LUMBER RECOVERY, A LEAF AREA MODEL, AND WATER USE IN RESPONSE TO COMMERCIAL THINNING FOR PLANTATION-GROWN BLACK SPRUCE (*PICEA MARIANA* [MILLS] B.S.P.)

by

Steven M. Young

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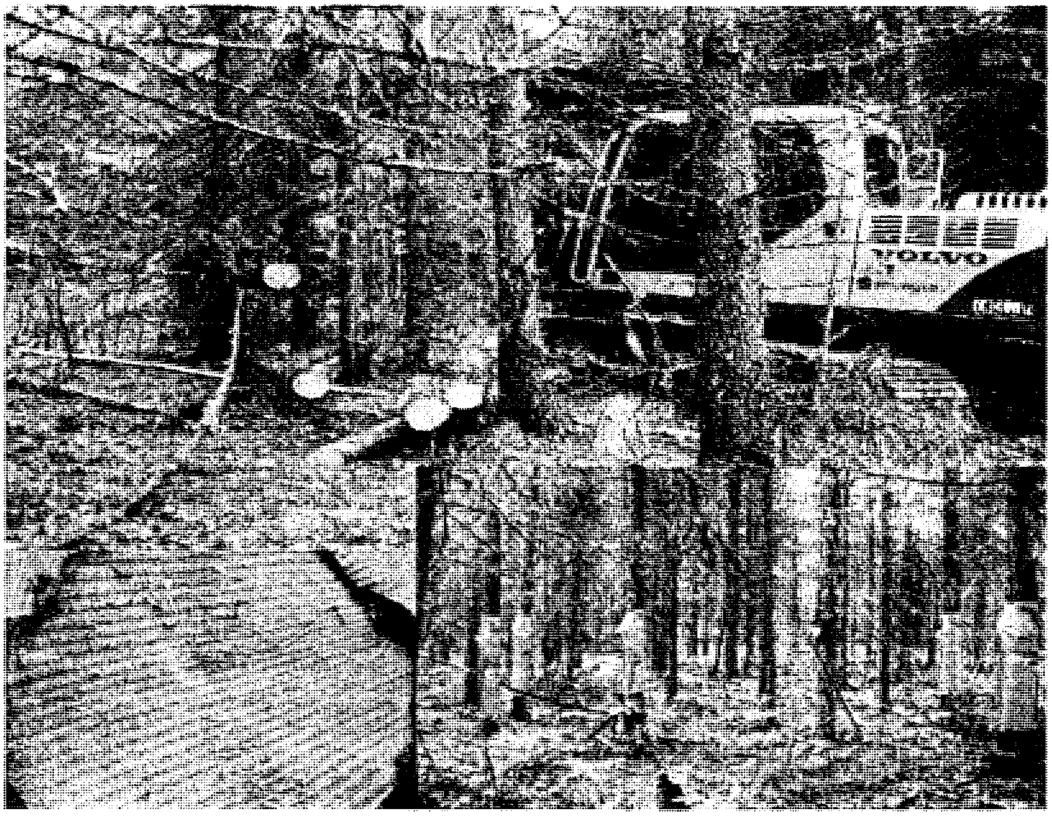

Faculty of Forestry and the Forest Environment

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September 2008

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Abstract

Young, S.M. 2008. Lumber recovery, a model to predict leaf area, and water use in response to thinning in plantation grown black spruce (Picea mariana [Mills] B.S.P.), 95 pp.

Key words: Black Spruce, Commercial Thinning, Daily Water Use, Density Management, Economic Value, Plantations, Leaf Area: Sapwood Area Relationship, Lumber Grade Recovery, Lumber Quality, Penetrometer, Residual Stand Damage, Sapflow, Site Disturbance, Soil Disturbance, Stomatal Conductance, Transpiration

Three black spruce (*Picea mariana* [Mills] B.S.P.) plantations (Airstrip, Boom Lake and Tyrol Lake), in northwestern Ontario, with varied stand densities (2806 stems ha^{-1}, 2285 stems ha^{-1}, and 3578 stems ha^{-1}, respectively) and site indices (11.8 m, 13.3 m, 10.9 m, respectively) were studied to determine lumber properties and yield and to develop a model to predict leaf area. The Boom Lake site was also studied to assess the impacts of site disturbance and residual tree damage from commercial thinning on tree water use.

With respect to lumber recovery, all three sites produced over 87% No. 2 and Better grades lumber. Wane and skip were the two most prominent defects causing lumber downgrades. The lowest quality site with the highest stand density produced significantly stronger (modulus of rupture, MOR) and stiffer (modulus of elasticity, MOE) lumber than either the best quality site with a lower stand density or the medium quality site with a similar stand density. The best site with the lowest stand density also produced significantly stronger and stiffer lumber than the medium site with higher stand density. Lumber sawn from log sections taken from below the live crown were significantly stronger but not significantly stiffer than lumber sawn from logs from within the live crown. There were no significant differences in bending MOE and MOR between visual grades. Economy grade lumber was denser than the other grades and had a smaller average ring width than the Grades No. 1 and No. 2. There were weak negative relationships between average ring width and basic wood density. There were weak positive relationships between basic wood density and MOE or MOR. Three scenarios were examined for relative economic return. Regardless of economic scenario, the Boom site (best site quality) produced the highest value per hectare followed by Tyrol (poorest site quality) and then Airstrip. Generally, MSR grading produced the highest value per hectare (maximum $28,000/ha at the Boom site).

The model to predict whole tree leaf area was developed from 37 plantation grown black spruce trees collected from all 3 sites. Allometric equations to describe needle weight (W_n), leaf area (A_l) and A_l: breast height sapwood area (A_s) relationships are described. Specific leaf area (SLA, m^2/g) was measured on needles from 4 needle age classes on 4 sub-sampled branches taken from 3 crown sections of equal length on each of the 37 trees. SLA varied by site, needle age and crown section. SLA of needles from the Airstrip was significantly larger than those from the Tyrol site, while needle SLA from the Boom site was not significantly different from either. Linear and nonlinear allometric models were built to appropriately scale up to whole tree leaf area based on live branch diameters measured in the field, and compared against trees (9 total, 3 from each site) where the entire crown was collected. Nonlinear models for crown sections 1 (top section) and 2 (middle section) revealed an unbiased predictive ability whereas both linear and nonlinear models showed a general tendency to over predict the needle weight of crown section 3 (bottom section). Nevertheless, a linear model to predict A_l from A_s was developed that showed to no evidence of bias.

Sapflow was measured from May 2007 to August 2008 to assess the impacts of site disturbance and residual tree damage from commercial thinning on tree water use. Twelve black spruce trees were instrumented with thermal dissipation sap flow sensors in the spring following a fall season harvest. Soil resistance to penetration was measured with an Eijkelkamp 06.15.SA model Penetrologger Set. The twelve trees were classified based on damage and adjacency to trails resulting in 4 treatment groups; TD (adjacent to the trail with apparent damage), TN (adjacent to the trail with no damage), ID (away from the trail with apparent damage) and IN (away from the trail with no damage). There was no significant difference between the soil resistance to penetration on or between harvest trails. Daily water use (Q_d) was a high as 20.71 l day^{-1} and as little as 0.06 l day^{-1}. There were no significant differences detected between treatment groups for diameter at breast height (DBH), height (H), length of live crown (LC), sapwood area (A_s) or leaf area (A_l). The TD trees appeared to have the lowest Q_d, while the TN trees appeared to have lowest mean sap velocity (v_s) and low Q_d. Transpiration (Q_l) and stomatal conductance (G_c) levels appeared to generally be lower for the TN group when compared to other treatment groups. The data suggests that Q_l and G_c may not be affected by adjacency to trails and/or mechanical damage in the first year following thinning treatment.

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I would like to thank the following funding contributors who have been vital in helping me pursue my endeavor and gain these phenomenal experiences: Supervisor Dr. Douglas Reid – Ontario Ministry of Natural Resources (OMNR), Centre for Northern Forest Ecosystem Research (CNFER); Natural Science and Engineering Research Council (NSERC) for the Industrial Postgraduate Scholarship (IPS); my industrial sponsor for the IPS, the Forest Ecosystem Science Co-op and co-op partner Domtar Inc. I would also like to extend my gratitude to Committee member Dr. Dave Morris (OMNR – CNFER) for helping build statistical models, reviewing documents and providing summary numbers for model building; Committee member Dr. Lense Meyer for feedback during the project development and Committee member Janet Lane for feedback during the project development, representing the Forest Science Ecosystem Co-op and for setting up a work station with the Domtar group in Dryden, ON; Philippe Meek of FERIC for helping answer questions and assisting in the modeling of harvest systems; Nick Buda (OMNR-CNFER) for providing summary numbers for model building; Eric Kahkonen and the numerous technical staff at CNFER for helping gather field data, set up plots and maintenance of equipment; Dr. S.Y. Zhang, Dr. Tessie Tong, and Francis Tanguay of FPInnovations – Forintek Division for guidance, field and laboratory analysis with the wood properties section; Garth Wintle of OMNR Northwestern Regional Fire Centre for providing supplementary weather data; and the staff of the OMNR's Provincial Measurement Unit (Ken Widdifield, Bill Renaud, Brian Duquette, Nick Dryhorub and Noelle Dumas) for providing me with volume and defect data pertinent to explanations.

Dedication

I dedicated this to my wife, Anne, my son, Alexander, our families and our friends, as well as colleagues who help along the way. I may not have completed this opportunity without the support and encouragement of my family and closest friends. Thanks to everyone who was there in the good and the bad times. I appreciated it very much.

Table of Contents

List of Figures

List of Tables

Chapter 1: Commercial thinning: a literature review of commercial thinning, physiological expectations, and effects on the site and stand.

1.1 Introduction

A reduction in basal area (henceforth referred to as thinning) of forest stands are becoming of interest in northern Ontario with regard to boreal tree species. With the continued pressure on wood supply and the expected shortfall of harvestable timber in northern Ontario, there is a need to assess how to acquire additional fibre (Day 1997; Ontario Ministry of Natural Resources [OMNR] 2000). Short-term rotation forestry may be a tool in a forest management strategy to meet demands when supply is low. The goals of short-term rotation forestry are to improve and maintain stand condition and growth (Meek 2000). Commercial thinning is a secondary management objective, within a short-term rotation management plan, where a portion of the harvested timber meets commercial specifications and is marketable (Meek 2000). If thinning is not commercially viable then it should be considered an investment similar to other intensive management scenarios (*i.e.,* tree planting) (Meek 2000).

It is important to be aware of and understand the underlying physiological responses of trees to varied stresses. Physiologically, trees respond differently to different stresses. Thinning can introduce stresses resulting from extraction roads and traffic leading to compaction (Nadezhdna *et al.* 2006; Miller *et al.* 1995) or from new canopy openings that increase light intensity. There have been many studies that look at the physiological response of trees to thinning and varied thinning intensities. Soil water availability and individual tree water use will increase with the removal of competing trees (Feeney *et al.* 1998; Kolb *et al.* 1998; McDowell *et al.* 2003; McJannet and Vertessy 2001; Reid *et al.* 2006; Sala *et al.* 2005; Zausen *et al.* 2005).

Primarily, thinning increases the light availability per tree (Lagergren and Lindroth 2004). In turn, increased light availability enhances the physiological activity to the lower crown positions foliage (Medhurst and Beadle 2005; Tang *et al.* 2003). Tang *et al.* (2003) reported for loblolly pine (*Pinus taeda* L.) growing in the gulf coastal plain region, photosynthesis was highest in the spring and closely related to light intensity. McJannet and Vertessy (2001) noted that eucalyptus (*Eucalyptus globulus* Labill.) trees growing on the edge (a boundary between different stands and/or openings (Cancino 2005)) of plantations tended to be the largest. The 'edge effect' for *E. globulus* was noticeable for approximately 9 meters (McJannet and Vertessy 2001). However, edge effect could be expected to vary by (1) species composition (due to silvics), (2) density and (3) the type of edge (*i.e.,* open edge to forested edge vs. forested edge to forested edge) (Delgado *et al.* 2007; Li *et al.* 2007). Responses to these stresses could be used to guide the development of management decisions by foresters.

Thinning increases physiological activities in individuals resulting in increased growth, carbon uptake, water and nitrogen use (Feeney *et al.* 1998). Some species, such as *E. globulus* growing in drought prone areas, reduce transpiration rate to conserve water within the plant (McJannet and Vertessy 2001). Tree competition increases the strain on water resources (Zausen *et al.* 2005) and thinning can potentially alleviate a portion of this stress (Feeney *et al.* 1998; Kolb *et al.* 1998; McDowell *et al.* 2003; McJannet and Vertessy 2001; Reid *et al.* 2006; Sala *et al.* 2005). Tree vigor is a measure of tree growth to a hypothetical optimum (Drew and Flewelling 1977; 1979; Luther and Carroll 1999; Waring *et al.* 1980). Luther and Carroll (1999) reported that stressed balsam fir (*Abies balsamea* (L.) Mill.) trees have decreased tree vigor. Thinning may be able to capture future volume losses by removing trees of poor vigor while helping to increase resources to residual trees.

The way a tree responds physiologically could be used to determine which management practice(s) is best applied to a particular forest stand (Wang *et al.* 1995). Literature on thinning and physiology has identified several areas of focus for evaluating the physiological response of trees to thinning regimes. Several key areas of interest include effects on photosynthetic response, effects on nutrient usage, effects on water movement and use, effects on residual tree growth and levels of site damage or disturbance. An understanding of these physiological processes can help develop a silviculture monitoring plan that encompasses both pre- and post-thinned stands.

1.2 Commercial Thinning

1.2.1 Background

The development and use of the commercial thinning practice is deeply rooted in European countries (Day 1997; James and Tarlton 1990). The change from mass resource availability to scarcity in forest resources centuries ago initiated a change in forest management practices in European nations (Day 1997) and led to the creation of short-term rotation forestry.

The essence, or underlying purpose, of thinning is density management. Density management begins with an understanding of how density (*i.e.,* stems per hectare), height and volume interact. Research by Yoda *et al.* (1963) led to the development and understanding of the 3/2 (actually -3/2) self-thinning law (as reported in Drew and Flewelling 1977). The 3/2 self-thinning law describes the point where competition between neighboring plants of similar size will induce mortality and begin to naturally reduce density. Figure 1 illustrates the relationship between density, volume and the self-thinning law. Plants growing at higher densities (*e.g.,* Figure 1; vertical line 1) will begin to self-thin at lower volumes than plants at lower densities (*e.g.,* Figure 1; vertical line 4), due to competition induced mortality.

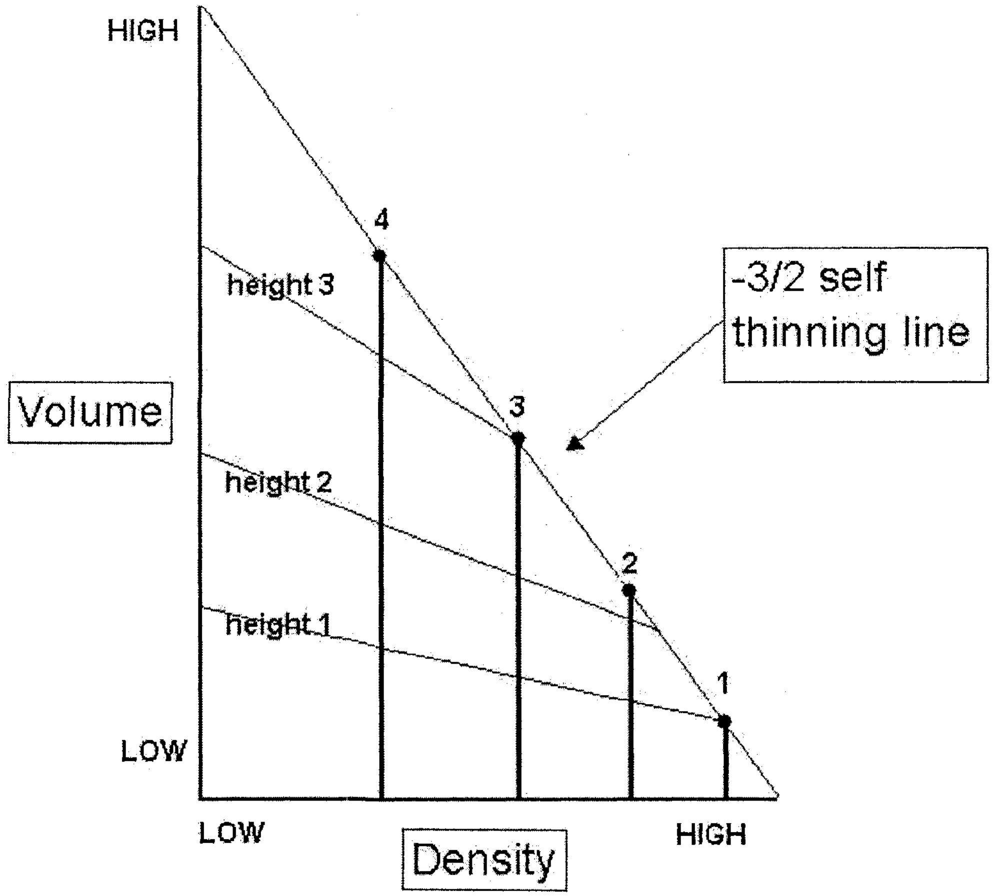

Figure 1. Simplified, conceptual density management diagram explaining the relationship between the self-thinning law, height, volume and density. Numbers 1 – 4 indicate where self-thinning is likely to occur for a given density (Drew and Flewelling 1977).[1]

Drew and Flewelling (1977, 1979) discussed relationships between individual tree vigor and mortality, specifically the concept of the zone of imminent competition mortality. The zone of imminent competition mortality is the line above which competition mortality starts to occur. Understanding these concepts of density management is fundamental to an efficient use of thinning practices. Commercial thinning should always be about individual tree selection that will improve the desirable characteristics of the residual stand (Meek 2000; Mitchell 2004). By selecting trees of poorer quality to harvest, thinning operations can reduce stand density while

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[1] Figure 1 is a simplified version of the density management diagram. Please refer to Drew and Flewelling (1977) for accurate axis scales, proper curves and actual density management diagrams.

improving stand quality and thus reduce the likelihood of individual tree mortality due to competition. Secondary objectives, or alternate motives, should not be pursued at the expense of improving the residual stand (*i.e.,* harvesting a single-stemmed tree before a forked tree) (Nyland 1996).

Nyland (1996) presented 5 thinning methods: 1) thinning from below (removing trees in lower canopy positions), 2) thinning from above (removing some dominant and co-dominant trees), 3) selection thinning (removing larger trees favoring smaller trees with good growth form), 4) mechanical thinning (either removal of selected plantation rows or removing the neighboring trees of a crop tree) and 5) free thinning or crop tree release (favoring elite trees by removing trees that compete for similar crown space). The most common methods of commercial thinning in use today are thinning from above and thinning from below (Day 1997).

1.2.2 Cost-Benefit Analysis

Management objectives will be the driving force behind whether or not commercial thinning is a viable management tool. When comparing the present day value of a first entry commercial thinning to a typical clear-cut logging scenario, commercial thinning is more expensive than clear-cut logging (estimated nearly \$16 more per m^3), Table 1[2] (Interface 2006).

Forest harvest operations are not all the same with respect to processes. Mechanical cut-to-length systems typically involve felling (Figure 2a), delimbing and processing the tree to specified lengths at the stump, using a single piece of equipment. The processed wood is later moved to roadside using a forwarder. Mechanical full tree systems typically involve felling the tree and then placing the felled tree(s) in bunches as the harvester moves around the harvest block (Figure 2b). A skidder then moves the felled trees to roadside where a delimber removes the branches.

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[2] Table 1 provided complements of FERIC, (Interface 2006), with numbers provided from comparable stands complements of researchers Dr. David Morris and Dr. Douglas Reid with the Ontario Ministry of Natural Resources', Centre for Northern Forest Ecosystem Research.

Table 1. Comparison of the costs associated with a first entry commercial thinning (mechanical) to the cost associated with clear-cut harvesting (mechanical), at present day value (Interface 2006).

Cut-to-length			Full-tree	
	CT	Clear cutting		
Average tree size (m^3)	0.06^{*1}	0.1^{*2}	0.1^{*2}	
Felling-processing (\$/m^3)	21.36	10.78	5.35	Felling (\$/m^3)
Forwarding (0-300 m) (\$/m^3)	7.27	5.82	5.31	Skidding (0-300 m) (\$/m^3)
	-	-	5.94	Delimbing (\$/m^3)
Supervision (\$/m^3)	2.50	-	-	
Profit + other charges (\$/m^3)	3.11	1.66	1.66	
Total roadside (\$/m^3)	34.25	18.26	18.26	
CT – CC cost differences (\$/m^3)		15.99		

*1: numbers generated from inventory data measured in the Limestone Lake black spruce plantations; 45 years old; density = 2500 stems/ha; Net Merchantable Volume = 160 m^3/ha.
*2: numbers based on natural conifer stands in northern Ontario with similar site characteristics as the Limestone Lake plantations; 100-120 years old; density = 2100 stems/ha; Net Merchantable Volume = 203 m^3/ha.

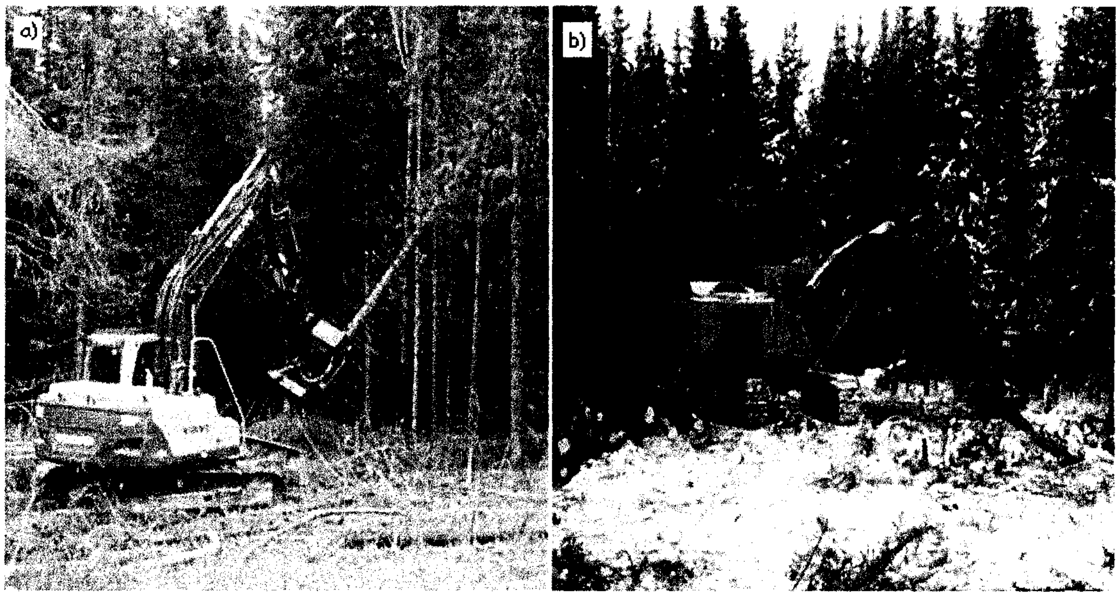

Figure 2. examples of harvesting equipment used in a) cut-to length systems and b) full tree systems.

Associated costs are really dependant upon the processes involved within each harvest system. If trees are to be slashed at the roadside (the process of turning full trees into specified lengths) the cost associated with the full tree systems will increase (not included in the cost scenario, Table 1). Higher costs of thinning can be attributed to such things as: slower productivity per machine hour (a function of individual tree piece size and the time required to harvest the stem), the skill of machine operators (quickly being able to select appropriate trees), the sensitivity of machines to mechanical down time (smaller machines tend to require more maintenance), time required to load and move logs from the harvest block to roadside (Meek 2000; Mitchell 2004). Overall system costs (commercial thinning or clear cut harvesting) are closely linked to individual piece size (Table 1) so as piece size increases, costs decrease (a function of productivity) (Meek 2000; Mitchell 2004).

Considerations for commercial thinning (or thinning in general) should be balanced in the overall picture. Proper forecasting should take into account future stand structure, increased productivity, an already established road network and expected revenues (Meek 2000). Understanding of current and future stand age class structure and volume targets will allow for proper management planning incorporating tools, such as planting, precommercial and commercial thinning, and balancing expected targets (Day 1997; Meek 2000).

