

Article

Modeling Wood Fibre Length in Black Spruce (*Picea mariana* (Mill.) BSP) Based on Ecological Land Classification

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Academic Editors: Lisa Samuelson and Eric J. Jokela

Received: 30 July 2015 / Accepted: 16 September 2015 / Published: 24 September 2015

Abstract: Effective planning to optimize the forest value chain requires accurate and detailed information about the resource; however, estimates of the distribution of fibre properties on the landscape are largely unavailable prior to harvest. Our objective was to fit a model of the tree-level average fibre length related to ecosite classification and other forest inventory variables depicted at the landscape scale. A series of black spruce increment cores were collected at breast height from trees in nine different ecosite groups within the boreal forest of northeastern Ontario, and processed using standard techniques for maceration and fibre length measurement. Regression tree analysis and random forests were used to fit hierarchical classification models and find the most important predictor variables for the response variable area-weighted mean stem-level fibre length. Ecosite group was the best predictor in the regression tree. Longer mean fibre-length was associated with more productive ecosites that supported faster growth. The explanatory power of the model of fitted data was good; however, random forests simulations indicated poor generalizability. These results suggest the potential to develop localized models linking wood fibre length in black spruce to landscape-level attributes, and improve the

sustainability of forest management by identifying ideal locations to harvest wood that has desirable fibre characteristics.

Keywords: tracheid; ecosite; hierarchical classification; boreal forest

1. Introduction

The Canadian forest industry generates approximately 53 billion dollars in revenue from manufactured forest goods annually, representing 1.25% of the national gross domestic product [1]. Black spruce (*Picea mariana* (Mill.) BSP), because of its abundance and advantageous fibre characteristics, is the most important species for the pulp and paper industry in Canada [2]. Variation in wood fibre length influences the best use of wood resources, impacting paper grading quality and the reinforcement strength of paper products; for example, longer fibres (≥ 3 mm) are more valuable because they are used as a reinforcement pulp, adding strength and value to paper products [3]. Wood fibre length also influences the mechanical and physical properties of fibre board products [4] and the tensile strength of wood-plastic composites [5]. 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, mills, forest product companies and government agencies responsible for forest management [6]. 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 [7].

Canadian wood fibre is known for its exceptional qualities of fibre length and strength, which have been attributed to the slow growing conditions imposed by the Canadian climate [8]. Given these limitations on growth, the Canadian forest industry is moving its focus towards a value-based market rather than a volume-based market, to better compete with fast-growing, low-quality forests of southern regions [9]. For example, Brazilian *Eucalyptus* plantations can typically attain an annual production of approximately $35\text{--}45\text{ m}^3\cdot\text{ha}^{-1}$ [10], while black spruce stands of the Ontario boreal forest produce approximately $2\text{ m}^3\cdot\text{ha}^{-1}$ annually [11]. 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 these specific wood characteristics may be marketed [9]. Value chain optimization 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 [8]. Past research has shown that, in general, fibre properties are highly correlated to the growth rate of trees [12] and that crown size is an indication of this growth [13]. Growth rate of trees varies with site conditions [14], and these site conditions are captured in ecological land classification (ELC) systems. For example, individual black spruce diameter growth rates have been shown to differ depending on the ecological site type (ecosite) that trees are occupying [15].

Relationships between ecosite, growth rate and wood anatomy may be quantified by a model that links microscopic properties (e.g., wood fibre length) to the landscape scale (e.g., site quality indicators) [16]. The use of ecosites as a base unit for modeling can be viewed as a more holistic (*sensu* Billings [17]) approach to creating growth and yield models in forestry, as ecosite classification

captures many aspects of the complex environment [18]. Nonparametric hierarchical classification models such as regression tree analyses and random forests [19] provide a good approach for developing models that make predictions about wood fibre attributes for specific ecosites at the landscape scale. However, for these models to become a useful tool for forest managers, the information would need to be integrated into a spatial forest resources inventory (FRI). Forest resource inventories are important tools for forest management and planning throughout the world [16]. In the province of Ontario, Canada, due to changing economic conditions, companies have been looking for ways to make harvesting more efficient, which requires improved spatial and temporal accuracy of inventory information. Forest certification systems that focus on sustainability have also led to the need for more detailed inventory information and improved spatial accuracy. 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 [20]. This change to the fundamental structure of the FRI allows for the use of ecosites as projection units in the creation of growth and yield models, and this creates the potential to provide predictions at a finer, ecologically meaningful scale.

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.* [13] found that crown width was a good predictor variable for wood characteristics such as fibre diameter in plantation-grown white spruce. Past studies have revealed that 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 [21]. The objectives of this study were (i) to determine if tree-level mean wood fibre length estimates are related to ecosite classification in populations of black spruce from the boreal forest of northeastern Ontario; and (ii) to develop a predictive spatial model of tree-level mean wood fibre length from the relationships identified with ecosite and/or other inventory variables. This study could demonstrate an approach that would help in the identification of ecosites ideal for intensive silviculture and the production of high value black spruce fibre.

2. Experimental Section

2.1. Study Area Description

This study was carried out in two Boreal forest locations in northeastern, Ontario, Canada; the Hearst Forest (HF) centered on the town of Hearst, and the Romeo Malette Forest (RMF) situated near Timmins (Figure 1). The HF is a management unit of 1,231,707 ha and includes private, crown and protected land. The entire HF is situated within the northern claybelt section of the boreal forest and is mostly flat to undulating [22]. The north and central portions of the forest are dominated by flat, clay and silty clay soils originating from glacial-lacustrine sediments as part of the Clay Belt. The southern, southwestern, and northeastern portions of the forest are characterized by gently rolling to hilly topography (elevation 84 m to 442 m above sea level), with soils ranging from pre-Cambrian bedrock outcrops to loams and sands associated with various glacial deposits. Interspersed throughout are areas of organic soils associated with poor drainage. Black spruce is the most common species on the HF, occupying approximately 65% of the forest area, spanning the range from dry mineral to wet organic

sites [23]. Data collected at the nearest weather station in Kapuskasing, Ontario, Canada, indicate the area has an annual mean daily temperature of 1.3 °C. The mean daily temperatures range from −17.9 °C in the coldest month (January) to 17.4 °C in the warmest month (July). The average precipitation each year for the HF is 830 mm, comprised of 556 mm of rainfall and 308 cm of snowfall [24].

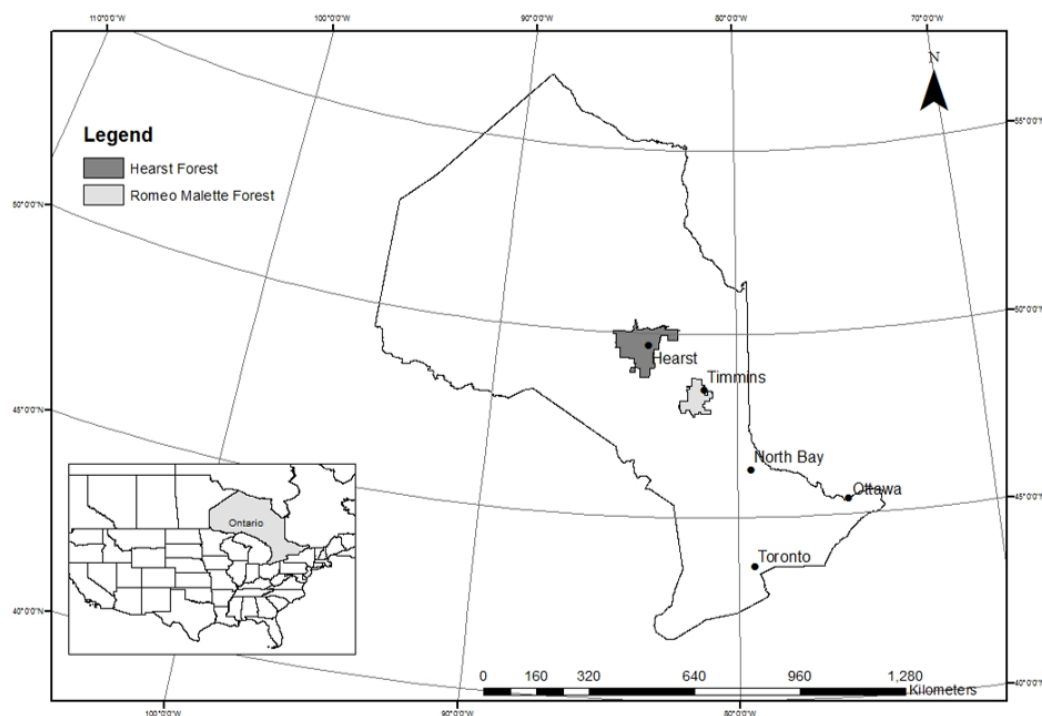


Figure 1. The location of the Hearst and Romeo Malette Forests in Ontario, Canada.

