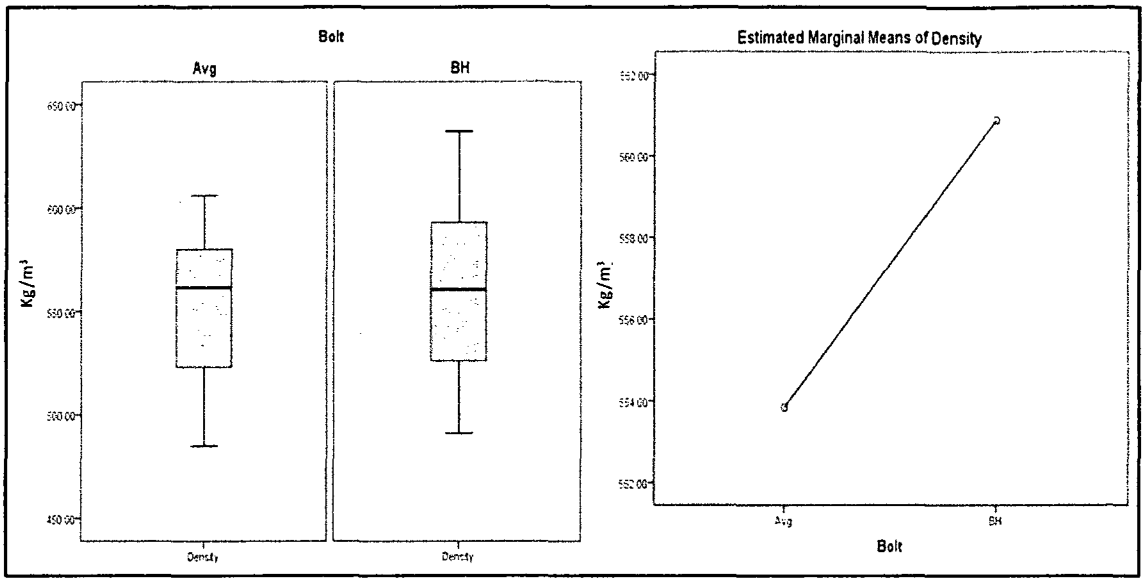


Figure 102. Box plot of breast height and 10 bolt sampling comparison of relative density$_{OD}$ means at p<0.001.

Figure 103 shows that breast height sampling reported higher radial means for relative density$_{OD}$ at varying degrees between sites, and displayed a less abrupt decrease in relative density$_{OD}$ from the outer heartwood zone to the bark. The reduced radial variance pattern displayed by breast height sampling of relative density$_{OD}$ means may explain the conflicting values reported on northwestern Ontario tree species reported across Canada.

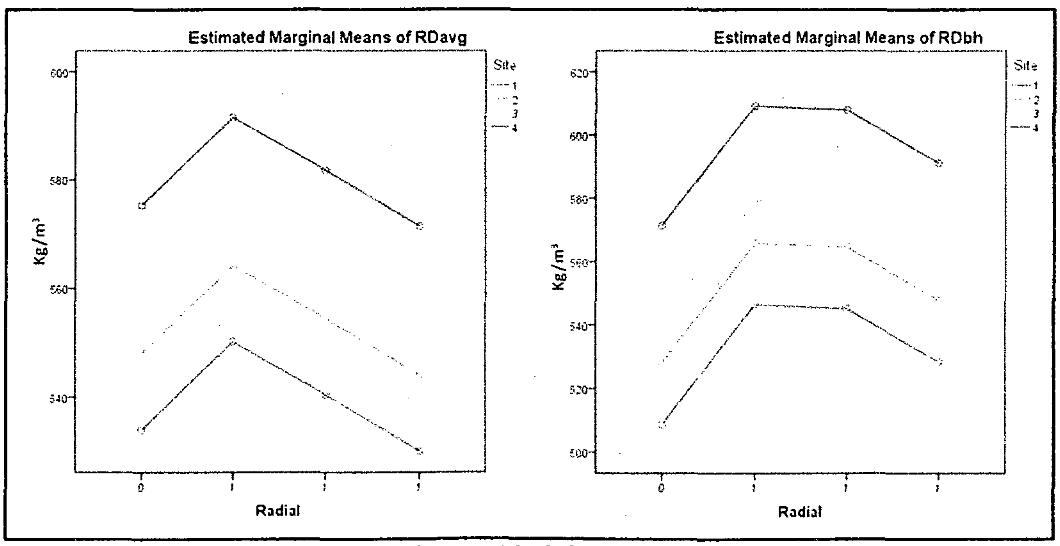


Figure 103. Graphical comparison of breast height and 10 bolt sampling of relative density$_{OD}$ means at p<0.001.

Figure 104 compared the relative density$_{OD}$ grand means reported across Canada by the literature. The percent difference between 10 Bolt and breast height relative density$_{OD}$ grand means for the TBD study was 1%. The percent difference between the TDB 10 bolt means and other breast height studies' grand means ranged between -2% to -9%. Alemdag (1984) attributed these differences to different processing and calculation methods.

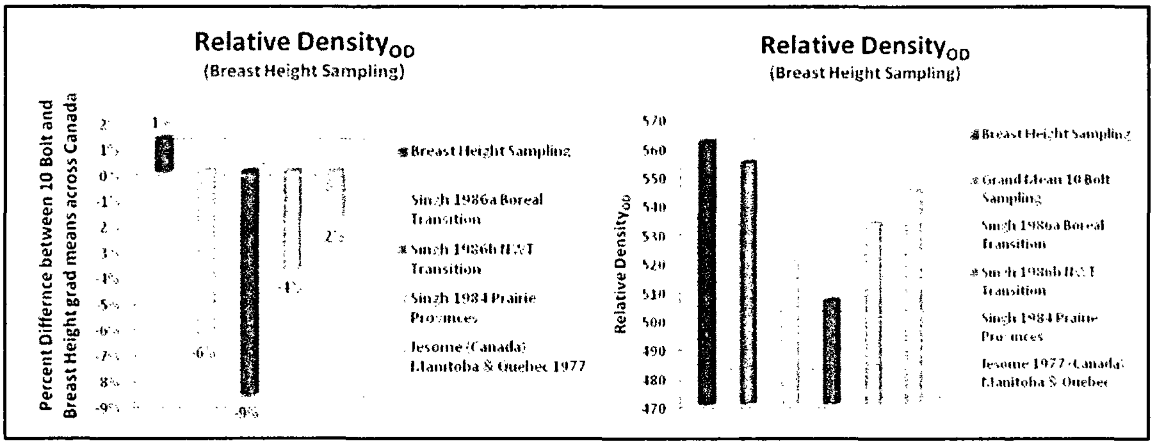


Figure 104. Comparison between 10 bolt sampling to breast height sampling relative density grand means across Canada.

Alemdag (1984) used 4 bolt sampling to determine relative density$_{30\%}$ grand means. Alemdag (1984) reported the same -2% percent difference between his 4 bolt study on wood density of eastern larch and Jessome (2000), as was found with the TDB 10 bolt sampling of wood density and Jessome (2000). Thus, wood density values for northwestern Ontario tree species reported from breast height sampling studies, are merely "fair estimate(s)" (Jessome, 2000) of the species' populations.

Based on the t-test results, the null hypothesis, no difference between the relative density$_{OD}$ results of the two test procedures, was accepted at 99.9% probability.

4.3.1.2 Comparison of breast height MOE

The comparison of MOE means between 10 Bolt sampling and breast height sampling were analyzed using SPSS 18 software, the t-test results (Table 33) indicated that breast height and 10 bolt MOE means were not significantly different at 99.9% probability. Figure 105 shows variance between means is greater in breast height sampling than 10 bolt sampling, and breast height sampling had a higher grand mean than 10 bolt sampling.

Table 33. T-test results for breast height and 10 bolt sampling comparison of MOE means at p<0.001.

		t-test for Equality of Means						
							95% Confidence Interval of the Difference	
		t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
MOE	Equal variances assumed	-1.085	62	.282	-264.125	243.523	-750.921	222.671

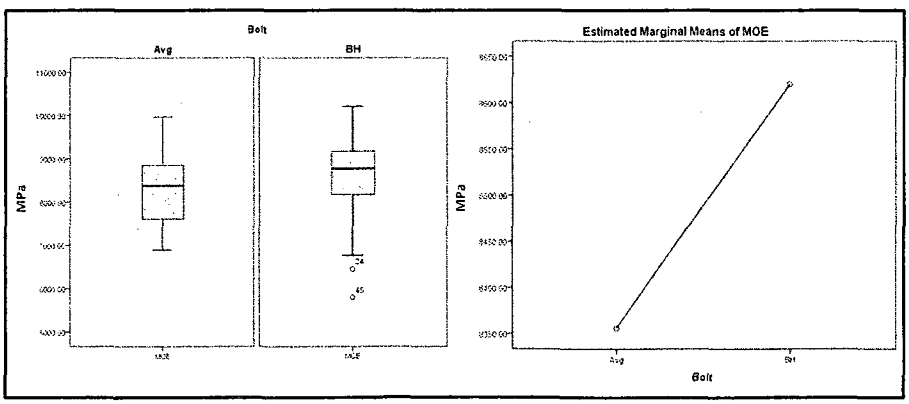


Figure 105. Box plot of breast height and 10 bolt sampling comparison of MOE means at p<0.001.

Figure 106 shows that breast height sampling reported mixed effects on radial means for MOE at varying degrees between sites, displaying greater radial variance generally and a more abrupt decrease in MOE from the inner sapwood zone to the bark. Breast height sampling produced lower MOE site means for sites 2 and 3 and higher MOE site means for bolts 1 and 4. The percent difference between 10 Bolt and breast height MOE grand means for the TDB study was 3%.

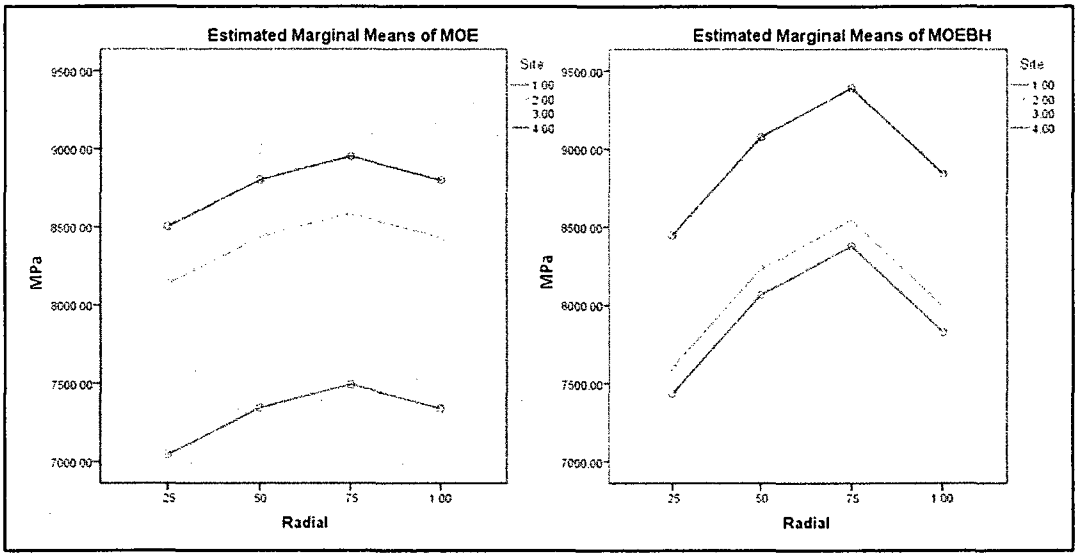


Figure 106. Graphical comparison of breast height and 10 bolt sampling of MOE means at p<0.001.

The comparison between breast height and 10 bolt MOE means of eastern larch supports the earlier findings for wood density, that there is no significant difference between the means of the two sampling methods, however variance patterns are different. Based on the t-test results, the null hypothesis, no difference between the MOE results of the two test procedures, was accepted at 99.9% probability.

4.3.1.3 Comparison of breast height MOR

The comparison of MOR means between 10 Bolt sampling and breast height sampling were analyzed using SPSS 18 software, the t-test results (Table 34) indicated that breast height and 10 bolt MOR site means were not significantly different at 99.9% probability. Figure 107 shows variance between means is greater in breast height sampling than 10 bolt sampling, due to outliers, and breast height sampling reported a higher grand mean than 10 bolt sampling.

Table 34. T-test results for breast height and 10 bolt sampling comparison of MOR means at p<0.001.

		t-test for Equality of Means						
							95% Confidence Interval of the Difference	
		t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
MOR	Equal variances assumed	-1.451	62	.152	-3.43750	2.36977	-8.17460	1.29960

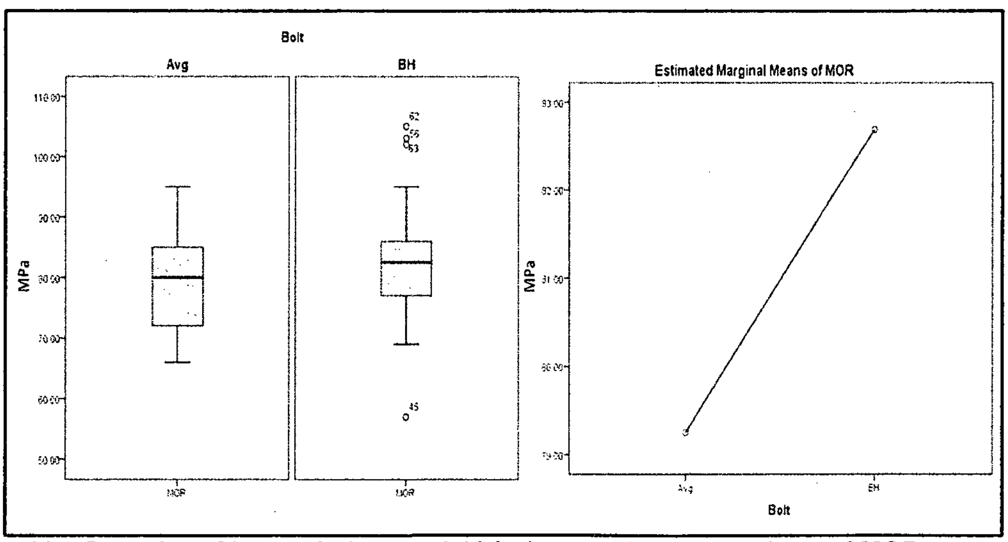


Figure 107. Box plot of breast height and 10 bolt sampling comparison of MOR means at p<0.001.

Figure 108 shows that breast height sampling reported mixed effects on radial means for MOR at varying degrees between sites, displaying greater variance with regard to the degree that MOR increased from the pith to the outer sapwood. Breast height sampling produced higher MOR site means for site 1 and lower MOR site means for bolts 2, 3, and 4. The percent difference between 10 Bolt and breast height MOR grand means for the TDB study was 3%.

The comparison between breast height and 10 bolt MOR means of eastern larch supports the earlier findings for wood density and MOE, that there is no significant difference between the means of the two sampling methods, however variance patterns are different. Based on the t-test results, the null hypothesis, no difference between the MOR results of the two test procedures, was accepted at 99.9% probability.

