ECOLOGICALLY-BASED MODELING OF WOOD FIBRE LENGTH IN BLACK SPRUCE (*PICEA MARIANA*)

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Abstract

Fibre length is one of the most important attributes influencing the quality of wood resources, and the ultimate value of forest products. Effective planning to optimize the forest value chain requires accurate and detailed information about the resource; however, information about the distribution of fibre properties on the boreal landscape is unavailable prior to harvest. Recent studies have shown that the growth rates of black spruce (*Picea mariana* (Mill) B.S.P.) are strongly linked to ecosite classifications, which represent standard combinations of substrate characteristics and canopy vegetation. The objective of this study was to create a model that links the microscopic cellular properties of wood (fibre length) to ecosite classification at the landscape scale. A series of black spruce increment cores were collected from nine different ecosite types within the boreal forest of northeastern Ontario and were processed using standard techniques for maceration and fibre length measurement. Hierarchical classification approaches including regression tree analysis and random forests were used to fit spatial classification models and find the most important predictor variables for four response variables; mean fibre length, standard deviation of fibre length, coefficient of variation (CV) and percentage area of stem containing ideal (≥ 3 mm) fibre. Stand basal area (BA) was the best predictor of mean fibre length, crown width class was found to be the best predictor of CV, and ecosite classification was the best variable for predicting the percentage of stem area containing ideal fibre lengths. The explanatory power of the above mentioned models ranged from 67-75%. By creating a model that links wood fibre length attributes to the landscape scale this research could be used to improve the sustainability of forest management by identifying ideal locations for harvest and silvicultural activities.

Keywords

Wood fibre length, ecosite, crown width, regression tree classification

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I am especially grateful for the support of my friends and family throughout my educational endeavors, in particular my parents who have always been supportive and encouraging.

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1 Modeling Wood Fibre Length in Black Spruce (*Picea mariana*)

1.1 Introduction

The Canadian forest industry generates approximately 60 billion dollars in revenue from forest products annually, representing 2% of the national gross domestic product (Natural Resources Canada 2012). Black spruce, because of its abundance and the quality of its fibre attributes, is the most important species for the pulp and paper industry in Canada (Viereck and Johnson 1990). Wood fibre length is a critical determining factor in the quality of pulpwood, and is one of the most important attributes to the pulp and paper industry (Watson and Bradley 2009). Variation in wood fibre length determines the best use of wood resources, impacting paper grading quality and the reinforcement strength of paper products (Watson and Bradley 2009). For example, longer fibres (≥ 3 mm) are more valuable because they are used as a reinforcement pulp adding strength and value to paper products (Watson and Bradley 2009). Wood fibre properties such as fibre length are critical to the successful development of products in the forest sector, and information on the characteristics of wood before harvest would be of enormous benefit to forest harvesters, managers, mills, forest product companies and the Ministry of Natural Resources (Hilker *et al.* 2012). New innovations in the forest bioeconomy, such as the nanocrystalline cellulose (NCC) industry, could also benefit from a model that links wood fibre attributes to ecosites (Natural Resources Canada 2012). To maximize the value of wood resources by allocating them to their best use in wood products, it is important to have information on wood fibre characteristics before harvest (Vincent *et al.* 2011).

Canadian wood fibre is known for its exceptional qualities of fibre length and strength, which can be attributed to the slow growing conditions imposed by the Canadian climate (Li, 2009). Given these limitations on growth, the Canadian forest industry moved their focus towards a value-based market rather than a volume-based market, as competition in volume-based markets against southern regions with long growing seasons would be futile (MacKenzie and Bruemmer 2009). For example, Brazilian *Eucalyptus* plantations boast an annual production of approximately $60m^3$ ha^{-1} (Couto 2002) while black spruce stands of the Ontario boreal forest produce approximately $2m^3$ ha^{-1} annually (Archibald and Arnup 1993). With the move towards a value-based market it has become increasingly important to understand how key attributes, such as fibre length, vary across the landscape and how specific wood supply characteristics could be located using inventory systems (Mackenzie and Bruemmer 2009). The value chain is a wood fibre usage strategy emerging from the value-based market approach which strives to match suitable fibres with appropriate products at fair prices (Li, 2009). Past research has shown that in general fibre properties are highly correlated to the growth rate of trees (Makinen *et al.* 2002) and that crown size is an indication of this growth (Lenz *et al.* 2012). Growth rate of trees varies dependent on site conditions (Larson, 1964), and these site conditions are captured in ecological land classification systems (ELC). For example, individual black spruce diameter growth rates have been shown to differ depending on the ecosite trees are occupying (Pokharel and Dech 2012).

Based on this information, it would appear the relationships between ecosite, growth rate and wood anatomy could be quantified in the formation of a model that links microscopic properties (e.g. wood fibre length) to the landscape scale (e.g. site quality indicators) (vanLeeuwen *et al.* 2011). The use of ecosites for predictive modeling is new, but has been promoted in the literature. For example Pokharel and Dech (2012), demonstrated the use of ecosite as a predictive variable for responses such as diameter increment in black spruce. The use of ecosites as a base unit for modeling is viewed as a more holistic (*sensu* Billings 1952) approach to creating growth and yield models in forestry, as ecosite classification captures many aspects of the complex environment (Pokharel and Dech 2011). Hierarchical classification models such as regression tree analysis and random forests provide a good approach for developing models that make predictions about wood fibre attributes for specific ecosites at the landscape scale. However in order for these models to become a useful tool for forest managers, the information would need to be integrated into a spatial inventory such as the forest resources inventory (FRI). Forest Resource Inventories are important tools for forest management and planning throughout the world (vanLeeuwan *et al.* 2011). The FRI is a spatial map layer of interpreted polygons depicting information about species composition, age, size and stocking (Dech 2012). Traditional FRI approaches, which had inconsistent accuracy, no longer suit the needs of users (Baskerville 1986; Rosehart *et al.* 1987). In Ontario, due to the changing face of forestry, companies have been looking for ways to make harvesting more efficient, which require improved spatial and temporal accuracy of inventory information. Forest certification systems that focus on sustainability have also led to the need for more detailed FRI information and improved spatial accuracy (Dech 2012). Recent improvements to the FRI in Ontario include a change from polygons delineated to represent broad areas of common species composition, to polygons that now segment the landscape into specific ecosites (OMNR 2009a, 2009b). This change to the fundamental structure of the FRI allows for the use of ecosites as prediction units in the creation of growth and yield models, and this creates the potential to provide predictions at a finer, ecologically meaningful and holistic level.

Tree crown size measurements represent another indicator of growth that could be used as a predictor variable of fibre length. Crown size is a direct indicator of access to resources such as water, nutrients and light. Lenz *et al.* (2012) found that crown width was a good predictor variable for wood characteristics such as fibre diameter in plantation-grown white spruce (Lenz *et al.* 2012). Past studies show there is a relationship between fibre length and fibre diameter, suggesting that crown size may be a good predictive variable for fibre length as well (Josza and Middleton 1994).

The objectives of this study were (i) to determine if tree-level wood fibre length estimates are related to ecosite classification in populations of black spruce from the boreal forest of northeastern Ontario; (ii) to determine if tree-level wood fibre length estimates are related to crown size of individual trees in populations of black spruce from the boreal forest of northeastern Ontario; and (iii) to develop a predictive spatial model of tree-level wood fibre length from the relationships identified with ecosite and/or crown characteristics.

With access to information such as mapped inventories of wood fibre lengths, there is an opportunity to create more efficient harvesting systems and marketing strategies, while at the same time helping to work towards sustainable management of forest resources in Canada (Hilker *et al.* 2012). Forest management approaches such as the triad functional zoning approach (Seymour and Hunter, 1992) could be better facilitated with inventory information on wood fibre attributes pre-harvest. The triad approach is an attempt to increase forest product yields while conserving biodiversity by focusing intensive silvicultural efforts on the best available sites across the landscape, thereby reducing the overall land requirement to sustain levels of production and creating the opportunity to leave more forested landscape intact for conservation purposes (Messier *et al.* 2009). This study could provide information that would help in the identification of ecosites ideal for intensive silviculture and the production of high value black spruce fibres.

1.2 Methods

Study Area

The samples that this study is based on were collected in 2009 and 2010 in two Boreal forest locations, the Hearst Forest (HF) near Hearst Ontario and the Romeo Mallete Forest (RMF) near Timmins Ontario (Figure 1). The Hearst Forest (HF) is a management unit of 1,231,707 hectares and includes private, crown and protected land. Hearst Forest Management Inc., Tembec, and several other sustainable forest license holders manage the HF. The entire HF is within the northern claybelt section of the boreal forest and is mostly flat to undulating. However, there is some variation in elevation across the area (86-435m). The area is characterized by poorly drained soils with glacial lacustrine and clay deposits (Rowe 1972). Scattered across the claybelt are various minor deposits (e.g. sand), the result of past glacial activity. Data collected at the nearest weather station in Kapuskasing, Ontario, Canada, indicate the area has an annual mean daily temperature of 0.7 °C. The mean daily temperatures range from -18.7 C in coldest month (January) to 17.2°C in the warmest month (July). The average precipitation each year for the HF is 831 millimeters, comprised of 544 millimeters of rainfall and 313 centimeters of snowfall (Environment Canada 2013). The predominant tree species cover in the HF is black spruce.