The RMF is a 628,958 ha area comprising of private and crown land, as well as several protected areas. Forests of the RMF are typical of the boreal forest region [20]. The RMF can be separated into the Northern claybelt section (1/3 of the forest) and the Missinaibi-Cabonga section (2/3 of the forest). The northern claybelt section has relatively flat to gently rolling topography (300–320 m), and the landscape is predominantly poorly drained clay deposits. The Missinaibi-Cabonga section is considered to have moderately rolling topography (300–380 m) 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 [25]. More than 50% of the forest in the RMF is dominated by black spruce, covering a range of site conditions from dry, mineral uplands to wet, organic lowlands. The annual mean daily temperature at the nearest weather station in Timmins, Ontario, Canada is 1.8 °C, and ranges from −16.8 °C in coldest month (January) to 17.5 °C in the warmest month (July). The average annual precipitation for the RMF is 835 mm, comprised of 558 mm of rainfall and 311 cm of snowfall [24].

2.2. Field Plot Selection

The samples for this study were derived from multi-purpose plot networks in the HF and RMF that were established to support a variety of forest inventory [23,26] and wood quality modelling [27] projects. These existing networks employed a stratified sampling design to represent the range of stand age/development classes (juvenile, mature or over-mature stands) and species (mixed wood, black

spruce, spruce pine and spruce fir) compositions present on the forest. Each plot in the network was a circular 400 m² unit, following the standards of permanent growth and yield plots for Ontario [28].

From these plot networks, a collection of large diameter (12 mm) black spruce increment cores was made during the 2010 (RMF) and 2011 (HF) field seasons. These cores were obtained according to a stratified sampling design, with the objective of achieving an unbiased representation of the range of ecological site types present on each forest. A total of 365 cores were extracted from 122 plots on the HF, and 80 cores were sampled from 26 plots on the RMF. Some of these cores ($n = 134$) were analyzed using SilviScan to develop models of wood density and other quality attributes in relation to ecological site characteristics [27]. Another subset of the core collection was selected for the present study ($n = 55$), with the majority of samples coming from the HF ($n = 41$), and those from the RMF ($n = 14$) filling gaps in the representation of site conditions.

An ecosite was assigned to every plot based on standard field classification methods [20], which involved examining a soil profile and identifying the dominant canopy vegetation. The stands selected for sampling were confirmed as homogeneous in substrate/vegetation (e.g., only one ecosite represented) and free of signs of any recent disturbance. Plot locations were determined using a differential (sub meter accuracy) global positioning system to ascertain the coordinates for the plot centre. Up to three black spruce trees were randomly selected for sampling from the pool of trees representing the mature age class and codominant crown position within each plot. Each selected black spruce tree in the HF plots was measured for the crown radius from the centre of the stem to the edge of the drip line (from the ground looking up) in four cardinal directions. The diameter at breast height (DBH) of every living tree in the plot was measured to calculate basal area (BA; m²·ha⁻¹) and quadratic mean diameter (QMD; cm).

2.3. Increment Core Sample Collection

Three increment cores were collected from sample 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 (*i.e.*, wood fibres) could be isolated for effective measurement of wood fibre lengths. Extraction of a single 12 mm increment core has been previously demonstrated to be sufficient for characterizing fibre lengths in black spruce [29], and has been generally shown to produce reliable estimates of fibre length in comparison to methods that require larger samples [30]. Samples were stored in a freezer prior to processing and analysis.

Data were partitioned into ecosite groups, which had to be created due to a lack of sufficient replication within specific ecosites. Ecosite groups were created based on soil characteristics outlined in the ecological land classification guide for Ontario [20], and involved combining a few ecosite types together to create the groups representing common substrate properties. Individual trees were the study unit of interest, and wherever possible all samples within a given ecosite group were collected from separate plots. In some cases, a lack of plots in the HF and RMF network representing the rarer ecosite conditions necessitated that more than one core sample from the same plot were included in the analysis. For the purposes of detecting and modelling basic relationships to ecosite and inventory

variables, we considered these samples to be independent. The sample size for the fitting data set used for this study consisted of 55 cores from nine ecosite groups, with 4–7 replicates per group.

2.4. Sample Processing

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 using standard dendrochronological protocols [31]. This half of the core was scanned and ring widths were measured using WinDendro 2012b (Regent Instruments, Quebec, QC, Canada). The ring width data were used to create regional growth curves (RGC) for each ecosite grouping [32]. The second half of the increment core was destructively sampled for fibre length measurements. Fibre measurements for sample cores were completed on a series of sub-samples extracted from every fifth complete annual ring from the bark to pith (e.g., 2011, 2006, 2001, 1996, *etc.*). Fibre sub-samples were collected separately from both the earlywood (EW) and latewood (LW) sections of each selected ring. The marked annual rings were cut away from the sample core tangentially using a razor blade. A standard maceration procedure [33] was used to bleach and chemically separate fibres. For maceration, 500 mL acetic acid and 500 mL hydrogen peroxide solution were added to each vial containing a wood sub-sample. The vials were placed in a beaker with water and brought to a boil for 1.5 h or less, until physical bleaching of fibres was observed. Once fibres were macerated, they were washed in a sodium carbonate solution and then rinsed using distilled water. Vials were then filled with distilled water to prevent drying and as solution for slide mounting [33].

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 sub-sample using a confocal microscope equipped with a camera that captured images at 40× magnification using simple white light. At this magnification, the fibre lengths were often longer than the field of view, so several images were taken to capture the entire sub-sample and labeled accordingly. These images were then assembled in a mosaic to create one large image using Adobe Photoshop Elements Version 5.0 (San Jose, CA, USA). Image mosaics were grayscale at 300 dpi resolution. Each year sub-sampled from each increment core was associated with one large image mosaic of EW fibres and another mosaic of LW fibres. The large image mosaics were imported into the WinCell program (Regent Instruments, Quebec, QC, Canada) in tagged image file format (tiff), where the measurement of fibres was completed. Whenever possible, the measurement of 30 fully intact fibres (tracheids) was completed for each large image mosaic. This number was considered sufficient to be comparable to other methods of fibre length analysis [30]. However, in some cases it was necessary to allow for a smaller sample to be collected, given that tracheids could be obscured, bent or broken as a result of the maceration and mounting of the sample. We required a minimum number of 10 clearly visible, intact tracheids for each mosaic. After completing this process, each sample core was represented by a series of fibre length measurements for the EW and LW of every fifth annual ring from bark to pith over the first fifty years of growth. This meant that the number of tracheids measured ranged from 100–300 per increment core over a fifty year span, which is a sampling intensity that has produced estimates of fibre length comparable to the analysis of large wood chips [30].

2.5. Data Management and Statistical Analysis

2.5.1. Response Variables

Differences between mean EW and LW fibre lengths in the entire sample were quantified by analysis of variance, with the fibre length measurements for the EW and LW of each annual ring being 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 years of growth, to remove any potential age-related confounding with ecosite as a predictor variable, which could arise if a given ecosite-type included trees of a higher mean age relative to the rest of the sample population. When samples did not strike the pith directly, the margin of the innermost complete ring was used as the starting point of the profile. A mean stem-level fibre length for the combined EW and LW of each tree was weighted by ring area to produce an average of fibre length (hereafter referred to as mean fibre length) over the first fifty years of growth. In addition, we calculated a variable describing the proportion of ideal fibre (PIF) in each stem. The PIF was calculated as the percentage of stem area with a mean fibre length of 3 mm or greater [34]. The PIF was calculated by determining the area of the stem at 50 years (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 reconstructed DBH at the year where mean fibre length surpassed the 3 mm threshold) and converting the difference to a percentage of total area.