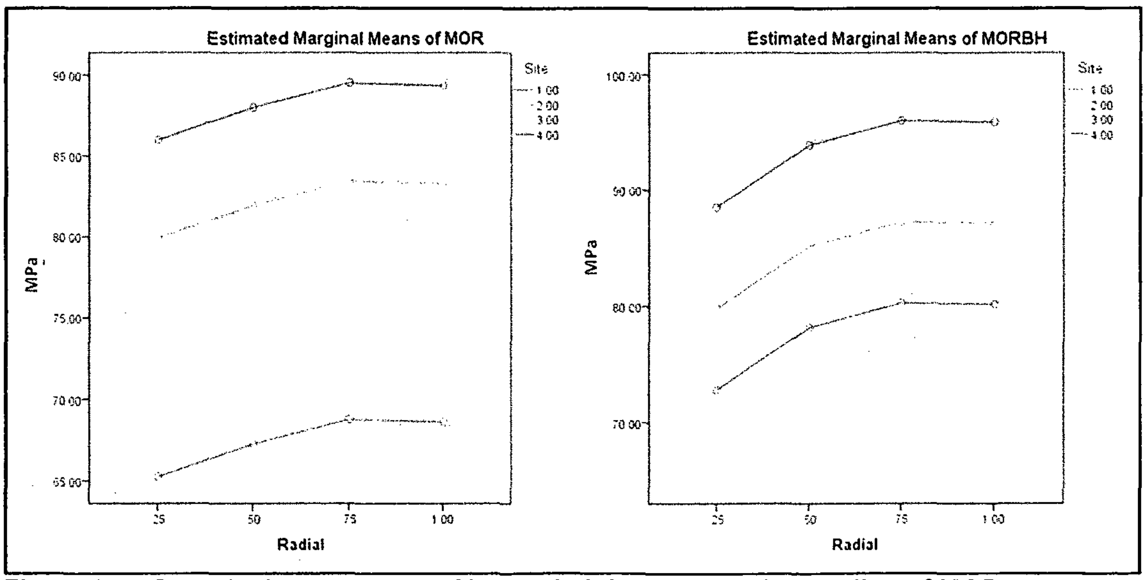


Figure 108. Graphical comparison of breast height and 10 bolt sampling of MOR means at p<0.001.

4.3.1.4 Comparison of breast height compression parallel to grain

The comparison of compression strength means between 10 Bolt sampling and breast height sampling were analyzed using SPSS 18 software, the t-test results (Table 35) indicated that breast height and 10 bolt compression site and radial position means were not significant difference at 99.9% probability. Figure 109 shows variance between means is greater in breast height sampling than 10 bolt sampling, and breast height sampling reported a higher grand mean than 10 bolt sampling.

Table 35. T-test results for breast height and 10 bolt sampling comparison of compression means at $p<0.001$.

		t-test for Equality of Means						
		t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	Upper
Comp	Equal variances assumed	-1.282	46	.206	-1.91667	1.49551	-4.92698	1.09365

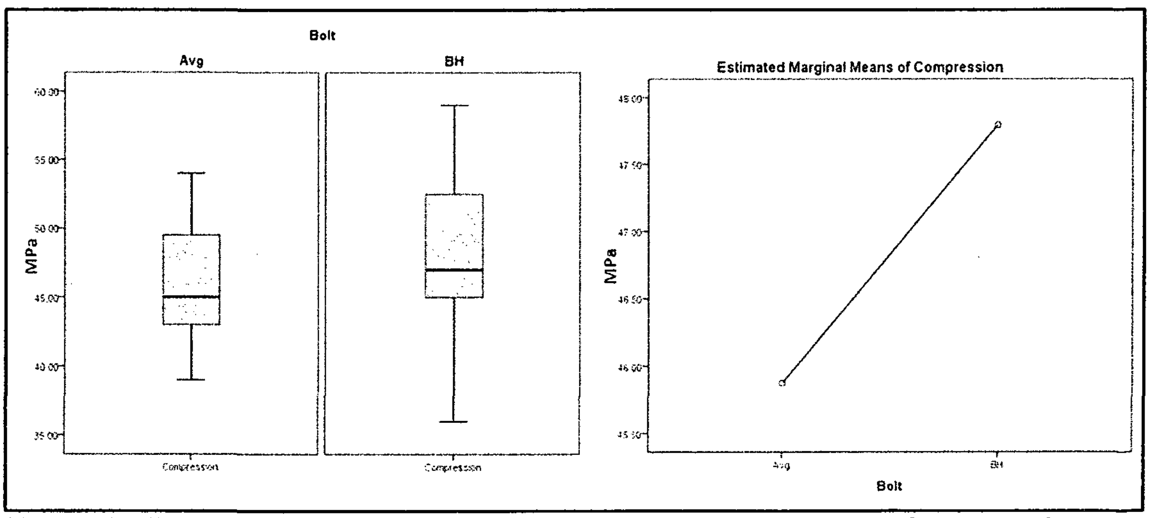


Figure 109. Box plot of breast height and 10 bolt sampling comparison of compression means at $p<0.001$.

Figure 110 shows that breast height sampling reported higher on radial means for compression at varying degrees between sites, displaying greater variance with regards to the degree that compression increased from the pith to a maximum at the outer sapwood and decrease to the bark. Breast height sampling produced higher compression strength site means, with an overall percent difference between 10 Bolt and breast height compression grand means for the TDB study of 4%.

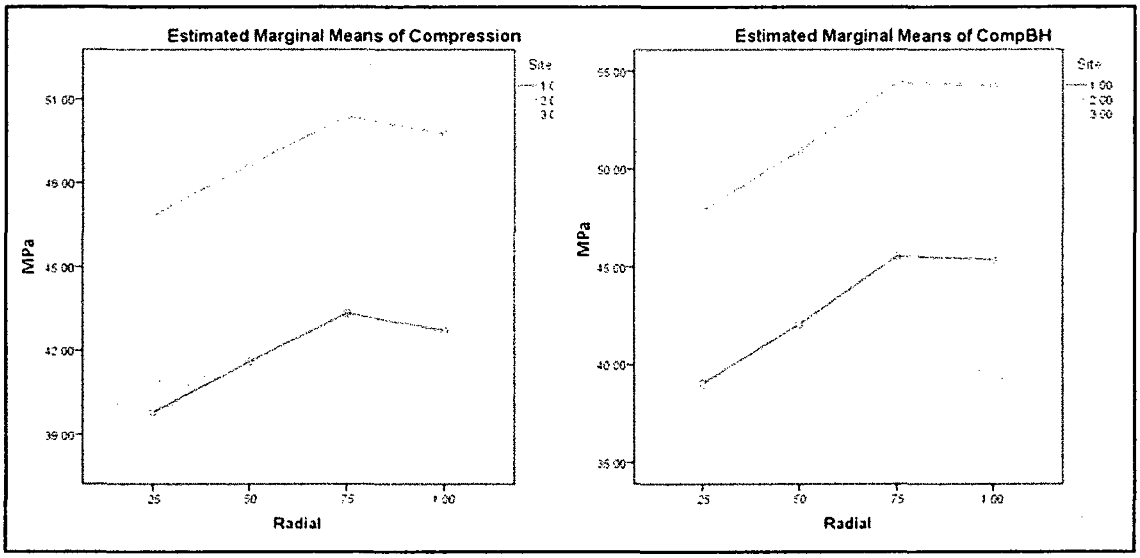


Figure 110. Graphical comparison of breast height and 10 bolt sampling of compression means at p<0.001.

The comparison between breast height and 10 bolt compression strength means of eastern larch supports the earlier findings for wood density, MOE, and MOR, that there is no significant difference between the means of the two sampling methods, however variance patterns are different. Based on the t-test results, the null hypothesis, no difference between the compression results of the two test procedures, was accepted at 99.9% probability.

4.3.1.5 Comparison of breast height Janka ball side hardness

The comparison of hardness means between 10 Bolt sampling and breast height sampling were analyzed using SPSS 18 software, the t-test results (Table 36) indicated that breast height and 10 bolt MOR site means were not significantly different at 99.9% probability. Figure 111 shows variance between means is greater in breast height sampling than 10 bolt sampling, and breast height sampling reported a higher grand mean than 10 bolt sampling.

Table 36. T-test results for breast height and 10 bolt sampling comparison of hardness means at p<0.001.

		t-test for Equality of Means						
		t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference Lower	Upper
Hard	Equal variances assumed	-1.828	62	.072	-178.75000	97.80245	-374.25431	16.75431

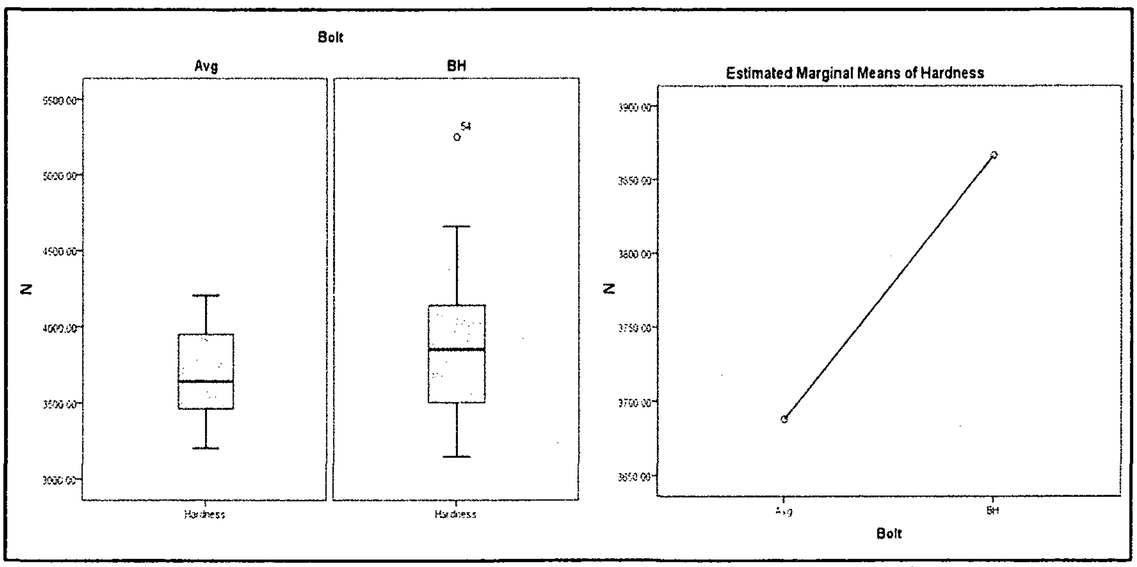


Figure 111. Box plot of breast height and 10 bolt sampling comparison of hardness means at p<0.001.

Figure 112 showed that breast height sampling reported higher radial means for hardness at varying degrees between sites, displaying greater variance with regards to the degree that hardness increased from the pith to the outer heartwood. Breast height sampling produced higher hardness site means, with an overall percent difference between 10 bolt and breast height hardness grand means of 5%.

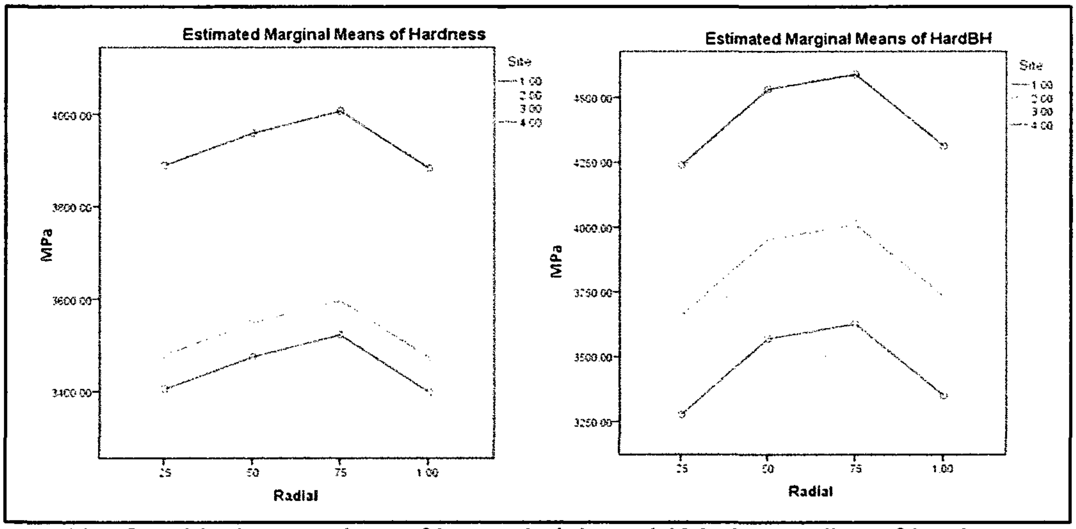


Figure 112. Graphical comparison of breast height and 10 bolt sampling of hardness means at p<0.001.

The comparison between breast height and 10 bolt hardness means of eastern larch supports the earlier findings for the other wood properties that there is no significant difference between the means of the two sampling methods, however variance patterns are different. Based on the t-test results, the null hypothesis, no difference between the hardness results of the two test procedures, was accepted at 99.9% probability.

4.3.2 Standards sampling compared to quadrant sampling

Relative density$_{OD}$ and MOE perpendicular to the grain were considered with respect to sampling methods. The data for these selected wood properties were analysized based on ASTM standard sampling procedures and 100% quadrant sampling. A t-test comparison between the means of ASTM standards sampling and 100% quadrant sampling was then completed.

4.3.2.1 Comparison of quadrant testing relative density$_{OD}$

The t-test comparison between quadrant and standards sampling relative density$_{OD}$ means were analyzed using SPSS 18 software. The t-test results (Table 37) indicated that differences between standards and quadrant sampling relative density$_{OD}$ means were not significant at 99.9% probability. The standards sampling grand mean for relative density$_{OD}$ was 553.7 and 553.4 for quadrant sampling.

Table 37. T-test results for standard testing and quadrant testing comparison of relative density$_{OD}$ means at $p<0.001$.

		t-test for Equality of Means						
							95% Confidence Interval of the Difference	
		t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
RD	Equal variances assumed	.048	158	.962	.28750	6.01133	-11.58543	12.16043

Figure 113 shows variance between grand means was minimal; quadrant sampling means ranged from 479 to 658 kg/m^3, while standards sampling means ranged from 491 to 658 kg/m^3; standard deviations were 37 and 38 respectively.

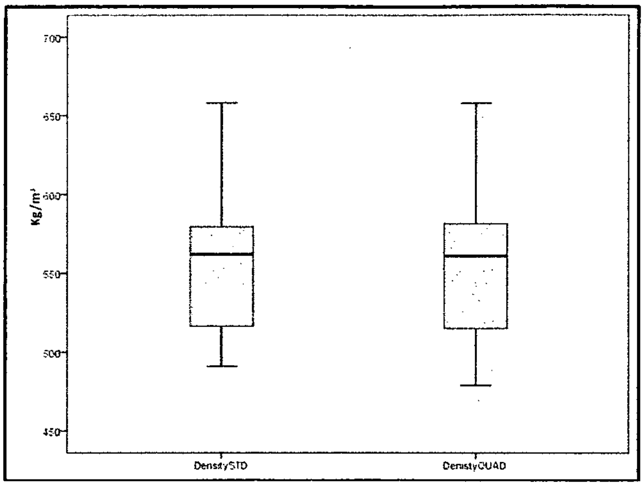


Figure 113. Box plot of standard and quadrant testing comparison of relative density$_{OD}$ means at p<0.001.

Figure 114 shows that there was minimal variance between the relative density$_{OD}$ site means for the two sampling procedures. Standards and quadrant sampling procedures produced equal relative density$_{OD}$ site grand means for sites 2, 3 and 4. For site 1, quadrant sampling relative density$_{OD}$ grand mean was 538.6 kg/m^3 compared to 537.5 kg/m^3 for standards sampling; a difference of 0.2%.

Based on the t-test results, the null hypothesis, no difference between the relative density$_{OD}$ means of the two sampling procedures, was accepted at 99.9% probability. These findings supported LUWSTF's hypothesis, that quadrant sampling improved specimen viability without degrading wood properties test results.