The benefits from commercial thinning depend on the context of the management strategy. For example, if there is an expected shortfall in fibre supply then commercial thinning presents an option for meeting short-term fibre supply without compromising the sustainability of future stocks. Essentially, forest managers today (who may be expecting lower harvestable volumes) can borrow from a surplus in the future.

Another benefit can come from the quality of round-wood being delivered to mills. As trees age and compete for resources within the stand, disease and natural mortality will occur (Drew and Flewelling 1979; 1977). For example, in northwestern Ontario there is a comprehensive sampling strategy in place for measuring defect (rotten, diseased or void portions of a log) by the Ministry of Natural Resources (OMNR 2007). Preliminary numbers, obtained from their Provincial Measurement Unit, indicate that there are less defective characteristics in wood harvested at the time of first entry thinning in black spruce (*Picea mariana (Mill.) B.S.P.*) plantations. Stands harvested at typical rotation age have a defect factor of 5.8% for spruce on the Lake Nipigon forest (OMNR 2007). The preliminary defect factor for spruce harvested from the Limestone Lake thinning area is 0.7% (OMNR 2007). Woods and Penner (2000) noted that *Armillaria* spp. (root rot) caused high mortality in sample plots of red pine (*Pinus resinosa* Ait.) where density competition was high but thinned stands did not experience similar mortality.

Thinning rotation and thinning intensity should also be considered. Hyytiainen and Tahvonen (2002) find that increasing the number of thinnings or the intensity of the removal can increase the rotation period, in Norway spruce (P*icea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.). By increasing thinning frequency, stands are being maintained near optimal states and growth can be expected beyond typical rotation periods (Hyytiainen and Tahvonen, 2002).

Product recovery should be an important consideration in planning commercial thinning operations. Due to the nature of commercial thinning operations, there are often large quantities of wood that are below minimum saw log utilization criteria (Meek 2000). Managers need to consider what product they desire, because if the desire is saw log or veneer material (which have minimum piece size and quality requirements) commercial thinning operations may not be able to provide immediate results. However, there may be an opportunity for a fibre trade. For example, if an area is clear cut for pulp material and the wood is useable for saw logs, then an agreement could be in place to exchange fibre whereby small wood from the thinning goes to a pulp mill and large wood from the conventional harvest goes to saw mill.

1.3 Physiological Responses

1.3.1 Photosynthesis/CO_2 Assimilation

Photosynthesis, the process of using light energy to fix carbon (Lambers *et al.* 2006) (sometimes referred to as carbon assimilation) is influenced by many factors. The processes that drive photosynthesis (*e.g.*, stomatal conductance, water use) within the leaf can be affected by the thinning of a stand (Luther and Carroll 1999; McDowell *et al.* 2003; 2006). Net photosynthesis (a.k.a. assimilation) is the transformation of inorganic compounds into organic compounds (Lambers *et al.* 2006) generally expressed on a leaf area basis. Within individual trees, net photosynthesis increases as density decreases (Medhurst and Beadle 2005; Tang *et al.* 1999; Waring *et al.* 1981). Generally, thinning increases the net photosynthesis of individual trees that contribute to the processes that fix carbon (Kolb *et al.* 1998; Medhurst and Beadle 2005; Sala *et al.* 2005; Tang *et al.* 1999; Wang *et al.* 1995).

The most notable aspect of a thinning is the increase in light availability to the lower and middle sections of the crown canopy (Gravatt *et al.* 1997; Tang *et al.* 1999; Wang *et al.* 1995). Increasing light to the lower and middle crowns will increase the overall stomatal conductance (exchange of CO_2 and/or water vapour through the stomata (Lambers *et al.* 2006)) and photosynthesis for a tree (Gravatt *et al.* 1997; McDowell *et al.* 2006; Medhurst and Beadle 2005; Sala *et al.* 2005; Tang *et al.* 1999; 2003). Medhurst and Beadle (2005) show that photosynthesis in eucalyptus (*E. nitens* (Deane and Maid.) Maid.) trees increased in the middle and lower crown positions as well as for the entire tree after thinning. However, Gravatt *et al.* (1997) note that photosynthetic activity is less in the upper crown of thinned loblolly pine trees than unthinned trees. McDowell *et al.* (2003) measured dominant ponderosa pine (*P. ponderosa* Dougl. Ex P. & C. Laws) trees during their study and noticed that the trees do not experience physiological changes to light availability after thinning. This could be expected since dominant trees already have the greatest access to light resources. Wang *et al.* (1995) report, for paper birch (*Betula papyrifera* Marsh.) growing in British Columbia, that leaves in thinned stands are more photosynthetically active than those of unthinned stands. This increase is associated with the per tree availability of photosynthetically active radiation (the light range between 400 and 700nm that drives photosynthesis (Lambers *et al.* 2006)), as well as higher foliar nitrogen concentrations (Wang *et al.* 1995). Such increases may not otherwise be available in denser stands or stands with higher leaf area index. Leaf area index refers to the total leaf area per unit of ground

(Lambers *et al.* 2006). Waring *et al.* (1981) find that Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands with higher leaf areas have lower rates of assimilation. Binkley and Reid (1984) find that thinning reduces the leaf area and is still noticeable 20-30 years after treatment, in Douglas fir stands.

Increased light penetration in the afternoon hours increases photosynthesis, stomatal conductance and transpiration in lower canopy foliage (Gravatt *et al.* 1997). However, there is concern with regards to thinning and the response of trees that have been suppressed from light for along time. Heavily suppressed trees reduce stomatal conductance and show no immediate increases in transpiration or hydraulic conductance (Simonin *et al.* 2006). Shade leaves and older foliage are unable to increase carbon assimilation to levels similar to sun leaves (Brooks *et al.* 1996) and new foliage (Medhurst and Beadle 2005) at full sunlight conditions. This indicates that trees below the upper canopy may have an extended delay to the response of the opening.

1.3.2 Transpiration and stomatal conductance

Many studies have shown that thinning increased the transpiration and stomatal conductance on foliage of residual trees. Transpiration is water loss associated with evaporation from within the leaf whereas stomatal conductance is the conductance of CO_2 or water through the stomata (Lambers *et al.* 2006). Sapflow, being a good approximation of tree transpiration (Granier *et al.* 1996), would indicate the tree level water use response to thinning. Sapwood area is the measure of the surface area of xylem vessels that move water through the tree. Thinning reduced stand level sapwood area (Reid *et al.* 2006) due to a reduction in stems per unit area but individual tree sapwood area can increase (Morling and Valinger 1999). Thinning also reduced the leaf area to sapwood area ratio (Granier *et al.* 1996; Morling and Valinger 1999; Reid *et al.* 2006; Simonin *et al.* 2006) due to the increase in individual tree sapwood area (subsequent increases in stand level sapwood area), the decrease in stand level leaf area or a combination of the two.

McDowell *et al.* (2003) used a method of carbon isotope discrimination to determine that stomatal conductance increased for dominant ponderosa pine in relation to the photosynthesis. Carbon isotope discrimination is a method of measuring specific carbon isotopes from the canopy gas exchange that are locked within the cellulose of tree rings. Transpiration and stomatal conductance can be expected to initially decreased as a result of thinning (Simonin *et al.* 2006). However Reid *et al.* (2006) noted that for lodgepole pine (*P. contorta*), thinned stands experienced immediate water stress (shown by a decrease in sapflow) but sapflow rates and stomatal conductance increase over time. Simonin *et al.* (2006) noted similar observations as Reid *et al.* (2006) for ponderosa pine, in which trees experience thinning shock and initially reduced stomatal conductance only to increase after a short period.

Increases in transpiration and stomatal conductance can be attributed to the physiological production of foliage in their respective crown position (Brooks *et al.* 1996; Feeney et al 1998; Gravatt *et al.* 1997; Medhurst and Beadle 2005; Simonin *et al.* 2006; Tang *et al.* 1999; 2003). Post thinning measurements show transpiration and stomatal conductance increased in the lower canopy (Tang *et al.* 2003). Tang *et al.* (2003) suggested that unthinned stands have higher levels of transpiration and stomatal conductance in upper canopy than the lower canopy positions. Thinned stands increase transpiration and stomatal conductance in lower canopy positions where they exhibit similar rates to upper canopy positions (Tang *et al.* 2003). This provides an overall increase in total transpiration and stomatal conductance.

1.3.3 Water Potential and Soil Moisture

Water movement from the soil, through the tree, to the leaves is the primary supply for physiological processes, such as photosynthesis (Lambers *et al.* 2006). Thinning has been reported to affect water movement and water use in several ways. Soil to leaf hydraulic conductance is upward movement of water, through the xylem vessels, from the roots to the leaf. Thinning is known to increase soil to leaf hydraulic conductance (Lambers *et al.* 2006; Simonin *et al.* 2006). Soil moisture is affected by soil physical properties, such as soil texture, particle size, organic matter and porosity (Krzic *et al.* 2004; Page-Dumroese *et al.* 2006; Stone *et al.* 1998; Sturm *et al.* 1996). Soil moisture conditions relate directly to the transpiration, water movement within trees (Simonin *et al.* 2006) and other plant physiological process (Lundblad and Lindroth 2002; Sturm *et al.* 1996). Frequency of rainfall events has an impact on available moisture and tree response (McJannet and Vertessy 2001; Tang *et al.* 1999). Drought-induced reductions of hydraulic conductance and transpiration can be less severe in thinned stands (McJannet and Vertessy 2001; Simonin, *et al.* 2006). Tang *et al.* (1999) report thinning to have little effect on water potential for stands of loblolly pine with frequent rainfall events, in Louisiana. As well, heavily suppressed trees reduce stomatal conductance when the canopy around them are opened as result of thinning (Simonin *et al.* 2006; Waring *et al.* 1980). Reducing stomatal conductance causes a reduction in hydraulic conductance and overall physiological efficiency (McDowell *et al.* 2003; 2006; Simonin *et al.* 2006; Waring *et al.* 1980).

McJannet and Vertessy (2001) noted that *Eucalyptus globulus* trees growing in drought prone areas of Australia were only obtaining water from the top meter of soil. Thinned stands have increased soil water content and decrease the stress on residual trees to obtain water (Feeney *et al.* 1998; McDowell *et al.* 2006; Reid *et al.* 2006; Sala *et al.* 2005; Simonin *et al.* 2006; Zausen *et al.* 2005). This allows for residual trees to utilize the available water (McDowell *et al.* 2006; Reid *et al.* 2006). Water potential has also been reported to be higher in thinned stands when compared to unthinned stands (McDowell *et al.* 2003; 2006; Sala *et al.* 2005; Simonin *et al.* 2006; Zausen *et al.* 2005). McDowell *et al.* (2003) suggests that carbon isotope discrimination within ponderosa pine can respond to available soil water. McDowell *et al.* (2003) also report that increased soil moisture levels following thinning can be mapped with carbon isotope discrimination and increased soil moisture levels are still apparent 15 years after treatment.

1.3.4 Nutrients

Although there are many nutrient inputs that can be considered, there are two pools of nutrients that need to be considered when dealing with physiological response to thinning: the soil pool and the plant pool. Soil nutrient pools are essential to maintaining plant nutrient pools (McDowell *et al.* 2003). Medhurst and Beadle (2005) found that thinning increased foliar nitrogen and phosphorus concentrations in *Eucalyptus nitens*. Similarly other research has found that thinned stands tend to have high concentrations of foliar nitrogen (Feeney *et al.* 1998; Luther and Carroll 1999). Kolb *et al.* (1998) and Luther and Carroll (1999) noted that thinning increased foliar nitrogen in ponderosa pine and balsam fir, respectively. Sala *et al.* (2005) found that nitrogen pools in the soil and leaves were similar between thinned and unthinned stands of ponderosa pine. Initially there was an increase in foliar nitrogen after thinning but increased nitrogen levels were undetectable 8-9 years after treatment. Thinning allows access to more nitrogen, on an individual tree basis, and thus aid in the development of sun leaves (Brooks *et al.* 1996; McDowell *et al.* 2003).

Sun leaves require more nitrogen than shade leaves (Brooks *et al.* 1996). This can be important to the physiological process because sun leaves are more efficient at utilizing available light (Brooks *et al.* 1996; Gravatt *et al.* 1997; McDowell *et al.* 2006; Medhurst and Beadle 2005; Sala *et al.* 2005; Tang *et al.* 1999; 2003). Brooks *et al.* (1996) reported an important relationship involving the chlorophyll/nitrogen ratio as an indicator of biochemical balance between light harvesting complexes and carbon fixation for pacific silver fir (*Abies amabilis* Dougl. Ex Loud.). The chlorophyll/nitrogen ratio is positively correlated to the light environment of foliage (Brooks *et al.* 1996; Luther and Carroll 1999). It is also important to know that nitrogen levels in sun leaves can change according to changes in light intensities (Brooks *et al.* 1996).

1.3.5 Growth

O'Hara (1989) indicated that irregular stand structure contributes to differences in stand growth efficiency. This describes the necessity to apply thinning to well managed stands that are generated from plantations or natural regenerated stands that have been managed for density control (*i.e.,* pre-commercial thinning). Density control influences physiological process. Photosynthesis, transpiration and basal area increment increased with higher density removal treatments (McDowell *et al.* 2006; McJannet and Vertessy 2001).

Research has shown that thinning stands increased per tree leaf biomass (Morling and Valinger 1999; Sala *et al.* 2005). Luther and Carroll (1999) noted that needle size increased within thinned (between 35 and 40% removal) blocks of balsam fir, in Newfoundland. Results have shown that individual tree leaf area increased in thinned stands (McJannet and Vertessy 2001; Sala *et al.* 2005). There have been several studies that link leaf area to the growth of trees (Binkely and Reid 1984; McJannet and Vertessy 2001; Waring *et al.* 1981; Waring *et al.* 1992). In two separate experiments on Douglas fir, Binkley and Reid (1984) and Waring *et al.* (1981) identify that as leaf area of the stand increased the average growth of individual trees decreased. McJannet and Vertessy (2001) suggested that the competition within lightly thinned *E. globulus* stands, where crown density is higher, may reduce radial growth and suppress trees beyond recovery. Waring *et al.* (1992) reported that leaf area decreased immediately following thinning but the efficiency of a tree to grow increased within two years after the treatment for Grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.) in Oregon. Feeney *et al.* (1998) and Kolb at al (1998) report that a decrease in basal area will result in an increase in resin production and foliar toughness for ponderosa pine.

Wood production increases the diameter and the height of a tree. Suppressed trees are less efficient at utilizing foliar physiological processes to produce wood (Zausen *et al.* 2005). Thinning is known to increase the overall mean growth of the tree (Feeney *et al.* 1998; Karlsson 2006; McDowell *et al.* 2006; Waring *et al.* 1981; Zausen *et al.* 2005). Trees from thinned stands increase both radial and height growth more than trees from the unthinned stands (Luther and Carroll 1999; McDowell *et al.* 2003; McJannet and Vertessy 2001; Sala *et al.* 2005; Sharma *et al.* 2006). Edge trees increased in diameter more than trees positioned in the middle of the stand (Cancino 2005; McJannet and Vertessy 2001). Overall, thinning contributes to increases and acceleration in stand growth (Feeney *et al.* 1998; Karlsson 2006; McDowell *et al.* 2006; O'Hara 1989; Sharma *et al.* 2006; Waring *et al.* 1981; Zausen *et al.* 2005).

1.4 Residual Tree and Site Damage

Damage to the residual trees is a high concern during thinning operations (Meek 2000; Mitchell 2004). Damage to residual trees (either root or stem) can lead to entry points for diseases (Albers, 2007; Nadezhdina *et al.* 2006), weaken trees structurally and make them higher risk for wind-throw events (Mitchell 2004). Mitchell (2004) suggested that the majority of damage caused is the result of the felling head contacting the stems of residual trees. The choice of harvesting system and equipment is important to reducing damage to residual stems. Like harvesters, forwarders can cause major damage to residual trees stems boarding extraction trails (Meek 2000). This risk is increased with narrower extraction trails, larger forwarders, uneven terrain and the presence of stumps (Meek 2000). All of these factors lead to the potential for equipment to shift balance (from side to side) and come into contact residual trees (Meek 2000). Some damage is inevitable; however, using the proper equipment with the proper management strategy can minimize the amount and severity of damage to the site and the residual stand (Hutchings *et al.* 2002; Krzic *et al.* 2004; Meek 2000; Mitchell 2004; Nadezhdina *et al.* 2006).

Commercial thinning operations bring associated risks that could lead to damage or disturbance to the site, roots or rooting zone of trees in the stand. Many factors influence the risk potential in thinning operations such as harvest season (Mariana *et al.* 2006), terrain, tree size, tree spacing, type of machinery, machine operators (experience and/or attitude) and trail width (Meek 2000; Mitchell 2004). Trees bordering trails are in a high-risk zone because machinery often enters within the critical root radius of these trees (Miller *et al.* 1995). The critical root radius is the function between the tree diameter at breast height (inches or cm) and a constant 1.5 (imperial) or 0.18 (metric) to give the radius of concern in feet or meters, respectively (Miller *et al.* 1995). Machinery can cause damage as severe as root breakage or varying degrees of root bark peel, especially to shallow root species (Nadezhdina *et al.* 2006). Measures are normally taken to reduce the potential for major damage. For example, many thinning operations implement the use of small feller/processor harvesting machines that are able to fell a tree, delimb it at the stump and cut it to a specified length (Meek 2000). These cut-to-length pieces are moved to a yarding area by another machine, such as a forwarder or skidder (Hutchings *et al.* 2002; Meek 2000; Mitchell 2004). This harvesting and forwarding equipment can be equipped with low-pressure tires that help reduce the impact to the site (Hutchings *et al.* 2002; Nadezhdina *et al.* 2006). During the harvest process, branches and treetops that are outside merchantability standards are often left on the harvester/forwarder trails (Meek 2000) to be used as a 'cushion-like' mat (Hutchings *et al.* 2002; Krzic *et al.* 2004; Nadezhdina *et al.* 2006). These brush mats often reduce damage to soil and roots (Hutchings *et al.* 2002; Nadezhdina *et al.* 2006) but have limitations, based on the number of machine passes, and cannot completely eliminate negative impacts to soil properties (Hutchings, 2002).

1.5 Stand assessment and suitability

Proper identification and knowledge of inventory are essential to being able to carry out a successful commercial thinning operation (Meek 2000). Drew and Flewelling (1979) suggest that proper density management should occur between crown closure and the zone of imminent competition mortality, to minimize natural mortality and to maintain growth. The optimal quality for spruce stands (natural or plantation), according to Meek (2000), is to have a stand with a basal area between 23 and 32 m^2 ha^{-1} and fewer than 3000 merchantable stems ha^{-1}.

The other criteria that may be important in site selection should deal with the harvest schedule. For example, spruces generally have a shallow root system that may be prone to damage (Lagergren and Lindroth 2004). This may dictate the suitability of a stand for thinning based on the timing of entry and the silvics of the crop. Kayahara *et al.* (2007) developed guidelines for use in Ontario for assessing stands for commercial thinning. Their recommendations are for stands to be fully stocked, on highly productive sites, have live crown ratios greater than 35% (best for response to light and reduce wind-throw risk) and a uniform 30-35% basal area thinning from below.

1.5.1 Pre-treatment surveys

Pre-treatment surveys can be carried out using any variety of methodologies. It is important to use a method that will thoroughly measure inventory and stand characteristics (or conditions) that will determine if the stand is a suitable candidate for thinning. Inventory is an assessment of the quantity and quality of timber in an area (Avery and Burkhart 1994). Stand characteristics refer to the description of the stand involving any combination of species composition, health, age, piece size, stand volume or spatial arrangement (Natural Resources Canada 1995). Some recommended survey types include: 1) variable radius plots (a prism sweep using a wedge prism to estimate basal area); 2) fixed-radius area plots or 3) strip cruises (a fixed area plot with a known measurement width for a measured transect). All methods will provide information that can be used to estimate volume, density and species composition (Avery and Burkhart 1994). Other things to consider in pre-treatment surveys are adding a method to survey crown closure (either crown widths or crown heights) (Drew and Flewelling 1977, 1979; Kayahara *et al.* 2007) and map the terrain and accessibility (Meek 2000).

1.5.2 Post-treatment surveys

A post-treatment survey has a different intent then pre-treatment survey. The intent of a post-treatment survey is to measure the effectiveness of the operation and/or to provide information to the harvest supervisor so that corrections can be made quickly as the operation continues (Meek 2000). A post-treatment survey should be able to effectively evaluate targets set in the harvest prescription (the operational targets of a management plan). Meek (2000) suggests using a fixed-radius area plot (5.64 m radius giving and a measurement area of 100 m^2) or a variable-radius plot (wedge prism sweep). There is a level of importance given to the residual stand; therefore assessing the quality of residual trees is also important. Mitchell (2004) suggested evaluating damage to residual trees by using a damage assessment category based on severity, area of damage, cause and at what height (from the ground) the damage is located. Assessing damage to residual trees should also extend beyond looking at the stem and crown; it should also consider root zones. Nadezhdina *et al.* (2006) indicated that damage to roots, especially root break, had an effect on water movement within the tree. An evaluation of the critical root radius for trees within post-treatment plots could be of value (Miller *et al.* 1995).

1.6 Problem Statement

Currently commercial thinning is not a recommended harvest practice for black spruce in Ontario (OMNR 2000). Research is needed to provide insight into how black spruce trees will respond to the harvest operations, increased stresses of open conditions and availability of resources, as well as the quality of product(s) that can be produced from selected Ontario black spruce plantations. In order for a change to occur in the status of recommended harvest practices for commercial thinning in black spruce, there cannot be a detrimental relationship between commercial thinning, product quality and physiological response in black spruce plantations. The following chapters explore and discuss the issues of lumber quality and quantity from mid-rotation age plantation-grown black spruce, the determination of a model to predict leaf area and tree water use following a commercial thinning harvest. The objective of this study is gather information that can be used to provide early insight to forest managers on potential wood quality issues, operational expectations and initial physiological responses that can affect overall tree development as result of commercial thinning operations in black spruce plantations.

1.7 Study Site Description

This study included 3 black spruce plantations located within 50 km of the town of Beardmore, Ontario (49 37' N, 88 15' W) (Figure 3). These plantations are situated in the Central Plateau (Tyrol Lake site) and Superior Forest Regions (Boom Lake and Airstrip sites) of northwestern Ontario (Rowe 1972), and fall within Ontario's Site Region 3W (Hills 1961). The climate in this region is classed as microthermal and humid, and is characterized by short, warm summers and long, cold winters with approximately 80 frost-free days and a mean annual temperature of 0.2°C (Chapman and Thomas 1968). On average, the area receives 760 mm of rainfall with 60% falling during the growing season (Environment Canada 2008).

The plantations selected for this study were established on a range of landform and soil types. The Tyrol Lake plantation (15.6 ha) is situated on moderately deep, morainal till overlying granitic bedrock. These are well-drained, very gravelly silt loams with coarse fragment content in excess of 50%. The profile is poorly developed characteristic of a Dystric Brunisol (Agriculture Canada Expert Committee on Soil Survey 1987). In contrast, the Boom Lake plantation (103.1 ha) was established on an extensive area of glaciofluvial-deposited medium to fine sand, overtopped with a thin, silty loess cap. This site has a well-developed Humo-ferric podzolic profile. The third plantation (Airstrip, 36.6 ha) is situated on a lacustrine clay plain, with prominent varves throughout the Orthic Gray Luvisolic profile. These are calcareous clays with carbonates present below 38 cm and parent material pH values above 6.5. The differences in mode of deposition, textural classes, and degree of profile development provide a range in soil quality, as expressed by site index (SI_{30}; height of dominant and co-dominant trees at breast height age 30). Based on the site index models developed by Kwiaton (2008) from stands of black spruce, the SI_{30} values of the study sites were 10.9 m (Tyrol Lake), 13.3 m (Boom Lake) and 11.8 m (Airstrip).