The RMF is a 628,958 hectare area contained within in the Boreal forest region (Rowe 1972) of northeastern Ontario. The RMF is comprised of private and crown land, as well as several protected areas. Forest cover in the RMF is typical of the boreal forest

Figure 1: A map indicating the location of the Hearst Forest (near Kapuskasing, Ontario) and Romeo Mallete Forest (near Timmins, Ontario) where sample collection was carried out in the 2009-2010 field season. Map sourced from http://geogratis.gc.ca/api/en/nrcan-rncan/ess-sst/77cbc287-6b17-5ab6-bf2d-d61cee44356c.html

(Rowe 1972). The RMF can be separated into the Northern claybelt section (1/3 the of the forest) section and the Missinaibi-Cabonga section (2/3 of the forest). The northern claybelt section has relatively flat to gently rolling topography (300-320m), and the landscape is predominantly poorly drained clay deposits. The Missinaibi-Cabonga section is considered to have moderately rolling topography (300-380m) and a substrate consisting mainly of glacial till. Other surface deposits found throughout the RMF are glacial lacustrine, glaciofluvial, sand and clay tills and organics (OMNR 2009c). The annual mean daily temperature at the nearest weather station in Timmins, Ontario, Canada is 1.3°C, and ranges from –17.5°C in coldest month (January) to 17.4°C in the warmest month (July). The average annual precipitation for the RMF is 871 millimeters, comprised of 558 millimeters of rainfall and 313 centimeters of snowfall (Environment Canada 2013). Forest harvesting activities are managed by the sustainable forest license holder, Tembec Enterprises Inc. (OMNR 2009c). More than 50% of the forest cover in the RMF is black spruce.

Site Selection

The study plots were chosen from a network of temporary sample plots previously established for a separate enhanced forest resources inventory project on the Hearst Forest. The network employed a systematic sample design to represent the varied growing conditions which occur in the Boreal forest. Plots were selected based on stand age/development class (juvenile, mature or overmature stands) and species (mixed wood, black spruce, spruce pine and spruce fir) compositions. Each plot in the network was a circular 400m^2 unit, with the design based on growth and yield permanent growth plot standards for Ontario (OMNR 2008). An ecosite was assigned to every plot based on a standard field classification (ONMR 2009b), which involved examining a partial soil profile and identifying the dominant canopy vegetation. Plot locations were determined using a differential (sub meter) GPS to ascertain the UTM coordinates for the plot centre. Up to three trees were randomly selected for increment core sampling in each plot. Trees were selected to satisfy criteria for age class (mature) and crown cover (co-dominant crown). The trees selected for increment core samples all had the maximum crown radius measured. Tree crown radius data was gathered by measuring the distance from the centre of the stem to the edge of the drip line (from the ground looking up) in four cardinal directions. The basal area (BA; $m^2 \cdot ha^{-1}$) and quadratic mean diameter (dbhq; cm) were calculated using the DBH measurements collected and recorded from every tree in the plot.

In the RMF, a stratified random sampling design was employed to establish plots based on stand age/development stage (mature < 50 years), accessibility (within 300m of a road) and species composition. Circular plots (400 m^2) were established in suitable locations following the OMNR permanent growth plot standards (OMNR 2008). The sampling design targeted a range of spruce-dominated ecosites, and a plot was established in a location if preliminary typing based on environmental data (soil type, moisture regime, etc.) as well as vegetation characteristics (OMNR, 2009) indicated that the site was representative of one of the targeted ecosites. Selected stands were also homogenous in substrate/vegetation (e.g. only one ecosite represented) and free of signs of any recent disturbance. The DBH and species of every living tree in the plot were recorded and used to calculate the basal area (BA; $m^2 \cdot ha^{-1}$) and quadratic mean diameter (dbhq; cm). Crown width measurements were not collected for RMF plots, so a crown width prediction model was created to provide estimates for these missing values (Appendix 1). Plot centre locations were registered using recreational grade GPS. Standard tree level measurements such as height (m) and diameter at breast height (DBH;cm), were measured for each tree selected for core sampling.

Increment Core Sample Collection

Single increment cores were collected from three trees within each plot. Sample trees were selected randomly to represent the dominant or co-dominant crown class of the plot. The trees selected for increment core sampling had to be free of visible signs of stress, disease, defects or injury. Sample cores were taken at breast height (1.3 m) from bark to pith using a 12 mm diameter boring tool to ensure that entire tracheids (ie. wood fibres) could be isolated for effective measurement of wood fibre lengths. Samples were stored in a freezer at the Nipissing University Forest Resources Laboratory prior to processing and analysis.

Samples were sub-set into ecosite groups, which had to be created due to a lack of sufficient replication within certain ecosites. Ecosite groups were created based on soil characteristics outlined in the ecological land classification guide for Ontario (OMNR 2009), and involved combining a few ELC types together to create the groups representing common substrate properties. Crown width variables were also used to stratify the sample into different crown width classes (0.00-2.49 m, 2.50-2.99 m, 3.00-3.49m and > 3.5 m). All of the work described above was completed as part of the AFRITS/Geoide and FBRC enhanced inventory project prior to the initiation of my study.

Sample Processing

From the archive of several hundred samples collected in the protocol described above, I used a sub-set (N=50) of increment cores that were selected for use in this study to represent particular ecosites and crown width groups. The selected increment cores were sawn in half, lengthwise, from bark to pith with a scroll saw. One half of the increment core was mounted, sanded, dated and crossdated, and growth rings were measured using standard protocols. The mounted samples were stored in the Forest Resources Laboratory (FRL) at Nipissing University. The ring width information was derived from the half of the core retained for dendrochronological sampling, this half of the core was scanned and ring widths were measured using Windendro program (Regent Instruments, Quebec, Canada). The ring width information was used to create regional growth curves (RGC). The second half of the increment core was sampled for fibre length measurements, this process resulted in the destruction of the second half of the sample. Fibre measurements were completed using samples extracted from complete annual rings marked in five-year intervals from the bark to pith (e.g 2009, 2004, 1999, 1994 etc.). The marked annual rings were then cut away from the sample tangentially using razor blades. Fibre samples were removed from both the earlywood (EW) and latewood (LW) sections of each selected ring using the same procedure. A standard maceration procedure (Franklin 1945) was used to bleach and chemically separate fibres. For maceration, 500 ml acetic acid and 500ml hydrogen peroxide solution were added to each vial containing a wood sample. The vials were placed in a beaker with water and brought to a boil for 1.5 hours or less until physical bleaching of fibres was observed. Once fibres were macerated they were washed in a sodium carbonate solution then rinsed using distilled water. Vials were then filled with distilled water to prevent drying and as solution for slide mounting (Franklin 1945).

Macerated fibres in distilled water were wet mounted with glycerin solution on microscope slides, and the cover slips were sealed for preservation. Imagery was acquired for each sample using a confocal microscope equipped with a camera that captured data at 40x magnification, using simple white light. At this magnification the fibre lengths were often longer than the field of view, so smaller images were taken to capture the entire sample and labeled accordingly. These images were then assembled together in a mosaic to create one large image using adobe photoshop elements 5.0. Image mosaics were grayscale at 300 dpi resolution (Figure 2). Each year sampled from each increment core was associated with one large image mosaic for both EW and LW fibres. The large image mosaics were imported into the WinCell program (Regent Instruments, Quebec, Canada) in tagged image file format (tiff), where the measurement of fibres was completed. The measurement of a minimum 10 and maximum of 30 fully intact fibres (tracheids) was completed for each large image mosaic. To ensure accurate measurements of fibre length it was necessary that fibres be unbroken and separated.

Data Management and Statistical Analysis

Response Variable

It was found that there was no difference between EW and LW fibre lengths, therefore, the fibre length measurements for the EW and LW of each annual ring were averaged to create a mean ring-level estimate of fibre length. The series of mean ring-level fibre lengths for the entire pith-to-bark profile was truncated to the first 50 yrs of growth,

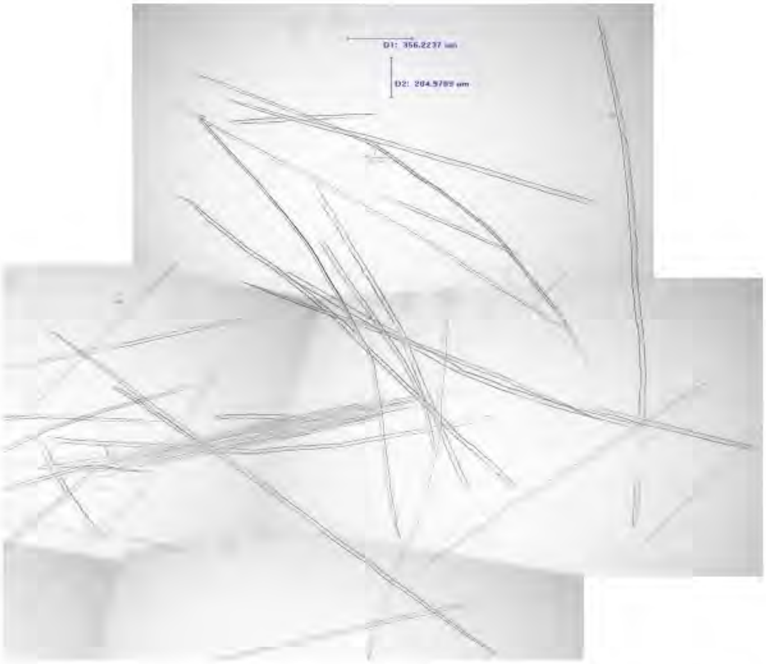

Figure 2: An example of an image mosaic of black spruce (*Picea mariana*) wood fibres. The images were acquired at 40x magnification under simple white light and the mosaic was created in adobe Photoshop version 5.0, the horizontal line represents 356.2 μm.

to remove any potential age-related confound with ecosite as a predictor variable, which could arise from the higher mean age of trees from conifer swamps relative to the rest of the sample population (Dech, unpublished data). A mean stem-level fibre length for the EW and LW of each tree over the first fifty years of growth was calculated as one of four response variables under investigation. The coefficient of variation and standard deviation of the mean stem-level fibre length over the first fifty years of growth were two other response variables that were calculated. The fourth response variable of focus was the proportion ideal fibre (PIF). This response was calculated as the percentage of stem area with mean fibre length of 3 mm or greater (MacDonald and Hubert 2002). This response variable was calculated by determining the area of the stem at 50 yrs (based on the reconstructed DBH at age 50) and subtracting from that the area of the stem where the mean fibre length was ≥ 3 mm (based on the resconstructed DBH at the year where mean fibre length surpassed the threshold) and converting the difference to a percentage of total area.

