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

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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.

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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; Kaschke 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,
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 × 10⁶ 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, this study has not yet used the dNBR index to evaluate fire severity in boreal forest ecosystems (but see Boucher et al., 2017a). This study 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. [Eidsenshink 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-Natashquian (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 (P. balsamea), jack pine (P. banksiana Lamb.), paper birch (B. papyrifera Marsh.), and trembling aspen (P. 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-m² circular plot representative of the burned stand was
delimited. Its position (latitude and longitude) was determined using a GPS receiver at the plot centre point. Plot elevation, slope, surficial deposit, drainage, pre-fire stand age, pre-fire stand density, aspect and potential vegetation were assigned using available cartographical variables generated from a digital elevation model (precision: 10 m) in combination with the most recent ecological forest survey data (MRNFQ, 2008). Potential vegetation refers to the late-successional vegetation that would be expected under given environmental constraints (climate, physiography), in the absence of human influence (Grondin et al., 2014). In each 400-m² plot, we recorded the species and the DBH, (in 2-cm classes) of all canopy trees (living or dead) with a DBH > 9 cm to infer the pre-fire density of the burned stand. We also collected a transversal disk at a 30-cm height on 5 canopy burned trees to approximate minimal stand age for each plot prior to fire. Black spruce seedling density and stocking were evaluated using 10 circular subplots (4 m² each) systematically distributed in each 400-m² plot. In addition, the thickness of the residual organic layer (in cm) and
the percent cover of mosses, *Sphagnum*, lichens, herbaceous plants, and ericaceous shrubs were visually estimated in 5 of the subplots in each plot, using 5% classes. Values of the 5 subplots were averaged to obtain a single value per site.

2.3. Data analyses

Basic statistics were calculated using the R software (v.3.3.3; R Development Core Team, 2015). Differences between means were tested using the non-parametric Mann-Whitney test (Zar, 2010). Based on minimal stocking density standards (see Candy, 1951) and expert knowledge, we established an a priori threshold for stand regeneration failure of <40% stocking. Considering the uneven distribution of natural regeneration in our study region, this stocking typically corresponds to <1750 seedlings/ha. We performed all statistical analyses using seedling density.

We used linear regressions calculated with the *lm* function of R to model black spruce post-fire seedling density as a function of explanatory variables. A log transformation was applied to the response variable to meet normality prerequisites. Multicollinearity among explanatory variables was assessed using the variance inflation factor (VIF) function of the car package (v.2.1-4). Given the small sample size and following Hair et al. (2009), we retained only explanatory variables with a VIF < 2 (Dormann et al., 2013). A total of 8 variables (Table 1) were selected from the larger set for modelling, compromising between retaining potentially informative and interpretable variables, while eliminating those that were strongly redundant (i.e., those that showed multicollinearity). Among these 8 variables, we also retained fire severity-initial assessment (FireSevIA) and fire severity-extended assessment (FireSevEA) to evaluate the most efficient assessment of fire severity to model black spruce regeneration. These two variables are highly redundant, but were never used together in a same set of candidate models (see below).

A total of 85 candidate models were built (22 models including FireSevIA, 22 models including FireSevEA, and 41 other models that did not include fire severity variables), based on subsets comprising a maximum of 3 variables to consider our small sample size (Hair et al., 2009). To evaluate model performance, we used the Akaike information criterion (AIC) using the *AICmodavg* package (v1.1-15), which allows the ranking of the candidate models (Burnham and Anderson, 2002). We used model averaging because the AICc weight (AICcwt) of the top-ranking model was <0.95. Average parameter estimates and associated unconditional standard errors and unconditional 90% confidence intervals (Burnham and Anderson, 2002) were calculated from the subset of the top-ranking models for which the sum of AICc weights reached or exceeded 0.95. This subset of models can be viewed as a confidence set on the Kullback-Leibler best model (Burnham and Anderson, 2002).