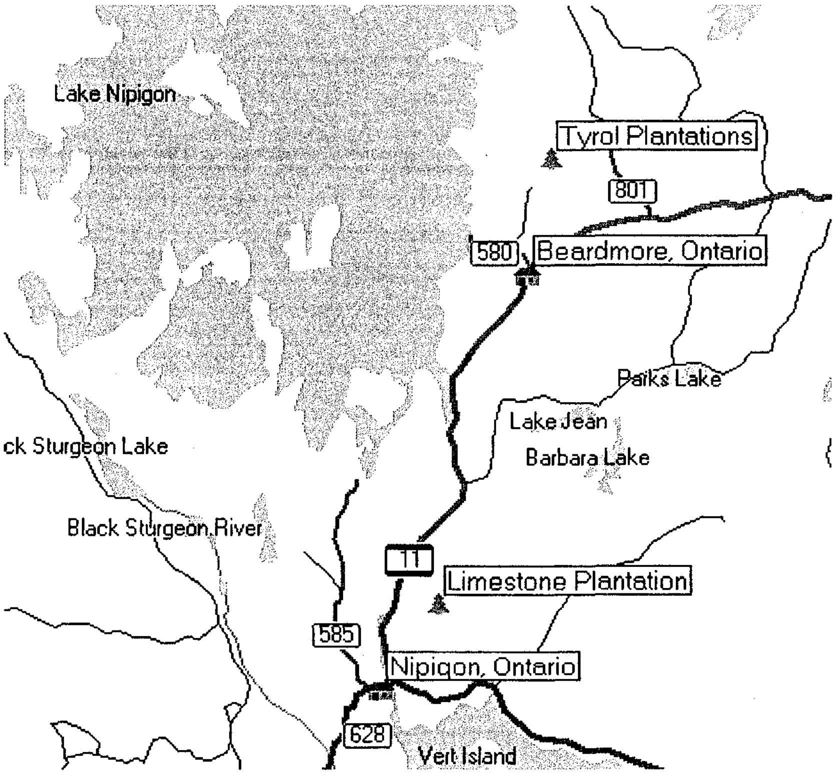

Figure 3. Map of study area relative to the town of Beardmore, ON. The Limestone plantation is the location of the Boom Lake and Airstrip sites.

The plantations were established in the early 1960's (Boom Lake: 1960; Airstrip: 1961; Tyrol Lake: 1962) using 2+2 bare root stock planted at variable densities (5 to 6 foot spacing). Both manual (2) and chemical (1) vegetation control treatments were applied in the first 15 years after establishment to maximize survival and early growth. Stand density varied in the study plantations: Boom Lake – 2285 stems ha^{-1}; Airstrip - 2806 stems ha^{-1}; Tyrol Lake - 3578 stems ha^{-1}. Current gross total stand volumes range from 195 - 285 m^3 ha^{-1} reflective of both stand density and site quality differences.

Chapter 2: Influence of site quality on plantation-grown black spruce lumber grade, yield, and value

2.1 Introduction

There has been a forecasted shortfall of harvestable timber in northern Ontario that has raised a need to assess how to acquire sufficient wood fibre (Canadian Council of Forest Ministers (CCFM) 2007; Day 1997; Ontario Ministry of Natural Resources [OMNR] 2000). Tens of thousands of hectares of land are planted every year in Ontario (CCFM 2007). Plantation black spruce, growing at a typical mid-rotation age, have been noticed to be comparable in size to late-rotation aged naturally regenerated black spruce from northern Quebec and Ontario (Zhang *et al.* 2002). As the forest management planning stages enter into the expected shortfall, managed plantations become appealing as a fibre source at a younger age (Day 1997; Zhang *et al.* 2002).

Black spruce is regarded as one of the most important commercial species in eastern and central Canada. It is in demand for both the sawmill industry and the pulp and paper industry. Due to its strong mechanical properties, black spruce is valued for machine stress rated (MSR) lumber (Liu *et al.* 2007a). Lumber mechanical properties are affected by the basic wood properties of the tree such as wood density, mircofibril angle, and defects (*e.g.,* knots, grain deviation) (Jozsa and Middleton 1994; Macdonald and Hubert 2002; Zhang *et al.* 2002).

Lumber strength (measured as the modulus of rupture (MOR)) and stiffness (measured as the modulus of elasticity (MOE)) are important measures of lumber quality (Liu *et al.* 2007a; Watt *et al.* 2006). Differences in lumber quality can be noticed between varied stand densities (Liu *et al.* 2007a; Persson *et al.* 1995; Zhang *et al.* 2002; 2006) and site quality (Daoust and Mottet 2006; Watt *et al.* 2006). These site and stand differences usually relate to proportions of juvenile wood (Jozsa and Middleton 1994; Zhang *et al.* 2002), wood density (Liu *et al.* 2007a;

Zhang *et al.* 2002) and tree growth characteristics, such as DBH and crown length (Liu *et al.* 2007a).

The bulk of the lumber produced in Canada is graded visually. In recent years, MSR grading of lumber has become a more common grading system in Canada. Visual grading rules are based on qualitative and quantitative visual criteria established by the NLGA to evaluate each piece of lumber (Griffin *et al.* 1999). MSR grading uses stiffness values (MOE) as a primary basis of grade evaluation, as well as strength (MOR) and certain visual criteria to evaluate and grade each piece of lumber (Courchene *et al.* 1998; Erikson *et al.* 2000; Griffin *et al.* 1999). A high percentage of high visual grades (No. 2 and Better) have been reported for mid-rotation aged plantation grown black spruce. However, a very low percentage of lumber met the design values requirements for those particular visual grades (Zhang *et al.* 2002). This led Zhang *et al.* (2002) to suggest that visual grading of mid-rotation aged plantation-grown black spruce is ineffective and MSR grading of plantation-growth resource should be used.

The yield of good quality lumber is important to consider when managing for sawlogs. The yield of top visually graded lumber in black spruce have been shown to be positively related to tree size (Liu and Zhang 2005; Liu *et al.* 2007b) and only negatively related to stem taper in plantation black spruce (Liu *et al.* 2007b). Low grade lumber is often associated with large knot sizes (Courchene *et al.* 1998; Zhang *et al.* 2002; 2006) and manufacturing defects such as wane and skip (Daoust and Mottet 2006; Zhang *et al.* 2002; 2006). Wane is the presence of bark or absence of wood along the edge of a piece of dimensional lumber (Random Lengths b 2008). Skip is a section of lumber that was missed by the planner (Random Lengths b 2008). Knots can cause lumber downgrades (Courchene *et al.* 1998; Zhang *et al.* 2002; 2006), but typically is not a major issue for black spruce (Liu *et al.* 2007b) as this species usually has small branches. However, decreasing stand density has been known to increase branch diameter and stem taper (Daoust and Mottet 2006; Zhang *et al.* 2002; 2006). When stand densities are lower than 2000 stems ha^{-1}, black spruce can produce knot sizes large enough to cause downgrades in 2x4 and 2x6 lumber (Zhang *et al.* 2002). An increased stem taper, from lower stand densities, can lead to manufacturing defects such as wane and grain deviation (Daoust and Mottet 2006). The purpose of managed plantations is to produce timber that will yield better quality products.

Although there is abundant information available on lumber quality, there is little known about the impact of site quality on lumber quality, yield and product value. In this study, I examine (1) the influence of site quality, tree size, and stem section on the wood and lumber properties, and lumber recovery; (2) the influence of average ring width and wood density on selected wood quality attributes and; (3) the potential value of harvesting for sawlog quality lumber from mid-rotation aged plantation grown black spruce, on the 3 sites. Information gained from this study will provide a base of knowledge that will help forest managers decide whether or not to commercially thin black spruce plantations, depending on the desired lumber product.

2.2 Materials and Methods

2.2.1 Site and Tree Selection and Measurement

The areas of each site range from 15.6 hectares at Tyrol, to 36.6 hectares at the Airstrip and 103.1 hectares at Boom. A full description of the sites can be found in Section 1.7. A combination of randomly-located fixed area plots (400 m^2) and prism sweeps were used to gather stand information, such as diameter distributions, density, and basal area. Up to 22 sample trees were selected from each plantation to represent the full range of diameters for that site (51 trees in total). Each tree was measured for outside bark diameter at breast height (DBH), total height, live crown length, and live crown width. Trees from the Airstrip and Boom Lake sites were felled, delimbed, and bucked into 8-foot sections. Trees from the Tyrol Lake site were felled, delimbed and transported to FPInnovtations-Forintek's Quebec lab as tree length (top diameter of 7 cm), where each tree was then bucked into 8-foot logs. All 8-foot logs were measured for diameter at both ends, and all were labeled in a way to easily track provenance. Average sample tree characteristics are summarized in Table 2.

Table 2. Selected stand and tree characteristics for the three sites studied.

	Airstrip			Boom			Tyrol		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Tree Breast Height Age	37.6	34.0	40.0	41.8	39.0	44.0	41.5	38.0	44.0
Tree Height (m)	11.9	6.2	15.0	13.3	10.4	16.9	12.1	2.3	14.7
DBH (cm)	13.1	9.6	18.4	15.2	11.3	16.9	13.2	2.6	20.5
Live Crown Ratio (%)	54.0	22.0	84.0	55.0	22.0	81.0	52.6	18.3	79.6
Basal Area (m2)	35.8	16.0	52.0	39.9	20.0	60.0	41.1	25.5	55.0
Total Volume (m3/ha)	193.8	71.9	302.5	237.4	121.0	420.0	-	-	-
Total Merch. Volume (m3/ha)	158.8	0.0	265.1	210.3	94.9	381.3	-	-	-
Total Spruce Volume (m3/ha)	162.8	0.0	279.2	205.5	13.1	336.2	236.7	146.5	310.5
Total Merch. Spruce Volume (m3/ha)	133.7	0.0	222.3	181.9	11.6	304.6	199.7	120.7	256.0
Stand Density (stems/ha)	2806	600	5600	2285	600	4600	2822	1800	4150

2.2.2 Lumber Conversion and Visual Grading

Lumber conversion was carried out with a portable "Wood Mizer" sawmill. Each log was converted into nominal 2x4 or 2x3 lumber, with priority given to maximize 2x4 production. The 51 sample trees yielded 292 pieces of lumber (191 2x4s; 101 2x3s). After kiln drying, each piece of lumber was dressed in a planner mill at FPInnovtations-Forintek's Quebec lab. A qualified inspector from the Québec Forest Industry Council graded each piece of lumber following the National Lumber Grades Authority (NLGA) standards. Grading rules determined the grade of each piece of lumber (*i.e.,* stud or economy stud); defects that resulted in downgrading of lumber grade were recorded for each piece of lumber. In addition, the lumber was also graded as "Structural Light Framing" (NLGA article 124; 2003) to improve the precision of visual grading in an effort to detect even small differences in lumber quality. The NLGA defines 5 visual grades for Structural Light Framing: Select Structural (SS), No. 1, No. 2, No. 3, and Economy. According to the current grading practice in Quebec, the SS and No. 1 grades were combined as No. 1. About 22% of the lumber pieces were trimmed to either 6 or 7 feet to improve grade and trimming reasons were recorded.

2.2.3 Lumber Bending Strength and Stiffness

Before conducting the bending tests, the lumber was stored in a conditioning chamber until moisture content (MC) of approximately 15% was reached. MOE and MOR in static third-point bending were determined for each piece of lumber to evaluate stiffness and strength, respectively. Immediately before the bending test, average MC of each piece of lumber was measured at a depth of 9 mm from the center of the lumber surface. Lumber was tested edgewise with third-point loading in general agreement with American Society for Testing and Materials (ASTM) D-4761-02a (ASTM 2003). Following the ASTM D-1900-00 (2002) (ASTM 2003), MOE and MOR were standardized to 15% MC. In addition, width effect on MOR was standardized to a 4 in width using the method described by Barrett and Lau (1994), and MOE was standardized to the span-to-depth ratio of 21 to 1 following the procedures described in NLGA SPS 2-2003 (NLGA 2003). Lumber pieces were further graded for MSR grades following procedures described in NLGA SPS 2-2003 (NLGA 2003).

Once the bending tests were completed, the types of failure were recorded. Two small blocks (c. 5 cm longitudinally x lumber width x lumber thickness) of clear wood sample were removed from each lumber piece on each side of the failure to evaluate the following wood characteristics: 1) basic wood density, 2) average ring width and 3) pith presence.

2.2.4 Evaluation of Economic Value

Product price information for visually graded and MSR graded lumber were generated from historical market prices for dimensional lumber (Random Lengths 2008). Product prices are based on a 4-year rolling average delivered to eastern markets. Only No. 2 and Better 2x4 dimensional lumber were considered for MSR premiums. MSR premiums were assigned based on the American Lumber Standard Committee rules, and the design values and lower limits outlined in Erikson *et al.* (2000). For example, the rules for assigning an MSR premium for grade MSR2100F-1.8E would require the average MOE for that group of lumber to be greater than or equal to 1.8 Mpsi (12,410 MPa) and MOR exceeding the design value of 2100psi. In addition, 95% of the lumber in this grade has to be above the acceptable lower limits for MOE (82% of 12,410 MPa = 10,176 MPa) and MOR (2.1 times 14.4MPa = 30.4 MPa). Finally, any board not assigned a MSR grade defaults to a visual grade below the design bending strength of the lowest MSR grade produced (MSR1650F-1.5E, with a design value of 10,342 MPa). Price premiums can be found in Table 3.

Table 3. Price premiums assigned by grade and dimensional lumber properties. Lengths are all 8 foot category unless otherwise noted.

Grade	Premium Price per board	Grade	Premium Price per board	Grade	Premium Price per board
MSR 2100F	$2.14*	2x4x7	$1.60*	Economy	$1.22*
MSR 1650F	$2.07*	No. 3	$1.56*	2x3x7	$1.14**
No. 1	$1.98*	2x4x6	$1.37**	2x3x6	$0.64**
No. 2	$1.98*	2x3x8	$1.32*		

* From Random Lengths (2008)
** From Tanguay (2007)

2.2.5 Statistical Analysis

A mixed, 3 factor model (site, tree, log position), as described by Snedecor and Cochran (1989), was applied to the lumber quality variables (MOE; and MOR). In this design, both site and log position were treated as fixed factors, and tree as random. The linear model was expressed as:

$$\mathbf{Y_{ijkl} = \mu + S_i + T_j + ST_{ij} + L_k + SL_{ik} + TL_{jk} + STL_{ijk} + \xi_{(ijk)l}} \qquad \mathbf{[1]}$$

where: Y_{ijkl} is the value of the given response variable, μ is the overall mean, S_i is the fixed effect of the i^{th} site, T_j is the random effect of the j^{th} tree[3], ST_{ij} is the interaction effect of the i^{th} site with the j^{th} tree, L_k is the fixed effect of the k^{th} log position, SL_{ik} is the interaction effect between the i^{th} site and the k^{th} log position, TL_{jk} is the interaction effect between the j^{th} tree and the k^{th} log

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[3] The factor Tree represents the random selection of a tree within a particular diameter class.

position, STL_{ijk} is the interaction effect between the i^{th} site, the j^{th} tree and the k^{th} log position, and $\xi_{(ijk)l}$ is the random effect of the l^{th} replication within the ijk^{th} treatment combination.

The PROC GLM procedure on SAS/STAT software (SAS Institute Inc. 1987) was used to perform the ANOVA's. Based on the Expected Means Squares, specific TEST statements were included in the model to calculate and test the appropriate F ratios. Student-Newman-Keuls (SNK) multiple range test was used for the post-hoc examination of the significant factors at the 0.05 level. The relationship between the 4 dependent wood quality attributes (MOE, MOR, basic wood density and average ring width) and the independent visual grades were evaluated by one-way ANOVA's. Simple linear regressions were also performed to examine the relationships between the 4 product quality attributes within each log position.

2.3 Results

Overall, there was a high yield of No. 1 grade (61%) and No. 2 and Better grades (90%) from the trees on these study sites (Figure 4). Nearly 1/3 of all lumber was downgraded as a result of wane and/or skip. Wane accounted for a large proportion of the total downgrades of lumber (72.7%, 43.1% and 41.5% for lumber from Airstrip, Boom and Tyrol trees, respectively). Skip and wane combined account for 95.5%, 82.4%, and 78.1% of all lumber downgrades from Airstrip, Boom and Tyrol trees, respectively. Knots accounted for little to no downgrades (0% Airstrip, 7.8% Boom and 2.5% Tyrol).

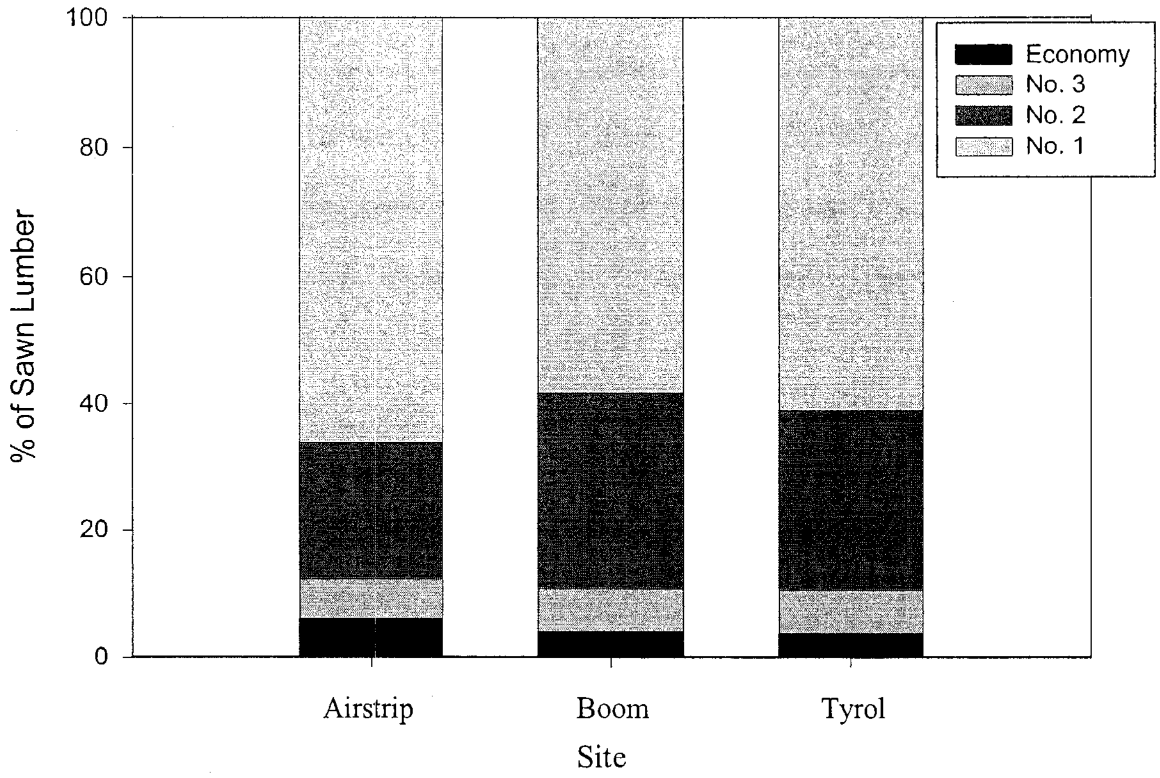

Figure 4. Percentage of lumber visual grades in each site.

Very distinct differences were noticed with respect to lumber meeting MOE design values between these study sites. With respect to No. 2 and Better lumber, only 8.9% and 52.3% of the lumber produced from the trees at Airstrip and Boom, respectively, met the MOE design values whereas 89.4% of the lumber produced from trees at the Tyrol site met the design values (Table 4). From the No. 2 and Better lumber that failed to meet the design standard, 28.6%, 44.0% and 19.1% of lumber from the Airstrip, Boom and Tyrol sites, respectively, were above the design value for No. 3 grade. Distinct differences were also noticed with respect to downgrading No. 2 and Better to No. 3 grade between these study sites. All No. 2 and Better lumber downgraded to No. 3 were above the design values for grade No. 3 from the Tyrol site, but 76.8% and 32.1% from Airstrip and Boom, respectively, were below the design value for grade No. 3. On average, visually graded lumber produced from Tyrol trees exceeded the design values for all grades while lumber produced from the Airstrip site trees had the weakest bending stiffness values (Table 4).

Table 4. Comparison of the average black spruce lumber MOE values with the design values for each site and the percentage of lumber pieces which meet the current grade requirements for bending stiffness design values.

		MOE (MPa)		
Dry Lumber grade	**Design value MOE (MPa)**	**Airstrip**	**Boom**	**Tyrol**
No. 1	9,500	8,071	9,389	11,113
No. 2	9,500	8,241	9,296	11,471
No. 3	9,000	8,143	9,147	11,009
Economy	-	8,220	9,250	9,815
Average	-	8,122	9,338	11,159
		% that met design value		
		Airstrip	**Boom**	**Tyrol**
No. 2 and Better	9,500	8.9	52.3	89.4
No. 3	9,000	25.0	50.0	100.0

Large differences were noticed between these study sites with respect to lumber meeting suitability to particular MSR grades. Nearly 18% of lumber produced from trees on the Tyrol site was suitable to be graded as 2100f-1.8E but no lumber from either Airstrip or Boom trees made this grade (Table 5). High percentages of lumber produced from trees on the Tyrol site were also capable of meeting the grade requirements for MSR 1650f-1.5E and 1450f-1.3E grades, 66.7% and 88.6% respectively (Table 5). However, much lower suitability was noticed for lumber produced from Boom trees (20.5% and 62.3% for 1650f-1.5E and 1450f-1.3E grades, respectively) and from Airstrip trees (0% and 21.9% for 1650f-1.3E and 1450f-1.3E grades, respectively) (Table 5).

Table 5. The percentage of lumber (visual grades of No. 2 and Better 2x4 only) that meets the design values for selected MSR grade from the three sites.

MSR grade	Design value	Airstrip	Boom	Tyrol	Grand total
2100F - 1.8E	1.8 Mpsi or 12,410 Mpa	0.0%	0.0%	18.1%	6.5%
1650F - 1.5E	1.5 Mpsi or 10,342 Mpa	0.0%	20.5%	66.7%	32.6%
1450F - 1.3E	1.3 Mpsi or 8,963 Mpa	21.9%	62.3%	88.6%	62.9%

Significant differences were found between sites ($p < 0.0001$) and between trees ($p < 0.0001$) in both MOE and MOR. Tyrol had the highest values and Airstrip had the lowest values (Figure 5). I also observed significant differences in MOR between log types ($p = 0.0158$) and the site by tree interaction (p = 0.0025) but not in MOE for log types (p = 0.4997) and the site by tree interaction (p = 0.154). Significant differences in MOE were also observed for the three-way interaction (p = 0.0038) but not for MOR (p = 0.1214).

Lumber coming from logs below the live crown (clear logs) had a significantly higher MOR value than lumber produced from logs within the live crown (Figure 6). A similar trend was found for MOE but this relationship was not significant (p = 0.4997). The variable tree is a random factor and as such is accepted as being highly variable with individual means having no importance (Lorenzen and Anderson 1993). Because the interaction between site and tree contains a random factor, it is also treated as a random factor (Lorenzen and Anderson 1993) and thus I can accept the fact that trees are highly variable on and between different sites.

I did notice significant differences between visual grades with respect to basic wood density (p = 0.0128) and average ring width (p = 0.037). Economy grade lumber was denser than the other grades and had a smaller average ring width than grades No. 1 and No. 2 (Figure 7). Lumber MOE and MOR values were ranked highest to lowest as No. 2, No. 1, No. 3 and Economy, however I found no significant differences between visual grades (p = 0.4165 and p = 0.5907, respectively).