Predictor Variables

The samples were ordered into nine different ecosite groupings. The groups ranged along a gradient of subsrate moisture regime from EG-2 (Dry, Sandy) through to EG-8P (Conifer Swamps) ecosites. Among these groups, EG-3 and EG-4 were the most mesic site types and EG-8P the most hydric and least productive site. The ecosites were organized as follows; EG-2 = Dry Sandy Ecosites, EG-3= Fresh Sandy or Dry to Fresh Coarse Loamy Ecosites, EG-4= Moist Sandy to Coarse Loamy Ecosites, EG-5= Fresh Clayey Ecosites, EG-6= Fresh Silty to Fine Loamy Ecosites, EG-7= Moist Silty to Fine Loamy to Clayey Ecosites, EG-8r= Rich Conifer Swamps, EG-8i= Intermediate Conifer Swamps and EG-8p= Poor Conifer Swamps.

Crown width was another variable chosen as a predictor for fibre length in black spruce. Based on field measurements of crown width, the data were stratified into five different crown width classes (0.00-2.49 m, 2.50-2.99 m, 3.00-3.49 m and >3.5 m). The increment cores collected from the RMF did not have associated crown width measurements, so a crown width prediction model was developed based on diameter at breast height and stand density (Appendix 1). Other predictor variables were derived from plot level field data collection.

Hierarchical Classification Models

Two statistical hierarchical classification approaches were used to determine the best predictor variables for the four response variables of interest. The classification approaches used were regression tree analysis "rpart" (Therneau *et al.* 2013) and random forest "randomforest" (Breiman *et al.* 2012) in the R statistical computing environment (R Development Core Team 2013). In both cases, the response variables were classified into groups representing a common characteristic (e.g. mean fibre length) that results from a combination of predictor variable states that are depicted in a dendrogram. Regression tree analysis is appropriate for analysis of complex ecological data, and also capable of explaining variation of a single response variable using one or more explanatory variables (De'ath and Fabricius 2000). The benefit of using regression trees is that the predictors can be both categorical and continuous, and the approach is non-parametric (does not require a normal response)(De'ath and Fabricius 2000). Regression trees were set to have a minimum bucket value of three and a minimum cross-validated (cp) value of 0.001, in order to follow standard procedures to identify the ideal number of nodes in the tree (Dech *et al.* In Press). The result of a regression tree is a dendrogram or "tree" which splits the data into smaller more homogenous groups based on the importance of variables on the nodes, the most important variables found on the top node and least important on lower nodes (De'ath and Fabricius 2000). Random forest is used to overcome some limitations of the regression tree approach, such as high sensitivity to alterations of data in a small dataset (Cutler *et al.* 2007). Random forests is capable of giving insight into the validity of the models developed in regression tree by fitting the data in 5000 trees drawn from random selections of cases and variables to produce an average result, thereby testing the generalizability of the models. In each of the 5000 trees, the data selected to create them is picked using random bootstrapping. Random forests was set to have 3 or more variables selected at each split, variable importance was derived from an average of 5000 trees.

1.3 Results

All trees increased in fibre length from pith to bark, reaching a plateau at some distance from the pith, regardless of ecosite (Figures 3 and 4). The mean length of EW fibres was 2425.1 μm and the mean length for LW fibres was 2463.4 μm. On average, latewood fibres were only 2% longer than EW fibres. There was no significant difference between EW and LW fibre length nor was there an apparent interaction between wood type and ecosite, based on analysis of variance (F value =0.5376 and p value =0.47).

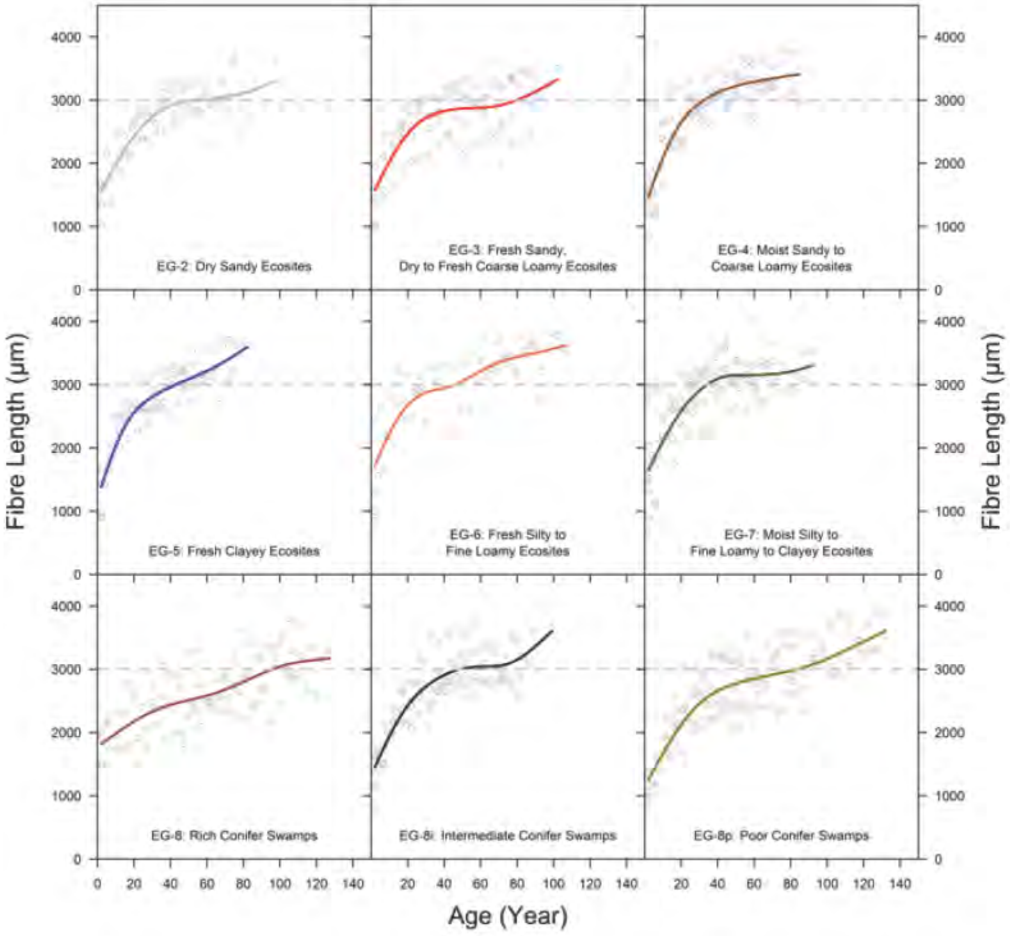

Figure 3: Mean fibre lengths for the earlywood of annual rings plotted against tree age at breast height for black spruce (*Picea mariana*) increment cores collected from the boreal forest of north eastern Ontario from 2009-2010. Values were plotted against age for all nine ecosite groups. The line was fit using a cubic smoothing spline.

