Forest Ecology and Management 313 (2014) 307–318

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

# Modeling wood fiber attributes using forest inventory and environmental data for Newfoundland's boreal forest

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A R T I C L E   I N F O

*Article history:*
Received 15 July 2013
Received in revised form 14 October 2013
Accepted 21 October 2013
Available online 21 November 2013

*Keywords:*
Wood fiber attributes
Akaike's information criterion
Environmental drivers
Landscape mapping
Spatial analysis
Multimodel inference

A B S T R A C T

We explore the possibility of predicting wood fiber attributes across Newfoundland for two commercial species: black spruce (*Picea mariana* (Mill.) B.S.P.) and balsam fir (*Abies balsamea* (L.) Mill.). Estimates of key fiber attributes (including wood density, coarseness, fiber length, and modulus of elasticity) were derived from measurements of wood cores taken from sample plots representing a wide structural gradient of forest stands. Candidate models for predicting fiber attributes at plot and landscape scales were developed using an information-theoretical approach and compared based on Akaike's information criterion. The most influential variables were stand age and the presence of precommercial thinning. Other significant explanatory variables included those that characterize vegetation structure (mean diameter at breast height, dominant height), climate (annual precipitation, mean temperature of the growing season), and geography (elevation, latitude) depending on the species and fiber attribute being modeled. At the plot level, model inference gave root mean square errors of 5.3–11.9% for all attributes. At the landscape level, prediction errors were similar (5.4–12.1%), with the added benefit of being suitable for mapping fiber attributes across the landscape. The results obtained demonstrate the potential for predicting and mapping fiber attributes over a large region of boreal forest in Newfoundland, Canada.



## 1. Introduction

There is a lack of information regarding the variation of wood fiber attributes across geographic locations for different species. However, this information is fundamental to optimize fiber use and improve competitiveness in the forest industry (MacKenzie and Bruemmer, 2009; Pitt and Pineau, 2009). Wood fiber attributes provide indicators of wood quality that are linked to product potential and performance (i.e., pulp yield, strength and stiffness of lumber) (Kennedy, 1995; MacDonald and Hubert, 2002; Zhang et al., 2002). For example, knowledge of fiber attributes while planning forest operations can lead to improved fiber input to the paper mill, leading to optimized industrial processes. Moreover, knowledge about fiber attributes may lead to the development of new products that require unique attributes. Obtaining information on fiber attributes is costly because direct measurement typically requires the extraction of core samples from trees. Thus, models are needed to predict fiber attributes from forest stand and environmental factors, which can be measured and mapped more easily over large areas.

Wood fiber can be described through a large array of attributes, and the most cited attributes describing wood fiber also correspond to those considered to be the most important for forest industry: wood density, coarseness, fiber length, and modulus of elasticity (Bergqvist et al., 2000; Schimleck et al., 2002; van Leeuwen et al., 2011; Watson and Bradley, 2009; Watt et al., 2008a). Many studies emphasize wood density as a key variable because it is a good indicator of wood strength and stiffness. Wood density also plays a role in biomass and carbon storage estimation (van Leeuwen et al., 2011; Zobel and van Buijtenen, 1989).

Studies on wood fiber attributes in boreal forests have focused on conifer species, such as white spruce (*Picea glauca* (Moench) Voss) (Lenz et al., 2012), black spruce (*Picea mariana* (Mill.) B.S.P.) (Liu et al., 2007), Scots pine (*Pinus sylvestris* L.) (Kilpeläinen et al., 2005), and Sitka spruce (*Picea sitchensis* (Bong.) Carrière) (MacDonald and Hubert, 2002). The relationships between wood fiber attributes and stand variables have been studied mainly in plantations of softwood species (Lei et al., 2005; Watt et al., 2008b), and only a few studies investigated those relationships in natural stands (Wilhelmsson et al., 2002; Liu et al., 2007). Previous arguments support the idea that environmental factors (climate and forest inventory variables) influence wood fiber attributes and provide promising avenues to develop predictive models both

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http://dx.doi.org/10.1016/j.foreco.2013.10.030

in managed and natural stands. To our knowledge, no predictive models using typical forest inventory data are currently available to inform decisions at the landscape scale.

Climate and site play an important role in tree growth, and many studies have reported correlations between fiber attributes and climatic variables. For example, temperature and precipitation influence wood density (Kilpeläinen et al., 2005; Swenson and Enquist, 2007; Watt et al., 2008b; Wimmer et al., 2002). Wood fiber attributes have also been linked to forest stand and tree variables, such as precommercial thinning (MacDonald and Hubert, 2002), age (Wilhelmsson et al., 2002), diameter at breast height (DBH, in cm measured at 1.3 m), height (Liu et al., 2007; van Leeuwen et al., 2011), competition, stand density (van Leeuwen et al., 2011), elevation (Swenson and Enquist, 2007), aspect and slope (Stage, 1976). Most of these relationships were quantified through various statistical techniques, such as analysis of variance, generalized linear models, linear mixed effects models, ordinary least squares regression, path analysis, or stepwise regression (Bergqvist et al., 2000; Bouriaud et al., 2004; Lei et al., 2005; Liu et al., 2007; Watt et al., 2008b; Wimmer et al., 2002). Akaike's information criterion (AIC) (Burnham and Anderson, 2002, 2004; Mazerolle, 2006) is another approach that is well designed for exploring the effect of multiple predictor variables and for identifying the most parsimonious models predicting wood fiber attributes in complex natural environments (Burnham and Anderson, 2002, 2004; Johnson and Omland, 2004; Mazerolle, 2006).