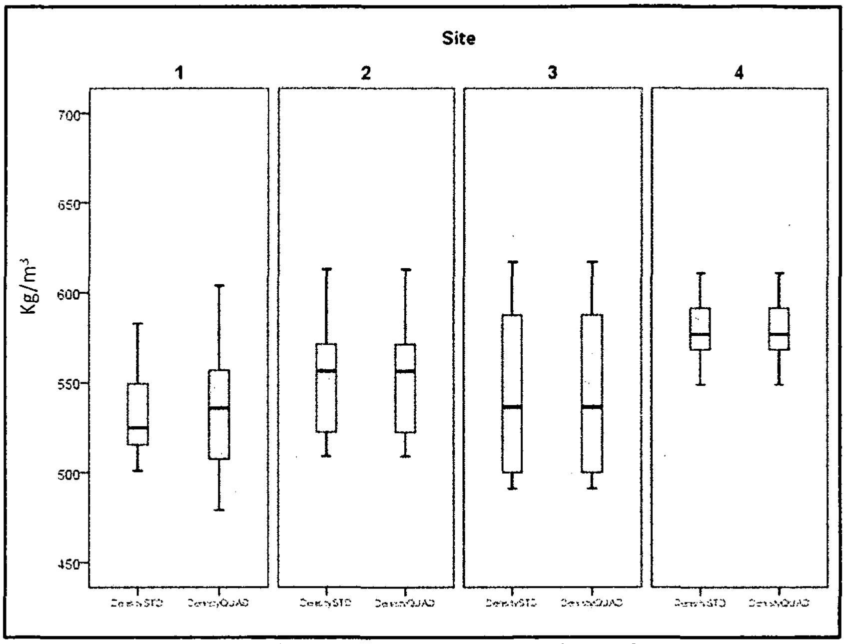


Figure 114. Box plot comparison between standards and quadrant testing relative density$_{OD}$ site means at p<0.001.

4.3.2.2 Comparison of quadrant testing MOE

A t-test comparison of MOE means between quadrant and standards sampling was completed using SPSS 18 software. The t-test results (Table 38) indicated that the difference between standards and quadrant sampling MOE means was not significant at 99.9% probability. The standards sampling grand mean for MOE was 8,356 MPa and 8,353 MPa for quadrant sampling.

Table 38. T-test results for standard and quadrant sampling of MOE means at p<0.001.

		t-test for Equality of Means						
							95% Confidence Interval of the Difference	
		t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
MOE	Equal variances assumed	-.015	158	.988	-2.85000	189.48360	-377.09757	371.39757

Figure 115 shows variance between MOE grand means was moderate; quadrant sampling means ranged from 5,660 to 11,090 MPa, while standards sampling means ranged from 5,618 to 10,947 MPa; standard deviations were 1210.2 and 1186.5 respectively.

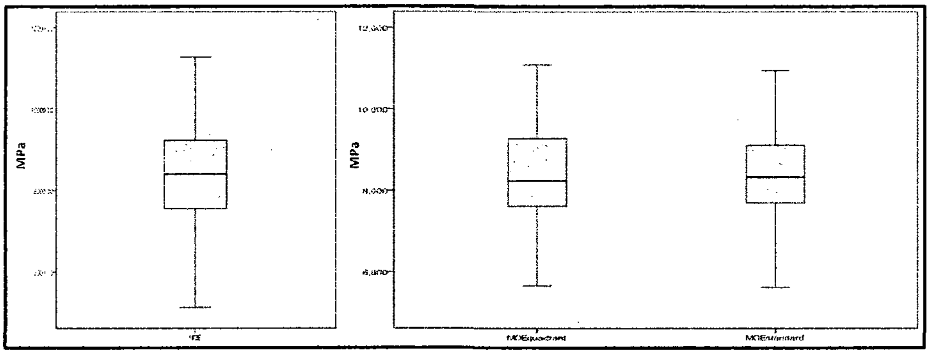


Figure 115. Box plot of breast height and quadrant testing comparison of MOE means at p<0.001.

Figure 116 shows that the difference between the MOE site means of the two sample methods was consistent, with quadrant sampling having 1% higher variance within site means than the standards sampling method.

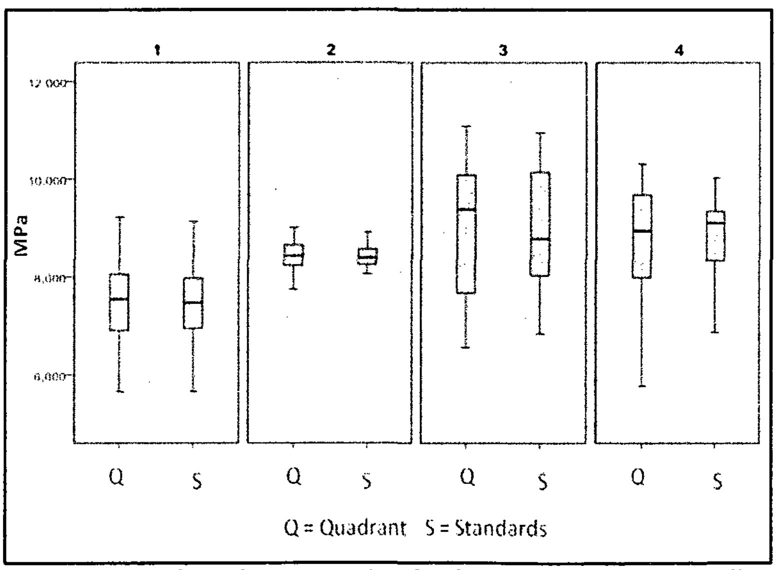


Figure 116. Box plot comparison between standards and quadrant sampling MOE site means at p<0.001.

Based on the t-test results, the null hypothesis, no difference between the MOE results of the two test procedures, was accepted at 99.9% probability. These findings support LUWSTF's hypothesis, that quadrant testing improves bolt specimen viability without degrading wood properties test results.

4.4 Identifying a predictor of wood quality

Understanding the interrelationships or correlations between wood characteristics is important for a number of reasons. With respect to wood morphology, understanding how changes in wood growth affect wood quality is important to identify. This thesis has identified that accelerated wood growth generally results is lower wood density in softwoods as observed by others (Zobel, 1984; Kellogg, 1989; Zobel and van Buijtenen, 1989; Kliger *et al.*, 1994; Zhang, 1995; Zhang, 2003; Rowell, 2005). Further, it was identified that the age of eastern larch is related to a decrease in physical and mechanical properties (Beaudoin *et al.*, 1989; Zhang and Koubaa, 2008). We have also found that there is minimal variance in wood properties within the juvenile core between young and mature eastern larch trees. These are examples of interrelationships, which can affect the quality of wood at harvest and can be used as predictors of wood quality at different rotation ages.

To assess the level of correlation between variables the correlation coefficient squared (squared correlation) or coefficient of determination, R^2 was used. The R^2 value tells us the level of variance which is accounted for by the data, because it is a fraction of the variance in the dependent variable that is accounted for by the independent variable. R^2 values are always between 0 and 1, thus are commonly reported as a percentage. The simplest way to understand R^2 is that a value of 1 means all of the variance in the dependant variable is accounted for by the independent variable and is said to be a perfect fit. An R^2 value of 0 means that none of the variance in the dependant variable is accounted for by the independent variable (Zar, 1984; DeVeaux *et al.*, 2008; Shahi, 2009; UCLA Academic Technology Services, 2010).

4.4.1 Relative density as a predictor of mechanical properties

Relative density was reported to be correlated or interrelated, in some degree, to most of the mechanical properties of wood (Zobel, 1984; Kellogg, 1989; Zobel and van Buijtenen, 1989; Kliger *et al.*, 1994; Zhang, 2003; Rowell, 2005). In softwoods correlations between relative density, MOE / MOR perpendicular to the grain, and compression parallel to the grain are generally linear (Zobel and van Buijtenen, 1989; Stiemer, 2010; Wiemann and Williamson, 2010). Further, it is generally accepted that correlation between wood density and mechanical properties of juvenile wood in softwoods was weak, while mature wood had a strong correlation (Wangaard, 1981; Zobel, 1984; Kellison *et al.*, 1984; Kellogg, 1989; Kliger *et al.*, 1994; Forest Products Laboratory, 1999; Zhang, 2003; Rowell, 2005). While Zhang (1994) reported that mechanical properties of both hardwoods and softwoods are generally more influenced by changes in growth rate than specific gravity (relative $density_{OD}$).

The literature seems to be contradictory on the relationship between wood density and mechanical properties. Predicting mechanical properties from relative density values seems to require a species specific approach (Zobel and van Buijtenen, 1989; Zhang, 1995). Our findings indicate that eastern larch variance patterns in mechanical properties are similar to that of hardwoods. Thus, the linear trend in relative density correlation to mechanical properties generally expected in softwoods may not exist for eastern larch.

Using SPSS18 software, model summary and parameter estimates with scatter plot graph showing three trend line regression formulae (linear, exponential, and logarithmic), were completed for each of the selected mechanical properties examined in relation to relative $density_{12}$.

4.4.1.1 Relative density of mature wood as a predictor of MOE

Relative $density_{12}$ and MOE had a positive correlation. Table 39 shows that there is significant relationship between the dependant variable (MOE) and the independent variable (relative $density_{12}$) at 99.9% probability.

Table 39. Model summary and parameter estimates for relative $density_{12}$ and MOE at $p<0.001$.

Dependent Variable: MOE perpendicular to grain							
Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Linear	.0700	11.938	1	158	.001	4123.825	8.263
Logarithmic	.0697	11.883	1	158	.001	-18955.180	4379.495
Exponential	.0628	10.632	1	158	.001	5035.048	.001
The independent variable is relative $density_{12}$.							

A comparison between actual and predicted MOE means was analyzed using SPSS 18 software, the t-test results (Table 40) indicated that actual and predicted MOE means were not significantly different at 99.9% probability, and that the two groups had approximately equal variance.

Table 40. T-test comparison between actual and predicted MOE means at $p<0.001$.

		t-test for Equality of Means						
		t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference: Lower	95% Confidence Interval of the Difference: Upper
MOE	Equal variances assumed	.003	318	.998	.29375	105.42908	-207.13291	207.72041

4.4.1.2 Relative density of mature wood as a predictor of MOR

Relative $density_{12}$ and MOR had a positive correlation. Table 41 shows that there is a significant relationship between the dependant variable (MOR) and the independent variable (relative $density_{12}$) at 99.9% probability.

Table 41. Model summary and parameter estimates for relative $density_{12}$ and MOR at $p<0.001$.

Dependent Variable: MOR perpendicular to grain							
Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Linear	.130	23.548	1	158	.000	29.085	.098
Logarithmic	.132	24.023	1	158	.000	-247.620	52.401
Exponential	.123	22.184	1	158	.000	41.379	.001
The independent variable is relative $density_{12}$.							

A comparison between actual and predicted MOR means was analyzed using SPSS 18 software, the t-test results (Table 42) indicated that actual and predicted MOR means were not significantly different at 99.9% probability, and that the two groups had approximately equal variance.

Table 42. **T-test Table comparison between actual and predicted MOR values at p<0.001.**

		t-test for Equality of Means						
							95% Confidence Interval of the Difference	
		t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
MOR	Equal variances assumed	-.165	318	.869	-.15625	.94485	-2.01519	1.70269

4.4.1.3 Relative density of mature wood as a predictor of compression

Relative density$_{12}$ and compression parallel to grain had a positive correlation. Table 43 shows that there is a significant relationship between the dependant variable (compression) and the independent variable (relative density$_{12}$) at 99.9% probability.

Table 43. **Model summary and parameter estimates for relative density$_{12}$ and compression at p<0.001.**

Dependent Variable: compression parallel to grain							
Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Linear	.214	32.182	1	118	.000	17.045	.058
Logarithmic	.224	34.008	1	118	.000	-148.398	31.279
Exponential	.212	31.819	1	118	.000	24.689	.001
The independent variable is relative density$_{12}$.							

A comparison between actual and predicted compression means was analyzed using SPSS 18 software, the t-test results (Table 44) indicated that actual and predicted compression means were not significantly different at 99.9% probability, and predicted MOR means were not significantly different at 99.9% probability, and that the two groups had approximately equal variance.

Table 44. **T-test comparison between actual and predicted compression values at p<0.001.**

		t-test for Equality of Means						
		t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference	
							Lower	Upper
Compression	Equal variances assumed	-.172	238	.863	-.09167	.53251	-1.14070	.95736

4.4.1.4 Relative density of mature wood as a predictor of hardness

Relative $density_{12}$ and Janka ball side hardness had a positive correlation. Table 45 shows that there is a significant relationship between the dependant variable (hardness) and the independent variable (relative $density_{12}$) at 99.9% probability.

Table 45. **Model summary and parameter estimates for relative $density_{12}$ and hardness at p<0.001.**

Dependent Variable: Janka ball side hardness							
Equation	Model Summary					Parameter Estimates	
	R Square	F	df1	df2	Sig.	Constant	b1
Linear	.188	36.479	1	158	.000	1391.011	4.385
Logarithmic	.186	35.985	1	158	.000	-10807.568	2316.298
Exponential	.189	36.802	1	158	.000	1984.507	.001
The independent variable is relative $density_{12}$.							

A comparison between actual and predicted hardness means was analyzed using SPSS 18 software, the t-test results (Table 46) indicated that actual and predicted hardness means were not significantly different at 99.9% probability, and that the two groups had approximately equal variance.

Table 46. **T-test comparison between actual and predicted hardness values at $p<0.001$.**

		t-test for Equality of Means						
							95% Confidence Interval of the Difference	
		t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Hardness	Equal variances assumed	.005	318	.996	.19375	36.06841	-70.76912	71.15662

4.4.1.5 Limitation of Relative density as a predictor of mechanical properties

Eastern larch wood seems to have a positive linear relationship between relative $density_{12}$ and the mechanical properties investigated, however, only 40% of the predicted values were at 99.9% accuracy. The correlation analysis produced similar results for logarithmic and exponential regression models. No prediction models for wood quality or mechanical properties were found for eastern larch. Modeling of eastern larch's resource attributes seems limited to some growth and yield models on mixed forest types which included eastern larch as a minor species component. The Forest Products Laboratory (1999) has developed general exponential models which use relative density to predict mechanical properties of softwoods and hardwoods (Table 47).

Table 47. **Functions relating to selected mechanical properties to specific gravity of clear, straight-grained wood (metric) (Forest Products Laboratory 1999)**

	Specific gravity–strength relationship	
	Wood at 12% moisture content	
Property	Softwoods	Hardwoods
MOR (kPa)	$y = 170{,}700\ x^{1.01}$	$y = 171{,}300\ x^{1.13}$
MOE (MPa)	$y = 20{,}500\ x^{0.84}$	$y = 16{,}500\ x^{0.7}$
Compression parallel (kPa)	$y = 93{,}700\ x^{0.97}$	$y = 76{,}000\ x^{0.89}$
Side hardness (N)	$y = 85{,}900\ x^{1.5}$	$y = 15{,}300\ x^{2.09}$

Using the TBD eastern larch test data, a comparison between the Forest Product Laboratories (1999) mechanical properties prediction models for softwoods (USDA softwoods) and hardwoods (USDA hardwoods), and TBD predictive models was completed for the selected four mechanical properties. Table 48 to Table 51 shows the comparison between predicted grand means for each mechanical property to actual values.

Table 48. Descriptive statistics comparison of three models for actual versus predicted MOE values at p<0.001.

99.9% Confidence Interval				
Dependent Variable MOE	Mean	Std. Error	Lower Bound	Upper Bound
TBD Actual	8471	88.142	8175	8767
TBD Model	8471	25.720	8385	8557
USDA Hardwood Model	10519	43.375	10373	10664
USDA Softwood Model	11948	59.246	11749	12147

Table 49. Descriptive statistics comparison of three models for actual versus predicted MOR values at p<0.001.

99.9% Confidence Interval				
Dependent Variable MOR	Mean	Std. Error	Lower Bound	Upper Bound
TBD actual	81	.603	79	83
TBD model	81	.309	80	82
USDA softwood Model	89	.531	87	91
USDA hardwood Model	83	.550	81	85

Table 50. Descriptive statistics comparison of three models for actual versus predicted compression values at p<0.001.

