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Regional variation in wood density and modulus of elasticity of Quebec's main boreal tree species

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ABSTRACT

Regional variation in wood density and modulus of elasticity (MOE) for the main boreal softwoods (black spruce, balsam fir, jack pine) and hardwoods (paper birch, trembling aspen) of Quebec, Canada, were estimated using near-infrared spectroscopy on 30,159 increment cores from 10,573 inventory plots. An automated near-infrared system was developed for this purpose and calibrated using SilviScan data. Large-scale spatial dependence in wood density and MOE was observed. On average, observations were spatially autocorrelated on longer distances in hardwoods (136–157 km) than softwoods (65–74 km). Overall wood density and MOE increased with temperature and precipitation regardless of species. In addition, a uniform latitudinal gradient related to climate was observed in paper birch and trembling aspen. Conversely, spatial distribution in wood density and MOE was not uniform in softwoods, suggesting a more limited environmental adaptability in comparison to the hardwood species studied. The natural variability of wood density and MOE in these species is now known for the study area. Regional estimates are thus available for various decision-making processes related to forest management, wood allocation, timber market value, protection priorities in firefighting and insect pest control, and forest carbon estimation.

1. Introduction

Spatial modeling of wood properties aims to produce local estimates and reveal significant regional differences. Given the importance of physical and mechanical properties in wood processing, this knowledge could provide a competitive advantage and have practical applications to aid decision-making in forestry (Briggs, 2010). For this purpose, several models were recently developed in Canada to predict local estimates of wood properties based on a combination of photo-interpreted vegetation (including ecology), climate, geography, and imagery data (Giroud et al., 2016; Lenz et al., 2014; Lessard et al., 2014; Pokharel et al., 2014) or by using only stand vegetation structure derived from LiDAR (Luther et al., 2014; Pokharel et al., 2016). Some of the spatial dependence in wood properties was usually attributed to climate and/or geography, although the number of sampled plots tended to be limited.

Regional variation in wood density and modulus of elasticity (MOE) have also been studied in other parts of the world, specifically loblolly pine (*Pinus taeda* L.) plantations in the US (Antony et al., 2011; Jordan et al., 2008) and Monterey pine (*Pinus radiata* D. Don) plantations in New Zealand (Palmer et al., 2013), and across various species and geoclimatic conditions in Neotropical (Chave et al., 2006; Swenson and Enquist, 2007), Bornean (Slik et al., 2010), and Chinese (Zhang et al., 2011) forests. These studies found that wood density and MOE frequently appeared to decrease with latitude and/or altitude including positive correlations with temperature and/or precipitation. Rossi et al. (2014) also observed higher values of wood density and MOE for Quebec's black spruce in lower latitudes or altitudes, where the radial growth rate was higher. Globally, wood formation appeared to be influenced by climate, producing more cells with thicker walls and more latewood when temperature and precipitation increased and the growing season was extended (Antony et al., 2011; Jordan et al., 2008; Rossi et al., 2014).

Spatial dependence or spatial autocorrelation can be measured using geostatistical techniques based on the first law of geography, according to which everything is related to everything else, but near things are more related than distant things (Tobler, 1970). The spatial variability pattern is usually described and estimated using a semivariogram. Spatial dependence can be incorporated into a regression model based on semivariogram parameters, including or excluding covariants (Littell et al., 2006). Different geostatistical techniques have already been used to predict and

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map regional variation in wood density and MOE for large-scale pine plantations (Antony et al., 2011; Jordan et al., 2008; Palmer et al., 2013). These geostatistical models require samples from numerous, widely-distributed sites. However measuring the wood properties of thousands of samples using current technologies is a daunting challenge.

Near-infrared (NIR) spectroscopy and its applications for wood is well-documented (Tsuchikawa and Kobori, 2015; Tsuchikawa, 2007). NIR spectroscopy is indeed a fast and relatively accurate technique that requires no sample preparation. NIR absorption spectra are obtained by exposing wood samples to NIR radiation, which covers the 780–2500 nm range of the electromagnetic spectrum. The spectra are then used to predict the wood properties using multivariate analysis. NIR calibration requires accurate measurements from reference methods. SilviScan was used in most studies to obtain the necessary data to model wood density and MOE (Schimleck, 2008). SilviScan is a system that combines X-ray densitometry, X-ray diffractometry, and image analysis (Evans and Ilic, 2001; Evans, 1994). Few NIR calibrations were developed using the radial profiles of wood properties measured by SilviScan (Giroud et al., 2015; Meder et al., 2011). Such calibrations are particularly interesting considering the high variability of wood properties from the pith to the bark. NIR spectra were usually collected by manually translating the wood samples or the handheld contact probe at a specific step size (Giroud et al., 2015; Xu et al., 2011). A motorized linear carriage coupled with a 1-mm diameter fiber-optic probe was also conceived for this purpose in Australia (Meder et al., 2011). Most of NIR calibrations, developed for the prediction of wood density and MOE, were species-specific. However, global calibrations (i.e., multi-site, multi-species) were also investigated (Schimleck et al., 2001, 2010). Schimleck et al. (2001) demonstrated that was possible to develop NIR calibrations for wood density and MOE using a wide range of softwood and hardwood species that displayed extreme variations in wood chemistry, anatomy and physical properties. Such global calibrations are of great interest in resource assessment to estimate the wood properties of many species, grown on a large range of a sites (Schimleck et al., 2010).