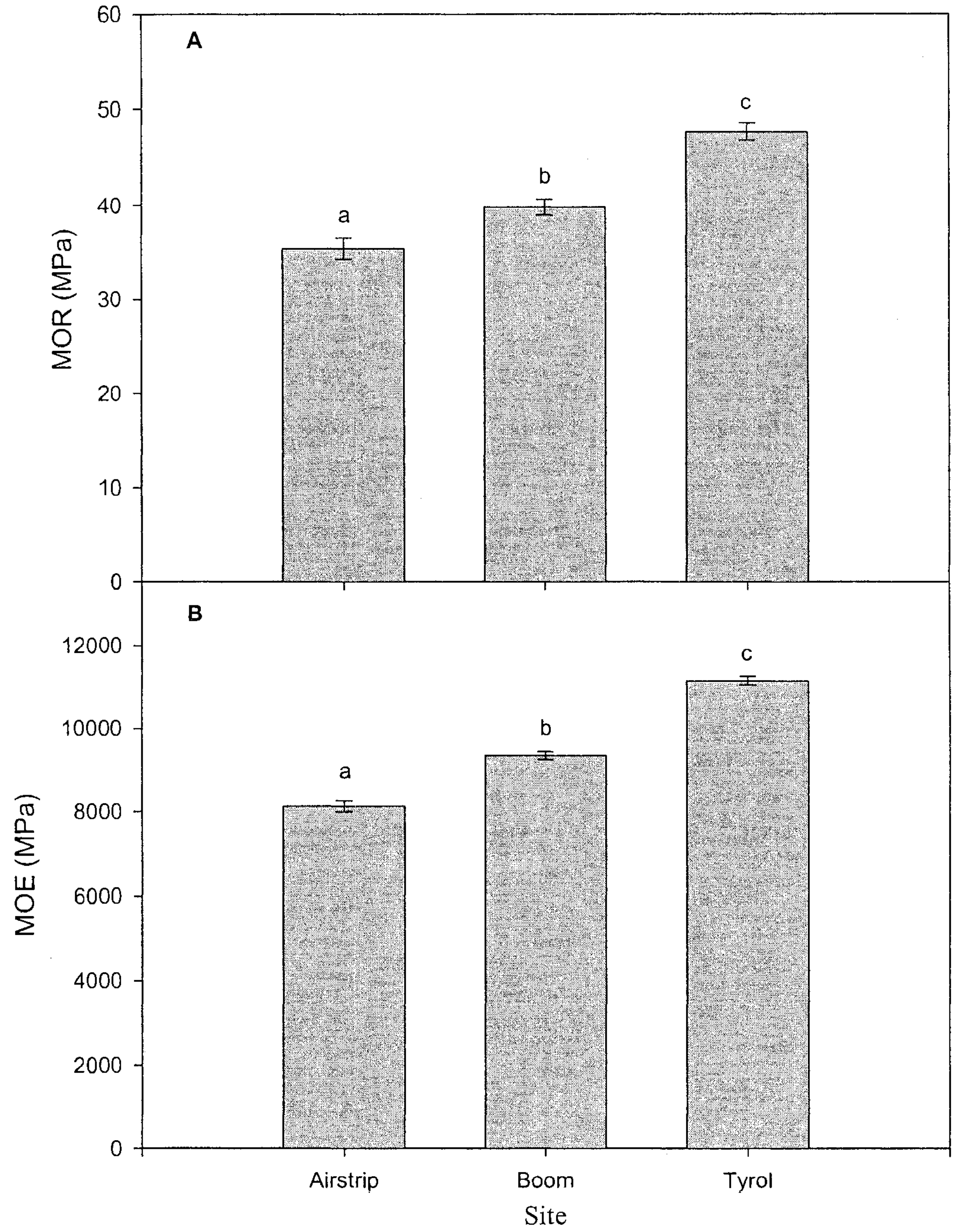

Figure 5. Mean MOR (A) and MOE (B) values per site. Sites with the same letter are not significantly different according to the SNK post-hoc results for MOE and MOR. Error bars represent one standard error.

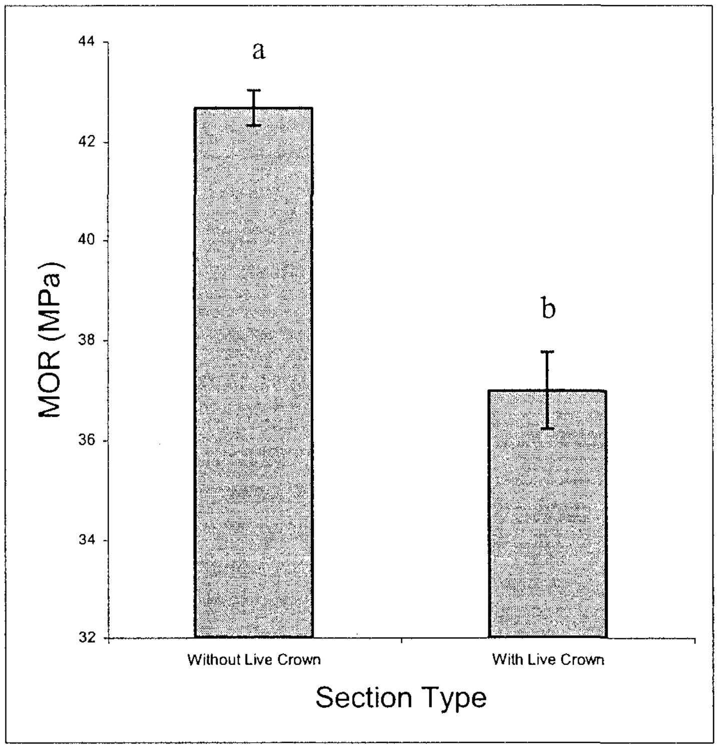

Figure 6. Mean MOR values of lumber from logs with live crown and logs from below live crown. Log types with the same letter are not significantly different according to the SNK post-hoc results for MOR. Error bars represent one standard error.

There were similar highly significant ($p = <0.0001$), but weak, relationships observed between average ring width and basic wood density, basic wood density and MOE, and basic wood density and MOR for lumber sawn from logs in stem sections with and without live crown . Average ring width and basic wood density had a negative relationship within each stem section (Figure 8). R-square values indicated that average ring width accounted for 18.6% and 22.5% of the variance in basic wood density for lumber produced from logs below the live crown and logs with live crown, respectively. Basic wood density and MOE (Figure 9), as well as basic wood density and MOR (data not shown), had positive relationships within each stem section. For these relationships, R-square values indicated that basic wood density accounted for nearly 22% of the variance in MOR or MOE for lumber produced from logs below the live crown and around 25 - 27% of the variance in MOR or MOE, respectively, for lumber produced from logs with live crown.

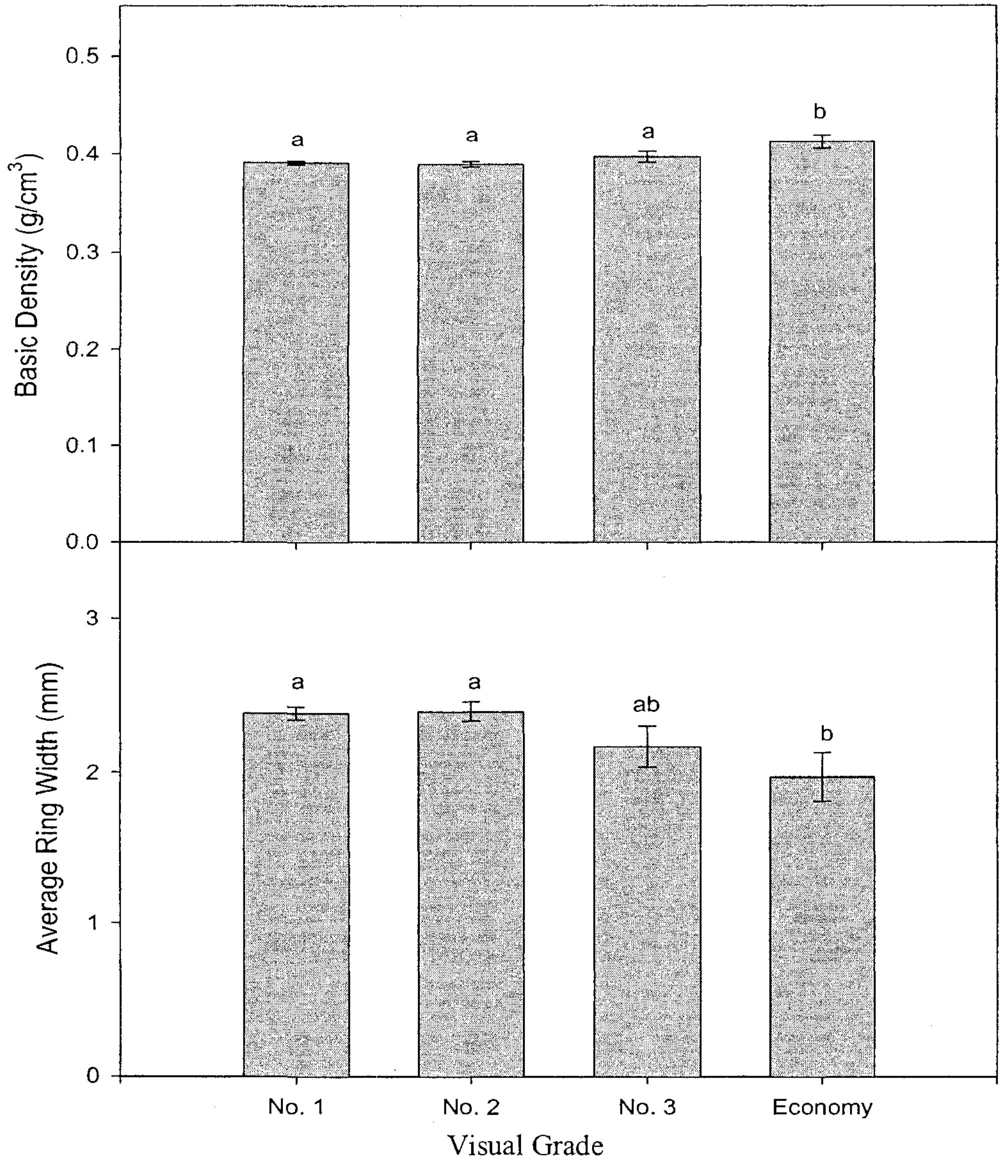

Figure 7. Mean basic wood density (above) and mean average ring width (bottom) values by visual grade. Visual grades with the same letter are not significantly different according to the SNK post-hoc results for basic density or average ring width. Error bars represent one standard error.

The Boom site produced the highest economic value per hectare, followed by Tyrol and then the Airstrip sites. In general, grading for MSR premiums will generate more revenue on a per hectare basis (Table 6). MSR graded lumber generates more revenue per hectare on these sites than the other scenarios (Table 6) (the Airstrip site had no 2100F or 1650F MSR quality lumber (Table 5)). Due to the salable product groupings, a large portion of lumber from these three sites falls within the 'Other' category (Table 7). MSR grade yield was best from the Tyrol site with 20% meeting standards of the highest MSR premium and an additional 26.7% in the lower MSR premium (Table 7). The Boom site had the largest trees (Table 2), the lowest distribution of lumber in the 'Other' category (Table 7) and the highest per hectare revenue in all three scenarios (Table 6).

Table 6. Approximate average per hectare revenue generated by site and pricing scenario. Premiums are average price of delivered product to eastern markets. Prices based on information presented Table 3.

Premium Pricing Scenario	Airstrip	Boom	Tyrol	Overall Average
Visual Grade Premiums only	$16,700	$27,300	$23,400	$22,500
MSR Premium rules	$16,700	$28,000	$24,900	$23,200
Visual Grade Premiums based on design values	$13,800	$24,000	$23,000	$20,300

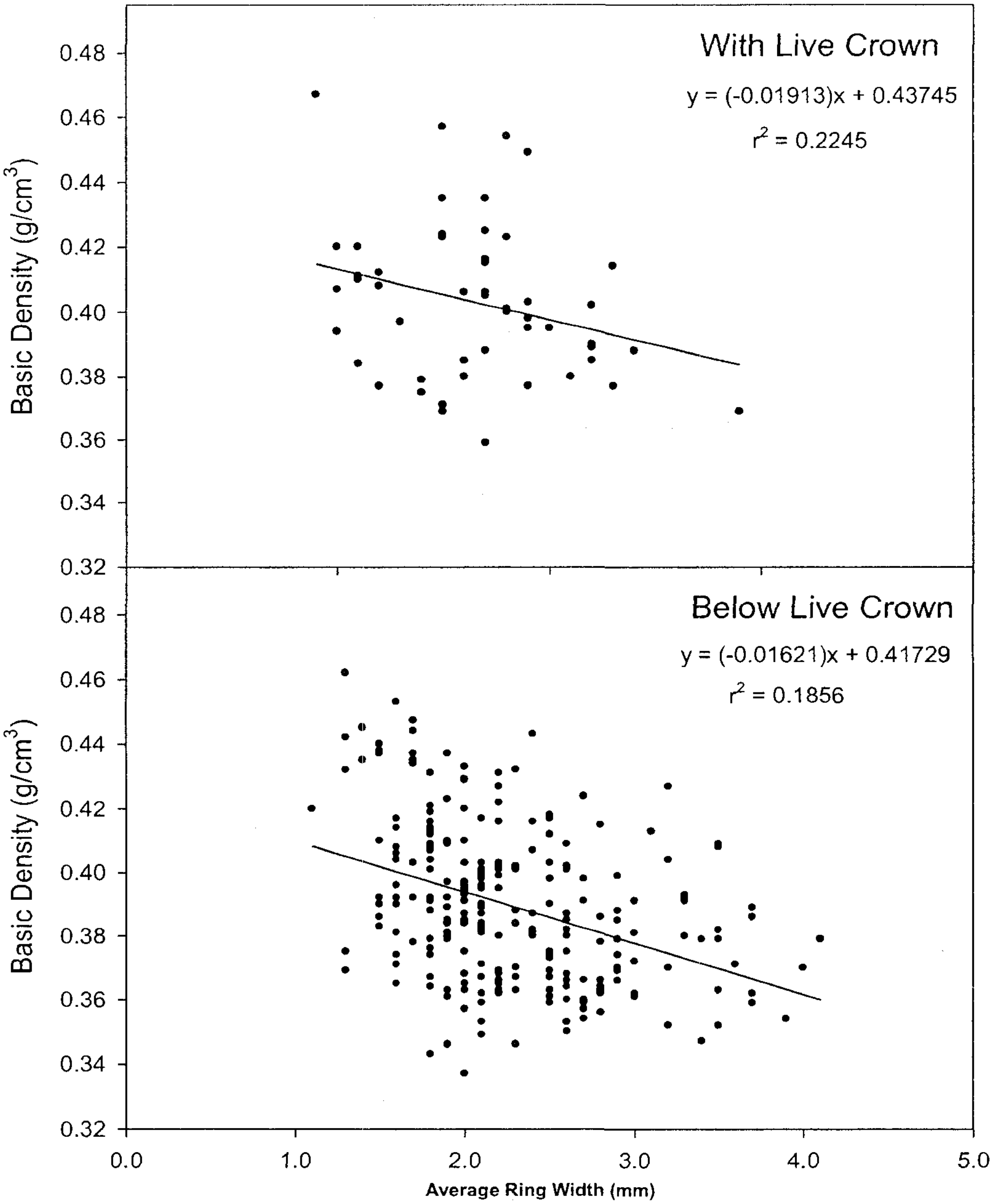

Figure 8. Relationship between average ring width and basic wood density for lumber produced from logs with live crown (above) and logs from below the live crown (bottom).

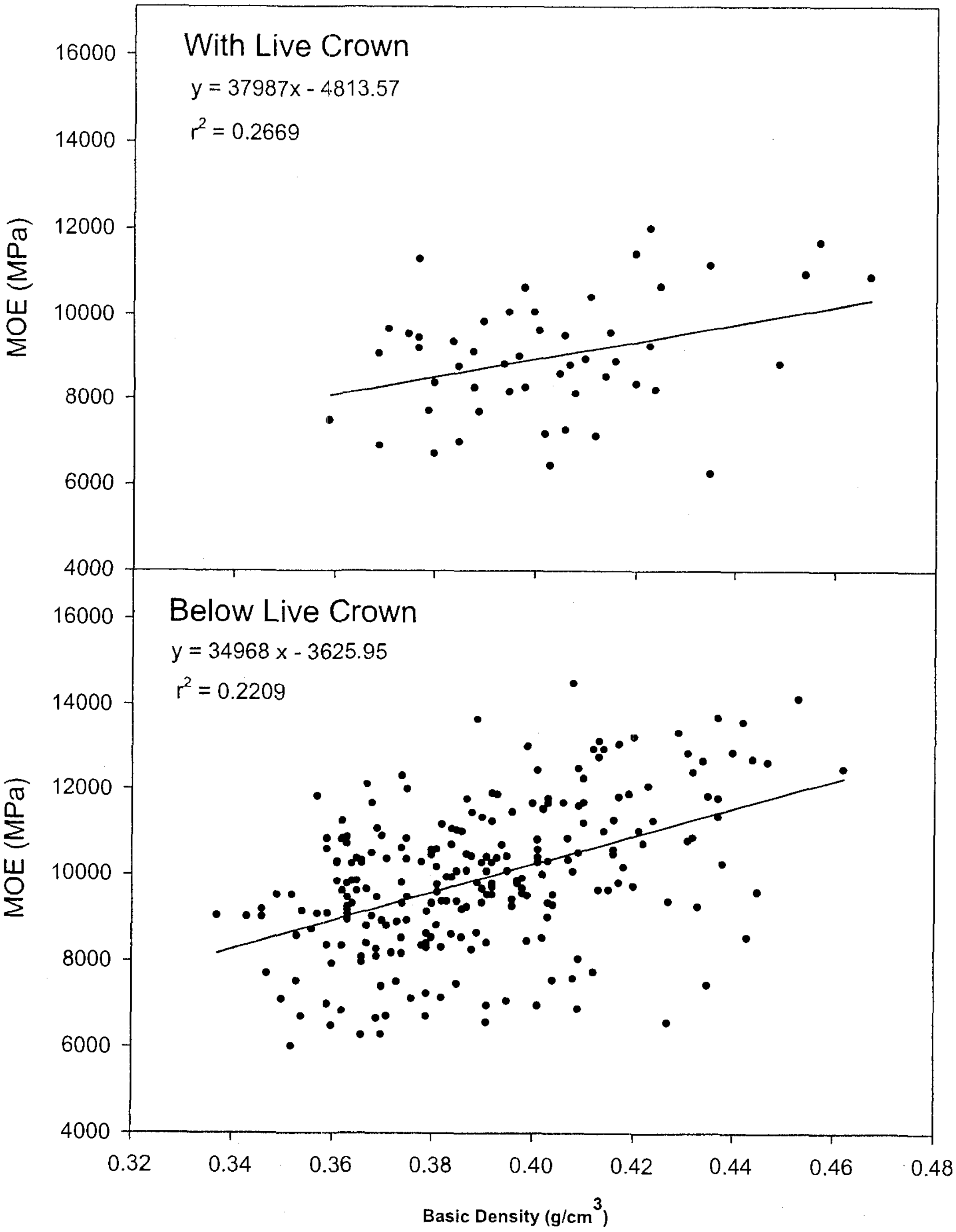

Figure 9. Relationship between basic wood density and MOE for lumber produced logs below the live crown. Relationship between basic wood density and MOE for lumber produced from logs with live crown.

Table 7. Percentage of lumber by market category from each site within each grade scenario and premium. Prices based on information present in Table 3.

			% Distribution		
Grade Scenario	Grade	Premium	Airstrip	Boom	Tyrol
Visual grade	No. 1	$1.98	35.9	34.4	22.9
	No. 2	$1.98	12.5	17.2	18.1
	No. 3	$1.56	4.7	4.9	2.9
	ECONOMY	$1.22	1.6	0.8	1.0
	Others	Others	45.3	42.6	55.2
MSR grade	MSR2100F	$2.14	0.00.0		20.0
	MSR1650F	$2.07	0.0	28.7	26.7
	No. 1	$1.98	35.9	18.9	1.0
	No. 2	$1.98	12.5	8.2	1.9
	No. 3	$1.56	4.7	4.9	2.9
	ECONOMY	$1.22	1.6	0.8	1.0
	Others	Others	45.3	38.5	46.7
Visual grade based on design value	No. 2 or better	$1.98	6.3	27.9	35.2
	No. 3	$1.56	14.1	5.7	7.6
	ECONOMY	$1.22	34.4	23.8	1.9
	Others	Others	45.3	42.6	55.2

2.4 Discussion

2.4.1 Visual Grade Yield

Based on visual grade, there is great potential to produce a percentage of high-grade lumber from the trees on these black spruce plantations (Figure 4). Of all lumber produced from the trees on these sites, 61% were graded as No. 1 and 89% were graded as No. 2 and Better (Figure 5). High quality visually graded lumber is regarded as the production of No. 2 and Better grades. A No. 2 graded lumber is a No. 1 graded lumber that has the presence of some minor form of a defect (*i.e.,* small area of wane). They are very similar in quality attributes (*i.e.,* design value of 9500 MPa) and as a result are often grouped together as No. 2 and Better (*i.e.,* for product premium). The yields of No. 2 and Better lumber in this study are similar to the yields reported for other plantation-grown black spruce (Zhang *et al.* 2002), as well as 90-year-old fire origin Sitka Spruce (*Picea sitchensis* (Bong.) Carrière) and Western Hemlock (*Tsuga heterophyla* (Raf.) Sarg.) from Alaska (Christensen *et al.* 2002). Other studies have looked at visual grade recovery from Douglas fir (Todoroki *et al.* 2005) and PCT fire origin jack pine (*Pinus banksiana* Lamb.) (Zhang *et al.* 2006) where the yield of No. 2 and Better lumber in these studies ranged between 77 and 88%. Not all plantation grown trees produce high yields of No. 2 and Better visually graded lumber. Compared to Daoust and Mottet (2006), this study had a higher yield of No. 2 and Better lumber than their 29-33 year old Norway spruce (54 - 74%) and white spruce (*Picea glauca* (Moenc) Voss) (63%) trees from weevil damaged plantations in Quebec.

The majority of defects leading to downgrades (mostly downgrading a No. 1 to a No. 2) were associated to wane and/or skip (83%). Both are considered manufacturing defects because wane, the presence of bark or missing wood along the edge of a piece of lumber, and skip, an area on the piece of lumber that was missed by the planner, can all be improved through different processing practices. My overall downgrades due to wane (48%) was lower than that reported by Zhang *et al.* (2002), where 70% of downgrades of black spruce plantation lumber was associated with wane. The high presence of wane can be attributed to either the choice to maximize 2x4 production from smaller trees (Zhang *et al.* 2002; 2006) or, possibly, to stem taper (Daoust and Mottet 2006; Liu *et al.* 2007b). My findings would support the ideas presented by Erikson *et al.* (2000) and Zhang *et al.* (2006) that small diameter trees may not be economically viable for conventional sawmills, unless processes are specifically adapted for such wood. Knot size was not a major contributor to the downgrade of lumber from trees on these black spruce plantations. Generally, branches from black spruce trees are not large enough to cause lumber downgrades (Liu *et al.* 2007b). Similarly, other studies involving black spruce plantations (Zhang *et al.* 2002; Liu *et al.* 2007b), Norway spruce and white spruce plantations (Daoust and Mottet 2006) report that knot size was not a major contributing defect. However, lower stand densities produce larger branch diameters that can lead more downgrades due to knots (Persson *et al.* 1995; Zhang *et al.* 2006; 2002).

Visual grades did not have significantly different mean MOE or MOR values. According to the Canadian Lumber Standards Accreditation Board (CLSAB) (2004), there is a need to ensure that the lumber produced for structural construction material can perform properly. Each visual grade has a set of design values that are intended to be a guarantee of quality (CLSAB 2004; Zhang *et al.* 2002). Trees from two of the three sites in this study consistently produced lumber that failed to meet the intended MOE design values for visual grades (Table 4). I found that 56.8% of all lumber produced from the trees on these sites met the design values for the assigned visual grade. Zhang *et al.* (2002) found that only 18.4% of the lumber produced from their plantation black spruce trees met their bending stiffness design values for their assigned visual grades. Managed plantations, designed to generate high yields and fast growth, produce wood that is more difficult to accurately estimate by visual grading (Griffin *et al.* 1999; Zhang *et al.* 2002). Although I noticed that trees from the Tyrol site produced a fairly accurate yield of visually graded lumber by all standards (Table 4), I am in agreement with Zhang *et al.* (2002) who suggest that visual grading of plantation lumber can be ineffective and suggested the need to machine stress rate this lumber.

2.4.2 Lumber bending Strength, Stiffness and MSR Recovery

I found inconsistent suitability to MSR grades for lumber produced from the trees on these sites (Table 5). Overall, I had higher proportions of lumber that met the same MSR grades for plantation black spruce as reported by Zhang *et al.* (2002), but lower than those reported by Erikson *et al.* (2000) for 45 year-old second grand fir and lodgepole pine (*Pinus contorta* Dougl. ex Loud.). Even though there is variability in the amount of lumber meeting MSR grades within and between species (Erikson *et al.* 2000; Zhang *et al.* 2002; 2006), MSR grading accurately produces a product out of managed, high yield forests where visual grading falls short (Zhang *et al.* 2002; 2006).

The yield of MSR graded lumber from trees on these sites varied greatly (Table 5), because MOE and MOR values were significantly different ($p < 0.001$) between sites (Figure 5). With respect to MSR lumber yield, trees from the poorest site (Tyrol) produced the highest percentage of MSR lumber, whereas the trees from the medium site (Airstrip) yielded the lowest percentage of MSR lumber. Trees from the best site (Boom) yielded medium percentage of MSR lumber. One of the highest stand densities (Tyrol) produced the highest MSR yield while the other (Airstrip) produced the lowest MSR yield. The lowest stand density (Boom) produced a higher yield of MSR lumber than a higher density stand (Airstrip). In this study I was unable to completely differentiate between the influences of site quality or stand density due to the confounding relationship between the two. However, the Tyrol site had the highest density and the highest yield of MSR lumber which is in agreement with stand density influences reported by previous studies (Daoust and Mottet 2006; Liu *et al.* 2007a; Persson *et al.* 1995; Zhang *et al.* 2002; 2006). As well, the site quality influences I noticed between Boom and Airstrip are similar to those published by Daoust and Mottet (2006) and Watt *et al.* (2006) who also reported that higher site quality increases wood quality attributes. The yield of MSR lumber can also be influenced by log position in the tree. Lumber produced from logs with live crown were weaker in MOR than lumber produced from logs without live crown (Figure 6). Butt logs produced stronger lumber than top logs, consistent with the results of other studies that have examined the influence of juvenile wood on wood strength (Fujimoto *et al.* 2006; Persson *et al.* 1995; Zhang *et al.* 2006).