99.9% Confidence Interval				
Dependent Variable compression	Mean	Std. Error	Lower Bound	Upper Bound
TBD actual	47	.370	46	48
TBD model	47	.228	46	48
USDA softwood Model	42	.285	41	43
USDA hardwood Model	50	.360	48	51

Table 51. Descriptive statistics comparison of three models for actual versus predicted hardness values at p<0.001.

99.9% Confidence Interval				
Dependent variable hardness	Mean	Std. Error	Lower Bound	Upper Bound
TBD actual	3698	26.879	3608	3789
TBD model	3698	13.650	3652	3744
USDA softwood Model	3286	29.386	3187	3384
USDA hardwood Model	4025	50.648	3855	4195

As expected, the TBD model produced the closest predictions to actual values with the lowest standard error. However, the USDA hardwoods model produced superior predictions for the mechanical properties of eastern larch grown in the TBD than the USDA softwoods models.

The USDA hardwoods models for MOR and hardness were within 3 and 9% respectively of actual values, compared to the USDA softwood models predictions for these properties which were 11 and -12% respectively. The USDA hardwoods model for MOE prediction was 24% higher than actual values while the USDA softwoods model prediction was 41% higher than actual eastern larch MOE values. The USDA softwood model for compression was 5% higher than actual values, which was superior to the USDA hardwoods model prediction at 10% of actual values.

The comparison between predictive models supports the earlier observation that variance patterns in the wood properties of eastern larch grown in TBD are similar to that of hardwoods. Further, the model comparisons illustrates that there are limitations to the relationship between relative density and mechanical properties that require site specific investigation. This seems particularly evident for a species like eastern larch with such a large growth range.

To better illustrate the need for site specific investigation of tree species' wood characteristic within northwestern Ontario, a comparison of the 3 predictive models was completed using the national averages for eastern larch wood properties reported by the Forest Products Laboratory (1999) for the United States and Jessome (2000) for Canada. Table 52 compares the grand mean predictions of the models to the reported national averages for eastern larch's mechanical properties using relative $density_{12}$.

Table 52. Comparison of three models for actual versus predicted using three different sources for relative $density_{12}$ and mechanical properties values at $p<0.001$.

Source	Relative $density_{12}$	MOR (Mpa)	MOE (Mpa)	Compression (Mpa)	Hardness (N)
USDA Wood Handbook (Forest Products Laboratory, 1999)	***0.53***	***80.0***	***11300***	***49.4***	***2600***
USDA Softwood Wood Model		89.9	12027	50.6	3314
USDA Hardwood Wood Model		83.6	10580	43.2	4059
TBD Model		81.0	8503	47.8	3715
Canadian Forest Service (Jessome, 2000)	***0.506***	***76.0***	***9380***	***44.8***	***3220***
USDA Softwood Wood Model		85.8	11568	48.4	3092
USDA Hardwood Wood Model		79.3	10242	41.4	3684
TBD Model		78.7	8305	46.4	3610

The TBD model provided the overall best fit between predictive and reported values for eastern larch using both Forest Products Laboratory (1999) and Jessome (2000) relative density averages. The TBD model produced the closest MOR predictions, which were within 1.3% of the Forest Products Laboratory (1999) reported values and within 3.5% of the Jessome (2000) reported values. The TBD model provided the closest predictions to the reported values for MOE using the Jessome (2000) eastern larch averages for

Canada, however, provided the weakest prediction of MOE using the Forest Products Laboratory (1999) data for eastern larch grown in the United States. The TBD model produced the closest compression strength predictions which were within -3.3% of the Forest Products Laboratory (1999) reported values and within 3.6% of the Jessome (2000) reported values. The TBD model for hardness provided a weak prediction for both Forest Products Laboratory (1999) and Jessome (2000) compared to the USDA softwood model. TBD model for hardness predictions were within 42.9% of reported values by Forest Products Laboratory (1999) for the United States and 12.1% of the Jessome (2000) values. You will recall that variation in side hardness between sites was 31% for the study, and the Forest Products Laboratory (1999) reports side hardness can vary as much as 20% within in clearwood test. Thus, hardness is an example of a mechanical property model, which may require local correction when using relative density as the independent variable.

The USDA hardwoods models provided better predictions than the USDA softwood models using the Jessome (2000) data set for eastern larch. However, USDA hardwoods models provided the weakest predictions for the mechanical properties of eastern larch grown in the United States reported by Forest Products Laboratory (1999).

The findings on the performance of the three predictive models using the national averages for eastern larch grown in the United States and Canada indicate that the relationship between relative density and mechanical properties seem generally consistent within a species. However, developing predictive models specific to hardwoods and softwoods may be too generalized to be useful. These findings are consistent with Zhang (1995) who examined the relationships between grouped or categorized tree species, relative density$_{OD}$ and selected mechanical properties; MOE, MOR, and compression. Zhang (1995) reported that relative density$_{OD}$ and mechanical properties vary differently with changes in silvicultural and environmental factors and between the species groups.

The Forest Products Laboratory (1999) reports that after reviewing the variance in mechanical properties from clear specimens testing of over 50 tree species grown in the United States, that the magnitude of variance within the selected wood properties are:

- MOR up to16% variance,
- MOE up to 22% variance,
- compression parallel to grain up to 18% variance,
- hardness up to 20% variance, and
- relative density$_{OD}$ up to 10% variance.

As discussed, the degree of variance of these properties changes based on species and environmental factors and that the direction of change (increase or decrease) is specific to tree species or species group. Therefore, it seems unlikely that relative density alone can provide an accurate prediction without site specific correction (Zhang, 1995; Forest Products Laboratory, 1999).

Mistakes in reporting wood density values are common errors and limit our understanding to the interrelationships of wood characteristics. For example, specific gravity, relative density, and density have been used interchangeably in the literature. The USDA's Forest Products Laboratory's publications have commonly reported a specific gravity, rather than relative density, at oven-dry mass in relation to a volume at a specified moisture content, which has caused some confusion within the literature. Johnston and Carpenter (1985) reported, "based on the ovendry weight and green volume, eastern larch's specific gravity (relative $density_{30}$) averages 0.49, and eastern Larch density at 12 percent moisture content is about 35 pounds per cubic foot ($Density_{12\%}$ approximately 0.56 g/cm^3)." However, the Forest Products Laboratory (1999) reports two specific gravity values, ovendry weight and green volume (relative $density_{30}$) of 0.49 g/cm^3, and ovendry weight and 12% MC (relative $density_{12\%}$) of 0.53 g/cm^3. This has created confusion within the literature, which has commonly reported the specific gravity of eastern larch as 0.49 g/cm^3 or 0.53 g/cm^3; meaning the relative $density_{OD}$. In order to develop accurate correlation models between relative density and mechanical properties the moisture content based on ovendry weight of the properties investigated must be consistent.

The importance of clearly understanding the relationships between relative density and the strength properties of northwestern Ontario tree species can not be emphasized enough. Design criteria of wood products are based on these relationships at the lower 5% probability of test values to ensure public safety (Figure 117) (Stiemer, 2010). When our understanding of the wood

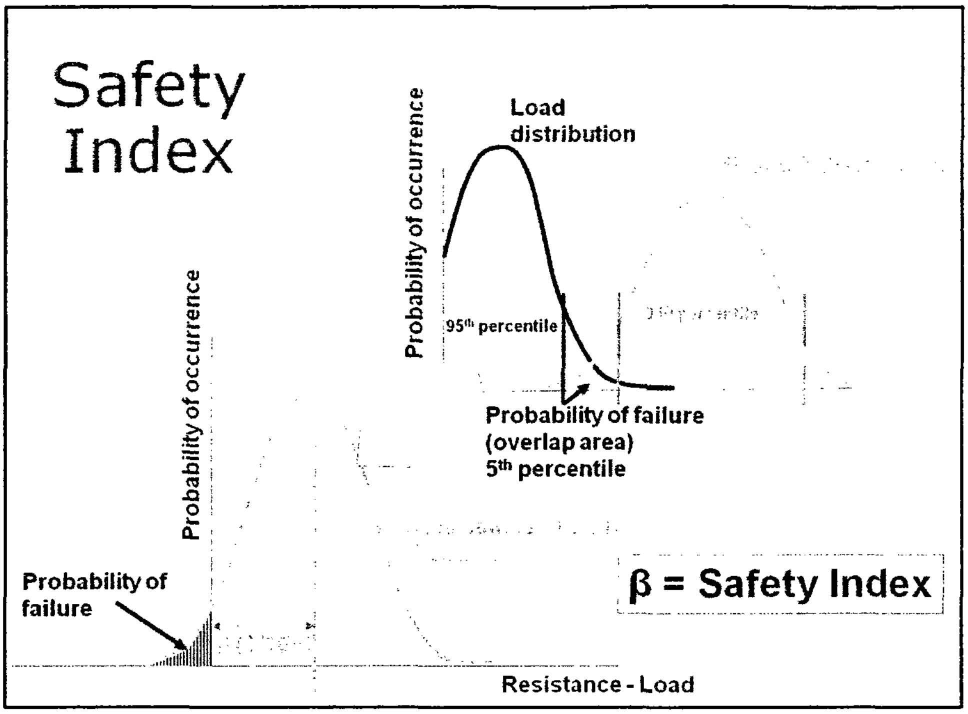


Figure 117. Example of down grading test values to ensure public safety (Stiemer, 2010).

characteristics of a tree species is unclear it reduces the utilization and value of the wood. For example, Pucci (2006) reported that the current Northern Species specific gravity used in Machine Stress Rated (MSR) lumber under valuates eastern larch within the market. Increasing the understanding of the "Real" specific gravity with regard to strength properties would make eastern larch "a commercially viable market species with the potential of making it the preferred species in specific uses" (Pucci, 2006).

4.4.1.6 Relative density and strength classes

The National Lumber Grade Authority (NLGA) regulates visual and MSR grades. Lumber grades are divided into three basic categories:

1. structural framing products; visually and/or mechanically graded (MSR) for strength and physical working ,

2. appearance products; graded for aesthetic qualities in non-structural applications,

3. industrial products, including a variety of structural and non-structural grades.

MSR grading uses nondestructive mechanical testing equipment inline with lumber processing, which measures and sorts the stiffness of the lumber into various MOE grades. MSR grading does not replace visual grading. Visual grades overrides machine decisions when visual defects are identified (NLGA, 2003b).

According to Stiemer (2010) MSR grading eliminates tree species as a consideration to material selection by designers and engineers. MSR grades can be produced from a multitude of wood species from a number of different sources. Thus, clients have the ability to (Stiemer, 2010):

- produce higher quality products with fewer failures,
- increase available suppliers do to standardized uniformity within grades,
- substitute expensive or scarce wood species with cheaper more abundant species.

According to Rozek (2010) MSR grading presents northwestern Ontario with the potential to better market the high-density under utilized species from the boreal forest, once it is recognized that they possess superior properties to the current Northern Species grade (Pucci, 2010).

Although MSR grades are divided into MOE classes, the grades are based on the interrelationship between specific gravity and select mechanical properties (NLGA, 2003a; NLGA, 2003b):

- Bending,
- Tension parallel to grain,
- Shear parallel to grain,
- compression parallel to grain,
- compression perpendicular to grain,
- Modulus of Elasticity.

For northwestern Ontario the Northern Species grade is used for all tree species other than Spruce-Pine-Fir. Thus, interrelationship between wood density and mechanical properties are based on a specific gravity (relative density$_{OD}$) of 0.42 g/cm^3. According to NLGA (2003b):

> "Specific gravity (SG) qualifications and subsequent quality control are required when the SG value exceeds the value assigned to the grade set forth."

For corporations like Buchanan Lumber, this grade rule required them to bare the extra expense for the continual testing of wood density so that they could market their products using the appropriate MSR grade (Pucci, 2010).

MSR grading of eastern larch provides use with a new measure for strength and variance of wood characteristics. Since MSR grades are strength classes based on set relative density$_{OD}$ and mechanical property values, it provides use with a measure of variance based on practical application or design value. These classes are based on thresholds, thus variance is reduced as the scale of comparison is broadened.

For example, using the strength groups from the Australian standard grading for seasoned structural timber (Gardiner, 2010) (Table 53), eastern larch specimens were given a strength group number and analyzed using SPSS 18 software. The ANOVA results (Table 54) indicate, strength group variance within eastern larch was limited to sites at 99.9% probability.

Table 53. Australian standard grading for seasonal structural timber (Gardiner 2010).

Minimum values for Strength Groups			
Strength Group	Modulus of Elasticity (Mpa)	Modulus of Rupture (Mpa)	Maximum Crushing Strength (Mpa)
SD1	10500	150	80
SD2	10500	130	70
SD3	10500	110	61
SD4	10500	94	54
SD5	10500	78	47
SD6	10500	65	41
SD7	9100	55	36
SD8	7900	45	30

Table 54. ANOVA table of strength groups for eastern larch.

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	34.062[a]	15	2.271	5.652	.000
Intercept	18361.800	1	18361.800	45702.484	.000
Site	30.625	3	10.208	25.409	.000
Bolt	3.263	9	.363	.902	.524
Radial	.175	3	.058	.145	.933
Error	122.137	304	.402		
Total	18518.000	320			
Corrected Total	156.200	319			

a. R Squared = .218 (Adjusted R Squared = .179)

A Duncan's post hoc test indicated there were two subsets of similarity (Table 55). Based on ANOVA results the null hypothesis, that no variance in strength groups, was rejected at 99.9% probability. These findings indicate that the site variance of strength values can affect end use suitability of TDB eastern larch. Thus it appears that TDB eastern larch is generally homogeneous within sites and trees; when product design criteria is the dependant variable.

Table 55. Duncan's post hoc test subsets of similarity for the strength groups of eastern larch.

Site	N	Subset	
		1	2
3	80	7.00	
4	80	7.00	
2	80		8.00
1	80		8.00
Sig.		.383	.383

Using SPSS 18 software a regression curve of relative density$_{OD}$ and strength group was completed; which produced a predictive model (Equation (6).

$$y = -0.0051x + 10.272 \ (R^2 = 0.0882) \qquad \textbf{Equation (6)}$$

Predicted strength values were compared for fit with actual strength values using SPSS 18 software, the t-test results (Table 56) indicated that actual and predicted strength values means were not significantly different at 99.9% probability, however, approximately equal variance between the two groups was not assumed. Based on these findings the null hypothesis, that there was no difference between predicted and actual values, was accepted at 99.9% probability.

Table 56. T-test comparison between actual and predicted strength values means at p<0.001.

		t-test for Equality of Means						
							95% Confidence Interval of the Difference	
		t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Strength	Equal variances not assumed	-1.853	318	.065	-.12500	.06745	-.25771	.00771

The predictive model decreased the strength values means of site 3 and 4 by 9% and increase strength values means of sites 1 and 2 by 3% (Figure 118). Grouping mechanical properties seem to prevent the development of a useful predictive model for strength groups.

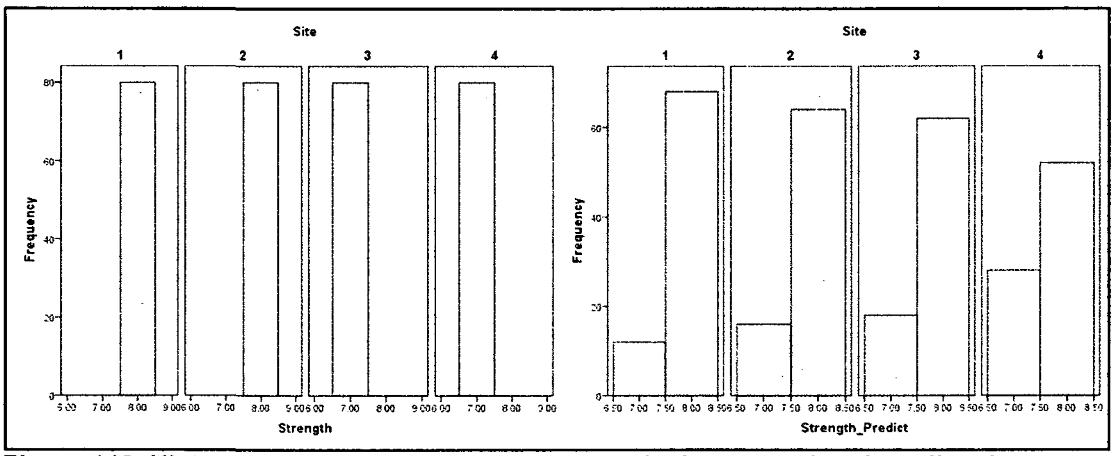


Figure 118. Histogram comparison between strength class actual and predicted.