2.5.2. Predictor Variables

The samples were ordered into nine different ecosite groupings following the standard ELC scheme for Ontario [20]; 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. These groups ranged along a gradient of substrate moisture regime from EG-2 through to EG-8p. Among these groups, EG-3 and EG-4 were the most mesic site types and EG-8p the most hydric and least productive site.

Crown width was another variable chosen as a predictor variable for modeling fibre length in black spruce. Crown width measurements were not collected for RMF plots, so a crown width prediction model was fit to provide estimates for these missing values. The crown width prediction model was developed using a sample population of 349 black spruce trees with crown width measurements collected from the HF. We chose candidate predictor variables from a suite of individual tree and stand level variables that were readily available from both HF and RMF. A crown width prediction model that used DBH (diameter at the breast height) and SPH (stems per hectare) as predictor variables, was chosen based on the fit statistics such as r^2 and RMSE among other competing models. The model fit was further improved by separating trees based on ecosite group, a categorical variable collected in both forests. The sign and magnitudes of the variables in the final model capture the biological description of individual tree crown growth and development. The general equation for the model was as follows:

$$CW = a + b \times DBH - c \times SPH + d \times \text{Ecosite Group}. \quad (1)$$

where, a , b , c and d are model parameters, DBH is diameter at the breast height in cm; SPH is stems per hectare, and Ecosite Groups as defined by the Ontario Ministry of Natural Resources and Forestry [20]. Details of the model parameters and fit statistics are provided in Townshend [35]. Other predictor variables (BA, QMD) were derived from plot level field data.

2.5.3. Hierarchical Classification Models

Two statistical hierarchical classification approaches were used to determine the best predictor variables for the response variable of interest. The classification approaches used were regression tree analysis “rpart” [36] and random forests “randomForest” [37] in the R statistical computing environment [38]. In both cases, mean fibre length was classified into groups representing a common characteristic that results from a combination of predictor variable states that are depicted in a dendrogram. Regression tree analysis fits a model from a single data set and is appropriate for analysis of complex ecological data and is also capable of explaining variation of a single response variable using one or more explanatory variables [39]. The benefit of using regression trees is that the predictors can be both categorical and continuous, and the approach is non-parametric (*i.e.*, does not assume a normal response) [39]. The regression tree was set to have a minimum bucket value of three and a minimum complexity parameter value of 0.001, in order to follow standard procedures to identify the ideal number of nodes in the tree [40]. 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 are found on the top node and least important on lower nodes [39]. The tree was pruned based on examination of the complexity parameter plot, which depicts the relationship between cross-validated error and tree length. A regression tree provides insights into the relationships evident within a single fitting data set; therefore, random forests is used to overcome some limitations of the regression tree approach, such as high sensitivity to alterations of data in a small dataset [41]. Random forests is capable of giving insight into the validity of the model developed in a regression tree by fitting the data in a large number of trees drawn from random selections of cases and variables to produce an average result, thereby testing the generalizability of the models. A total of 5000 trees was grown using bootstrapped sampling. Random forests was set to have five randomly-selected variables used at each split, and variable importance was derived from an average of the 5000 trees.

3. Results

3.1. Sample Population Description

Differences in several tree-level measurements were evident in the sample population based on the apparent differences in productivity between the ecosite groups (Table 1). EG-4 (moist coarse) had the tallest trees (19.05 m) as well as the largest average DBH (21.75 cm). EG-4 also had the highest basal area (BA) (48.82 m²/ha) and highest stems per hectare (2126). Conversely, the lowest average tree heights (13.9 m) and average DBH (15.7 cm) measurements were recorded in EG-8p (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. There was a general trend of decreasing mean crown width with decreasing site productivity when mean crown widths were compared against ecosite groups (Table 1).

Table 1. Descriptive statistics for sample population of black spruce (*Picea mariana*) trees representing nine different ecosite groups collected in the boreal forest of northeastern Ontario in 20–201.

Stand-Level Variables			Tree-Level Variables				Fibre Length Variables					n_1	n_2
Ecosites	Basal Area	Stand Density	QMD	Height	DBH	ABH	¹ Crown Diameter	² Mean	³ Std. Dev.	⁴ CV	⁵ Ideal Fibre		
	(m ² ·ha ⁻¹)	(stems·ha ⁻¹)	(cm)	(m)	(cm)	(years)	(m)	(µm)	(µm)	%	%		
EG-2	36.0	1,514	18.5	15.1	17.3	81	3.21	2,678	312	11.7	9.7	6	2
EG-3	32.0	1,055	20.9	14.7	18.7	82	2.99	2,604	283	10.9	41.4	6	3
EG-4	48.8	2,126	17.4	19.1	21.8	76	3.6	2,836	357	12.7	33.0	6	2
EG-5	28.1	1,472	15.7	14.8	18.4	66	2.97	2,815	345	12.3	57.2	6	3
EG-6	38.4	1,270	22.1	16.2	20.4	83	3.61	2,849	354	12.5	38.1	4	3
EG-7	34.9	1,525	17.8	17.7	20.7	65	3.14	2,842	337	12.0	39.8	8	7
EG-8r	35.8	1,514	17.6	16.0	22.1	118	2.59	2,384	237	10.0	9.8	6	5
EG-8i	24.5	1,576	14.4	14.5	16.7	82	2.54	2,644	363	13.7	18.5	6	5
EG-8p	30.3	1,819	14.5	13.9	15.8	99	2.39	2,431	356	15.0	12.2	7	6

Notes: ¹ Crown width in m measured from below the tree in the field; ² Population level mean of tree-level mean Fibre Length weighted by Basal Area; ³ Population level mean of tree-level standard deviation of fibre length calculated from a weighted variance function; ⁴ Population level mean of tree-level coefficient of variation ((St. Dev/Mean) * 100) calculated from a weighted variance function; ⁵ Population level mean of percent cross-sectional stem area with mean fibre length ≥ 3000 µm; QMD: quadratic mean diameter; DBH: diameter at breast height; ABH: age at breast height; n_1 : number of trees; n_2 : number of plots.

3.2. Comparison of Earlywood and Latewood Fibre Length

There was a consistent trend of increasing ring-level mean fibre length from pith to bark in both EW and LW across all ecosite types (Figure 2). The stem-level mean length of fibres was 2431 μm for EW and 2476 μm for LW. Overall, latewood fibres were only 1.9% longer than EW fibres. There was no significant difference between stem-level mean length of EW and LW fibres ($F_{1,108} = 0.63$ and $p\text{-value} = 0.43$). Thus, the stem-level mean of EW and LW fibre length combined was the response variable considered for all further analyses.

3.3. Comparison of Fibre Length among Ecosite Groups

There was a general trend in the stem-level mean fibre length-based response associated with the productivity of ecosites, with less productive sites having shorter mean fibre lengths (Figure 3). Mean fibre lengths for EG-4 (moist coarse) through to EG-7 (moist fine) were the longest, ranging from 2815 μm to 2842 μm . Sites EG-8r (rich conifer swamp) to EG-8p (poor conifer swamp) had the shortest mean fibre lengths, ranging from 2384 μm to 2644 μm . No clear trends in standard deviation related to ecosites were evident (Table 1). The highest average area-weighted standard deviation in fibre length was found in EG-4 (357), while EG-8r had the lowest (237). The highest coefficient of variation was 14.9% in EG-8p and the lowest was 10.0% in EG-8r. There was a clear relationship between ecosite group and percent ideal fibre (PIF). The PIF was greater for the fresh to moist ecosites, but dropped considerably on dry or wet ecosite groups (Figure 3). The highest mean PIF values were for productive ecosites EG-5, which had a mean PIF of 57.2%, and EG-3, which had a mean PIF of 41.4%. The least productive ecosite types (EG-2, EG-8r, EG-8i, EG-8p) had mean PIF values between 9.7% and 18.5%.