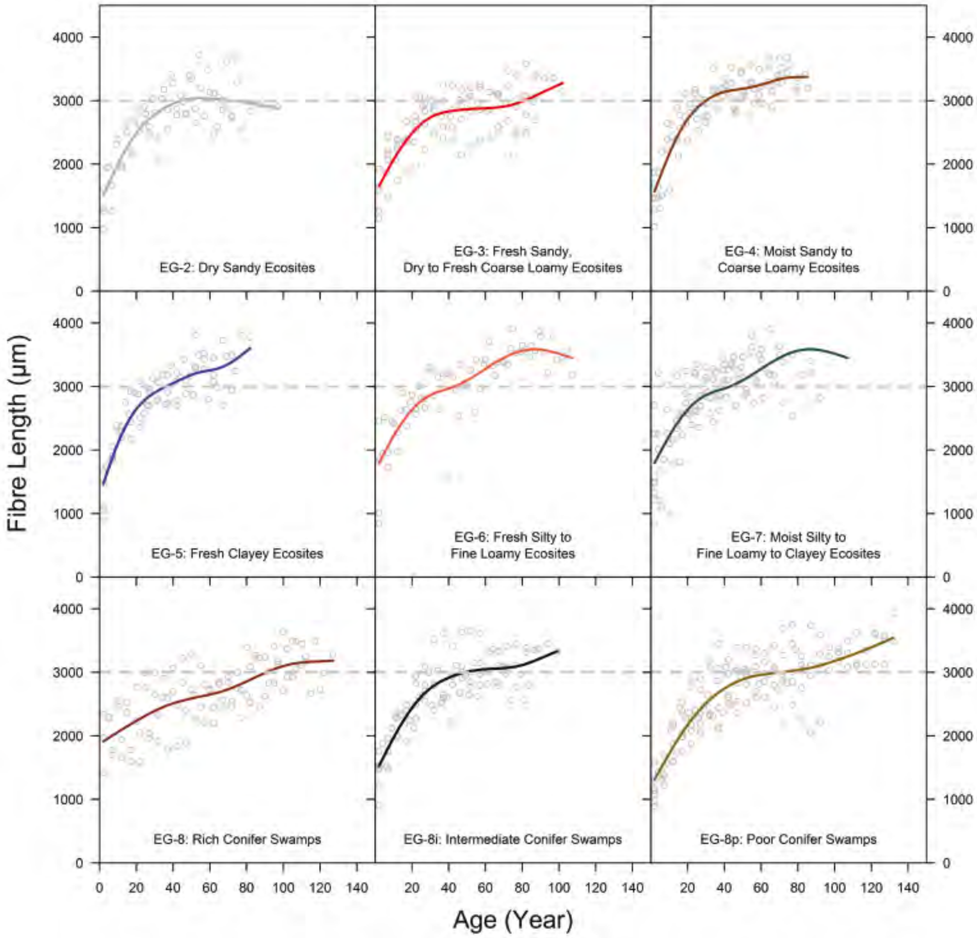

Figure 4: Mean fibre lengths for the latewood of annual rings plotted against tree age at breast height for black spruce (*Picea mariana*) increment cores collected from the boreal forest of north eastern Ontario from 2009 – 2010. The sample plots are separated into the nine different ecosite groups. The curve was fit using a cubic smoothing spline.

Sample Population Description: Ecosite Groups

Differences in several tree-level measurements were evident in the sample population based on the differences in productivity between the ecosite groups (Table 1). Ecosite group 4 (EG-4) (moist coarse) had the tallest trees (19.05m) as well as the largest average DBH (21.75 cm). EG-4 also had the highest basal area (BA)(48.82 m^2/ha) and highest stems per hectare (2125). Alternatively, the lowest average tree heights (13.9 m) and average DBH (15.7 cm) measurements were recorded in ecosite group EG-8P (organic poor conifer swamp). The lowest average stems per hectare were in EG-6 (825.6), considerably lower than all the other ecosite groups, which had a mean of 1604 stems per hectare. The highest quadratic mean diameter was 25.5 cm in EG-6 and the lowest was 14.4 cm in EG-8I.

Sample Population Description by Tree Crown Width

Tree crown width was strongly associated with all other measurements of tree size (Table 2). Trees with crown widths of >3.5m had the largest mean height and DBH at 19.12 m and 25.04 cm respectively. The trees with crown widths of 0-2.5 m had the smallest mean height at 13.96 m and smallest mean DBH at 15.46 cm. The smallest BA at 30.52 m^2 was also found in stands were trees fell into the 0-2.49 m crown width group, and the largest BA (38.13 cm^2) was found in stands were trees fell into the largest crown width group >3.5 m. The highest stems per hectare measured was in the 0-2.49 m crown width group, the lowest measurement of stems per hectare was in the 2.5-2.99 m crown width group (1397.6). The highest quadratic mean diameter was 19.8 cm in the >3.5 m crown width group, the lowest value was 15.6 cm in the 0-2.49 m crown width group. There was a general trend of decreasing mean crown width with decreasing site productivity when mean crown widths were plotted against ecosite groups (Figure 5).

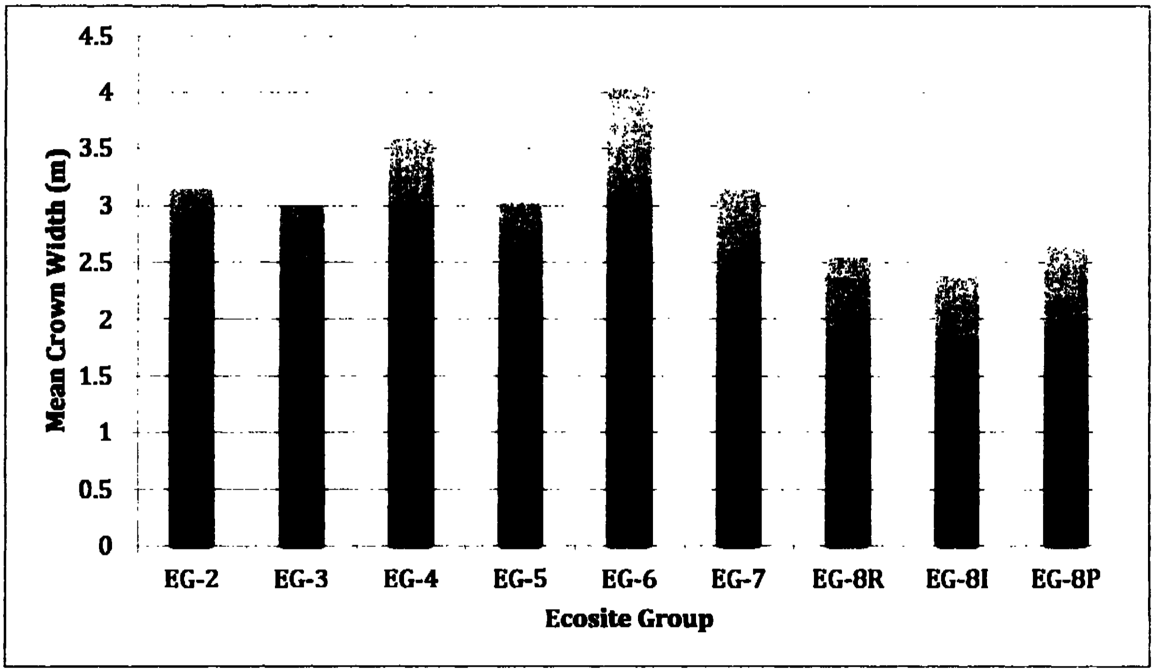

Figure 5: Mean crown width derived from measurements of black spruce (*Picea mariana)* in the Hearst Forest and a predicted crown width model for the Romeo Malette Forest of north eastern Ontario plotted for each of the nine ecosite groups.

Table 1: Descriptive statistics for sample population of black spruce (*Picea mariana)* plots (N) and trees (n) representing nine different ecosite groups collected in the boreal forest of northeastern Ontario in 2009-2010.

Ecosite Group	N	n	Height(m)	DBH(cm)	Basal Area (m^2ha^{-1})	Stems ha^{-1}	Quadratic Mean Diameter (cm)
EG-2 (dry sandy)	2	4	14.4	17.2	36.2	1807.5	16.7
EG-3(dry to fresh, coarse)	3	6	14.7	18.7	32	1054.9	20.9
EG-4(moist coarse)	2	6	19.1	21.8	48.8	2125.9	17.4
EG-5(fresh clayey)	3	5	15.4	19.1	29.4	1536	15.7
EG-6 (fresh silty to fine loamy)	2	4	18.4	24.8	38.4	825.6	25.5
EG-7 (moist fine)	7	8	17.7	20.7	34.9	1525.2	17.8
EG-8R (organic rich conifer swamp)	4	4	16.3	21.7	35.1	1388.4	18.2
EG-8I (organic/mineral intermediate conifer swamp)	5	6	14.5	16.7	24.5	1575.5	14.4
EG-8P (organic poor conifer swamp)	6	7	13.9	15.8	30.3	1818.7	14.5

Table 2: Descriptive statistics for sample population of black spruce (*Picea mariana*) trees representing different crown width classes collected from the boreal forest of north eastern Ontario in 2009-2010.

Crown Width	N	n	Height (m)	DBH (cm)	Basal Area (m^2ha^{-1})	Stems ha^{-1}	Quadratic Mean Diameter (cm)
0-2.49m	10	11	14	15.5	32.6	1777.5	15.6
2.5-3.00m	14	17	15.1	18.9	30.5	1397.6	17.6
3.01-3.49m	8	10	16.3	18.7	36.4	1589.4	17.8
>3.5m	8	12	19.1	25	38.1	1377.7	19.8

Response Variables in Relation to Ecosite

A general trend in these data showed that the fibre length-based response variables were associated with the productivity of ecosites, with less productive sites having shorter mean fibre lengths (Table 3). Mean fibre lengths for EG-4 (moist coarse) through to EG-7 (moist fine) were the longest, ranging from 2515.7 μm to 2608.3 μm. Sites EG-8R (organic rich conifer swamp) to EG-8P (organic poor conifer swamp) had the shortest mean fibre lengths ranging from 2201.7μm to 2433.7 μm. The longest mean fibre length (2608.3 μm) was found in EG-4 (moist coarse). The shortest fibres ($\bar{x}$ = 2201.7 μm) were found in EG-8P, (organic poor conifer swamps). No clear trends related to ecosite were evident in the standard deviation and coefficient of variation of fibre length values. The standard deviation for every fibre measured in the sample population was 796μm and the fibre lengths ranged from 392.44 μm to 5876.8 μm. The highest average standard deviation in fibre length was found in EG-4 (641.4), while EG-

8R had the lowest (298.3). The highest coefficient of variation was 26.7 in EG-8P and the lowest was13.3 in EG-8R. One of the more productive sites had the highest mean PIF; however, the three least productive swamp ecosites had relatively high percentages as well. The ecosite group with the highest mean PIF was EG-7 at 34.2 %, whereas EG-2 did not have a mean fibre length reaching 3 mm resulting in an estimate of PIF of zero. The two highest mean PIF values for productive ecosites were EG-6, which had a mean PIF of 14.1 % and EG-7, which had mean PIF of 34.2 %. The three swamp sites EG-8R had PIF means of 17.3 % EG-8I 18.5 % and EG-8P 14.6 %.