The overall goal of the study was to model and map wood fiber attributes across the merchantable forest area of Newfoundland. Our working hypothesis was that wood fiber attributes of black spruce and balsam fir (*Abies balsamea* (L.) Mill.) stands are related to environmental variables and forest variables measured in existing inventory plots or available from stand-level maps. Three key research questions were identified: (1) what are the relationships between fiber attributes and available forest inventory and environmental data? (2) to what extent can the relationships be used to predict and map fiber attributes across Newfoundland? and (3) what models can be used with the available spatial data to produce maps of fiber attributes for Newfoundland? Specific objectives were to:

(i) Identify environmental and forest inventory variables that can be used to predict wood fiber attributes.
(ii) Develop predictive models at the plot level for estimating fiber attributes from an extensive database of wood fiber attributes measured *in situ* at plot locations.
(iii) Develop predictive models at the landscape level for mapping fiber attributes for the island of Newfoundland using available spatial databases.

## 2. Methods

### 2.1. Study site

The study was conducted on the island of Newfoundland (111,390 km$^2$), located in eastern Canada (Fig. 1) centered around 48°32′30″N and 56°07′30″W. Topography varies from relatively rugged with flat valley bottoms in the western part of the island to gently rolling relief with large areas of low relief in the central part, and a rolling plateau in the eastern part. The area is characterized by the presence of many lakes, bogs, and rivers (Rowe, 1972). Located within Canada's boreal forest, the two dominant species are black spruce and balsam fir. Black spruce accounts for approximately one-third of the forests found on the island. This slow-growing tree is usually found on very humid or very dry soils and especially in areas affected by forest fires (Government of Newfoundland and Labrador, 2011; Mullins and McKnight, 1981; USDA Forest Service, 1990). Balsam fir stands dominate mainly moist and well-drained sites.

### 2.2. Plot-level data

The Newfoundland Department of Natural Resources collects inventory data through a network of permanent sampling plots (PSPs). All plots are rectangular in shape, with size varying for immature and semi-mature stand types and fixed at 1/25 ha for mature and over-mature types. Plot size is dependent on stand density and as a rule should contain a minimum of 75 trees. The PSP program consists of about 1,000 different locations across Newfoundland in natural and managed stands, and each PSP is revisited every 4–6 years. All the trees inside a plot are numbered. Tree characteristics are recorded in a database and updated every time there is a new inventory (Newfoundland Forest Service, 2011). For this study, a subsample of 194 PSPs (77 black spruce-dominated plots and 117 balsam fir-dominated plots) was selected across the island. The subsample targeted three replicates within each combination of species, height, crown density, and site index classes in order to capture a wide range of forest growing conditions within the merchantable forest area.

At each PSP, wood cores were extracted from a sample of ten live merchantable trees to measure fiber attributes. These ten trees were selected starting at 10 m outside the plot (at a 130° angle) from the plot's corner where the site conditions were the most representative of the PSP. The cores were sent to the FPInnovations laboratory in Vancouver for analysis of the suite of fiber attributes using a combination of optical microscopy, image analysis, X-ray densitometry, and X-ray diffractometry (Downes et al., 2002; FPInnovations, 2009; Schimleck et al., 2002; Schimleck and Evans, 2004; Sherson et al., 2007). Density (kg/m$^3$) was measured at 8% moisture content by irradiating a sample with X-rays and detecting the amount of radiation transmitted through the sample. X-ray absorbance was related to density according to Beer's Law. The measured density was scaled to match the average density of the core measured from its volume (micrometry) and its mass to ensure that average density of the sample matched the average density predicted by *SilviScan* technology (FPInnovations, 2009). Coarseness (μg/m) was calculated combining wood density and tracheid diameter profiles obtained from the *SilviScan* analysis. Fiber length (mm) was measured using a HiRes Fiber Quality Analyzer (HiRes FQA (Hawkesbury, ON)) (a commercial instrument developed jointly by Paprican, the University of British Columbia, and OpTest Equipment Inc.) using a fiber solution made from macerated wood cores. Modulus of elasticity (MOE in GPa), which is a measure of wood stiffness, was estimated from wood density and diffraction patterns of the wood obtained from a wide-angle X-ray detector (Evans and Ilic, 2001; FPInnovations, 2009; Sherson et al., 2007).

For all plots with a minimum of three trees of the species of interest (balsam fir or black spruce), an average plot value (weighted by basal area of all the sampled trees based on the basal area of a given species) was calculated for each fiber attribute (Table 1):

$$\text{Averaged Mean} = \sum\nolimits_{PSP}\left(\frac{\text{Fiber Attribute}_{tree} \times \text{Basal Area}_{tree}}{\sum \text{Basal Area}_{tree}}\right) \quad (1)$$

For each PSP, individual tree measurements were recorded *in situ* and aggregated to derive plot-level estimates. Specifically, DBH and species were recorded for each tree. Height was measured for a sample of trees at each plot, and species-specific relationships between DBH and height were developed for each ecoregion and