4.5 Wood characteristics mapping

Wood characteristics mapping charts the general variance patterns in wood characteristics based on zones of axial and radial similarity. Based on the test results and statistical analysis we have identified three broad zones of axial variance, and three zones of radial variance in TDB eastern larch (Figure 119). Each one of these zones of similarity possesses unique characteristics, which affect the potential end uses.

For example, variability in wood density was significant between radial positions but not axial positions. However, the percent volume of wood composed of knots and reaction wood increased with an increase in height. As we progress from the base of the tree to the tip, the axial and radial characteristics interact to create nine distinct zones of similarity.

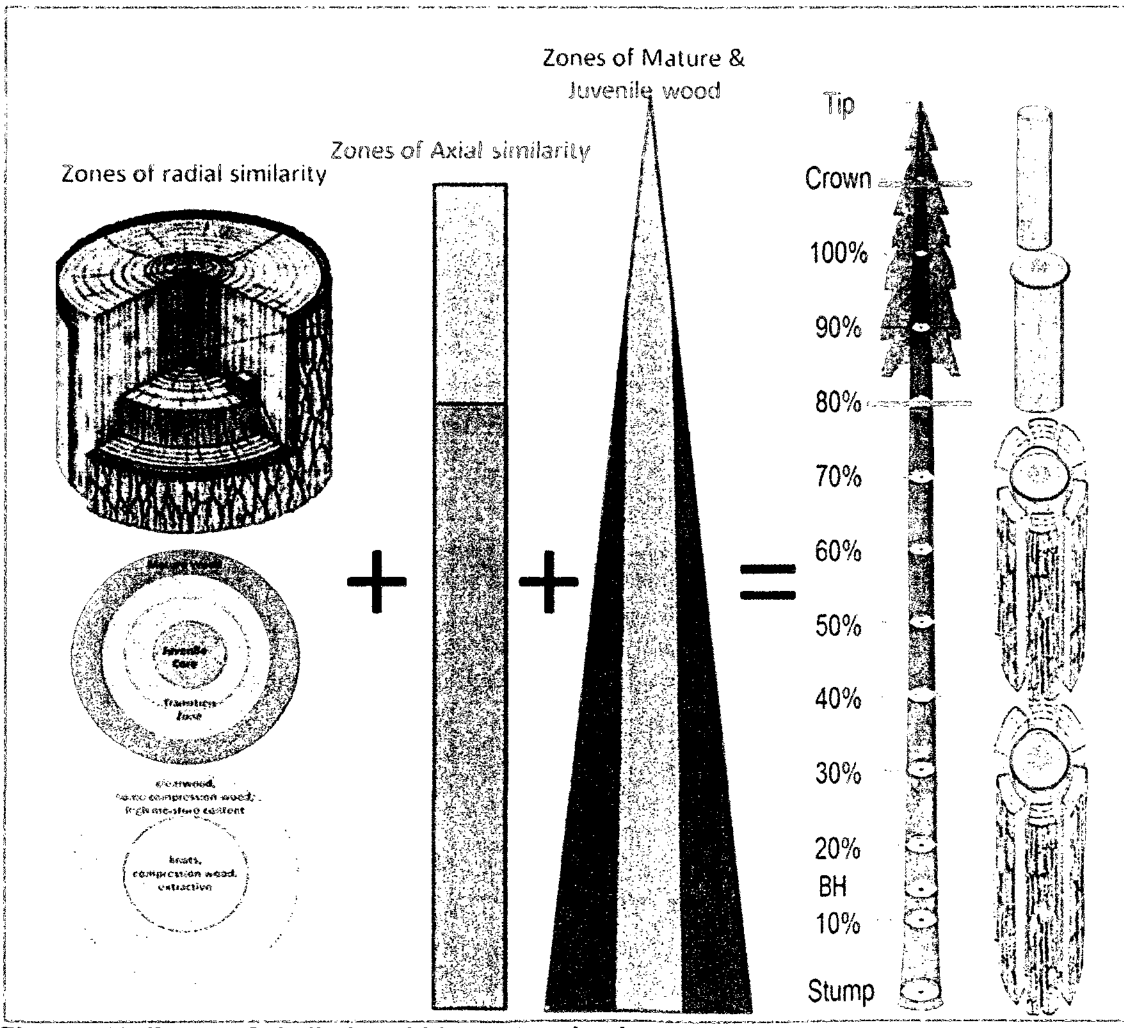
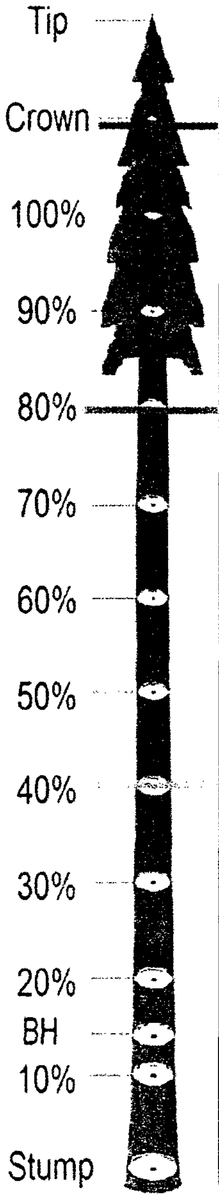


Figure 119. Zones of similarity within eastern larch.

Differences between the zones of similarity can be subtle, yet statistically significant. These zones of similarity could allow the forest sector of northwestern Ontario to better utilize eastern larch, making the species economically important. For example, LUWSTF analyzed a case study for eastern larch using optimization modeling software "Buck 2", comparing conventional harvesting and processing bucking lengths to the TDB wood characteristics map (Figure 120). When the zones of similarity were used as log processing criteria, overall tree value increase by 31% from $46.318/ha using conventional processing to $60,817/ha (Leitch *et al.*, 2010).

Based on the site variance finding of this study, it may be necessary to create two wood characteristics maps to ensure proper optimization of eastern larch. Eastern larch grown in extreme site conditions produce significantly different strength properties than trees grown on moist sites with some drainage (the classic eastern larch habitat). It is predicted that fast growing eastern larch, which would include plantation trees, would require a separate wood characteristics map in order to ensure maximum utilization and economic benefit.



Crown	**Products**				
small diameter high moisture content sapwood medium - high density wood is coarse spiral grain low strength	Panels Composites Pulpwood Bio-fuel				
Top Log Juvenile Core	**Products**	**Top Log Sapwood**	**Products**		
small/ diameter frequent knots spiral grain medium - high density low-medium strength	pulpwood panels composites biofuels, poles & posts	small/medium diameter frequent knots spiral grain common medium density medium strength	Lumber, engineered products Pulpwood Panels Composites Biofuels,		
Second Log Juvenile Core	**Products**	**Second Log Outer Heartwood / Inner Sapwood**	**Products**	**Second Log Outer Sapwood**	**Products**
small/medium diameter heartwood frequent knots spiral grain medium density medium strength wood is coarse	bioproducts pulpwood panels composites posts and poles value-added extractives lumber	medium diameter transition widely spaced knots some spiral medium density medium strength wood is coarse	bioproducts pulpwood panels composites posts and poles value-added extractives lumber joinery	medium / large diameter widely spaced pin knots with clearwood Straight grain medium density medium strength wood is coarse to medium grain	bioproducts pulpwood panels composites posts and poles value-added short clears lumber joinery engineered products
Bottom Log Juvenile Core	**Products**	**Bottom Log Outer Heartwood / Inner Sapwood**	**Products**	**Bottom Log Outer Sapwood**	**Products**
medium diameter heartwood frequent pin knots spiral grain medium-high density low-medium strength wood is coarse	Bioproducts Pulpwood panels composites posts and poles value-added extractives	medium / large diameter heartwood / sapwood transition widely spaced knots spiral grain common medium density medium strength wood is coarse to medium grain	bioproducts pulpwood panels composites lumber timbers posts and poles Value-added mouldings joinery extractives engineered products	large diameter clearwood Straight grain medium density medium strength wood is medium grain	bioproducts pulpwood panels composites lumber timbers posts and poles Value-added mouldings joinery veneer engineered products

Figure 120. Wood characteristics map for eastern larch.

5.0 Conclusions

The results of the literature review indicated that there was insufficient study on the tree species of northwestern Ontario and research is needed. The literature did, however, provide a general understanding on issues being assessed to allow for some specific conclusions:

1. Research to date has been driven by economic criteria alone, creating a knowledge gap between species. Research should be prioritized based on four criteria:

    a. level of previous study,

    b. potential market opportunity

    c. potential to increase utilization, and

    d. available volume.

2. Priority of research should be given to the following northwestern Ontario tree species:

    Softwoods; eastern white cedar (*Thuja occidentalis* L.), eastern larch (Larix laricina *(Du Roi) K. Koch*), and black spruce (*Picea mariana* (Mill.) B.S.P.),

    Hardwoods; black ash (*Fraxinus nigra* Marsh.), trembling aspen (*Populus tremuloides* Michx.), and white birch (*Betula papyrifera* Marsh.).

3. There appears to be a direct relationship between market end use attributes, manufacturing process attributes, and raw resource attributes or wood quality. This relationship indicates that understanding the morphology of wood is essential for:

    - proper forest management that promotes high quality wood,

- using the different woods of northwestern Ontario appropriately,
- producing premium high value products,
- utilizing all northwestern Ontario tree species, and
- optimizing the value chain to meet customer needs.

4. The best opportunity for product development identified for northwestern Ontario appears to be value-added wood products, bio-products, and integrating nanotechnology with existing manufacturing capacity to develop smart products. However, this requires extensive research and development activities. Research on wood characteristics related to end use design criteria, especially wood density, should be a priority for all species.

The greatest variability displayed by eastern larch wood grown in TBD was between sites and radial variance within trees. In all cases of TBD statistical analysis, variance between sites was significant. Radial variance was significant for all the selected wood properties tested except for MOE perpendicular to the grain. Longitudinal or axial variance was significant all the selected wood properties tested except for wood density. These findings support the following conclusions:

1. Increased growth rate affected the density of eastern larch at the extreme of its growth range; very dry sites had decreased density and sites with seasonal flooding had increased density.
2. It was found that the mechanical properties of eastern larch decreased with age, thus a short rotation age, between 30 to 60 years, is recommended.

3. Eastern larch was found to be very responsive to changes in site conditions. For example, increasing tree spacing and trenching increased growth, which decreased MOR and MOE values. Reducing tree spacing after site preparation would help maintain wood quality of TBD eastern larch while improving site conditions.
4. Our findings indicated that eastern larch had superior side hardness values compared to other softwoods grown in northwestern Ontario. Thus, eastern larch is well suited for value-added and specialty wood products.
5. Although the wood characteristics of eastern larch are significantly different between sites, the pattern of variance of the selected wood properties considered were highly consistent between sites.
6. Eastern larch has been reported be to highly variable, however this was not found to be true in the TBD study. A regression curve analysis of eastern larch relative $density_{12}$ correlated with mechanical properties allowed us to develop a simple linear model, which produced reasonable predictions, within 0.003% to 0.25% of actual grand means, for the selected mechanical properties of eastern larch grown within the TBD.

A t-test comparison between 10 bolt and breast height sampling showed no significant difference between the grand means, however, radial variance patterns displayed notable differences. Axial variance was not considered with breast height sampling, which was significantly variable in all the selected mechanical properties tested. When 10 bolt versus breast height sampling is considered with respect to wood characteristics mapping, some specific conclusions can be made:

1. Breast height sampling only provides a general understanding of the grand means for the selected wood properties, and is not helpful in understanding variability of wood characteristics within a stem.
2. Breast height sampling becomes less useful in second growth and small diameter trees, which have a higher proportion of reaction wood than over mature and old growth stands at that axial position.

Based on the results from a comparison of the TDB model to Forest Products Laboratory (1999) softwood and hardwood predictive models, we can conclude that eastern larch is unique in that it has the morphology of a softwood but displays wood properties variability patterns which are more consistent with hardwoods. Eastern larch's variance patterns are inconsistent with other softwoods which has led other researchers to conclude that the species is highly variable. The results of the eastern larch case study indicate that eastern larch has fairly homogeneous wood properties within the stem with respect to end use design criteria and that a predictive model for the species is possible. Thus wood characteristics mapping of eastern larch wood is possible. These findings support the following conclusions:

1. Mapping of wood characteristics of eastern larch will allow the forest sector of northwestern Ontario to optimize the value and utilization of the species and increase the overall value of eastern larch by as much as 31%.
2. Our findings indicate that the variance in wood properties of eastern larch is primarily related to the ratio of earlywood to latewood within the growth rings. Thus, correlations at this level of testing would produce better predictions for the species.

3. Comparing the results from wood property testing using SilvaScan, acoustic and x-ray diffractometry scanning would allow us to segregate mature wood, juvenile wood, and reaction wood and determine wood density and MOE values at the growth ring level.

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7.0 Appendices: wood properties' data sets

7.1 Mature trees data sets

7.1.1 Mature trees data sets site 1

7.1.1.1 Mature trees data sets site 1 tree 1

Site 1 Tree 1

Site	Tree	L	R	RD0%	D12	RD12%	MOE	MOR	Comp	Hard	Strength
1	1	0.1	0.25	533	657	509	7010	80	41	3937	8
1	1	0.1	0.50	521	642	498	8460	78	40	3809	8
1	1	0.1	0.75	498	613	476	7845	78	39	3420	8
1	1	0.1	1.00	505	622	482	6590	67	38	3290	8
1	1	0.2	0.25	526	648	503	8570	82	42	3370	8
1	1	0.2	0.50	557	686	532	9050	86	45	3523	7
1	1	0.2	0.75	562	692	537	9325	77	46	3550	7
1	1	0.2	1.00	523	644	500	9595	81	44	3380	7
1	1	0.3	0.25	510	628	487	8023	78	35	3448	8
1	1	0.3	0.50	554	683	530	8380	77	44	3180	8
1	1	0.3	0.75	530	653	507	7940	75	47	3305	8
1	1	0.3	1.00	530	653	507	7090	64	45	3220	8
1	1	0.4	0.25	557	686	532	9010	86	43	3195	7
1	1	0.4	0.50	585	721	559	8330	84	46	3358	8
1	1	0.4	0.75	558	687	533	7480	71	48	3550	8
1	1	0.4	1.00	529	652	506	7240	64	44	3580	8
1	1	0.5	0.25	594	732	568	8505	84	36	3318	8
1	1	0.5	0.50	616	759	589	7635	78	41	3468	8
1	1	0.5	0.75	594	732	568	7470	62	44	3263	8
1	1	0.5	1.00	499	615	477	6450	63	41	3070	8
1	1	0.6	0.25	594	732	568	5130	41	38	3528	8
1	1	0.6	0.50	616	759	589	7810	61	38	3528	8
1	1	0.6	0.75	594	732	568	9485	78	48	3703	7
1	1	0.6	1.00	499	615	477	9485	78	47	3510	7
1	1	0.7	0.25	605	745	578	5700	59	42	3930	8
1	1	0.7	0.50	601	740	574	5700	59	42	3930	8
1	1	0.7	0.75	562	692	537	8255	68	42	3785	8
1	1	0.7	1.00	562	692	537	8255	68	47	3710	8
1	1	0.8	0.25	658	811	629	5700	59	46	3683	8
1	1	0.8	0.50	658	811	629	5700	59	46	3683	8
1	1	0.8	0.75	658	811	629	7900	74	40	3615	8
1	1	0.8	1.00	658	811	629	7900	74	44	3615	8
1	1	0.9	0.25	520	641	497	5660	51	44	3410	8
1	1	0.9	0.50	520	641	497	5660	51	44	3410	8
1	1	0.9	0.75	520	641	497	5660	51	41	2960	8
1	1	0.9	1.00	520	641	497	5660	51	41	2960	8
1	1	1	0.25	520	641	497	5660	51	44	3383	8
1	1	1	0.50	520	641	497	5660	51	44	3383	8
1	1	1	0.75	520	641	497	5660	51	43	3383	8
1	1	1	1.00	520	641	497	5660	51	43	3383	8

