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Ecological drivers of post-fire regeneration in a recently managed boreal forest landscape of eastern Canada

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ABSTRACT

Clearcutting practices combined with the predicted increase in fire activity may induce post-fire regeneration failure in boreal forest landscapes. This study aims (1) to evaluate if recently managed landscape by clear cut logging is susceptible to be affected by post-fire regeneration failure; and (2) to explore the ecological drivers of black spruce (*Picea mariana* (Mill.) BSP) post-fire regeneration. In 2014, we surveyed the regeneration of 36 stands in northwestern Quebec that had burned in a major fire in 2005. Fire severity was evaluated for each site with the differenced Normalized Burn Ratio. Using linear models, we explored the relationship between environmental variables (fire severity, pre-fire stand maturity, nature of the seedbed, and physiographic variables) and black spruce post-fire regeneration. Black spruce post-fire seedling density was highly variable (range: 25–16 000 seedlings/ha; mean ± standard deviation: 4549 seedlings/ha ± 4752) within the studied fire, but did not significantly differ between stands that had been logged 50 years prior to fire and those that were mature prior to the 2005 fire. However, post-fire regeneration failure (defined as <40% stocking that corresponds in our study region to a regeneration density <1750 seedlings/ha) was observed in 48% of the stands that had been logged, but only in 29% of the stands that were mature prior to the fire. The presence of residual trees left after clearcutting may explain why regeneration level was relatively good (>50%) in stands affected by past logging activities. Our study illustrates how biological legacies, environmental conditions and fire severity determine post-fire recovery and resilience of black spruce-dominated ecosystems of eastern Canada. By identifying the drivers of post-fire regeneration success, our study will help forest managers allocating resources where restoration of productive forest are truly needed.

1. Introduction

The North American boreal forest is a vast ecosystem where fire is the main driver of natural stand-replacing disturbance dynamics (Payette, 1992; Bergeron, 2000; Kasischke et al., 2010). In eastern Canada and interior Alaska, black spruce (*Picea mariana* (Mill.) BSP) is by far the most abundant tree species. Its regeneration strategy enables the species to cope with relatively frequent fires (Zasada, 1971; Greene et al., 1999). Mature trees possess semi-serotinous cones filled with viable seeds that usually allow an abundant and rapid post-fire regeneration (Zasada, 1971; St-Pierre et al., 1992). Environmental variable reducing the availability of viable seeds, such as shorter intervals between disturbances affecting stand maturity, ecophysiological stress (insect epidemics, droughts) or fire severity, may, however, greatly affect regeneration (Simard and Payette, 2005; Johnstone et al., 2010). The nature of the post-fire seedbed, characterized by the depth of the organic layer, exposure of the mineral soil, and composition of the shrub and muscinal layers, are important drivers for black spruce post-fire regeneration (Cayford, 1965; Greene et al., 1999; Charron and Greene, 2002).

In eastern Canada, successive disturbances may affect the resilience of black spruce-dominated forests (Payette and Delwaide,

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2003; Girard et al., 2008; Côté et al., 2013). When successive disturbances (fire, clearcutting activities and/or insect epidemics) occur within a period too short to allow for an adequate supply of viable seeds (Simard and Payette, 2005; Viglas et al., 2013), regeneration can be impaired, which results in low-density post-fire stands of limited productivity (Lavoie and Sirois, 1998; Girard et al., 2008).

Recently, extreme fire years (2005–2010) have resulted in nearly 1.7×10^6 ha of burned forests in Quebec. This has led to a revision of provincial post-fire regeneration guidelines and the optimization of plantation efforts to minimize the land base occupied by low-density black spruce forests. Therefore, based on previous studies that have underlined that young stands are highly susceptible to post-fire regeneration failure (Girard et al., 2009; Viglas et al., 2013), forest managers in Quebec now schedule planting in nearly all stands that had been harvested less than 50 years prior to fire events in order to prevent regeneration failure and consequent losses of forest productivity. Given the high costs associated with plantation silviculture (seedling production, handling and planting, mechanical site preparation, stand tending), it is imperative to identify the drivers of regeneration success in these ecosystems so that management resources can be dedicated where restoration efforts are truly needed.

The aim of this study was thus (1) to quantify post-fire regeneration failure in stands harvested 50 years prior to fire in order to validate recent reforestation guidelines; and (2) to explore, using linear models, the ecological drivers of post-fire black spruce regeneration using explanatory variables such as pre-fire stand conditions, site conditions and fire severity derived from the remote-sensed differenced Normalized Burn Ratio (dNBR) index. In eastern North America, fire severity assessment and regeneration have already been investigated using a traditional (*in situ*) ground survey approach (Greene et al., 2004; Veilleux-Nolin and Payette, 2012; Boiffin and Munson, 2013). However, no study has yet used the dNBR index to evaluate fire severity in boreal forest ecosystems (but see Boucher et al., 2017a). This situation contrasts with western North America, where this approach has been widely used over the last decade at the local (Key and Benson, 2006; French et al., 2008; Soverel et al., 2010) and subcontinental scales (MTBS project in U.S. [Eidenshink et al., 2007]).