Regional variation in wood density and MOE were studied for the main tree species of Quebec's managed boreal forests: balsam fir (*Abies balsamea* (L.) Mill.), black spruce, jack pine, paper birch (*Betula papyrifera* Marsh.), trembling aspen (*Populus tremuloides* Michx.), and white spruce (*Picea glauca* (Moench) Voss). Thousands of increment cores taken from Quebec's provincial forest resources inventory were used for this purpose. More specifically, the objectives were to (i) develop a fast and reliable method to estimate wood density (basic density) and MOE using increment cores, (ii) incorporate spatial dependence into predictive models, and (iii) map and discuss the intraspecific and interspecific spatial distribution of wood density and MOE. To our knowledge, NIR spectroscopy and geostatistics have never been combined to predict and map regional variation in wood density and MOE in natural forests.

2. Materials and methods

2.1. Materials and study area

The study area was located in the centre of the Canadian province of Quebec, approximately from 71°W to 79°W and from 45°N to 51°N, covering a large latitudinal gradient across the managed forest and, consequently, a large range of growing conditions (Fig. 1). Data generated for the study area using BioSIM, a climate simulation software developed by the Canadian Forest Service (Régnière et al., 2014), indicates that for the period covering 1981–2010, the normal July mean temperature ranges from approximately 11.9 °C to 21.7 °C, growing season precipitation ranges from 310 mm to 776 mm, snowfall from 229 mm to 577 mm, and aridity from 1 to 85 mm (Fig. 2). Aridity was calculated using Thornthwaite's monthly potential evapotranspiration minus monthly growing season precipitation. Forest data and increment cores were provided by Quebec's provincial forest resources inventory, a two-phase inventory design based on photo-interpretation and field sampling. Forest stand composition, structure, and ecology are photo-interpreted every 10 to 15 years. Productive and accessible forest stands of 7 m and higher were sampled in temporary plots in accordance with provincial standards and procedures. This inventory data is used to assess the current state of the forest, including available standing volume. Care was taken to precisely measure the metrics and features of three sample trees per temporary plot. Increment cores were collected from these trees at 1 m above ground. Ring width and age were systematically measured from the increment cores using WinDENDRO (Regent Instruments Inc., Quebec City, Quebec, Canada).

2.2. Spectral data acquisition

The wood surface was sanded using three sandpaper grits (120, 220, and 320) and cleaned to remove dust. The increment cores were conditioned for 24 h at 40% relative humidity and 20 °C, before being scanned by NIR spectroscopy to measure the wood properties. A NIR system was developed by Centre de Recherche Industrielle du Québec (CRIQ) to automatically acquire NIR spectra and high resolution images from increment cores (Fig. 3). For this purpose, a FT-NIR spectrometer (Matrix-F model, Bruker, Billerica, Massachusetts, USA) was equipped with a 2-mm diameter reflector probe (Reflector model, Solvias, Kaiseraugst, Switzerland). A 2-mm diameter probe was chosen because of the size of the increment cores, which are about 4–5 mm wide. The spectra were acquired between 4000 and 12,000 cm^{-1} (830–2500 nm). Four scans were accumulated and averaged to give a single spectrum per spot. A ceramic standard was used as instrument reference and measured every hour. The spectra were collected in 5-mm increments, from bark side to pith, using a motorized linear carriage, with a 3-mm unscanned gap between each spot. The increment size and the number of scans accumulated were chosen as a result of a compromise between spectral quality and productivity in terms of scanning time.

2.3. Calibration of NIR models

Near-infrared calibrations were based on 1636 wood samples measured by X-ray diffractometry and X-ray densitometry, using SilviScan-3 at FPInnovations in Vancouver, British Columbia (Table 1). These reference samples were chosen from a collection of wooden disks harvested across the province to develop stem taper equations and site index estimates in the 2000s (Laflèche et al., 2013). Only co-dominant and dominant trees from mature stands were sampled. Some of these wooden disks were kept frozen by the federal government for future research on wood fiber. Only wooden disks collected at breast height were retained, since too few samples collected at 1 m above ground were kept. SilviScan processing was described by Giroud et al. (2015). The transverse face of reference samples was scanned by NIR spectroscopy, even though SilviScan works with the radial face. Schimleck et al. (2005) tested NIR calibrations on both faces of SilviScan samples for density, MOE, microfibril angle and several tracheid morphological characteristics. They concluded that either face could be used for NIR analysis. In addition, in our study, only the transverse face of increment cores is prepared and sanded for ring analysis, and can thus be scanned by NIR spectroscopy.