Response Variables in Relation to Crown Width

The response variables showed a general trend of increasing fibre length in relation to increasing tree crown widths (Table 4). The smallest crown width group 0-2.49 m also had the shortest mean fibre length at 2282.8 μm, while the largest crown width group >3.5 m had the largest mean fibre length at 2584.1 μm. The pattern of increasing mean fibre length as tree crown width increases was followed for all crown width groups. Crown width group 2.5-2.99 m had the lowest mean standard deviation (478) and lowest mean coefficient of variation (19.8). Crown width group 3-3.49 m had the highest mean standard deviation (645) and highest coefficient of variation (25.7). The crown width group >3.5 m had the highest PIF value at 17.9% the 3-3.49 m crown width group had the lowest percentage at 10.0%.

Table 3: Descriptive statistics representing four different response variables for a sample of black spruce (*Picea mariana*) increment cores collected from the boreal forest of north eastern Ontario in 2009 – 2010. The response variable values are estimates for the trees within each ecosite group.

Ecosite Group	Mean Fibre Length(μm)	Standard Deviation	Coefficient of Variation	% Stem Area with Ideal Fibre (PIF)
EG-2	2459.90	569.28	23.28	0.00
EG-3	2423.77	495.90	20.56	8.13
EG-4	2608.25	641.42	24.77	6.58
EG-5	2525.60	606.79	23.97	3.47
EG-6	2515.72	632.89	25.79	14.07
EG-7	2589.43	591.07	23.57	34.24
EG-8R	2244.32	298.27	13.30	17.28
EG-8I	2433.70	571.99	23.31	18.53
EG-8P	2201.73	590.69	26.67	14.61

Table 4: Descriptive statistics representing four different response variables for a sample of black spruce (*Picea mariana*) increment cores collected from the boreal forest of north eastern Ontario in 2009 -2010. The response variable values are estimates for the trees within each crown-width group.

Crown Width Class	Fibre Length (μm)	Standard Deviation	Coeffiecient of Variation	% Stem Area with Ideal Fibre (PIF)
0-2.5m	2282.8	581.3	25.3	12.7
2.5-3m	2436.2	478.0	19.8	16.4
3-3.5m	2515.3	645.2	25.7	10.1
3.5m+	2584.1	572.5	22.5	17.9

Classification using regression trees and random forest

Basal Area (BA) was identified as the most important variable for predicting mean wood fibre length in black spruce based on the mean of EW and LW fibre length. The secondary nodes of the regression tree were tree height and DBH (Figure 5). The regression tree explained 76% of the total variance. The regression tree information showed that trees in stands with a BA < 40.7 m^2/ha and a height less than 12.4 had a mean fibre length of 2097 μm, whereas trees with a BA > 40.7 m^2/ha and a DBH $<$ 18.85 cm would have a mean fibre length of 2910 μm. This suggests that the fibre lengths fall

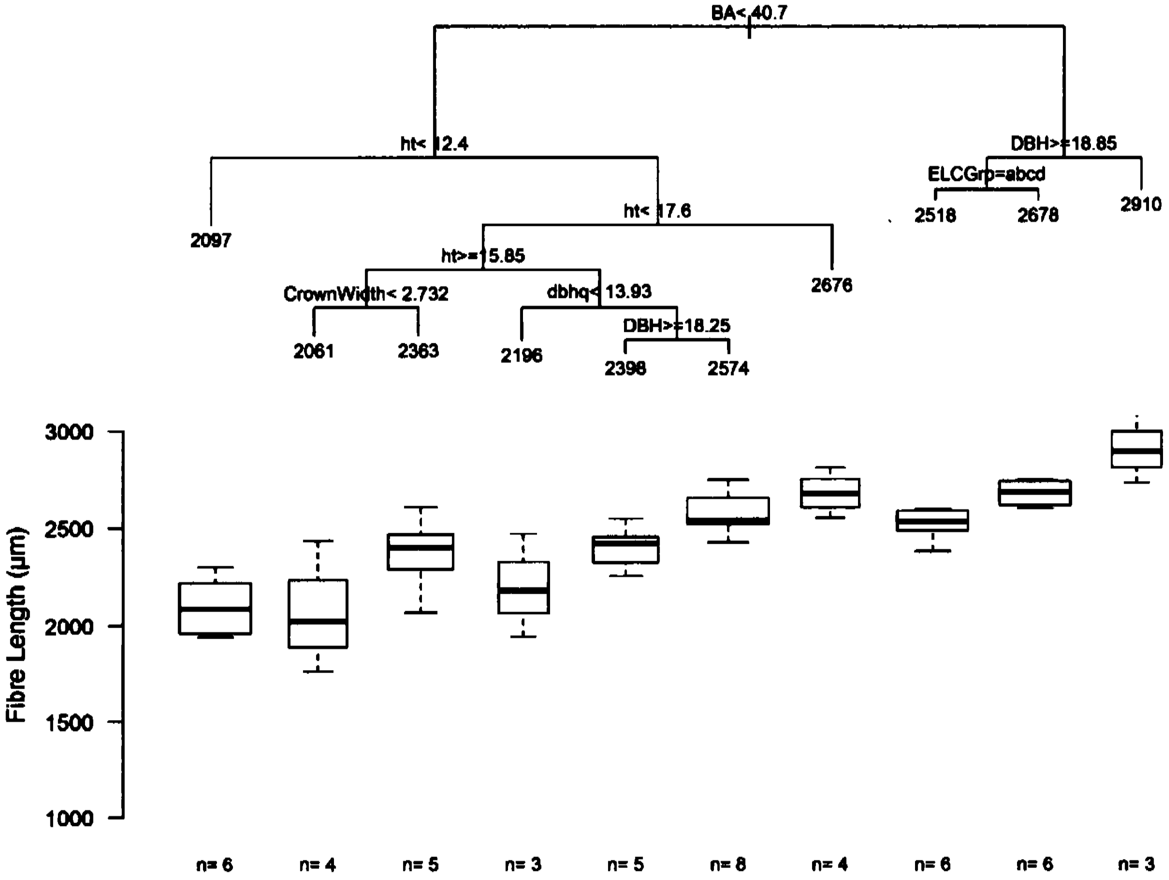

Figure 6: Regression tree analysis of mean fibre length of black spruce (*Picea mariana*) using site, tree and stand level variables for a sample population collected in northeastern Ontario, Canada. Ecosite group (a= EG-2, Dry Sandy Ecosites; b= EG-3, Fresh Sandy or Dry to Fresh Coarse Loamy Ecosites; c= EG-4, Moist Sandy to Coarse Loamy Ecosites; d= EG-5, Fresh Clayey Ecosites; e = EG-6, Fresh Silty to Fine Loamy Ecosites; f = EG-7, Moist Silty to Fine Loamy to Clayey Ecosites; g = EG-8r, Rich Conifer Swamps; h = EG-e8i, Intermediate Conifer Swamps and i = EG-8p Poor Conifer Swamps). Variable definitions BA= basal area (m^2/ha), ht= tree height (m), DBH=diameter at breast height (cm), dbhq= quadratic mean diameter (cm) and SPH= stems per hectare

along a gradient of site occupancy, stands with lower BA and lower tree heights had shorter fibre lengths and stands with greater occupancy had longer fibre lengths. The random forests analysis demonstrated that the regression tree model was sensitive to changes in the fitting data, resulting in an average model that explained only 4.3% of the variance.

There was little variation in coefficient of variation between sites. Except for site EG-8R (13.45), the ranges for coefficient of variation were narrow, spanning only from 21.28. to 27.39 %. Stems per hectare was identified as the most important variable for predicting the coefficient of variation of fibre length. Height and DBH were identified as the secondary nodes on the regression tree (Figure 6). The regression tree depicted a gradient of size and occupancy. The lowest value node occurred for trees in the 0-2.49m crown width group and the highest node (32.73) was based on having SPH > 1300, a BA<35.08 m^2/ha and a crown width >2.8 m. There was an explained variance of 67% for the regression tree. Random forest simulations produced an average model that explained only 5.5% of the variance in the coefficient of variation response variable.

Ecosite was identified as the most important variable for predicting PIF. The secondary nodes of the regression tree were DBH and BA (Figure 7). The regression tree depicted a gradient of site quality for the PIF variable, which ranged from 0-65.43%. The left node resulting in a PIF of 0.94 %, was for trees within EG-2 to EG-5 with a DBH< 21cm. The right node of the tree had the highest value of 65.43% and was based on trees falling within EG-6 to EG-8p having a BA > 41.23. The regression tree explained 66% of the total variance. Random forests results reported an explained variance of -12.3% and found that ecosite group was the most important variable in predicting PIF with a %MSE of 25. The second most important variable found by random forests was BA and the third was tree height.

