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Changes in forest structure along a chronosequence in the black spruce boreal forest: Identifying structures to be reproduced through silvicultural practices

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ABSTRACT

In managed boreal forests, partial harvesting has been proposed to promote forest structural complexity and to therefore maintain associated biodiversity. However, there have been few studies identifying forest structures that should be maintained within the forest matrix, and fewer still on changes in these structures during succession. Consequently, there is no tool to identify these different structures in the field or their sequence along natural succession. This study proposes a key that can be used in the field and allows for the identification of different forest diameter structures along a successional sequence in the black spruce boreal forest. The specific objectives of this study were (1) to classify the types of forest structures encountered in natural black spruce boreal forest based on their diameter distribution, and (2) to link this classification to time since last fire and its spatial homogeneity at the stand level. This study shows that the forest stand structure, in black spruce forests, is varied and that this structural variety is mainly controlled by time since last fire. It also shows that the timing of stand structural maturation varies with severity of the last fire and surficial deposit. The identification key suggests that based on tree diameter distribution it is possible to discriminate among young, mature and old forest structures, which could help forest managers select stands to be harvested according to different objectives and hence maintain the variety of black spruce forest structures at the landscape scale.

1. Introduction

During forest management the preservation of ecosystem services provided by forests is an important challenge for the international community (MEA, 2005). In the boreal forest, the use of a short rotation period leads to the rejuvenation of forest age structure and reduction of the proportion of old-growth forest across the landscape (Bergeron et al., 2007; Cyr et al., 2009). In managed boreal forests, maintaining a structural variability comparable to that encountered in natural forests should maintain biodiversity and essential ecological functions (Franklin, 1993; Gauthier et al., 1996). To ensure the preservation of its forests and its socio-economic services, Canada now encourages ecosystem-based forest management, which promotes the diversification of silvicultural practices and the maintenance of forest stands of various structures (Gauthier et al., 2008). In this context, partial harvesting has appeared, over the last fifteen years as an alternative to clearcutting in order to reduce the differences at the stand and landscape scale between natural and managed forests (Franklin et al., 1997; Beese et al., 2003). Partial harvesting is applied with the objective to promote forest continuity and heterogeneity of habitats that can maintain both the structural complexity and biodiversity associated with old-growth forests (Rosenvald and Lohmus, 2008).

However, boreal forest stands are complex systems in which many factors and processes may influence both stand composition and structure over time (Lecomte and Bergeron, 2005; Lecomte et al., 2005; Taylor and Chen, 2011; Puettmann et al., 2012). Nevertheless, as fire is an integral part of the boreal forest dynamics (Payette, 1992; Hunter, 1993; Bergeron et al., 1998), time since last fire (TSF) is generally the most frequently stated factor in the literature to explain changes in both forest structure and composition. From a compositional standpoint, in the boreal forest changes in both forest structure and composition after fire result in the recolonization of the burned matrix by early-successional species pre-adapted to open post-fire conditions (e.g. increased light availability), i.e., trembling aspen (*Populus tremuloides* Michx.),

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white birch (*Betula papyrifera* Marsh.), jack pine (*Pinus banksiana* Lamb.) and black spruce (*Picea mariana* [Mill.] BSP) (Bergeron, 2000). With time, most of these species are gradually replaced by shade-tolerant and more competitive late-successional species such as balsam fir (*Abies balsamea* (L.) Miller) (Larson and Oliver, 1996; Lecomte et al., 2005). While this multispecies succession is much studied, there has been little attention given to monospecific succession.

In the case of the generally monospecific boreal black spruce forest, changes that occur over time are structural rather than compositional. With respect to diameter structure, an unimodal regular diameter structure is often associated with young stands, whereas irregular and complex diameter structures are associated with mature stands (Smith et al., 1997; Boucher et al., 2003). Although this structural complexity has been recognized in the literature (Kuuluvainen et al., 1996; Franklin and Van Pelt, 2004), little attention has been given to the classification of stands with respect to their diameter structure. With the exception of Chaieb et al. (2015) and Moussaoui et al. (2016a) (who studied the structure of post-fire and post-harvest residual black spruce patches in the context of sustainable forest management), and Boucher et al. (2003) (who compared the diameter structure of eastern and western black spruce stands and characterized them into three classes i.e. regular, irregular and inverted J distribution structures), there is no such reference structural classification of black spruce stands permitting their identification.