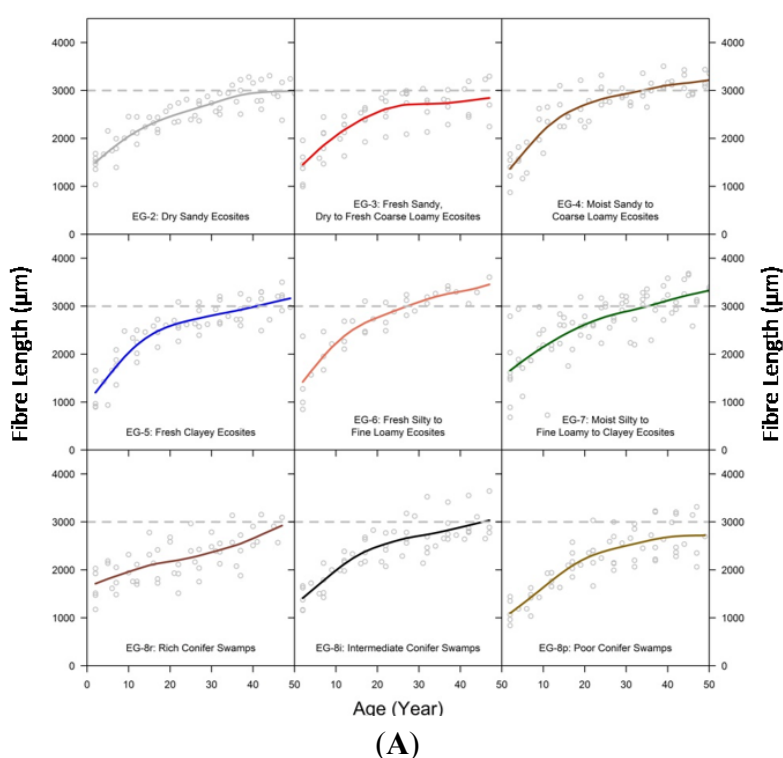


Figure 2. Cont.

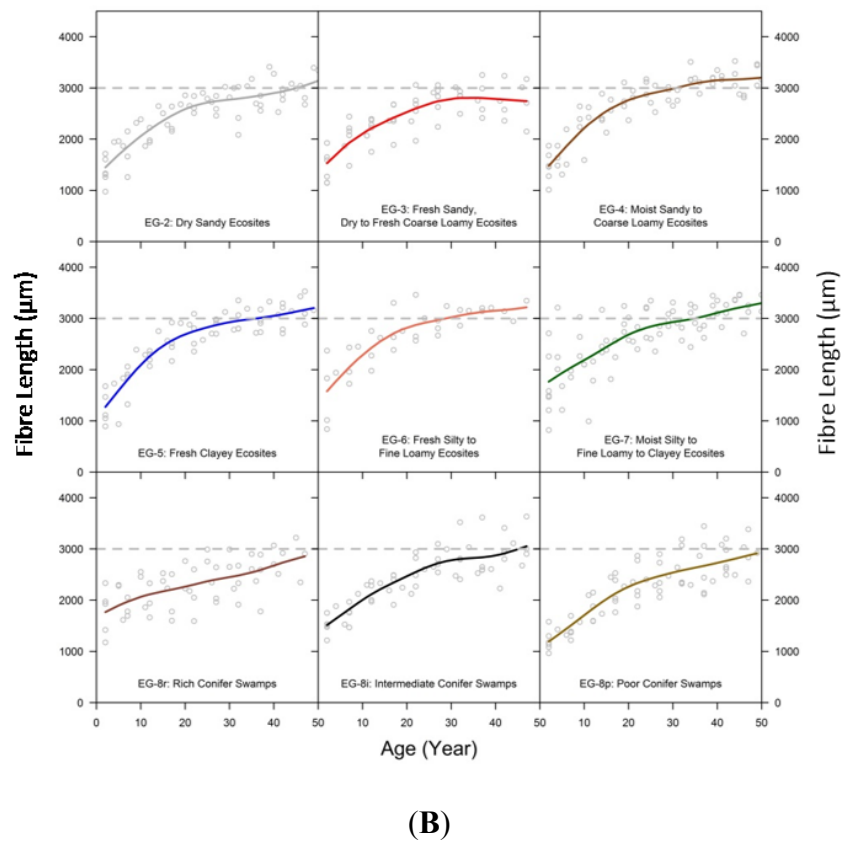


Figure 2. Mean fibre lengths for the earlywood (A); and latewood (B) of annual rings plotted against tree age at breast height for black spruce increment cores collected from the boreal forest of north eastern Ontario from 2010–2011. The fibre length—age relationship was fit with a cubic smoothing spline for each of nine ecosite groups. The dashed horizontal line indicates a threshold fibre length value of 3000 µm.

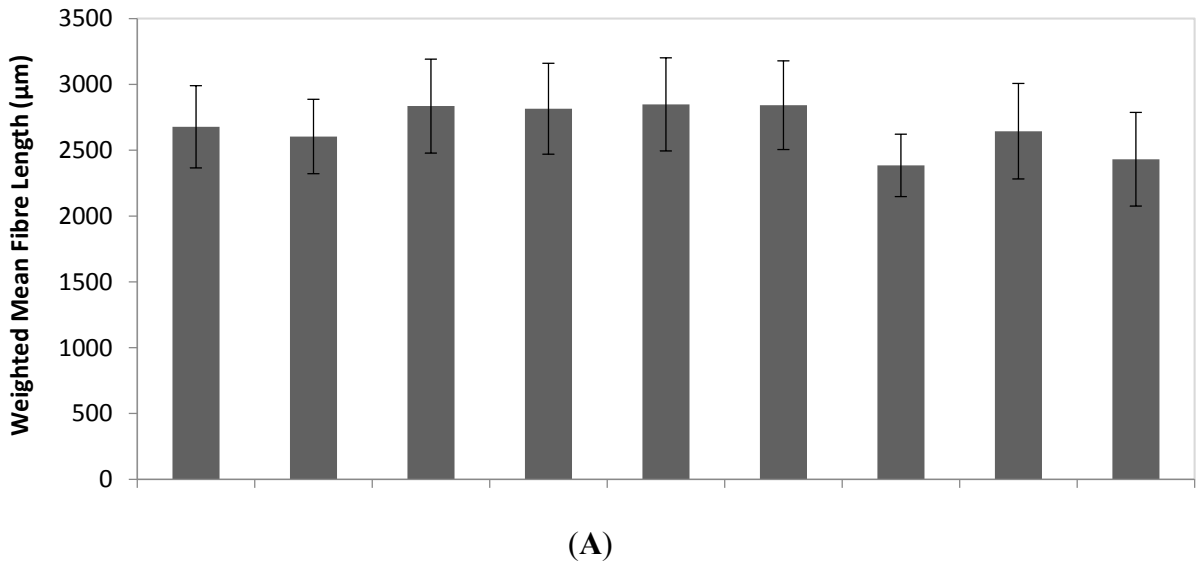


Figure 3. Cont.