Economy grade lumber sawn from the sample trees had a smaller average ring width (Figure 8) and a higher wood density (Figure 7) than any of the other visual grades. In this study, almost all the lumber pieces graded as economy were downgraded due to wane, indicating the likelihood that the lumber was sawn from the outer portion of the log. As well, most of the economy grade lumber came from below the live crown. This would explain part of the reason why MOE and MOR values were not significantly different between visual grades. Economy lumber would have a similar or greater mature wood content compared to other grades based on its higher wood density and smaller ring width (Persson *et al.* 1995; Watt *et al.* 2005). Decreasing stand density will increase annual ring widths during early stand development, which in turn increases juvenile wood content (Alteyrac *et al.* 2006; Persson *et al.* 1995). An early study (Zhang *et al.* (2002) reported that Economy grade lumber in black spruce had a significantly higher wood density than the SS grade, which is similar to my findings, but they noted that Economy grade lumber came from near the pith (wider ring widths), which is contrary to my results. In this study, very a few pieces of Economy grade lumber with high wood density showed characteristics known to be found near the pith (*i.e.,* wide ring widths). Higher wood density in these Economy grade lumber could be due to the fact that early cambial development in black spruce produces dense wood (Zhang *et al.* 2002).

I found weak but significant relationships between average ring width and basic wood density (Figure 8) as well as basic wood density and MOE (Figure 9) & MOR (data not shown). The relationships between ring width and wood density in this study are similar to those presented by Koga and Zhang (2004) for balsam fir and Watt *et al.* (2005) for radiata pine (*Pinus radiata* D. Don). Wider ring widths are known to be related to lower wood density (Aubry *et al.* 1998; Jozsa and Middleton 1994; Persson *et al.* 1995; Watt *et al.* 2005; Zhang *et al.* 2002). I found that decreases in basic density were also related to poorer lumber bending properties (MOE and MOR) which were similar to results presented by Liu *et al.* (2007a) and Zhang *et al.* (2002) for black spruce, by Persson *et al.* (1995) for Scotts pine, and by Watt *et al.* (2005) for radiata pine.

2.4.3 Economic Value

The purpose of grading lumber is the capture market premiums for a specific product. If lumber produced from plantation timber consistently fails to meet the design standards set for visual grading, it will have to be treated differently than lumber produced from naturally grown stands (Zhang *et al.* 2002). The difference between the 'visual grade premium' scenario and the 'visual grade premium based on design values' scenario is representative of the potential loss in revenue from products not meeting the current design requirement for bending stiffness (MOE). This difference is estimated to be $3,200 and $3,600 per hectare for the Airstrip and Boom sites, respectively (Table 6). There is a small per hectare difference between the 'visual grade premium' scenario and the 'visual grade premium based on design values' scenario at the Tyrol site (Table 6). This means that the lumber from this site better meets the current bending design values for visual grades.

The fact that the 'MSR Premium rules' scenario has a higher (or equal) per hectare value to the other scenarios (Table 6) identifies the direct benefit of MSR grading. Part of the benefit is that MSR graded lumber can be sold as random length lumber, so a short 2x4 can still get a MSR grade premium (Random Lengths 2008). The Erikson *et al.* (2000) study also showed an increase in value from 'visual grade only' scenarios to MSR grading scenarios for grand fir and lodgepole pine. The Boom site produced bigger trees and higher volume per tree (Table 2) resulting in fewer pieces of 2x3 or short 2x4 lumber (Table 7). This is why the Boom site produces the highest value regardless of premium scenario (Table 6). Even though the Tyrol site produced a higher yield of MSR lumber, the Boom site produced a greater quantity of lumber from its trees with a lower yield of MSR lumber but with a high yield of No. 2 and Better visual grade lumber and this combination generated higher revenues (Table 7). Individual stem size plays a major role in predicting value because stem size (diameter and height) determines how many logs are produced per tree and log size determines how much lumber is produced per log (Aubry *et al.* 1998; Liu *et al.* 2007c).

2.4.4 Silviculture Implications

This study showed that there is potential to generate higher yields of MSR and No. 2 and Better visually graded quality lumber products at younger rotation ages but the best products are produced from slow growing timber (Persson *et al.* 1995; Zhang *et al.* 2002) and high stand densities (Liu *et al.* 2007a; Persson *et al.* 1995; Zhang *et al.* 2002; 2006). Plantations and other managed stands that are subject to early density regulation tends to produce bigger trees sooner, and as result are appealing to forest managers. Industry in Ontario has invested heavily into density-regulated stands (CCFM 2007) and there are expectations for this timber. Mature, naturally grown stands provide good quality products (Persson *et al.* 1995; Zhang *et al.* 2002). However, plantations that are 1/3 to 1/2 the rotation age of natural stands, with similarities in size, will not produce the same quality of products (Aubry *et al.* 1998; Daoust and Mottet 2006; Makinen and Hein 2006; Zhang *et al.* 2002; 2006). There are always risks and tradeoffs to be made with managed, high yield forests. Reducing the final harvest rotation age will increase the risk of low wood quality and poor quality products (Zhang *et al.* 2002; 2006) but allow access to fibre sooner. Extending the time to final harvest under fast growing conditions increases the relative proportion of mature wood to juvenile wood (Alteyrac *et al.* 2006); mature wood is a desired wood quality attribute for solid wood products (Jozsa and Middleton 1994; Persson *et al.* 1995; Watt *et al.* 2005; Zhang *et al.* 2002). The full benefits that can be obtained from managed, high yield forests will not necessarily be observed at early ages (Persson *et al.* 1995; Zhang *et al.* 2002; 2006), so there is a need to examine how extending the rotation will affect wood quality attributes in these kinds of stands. Silvicultural tools such as plantation planning and management, pre-commercial thinning, and single and multiple commercial thinning entries need to be explored further to determine if improvements in wood quality can be achieved from managed, high yield forests.

Chapter 3: Leaf area and sapwood area relationships in plantation-grown black spruce

3.1 Introduction

Many ecological and plant physiological studies involving forest stands use leaf area or leaf area relationships as an indicator of plant productivity (Buckley and Roberts 2005; McDowell *et al.* 2002; Mencuccini and Grace 1995; Reid *et al.* 2004). Leaf area is an important factor needed to evaluate whole tree physiological processes, such as photosynthesis (McDowell *et al.* 2006; Medhurst and Beadle 2005) and transpiration (Bovard *et al.* 2005; Ewers *et al.* 2005; Ma *et al.* 2008; McJannet and Vertessy 2001; Reid *et al.* 2006; Samuelson and Stokes 2006). The direct measurement of leaf area and branch biomass is a time consuming and costly process. Allometric relationships between two or more parts of a tree are commonly used to mathematically predict one factor based on others (Long and Smith 1989; Reid *et al.* 2004; Xiao *et al.* 2006) and can be a timesaving investment.

It has long been recognized that leaf area can be predicted from sapwood area based on the pipe model theory (Waring *et al.* 1982). While subsequent studies consistently demonstrated that sapwood area and leaf area are closely related (Binkley and Reid 1984; Long and Smith 1989; Mencuccini and Grace 1995; Monserud and Marshall 1999), this relationship is affected by climate, stand density and site quality.

Specific leaf area (SLA) is another important parameter used to estimate aboveground biomass (Sellin and Kupper 2006). SLA is a leaf area to leaf mass ratio that can indicate the degree of light interception per unit of foliar biomass (Wang *et al.* 1995). SLA is commonly used to scale up measured canopy leaf weights to canopy leaf areas (Kostner *et al.* 2002; Sellin and Kupper 2006; Simonin *et al.* 2006). Variation in SLA is known to exist between crown sections (Meadows and Hodges 2002; Medhurst and Beadle 2005; Sellin and Kupper 2006) and between needle ages (Del Rio and Berg 1979; Xiao *et al.* 2006) due to the differences in leaf morphology between sun and shade leaves (Del Rio and Berg 1979; Wang *et al.* 1995).

Black spruce is common in boreal, sub-boreal and sub-alpine forests across Canada, and is a tree species of commercial and ecological importance within Central and Eastern Canada. The objectives of this study were; to evaluate the variability in SLA between crowns sections and needle age classes, to develop a model (or models) that can be used to accurately predict branch leaf area from branch diameter, and to develop a model that can be used to accurately predict the whole tree leaf area of plantation grown black spruce trees from sapwood area.

3.2 Materials and Methods

3.2.1 Tree Selection and Measurement

3.2.1.1 Field Measurement

A series of randomly-located fixed area plots (400 m^2) were used to gather stand information in all three stands previously describe in Section 1.7. Sample trees were chosen to represent the range of diameters found on each site. Each tree was inspected prior to measurement to ensure that the stem and crown were free of any damage, disease or major deformities. Target trees were then marked and measured for outside bark diameter at breast height (DBH, 1.3m) and then felled. On felled trees, the base of the live crown was determined to be the lowest whorl of live branches at the base of a continuous crown. Sporadic live branches below the determined live crown were measured and recorded accordingly. All felled trees were then measured for total height, live crown length, live crown widths at the crown base, 1/3 and 2/3 of the crown height. Between May and July 2006, 15 sample trees were randomly selected from the airstrip plantation (3 were later discarded due to sample storage issues). Trees collected in 2006 were bucked into 8 foot logs for analysis of wood properties (Chapter 2), with disks removed between each log segment. Disks were collected at the stump and at the top end of every 8 foot log. Breast height sapwood areas were estimated for the 2006 data using the following equation:

$$A_s^{BH} = A_s^{SH} - [(1.3m - SH)/2.4892m] * (A_s^{SH} - A_s^{LH}) \quad [2]$$

where A_s^{BH} is sapwood area at breast height, A_s^{SH} is sapwood area at stump height (SH), and A_s^{LH} is the sapwood area at the top of the first 8 foot log. Disks were then labeled and transported to the lab for further measurement.

Between April and September 2007, 3-18 sample trees were randomly selected from each plantation. Wood disks, 1-3 cm thick, were removed at the stump, breast height, clear sections of the stem (2 from either a) 1/3 and 2/3 the length from the ground to the base of the live crown; or b) 1/3 and 2/3 the length from breast height (1.3 m) to the base of the live crown), crown base and mid crown for all trees collected in 2007. Average height, crown length and distance from breast height to mid-crown (D) by site for are displayed in Table 8.

Table 8. Mean total tree height (H), length of live crown (LC) and distance from breast height to mid-crown (D) for all trees sampled.

Site	H (m)	LC (m)	D (m)
Airstrip (n = 15)	11.79	6.30	7.34
Boom (n = 16)	13.38	5.92	9.12
Tyrol (n = 6)	13.05	5.07	9.22
Average (n=37)	12.68	5.93	8.42

For all trees sampled, the crowns were then cut into 1/3 sections and separated. All live branches were removed from each crown section. From each crown section, 4 live branches were randomly selected for intensive measurements. These branches were measured for total length (cm), green length (length with live needles present, cm) and branch diameter (mm). For the uppermost crown section (crown section 1), the leader, including 5 years of growth, was always collected and processed in a similar fashion as the other 3 branches from that section. The intensively measured branches were then bagged and returned to the lab for further measurement.

The basal diameter (mm) of all live branches in each crown section were measured, as well as any live branches below the identified crown base. The entire crowns of three of the sampled trees on each site were collected after branch diameter measurements and returned to the lab to be used to evaluate the accuracy of the methodology in determining whole tree leaf area. When entire crowns were collected, the branches were separated by crown section.

3.2.1.2 Lab measurement

Sampled stem sections (disks) were stored in the freezer in airtight bags until they could be processed. The sapwood/heartwood boundary was marked using an intense backlight. Disks were then placed marked side down and scanned using a desktop scanner. Scanned images were then measured using Sigma Scan-Pro® image analysis software to determine sapwood areas and heartwood area for each disk.

Sub-sampled branches were stored in a cool environment (+4°C) and attempts were made to process in a timely fashion. Branches stored in excess of 3 weeks began to degrade and mold considerably and became unusable. Needles were removed from each branch and subdivided by branchlet age group. Needles were classified as age 1, 2, 3 and 4 + years. Once the branch was completely subdivided, portions of 40-60 fresh needles were removed from each corresponding age group. These fresh needles were then scanned using the Sigma Scan Pro® image analysis software to determine the surface area of the sub-sampled needles. All needles were placed in paper bags by age grouping and both sets of needles, scanned and unscanned, were oven-dried at 78°C for a minimum of 48 hours until a constant mass was obtained, and weighed. All references to weights in this study refer to oven-dried weights. Unscanned needles were removed from the oven after an initial drying of 24 hours to allow for the removal of chaff (twigs/bark) and re-dried. Specific leaf area (SLA; m^2 g^{-1}) was determined from the measured fresh needle area and measured oven-dry weight of the scanned needles.

3.2.2 Statistical Analysis

A hierarchical, 4 factor nested model (site, tree within site, crown section within tree, and age class within crown section), as described by Lorenzen and Anderson (1993), was applied to the specific leaf area (SLA) variable. In this design, site was treated as a fixed factor, whereas tree, crown section and age class were random. Within a nested model, nested factors are treated as random (Lorenzen and Anderson 1993). The linear model was:

$$\mathbf{Y_{ijklm} = \mu + S_i + T_{(j)i} + C_{(k)ij} + A_{(l)ijk} + \xi_{(ijkl)m}} \qquad [3]$$

where: Y_{ijklm} is the value of the given response variable (in this case SLA), μ is the overall mean, S_i is the fixed effect of the i^{th} site, $T_{(j)i}$ is the random effect of the j^{th} tree within the i^{th} site, $C_{(k)ij}$ is the random effect of the k^{th} crown section within the i^{th} site and j^{th} tree, $A_{(l)ijk}$ is the random effect of the l^{th} needle age class within the i^{th} site, j^{th} tree and k^{th} crown section, and $\xi_{(ijkl)m}$ is the random effect of the m^{th} replication within the $ijkl^{th}$ treatment combination. The PROC GLM procedure on SAS/STAT software (SAS Institute Inc. 1987) was used to perform the analysis. Based on the Expected Means Squares, specific TEST statements were included in the model to calculate and test the appropriate F-ratios. The Student-Newman-Keuls (SNK) multiple range test was used for the post-hoc examination of the significant factors and are reported significant at the 0.05 level.

The scaling up of W_n per age class to W_n per branch involved combining the weight of the needles for the scanned sample with the weight of the needles for the unscanned sampled which accounted for the variation in needle age. This produced a W_n per age class. Then combining each age class on each branch produced a total W_n per branch.

The scaling up to A_l per branch involved using the SLA for each needle age class and multiplying it by the W_n of each needle age class which accounted for the variation in needle age. This determined the A_l per needle age class. Combining the A_l of each needle age class determined the A_l per branch. This resulted in a W_n or A_l for each measured branch diameter in the subsample.

To account for the variation between crown section positions, each model estimating W_n or A_l by branch diameter was determined for each crown section position. The residuals from the weight model, by crown section position, compared with the bulk tree needle weight data was visually inspected to determine if each crown section position model was free of bias.

Preliminary inspection of the data revealed a general trend of nonlinearity for branch W_n within each crown section position. The following relationship can be used for predicting W_n or A_l per branch:

$$\mathbf{Y= aBD^{b}} \qquad \textbf{[4]}$$

Where Y is the unknown or predicted value, a and b are calculated parameters from the nonlinear regression analysis and BD is the measured branch diameter (mm).

The NLIN procedure on SAS/STAT software (SAS Institute Inc. 1987) was used to analyze nonlinear relationships. The R^2 values reported for nonlinear models should not be interpreted as a goodness of fit, but served as a ranking tool during nonlinear model construction

3.3 Results

Specific leaf area (SLA) varied by site ($p = 0.0357$), crown position ($p < 0.0001$) and needle age ($p < 0.0001$). The mean SLA for needles on the trees at the Airstrip site was significantly higher than that of the Tyrol site, while that of the Boom site was not significantly different than either the Airstrip or Tyrol sites (Figure 10). Needles from crown section 1 had a lower mean SLA than crown sections 2 or 3, and crown section 2 had a lower mean SLA than crown section 3 (Figure 11). Needle age class was also highly significant and the post hoc analysis indicated that the mean SLA for needle age class 1 was significantly higher than needle age class 2, which was significantly higher than needle age class 3, which was significantly higher that needle age class 4 (Figure 12). The factor Tree was also highly significant ($p < 0.0001$).

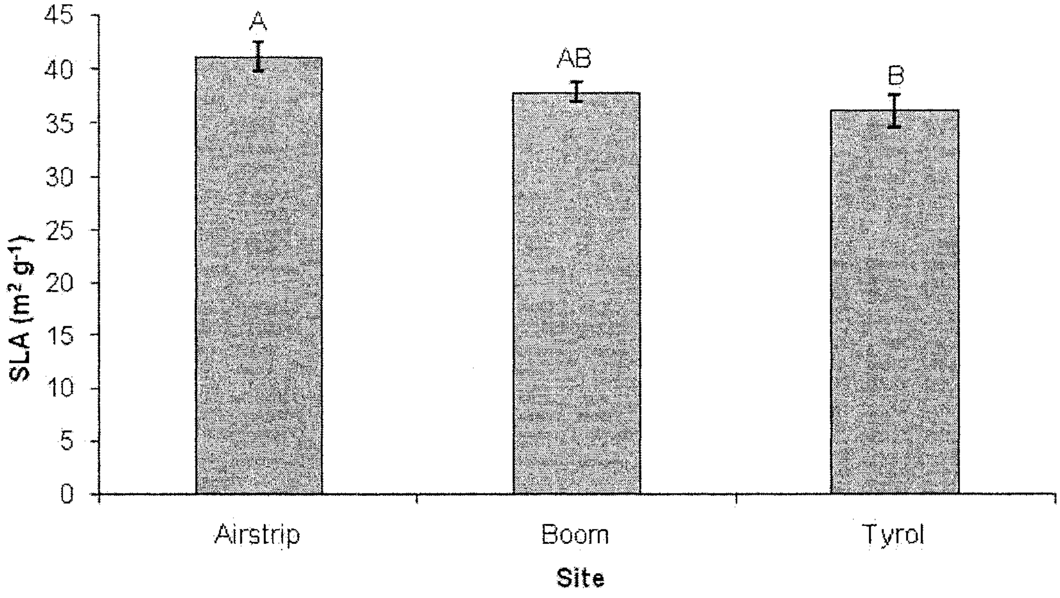

Figure 10. Mean specific leaf area (SLA) values by site. Sites with the same letter are not significantly different according to the SNK post hoc results for SLA. Error bars represent one standard error.

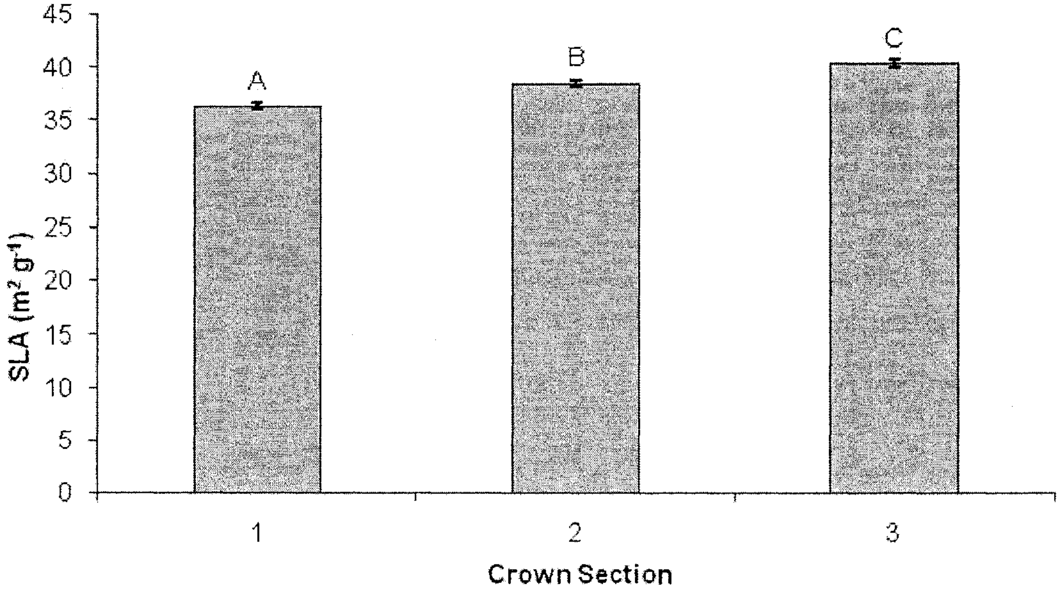

Figure 11. Mean specific leaf area (SLA) values by crown section. Crown sections with the same letter are not significantly different. Error bars represent one standard error.

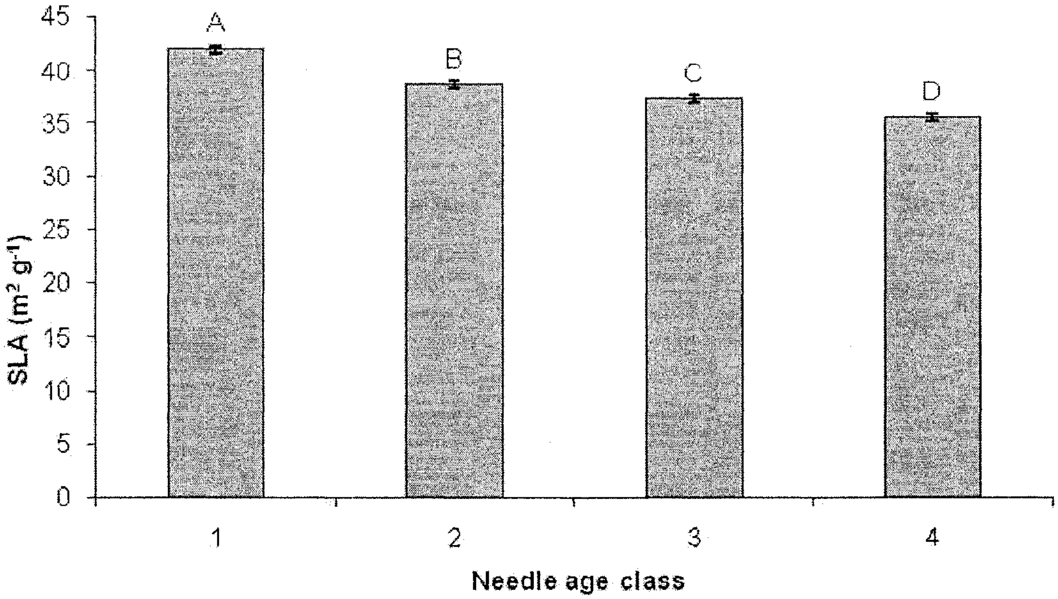

Figure 12. Mean specific leaf area (SLA) values by needle age class. Needle age classes with the same letter are not significantly different. Error bars represent one standard error.

Using Equation (4) to predict W_n (g), a is 0.1493 (SE = 0.0668), b is 2.4539 (SE = 0.1853) for crown section 1 (n = 50; $R^2 = 0.93$; $p < 0.0001$); a is 0.5254 (SE = 0.1450), b is 1.9323 (SE = 0.0992) for crown section 2 (n = 76; $R^2 = 0.96$; $p < 0.0001$). The residual plots for the predicted total needle weight versus measured total needle weight for crown sections 1 and 2 indicate an unbiased model (Figure 13a & b). The nonlinear approach for crown section 3, based on Equation (4), where a is 0.7145 (SE = 0.4165), b is 1.6815 (SE = 0.1970) (n = 80; $R^2 = 0.78$; $p < 0.0001$) showed a large bias towards over predicting total needle weight (Figure 13c). Further attempts at using nonlinear models and parameters to predict total needle weight for crown section 3, with limited variable options, failed to improve the predictive status (data not shown).