Nevertheless, it has been proposed that in the Canadian boreal forest multi-cohort management could maintain structural diversity as well as respect the successional development that follows natural disturbances, which have been well described (Bergeron et al., 1999; Fenton et al., 2013). Paludification is a phenomenon that can via the accumulation of a thick organic layer transform a forest stand on mineral soil into a forested peatland (Payette and Rochefort, 2001; Fenton et al., 2009). In paludified black spruce forest, severity or depth of burn of the organic layer of the forest floor has significant consequences for forest structure and productivity (Lecomte et al., 2006a,b; Simard et al., 2007; Lafleur et al., 2016). High-severity fires that consume most of the organic layer promote the establishment of productive stands on mineral soil (Dyrness and Norum, 1983; Greene et al., 2005; Simard et al., 2007). In contrast, low-severity fires that leave the organic layer almost intact, stimulate the development of very thick organic layers that may develop into peatlands (Fenton et al., 2005; Simard et al., 2007). Following a high severity fire, a first structural cohort composed of trees of similar size (creating a closed stand with a regular or even-aged structure) establishes. When trees of the first cohort start to dieback and fall on the ground (gap dynamics according to Larson and Oliver (1996)), small-sized trees growing under the tree cover take over the canopy. This second structural cohort displays a wider stem diameter distribution. Tree mortality within this 2nd cohort leads to a loss of density and further opening of the stand (Bergeron et al., 1999; Fenton et al., 2013). A third cohort of trees originated mainly from layering then dominates the canopy and this cohort tends to show a classic inverse-J distribution (Bergeron and Harvey, 1997). In contrast, following a low severity fire, the residual post-fire thick organic layers (> 40 cm) over mineral soil (Fenton et al., 2005) limits establishment and growth of black spruce regeneration leading to less dense and less productive stands, i.e., stands with an irregular open structure (Lecomte et al., 2009).

It is generally suggested that the use of selection harvest approaches within partial harvesting could reproduce the structural complexity of these different types of structural cohorts and emulate natural gap dynamics typical of old-growth stands (Etheridge and Kayahara, 2013). To date there is no tool to identify these different structures in the field or their sequence along the natural chronosequence. In forest management, the structural issues have always been addressed in generic terms such as total density, basal area, and deadwood volume that give few indications on specific target structures to be reproduced. In this context, the ability of partial harvesting to reproduce forest habitat conditions favorable to maintaining biodiversity and structural complexity remains to be validated. If partial harvesting is to favor the conservation of old-growth forest structures, it is necessary to propose a user-friendly method to identify young, mature and old structures, and which can help forest managers to select stands to be harvested according to different objectives.

This study aims to propose a key to facilitate the identification of different diameter structures along a chronosequence in the boreal black spruce forest. Our objectives are to (1) conduct a classification of stand structural types encountered in natural boreal black spruce forests based on their diameter distribution, and (2) to validate this classification by establishing a link with time since the last fire and verify the spatial homogeneity of the structural classification at the stand level. In order to determine whether the differences among identified structural types were controlled by other explanatory variables, we also considered the influence of soil drainage, the importance of companion species such as white birch and trembling aspen, the presence or absence of balsam fir, and the density of black spruce saplings. Finally, an identification key for these structural types was developed. To achieve this, we used an extensive database of over two thousand forest inventory plots collected by the Quebec Ministry of Natural Resources (QMNR), and for time since fire data was available.

2. Methods

2.1. Forest inventory data and study area

Data were retrieved from the 400-m^2 forest inventory plots established by the QMNR between 1985 and 1997, for which time since last fire data was available from a fire map developed by Bergeron et al. (2004). They used the age of the trees established after the last fire or dating fire scars on surviving trees for fires that occurred prior to 1880 using historical record and aerial photographs (Belleau et al., 2012). In this study, we used 2100 400-m^2 plots of the forest inventory, which are located in the western section of the boreal forest of Quebec (Matagami Lowland), at the border between Quebec and Ontario (Bergeron et al., 2004). The study area (from 78°30′ to 79°30′ W and from 49°00′ to 50°00′ N) belongs to the black spruce-moss bioclimatic domain referred as coniferous region (Robitaille and Saucier, 1998) (Fig. 1).

The study area is dominated by black spruce in addition to companion species such as jack pine, trembling aspen, balsam fir and white birch. The climate is continental with cold winters and warm summers, and according to the nearest weather station (1981–2010), Lebel-Sur-Quévillon, Quebec, mean annual temperature is 1 °C and mean annual precipitation is 928 mm (Environment Canada, 2015). The topography of this area forms an undulating plain. In the northern part of the study area, the surficial deposit was affected during the last glaciation by late southward glacial surges that restructured the glaciolacustrine fine clay deposits; these soils are known as the Cochrane Till (Robitaille and Saucier, 1998). In this region, stand-replacing fires are the main drivers of natural forest dynamic. Since 1920, the fire cycle is estimated at over 400 years and average stand age is over 150 years (Bergeron et al., 2004). Nevertheless, in the last 30 years, the landscape mosaic is as likely to have been shaped by harvest as by fire (Bergeron et al., 1998; Imbeau et al., 2015).

The forest inventory plots were established along transects that generally extended from 500 to 1500 m in length; with each transect usually comprising between four and seven plots. Transect locations were selected using a stratified sampling design that aimed to characterize the different stand structures of the region. In each forest inventory plot, diameter at breast height (DBH) of all commercial stems of all trees (DBH ≥ 9 cm) and saplings (DBH < 9 cm) was measured, identified to species, and average height measured using a clinometer. Surficial deposit was also identified and then grouped into two types: well-drained soil (clay) and poorly drained soil (organic, Cochrane till). In well-drained soil, deposits show generally a moderate drainage where water infiltrates at a medium rate whereas poorly drained soils present a high sensitivity to paludification (Veillette and Thibaudeau, 2007).