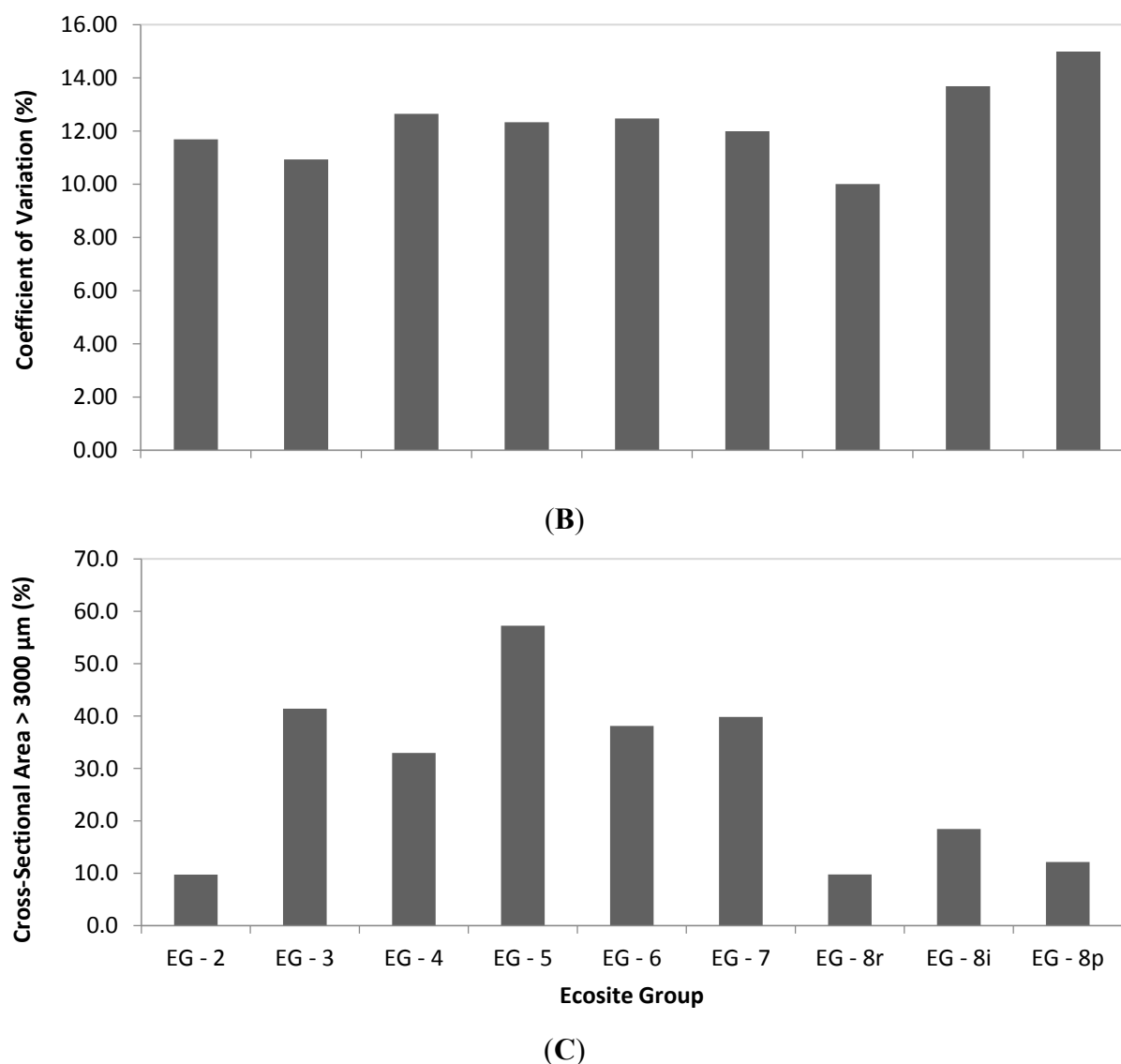


Figure 3. (A) stem level mean fibre length ± 1 standard deviation; (B) stem-level coefficient of variation of fibre length; and (C) percent cross-sectional area ideal fibre length (PIF) at breast height for black spruce (*Picea mariana*) wood samples collected from the boreal forest of northeastern Ontario from 2010–2011.

3.4. Fibre Length in Relation to Crown Width

Mean fibre length showed a general increasing trend in relation to crown widths (Table 1). The smallest crown-width group (EG-8p) also had the shortest mean fibre length, while the largest crown-width group (EG-6) also had the largest mean fibre length. The pattern of increasing mean fibre length as tree crown width increases was followed for all ecosite groups. Crown width variation among ecosite groups was also related to PIF values; however, there was no relationship between crown width and fibre length variation (standard deviation or coefficient of variation) among the groups (Table 1).

3.5. Classification Using Regression Trees and Random Forests

The regression tree approach identified ecosite group as the most important variable for predicting mean wood fibre length in black spruce based on the area weighted mean of EW and LW fibre length. The secondary nodes of the regression tree were related to crown width and stand basal area (Figure 4). The collective relationships depicted in the regression tree explained 69% of the total variance in weighted mean fibre length. The division by ecosite groups produced a substantial difference in mean fibre length (Figure 3), and the bivariate associations to the secondary predictors were strong (Table 2).

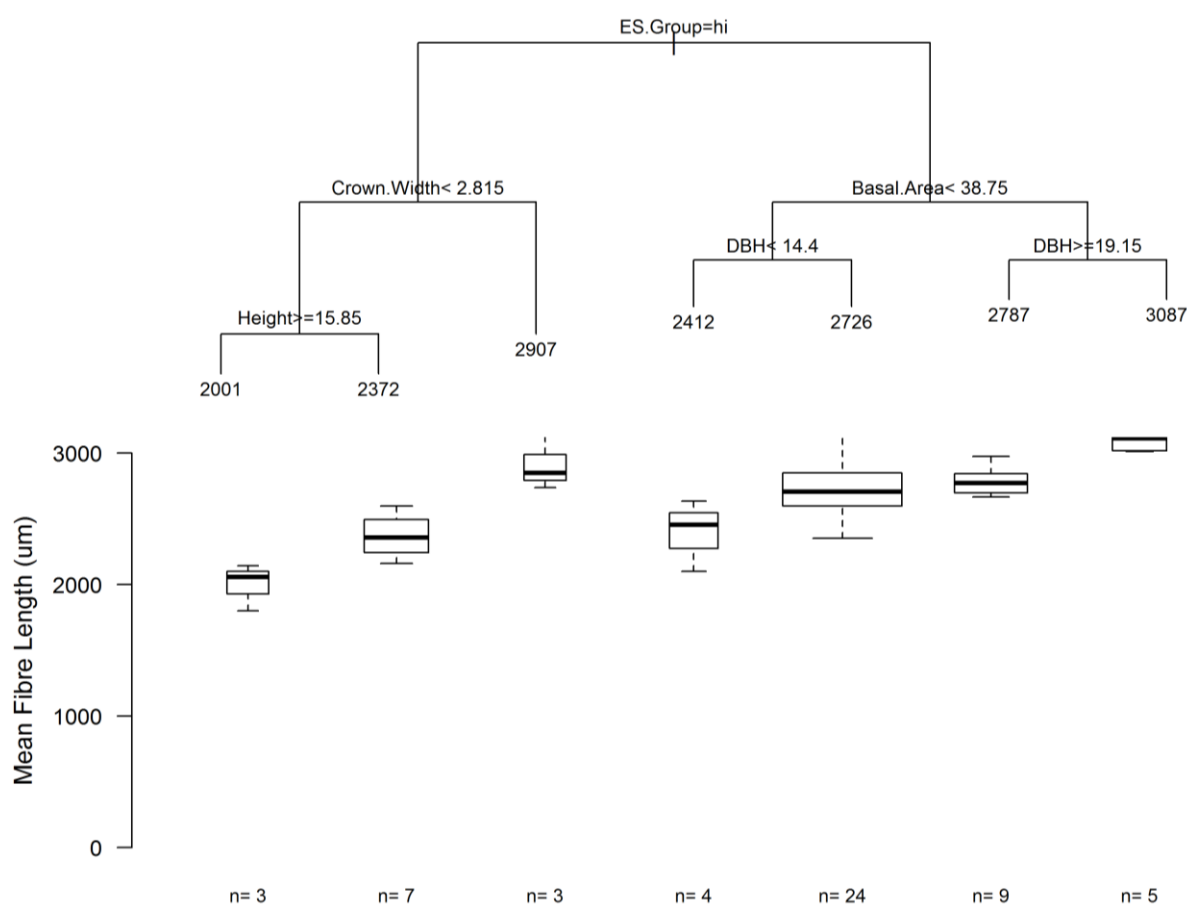


Figure 4. Regression tree analysis of area-weighted stem level mean fibre length of black spruce using site, tree and stand level variables for a sample population collected in northeastern Ontario, Canada. ES. Group is ecosite group (a = EG-2, Dry Sandy Ecosites; b = EG-3, Fresh Sandy or Dry to Fresh 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-8i, Intermediate Conifer Swamps; h = EG-8r, Rich Conifer Swamps and i = EG-8p, Poor Conifer Swamps). Variable definitions Basal Area = stand basal area ($\text{m}^2 \cdot \text{ha}^{-1}$), Height = tree height (m), DBH = diameter at breast height (cm) and Crown Width = crown width in (m). If a condition is met on the dendrogram, the path to the left is followed.