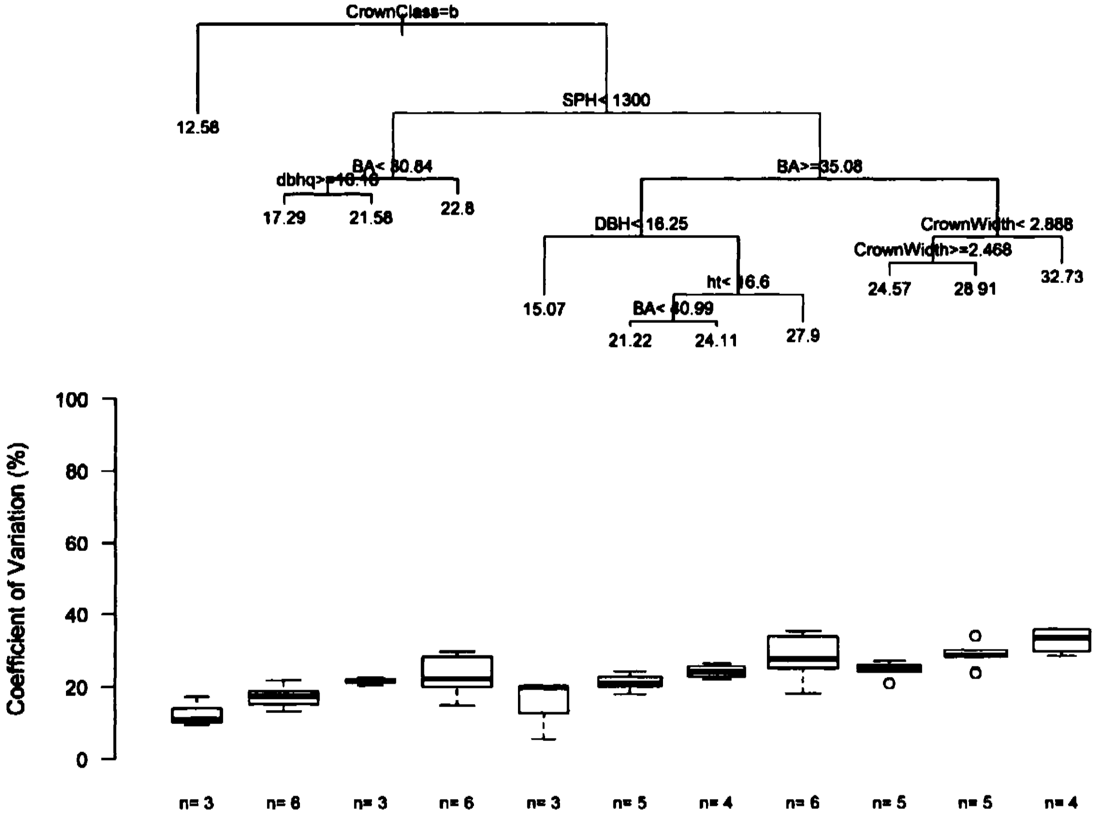

Figure 7: Regression tree analysis of coefficient of variation of mean fibre length using site, tree and stand level variables for a black spruce sample population collected in northeastern Ontario. Crown width groups (a= 0-2.49m, b=2.5-2.99m, c=3-3.49m and d=>3.5m). Variable definitions BA= basal area (m^2/ha), ht= tree height (m), DBH=diameter at breast height (cm), dbhq= quadratic mean diameter (cm) and SPH= stems per hectare

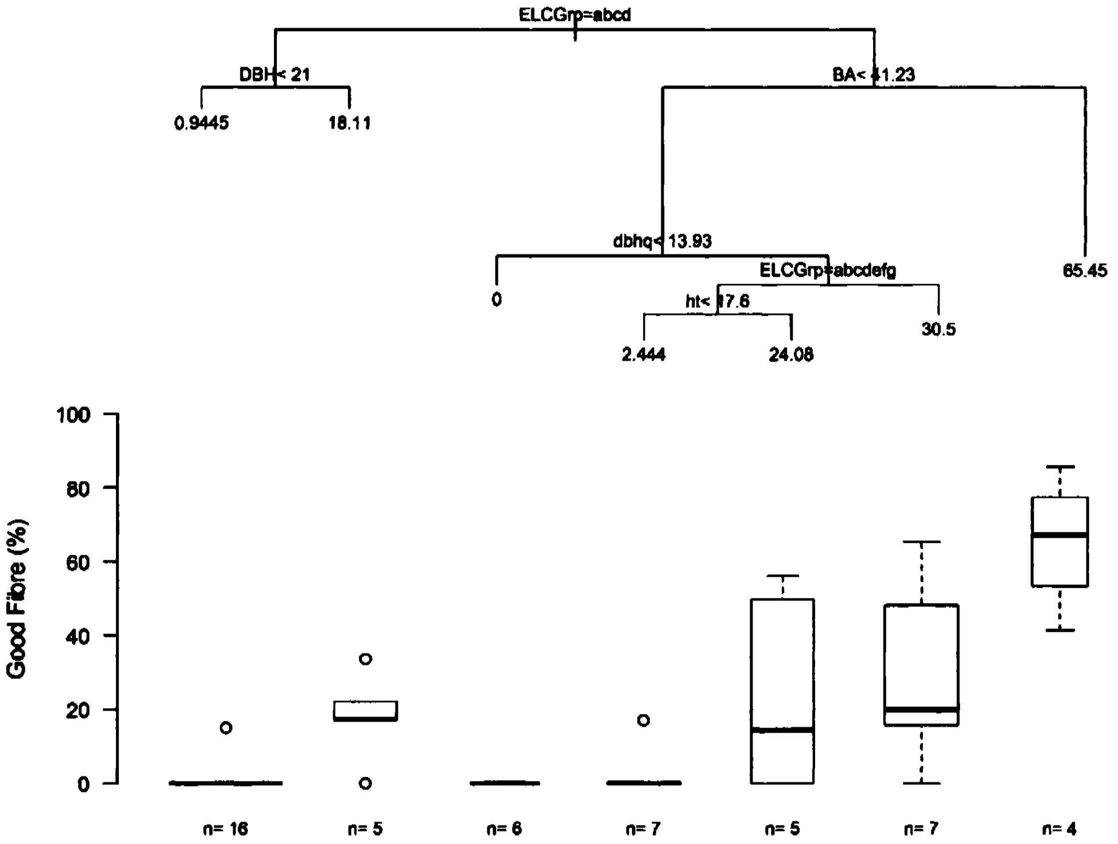

Figure 8: Regression tree analysis of % stem area with ideal fibre > 3mm (PIF) in stem of black spruce (*Picea mariana*), using site, tree and stand level prediction variables for a sample population of black spruce in northeastern Ontario, Canada.Ecosite group (a= EG-2, Dry Sandy Ecosites; b= EG-3, Fresh Sandy or Dry to Fresh Coarse Loamy Ecosites; c= EG-4, Moist Sandy to Coarse Loamy Ecosites; d= EG-5, Fresh Clayey Ecosites; e = EG-6, Fresh Silty to Fine Loamy Ecosites; f = EG-7, Moist Silty to Fine Loamy to Clayey Ecosites; g = EG-8r, Rich Conifer Swamps; h = EG-e8i, Intermediate Conifer Swamps and i = EG-8p Poor Conifer Swamps) Variable definitions BA= basal area (m^2/ha), ht= tree height (m), DBH=diameter at breast height (cm), dbhq= quadratic mean diameter (cm) and SPH= stems per hectare.

Fibre length and ring width response curves were compared to determine if there was a consistent relationship between these variables among the different ecosite groups. In some cases there was a clear correspondence between fibre length and ring width variation with respect to age, but this result was not consistent in all ecosites. The best example of correspondence between the fibre length curves and the RGC curves is seen in the EG-4 of figure 9. In figure 10 all groups (EG-5-EG-7) have a relatively well-corresponded fibre length and ring width (RGC) curves. The poor ecosites (EG-8p, EG-8i, EG-8r) shown in figure 11 show discordance between fibre length and RGC.

1.4 Discussion

There was no difference in mean stem-level estimates of fibre length between the EW and LW of black spruce trees from the boreal forest of northeastern Ontario. Previous studies have suggested that latewood (LW) fibres are generally known to be longer than earlywood (EW) fibres (Denne 1989), as LW is formed during a less productive part of the growing season for most tree species (Panshin and de Zeeuw 1970). The main difference between EW and LW is that LW has thicker cell walls and a narrower lumen compared to EW and this difference in characteristics can be attributed to the more water stressed period in which LW develops (Larson 1962).LW cells develop these characteristics to avoid cavitation in times of water stress. My findings suggest that fibre length in black spruce is not responsive to the water stress, as there was not a significant difference between the EW and LW tracheids in length. These results also differ from the response of other wood quality attributes of black spruce (e.g. wood density), which does vary strongly between EW and LW (Pokharel *et al.* accepted). The