7.1.1.2 Mature trees data sets site 1 tree 2

Site 1 Tree 2

Site	Tree	L	R	**$RD_{0\%}$**	D_{12}	**$RD_{12\%}$**	MOE	**MOR**	Comp	**Hard**	Strength
1	2	0.1	0.25	**520**	641	**497**	6311	**68**	33	**3548**	8
1	2	0.1	0.50	**534**	657	**510**	7218	**68**	36	**3705**	8
1	2	0.1	0.75	**531**	654	**507**	8077	**70**	38	**4033**	8
1	2	0.1	1.00	**527**	649	**504**	8290	**72**	41	**3578**	8
1	2	0.2	0.25	**491**	605	**469**	6920	**70**	36	**3370**	8
1	2	0.2	0.50	**520**	640	**497**	7600	**72**	37	**3523**	8
1	2	0.2	0.75	**528**	650	**505**	8486	**77**	45	**3550**	8
1	2	0.2	1.00	**550**	678	**526**	7875	**78**	49	**3380**	8
1	2	0.3	0.25	**466**	574	**445**	6030	**56**	35	**3448**	8
1	2	0.3	0.50	**490**	603	**468**	6030	**56**	34	**3118**	8
1	2	0.3	0.75	**513**	632	**490**	5355	**56**	36	**3305**	8
1	2	0.3	1.00	**534**	658	**510**	5355	**56**	33	**3220**	8
1	2	0.4	0.25	**501**	617	**478**	7140	**71**	36	**3195**	8
1	2	0.4	0.50	**509**	627	**487**	6799	**67**	41	**3358**	8
1	2	0.4	0.75	**518**	638	**495**	6599	**67**	44	**3550**	8
1	2	0.4	1.00	**531**	654	**508**	5930	**66**	41	**3580**	8
1	2	0.5	0.25	**509**	627	**487**	5830	**58**	39	**3318**	8
1	2	0.5	0.50	**526**	648	**503**	7120	**67**	45	**3468**	8
1	2	0.5	0.75	**518**	638	**495**	7706	**71**	49	**3263**	8
1	2	0.5	1.00	**510**	628	**487**	7150	**72**	47	**3070**	8
1	2	0.6	0.25	**540**	665	**516**	6643	**57**	38	**3528**	8
1	2	0.6	0.50	**539**	664	**515**	7330	**62**	38	**3528**	8
1	2	0.6	0.75	**536**	660	**512**	7510	**68**	42	**3703**	8
1	2	0.6	1.00	**536**	660	**512**	7510	**68**	41	**3510**	8
1	2	0.7	0.25	**551**	678	**526**	8067	**70**	43	**3930**	8
1	2	0.7	0.50	**551**	678	**526**	8067	**70**	43	**3930**	8
1	2	0.7	0.75	**524**	646	**501**	8295	**73**	46	**3785**	8
1	2	0.7	1.00	**524**	646	**501**	8295	**73**	46	**3710**	8
1	2	0.8	0.25	**532**	655	**508**	6870	**70**	39	**3318**	8
1	2	0.8	0.50	**532**	655	**508**	6870	**70**	39	**3318**	8
1	2	0.8	0.75	**503**	620	**481**	7360	**62**	44	**3150**	8
1	2	0.8	1.00	**503**	620	**481**	7360	**62**	44	**3150**	8
1	2	0.9	0.25	**523**	644	**499**	8460	**67**	45	**3410**	8
1	2	0.9	0.50	**523**	644	**499**	8460	**67**	45	**3410**	8
1	2	0.9	0.75	**490**	604	**468**	7850	**71**	41	**2960**	8
1	2	0.9	1.00	**490**	604	**468**	7850	**71**	41	**2960**	8
1	2	1	0.25	**506**	623	**484**	7830	**71**	40	**3383**	8
1	2	1	0.50	**506**	623	**484**	7830	**71**	40	**3383**	8
1	2	1	0.75	**524**	646	**501**	7930	**63**	43	**3383**	8
1	2	1	1.00	**524**	646	**501**	7930	**63**	43	**3383**	8

7.1.2 Mature trees data sets site 2

7.1.2.1 Mature trees data sets site 2 tree 1

Site 2 Tree 1

Site	Tree	L	R	**RD$_{0\%}$**	D_{12}	**RD$_{12\%}$**	MOE	**MOR**	Comp	**Hard**	Strength
2	1	0.1	0.25	**558**	687	**533**	9327	**85**	45	**3474**	7
2	1	0.1	0.50	**599**	738	**572**	8778	**85**	45	**3710**	8
2	1	0.1	0.75	**552**	680	**528**	9008	**86**	49	**3815**	7
2	1	0.1	1.00	**545**	671	**521**	8220	**95**	46	**4030**	8
2	1	0.2	0.25	**532**	655	**508**	9218	**84**	47	**3387**	7
2	1	0.2	0.50	**551**	679	**527**	9130	**86**	47	**3478**	7
2	1	0.2	0.75	**560**	689	**535**	8470	**85**	50	**4550**	8
2	1	0.2	1.00	**579**	713	**553**	6450	**76**	48	**3830**	8
2	1	0.3	0.25	**494**	609	**472**	7525	**70**	37	**3188**	8
2	1	0.3	0.50	**540**	665	**516**	7793	**74**	44	**3556**	8
2	1	0.3	0.75	**533**	657	**510**	7940	**74**	43	**3710**	8
2	1	0.3	1.00	**553**	681	**528**	8980	**84**	43	**3865**	8
2	1	0.4	0.25	**496**	611	**474**	7475	**71**	37	**2845**	8
2	1	0.4	0.50	**517**	637	**494**	7404	**74**	41	**3440**	8
2	1	0.4	0.75	**509**	628	**487**	7620	**80**	44	**3760**	8
2	1	0.4	1.00	**542**	667	**518**	8167	**80**	48	**3573**	8
2	1	0.5	0.25	**498**	613	**476**	7254	**69**	38	**3035**	8
2	1	0.5	0.50	**513**	632	**491**	7580	**74**	46	**3010**	8
2	1	0.5	0.75	**538**	663	**514**	7370	**76**	44	**3380**	8
2	1	0.5	1.00	**545**	671	**521**	8840	**84**	43	**3433**	8
2	1	0.6	0.25	**511**	629	**488**	8060	**80**	41	**3045**	8
2	1	0.6	0.50	**524**	646	**501**	8551	**80**	46	**3297**	8
2	1	0.6	0.75	**524**	645	**501**	8535	**80**	46	**3513**	8
2	1	0.6	1.00	**504**	621	**482**	9110	**83**	46	**3690**	7
2	1	0.7	0.25	**496**	611	**474**	7870	**76**	42	**3037**	8
2	1	0.7	0.50	**500**	616	**478**	8577	**83**	42	**3065**	8
2	1	0.7	0.75	**503**	620	**481**	8463	**83**	43	**3165**	8
2	1	0.7	1.00	**535**	659	**511**	8470	**85**	47	**3215**	8
2	1	0.8	0.25	**512**	631	**490**	7687	**72**	40	**3080**	8
2	1	0.8	0.50	**515**	635	**492**	8673	**77**	40	**3080**	8
2	1	0.8	0.75	**528**	650	**504**	8688	**83**	44	**3235**	8
2	1	0.8	1.00	**528**	650	**504**	8688	**83**	44	**3355**	8
2	1	0.9	0.25	**529**	652	**506**	9120	**88**	47	**3258**	7
2	1	0.9	0.50	**531**	655	**508**	9120	**88**	47	**3258**	7
2	1	0.9	0.75	**493**	607	**471**	9693	**95**	48	**3435**	7
2	1	0.9	1.00	**493**	607	**471**	9693	**95**	45	**3435**	7
2	1	1	0.25	**525**	646	**502**	8260	**78**	48	**3673**	8
2	1	1	0.50	**563**	694	**538**	8260	**78**	48	**3673**	8
2	1	1	0.75	**596**	734	**570**	9578	**90**	51	**3715**	7
2	1	1	1.00	**596**	734	**570**	9578	**90**	51	**3715**	7

7.1.2.2 Mature trees data sets site 2 tree 2

Site 2 Tree 2

Site	Tree	L	R	**$RD_{0\%}$**	D_{12}	**$RD_{12\%}$**	MOE	**MOR**	Comp	**Hard**	Strength
2	2	0.1	0.25	**581**	715	**555**	8073	**87**	46	**3850**	8
2	2	0.1	0.50	**583**	719	**557**	8100	**89**	46	**3850**	8
2	2	0.1	0.75	**653**	805	**624**	8165	**93**	51	**3937**	8
2	2	0.1	1.00	**635**	782	**607**	8165	**93**	54	**3120**	8
2	2	0.2	0.25	**494**	609	**472**	8498	**82**	53	**3990**	8
2	2	0.2	0.50	**589**	726	**563**	8780	**84**	53	**3990**	8
2	2	0.2	0.75	**585**	721	**559**	9100	**91**	58	**4183**	7
2	2	0.2	1.00	**522**	643	**499**	9100	**91**	59	**3300**	7
2	2	0.3	0.25	**552**	680	**528**	7915	**79**	45	**3353**	8
2	2	0.3	0.50	**604**	744	**577**	8185	**83**	45	**3353**	8
2	2	0.3	0.75	**581**	715	**555**	8580	**83**	50	**3648**	8
2	2	0.3	1.00	**515**	634	**492**	8580	**83**	50	**3648**	8
2	2	0.4	0.25	**575**	708	**549**	7230	**75**	53	**3805**	8
2	2	0.4	0.50	**598**	737	**572**	8565	**84**	53	**3805**	8
2	2	0.4	0.75	**595**	732	**568**	8270	**88**	56	**3650**	8
2	2	0.4	1.00	**595**	732	**568**	8270	**88**	56	**3650**	8
2	2	0.5	0.25	**547**	674	**523**	8435	**83**	55	**3970**	8
2	2	0.5	0.50	**602**	742	**576**	8435	**83**	55	**3970**	8
2	2	0.5	0.75	**542**	667	**518**	8508	**84**	58	**3265**	8
2	2	0.5	1.00	**542**	667	**518**	8508	**84**	58	**3265**	8
2	2	0.6	0.25	**551**	679	**527**	8650	**85**	52	**3600**	8
2	2	0.6	0.50	**602**	742	**575**	8650	**85**	52	**3600**	8
2	2	0.6	0.75	**532**	655	**508**	8500	**87**	56	**3130**	8
2	2	0.6	1.00	**532**	655	**508**	8500	**87**	56	**3120**	8
2	2	0.7	0.25	**563**	694	**539**	8270	**78**	56	**3340**	8
2	2	0.7	0.50	**625**	770	**597**	8270	**78**	56	**3340**	8
2	2	0.7	0.75	**585**	721	**559**	8430	**78**	54	**3257**	8
2	2	0.7	1.00	**585**	721	**559**	8430	**78**	54	**3257**	8
2	2	0.8	0.25	**595**	734	**569**	8210	**74**	51	**3377**	8
2	2	0.8	0.50	**597**	735	**571**	8210	**74**	51	**3377**	8
2	2	0.8	0.75	**549**	677	**525**	8570	**87**	54	**3500**	8
2	2	0.8	1.00	**549**	677	**525**	8570	**87**	54	**3500**	8
2	2	0.9	0.25	**587**	723	**561**	8245	**78**	56	**3640**	8
2	2	0.9	0.50	**594**	731	**567**	8245	**78**	56	**3640**	8
2	2	0.9	0.75	**570**	703	**545**	8245	**78**	47	**3370**	8
2	2	0.9	1.00	**570**	703	**545**	8245	**78**	47	**3370**	8
2	2	1	0.25	**630**	777	**603**	8255	**79**	54	**4350**	8
2	2	1	0.50	**575**	708	**550**	8255	**79**	54	**4350**	8
2	2	1	0.75	**532**	655	**508**	8255	**79**	54	**3730**	8
2	2	1	1.00	**532**	655	**508**	8255	**79**	54	**3730**	8

7.1.3 Mature trees data sets site 3

7.1.3.1 Mature trees data sets site 3 tree 1

Site 3 Tree 1

Site	Tree	L	R	RD0%	D12	RD12%	MOE	MOR	Comp	Hard	Strength
3	1	0.1	0.25	517	637	494	7788	78	42	4098	8
3	1	0.1	0.50	549	677	525	7460	78	48	4340	8
3	1	0.1	0.75	478	589	457	7490	76	42	4403	8
3	1	0.1	1.00	458	564	437	5975	67	38	3475	8
3	1	0.2	0.25	495	609	473	6770	72	39	3147	8
3	1	0.2	0.50	526	648	503	8670	78	47	3767	8
3	1	0.2	0.75	529	652	506	8730	83	50	3578	8
3	1	0.2	1.00	501	617	479	8768	84	47	3580	8
3	1	0.3	0.25	481	593	460	8830	74	40	3385	8
3	1	0.3	0.50	524	646	501	9230	77	49	3707	7
3	1	0.3	0.75	527	649	503	9247	79	49	3375	7
3	1	0.3	1.00	469	578	449	8240	83	39	3325	8
3	1	0.4	0.25	485	598	464	9490	77	41	3213	7
3	1	0.4	0.50	538	663	515	10725	79	51	3538	6
3	1	0.4	0.75	498	613	476	10243	77	51	3623	6
3	1	0.4	1.00	519	639	496	10243	77	51	3510	6
3	1	0.5	0.25	488	602	467	7820	79	40	3013	8
3	1	0.5	0.50	523	644	500	8950	81	46	3563	8
3	1	0.5	0.75	508	626	485	8150	77	47	4110	8
3	1	0.5	1.00	485	598	464	9760	85	49	3990	7
3	1	0.6	0.25	486	599	464	10050	89	40	3480	6
3	1	0.6	0.50	497	612	475	9215	82	40	3520	7
3	1	0.6	0.75	546	672	522	9250	80	48	4030	7
3	1	0.6	1.00	502	618	479	9250	80	44	3390	7
3	1	0.7	0.25	463	571	443	6995	63	42	3035	8
3	1	0.7	0.50	500	616	478	8370	71	42	3035	8
3	1	0.7	0.75	513	632	491	8855	77	47	3268	8
3	1	0.7	1.00	494	609	472	8855	77	49	3480	8
3	1	0.8	0.25	493	607	471	8220	77	44	3320	8
3	1	0.8	0.50	528	650	505	8220	77	44	3320	8
3	1	0.8	0.75	499	614	477	8765	78	45	3455	8
3	1	0.8	1.00	471	580	450	8765	78	41	3455	8
3	1	0.9	0.25	509	627	486	5930	67	44	3267	8
3	1	0.9	0.50	508	625	485	5930	67	44	3267	8
3	1	0.9	0.75	481	593	460	8313	66	42	3245	8
3	1	0.9	1.00	481	593	460	8313	66	42	4660	8
3	1	1	0.25	510	628	487	6680	75	42	3643	8
3	1	1	0.50	510	628	487	6680	75	42	3643	8
3	1	1	0.75	472	582	452	7510	78	42	3643	8
3	1	1	1.00	472	582	452	7510	78	42	3643	8