Table 2. Pearson correlation coefficients between mean stem-level area weighted fibre length and continuous predictor variables entered into the regression tree analysis.

Variable	<i>r</i>
Height (m)	0.292 *
Diameter at Breast Height (cm)	0.242
Crown Width (m)	0.419 **
Stand Density (stems·ha ⁻¹)	0.138
Quadratic Mean Diameter (cm)	0.083
Basal Area (m ² ·ha ⁻¹)	0.275 *

* $p < 0.05$; ** $p < 0.01$.

The regression tree predicted that trees in stands belonging to EG-8r or EG-8p with crown width less than 2.8 m and height less than 15.85 m would have the lowest mean fibre length of 2001 μm , whereas trees from the other ecosite groups, in stands with a BA > 38.75 m²/ha and with DBH greater than 19.15 cm would have the highest mean fibre length of 3087 μm . This regression tree structure suggests that the fibre lengths fall along a gradient of site quality and occupancy; small trees in stands with low productivity had shorter fibre lengths, whereas larger trees in stands on productive sites with greater occupancy had longer fibre lengths. This is a potentially useful result; however, 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 12.2% of the variance. Nevertheless, crown width and ecosite group were identified as the most important predictors in the random forests simulations, producing an increase of 30%–40% of model mean-squared error when not included as predictors.

3.6. Relating Fibre Length to Ring Width

Fibre length and ring width response curves were compared to determine if there was a consistent association between these variables among the different ecosite groups (Figure 5). In some cases, there was a clear correspondence between fibre length and ring width variation with respect to age at breast height, but this result was not consistent in all ecosites. The best example of correspondence between the fibre length curves and the regional growth curves was observed in EG-4 (Figures 5 and 6). In general, all of the productive ecosite groups (EG-4 to EG-7) have a relatively strong linear association between fibre length and ring width. The poorer ecosite groups (EG-8p, EG-8i, EG-8r) have less variation in fibre length and ring width, and therefore a weak association between the two response variables. Fibre lengths reach a stable plateau of 3000 μm at a specific distance from the pith (Figure 7). This varies among ecosite groups but typically occurs between 50 and 60 mm. There are some notable exceptions, such as EG-8r, which does not reach an average fibre length of 3000 μm within the first fifty years.

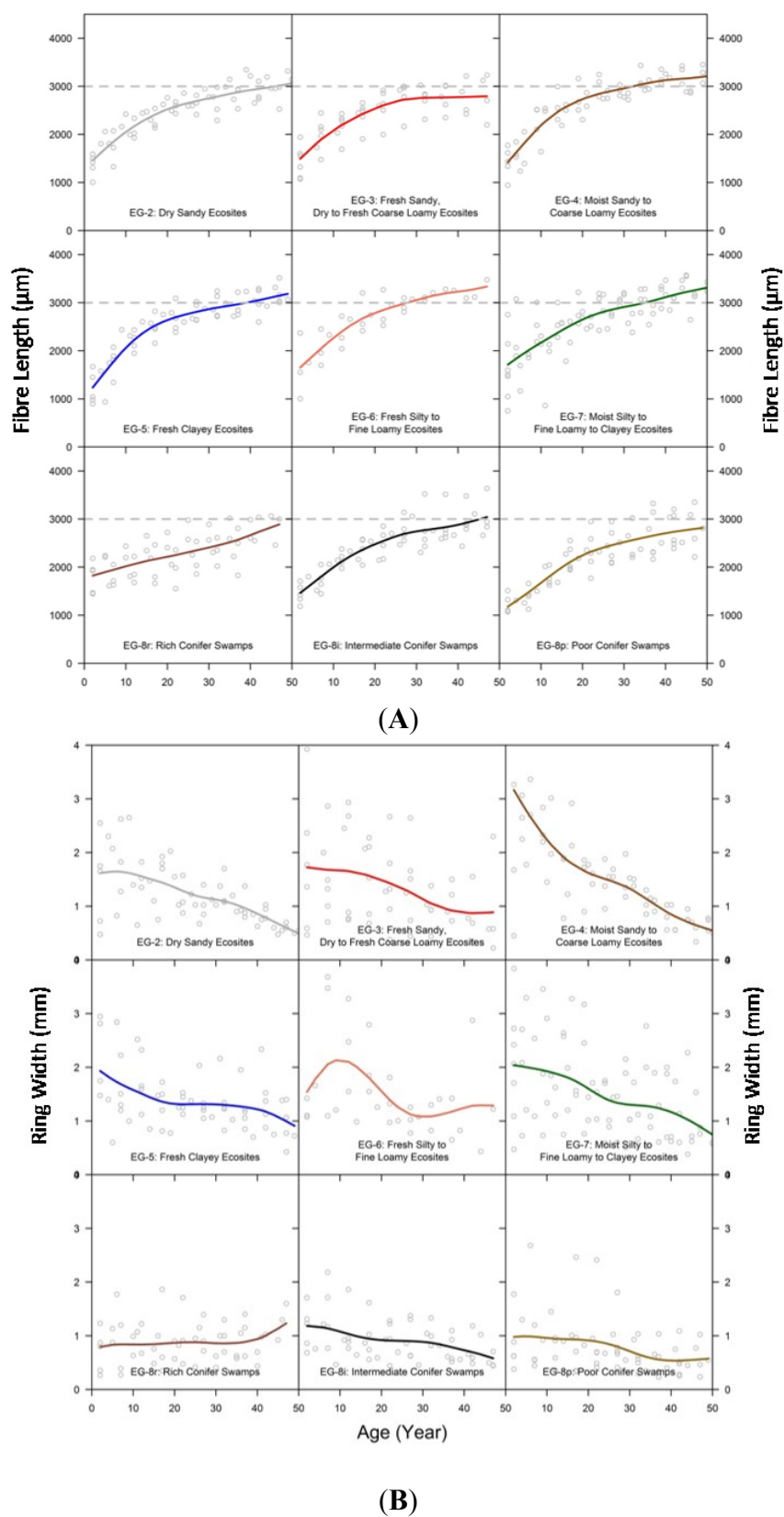


Figure 5. (A) Fibre length response curve (mean fibre length against age at breast height); (B) Regional growth curve (ring width measurements against age at breast height) from black spruce increment cores representing different ecosite groups collected from the boreal forest of north eastern Ontario from 2010–2011.