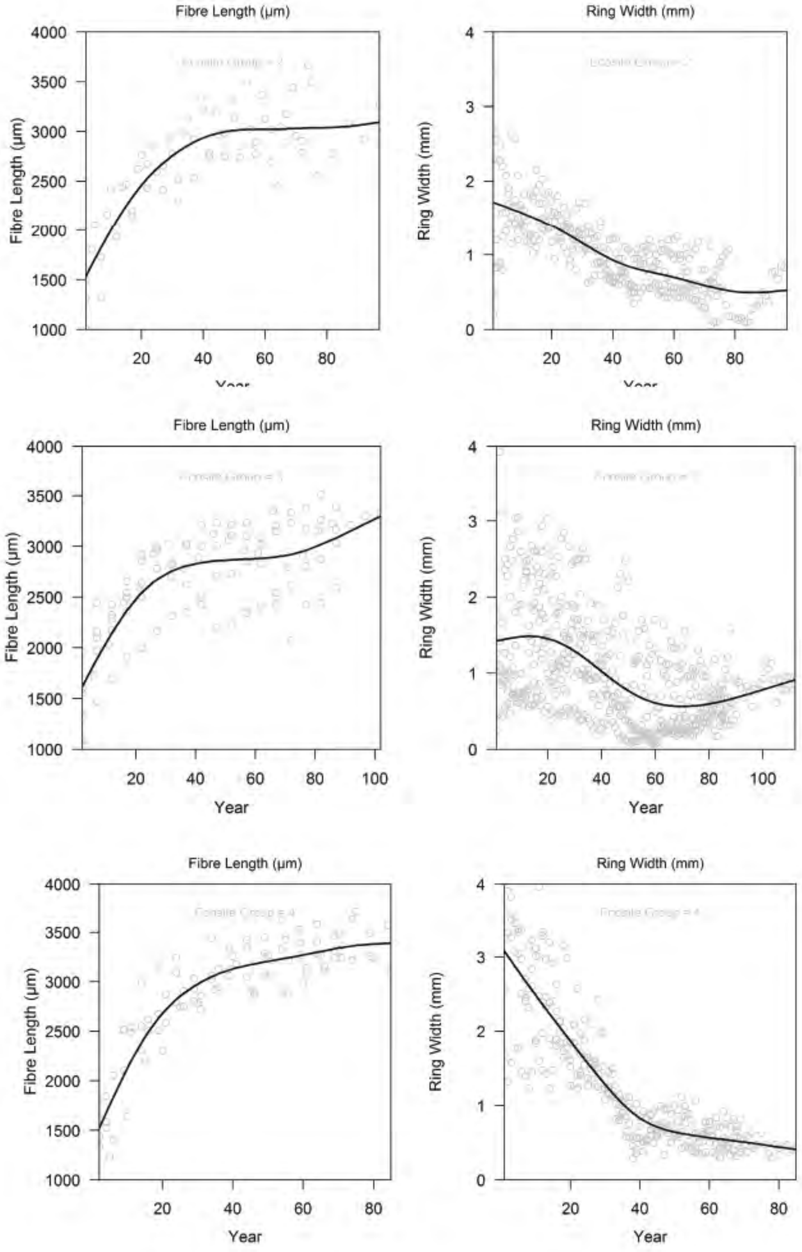

Figure 9: A comparison of fibre length response curve to the regional growth curve (RGC) (ring width measurements against year) for the low to moderate production ecosite groups sampled (EG-2, EG-3 and EG-4). The curve of the line was fit using a cubic smoothing spline using five degrees of freedom

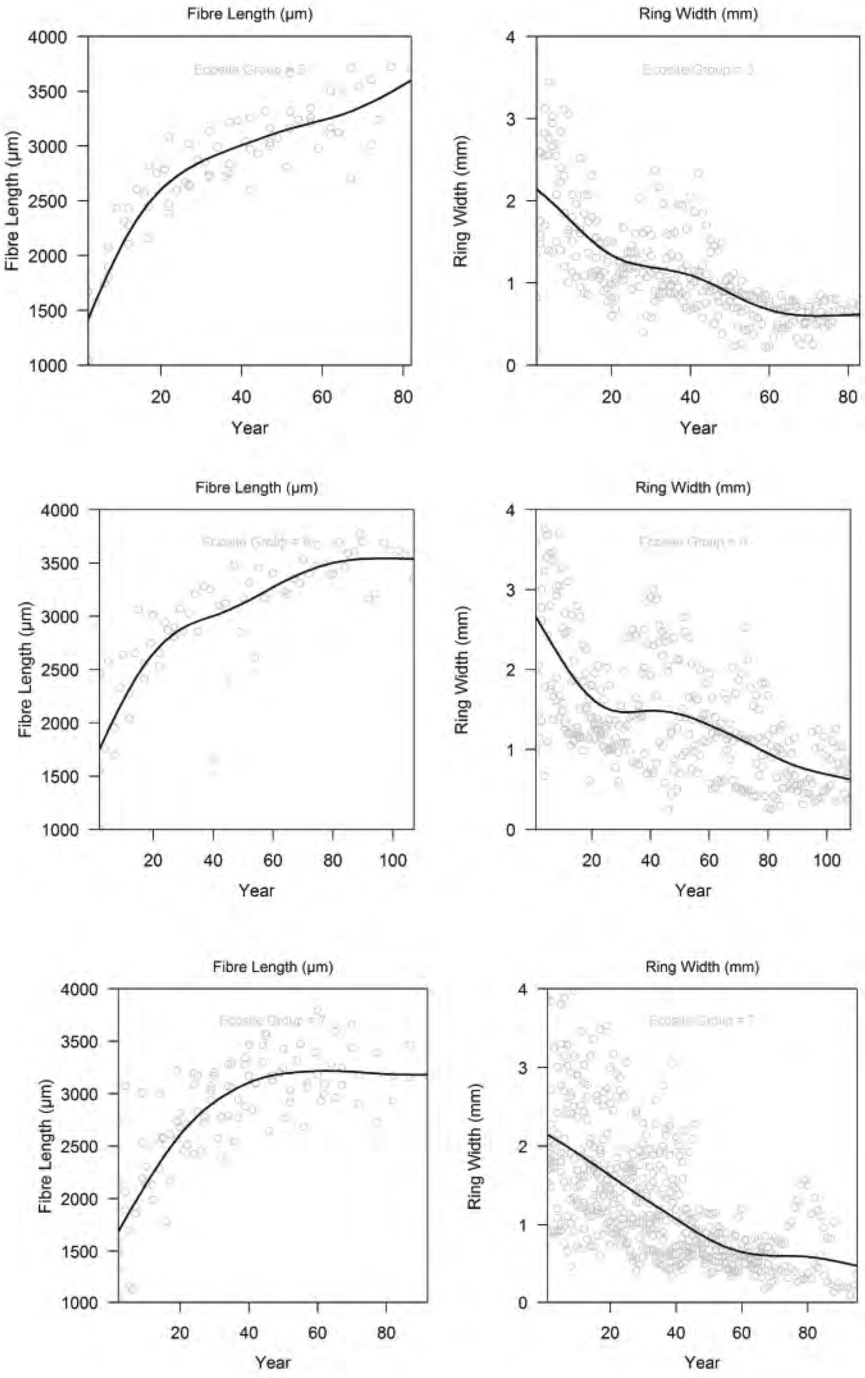

Figure 10: A comparison of fibre length response curve to the regional growth curve (RGC) (ring width measurements against year) for the three most productive ecosite groups sampled (EG-5, EG-6 and EG-7). The curve of the line was fit using a cubic smoothing spline using five degrees of freedom

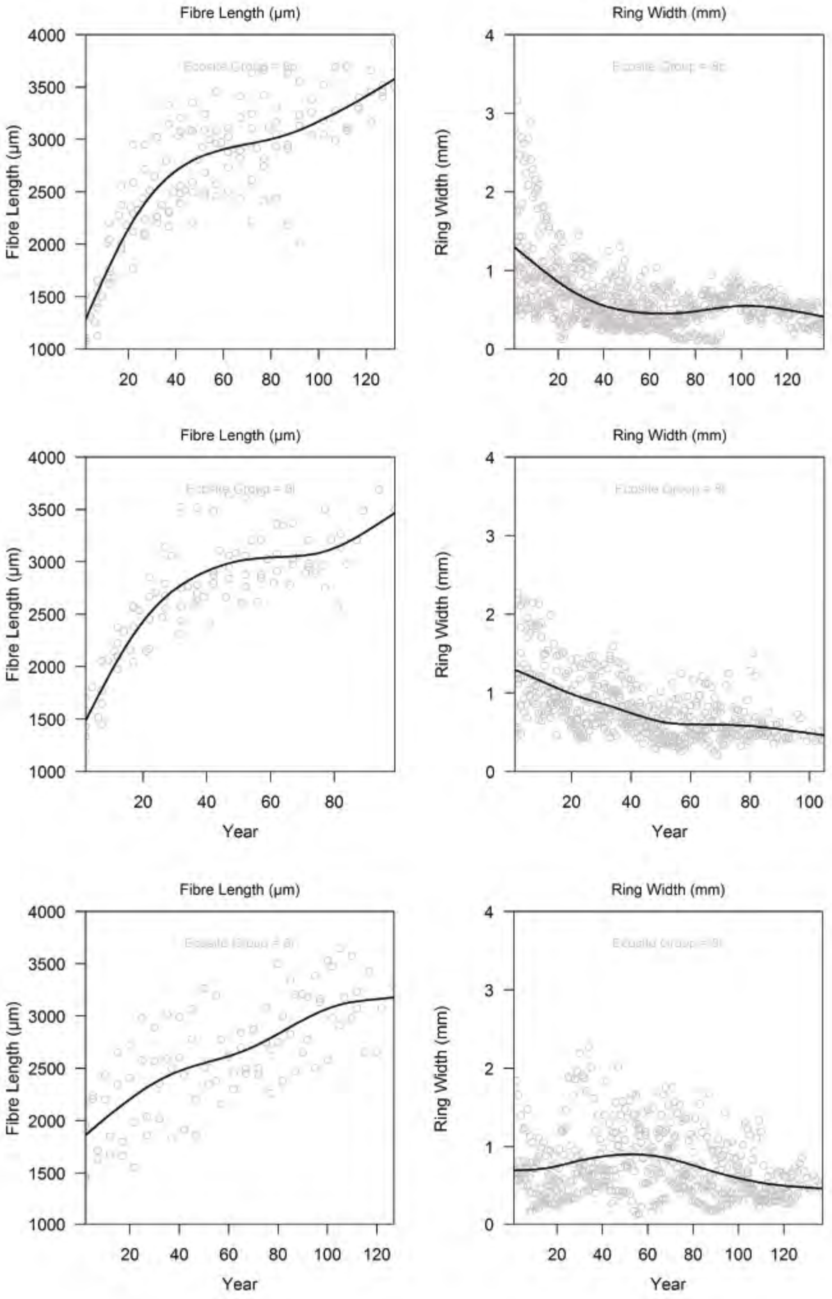

Figure 11: A comparison of fibre length response curve to the regional growth curve (RGC) (ring width measurements against year) for the three least productive ecosite groups sampled (EG-8i, EG-8r and EG-8p). The curve of the line was fit using a cubic smoothing spline using five degrees of freedom

trend of mean fibre length increasing with cambial age and then reaching a plateau at the onset of maturity has been seen in many other studies on wood fibre length and among many different tree species including black spruce (Mansfield *et al.* 2009, Makinen and Hynynen 2012). Makinen and Hynynen (2012) stated that the main factor causing variation in fibre length is the change over time from juvenile to mature wood. This suggests that EW and LW fibre lengths are not responding to seasonal changes but instead to the overall growth of the stem, which agrees with my findings.

