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Effects of topography and thickness of organic layer on productivity of black spruce boreal forests of the Canadian Clay Belt region

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Northern Canadian boreal forest has a considerable ecological and economic importance, with the black spruce forest type occupying a large extent of this ecosystem. Organic layer thickness and its relationship to topography are two key factors affecting tree growth and productivity of black spruce boreal forests of the Canadian Clay Belt region. This study linked multi-scale models of organic layer thickness and topography to improve our understanding of how these variables influence forest productivity and its distribution at different spatial scales within the Clay Belt region, northwestern Quebec. Field data were used to calculate site indices, which were used as estimators of forest productivity. Organic layer thickness was determined from field measurements obtained by manual probing, whereas topographic variables were extracted from multi-scale LiDAR-derived digital terrain models (DTM) at four resolutions, i.e., 5-, 10-, 15- and 20-m. Correlations between individual predictors and site index were found to be weak; however, few were significant, viz., organic layer thickness. Regression tree-based models were fitted using two different sets of explanatory variables at the four scales: organic layer thickness and topography (model 1); and topographic variables only (model 2). Organic layer thickness, aspect, and slope were the most important variables explaining forest productivity (63% and 31% total variance explained for models 1 and 2, respectively). Model 1 was found to be scale-independent, since the total explained variance was similar under the four resolutions, whereas with model 2, effects of topography on productivity were greater for coarser scales (highest R^2 at 20-m resolution). Both models indicated higher forest productivity on southwest-facing slopes (i.e., >2.2%) with shallow organic layers (<35 cm), so then where organic horizons are the deepest the tree productivity is low. In contrast, lowest site indices (expressing low productivity) were found in areas with very deep organic layers (>85 cm). The resulting models could be applied at operational scales to predict site index at locations for which organic layer thickness information and DTM exist. Such information could be used to help forest managers in predicting how forest growth will respond to various harvesting activities.

1. Introduction

The Canadian boreal forest has considerable ecological and economic importance. First, it provides habitat for diverse wildlife. Second, it acts as a reservoir for maintaining biological and genetic diversity. Third, it stores carbon, purifies air and water, and helps regulate regional and global climates. Last, it is the source of numerous resources for the industry in Canada. The forest type that is dominated by black spruce (*Picea mariana* (Mill.) B.S.P.) occupies a large extent of the northern Canadian boreal biome and is considered to be an important source of timber (Koubaa et al., 2005). However, these northern boreal forests are characterized by extensive paludified areas with low forest productivity. Paludification is a natural process where organic material accumulates on the ground surface over time. These accumulations can lead to reductions in soil temperature, organic matter decomposition rates and nutrient availability that result in restricted tree

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growth, together with higher soil moisture levels and elevated water tables (Crawford et al., 2003; Lavoie et al., 2005; Vygodskaya et al., 2007). These conditions alter dynamic succession and favour the invasion of *Sphagnum* moss species (Fenton et al., 2005; Fenton and Bergeron, 2006, 2007; Thiffault et al., 2013), which can lead to the development of forested peatlands and substantial decreases in forest productivity (Simard et al., 2007, 2009). Forest productivity refers to the quantity of timber that a stand is capable of producing within a given period of time (Skovsgaard and Vanclay, 2008), and depends mainly upon a combination of climatic and physical environmental variables. In boreal black spruce forests, time-since-last fire and topography are reported to be two of the main factors causing paludification (Fenton et al., 2005; Simard et al., 2009) and, consequently, negatively affect forest productivity.

Many studies have investigated the effect of topography alone (i.e., Bonan and Shugart, 1989; Grant, 2004; Kljun et al., 2006; McKenney and Pedlar, 2003), or its effects in combination with paludification (i.e., Giroux et al., 2001; Hollingsworth et al., 2006; Laamrani et al., 2014a,b; Lavoie et al., 2005, 2007; Simard et al., 2007, 2009), on forest productivity in boreal black spruce forests. To our knowledge, we are not aware of other studies that have examined the spatial scale at which topography and paludification will affect productivity, or which have quantified spatial variation in productivity of black spruce forests at the landscape scale, especially within the Clay Belt. The issue of spatial scale is important for productivity research because some factors are expected to act at local scales, i.e., influencing productivity at sites within metres of one another, while the effect of other factors is not likely to be observed until sites are many hundreds of metres apart. Therefore, knowledge of the spatial scale at which these factors will affect forest productivity is of great importance to forest managers because it would allow them to make better cost-effective management decisions that optimize forest productivity and ensure sustainability of the forest.