3. Results

3.1. Post-fire seedling density and mean age of canopy trees

Black spruce seedling density varied greatly among the sampled sites in the studied fire (range: 25–16000 seedlings/ha; mean ± standard deviation: 4549 seedlings/ha ± 4752). Post-fire seedling density did not differ significantly between plots located in stands that had been logged before the 2005 fire and those located in stands that were mature before the fire (Mann-Whitney test: Z = 87; p = 0.236). Using the a priori post-fire regeneration failure threshold, we distinguished stands showing regeneration failure from those that were well regenerated, and formed two groups with significantly different seedling densities (Mann-Whitney test: W = 300; p < 0.001; Fig. 2). Overall, regeneration failure occurred in 44% of the sites (16/36), and the mean post-fire seedling density of these sites was 1391 seedlings/ha ± 1329. In comparison, the 56% of the plots (20/36) that were above the regeneration failure threshold had a mean post-fire regeneration density of 7075 ± 5009 seedlings/ha. Regeneration failure occurred in 48% (14/29) of the stands that had been logged before the 2005 fire, and in 29% (2/7) of the stands that were mature at the time of the fire. Mean age of pre-fire canopy trees in 2005 was relatively high (100 years ± 34) and was significantly greater (W = 87; p = 0.03) in stands that were mature before the fire (131 years ± 39), compared to stands that had been logged (93 years ± 28) (Fig. 3).

3.2. Modelling the relationship between post-fire black spruce seedling density and environmental variables

The 6 top-ranking models (AICc weight of 0.96; Table 2), predicting black spruce seedling density always included *Sphagnum*

![Regeneration level](image-url)  
**Fig. 2.** Box plot of post-fire black spruce seedling density (seedlings/ha) according to regeneration level. Regeneration failure is associated to stands in which black spruce stocking was less than 40% or <1750 seedlings/ha; Candy, 1951; MRNFQ, 2000.)

### Table 1

<table>
<thead>
<tr>
<th>Variable (abbreviation)</th>
<th>Variable type</th>
<th>Mean [range]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire severity-initial assessment (FireSevIA)</td>
<td>Continuous</td>
<td>0.79 [0.24–1.28] (unitless)</td>
</tr>
<tr>
<td>Fire severity-extended assessment (FireSevEA)</td>
<td>Continuous</td>
<td>0.80 [0.27–1.21] (unitless)</td>
</tr>
<tr>
<td><em>Sphagnum</em> cover</td>
<td>Continuous</td>
<td>5.81 [0.00–47.00] (%)</td>
</tr>
<tr>
<td>Residual organic layer thickness (cm) (ROLT)</td>
<td>Continuous</td>
<td>17.67 [6.00–40.00] (cm)</td>
</tr>
<tr>
<td>Mean age of canopy trees prior to fire (cored at 0.30 m from ground level – minimum age; AgeCT)</td>
<td>Continuous</td>
<td>100.00 [39.00–185.00] (years)</td>
</tr>
<tr>
<td>Tree density (DBH &gt; 9 cm) prior to fire (stems/ha) (TreeDens)</td>
<td>Continuous</td>
<td>890 [200–1550] (stems/ha)</td>
</tr>
<tr>
<td>Potential vegetation (PotVeg)</td>
<td>Categorical (2 levels)</td>
<td>BF-BS pv (balsam fir–black spruce forest on rolling topography), BS pv (black spruce-dominated forest on flat lands)</td>
</tr>
<tr>
<td>Drainage (Drainage)</td>
<td>Categorical (3 levels)</td>
<td>Xeric, Subhydric, Mesic</td>
</tr>
</tbody>
</table>
regeneration failure was less frequent than expected in stands that received proper post-fire regeneration of black spruce. Post-fire rainfall was not significant, as the 90% CI of its average coefficient included 0. AgeCT, and Drainage were not significant, as the 90% CI of their average coefficients included 0. This indicates that these 3 predictors were significantly different in AICc (Table 2). FireSevIA was always a better predictor than FireSevEA.

We used the 6 top-ranking models to conducted model averaging to draw inferences about the predictor variables correlated to black spruce regeneration (Table 3). The predictors in these models were Sphagnum, PotVeg, FireSevIA, ROrgMat, TreeDens, AgeCT and drainage as predictor variables. The 90% unconditional confidence interval (CI) of the average coefficients for Sphagnum and PotVeg excluded 0. This indicates that these 3 predictors were significantly correlated with black spruce seedling density. The correlation was positive for Sphagnum ($r = 0.57$) and negative for FireSevIA ($r = -0.42$). Regarding PotVeg, black spruce seedling density was greater ($r = 0.39$) on sites characterized by a BF-BS pv than on sites characterized by BS pv. All other predictors (ROrgMat, TreeDens, AgeCT, and Drainage) were not significant, as the 90% CI of their respective average coefficients included 0.