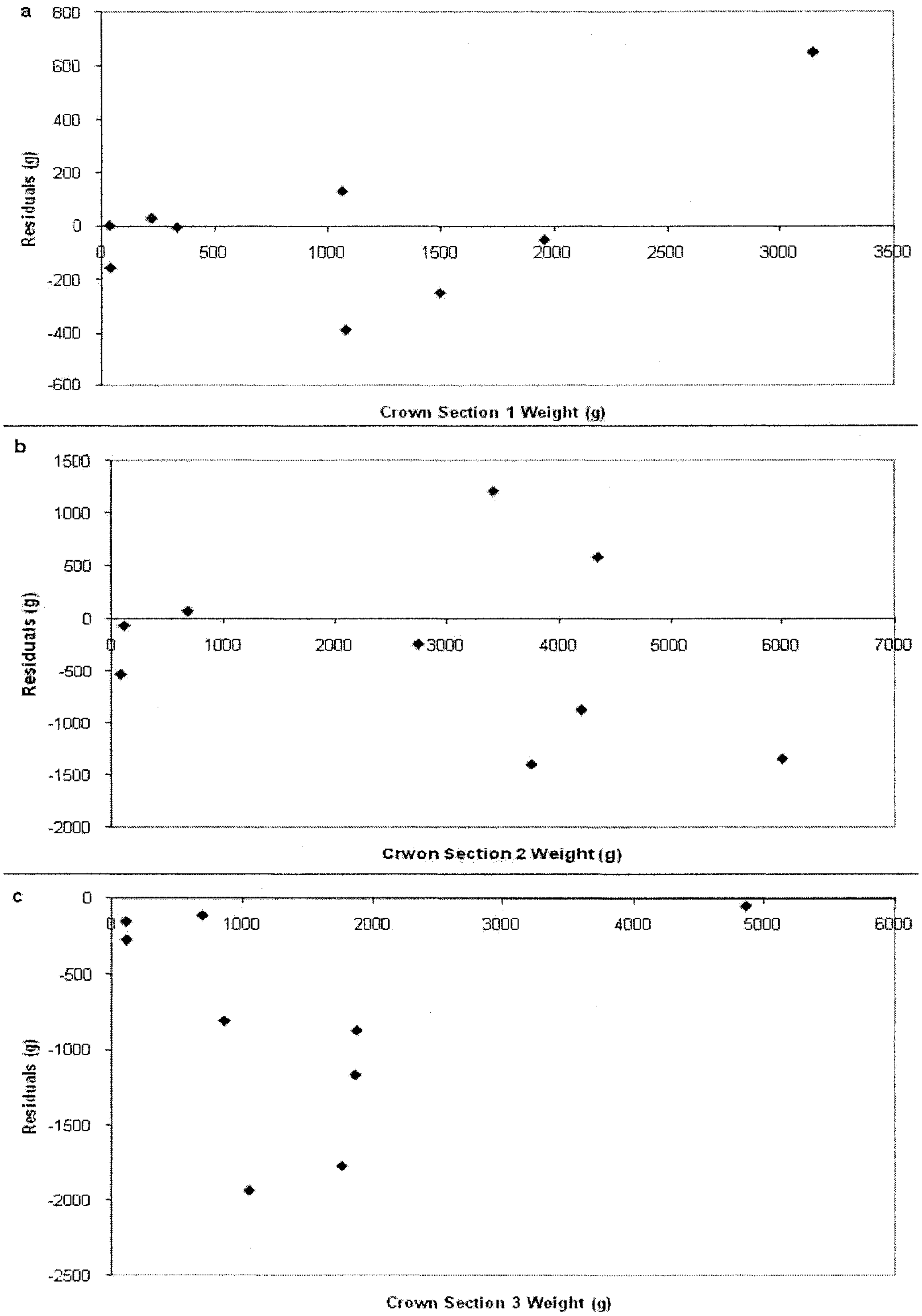

Figure 13. Residual plots (observed minus predicted) of projected total needle weight for the nonlinear model for (a) crown section 1, (b) crown section 2, (c) crown section 3.

The next approach was to convert branch diameter into branch basal area (mm^2) and use a linear model, with the line forced through the origin, in the form of:

$$W_n = 0.3459 * B_{ba} \quad [5]$$

Where W_n is the needle weight, B_{ba} is the measured branch basal area (mm^2) (SE = 34.6952; n = 100; $R^2 = 0.76$; $p < 0.0001$). This model and parameters only slightly improved the prediction of total needle weight of crown section 3 but this crown section was still showing a large bias towards over predicting total needle weight (Figure 14).

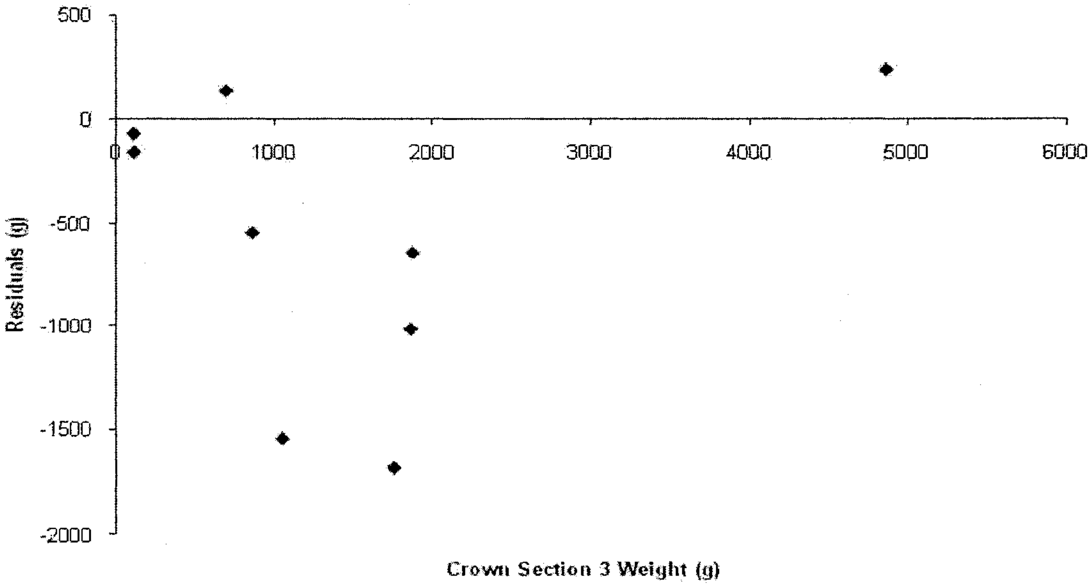

Figure 14. Residuals (observed minus predicted) of project total needle weight for crown section 3 using the linear model with the y intercept set to zero.

Using Equation (4) to predict A_l (m), a is 0.000492 (SE = 0.000174), b is 2.498 (SE = 0.1466) for crown section 1 (n = 72; $R^2 = 0.93$; $p < 0.0001$); a is 0.00163 (SE = 0.000386), b is 1.993 (SE = 0.0856) for crown section 2 (n = 98; $R^2 = 0.96$; $p < 0.0001$); a is 0.00185 (SE = 000987), b is 1.8016 (SE = 0.1797) for crown section 3 (n = 100; $R^2 = 0.76$; $p < 0.0001$); and a is 0.000064 (SE = 0.000116), b is 2.8657 (SE = 0.5065) for the leader (n = 25; $R^2 = 0.91$; $p < 0.0001$). The residual plots for predicted leaf area versus measured leaf area showed unbiased models for crown sections 1, 2 and the leader with increasing A_l (Figure 15a, b & d). Crown section 3 showed biased model predictions when the residuals for predicted leaf area versus measured leaf area are shown for increasing A_l (Figure 15c). Again, attempts were made to fit Crown section 3 to a linear model for predicting A_l from BD and B_{ba} but this too failed to produce a better fit to the data (data not shown).

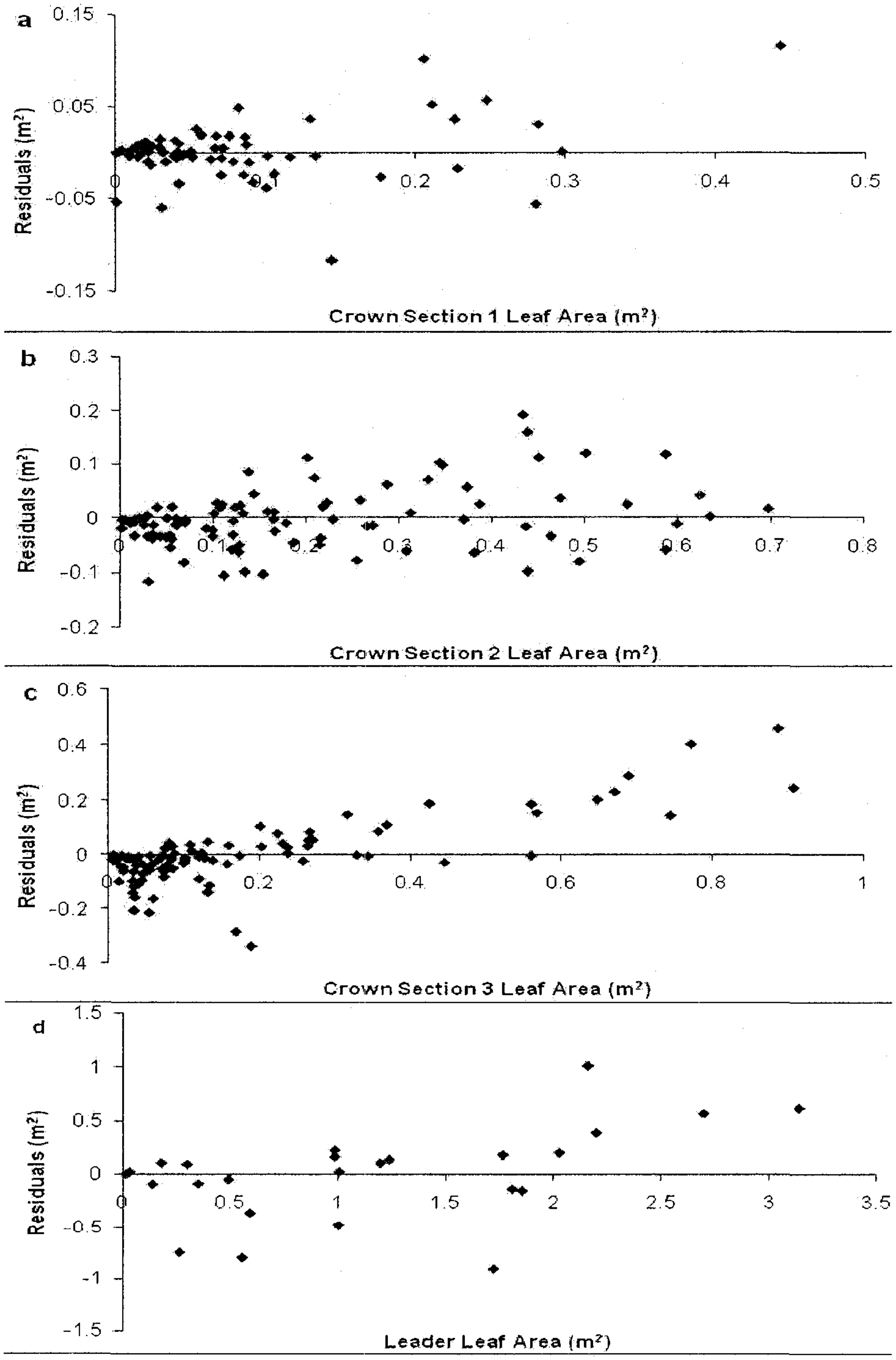

Figure 15. Residuals plots of project leaf area for the nonlinear model for a) crown section 1, b) crown section 2, c) crown section 3 and d) the leader.

There was a significant linear relationship between predicted leaf area and sapwood area at breast height ($p < 0.0001$). From the 37 trees used in this study, the linear model for predicting leaf area from sapwood area is:

$$\mathbf{A_l = 0.4353 * A_s - 2.314} \qquad \textbf{[6]}$$

Where A_l is leaf area (m^2) and A_s is sapwood area (cm^2) ($n = 37$; $R^2 = 0.84$; $SE = 6.73$) (Figure 16). The residuals from this linear model showed no bias in estimating A_l from A_s (Figure 17a).

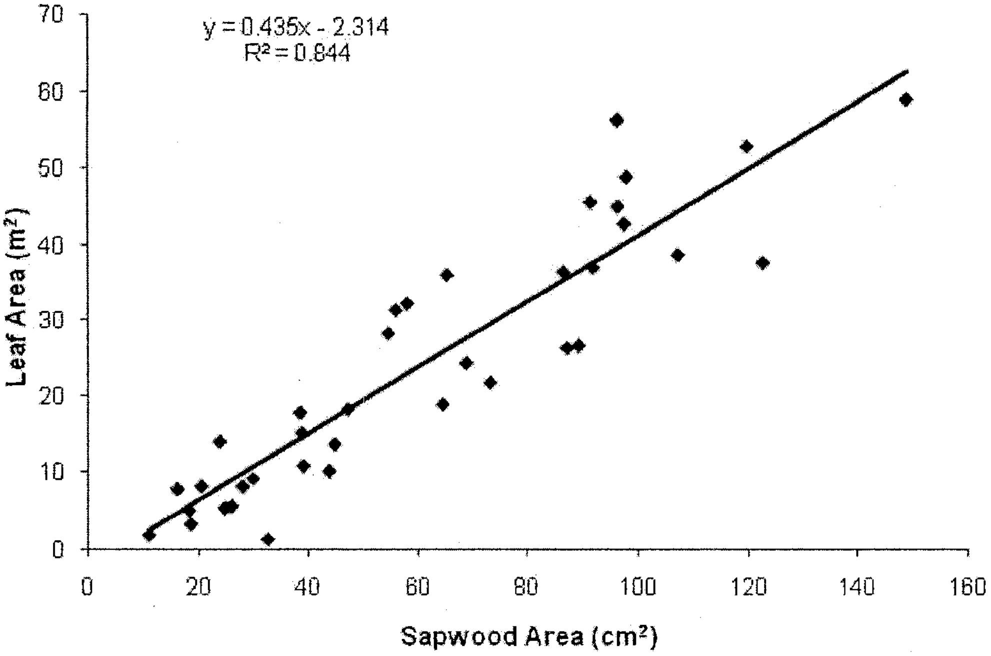

Figure 16. Linear relationship between whole tree leaf area (m^2) and sapwood area at breast height (cm^2).

Long and Smith's (1989) study noted a bias in estimating leaf area from a constant A_l: A_s ratio. I chose to repeat their analysis and derive parameters for a nonlinear model based in the relationship defined as:

$$A_l = 0.1870 * (A_s^{0.9496}) * D^{0.4434} \qquad [7]$$

Where A_l is leaf area (m^2), A_s is sapwood area (cm^2) and D is distance from breast height to the center of the live crown (m) ($n = 37$; $R^2 = 0.95$; $p < 0.0001$). The residuals from this model showed an unbiased estimate of A_l from both A_s and D (Figure 17b) but failed to show a decisive improvement over the linear model (Figure 16a).

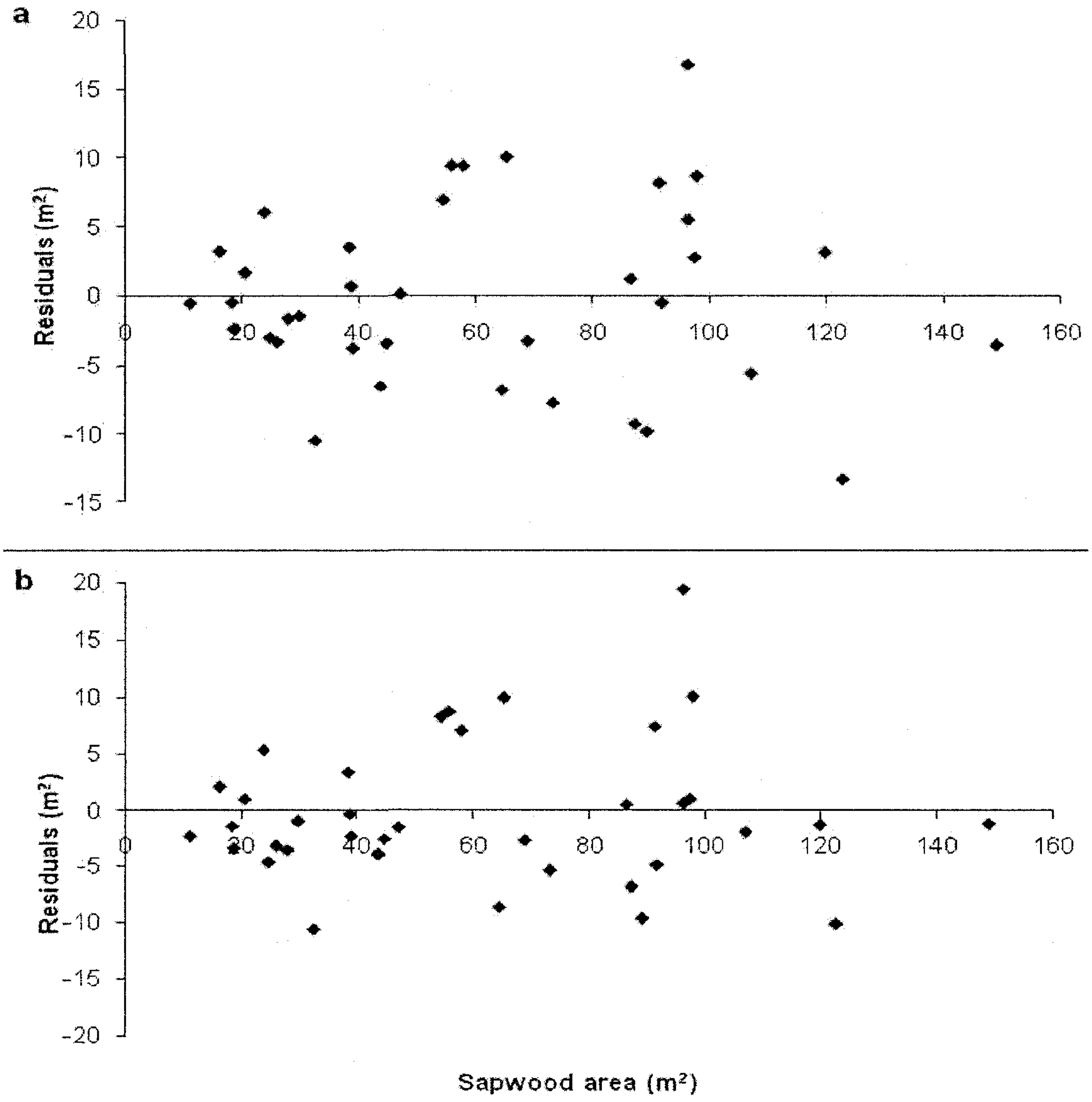

Figure 17. Residuals of projected leaf area (m^2) estimated from a) a constant leaf area: sapwood area ratio with respect to sapwood area (cm^2) and b) a nonlinear leaf area: sapwood area ratio with respect to sapwood area (cm^2).

3.4 Discussion

To accurately estimate whole tree leaf area from SLA in plantation-grown black spruce trees, the variability in SLA by needle age class and crown section position must be accounted for. My observations are consistent with previous studies, which found that SLA decreases with needle age (Borghetti *et al.* 1986; Del Rio and Berg 1979; Xiao and Ceulemans 2004; Xiao *et al.* 2006). Older needles tend to be less productive in a light harvesting role and, in addition to reduced light harvesting, serve more towards storage of nutrients (Drenkhan *et al.* 2006; Maier *et al.* 2008), which can be redistributed to younger needles before senescence (Helmisaari 1992). Others have also found SLA to decrease from the top to the bottom of the crown (Monserud and Marshall 1999; Sellin and Kupper 2006). Greater leaf area per unit mass (higher SLA) is typical for needles active in light harvesting (Del Rio and Berg 1979), whereas shade needles, like older needles, tend to store nutrients instead of maximizing photosynthesis (Brooks *et al.* 1996; Makoto and Koike 2007). Since estimates of whole tree leaf area are commonly used to determine transpiration and photosynthetic rates in large trees (Bovard *et al.* 2005; Ewers *et al.* 2005; Ma *et al.* 2008; McDowell *et al.* 2006; McJannet and Vertessy 2001; Medhurst and Beadle 2005; Reid *et al.* 2006; Samuelson and Stokes 2006), needle age and crown position should be accounted for when SLA is used to develop models for estimating leaf area.

I found that accurate estimates of branch W_n and A_l could be made in crown sections 1 and 2 (Figure 13a, b and Figure 15a, b, respectively). Branch dimension models for predicting leaf mass or leaf area in previous studies were also useful (Mencuccini and Grace 1995; Monserud and Marshall 1999). However, there was noticeable difficulty in accurately estimating branch W_n and A_l for crown section 3. Contrary to my findings, Monserud and Marshall (1999) suggest that correction in models for crown position is not necessary for foliage mass in Douglas fir, ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.) or western white pine (*Pinus monticola* Dougl. ex D. Don). This may relate to shade tolerance of the species involved and their abilities to maintain foliage in shaded crown positions longer (Mori and Takeda 2004).

When compared to actual crown weights in this study, predicted weights of crown section 3 were very biased towards an over estimation (Figure 6c, Figure 14). Lower crown sections of trees growing at or near crown closure are in a continual state of change. Branches in these sections are gradually reducing hydraulic conductivity, experiencing needle mortality, and eventual branch mortality (Protz *et al.* 2000). Each tree may be experiencing differing magnitudes of lower branch mortality and crown lifting, resulting in variability and unpredictability in lower crown sections. Using branch diameters to estimate lower crown section needle weights or needle areas is somewhat unpredictable, and caution should be taken if using this approach. The tendency is to overestimate the leaf weight or area of small diameter branches while underestimating the leaf weight or area of large diameter branches (Figure 15c).

In this study, attempts were made to follow the model presented by Long and Smith (1989) to incorporate other measured variables (such as foliated length of the branch and total branch length) to better predict needle weights and areas for the lower crown section position but were unsuccessful (data not shown). More research is needed to develop tools to accurately estimate lower crown section leaf weight and/or leaf area. The best solution may be to measure all the foliage from the lower crown section in the lab to gain needed accuracy. However, Whitehead *et al.* (1984) concluded that although there is often some level of skewness or kurtosis associated with the canopy structure of conifer species (Sitka spruce and lodgepole pine), the use of a normal function is appropriate to describe vertical distribution of foliage and that the normal function allows estimation without the need of detailed measurements. The issue of lower crown sections may not pose a serious problem in estimating overall whole tree leaf area or weights, because these changes would be reflected through changes in sapwood area (Whitehead *et al.* 1984). In addition, this particular crown section is not likely going to influence estimating photosynthesis or transpiration because the lower crown position is mainly comprised of shade leaves and, on a per unit leaf area basis, photosynthetic values are three times less in the lower canopy compared to the upper canopy (Gravatt *et al.* 1997). Shade leaves are not as efficient at the light harvesting role (Del Rio and Berg 1979; Drenkhan *et al.* 2006; Maier *et al.* 2008) which would not necessarily maintain the same demand for resources through the sapwood as sun leaves. The upper portions of the canopy, middle and top crown sections, serve more to the roles of light harvesting (Del Rio and Berg 1979; Medhurst and Beadle 2005), as indicated by the differences in SLA between crown sections and the models in this study are highly effective for the top and middle crown positions.

My linear model did not show bias in estimating A_l with increasing A_s (Figure 17a). This is contrary to the findings of Long and Smith (1989). Sapwood areas of the trees in this study ranged between 0-160 cm^2, approximately, whereas Long and Smith (1989) data set included much larger trees with sapwood areas up to almost 300 cm^2. The bias in the linear relationship appears to become apparent beyond the 150 cm^2 sapwood area (Long and Smith 1989), which is near the end range of the data from the trees in this study. A close examination of the models derived in this study (Equations 6 & 7) revealed that A_l can be predicted from A_s using a linear relationship. The calculated parameter driving A_s in Equation (7) is 0.9496, if assumed to be 1.0, this would make A_s linearly related to A_l. In the nonlinear model, D is influenced by the calculated parameter of 0.4434 (Equation 7), which suggests the distance between breast height and mid-crown to be less than the square root of D. If D is fitted to the overall mean value in Table 8 and multiplied with the 'slope' parameter from Equation (7) (0.1870), the 'new slope' is close to the linear slope derived in Equation (6). Essentially, Equation (7) can be quantified linearly as:

$$\mathbf{A_l = 0.4809 * A_s} \qquad \textbf{[8]}$$

The linear relationship (Equation 6) between A_l and A_s is sufficient for predicting leaf area for plantation grown black spruce from sapwood areas within the range of sapwood areas used for this study. The linear model (Equation 6) is a suitable model to use in estimating leaf area from sapwood area for plantation grown black spruce trees. Extrapolation of this model beyond the kinds of trees and stands described in this study may result in error.