7.1.3.2 Mature trees data sets site 3 tree 2

Site 3 Tree 2

Site	Tree	L	R	**$RD_{0\%}$**	D_{12}	**$RD_{12\%}$**	MOE	**MOR**	Comp	**Hard**	Strength
3	2	0.1	0.25	**629**	775	**602**	7031	**77**	41	**4497**	8
3	2	0.1	0.50	**624**	768	**596**	7200	**80**	47	**4460**	8
3	2	0.1	0.75	**592**	729	**566**	7020	**81**	45	**4315**	8
3	2	0.1	1.00	**578**	712	**553**	6100	**74**	40	**4335**	8
3	2	0.2	0.25	**597**	735	**570**	5800	**57**	46	**4040**	8
3	2	0.2	0.50	**629**	775	**602**	7830	**69**	52	**3890**	8
3	2	0.2	0.75	**637**	784	**608**	8480	**70**	53	**4167**	8
3	2	0.2	1.00	**606**	747	**579**	9110	**82**	54	**3870**	7
3	2	0.3	0.25	**537**	662	**513**	9980	**78**	44	**3583**	7
3	2	0.3	0.50	**590**	727	**564**	10970	**86**	44	**3938**	6
3	2	0.3	0.75	**657**	809	**628**	11117	**86**	51	**4077**	6
3	2	0.3	1.00	**560**	690	**536**	11117	**86**	48	**4090**	6
3	2	0.4	0.25	**565**	697	**540**	8900	**79**	44	**3880**	8
3	2	0.4	0.50	**571**	703	**545**	8717	**85**	44	**4213**	8
3	2	0.4	0.75	**639**	787	**611**	8015	**86**	50	**4170**	8
3	2	0.4	1.00	**555**	684	**530**	8015	**86**	49	**3770**	8
3	2	0.5	0.25	**566**	698	**541**	8350	**68**	45	**3950**	8
3	2	0.5	0.50	**586**	722	**560**	8783	**89**	45	**3950**	8
3	2	0.5	0.75	**641**	790	**613**	10310	**90**	54	**4450**	6
3	2	0.5	1.00	**589**	726	**563**	10310	**90**	55	**3680**	6
3	2	0.6	0.25	**553**	681	**528**	9934	**87**	50	**4135**	7
3	2	0.6	0.50	**619**	763	**592**	10497	**87**	50	**4135**	6
3	2	0.6	0.75	**603**	742	**576**	11040	**86**	55	**3828**	6
3	2	0.6	1.00	**586**	721	**560**	11040	**86**	54	**3850**	6
3	2	0.7	0.25	**593**	731	**567**	10370	**83**	52	**4180**	6
3	2	0.7	0.50	**562**	693	**538**	10195	**83**	52	**4180**	6
3	2	0.7	0.75	**605**	746	**578**	10195	**83**	54	**4600**	6
3	2	0.7	1.00	**573**	706	**548**	9720	**75**	49	**4240**	7
3	2	0.8	0.25	**595**	733	**568**	10620	**88**	53	**4150**	6
3	2	0.8	0.50	**595**	733	**568**	10620	**88**	53	**4150**	6
3	2	0.8	0.75	**534**	658	**511**	11273	**91**	48	**3873**	6
3	2	0.8	1.00	**534**	658	**511**	11273	**91**	48	**3873**	6
3	2	0.9	0.25	**531**	654	**507**	10950	**88**	52	**4253**	6
3	2	0.9	0.50	**588**	724	**562**	10950	**88**	52	**4253**	6
3	2	0.9	0.75	**561**	691	**536**	10510	**90**	52	**4620**	6
3	2	0.9	1.00	**561**	691	**536**	10510	**90**	52	**4620**	6
3	2	1	0.25	**623**	768	**596**	9420	**81**	49	**4015**	7
3	2	1	0.50	**560**	690	**535**	9420	**81**	49	**4015**	7
3	2	1	0.75	**586**	722	**561**	9420	**81**	49	**3950**	7
3	2	1	1.00	**586**	722	**561**	9420	**81**	49	**3950**	6

7.1.4 Mature trees data sets site 4

7.1.4.1 Mature trees data sets site 4 tree 1

Site 4 Tree 1

Site	Tree	L	R	$RD_{0\%}$	D_{12}	$RD_{12\%}$	MOE	MOR	Comp	Hard	Strength
4	1	0.1	0.25	584	719	558	8709	85		4,040	8
4	1	0.1	0.50	643	792	614	10350	88		4,040	6
4	1	0.1	0.75	658	810	628	10493	95		4,600	6
4	1	0.1	1.00	632	778	604	12329	106		3,990	5
4	1	0.2	0.25	570	702	545	9046	82		4130	7
4	1	0.2	0.50	637	785	609	9136	84		5250	7
4	1	0.2	0.75	629	775	601	10044	95		4580	6
4	1	0.2	1.00	608	749	581	10076	102		4660	6
4	1	0.3	0.25	607	748	580	8367	79		4825	8
4	1	0.3	0.50	608	749	581	8652	84		4135	8
4	1	0.3	0.75	591	728	565	9599	94		3980	7
4	1	0.3	1.00	585	721	559	9893	101		4230	7
4	1	0.4	0.25	570	702	545	8562	71		4135	8
4	1	0.4	0.50	576	710	551	8559	89		3760	8
4	1	0.4	0.75	560	690	535	9259	89		3980	7
4	1	0.4	1.00	538	663	514	9259	89		3583	7
4	1	0.5	0.25	553	681	529	7828	73		3633	8
4	1	0.5	0.50	598	737	572	9407	94		3968	7
4	1	0.5	0.75	575	708	550	9664	107	No Samples	3675	7
4	1	0.5	1.00	556	685	531	9664	107		3060	7
4	1	0.6	0.25	595	733	569	7376	79		3385	8
4	1	0.6	0.50	605	745	578	7376	79		3385	8
4	1	0.6	0.75	551	679	527	9470	85		3375	7
4	1	0.6	1.00	551	679	527	9470	85		3810	7
4	1	0.7	0.25	602	742	575	6921	78		4183	8
4	1	0.7	0.50	606	747	579	8185	83		4183	8
4	1	0.7	0.75	580	715	554	8775	83		4500	8
4	1	0.7	1.00	580	715	554	8775	83		3170	8
4	1	0.8	0.25	604	744	577	5723	64		4165	8
4	1	0.8	0.50	595	733	569	6370	74		4165	8
4	1	0.8	0.75	557	686	532	7766	83		4485	8
4	1	0.8	1.00	557	686	532	7766	83		4485	8
4	1	0.9	0.25	561	691	536	6873	72		3723	8
4	1	0.9	0.50	561	691	536	6873	72		3723	8
4	1	0.9	0.75	620	764	593	6873	72		4365	8
4	1	0.9	1.00	620	764	593	6873	72		4365	8
4	1	1	0.25	568	700	543	5618	63		3,685	8
4	1	1	0.50	568	700	543	5618	63		3,685	8
4	1	1	0.75	568	700	543	5618	63		3,685	8
4	1	1	1.00	568	700	543	5618	63		3,685	8

7.1.4.2 Mature trees data sets site 4 tree 2

Site 4 Tree 2

Site	Tree	L	R	**$RD_{0\%}$**	D_{12}	**$RD_{12\%}$**	MOE	**MOR**	Comp	**Hard**	Strength
4	2	0.1	0.25	**607**	748	**580**	9240	**96**	No Samples	**4040**	7
4	2	0.1	0.50	**572**	704	**546**	9238	**94**		**4273**	7
4	2	0.1	0.75	**541**	667	**517**	7975	**84**		**4400**	8
4	2	0.1	1.00	**579**	714	**554**	6535	**80**		**4122**	8
4	2	0.2	0.25	**594**	732	**568**	10210	**92**		**4068**	6
4	2	0.2	0.50	**592**	729	**565**	9870	**105**		**4423**	7
4	2	0.2	0.75	**561**	691	**536**	9940	**103**		**4148**	7
4	2	0.2	1.00	**568**	700	**543**	7190	**86**		**4090**	8
4	2	0.3	0.25	**554**	683	**530**	10883	**100**		**3708**	6
4	2	0.3	0.50	**577**	710	**551**	10923	**96**		**3905**	6
4	2	0.3	0.75	**549**	676	**525**	10090	**95**		**3948**	6
4	2	0.3	1.00	**596**	734	**570**	8220	**81**		**3150**	8
4	2	0.4	0.25	**545**	671	**521**	9810	**99**		**3280**	7
4	2	0.4	0.50	**556**	685	**531**	9451	**92**		**3453**	7
4	2	0.4	0.75	**542**	668	**518**	9087	**89**		**3550**	7
4	2	0.4	1.00	**551**	679	**527**	7660	**83**		**3330**	8
4	2	0.5	0.25	**583**	718	**557**	10500	**95**		**3655**	6
4	2	0.5	0.50	**589**	726	**563**	10173	**90**		**3790**	6
4	2	0.5	0.75	**552**	680	**528**	8160	**87**		**3817**	8
4	2	0.5	1.00	**553**	681	**529**	8160	**87**		**3360**	8
4	2	0.6	0.25	**574**	707	**549**	9803	**94**		**3743**	7
4	2	0.6	0.50	**578**	712	**552**	9803	**94**		**3743**	7
4	2	0.6	0.75	**558**	687	**533**	8975	**92**		**3768**	8
4	2	0.6	1.00	**558**	687	**533**	8975	**92**		**3505**	8
4	2	0.7	0.25	**591**	728	**565**	10800	**95**		**3683**	6
4	2	0.7	0.50	**589**	726	**563**	10800	**95**		**3683**	6
4	2	0.7	0.75	**593**	731	**567**	9030	**91**		**3818**	7
4	2	0.7	1.00	**593**	731	**567**	9030	**91**		**3720**	7
4	2	0.8	0.25	**597**	736	**571**	9480	**94**		**3805**	7
4	2	0.8	0.50	**597**	736	**571**	9480	**94**		**3805**	7
4	2	0.8	0.75	**529**	652	**506**	8737	**95**		**4170**	8
4	2	0.8	1.00	**529**	652	**506**	8737	**95**		**4170**	8
4	2	0.9	0.25	**579**	713	**553**	9480	**94**		**4090**	7
4	2	0.9	0.50	**579**	713	**553**	9480	**94**		**4090**	7
4	2	0.9	0.75	**609**	750	**582**	8737	**95**		**4090**	8
4	2	0.9	1.00	**579**	713	**553**	8737	**95**		**4090**	8
4	2	1	0.25	**583**	718	**557**	9480	**94**		**4060**	7
4	2	1	0.50	**583**	718	**557**	9480	**94**		**4060**	7
4	2	1	0.75	**574**	707	**549**	8737	**95**		**4060**	8
4	2	1	1.00	**574**	707	**549**	8737	**95**		**4060**	8

7.2 Juvenile trees data sets

7.2.1 Juvenile trees data sets site 1 and 2

Site 1 JV

Site	Tree	L	$RD_{0\%}$
1	1	0.1	**533**
1	1	0.2	**526**
1	1	0.3	**510**
1	1	0.4	**557**
1	1	0.5	**594**
1	1	0.6	**594**
1	1	0.7	**605**
1	1	0.8	**658**
1	1	0.9	**520**
1	1	1	**520**
1	2	0.1	**503**
1	2	0.2	**486**
1	2	0.3	**440**
1	2	0.4	**488**
1	2	0.5	**501**
1	2	0.6	**532**
1	2	0.7	**535**
1	2	0.8	**526**
1	2	0.9	**535**
1	2	1	**522**
1	3	0.1	**597**
1	3	0.2	**543**
1	3	0.3	**544**
1	3	0.4	**577**
1	3	0.5	**502**
1	3	0.6	**480**
1	3	0.7	**495**
1	3	0.8	**487**
1	3	0.9	**480**
1	3	1	**495**

Site 2 JV

Site	Tree	L	$RD_{0\%}$
2	1	0.1	**494**
2	1	0.2	**511**
2	1	0.3	**479**
2	1	0.4	**498**
2	1	0.5	**474**
2	1	0.6	**501**
2	1	0.7	**471**
2	1	0.8	**518**
2	1	0.9	**510**
2	1	1	**521**
2	2	0.1	**581**
2	2	0.2	**494**
2	2	0.3	**552**
2	2	0.4	**575**
2	2	0.5	**547**
2	2	0.6	**551**
2	2	0.7	**563**
2	2	0.8	**595**
2	2	0.9	**587**
2	2	1	**630**
2	3	0.1	**598**
2	3	0.2	**578**
2	3	0.3	**609**
2	3	0.4	**655**
2	3	0.5	**609**
2	3	0.6	**599**
2	3	0.7	**667**
2	3	0.8	**579**
2	3	0.9	**564**
2	3	1	**547**

7.2.2 Juvenile trees data sets site 3 and 4

Site 3 JV

Site	Tree	L	$RD_{0\%}$
3	1	0.1	**476**
3	1	0.2	**508**
3	1	0.3	**476**
3	1	0.4	**476**
3	1	0.5	**477**
3	1	0.6	**485**
3	1	0.7	**463**
3	1	0.8	**493**
3	1	0.9	**408**
3	1	1	**509**
3	2	0.1	**629**
3	2	0.2	**559**
3	2	0.3	**537**
3	2	0.4	**565**
3	2	0.5	**566**
3	2	0.6	**552**
3	2	0.7	**593**
3	2	0.8	**595**
3	2	0.9	**530**
3	2	1	**623**
3	3	0.1	**644**
3	3	0.2	**647**
3	3	0.3	**652**
3	3	0.4	**624**
3	3	0.5	**648**
3	3	0.6	**592**
3	3	0.7	**587**
3	3	0.8	**579**
3	3	0.9	**614**
3	3	1	**610**

Site 4 JV

Site	Tree	L	$RD_{0\%}$
4	1	0.1	**593**
4	1	0.2	**576**
4	1	0.3	**577**
4	1	0.4	**556**
4	1	0.5	**556**
4	1	0.6	**579**
4	1	0.7	**599**
4	1	0.8	**586**
4	1	0.9	**572**
4	1	1	**582**
4	2	0.1	**637**
4	2	0.2	**505**
4	2	0.3	**554**
4	2	0.4	**506**
4	2	0.5	**503**
4	2	0.6	**509**
4	2	0.7	**597**
4	2	0.8	**642**
4	2	0.9	**575**
4	2	1	**583**
4	3	0.1	**564**
4	3	0.2	**530**
4	3	0.3	**517**
4	3	0.4	**519**
4	3	0.5	**469**
4	3	0.6	**472**
4	3	0.7	**444**
4	3	0.8	**439**
4	3	0.9	**443**
4	3	1	**443**