2. Material and methods

2.1. Study area

The studied fire area is located in the boreal zone of eastern Canada, in central Quebec (lat. 49°19′03″N and long. 73°48′24″W; Fig. 1) and belongs to the Chibougamau-Natashquan (B.1b) forest section (Rowe, 1972). According to Quebec's ecological land classification, it is part of the spruce–moss domain and the Nestaocano River hills (6e) ecological region (Blouin and Berger, 2004). The climate is subpolar, subhumid, with a short growing season (2000 growing degree-days), average temperatures ranging from −2.5 to +0.0 °C and annual precipitations of 1000 mm (Robitaille and Saucier, 1998). The landscape is dominated by gentle rolling hills interspersed with flat lowlands and covered by deep till. The most abundant species in the region is black spruce, but balsam fir (*Abies balsamea* (L.) Mill.), jack pine (*Pinus banksiana* Lamb.), paper birch (*Betula papyrifera* Marsh.) and trembling aspen (*Populus tremuloides* Michx.) are also present. The natural stand-replacing disturbance regime is dominated by large fires of varying severity with a return interval of 100–250 years (Mansuy et al., 2010; Bélisle et al., 2011). Spruce budworm epidemics are a typical chronic (30–40 years) disturbance affecting the study region (Jardon et al., 2003). Regional forest landscapes have been intensively managed using clearcutting since the early 20th century, to provision large mills located around the Lake Saint-Jean area (Côté, 1999). It has rejuvenated the landscape age structure over large areas (Cyr et al., 2009; Boucher et al., 2014, 2017b). At the stand scale, clearcutting removes all merchantable trees (diameter at breast height [DBH] [1.3 m] > 9 cm). In this study, we investigated the "Lake Aigremont" fire, which was ignited by lightning on May 31, 2005 and affected a large area (30 328 ha) on public lands, located 75 km south-east of the city of Chibougamau (Fig. 1). The year 2005 was characterized by a very fire-conducive climate that triggered several large fires that burned a total area of 400 000 ha throughout Quebec (Fig. 1). The nearest meteorological station (Chibougamau-Chapais airport), located 50 km north of our study area, shows that post-fire conditions (May 2005 to June 2007) were drier than climate normals (1981–2010) (Environment Canada, 2016; Appendix 1).

2.2. Site selection, sampling design and data acquisition

The lake Aigremont fire was selected because it is representative of several large fires that have affected black spruce-dominated forest in 2005 (Fig. 1) and it is easily accessed by road. Within the fire, we restricted field sampling to areas that showed fire evidences and that had not been subjected to either post-fire salvage logging or mechanical site preparation for planting. We determined the logging and fire history in the study area using management plan archives, aerial photographs (1948, 1959 and 1969) and the last four provincial ecological forest surveys (1970, 1983, 1990 and 2010; MRNFQ, 2008). We identified two types of stands prior to the 2005 fire: (1) stands that had been clearcut in 1955 (n = 29); and (2) unlogged mature stands (>100 years; n = 7). Thus, a total of 36 stands (hereafter referred to as "sites") were selected following a systematic random sampling design over the studied fire.

The severity of the 2005 fire was assessed at the landscape scale using the dNBR index derived from Landsat imagery (Key and Benson, 2006). Images were acquired from the Landsat Thematic Mapper 5 (TM5) with surface reflectance images from the United States Geological Survey (USGS) produced by the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) expert software (Masek et al., 2006). We followed the steps proposed by Boucher et al. (2017a) for image acquisition and preparation, and used the equations proposed by Key and Benson (2006). The initial assessment (IA) compared the pre-fire image acquired on September 19, 2004 with an image acquired just after the fire on July 20, 2005. The extended assessment (EA) compared the same pre-fire image with an image acquired the year after fire on June 21, 2006. We validated the dNBR index values using the relationship between the dNBR index and the Composite Burn Index (CBI) established by Boucher et al. (2017a) for black spruce-dominated forest of eastern Canada. The CBI relies on field sampling to quantify fire severity through its impact on each stratum of the ecosystem: substrate (soil) layer, herbaceous plants, shrubs, understory trees and overstory trees (Key and Benson, 2006).

Field sampling was done from June 15 to August 21, 2014. The sampling plots were located according to the pre-fire abundance of black spruce-dominated stands (>75% of basal area occupied by black spruce) and stratified by the gradient of fire severity. Considering that black spruce establishment is maximized 4 years after fire (St-Pierre et al., 1992; Charron and Greene, 2002) and that seedling mortality is very low after the establishment phase (i.e., the first 10 years after a fire; Charron and Greene, 2002; Johnstone et al., 2004), we assumed that evaluating regeneration 9 years after the fire was a reasonable estimate of seedling density at the end of the establishment mortality phase. At each sampling site, a 400-m^2 circular plot representative of the burned stand was