Until recently, the availability of accurate topographic information at different spatial scales was a limiting factor for relating these data to forest productivity. Recent advances in remote sensing now permit the generation of appropriate data for determining these relationships at different spatial resolutions (scales). In fact, Light Detection And Ranging (LiDAR) is one of the most effective and reliable active remote sensing technologies that could be used directly or indirectly to assess forest productivity at different spatial scales in boreal forested environments (i.e., Bolton et al., 2013; Laamrani et al., 2014a,b; Magnussen and Wulder, 2012). Unlike previous studies that were conducted over a much more limited spatial extent and used simple topographic variables, such as slope, which were calculated in the field (e.g., Giroux et al., 2001; Simard et al., 2009), the current study has benefited from the application of LiDAR, which provided an opportunity (i) to investigate how forest productivity is related to both local- and landscape-scale topographic features across boreal forest areas, (ii) to derive more complex indices (i.e., topographic wetness and position indices), thereby obtaining information on morphological and wetness conditions, which are presumably linked to both more productive and less productive sites, and (iii) to document the effects of topography and paludification on black spruce forest productivity at the landscape scale, which has been done in only few studies (i.e., Hollingsworth et al., 2006; Laamrani et al., 2014b).

The overall goal of the present study was to link productivity data (the response variable) with organic layer thickness and a set of topographic variables (predictor variables) at different spatial resolutions to improve our understanding of how these variables influence tree growth and productivity within the Clay Belt, a region in the southern portion of the Canadian Hudson Bay–James Bay Lowlands. The specific objectives of this study were (1) to investigate quantitatively the relationships between forest productivity and both organic layer thickness and topography; (2) to assess the effect of various resolutions (scale) on these relationships; (3) to predict forest productivity from soil and topographic data using a regression tree-based model; and (4) to use these relationships to produce landscape-scale maps of productivity.

2. Materials and methods

2.1. Study area

This study was conducted within the western black spruce-feather moss bioclimatic domain (Robitaille and Saucier, 1998). The study area was located in northwestern boreal Quebec (49°30′N, 78°30′W) within the Clay Belt region (Fig. 1A). The topography is generally characterized by flat plains, which were generated by extensive and thick glaciolacustrine clay deposits that were left behind by pro-glacial Lake Ojibway (Veillette, 1994). Elevation ranges between 268 m and 362 m, averaging 304 m above sea level (Fig. 1B). Slope ranges from 0.0 to 34.3%. About 65% of the area has a slope ⩽3.2%, whereas slopes ⩾16.3% represent about 1% of the area.

Three major soil types are found in the study area, Luvisols, Gleysols, and Organic soils (Soil Classification working Group, 1998), which reflect the variable thickness of organic layer (5–150 cm). About three-quarters of the sampled area is overlaid by organic deposits ⩾30 cm thick, lying mostly over clay deposits. Organic soils in the study area have developed over time on flat and gentle slopes, whereas the most common soil types on well-drained clay deposits are Luvisols. The mineral soil beneath the organic layer is variable, ranging in composition from clay to till (Laamrani et al., 2013, 2014b). The underlying bedrock is a complex mixture of Precambrian granitic rock types that occasionally appears at the ground surface and which form scattered gentle hills across the landscape.

The study area is characterized by both open low productivity forest and forested bogs on flat, gentle slopes and productive forests on well-drained soils, where peat-forming mosses accumulate directly over mesic soils. Fig. 2 shows an example of site variability in forest productivity that was present across the area under investigation. Black spruce was the most dominant species, followed by jack pine (*Pinus banksiana* Lamb.) and trembling aspen (*Populus tremuloides* Michx.). Other species such as eastern larch or tamarack (*Larix laricina* [Du Roi] K. Koch), balsam fir (*Abies balsamea* (L.) Miller), and paper or white birch (*Betula papyrifera* Marshall) covered a very small portion of the area (Laamrani et al., 2014a). The understory was composed of *Sphagnum* spp., feather mosses (principally *Pleurozium schreberi* [Brid.] Mitten), and shrubs (mainly dwarf ericaceous species) with variable coverage across the landscape. Fire is the most natural important disturbance in the region (Bergeron et al., 2001).

The climate is characterized by long cold winters (November–April) and short rainy summers. Mean annual temperature for the study area is −0.7 °C, with June, July and August as the warmest months, with a mean temperature of 14.4 °C; and December, January, February and March as the coldest months, with a mean temperature of −15.9 °C. Total annual precipitation is about 906 mm, of which more than one-third falls during the peak growing season, i.e., between June and early September (Environment Canada, 2011; Matagami weather station, about 60 km NE of the study area).

2.2. Sampling design and field data collection

As part of a larger project that dealt with the effects of environmental variables and forest harvesting on paludification and