7.3 Breast height sampling data

7.3.1 Breast height sampling data site 1 and 2

Site 1 & 2

Site	Tree	L	R	**$RD_{0\%}$**	MOE	**MOR**	Compress	**Hardness**	**Strength**
1	1	Avg	0.25	**562**	6897	**67**	41	**3520**	**8**
1	1	Avg	0.50	**575**	7239	**68**	43	**3527**	**8**
1	1	Avg	0.75	**560**	7702	**69**	44	**3453**	**8**
1	1	Avg	1.00	**534**	7393	**66**	43	**3372**	**8**
1	1	BH	0.25	**526**	8570	**82**	42	**3370**	**8**
1	1	BH	0.50	**557**	9050	**86**	45	**3523**	**7**
1	1	BH	0.75	**562**	9325	**77**	46	**3550**	**7**
1	1	BH	1.00	**523**	9595	**81**	44	**3380**	**7**
1	2	Avg	0.25	**514**	7010	**66**	39	**3445**	**8**
1	2	Avg	0.50	**523**	7332	**67**	40	**3474**	**8**
1	2	Avg	0.75	**518**	7517	**68**	43	**3468**	**8**
1	2	Avg	1.00	**523**	7355	**68**	43	**3354**	**8**
1	2	BH	0.25	**491**	6920	**70**	36	**3370**	**8**
1	2	BH	0.50	**520**	7600	**72**	37	**3523**	**8**
1	2	BH	0.75	**528**	8486	**77**	45	**3550**	**8**
1	2	BH	1.00	**550**	7875	**78**	49	**3380**	**8**
2	1	Avg	0.25	**515**	8179	**77**	42	**3202**	**8**
2	1	Avg	0.50	**535**	8387	**80**	45	**3357**	**8**
2	1	Avg	0.75	**534**	8537	**83**	46	**3628**	**8**
2	1	Avg	1.00	**542**	8620	**85**	46	**3614**	**8**
2	1	BH	0.25	**532**	9218	**84**	47	**3387**	**7**
2	1	BH	0.50	**551**	9130	**86**	47	**3478**	**7**
2	1	BH	0.75	**560**	8470	**85**	50	**4550**	**8**
2	1	BH	1.00	**579**	6450	**76**	48	**3830**	**8**
2	2	Avg	0.25	**568**	8178	**80**	52	**3727**	**8**
2	2	Avg	0.50	**597**	8370	**82**	52	**3727**	**8**
2	2	Avg	0.75	**572**	8462	**85**	54	**3567**	**8**
2	2	Avg	1.00	**558**	8462	**85**	54	**3396**	**8**
2	2	BH	0.25	**494**	8498	**82**	53	**3990**	**8**
2	2	BH	0.50	**589**	8780	**84**	53	**3990**	**8**
2	2	BH	0.75	**585**	9100	**91**	58	**4183**	**7**
2	2	BH	1.00	**522**	9100	**91**	59	**3300**	**7**

7.3.2 Breast height sampling data site 3 and 4

Site 3 and 4

Site	Tree	L	R	$RD_{0\%}$	MOE	MOR	Compress	Hardness	Strength
3	1	Avg	0.25	493	7857	75	41	3360	8
3	1	Avg	0.50	520	8345	76	45	3570	8
3	1	Avg	0.75	505	8655	77	46	3673	8
3	1	Avg	1.00	485	8568	77	44	3651	8
3	1	BH	0.25	495	6770	72	39	3147	8
3	1	BH	0.50	526	8670	78	47	3767	8
3	1	BH	0.75	529	8730	83	50	3578	8
3	1	BH	1.00	501	8768	84	47	3580	8
3	2	Avg	0.25	579	9135	79	48	4068	7
3	2	Avg	0.50	592	9518	84	49	4118	7
3	2	Avg	0.75	606	9738	85	51	4205	7
3	2	Avg	1.00	573	9662	84	50	4028	7
3	2	BH	0.25	597	5800	57	46	4040	8
3	2	BH	0.50	629	7830	69	52	3890	8
3	2	BH	0.75	637	8480	70	53	4167	8
3	2	BH	1.00	606	9110	82	54	3870	7
4	1	Avg	0.25	581	7502	75	No Samples	3990	8
4	1	Avg	0.50	600	8053	81		4029	8
4	1	Avg	0.75	589	8756	87		4123	7
4	1	Avg	1.00	579	8972	89		3904	7
4	1	BH	0.25	570	9046	82		4130	7
4	1	BH	0.50	637	9136	84		5250	7
4	1	BH	0.75	629	10044	95		4580	6
4	1	BH	1.00	608	10076	102		4660	6
4	2	Avg	0.25	581	9969	95		3813	7
4	2	Avg	0.50	581	9870	95		3922	7
4	2	Avg	0.75	561	8947	92		3977	8
4	2	Avg	1.00	568	8198	89		3760	8
4	2	BH	0.25	594	10210	92		4068	6
4	2	BH	0.50	592	9870	105		4423	7
4	2	BH	0.75	561	9940	103		4148	7
4	2	BH	1.00	568	7190	86		4090	8

7.4 Ring analysis data

7.4.1 Ring density data

Site 1

Site	Tree	L	R	Ring Width	RD_{12}
1	1	0.1	0.25	4.39	711
1	1	0.1	0.5	6.57	679
1	1	0.1	0.75	5.61	661
1	1	0.1	1.0	3.41	624
1	1	BH	0.25	**4.41**	**549**
1	1	BH	0.5	**3.41**	**588**
1	1	BH	0.75	**4.52**	**564**
1	1	BH	1.0	**3.00**	**458**
1	1	1.0	0.25	2.50	432
1	1	1.0	0.5	3.05	458
1	1	1.0	0.75	8.14	596
1	1	1.0	1.0	4.78	578
1	2	0.1	0.25	**2.57**	**546**
1	2	0.1	0.5	**5.27**	**563**
1	2	0.1	0.75	**3.91**	**525**
1	2	0.1	1.0	**2.28**	**503**
1	2	BH	0.25	4.19	509
1	2	BH	0.5	4.97	560
1	2	BH	0.75	3.84	539
1	2	BH	1.0	1.92	496
1	2	1	0.25	**2.81**	**552**
1	2	1	0.5	**4.03**	**545**
1	2	1	0.75	**4.09**	**488**
1	2	1	1.0	**2.39**	**464**

Site 2

Site	Tree	L	R	Ring Width	RD_{12}
2	1	0.1	0.25	2.61	674
2	1	0.1	0.5	2.34	631
2	1	0.1	0.75	3.48	541
2	1	0.1	1.0	2.81	530
2	1	BH	0.25	**2.31**	**627**
2	1	BH	0.5	**2.21**	**625**
2	1	BH	0.75	**2.80**	**583**
2	1	BH	1.0	**3.02**	**528**
2	1	1	0.25	2.11	729
2	1	1	0.5	3.15	609
2	1	1	0.75	2.51	471
2	1	1	1.0	2.14	492
2	2	0.1	0.25	**2.61**	**603**
2	2	0.1	0.5	**2.61**	**631**
2	2	0.1	0.75	**0.90**	**645**
2	2	0.1	1.0	**1.03**	**622**
2	2	BH	0.25	2.46	577
2	2	BH	0.5	2.11	571
2	2	BH	0.75	0.80	519
2	2	BH	1.0	0.72	442
2	2	1	0.25	**0.76**	**635**
2	2	1	0.5	**1.16**	**569**
2	2	1	0.75	**1.31**	**521**
2	2	1	1.0	**0.90**	**448**

Site 3

Site	Tree	L	R	Ring Width	RD_{12}
3	1	0.1	0.25	2.61	674
3	1	0.1	0.5	2.34	631
3	1	0.1	0.75	3.48	541
3	1	0.1	1.0	2.81	530
3	1	BH	0.25	**2.31**	**627**
3	1	BH	0.5	**2.21**	**625**
3	1	BH	0.75	**3.17**	**585**
3	1	BH	1.0	**3.02**	**528**
3	1	1	0.25	2.11	729
3	1	1	0.5	3.15	609
3	1	1	0.75	2.51	471
3	1	1	1.0	2.14	492
3	2	0.1	0.25	**1.89**	**573**
3	2	0.1	0.5	**1.95**	**573**
3	2	0.1	0.75	**3.01**	**529**
3	2	0.1	1.0	**2.41**	**470**
3	2	BH	0.25	2.85	691
3	2	BH	0.5	3.40	681
3	2	BH	0.75	3.61	622
3	2	BH	1.0	3.89	470
3	2	1	0.25	**3.51**	**667**
3	2	1	0.5	**3.34**	**574**
3	2	1	0.75	**3.21**	**512**
3	2	1	1.0	**2.21**	**531**

Site4

Site	Tree	L	R	Ring Width	RD_{12}
4	1	0.1	0.25	2.02	566
4	1	0.1	0.5	2.22	631
4	1	0.1	0.75	1.55	665
4	1	0.1	1.0	1.62	567
4	1	BH	0.25	**2.20**	**664**
4	1	BH	0.5	**2.67**	**631**
4	1	BH	0.75	**1.62**	**588**
4	1	BH	1.0	**1.43**	**509**
4	1	1	0.25	1.73	621
4	1	1	0.5	1.11	519
4	1	1	0.75	1.20	571
4	1	1	1.0	0.89	485
4	2	0.1	0.25	**1.33**	**656**
4	2	0.1	0.5	**1.51**	**577**
4	2	0.1	0.75	**2.81**	**567**
4	2	0.1	1.0	**2.69**	**489**
4	2	BH	0.25	1.72	601
4	2	BH	0.5	1.25	600
4	2	BH	0.75	2.02	564
4	2	BH	1.0	2.23	567
4	2	1	0.25	**2.37**	**680**
4	2	1	0.5	**1.96**	**545**
4	2	1	0.75	**1.09**	**541**
4	2	1	1.0	**1.15**	**555**

7.4.2 Ring ANOVA

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	RingDensity	24905.250[a]	4	6226.313	20.286	.000
	PercentLatewood	88.750[b]	4	22.188	3.921	.032
	LatewoodRingDensity	57424.500[c]	4	14356.125	6.884	.005
	RingWidth	15.240[d]	4	3.810	4.127	.028
Intercept	RingDensity	5029927.563	1	5029927.563	16388.072	.000
	PercentLatewood	24025.000	1	24025.000	4245.382	.000
	LatewoodRingDensity	8664192.250	1	8664192.250	4154.356	.000
	RingWidth	105.216	1	105.216	113.962	.000
Site	RingDensity	18465.187	3	6155.062	20.054	.000
	PercentLatewood	32.500	3	10.833	1.914	.186
	LatewoodRingDensity	42662.250	3	14220.750	6.819	.007
	RingWidth	12.426	3	4.142	4.486	.027
Bolt	RingDensity	6440.063	1	6440.063	20.982	.001
	PercentLatewood	56.250	1	56.250	9.940	.009
	LatewoodRingDensity	14762.250	1	14762.250	7.078	.022
	RingWidth	2.814	1	2.814	3.048	.109
Error	RingDensity	3376.188	11	306.926		
	PercentLatewood	62.250	11	5.659		
	LatewoodRingDensity	22941.250	11	2085.568		
	RingWidth	10.156	11	.923		
Total	RingDensity	5058209.000	16			
	PercentLatewood	24176.000	16			
	LatewoodRingDensity	8744558.000	16			
	RingWidth	130.612	16			
Corrected Total	RingDensity	28281.438	15			
	PercentLatewood	151.000	15			
	LatewoodRingDensity	80365.750	15			
	RingWidth	25.396	15			

a. R Squared = .881 (Adjusted R Squared = .837)

b. R Squared = .588 (Adjusted R Squared = .438)

c. R Squared = .715 (Adjusted R Squared = .611)

d. R Squared = .600 (Adjusted R Squared = .455)

7.4.3 Ring width and percent latewood

Descriptive Statistics

Specimen	Mean
S1T1B1Ringwidth	4.6595
S1T1BbhRingwidth	3.7330
S1T1B10Ringwidth	4.0033
S1T2B1Ringwidth	3.1436
S1T2BbhRingwidth	3.3427
S1T2B10Ringwidth	2.9840
Average	3.64
S2T1B1Ringwidth	1.5006
S2T1BbhRingwidth	1.6125
S2T1B10Ringwidth	1.1352
S2T2B1Ringwidth	1.4099
S2T2BbhRingwidth	1.1366
S2T2B10Ringwidth	.9862
Average	1.30
S3T1B1Ringwidth	2.7528
S3T1BbhRingwidth	2.6044
S3T1B10Ringwidth	2.4509
S3T2B1Ringwidth	3.3768
S3T2BbhRingwidth	2.2687
S3T2B10Ringwidth	2.9733
Average	2.74
S4T1B1RingWidth	5.1882
S4T1BbhRingWidth	1.8184
S4T1B10Ringwidth	1.1600
S4T2B1Ringwidth	1.8442
S4T2BbhRingwidth	1.7002
S4T2B10Ringwidth	1.4695
Average	2.20

Descriptive Statistics

Specimen	Mean
S1T1B1LatewoodPercent	38
S1T1BbhLatewoodPercent	35
S1T1B10LatewoodPercent	32
S1T2B1LatewoodPercent	41
S1T2BbhLatewoodPercent	42
S1T2B10LatewoodPercent	36
Average	37
S2T1B1LatewoodPercent	41
S2T1BbhLatewoodPercent	39
S2T1B10LatewoodPercent	36
S2T2B1LatewoodPercent	43
S2T2BbhLatewoodPercent	38
S2T2B10LatewoodPercent	36
Average	39
S3T1B1LatewoodPercent	37
S3T1BbhLatewoodPercent	40
S3T1B10LatewoodPercent	41
S3T2B1LatewoodPercent	39
S3T2BbhLatewoodPercent	41
S3T2B10LatewoodPercent	37
Average	39
S4T1B1LatewoodPercent	42
S4T1BbhLatewoodPercent	41
S41TB10LatewoodPercent	37
S4T2B1LatewoodPercent	44
S4T2BbhLatewoodPercent	41
S4T2B10LatewoodPercent	40
Average	41

7.4.4 Earlywood density, latewood density, and ring density

Descriptive Statistics

Specimen	Mean
S1T1B1EarlywoodDensity	339
S1T1BbhEarlywoodDensity	343
S1T1B10EarlywoodDensity	279
S1T2B1EarlywoodDensity	336
S1T2BbhEarlywoodDensity	336
S1T2B10EarlywoodDensity	312
Average	324
S2T1B1EarlywoodDensity	355
S2T1BbhEarlywoodDensity	338
S2T1B10EarlywoodDensity	347
S2T2B1EarlywoodDensity	383
S2T2BbhEarlywoodDensity	371
S2T2B10EarlywoodDensity	353
Average	358
S3T1B1EarlywoodDensity	400
S3T1BbhEarlywoodDensity	423
S3T1B10EarlywoodDensity	171
S3T2B1EarlywoodDensity	408
S3T2BbhEarlywoodDensity	357
S3T2B10EarlywoodDensity	330
Average	348
S4T1B1EarlywoodDensity	346
S4T1BbbEarlywoodDensity	389
S4T1B10EarlywoodDensity	383
S4T2B1EarlywoodDensity	314
S4T2BbhEarlywoodDensity	340
S4T2B10EarlywoodDensity	353
Average	354

Descriptive Statistics

Specimen	Mean
S1T1B1LatewoodDensity	665
S1T1BbhLatewoodDensity	732
S1T1B10LatewoodDensity	608
S1T2B1LatewoodDensity	728
S1T2BbhLatewoodDensity	738
S1T2B10LatewoodDensity	624
Average	682
S2T1B1LatewoodDensity	828
S2T1BbhLatewoodDensity	842
S2T1B10LatewoodDensity	794
S2T2B1LatewoodDensity	838
S2T2BbhLatewoodDensity	887
S2T2B10LatewoodDensity	729
Average	820
S3T1B1LatewoodDensity	730
S3T1BbhLatewoodDensity	727
S3T1B10LatewoodDensity	640
S3T2B1LatewoodDensity	823
S3T2BbhLatewoodDensity	679
S3T2B10LatewoodDensity	731
Average	722
S4T1B1LatewoodDensity	720
S4T1BbhLatewoodDensity	877
S4T1B10LatewoodDensity	727
S4T2B1LatewoodDensity	798
S4T2BbhLatewoodDensity	872
S4T2B10LatewoodDensity	791
Average	798

Descriptive Statistics

Specimen	Mean
S1T1B1Density	506
S1T1BbhDensity	535
S1T1B10Density	492
S1T2B1Density	530
S1T2BbhDensity	520
S1T2B10Density	484
Average	511
S2T1B1Density	568
S2T1BbhDensity	555
S2T1B10Density	557
S2T2B1Density	629
S2T2BbhDensity	580
S2T2B10Density	549
Average	573
S3T1B1Density	600
S3T1BbhDensity	596
S3T1B10Density	570
S3T2B1Density	626
S3T2BbhDensity	541
S3T2B10Density	567
Average	583
S4T1B1Density	604
S4T1BbhDensity	616
S4T1B10Density	538
S4T2B1Density	583
S4T2BbhDensity	579
S4T2B10Density	568
Average	582