Chapter 4: Post-thinning influences on stomatal conductance, transpiration and water use in a black spruce plantation.

4.1 Introduction

Black spruce is one of the most important commercial tree species in eastern Canada. It is in high demand for both the saw-milling and the pulp and paper industries. Thousands of hectares of land are planted every year in Ontario (Canadian Council of Forest Ministers (CCFM) 2007). Continuing to manage plantations, through a scheduled thinning regime, is a commitment towards improved stand characteristics and future products through improving and maintaining stand condition and growth (Meek 2000). In northern Ontario, there is an expected shortfall of harvestable timber and this presents a need to reassess how to manage the fibre supply (Day 1997; Ontario Ministry of Natural Resources [OMNR] 2000). Establishing a consistent thinning regime may be a tool in a forest management strategy that can prevent or mediate a dip in supply.

Thinning operations are particularly invasive when large machines are operating within the confines of a plantation (Figure 18). The potential for negative impacts on the site (*e.g.,* soil compaction) and stand (*e.g.,* physically damaged trees) that could result from operational traffic and felling are numerous (Nadezhdna *et al.* 2006; Miller *et al.* 1995). Thinning will also result in physiological impacts on residual trees in terms of transpiration, stomatal conductance and water use. It is known that soil water availability and individual tree water use will increase with the removal of competing trees (Feeney *et al.* 1998; Kolb *et al.* 1998; McDowell *et al.* 2003; McJannet and Vertessy. 2001; Reid *et al.* 2006; Sala *et al.* 2005; Zausen *et al.* 2005). However, there is very little information available describing physiological impacts on residual trees of mechanical damage and machine traffic from commercial thinning operations in black spruce plantations.

Figure 18. Commercial thinning being carried out in black spruce.

This study explores diurnal variation in transpiration, whole tree water use and stomatal conductance in relation to mechanical damage and tree proximity to harvest/extraction trails. Specifically, I sought to assess (1) the physiological response of black spruce trees, on a good site, during the first growing season following a fall commercial thinning harvest; and (2) influences of machine traffic on trees adjacent to harvester/forwarder trails. This study provides a building block for additional research into monitoring of long-term effects of commercial thinning.

4.2 Materials and Methods

4.2.1 Harvest Activity

The harvest activity was conducted in late September to early November of 2006 on the Boom Site, previously described in Section 1.7. Approximately 30% of the basal area was removed during the thinning. The harvester was a tracked Volvo EC140B with a 12 m-boom reach and a Hahn single grip processing head. A Valmet 644 rubber wheeled forwarder followed after the harvesting activities. Harvester/forwarder trails were spaced every 20 m; which involved the removal of an entire row of trees for a distance up to 300 m. The harvester felled the trees and processed them at the stump, leaving tops and branches in the trail to provide a brush-mat. All harvesting and forwarding activities were conducted from these trails. Typically the harvester processed trees and left bundles of 2.5 m and/or 5.1 m length logs on the trailside. Once felling was complete the forwarder picked up and moved the logs to roadside yarding areas.

4.2.2 Residual stand measurements

In late May of 2008, following the commercial thinning operation, the residual stand was assessed using three, randomly located, 11.28 m radial (400 m^2) plots. Within each plot individual trees were assessed for observable mechanical damage to the stem, crown and rooting area, and a systematic assessment of soil resistance to penetration was conducted. On all trees in each plot the stem and crown were visually inspected and the dimensions of all observable damage were measured. Damage to the rooting zone was assessed visually within the critical root radius, as describe by Miller *et al.* (1995). An Eijkelkamp, 06.15.SA model Penetrologger Set, penetrometer was used to measure soil penetration resistance on a total of 20 points (21 grid points, one randomly removed to accommodate data-logger storage), equally spaced on a 5m x 5m grid within each 11.28 m radius plot. Measured points fell on and between trails in all plots. The penetrometer was fitted with a 2 cm^2 cone with a 60° deflection angle and was inserted at a rate of 2cm sec^{-1}.

4.2.3 Tree selection and measurement

In the spring following the harvest, a suitable location was chosen to setup and install sapflow monitoring equipment. The location was chosen based on residual basal area harvest objectives, a central location to install a tower close to a suitable number of target trees with noticeable damage and evenly spaced harvest trails. The sapflow monitoring equipment included sapflow sensors (Dynamax TDP-30; after Granier 1987), a datalogger and a 12-volt DC power supply. The sapflow sensors consisted of a pair of fine-wire copper-constantan thermocouples connected at the constantan leads allowing for measurement of electrical potential difference (Voltage difference or ΔV) between the two leads. The upper and lower probes were separated by 4 cm. The upper position probe contained both a thermocouple and a heat producing resistor that was continually heated, generating a temperature difference between the two thermocouples that was reflected by the ΔV recorded by the datalogger. The difference in temperature between the heated probe and the unheated reference probe were interpreted, through differences in ΔV, to measure vertical sapflow. When vertical sapflow was minimal, heat dissipation was governed by conduction. When vertical sapflow was high the applied heat was dissipated more rapidly due to convection and ΔV declined. The sapflow sensors were installed into the sapwood (at breast height (1.3m)) to a depth of 2 cm, on the north facing side of each tree. The trees were wrapped from near the base of the stem to 30 cm above the thermocouple with insulating, reflective padding to help prevent heat gain from direct sunlight. Voltage differences were recorded every 30-minutes, with constant heating of the probe. The dataloggers were downloaded frequently to monitor the function of the equipment and to minimize loss of data, where possible, due to animal damage or faulty equipment.

Figure 19. Sapflow monitoring equipment showing insulation wrapped sensor trees.

Zero sap flux typically occurred after several hours of darkness and the stable maximum voltage difference was observed (ΔV_{max}). ΔV_{max} was determined over a period of up to 10 consecutive days (Lu *et al.* 2004). Mean sap velocity (Equation 9) on a sapwood basis (v_s, m s^{-1}; (Edwards *et al.* 1997)) along a radius can be estimated after Granier (1987) as:

$$\mathbf{v_s = 119 \times 10^{-6} \left[(\Delta V_{max} - \Delta V) / \Delta V\right]^{1.231}} \qquad \textbf{[9]}$$

Instruments were installed on 12 trees; 6 were immediately adjacent to trails and 6 were away from the trails (interior). From each of these groups, 3 trees were selected according to presence or absence of noticeable mechanical damage (ranging from bark scuffs to severed roots) (Table 9). Height, live crown length and sapwood depth was also measured on all instrumented trees after the measurement period. Tree heights and crown lengths were measured with a laser hypsometer.

Table 9. DBH, location relative to trails and damage classification for all instrumented trees.

Tree	DBH (cm)	Location	Damage type	Tree	DBH (cm)	Location	Damage type
1	20.3	Interior	Scuff	7	13.5	Trail	None
2	19.5	Interior	Scrape	8	19.4	Trail	None
3	20.8	Interior	Gouge	9	16.9	Trail	None
4	17.2	Trail	Gouge root	10	20.0	Interior	None
5	12.5	Trail	Root damage	11	19.2	Interior	None
6	16.2	Trail	Severed root	12	18.0	Interior	None

4.2.4 Sapflow estimation

Stem sapwood area (A_s; m^2) was determined from sapwood depths measured on 3 cores taken at 1.3 m height on the 12 black spruce trees equally spaced around the bole of the tree. The sapwood area of each tree was estimated from the three cores taken immediately adjacent to the probe site and 1/3 the distance on either side of the probe. My estimation of sapwood area is based on the assumption that the trees are dimensionally circular in cross section and can be fitted to area = πR^2. Whole tree sapflow (Q; $m^3\ s^{-1}$) was estimated from v_s by multiplying it by A_s. Adjustments were made to Q for trees with less than 2 cm of sapwood depth at the probe site according to Lu *et al.* (2004). Transpiration (Q_l; converted to mmol $m^{-2}\ s^{-1}$); a.k.a. leaf-related sapflow (Edwards *et al.* 1997)) was estimated from Q divided by whole tree leaf area (A_l). I estimated A_l from A_s using the equation I derived in Chapter 3,

$$\mathbf{A_l = 0.4353(A_s) - 2.314} \qquad \mathbf{[10]}$$

Total daily water use (Q_d) was also estimated by summing the ½ hourly Q data for each tree.

4.2.5 Meteorological measurements

Concurrent with sapflow measurements, meteorological measurements were collected every 30 minutes at a weather station located within ½ km of the study site. The weather station collected relative humidity (RH; %), air temperature (Temp; °C), net radiation (Q*; Wm^{-2}) (assuming a maximum albedo of 0.1, typical for a spruce forest (Chang 2003) and wind speed (*u*; m s^{-1}) above the canopy. Rainfall data was not collected onsite during this study but daily totals were obtained from the MacDiarmid fire weather station, 30 km NW of the study site. Atmospheric moisture demand, or potential evaporation, was estimated using the original Penman-combination Equation 10:

$$E_o = \frac{(\Gamma \Pi) + \gamma\left((0.263 + 0.138u)D\right)}{(\Gamma + \gamma)} \qquad \textbf{[11]}$$

where Γ is the slope of the saturation vapor pressure vs. temperature curve (kPa K^{-1}), Π is net radiation (Q*) expressed as an equivalent water depth (Π (mm day^{-1}) = 0.0353 Q* (W m^{-2}) (Giambelluca and Nullet 1992)), *u* is the canopy wind speed (m s^{-1}), γ is the psychromic constant (0.067 kPa K^{-1}), and D is the vapor pressure deficit of the air ($e_s - e_a$; kPa). In the case of trees without canopy at or around breast height, there can be a lag in time associated with observations and measurements noticed in the canopy (*i.e.*, E_o) and observations and measurements noticed at breast height (*i.e.*, v_s). In such a case, the data was visually inspected to adjust corresponding values to both canopy and breast height measurements accordingly. Increases in E_o tended to occur approximately 2 hours before noticed increases in v_s.

4.2.6 Statistical analysis

The statistical analysis is limited to a qualitative description of Q, Q_l, Q_d and G_c because the treatment plot was not replicated. Differences between tree characteristics were compared using an ANOVA and are reported significant at the 0.05 level.

4.3 Results

Meteorological conditions varied considerably throughout the measurement period. Mean mid-day (11:00-15:00) values are presented for atmospheric variables (Figure 20) to provide an indication of conditions during the period when peak daily v_s was observed. The growing season started out warm and dry early in the month of May and proceeded to become cool and wet with 77 mm of rainfall during May and a monthly mean temperature of 10.5 °C. June and July experienced the most rainfall, monthly totals of 91 mm and 120 mm respectively, and were relatively warm with monthly mean temperatures of 15.2 and 16.8 °C respectively. August was the warmest and driest month with a mean monthly temperature of 18.3 °C and 51 mm of total rainfall. Temperatures for May and June were about 1.5 °C above normal and August was about 2.5 °C above normal (Environment Canada, 2008). Rainfall for May, June and July were all above average and August received much less rainfall than normal (Environment Canada, 2008). Throughout the measurement period the mid-day Q* averaged 606.3 Wm^{-2} and ranged between 1276.9 – 5.6 Wm^{-2} (Figure 20) indicating a general mix between sunny days to occasional cloud cover to heavy cloud cover. During mid-day periods, E_o averaged 0.89 mm hr^{-1} (1.88 – 0 mm hr^{-1}) and generally mirrored Q* but was also influenced by D (mid-day average of 0.41 kPa (1.57 – (-0.08) kPa); Figure 21a), and wind throughout the measurement period. During mid-day, the relative humidity averaged 65% (60 – 71%) for the months during the measurement period, which contributed to a lower D.

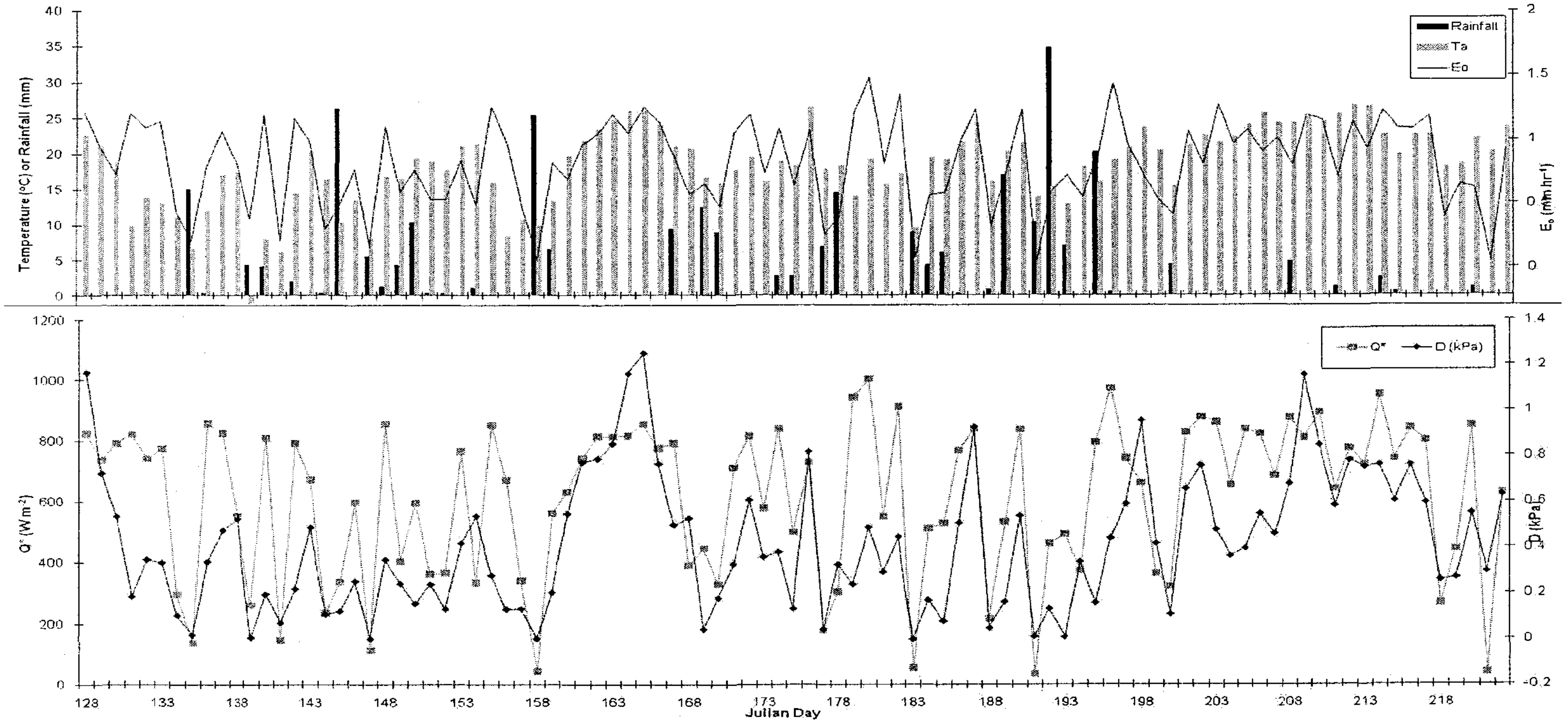

Figure 20. Mean mid-day potential evapotranspiration (Eo), air temperature (Ta), net radiation (Q*) and air vapour pressure deficit (D). Rainfall is daily accumulation (mm).

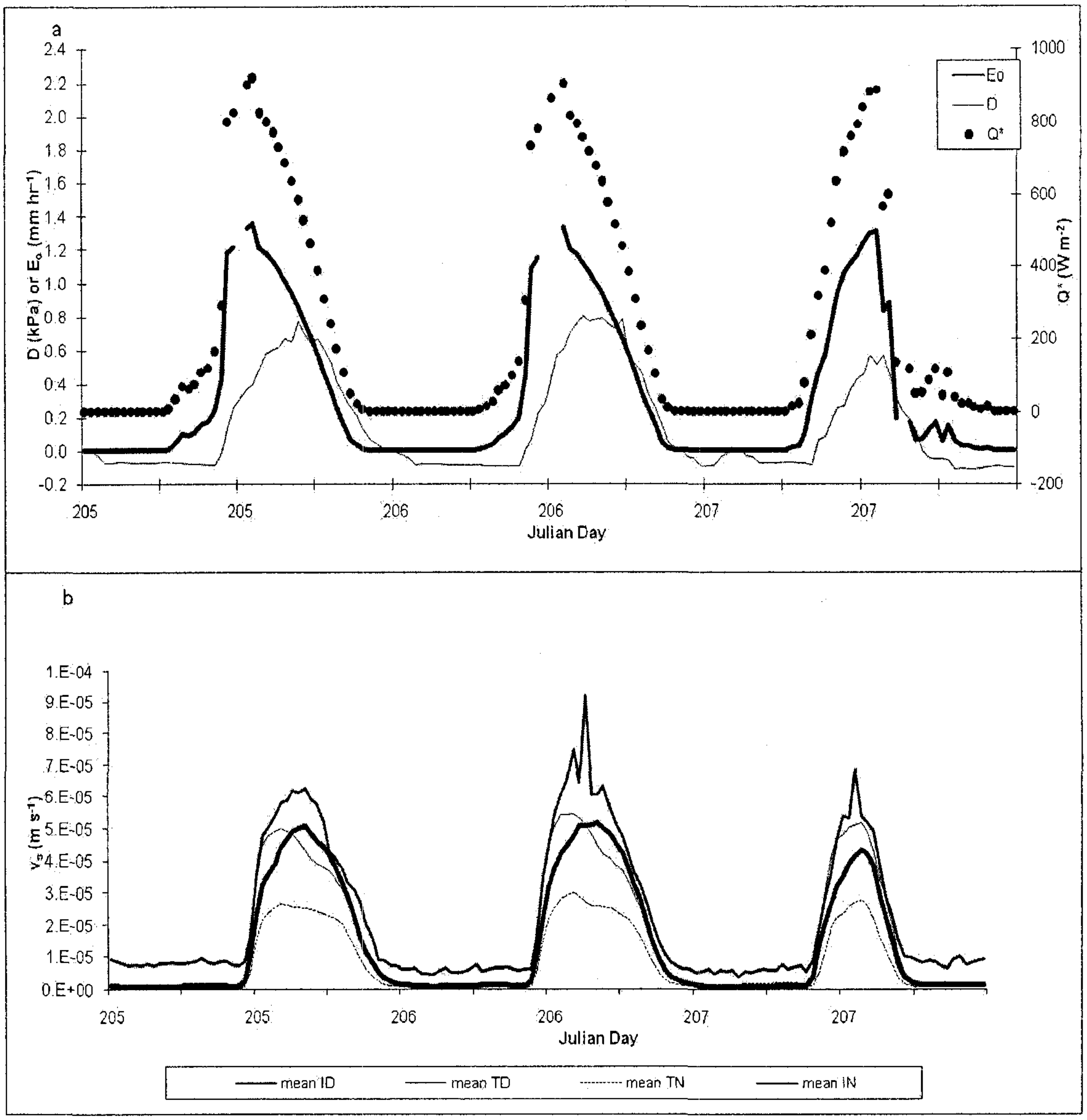

Figure 21. Typical 3 day pattern of a) concurrent changes in vapor pressure deficit (D), potential evaporation (Eo) and net radiation (Q*) and b) vapor pressure deficit (D), mean sap velocity on a sapwood area basis (vs) for thinned trees that are between trails with damage (ID), adjacent to trails with damage (TD), adjacent to trails without damage (TN) and between trails without damage (IN).

There was a consistent diurnal pattern of sapwood area related sap velocity (v_s, m s^{-1}) measured at breast height (1.3m). Generally v_s was detected after a couple of hours of daylight, increased steadily to a maximum in the early afternoon, then decreased to low flow a couple of hours after sunset (Figure 21b). Erratic v_s during the mid-day can be attributed to sudden changes in Q* and D (Figure 21a, b) most likely due to frequent cloud cover. Zero flow (ΔV_{max}) was typically noticed during pre-dawn hours and the hours shortly after sunrise when D was low, temperature and humidity were low (Figure 21b). Generally changes in v_s were observed quickly in relation to changes in D and/or gradually in relation to Q* (Figure 21b). On days following a period of dry conditions and with full sunlight, the highest v_s was typically observed between 2 and 3 hours following peak Q* and E_o and almost simultaneously with D (Figure 21). I observed marked fluctuation in Q* and D throughout the measurement period, and in general D remained relatively low compared to the maximum value observed (DOY 165 – 1.25 kPa, Figure 20).

Plots of mean transpiration per unit leaf area (Q_l) versus potential evaporation (E_o), by treatment groups, during periods of higher irradiance and D had typically resulted in asymptotic curves (Figure 22). The data presented in Figure 22 is taken from about 1 hr before sunrise, where E_o is lowest, to the time of day where E_o peaks. On most days, early morning Q_l increased quickly as E_o increased then rose rapidly in late morning. Generally, Q_l flattened out in late morning/early afternoon as E_o peaked in early afternoon (Figure 22). In most of the trees I studied Q_l tended to stabilize between 0.33 – 0.78 mmol m^{-2} s^{-1}. However, the Q_l for the TN group was generally lower (stabilizing between 0.22 – 0.38 mmol m^{-2} s^{-1}) for an associated E_o (Figure 22).

It appeared that the Interior trees in the treatment groups 'Interior without Damage' (IN) and 'Interior with Damage' (ID) had a higher daily water use (Q_d) than the trees in the other treatment groups on most days throughout the measurement period (Figure 23a). Average Q_d over the measurement period for 2007 was 5.45 L for ID trees, 2.97 L for 'Trail with Damage' (TD) trees, 4.08 L for the 'Trail without Damage' (TN) trees and 6.20 L for the 'Interior without Damage' (IN) trees. Over the measurement period, individual trees transpired as much as 20.71 L (Tree 12 (IN) on day 195) and as little as 0.06 L (Tree 2 (ID) & 5 (TD) on day 284).

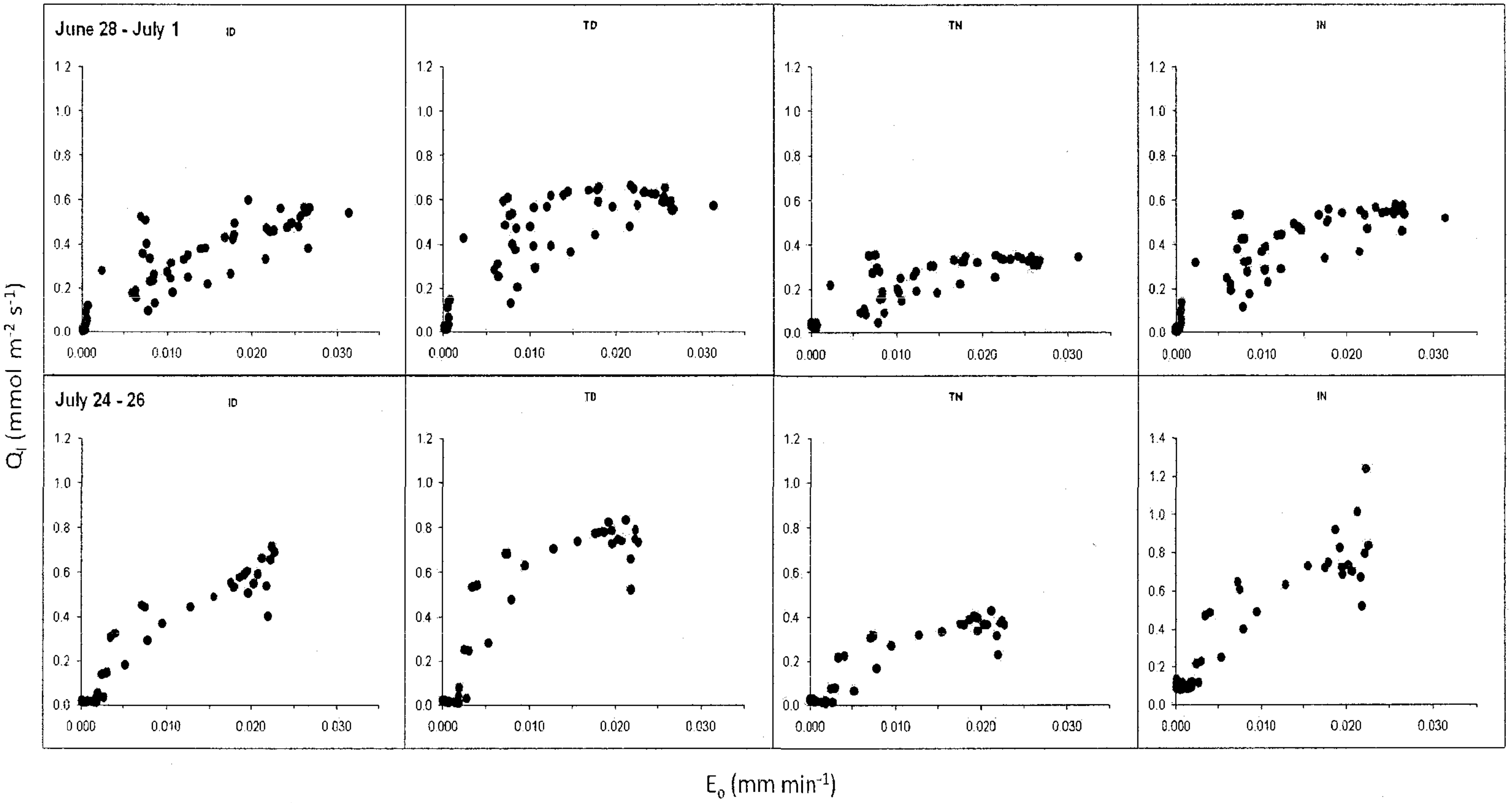

Figure 22. Mean transpiration per unit leaf area (Q_l) vs. potential evaporation (E_o) for 30 minute intervals during 2 periods of high evaporative demand.

