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Ecogeographic variation in black spruce wood properties across Quebec's boreal forest

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ABSTRACT

Ecogeographic variation in black spruce clear wood properties was investigated for the two main vegetation types of the managed boreal forest of the province of Quebec, Canada. In total, 409 co-dominant and dominant trees from 82 mature stands were sampled. Basic wood density, modulus of elasticity and microfibril angle were measured using SilviScan. Mature fiber length was determined using a high-resolution Fiber Quality Analyzer. Wood growing in pure black spruce stands had longer mature fibers, a significantly denser wood with better mechanical characteristics than the wood growing in mixed stands with balsam fir. All wood properties were clearly influenced by radial growth and species composition.

Given the limited number of sample plots for mapping purposes, a two-stage modeling approach was assessed to predict stand-level estimates of black spruce clear wood properties. This scaling-up method, based on field measurements and ring data from 3350 inventory plots, has improved the performance of all models. Stand-level models explained 47%, 57%, 63% and 63% of variance in wood density, modulus of elasticity, microfibril angle and mature fiber length respectively with estimated root mean square errors of 8.9 kg/m^3, 0.52 GPa, 0.60° and 0.06 mm.

An east-west gradient in black spruce clear wood properties was revealed as possibly the by-product of the change in relative proportions of both studied vegetation types across the study area. The results indicate that the black spruce wood from western regions of the managed boreal forest has a better potential for producing pulp and paper, lumber or engineered products due to its longer mature fibers and higher mechanical properties.

1. Introduction

Spatial variation in wood properties is still not well known in natural forests (Briggs, 2010). Wood density, however, has been studied as a functional trait of plants at the landscape scale (Chave et al., 2009; Malhi et al., 2006; Swenson and Enquist, 2007). The data of these studies were mainly compiled from the literature in order to compare the evolution of wood density between angiosperms and gymnosperms across geographic and topographic gradients. Wood density has always created a lot of interest given its close relationship with mechanical support, water transport and storage capacity (Chave et al., 2009). Performing large-scale research on wood properties for a given species requires significant investments to collect samples and perform laboratory measurements. That reality has always been an impediment to research in this field. Most studies focus on a few sites and, consequently, the scope of results is often narrow.

Black spruce (*Picea mariana* (Mill.) B.S.P.) grows in a variety of conditions, suggesting differences in wood fiber quality between sites. Its reproduction is particularly adapted to fire because of its serotinous cones (Gauthier et al., 2001). In regions with high fire frequency, black spruce forms extensive and even-aged stands. Otherwise, it mainly reproduces by vegetative layering forming irregular stands particularly in open sites with abundant humus. Black spruce largely dominates Quebec's boreal forest. It represents approximately 75% of the total gross merchantable volume of this region, followed by balsam fir (*Abies balsamea* (L.) Mill.) (15%) and jack pine (*Pinus banksiana* Lamb.) (8%), according to data provided by the Ministère des Forêts, de la Faune et des Parcs du Québec (MFFPQ). Black spruce wood is highly desirable for lumber,

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pulp manufacturing and engineered wood products (Viereck and Johnston, 1990; Zhang and Koubaa, 2008). Compared with balsam fir, black spruce has a denser wood, a higher modulus of elasticity (MOE) and modulus of rupture (MOR), and a higher coarseness for a similar fiber length (Jessome, 2000; Lessard et al., 2014). Compared with jack pine, black spruce has relatively similar values for wood density and mechanical properties (MOE, MOR), but smaller knots and much less resin (Jessome, 2000; Panshin and Zeeuw, 1980).

Numerous studies have focused on the influence of growth conditions on black spruce wood properties across Canada, given its merchantable importance. However wood fiber quality in relation to ecological site conditions has not been studied much until now. The importance of ecological land classification to predict black spruce wood properties was investigated in the boreal forest of northeastern Ontario (Pokharel et al., 2014; Townshend et al., 2015). Ecosite group was the most important explanatory variable for these studies. Higher values in wood density and latewood proportion were observed for intermediate and poor swamp ecosites. Pokharel et al. (2014) explained these results as the constraining effects of wet, nutrient-poor conditions in swamp ecosites. Townshend et al. (2015) found that longer fiber length was associated with more productive ecosites that supported faster growth. The influence of growing conditions on wood formation was also recently investigated in black spruce and balsam fir by Groot and Luther (2015). Negative correlations of wood density to radial growth rate at the ring, tree, and plot levels of aggregation were found from 330 black spruce and 680 balsam fir increment cores collected across Newfoundland. However, the authors mentioned that growth rate alone was insufficient to explain variation in wood density at all levels. Model performance was also particularly improved with the aggregation level of wood density models: ring to tree to plot. This improvement was mainly explained by the decrease in wood density variance with the aggregation level. Torquato et al. (2013) have assessed the influence of stand origin and structure on the mechanical properties of black spruce in 28 sites across Quebec. MOE and MOR were found significantly higher for samples from regular stands compared with those from older, irregular stands. The authors suggested that a higher incidence of mild compression wood associated with vegetative layering in irregular stands could explain these differences.