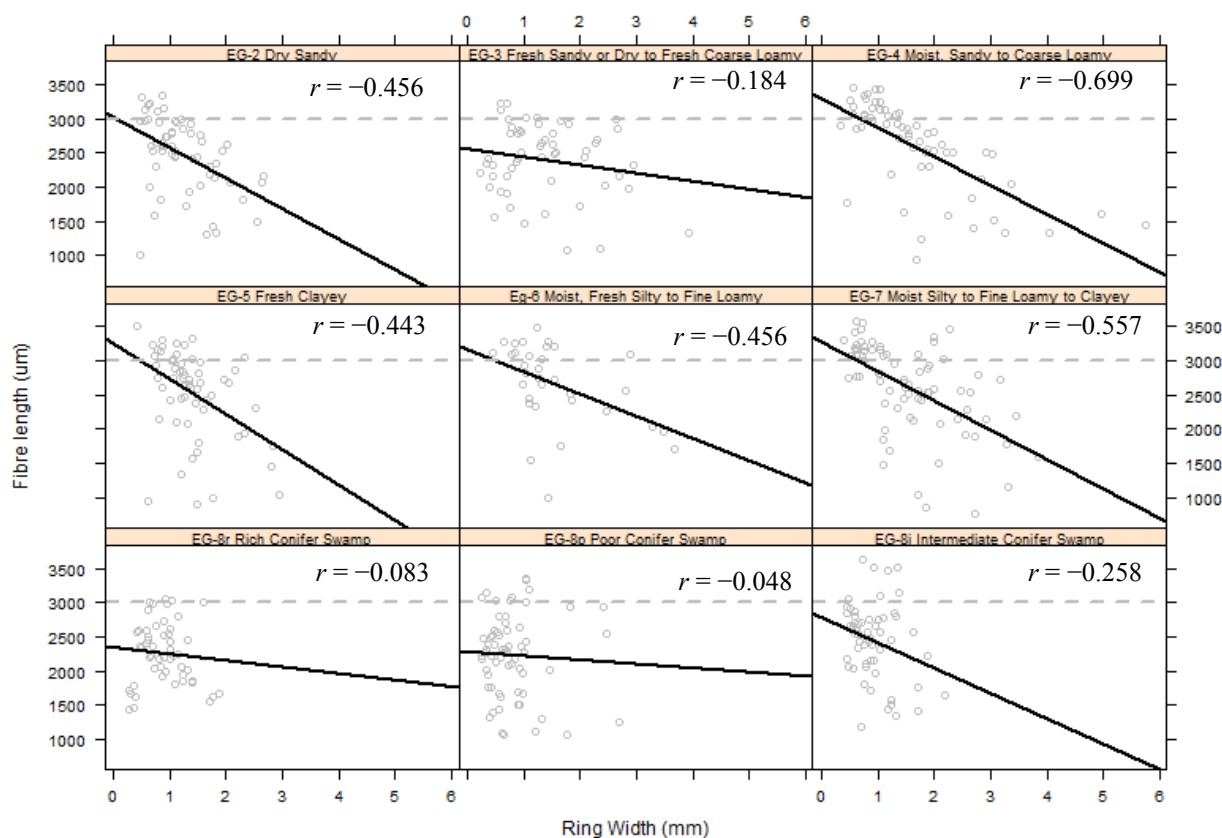


Figure 6. Scatterplot of mean fibre length (combined earlywood and latewood) and ring width for black spruce increment cores representing different ecosite groups collected from the boreal forest of north eastern Ontario from 2010–2011. r = Pearson correlation coefficient.

4. Discussion

The range of fibre lengths we observed was comparable to other studies of black spruce [29,42,43]; however, we found no significant 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. The formation of latewood is related to a complex series of seasonal environmental and physiological changes that influence cell division and elongation [44]. In general, LW is formed during a less productive part of the growing season for most tree species [45], which may be linked to water stress induced by a change in day length [46,47]. Latewood cells are characteristically thick-walled and have a narrow lumen in comparison to EW, and previous studies have suggested that LW fibres are generally longer than EW fibres [48]. It has been suggested that LW characteristics develop in times of water stress as a mechanism to avoid cavitation [14]. Experimental studies indicate that tracheid dimensions are reduced under periods of imposed drought [49]; however, responses of tracheid length to seasonal change are not completely understood and are not always clearly linked to changes in weather [46]. These responses may be dependent on the timing of water stress, and may not be evident until severely negative water potential (e.g., -2.0 MPa) exists [49]. Our findings suggest that tracheid length in black spruce does not change in a systematic way throughout the growing season, and may not be part of the overall response to seasonality. These results differ from the response in some other wood quality attributes of black spruce such as wood density, which varies strongly between EW and LW across all

ecosite types [27]. However, we have also observed that mean microfibril angle is similar between EW and LW samples from black spruce across all ecosite groups. It is important to note that the comparison we are making here is across multiple years, and that there might be differences between LW and EW fibres in particular years. Deslauriers *et al.* [50] suggest that flexibility in the seasonal pattern of tracheid growth would be advantageous, given the variability of optimal conditions from year to year in the boreal forest.

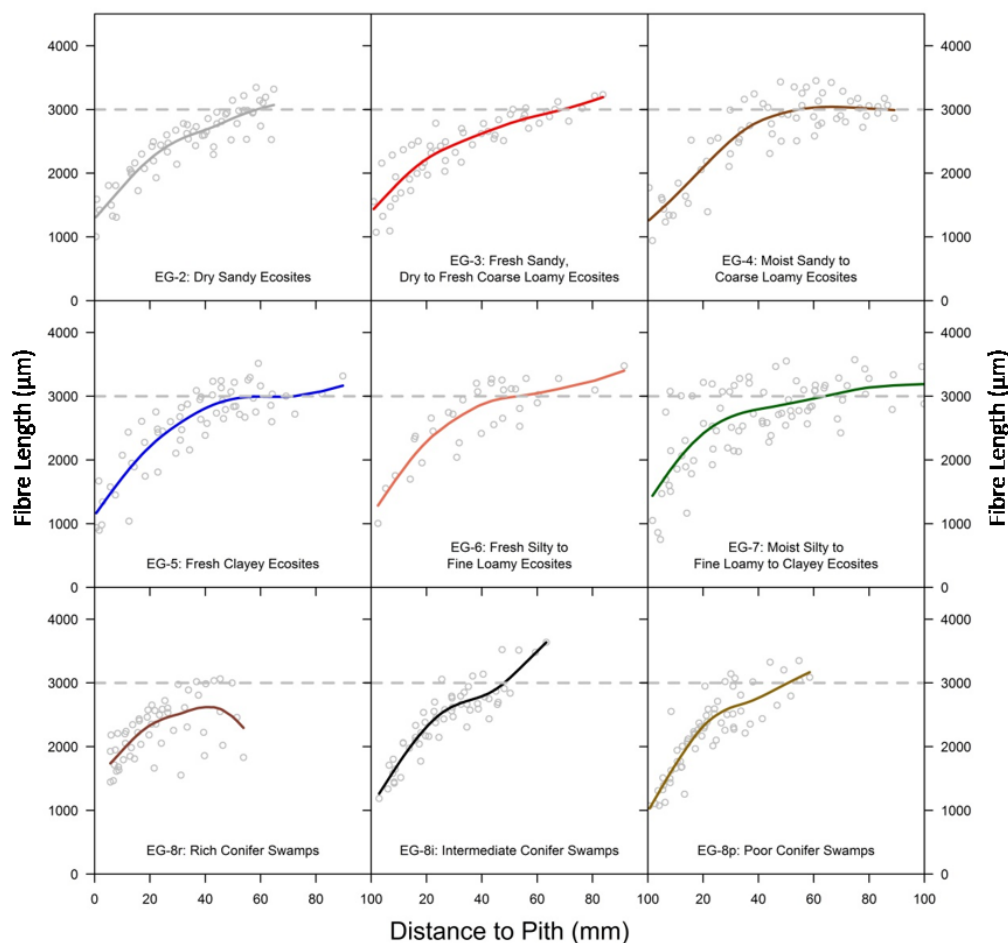


Figure 7. The fibre length response curve (mean fibre length against distance from the pith (mm)) at breast height of black spruce increment cores representing different ecosite groups collected from the boreal forest of north eastern Ontario from 2010–2011. The curve was fit with a cubic smoothing spline with five degrees of freedom.

The 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 [51,52]. Makinen and Hynynen [52] stated that the main factor causing variation in fibre length from bark to pith is the change over time from juvenile to mature wood. This suggests that the differences in EW and LW fibre lengths that would arise from seasonal fluctuations are not as important to the fibre attribute profile of a given stem as the overall pattern of growth that develops as the stem matures. Thus, stem-level mean fibre length was found to be responsive to ecosites as well as to variables relating to stand occupancy and competition. We found a general trend

that trees from more stressful ecosites produced shorter average stem-level fibre lengths, similar to Watson and Bradley [3], who found 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 [12,53,54]. Mansfield *et al.* [51] found that site conditions had no significant effect on the initial age of increasing fibre length for lodgepole pine. St-Germain and Krause [55] 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. Our study found that good site quality (as depicted by an ecological land classification system) had a positive effect on the weighted average of stem-level mean fibre length for 50 year old black spruce stems. This relationship was further elucidated by the linear association of short fibre lengths with wide tree rings (faster growth rates) observed for some of the ecosite groups (e.g., EG-4 to EG-7). This relationship suggests that trees on good sites have reached a plateau in growth rate by 50 years of age at breast height due to the effects of competition, and therefore contain a higher proportion of wood composed of narrow rings that have long fibre lengths. While the differences in mean fibre length among ecosite groups are relatively small (2384–2849 μm), they fall within the range of lengths where increases have a substantial impact on important mechanical properties such as tensile strength [54]. Furthermore, these ecosite groups also exhibited substantial variation in mean wood density (498–573 $\text{kg}\cdot\text{m}^{-3}$) and latewood percentage (20%–30%) across the gradient they represent [27]. Thus, ecological land classification variables offer valuable insights into landscape-level variation in basic wood properties, which collectively could be considered when developing a strategy to optimize the value-chain [8].