At the beginning of the measurement period (DOY 130-152) the TD trees averaged ½ the daily water use than the other treatment groups, while the other treatment groups were all relatively similar (Figure 23a). Between days 172 and 190 (June 20 – July 8) I observed a slight increasing trend of Q_d for the Interior groups (IN and ID). The Interior groups were averaging twice the level of Q_d as the Trail groups (TN and TD), which had not increased much from the beginning of the measurement period. After day 190 and to the end of the measurement period the Interior groups (IN and ID) tended to use more water than the trail trees (higher Q_d) and the IN group, on most days, had higher Q_d than all other groups. The Q_d values for the IN group were nearly 3 times higher than those of the TD and TN groups, which remained consistently lower throughout the entire measurement period. The values of Q_d observed in trees adjacent to trails (TN and TD) remained fairly consistent throughout the measurement period (Figure 23a).

The mean mid-day leaf related transpiration (Q_l) and canopy stomatal conductance (G_c) appeared to be consistently higher for trees in the IN treatment group (Figure 23b, c). Early in the measurement period, I observed similar Q_l and G_c in all of the instrumented trees. Towards the later half of the measurement period, and after a couple of days of consistent rainfall (over 30 mm in 4 days between DOY 167 - 170, Figure 20a) I observed separation between groups and greater differences in both Q_l and G_c (Figure 23b, c). The trail-damaged trees (TD) and the interior-undamaged trees (IN) appeared similar in terms of mid-day Q_l and G_c throughout the entire measurement period, though the IN group seemed slightly higher. Toward the end of the measurement period I noticed generally higher Q_l compared to the beginning of the measurement period for the ID, IN and TD groups while the TN group failed to show such a trend and remained relatively unchanged. All treatment groups reacted in similar fashion on days when D and Q* were low and rainfall was high, with generally low G_c, Q_l, and Q_d (*i.e.*, DOY 183 – Figure 20a, b, Figure 23a, b, c).

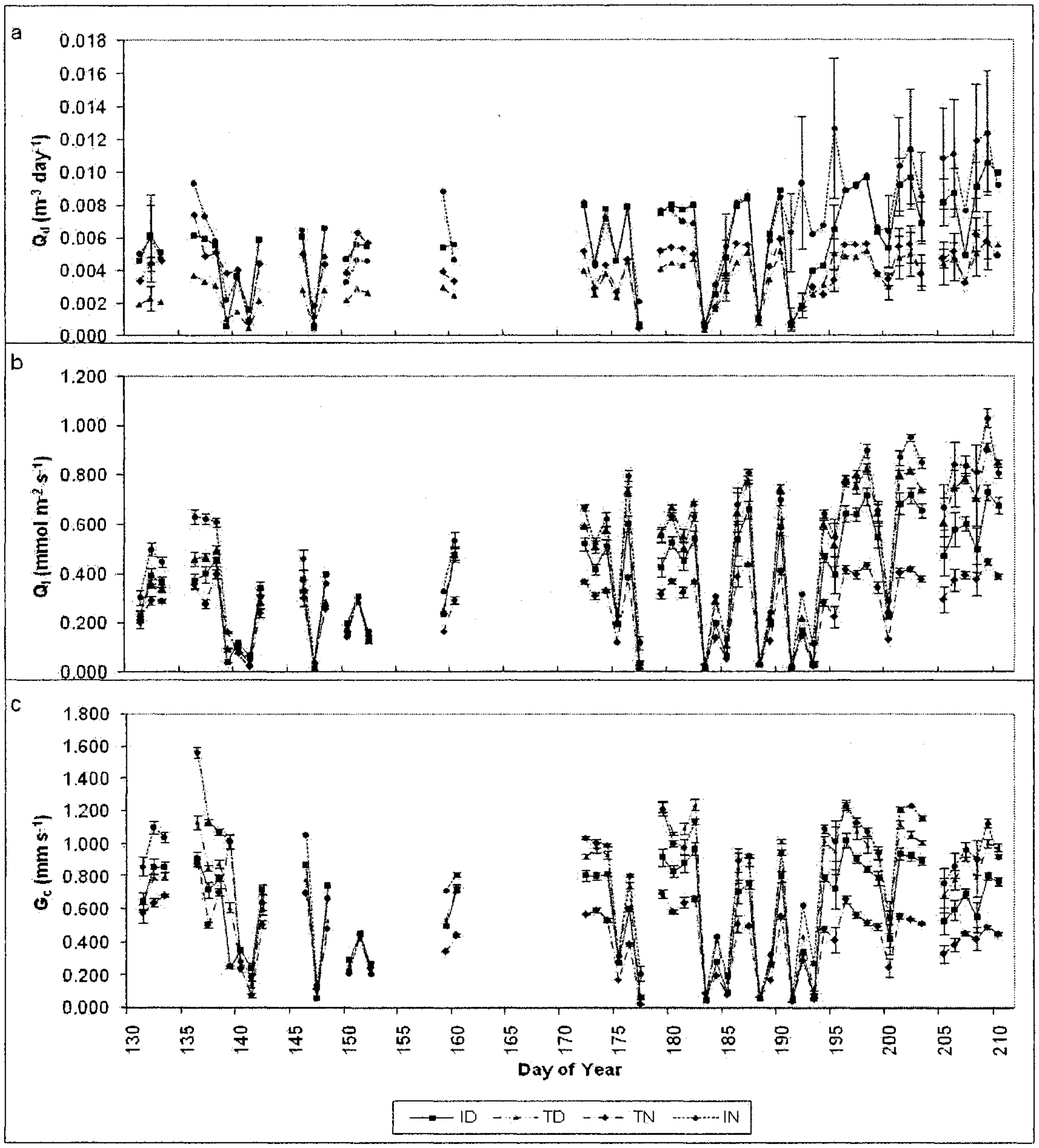

Figure 23. Daily means for total sapflow (Q_d), midday leaf related transpiration (Q_l) and midday whole canopy average stomatal conductance (G_c) of Interior Damaged (ID) trees, Trail Damaged (TD) trees, Trail No-damage (TN) trees and Interior No-damage (IN) trees. Error bars represent one standard error, and are only presented where at least one does not overlap either of the other four.

Treatment groups tended to consistently rank IN, TD, ID, TN, going from highest to lowest for both Q_l and G_c, though the highest values of both variables were occasionally observed in the TD group (*e.g.,* DOY 179-182). In general, I observed a close coupling of Q_d, Q_l and G_c with atmospheric conditions of Q* and D. As Q* and D drop dramatically, trees in all of the groups responded similarly by reducing Gc to near zero, along with corresponding decreases in Q_l resulting in very low Q_d on cool, wet and/or cloudy days.

Table 10. Average Sapwood Area (A_s), Leaf Area (A_l), Tree Height (H), Length of Live Crown (LC) and Diameter at Breast Height (DBH) for treatment groups Interior Damaged (ID), Trail Damaged (TD), Trail undamaged (TN) and Interior undamaged (IN).

	ID	*TD*	*TN*	*IN*
A_s (cm^2)	59.20	32.70	63.19	56.96
A_l (m^2)	20.58	11.03	21.63	19.06
Height (m)	14.45	13.07	14.59	15.78
LC (m)	6.68	7.36	5.66	7.73
DBH (cm)	20.20	15.30	18.15	19.07
Sample size	3	3	2*	3

*sample size reduced to 2 when post measurement of sapwood depths revealed that tree 7 had 65% of the probe in non-conductive heartwood and was removed from the dataset.

In general, the selected interior trees were larger in terms of DBH than trees selected close to the trails ($p = 0.013$, Table 10). There was no significant difference in terms of DBH between damaged and undamaged trees ($p = 0.945$), nor was there a significant interaction between damage condition and location ($p = 0.328$). There were no significant differences observed between the damaged group, the location group means or interactions for A_s, A_l, height, and live crown length (Table 11). Mean soil resistance to penetration values for both trail and interior locations gradually increased comparably with soil depth to about 30 cm (Figure 24). Soil resistance to penetration did not differ between trails for either the 0-15 cm layer ($p = 0.438$) or the 15-30 cm layer of soil ($p = 0.691$) (Table 12).

Table 11. Test statistics from ANOVA for sapwood area (A_s), Leaf Area (A_l), Height and Length of Live Crown for factors damage (damaged/not-damaged), Location (Interior or Adjacent to Trail) and the interaction effect

Factor	A_s	A_l	*Height*	*Live Crown*
Damage	p = 0.613	p = 0.613	p = 0.460	p = 0.651
Location	p = 0.122	p = 0.122	p = 0.073	p = 0.357
Interaction	p = 0.449	p = 0.449	p = 0.551	p = 0.092

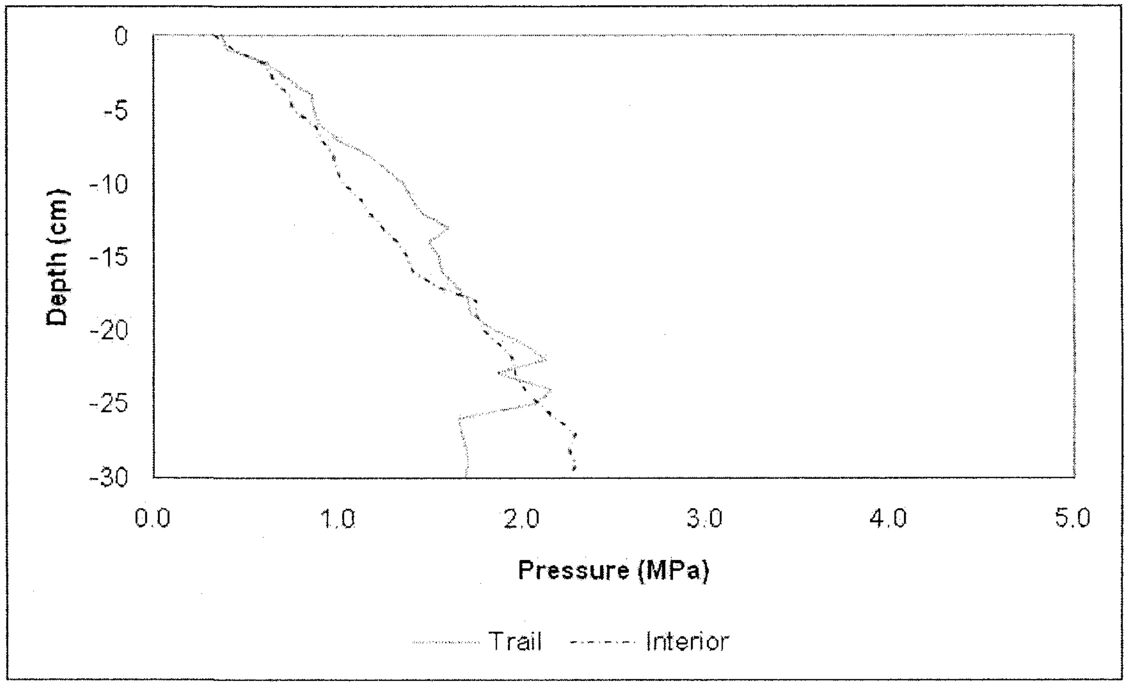

Figure 24. Mean resistance to penetration values on and between trails.

Table 12. ANOVA results for penetration resistance on and between trails for the top 30 cm of mineral soil.

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
0-15 cm						
Location	0.2302	1	0.2302	0.6100	0.4379	4.0068
Error	21.889	58	0.3774			
15-30 cm						
Location	0.0956	1	0.0956	0.1593	0.6912	4.0129
Error	33.5982	56	0.5999			

4.4 Discussion

The diurnal patterns of v_s I observed (Figure 21) were similar to patterns observed in previous studies (Ma *et al.* 2008; Reid *et al.* 2006; Bovard *et al.* 2005; Meinzer *et al.* 2006). The IN group had noticeable spiking during the peak of the sapflow (Figure 21). Lu *et al.* (2004) identify several possible causes of spiking, such as the possibility of insufficient insulation along the stem of one or more trees in that treatment group, an increased amount of solar radiation caused heating of the soil in the rooting zone, heat storage, sapflow sensors too close to the ground or poor contact between the sensors and the conductive sapwood. Since these trees were located away from the trail, heating to the rooting zone is not likely the cause. I would not expect that heat storage (typically occurs in small stems/branches) or proximity of the sensor to the ground to be an issue (all at 1.3 m) either. After examining the sapflow patterns for the entire measurement period (data not shown), this spiking is quite infrequent which would rule out poor sensor contact. The most likely cause is that the insulation around the sensors had come loose and was not corrected for a few days.

The TN group consistently appeared to have the lowest levels of midday v_s (Figure 21) indicating some restriction on sapflow. Typically, thinning increases transpiration and stomatal conductance due to increases in light availability to lower crown positions (Gravatt *et al.* 1997; Tang *et al.* 1999; 2003). The two possible restrictions may be 1) that the rooting zone for these trees were damaged limiting the trees' ability to effectively utilize soil water (Alaoui and Helbling, 2006; Page-Dumroese *et al.* 2006; Startsev and McNabb, 2001); and/or 2) that the crowns are limiting stomatal conductance, thereby reducing water loss in order to maintain leaf water potential (Ewers *et al.* 2005; Gravatt *et al.* 1997; Samuelson and Stokes 2006; Whitehead 1998; Whitehead and Beadle 2004) and thus water movement is less (Ma *et al.* 2008; Reid *et al.*

2006; Whitehead 1998). However, Liang *et al.* (1996) found that soil compaction limited stomatal conductance for *Acacia confuse* Merr. and *Litsea glutinosa* (Lour.) C.B. Rob. in south-east Asia. The analysis of the rooting zone impact (soil resistance to penetration) indicated that there were no significant differences between interior and trail rooting zones (Table 12). It may be that the method used to assess soil compaction was flawed and failed to truly represent the potential differences between soil compaction on the trail and the undisturbed interior plots. To further support the possibility that stomatal conductance was actually limited for the TN group, daily G_c trends were consistently lower for this treatment group throughout the measurement period than for other treatment groups (Figure 23c). Similarly, my analysis of crown size (length of live crown) indicted no significant differences between the 4 treatment groups (Table 11). However, the sample size for the tree characteristics analysis is small (only 2-3 samples in each treatment group) which increased the chances of committing a type 2 error and the TN group did have the smallest average length of live crown (Table 10). The TD group had higher levels of v_s than the TN group (Figure 21) indicating that it may not have been experiencing the same restriction on sapflow. The levels of Q_d appeared lower for the TD group than the TN group, but levels of Q_l and G_c were higher and showed similar trends as the Interior trees. This most likely reflects the fact that trees in the TD group had smaller sapwood and leaf areas (Table 10).

Mean sap velocity (v_s) responded quickly to changes in both Q* and D (Figure 21), with a time delay noticed in the unadjusted raw data between Q* and v_s (data not shown). Q* and D are known to play a major role in regulating sapflow (Ma *et al.* 2008). On days when Q* and D were low, there was a noticeable decrease in v_s compared to days when Q* and D are high, which is similar to patterns noticed in previous studies (Bovard *et al.* 2005; Ewers *et al.* 2005; Ma *et al.* 2008; Reid *et al.* 2006; Samuelson and Stokes 2006). As light initiates the physiological processes in the canopy, such as photosynthesis and transpiration, this creates demand for resources. For older or larger trees, time lags can be expected in sapflux determined transpiration due to the time required for chemical signals from the canopy to initiate a response from lower sections of the tree (Meinzer *et al.* 2006) and depending on availability of resources in or near the canopy (Ma *et al.* 2008). In this study, a time lag of about 2 hours was observed between first light and when sapflow began to increase at breast height and the opposite at sundown.

My observations of Q_l (Figure 22) show a leveling off with peaking E_o near midday hours. This suggests that for the trees I studied, stomatal behavior had a strong influence on transpiration during sunny days with relatively high evaporative demand. The TN treatment group is the only group that had a noticeable difference in Q_l levels in relation to E_o for both periods of high evaporative demand (Figure 22) and this is most likely caused by a limitation of stomatal conductance affecting transpiration (Ewers *et al.* 2005; Martinez-Vilalta and Pinol 2004; Whitehead 1998). My expectation was that due to the rooting behavior of black spruce, I would notice reduced levels of stomatal conductance (G_c) and lower levels of Q_l, an indication of stress (Islam *et al.* 2003; Nadezhdina *et al.* 2006; Kamaluddun and Zwiazek, 2002) to trees adjacent to trails as has been observed in other species (Becker 2006).

Results from the penetrometer measurements on and between trails (Table 12) coupled with the obvious lack of a noticeable difference in Q_l for a given E_o (Figure 22) suggests that there was no difference in soil conditions experienced between trees in the interior areas and trees adjacent to trails. Thus I might conclude that the machine traffic did not appear to affect root function and tree physiological activity on this site. However, others have shown that machine traffic can cause soil compaction (Alaoui and Helbling, 2006; Nadezhdina *et al.* 2006; Page-Dumroese *et al.* 2006; Startsev and McNabb, 2001; Zhang *et al.* 2006) and negatively affect tree rooting behavior and eventually overall tree health (Becker *et al.* 2006; Miller *et al.* 1995; Stone and Elioff, 1998). Soil compaction may have been avoided on this site because the thinning operation was carried out in the fall season on relatively dry soil conditions (2006 was a drought year), reducing the risk of soil compaction. In addition, the harvester/processor operator was careful to create a thick brushmat from tops and branches, which can reduce the impacts from machine traffic (Hutchings *et al.* 2002).

I did not notice a limitation of stomatal conductance (G_c) for the damaged trees or lower levels of transpiration (Q_l) compared to the undamaged trees (Figure 23b, c). However, Dujesiefken *et al.* (2005) found that wounds created on beech (*Fagus sylvatica*) and oak (*Quercus rubra*) during the dormant season did not close as quickly as wounds created during the growing season and can become prone to pathogens. This issue raises the need to further investigate if wounding from machine activity can cause long term detrimental effects to water movement within trees in the years following the operation.

I observed that the trees in the Interior treatment groups (ID and IN) had the highest daily water use throughout the entire measurement period (Figure 23a). I also noticed that daily water use (Q_d) did not increase in the Trail groups (TD and TN) towards the end of the measurement period (after consistent precipitation), but did appear to increase in the Interior groups (ID and IN) (Figure 23a). In this case, it is not surprising to see the TD group display lower total daily water use (Q_d) because it had the smallest average sapwood area (A_s) (Table 10). This observation is supported by the pipe model theory describe by Waring *et al.* (1982) whereby sapwood area has a constant relationship with leaf area and demand for water. Maguire and Kanaskie (2002) suggest reductions in leaf area relate to reductions in sapwood area but how this relationship is maintained is still unclear. If the TN group has limited stomatal conductance, as describe above, then this would account for the reduction in Q_d. The late season increase in Q_d for the Interior groups are indicative of expected post thinning responses to water availability and use (Kolb *et al.* 1998; Reid *et al.* 2006; Wang *et al.* 1995).

The apparent lack of response in terms of leaf area related transpiration (Q_l) for the TN group (Figure 23b) may be related to an over estimation of leaf area resulting in an underestimation of Q_l for this group trees. Since my model for estimating leaf area is based on sapwood area (Equation 10), a large amount of sapwood indicates large leaf area. However, the maintenance of the sapwood area to leaf area relationship is unclear but there is a belief that after leaf senescence, the relating sapwood may last for some time (Buckley and Roberts 2005) which would allow for the possibility to over estimate leaf area. I did have observed levels of both Q_l and G_c for the TD group exceeding the IN group on DOY 179-182. These dates correspond to days of highest irradiance (Q*) and trees adjacent to trails have increased open area (greater than that of interior trees) where greater portions of leaf area are exposed to direct sunlight allowing occasional increases in Q_l and G_c (Medhurst and Beadle, 2005; Wang *et al.* 1995). Overall the observations indicate no apparent differences in Q, Q_l or G_c resulting from a trees proximity to trails or presence of mechanical damage immediately following the fall thinning operation.

Chapter 5: Summary: bringing it all together.

Commercial thinning is silvicultural tool that has been used successfully in European countries for decades (Day 1997) but is not so common or accepted in most places in Canada. Canada has been known for its vast resources but public perception and increased pressure from non-government organizations, stakeholders and special interest groups have led to changes that affect how and where forest companies can harvest. In Ontario, the forest management planning process is designed to try to meet the needs of all forest users. As result, there is a constant change involved in where and when harvest activities can take place. These changes are ultimately limiting the vast resource availability in Ontario forest management units into smaller parcels of forested land. This places pressure on companies that manufacture wood products to find required wood supply and to continue to run their operations. This is where a silvicultural tool, like commercial thinning, becomes important. Thinning can provide an opportunity to capture some wood sooner and establish a rotation that would allow for a periodic harvest to supply fibre.

The most important aspect of harvesting timber is quality of product. The lumber produced from the trees on the sites in this study revealed a variety of options. The Tyrol site produced stronger and stiffer lumber that was suitable for MSR premiums. The Boom site produced some MSR premium lumber but generally lumber from this site was not as strong or as stiff as Tyrol. A high percentage of the lumber from all three sites met higher visual grades. This indicates the potential for harvesting plantations, similar to these, for a sawlog or stud mill supply. Expectations from a first entry commercial thinning operation should be to get timber capable of producing 2x4 or 2x3 dimensional lumber. However, the numbers presented in this study would not reflect those of a commercial thinning operation. Commercial thinning operations will harvest mostly smaller piece sizes and this in turn decreases lumber production and dimensional lumber options (decreased 2x4 products) and revenue will be less. Managers must keep in mind the economic viability of such operations since the majority of timber being harvested is smaller in diameter and not necessarily suited to conventional sawmills (Erikson *et al.* 2000; Zhang *et al.* 2006). Although not examined in this study, some wood may be suitable to be used for specialty lumber products (*e.g.*, 1x4), if such facilities exist within reasonable proximity of the harvest location. It appears that the key to getting higher quality lumber from plantation wood is getting the plantations to reach crown closure early so that mature wood is being produced in early years (Daoust and Mottet 2006; Liu *et al.* 2007a; Persson *et al.* 1995; Zhang *et al.* 2002; 2006) although the result of this study failed to show a definitive stand density impact.

The leaf area and sapwood area relationships provide a basis for ecological studies. By establishing these relationships before harvesting, future research could explore how thinning operations affect the leaf area to sapwood area relationship. This would have direct links to the physiological processes maintained within these trees (Bovard *et al.* 2005; Ewers *et al.* 2005; Ma *et al.* 2008; McDowell *et al.* 2006; McJannet and Vertessy 2001; Medhurst and Beadle 2005; Reid *et al.* 2006; Samuelson and Stokes 2006).

The bottom line is whether or not commercial thinning is appropriate in black spruce plantations. Through these studies, it appears that initially there were no detrimental physical damage (soil compaction or tree damage) or physiological effects resulting from the thinning operation. The trees monitored in this study all seemed to react in similar fashion with respect to transpiration patterns. Scrapes and scuffs to the bark, occasional root breakage and minor soil displacement did not seem to influence water movement within the trees monitored. Long term studies are needed to fully explore how these physical and physiological processes are affected over larger time spans. From the observations presented through these studies, there does not appear to be evidence suggesting that commercial thinning in black spruce plantations should not be explored further as a silvicultural method.

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