4. Discussion

The availability of viable seeds prior to fire is a sine qua non condition for effective post-fire regeneration of black spruce. Post-fire regeneration failure was less frequent than expected in stands that had been logged 50 years before the 2005 fire. Viglas et al. (2013) estimated that 50 years is the minimum age at which black spruce produces enough viable seeds to regenerate on a highly favorable post-fire seedbed composed of exposed mineral soil. This minimum age may increase to 150 years on lower-quality seedbeds such as the thick organic layer (Zasada et al., 1992) characterizing the soil of our study sites. Thus, it is unlikely that trees established after the 1955 clearcuts served as seed trees after the fire. More likely, residual mature trees left after the 1955 logging (which represented ~10–15% of the forest cover, according to aerial photographs taken in 1959 and 1969 [see Appendix 1]) contributed to the relatively good post-fire recovery. This hypothesis is supported by the relatively old age (93 years ± 28) recorded for canopy trees in the stands logged prior to the 2005 fire. Tree age at the time of fire could also explain why the proportion of regeneration failure was lower in the stands that were mature at the time of fire, since canopy trees in this group were older than in logged stands.

In similar environments of northern Québec, the timing of past disturbances (for example, spruce budworm epidemics occurring a few years prior to fire) has been shown to reduce regeneration of black spruce through its effect on cone production (Payette et al., 2000; Payette and Delwaide, 2003; Côté et al., 2013). However, the 2005 Aigremont fire occurred more than 25 years after the last outbreak that affected our study region (Jardon et al., 2003). The gap between these two disturbances was probably long enough for black spruce to recover and produce enough viable seeds to induce a much denser regeneration than what was reported by Payette and Delwaide (2003) and Côté et al. (2013) on sites near our study area.

Our modelling approach has evidenced 3 important drivers that explain post-fire black spruce regeneration in the lake Aigremont fire: percent cover of Sphagnum, potential vegetation and fire severity. Over the last decades, many studies have underlined the positive influence that the moist Sphagnum mat can have on black spruce seedling establishment and survival, either in post-fire (Chrosiewicz, 1976; Greene et al., 2004; Lloyd et al., 2007; Veilleux-Nolin and Payette, 2012; Boiffin and Munson, 2013) or post-logging contexts (Cayford, 1965; Brumelis and Carleton, 1988). The water retention capacity of dense Sphagnum mats (Price et al., 1997; McCarter and Price, 2014) is a critical property.

Table 2
Six top-ranking models (AICcwt > 0.95) retained for model averaging among the 85 candidate models to predict black spruce seedling density, as assessed by Akaike’s information criterion corrected for small sample sizes (AICc). Variable abbreviations are defined in Table 1. Number of estimated parameters including the intercept (K), AICc, the difference in AICc (AAICc), and AICc weight (AICcwt) are provided.

<table>
<thead>
<tr>
<th>Model rank</th>
<th>Variables</th>
<th>K</th>
<th>AICc</th>
<th>AAICc</th>
<th>AICcwt</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sphagnum + PotVeg + FireSevIA</td>
<td>5</td>
<td>86.02</td>
<td>0.00</td>
<td>0.38</td>
</tr>
<tr>
<td>2</td>
<td>Sphagnum + PotVeg</td>
<td>4</td>
<td>87.42</td>
<td>1.40</td>
<td>0.19</td>
</tr>
<tr>
<td>3</td>
<td>Sphagnum + PotVeg + ROrgMat</td>
<td>5</td>
<td>87.49</td>
<td>1.48</td>
<td>0.18</td>
</tr>
<tr>
<td>4</td>
<td>Sphagnum + PotVeg + AgeCT</td>
<td>5</td>
<td>88.69</td>
<td>2.68</td>
<td>0.10</td>
</tr>
<tr>
<td>5</td>
<td>Sphagnum + PotVeg + TreeDens</td>
<td>5</td>
<td>89.96</td>
<td>3.94</td>
<td>0.05</td>
</tr>
<tr>
<td>6</td>
<td>Sphagnum + PotVeg + Drainage</td>
<td>6</td>
<td>90.11</td>
<td>4.10</td>
<td>0.05</td>
</tr>
</tbody>
</table>