Spatial variation in black spruce wood properties was also little investigated, and the available results are often divergent. Latitudinal variations in tree-ring and wood cell characteristics were observed in 15 black spruce mature stands sampled along a 500 km transect from 47°N to 52°N across the Quebec's boreal forest (St-Germain and Krause, 2008). Tree ring, earlywood, and latewood widths, cell numbers, latewood radial cell diameter, and cell wall thickness declined with latitude, but no significant variations were observed on tracheid length and latewood proportion. Rossi et al. (2014) found higher wood density and mechanical properties for sites located at lower latitudes and altitudes. In both studies, the influence of ecosite was however not considered. Spatial variation in wood properties has also been investigated in other North American species. To our knowledge, Lenz et al. (2014) were the first to use the ecological land classification of Quebec to study spatial variation in wood fiber properties. Significant differences in white spruce (*Picea glauca* (Moench) Voss) wood properties among ecological regions were observed in 56 sites across Quebec. Maximum temperature, degree days, geographic location, tree height, and diameter were the best predictors of white spruce wood properties. Significant regional variations in wood properties were also observed in planted loblolly pine (*Pinus taeda* L.) in the United States. Latewood proportion, wood density and mechanical properties were higher in southern and coastal regions characterized by more abundant summer precipitation and longer growing seasons (Finto et al., 2011; Jordan et al., 2008).

Several studies concluded that stand-level models could theoretically be developed to map wood properties over broad areas (Briggs, 2010; Lenz et al., 2014; Pokharel et al., 2014; Van Leeuwen et al., 2011). For practical reasons as previously mentioned, very few studies have gone so far to date. The proof of concept was recently done for black spruce and balsam fir in Newfoundland (Lessard et al., 2014). Stand-level estimates were predicted using climate, geographic and photo-interpreted data. Maps were produced for Newfoundland. These models were developed using the average plot values of wood properties measured in 77 black spruce and 117 balsam fir sites. Sample size is the main limitation to the production of accurate regional maps of wood properties in order to take into account, as widely as possible, the ecological variability of the study area. To our knowledge, a two-stage modeling approach has never been investigated to predict stand-level estimates of wood properties. In the present study, the two-stage modeling approach consisted in developing tree-level models to predict individual tree values from provincial inventory plots, in order to increase the sampling intensity to develop stand-level models. The two-stage modeling approach refers to the concept of double sampling, or two-phase sampling, which is used in forest inventories for several decades (Tuominen et al., 2006).

The present study was based on Quebec's ecological land classification and on a large provincial forest resources inventory dataset. This study aimed to investigate the spatial variation of black spruce clear wood properties in different site types across the managed boreal forest of Quebec. More specifically, the objectives were (i) to assess the influence of ecological conditions on black spruce clear wood properties, and (ii) to develop a modeling approach to produce regional maps.

2. Materials and methods

2.1. Study area and sampled ecosites

The study area was the "black Spruce – moss" bioclimatic domain, located approximately from 48°N to 52°N, in the boreal forest of Quebec, Canada (Fig. 1) (Blouin and Berger, 2004, 2005; Morneau and Landry, 2007, 2010a, 2010b). Bioclimatic domain is the highest level of the ecological land classification of the province of Quebec. It is characterized by a particular type of vegetation in the final stage of succession, reflecting the balance between climate and potential vegetation on mesic sites (well-drained soils). The climate of the "black Spruce – moss" domain is continental, with a short growing season. It is divided into two precipitation-based subdomains. Unlike the western subdomain, the eastern subdomain is characterized by more precipitation, a longer fire cycle and more balsam fir than the western subdomain.

Potential vegetation is the typical vegetation of end succession for a given site. The two main potential vegetations are the "balsam Fir – black Spruce" vegetation ("RS2") and the "black Spruce – moss or ericaceous" vegetation ("RE2"), representing 74% and 14% of the total forest area of the eastern subdomain, and 21% and 48% of the total forest area of the western subdomain, according to data provided by MFFPQ, respectively. The forest dynamics are very different in both types of potential vegetation (Blouin and Berger, 2004, 2005; Morneau and Landry, 2007, 2010a,b). The stands associated with RE2 vegetation are almost always black spruce even-aged stands continuously renewed by recurring fires, and characterized by seed reproduction. On the other hand, the main natural disturbances related to RS2 vegetation are fires, windthrows and insect outbreaks