We also found that BA and crown width were important factors in predicting fibre length; these variables are related to stand density and competition, which produces trees with greater height: DBH ratios and greater height variation in a stand. This suggests that mean stem level fibre length is responding to competition, and highly occupied stands with more competition produced wood with longer mean fibre lengths. Trees on poor sites with lower canopy cover would experience less competition for light, and the profile of fibre length and ring-width with age does not develop the same shape. On these poor sites, fibre length is less variable and does not reach the critical distance from the pith (50–60 mm) that seems to initiate the shift to longer fibre lengths, within the first 50 years sampled here. Makinen *et al.* [12] found that thinning to reduce stand density of Norway spruce resulted in shorter fibres, which supports the idea that higher competition sites (for light) produce longer fibre lengths. Based on our data, fibre length was also responsive to crown width. This was perhaps another expression of the site-growth rate-fibre length relationship, as there was a general trend of increasing mean fibre length with increasing crown width. Several studies agree that crown size should influence wood fibre properties, including fibre length [51,56]. Uniformity of fibres is important for the pulp wood industry [3]. The black spruce cores analyzed in this study were fairly uniform according to the observed coefficient of variation values, which were all generally low.

The 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 mesic sites, also suggests that rapid growth rates on productive sites influences fibre length in black spruce. 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 prevailing physiological conditions over the duration of stem growth. Based on the data, more productive ecosites produce longer fibres earlier than those in less productive ecosites. Studies e.g., [52] have stated that the proportion of stem wood produced at different times of development (e.g., juvenile vs. mature stages of growth) is the most important factor in predicting fibre length. Lachenbruch *et al.* [57] describe a typical pattern of radial variation in the stem-level wood properties that identifies a transition from corewood to outerwood, mainly characterized by a decreasing proportion of earlywood in annual rings from pith to bark. There are several hypotheses that have been advanced to explain the functional characteristics of the outerwood, including cambial maturity, the selective pressure for increased resistance to cavitation, or selection for increased mechanical support [57]. From a physiological perspective, Gartner [58] argues that many properties that vary from pith to bark (e.g., density, fibre length) can be explained based on the need for trees to maintain hydraulic conductivity by producing long tracheids with narrow diameters and thick cell walls in order to resist cavitation as they mature. It is further hypothesized that radial changes will stabilize when the effect of cambial maturity is overwhelmed by environmental constraints [57]. Here, we build on this notion by suggesting that the rate of change in fibre length along the radial profile, as well as the point at which properties stabilize, is related to environmental constraints that could be predicted based on ecological site characteristics. Perhaps the trees growing on productive sites reach maturity faster than those on poor sites. Indeed, our data suggest that black spruce that grow on better sites more quickly reach a critical threshold diameter of approximately 10–12 cm (50–60 mm radial distance from the pith), at which fibre lengths stabilize at approximately 3 mm. However, we cannot eliminate the possibility that the change in fibre length associated with distance from the pith is the result of a mechanical constraint. Perhaps black spruce must reach a certain stem size and rigidity before maximum fibre length is possible.

We detected relationships using the regression tree analysis, but they could not be generalized in the random forests analysis. With a sample size of only 55 trees, each randomly drawn case selected in the bootstrapping procedure of random forests has a greater overall impact on the outcome of the tree. Thus, even if each of 5000 trees are built with a random selection of 55 cases, the trees may be quite variable depending on the cases that are selected to fit the model. Ideally, more samples would have been collected from many different plots to represent the ecosites. New techniques for measuring wood fibre length such as X-ray micro-computed tomography [59], could offer a rapid and accurate alternative to the traditional microscopy and image analysis we conducted, which would increase the number of samples that could analyzed in future studies. In some cases an ecosite group had more than one sample coming from the same plot, so some of the plot variables (BA, SPH and QMD) were the same for all of those samples. Despite this we suggest that the results found are encouraging and follow-up efforts that collect and analyze more samples are warranted.

Correspondence between the fibre length response curves and RGC (regional growth curves) was visible in some ecosites (EG-4) but not others (EG-8i). The discordance between the two variables for particular groups of ecosites may be due to noise (climate, disturbance) impacting the shape of the fibre length response curve or the ring width response, so that it is no longer reacting to the age related growth trend implicit for that type of site, which we hypothesize is driven by light competition. More samples would allow for improved matching of curves by removing samples affected 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, given that a model could be developed that converts ring width information into predictions of fibre length information for some site types.

Duchesne *et al.* [60] 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 the final product of the wood. Results from the mean fibre length regression tree could be useful information to forest managers, showing that ecological land classification (ecosite) and competition variables (BA, height, SPH) could be used to find the best trees and sites for growing high-valued wood fibre, and this sort of information could realistically be utilized within the FRI (Forest Resources Inventory). Ontario's current forest resources inventory, has information on ecosite polygons, and also has information that could be used to derive SPH and BA which could then be used to estimate the level of competition on a site. Ecosite information could be used to highlight plots with harsh growing conditions, which would have decreased fibre lengths and PIF values.

Ecosystem classification systems have been developed in many jurisdictions since the concept was originated in the boreal forests of Finland [61], including habitat types in the United States [62,63], the Land Environments of New Zealand (LENZ) system [64], and the ecological site classification for forestry in the United Kingdom [65]. These national systems vary across jurisdictions in their specific criteria for defining site types, and in their hierarchy of organization, but in general they share a fundamental focus on depicting the variation in topography, substrate and vegetation characteristics across the landscape at a scale that is appropriate for supporting decisions relevant to forestry, wildlife habitat and other ecological services [66]. These systems have proven useful for capturing site-specific differences in forest growth and yield [67–69], and our results suggest that ecological land classification systems may also be useful for examining general patterns in the wood quality properties of trees across the landscape.

5. Conclusions

Our analyses of black spruce trees over their first fifty years of growth in the boreal forest of Ontario Canada indicate that stem-level mean fibre length was related to ecological site type, with the longest fibre lengths being associated with the more productive ecosites. Interestingly, the relationship between fibre length and ring width (growth rate) was negative, and strongest on the productive sites. This apparent contradiction arises from the pattern of variation in fibre length with age across the different site types. On productive sites, fibre length increases rapidly over the first 20–30 years of growth and then reaches a phase characterized by uniform fibre lengths that are typically greater than 3 mm. On poor sites, trees do not reach such a uniform phase of production of longer-fibred wood within the first fifty years. Thus, the rapid maturation of trees on productive sites results in their having longer mean fibre length, and a greater proportion of wood representing ideal fibre (>3 mm) in the first fifty years of growth. We hypothesize that this difference in maturation related to site conditions could be caused by the more rapid stand closure and initiation of intense light competition on good sites, or mechanical constraints imposed by slow growth and limited size on poor sites.

Acknowledgments

Murray Woods and Paul Treitz provided helpful suggestions that improved the field sampling and data collection protocols. We thank Adam Csank for his insights regarding the analysis of the dendrochronological data. The capable field assistance of Shawn Mayhew-Hammond, Fraser McLeod, Graham Pope, Paul Courville, Whitney Winsor and Scott Perry is gratefully acknowledged. Special thanks to Michelle Bowman, Jacob McAneney and Scott Roscoe for their assistance with sample processing; and to Ashley Ryan for helping with the wood maceration method. This work was supported by the Nipissing University Forest Bioproducts Research Chair boreal ecosite project (a partnership of the Northern Ontario Heritage Fund Corporation, FedNor, Tembec, Forestry Research Partnership and Nipissing University), the AFRIT/Geoide enhanced FRI Projects, and the Canadian Wood Fibre Centre through the Natural Resources Canada Forest Innovation Program.

Author Contributions

Elisha Townshend, Jeffery P. Dech and Bharat Pokharel conceived and designed the experiments. Elisha Townshend carried out the experiments. Elisha Townshend, Jeffery P. Dech and Bharat Pokharel analyzed the data. Jeffery P. Dech contributed materials and analysis tools. Elisha Townshend, Jeffery P. Dech, Bharat Pokharel, Art Groot and Doug Pitt interpreted the findings and wrote the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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