Stem level mean fibre length was not found to be responsive to ecosite but instead responded more to variables relating to stand occupancy and competition. I found a general trend that trees from more stressful ecosites produced shorter average stem-level fibre lengths, similar to Watson and Bradley (2009), who found that harsher growing conditions produced shorter fiber lengths, for a blend of spruce, pine and fir fibres grown in a silviculturally managed conditions. The relationship between site conditions, growth rate and wood properties has been inconsistent as reported in the literature. Many studies have found that higher growth rates (better environmental conditions) result in shorter fibre lengths (Bannan 1967, Zobel and van Buijtenen 1989, Makinen *et al.* 2002). Mansfield *et al.* (2009) found that site conditions had no significant effect on the initial age of increasing fibre length for lodgepole pine. St-Germain and Krause (2008) studied the effect of latitude and associated growth rate reduction in black spruce and found that slower growth rates had no impact on fibre length. My study found that BA and height were two of the most important factors in predicting fibre length; these variables are both related to stand density and competition, which produces taller trees and greater height variation in a stand. This suggests that mean stem level fibre length is responding to competition and denser stands with more competition produced wood with longer mean fibre lengths. Makinen *et al.* (2002) found that thinning stand density of Norway spruce resulted in shorter fibres, which supports the idea that higher competition sites produce longer fibre lengths. Based on my data fibre length was not responsive to ecosite but did respond to crown width, there was a general trend of increasing mean fibre length with increasing crown width. This does not challenge the notion that competition is influencing fibre length because crown widths were related to site occupancy, so even if the trees were in competitive stands, the trees sampled could still achieve large crown widths. Several studies agree that crown size should influence wood fibre properties, including fibre length (Mansfield et al. 2009, Amarasekara and Denne 2002).

Uniformity of fibres is important for the pulp wood industry (Watson and Bradley 2009). The black spruce analyzed in this study were fairly uniform according to the observed coefficient of variation values, which were all generally low. Shorter trees on more competitive sites (that likely took a lower position in the hierarchy of canopy positions) were found to have the highest coefficient of variation values. It appears that canopy position and competition impacts the uniformity of fibre length and therefore the quality pulp that could be produced. Shorter trees in the understory on more competitive sights would be undergoing more suppression and release cycles due to upper canopy trees controlling light access, thus creating more variable fibre lengths.

The regression PIF results were interesting, as there was a clear division of ecosites between those with high and low PIF values. The observation of increasing PIF on more stressful sites, with the exception of EG-7, suggests that the distribution of juvenile and mature wood influences fibre length in black spruce, and that more stressful sites have higher proportions of mature wood in the first fifty years of growth. The stem level mean fibre length was not found to be related to ecosite, yet the PIF variable was, because the mean fibre length was based on a stem level average, a single number for the whole stem, which is incapable of reflecting the amount of juvenile and mature wood. The PIF value was reflective of the variation in fibre lengths over time, and was therefore based on the shape of the curve which reflects the amount of juvenile and mature wood. Based on the data more productive ecosites produce mature wood (longer fibres) earlier than those in less productive ecosites. Many studies including, Makinen and Hynynen (2012) have stated that the ratio of mature to juvenile wood is the most important factor in predicting fibre length and that mature wood has longer fibres than juvenile wood. In fact, juvenile to mature wood ratio drives overall wood quality, as Pokharel *et al.* (accepted) observed that more stressful sights had increases in fibre density, and percent LW also. Forest managers would be interested to know that these stressful or low production ecosites have increased fibre density, percent LW and PIF. The largest crown width group (>3.5 m) had the highest PIF values yet the smaller sized crown groups still had relatively high percentages. The 0-2.49 m crown width group had 12.7% stem area with ideal fibre, only 1.4x smaller than the >3.5m group. This finding agrees with much of the literature stating that poor growing conditions (reflected by small crown size) produce longer fibres (Makinen *et al.* 2002), but disagrees with the other findings that have found the most productive sites produces the longest fibres (Watson and Bradley 2009).

Relationships were detected using the regression tree analysis but they could not be generalized in the random forest analysis. Using a sample size of 50 each randomly drawn case has a greater overall impact on the outcome of the tree, with an increase in sample size the less impact each case would have on the tree. The model was meant to be general but the sample size may have ended up being too small to be generalized. Ideally more samples would have been collected from many different plots to represent the ecosites. In some cases an ecosite group had most of the samples coming from the same plot, so some of the plot variables (BA, sph and DBHq) were the same for all of those samples. Despite this I believe that the results found were encouraging and the study would be improved with more samples. Considerable time and effort was spent reaching a sample size of 50. An expansion of the dataset would be recommended as a continuation of the project, it would be interesting to see if this would improve the random forest results that could be used to improve the forest inventory.

Correspondence between the fibre length response curves and RGC (regional growth curves) were visible in some ecosites (EG-4) but not others (EG-8i). The discordance between the two variables may be due to noise (climate, disturbance) impacting the shape of the fibre length response curve or the RGC so that it is no longer reacting to the age related growth trend. More samples would allow for improved matching of curves by removing samples effected by noise. A relationship can be described for some of the ecosites that have corresponding curves. This relationship would be useful for researchers or forest managers as a model could be developed that converts ring width information into fibre length information.

Duschene *et al.* (1997) highlight the importance of being able to sort wood based on basic characteristics such as species and size, which can improve wood sorting by fibre properties that ultimately increases value in final product of the wood. Results from both the PIF variable and mean fibre length regression trees could be combined as useful information to forest managers, showing that competition variables (BA, height, SPH) and ecosite could be used to find the best trees and sites for valuable wood fibre, and this sort of information could realistically be utilized within the FRI (Forest Resource Inventory). The FRI as mentioned has information on ecosite polygons but also has information on SPH and BA which could be used to determine the level of competition on a site. Ecosite information could be used to highlight plots with harsh growing conditions which would have increased PIF values. Access to information linking wood fibre length information to the landscape scale will ultimately improve quality of wood harvested and result in higher value products (Briggs 2010).

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Appendices

Appendix A:

Crown Width Prediction Model

A crown width prediction model was developed using a sample population of 349 black spruce trees with crown measurements collected from the Hearst Forest. The crown width prediction model used DBH (diameter at breast height) and SPH (stems per hectare) as predictor variables, which were collected in both the Hearst Forest and the Romeo Mallette Forest. The model was further improved by separating trees based on ecosite, another variable collected in both forests. The equation for the model was as follows CW = a + b*DBH+c*SPH+e*Ecosite Group. Climate variables including mean annual temperature, growing season days and annual precipitation were investigated from 1901 to 2010 for the RMF and HF to assess if there has been a significant change in climate.

Appendix : Parameter estimates for crown width model

	Estimate	Std. Error	t value	Pr(>|t|)	
(Intercept)	1.782000	2.26E-01	7.883	4.48E-14	***
DBH	0.096690	6.78E-03	14.271	< 2e-16	***
SPH	-0.000159	4.61E-05	-3.444	0.000646	***
Ecosite Group e3	-0.106500	2.11E-01	-0.505	0.613744	
Ecosite Group e4	0.152900	2.65E-01	0.577	0.564437	
Ecosite Group e5	-0.492900	2.13E-01	-2.316	0.021131	*
Ecosite Group e6	-0.079680	2.22E-01	-0.359	0.720073	
Ecosite Group e7	-0.184000	1.98E-01	-0.931	0.352719	
Ecosite Group e8i	-0.764400	1.97E-01	-3.881	0.000125	***
Ecosite Group e8p	-0.789900	1.92E-01	-4.108	5.01E-05	***
Ecosite Group e8r	-0.767400	2.11E-01	-3.636	0.00032	***

CW = a + b*DBH+c*SPH+e*Ecosite Group

R square 0.5613

RMSE = 0.4585

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.4585 on 337 degrees of freedom

Multiple R-squared: 0.5613, Adjusted R-squared: 0.5483

F-statistic: 43.12 on 10 and 337 DF, p-value: < 2.2e-16

Curriculum Vitae

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Townshend, E., Dech, J.P., Pokharel, B., and Pinto, F. 2013. Black Ash Stand Dynamics in Rich Hardwood Swamps of the Great Lakes St. Lawrence Forest Region. Poster presented at the North American Forest Ecology Workshop, Bloomington, IN, USA, June 16-20, 2013.

Townshend, E. 2011. Stand dynamics of Black Ash swamps and their influence on habitat quality for flooded jellyskin (*Leptogium rivulare*). B.Sc. Thesis Project, Department of Biology, Nipissing University, North Bay, ON, Canada, 43 pp.