The 90% confidence intervals of coefficients in bold excluded 0.
of this germination substrate, given the high sensitivity of black spruce to desiccation during its early establishment phase (Greene et al., 2004). Sphagnum should be considered as an important microsite for black spruce establishment and survival, particularly in dry post-fire conditions such as those observed in our study area (9 consecutive months [July 2005 to June 2007; See Appendix 1]). Our study did not include variables describing the physico-chemical characteristics of the soil that could have influenced germination success. Wildfires generally have an immediate, positive effect on soil nutrient availability (the “assart” effect; Kimmins, 1997). Soil macronutrient concentrations then decline with time since fire due to gradual site encroachment by ericaceous species such as Kalmia angustifolia L. (Bloom and Mallik, 2006). Limitations to early germination due to low soil fertility are thus unlikely.

Our results show that severe fires may significantly hinder black spruce regeneration. At the canopy level, severe fires such as those observed in 2005 in Quebec have probably destroyed a significant proportion of the viable seeds contained in aerial seed-banks (Zasada et al., 1979; Lavoie and Sirois, 1998; Veilleux-Nolin and Payette, 2012). This could explain the low regeneration level we measured in the lake Aigremont fire, even in mature stands that would otherwise have been characterized by an abundant bank of viable seeds. However, there is still a need to empirically examine how post-fire seed bank viability is directly affected along a gradient of fire severity. In contrast, several elements suggest that the fire in the study was not severe at the ground level. First, the fire occurred in late May, when the soil in this region has typically just finished thawing and is waterlogged. Second, the thickness of the residual organic layer (mean ± standard deviation: 18 cm ± 9; range: 6–40 cm) compares to that observed in other spring fires investigated in Quebec by Boiffin and Munson (2013; 17 cm ± 8) and Veilleux-Nolin and Payette (2012; 10–23 cm), who also concluded that a thick residual organic layer is characteristic of less severe fires at the ground level.

Surprisingly, although the fire was not considered severe at the ground level and had not exposed the mineral soil or reduced the thickness of the organic matter down to a thin layer (~2 cm), we observed a relatively strong negative relationship \( r = -0.55; \) \( p < 0.001 \) between the post-fire thickness of the residual organic layer and the dNBR index. Our results are in line with those of Key and Benson (2006); they suggest that the dNBR index may be a good estimator of fire severity at the ground level. In North America, very few studies have evaluated the direct influence of dNBR index or other satellite-derived indices on the organic layer reduction (substrate) in black spruce-dominated forests. In Alaska, Allen and Sorbel (2008) found a strong linear relationship \( r = 0.74 \) between dNBR index and substrate severity, whereas Kasischke et al. (2008) found a poor linear relationship \( R^2 = 0.19 \). More research is needed in that field (such as the modulation of the CBI for boreal forest ecosystems) to better estimate fire severity in black-spruce ecosystems using satellite-derived indices. For now, the dNBR index appears promising for the evaluation of the impact of fire severity in that context.

Potential vegetation is an integrative variable that describes vegetation patterns observed in various physical environments and for similar biogeoclimatic units (Grondin et al., 2014). Our results show that black spruce post-fire seedling density was significantly higher in stands characterized by the BF-BS potential vegetation than in those characterized by the BS potential vegetation. Although potential vegetation can hide the influence of other physiographic variables, our results support the hypothesis that contrasting fire regimes may exist between these two types of potential vegetation, since fires are larger, more severe and more frequent in the BS potential vegetation than in the BF-BS potential vegetation (Bergeron et al., 2004). Likewise, the higher occurrence of less-flammable deciduous species such as paper birch or trembling aspen in the BF-BS potential vegetation (where they can occupy up to 25% of the pre-fire stand basal area; Blouin and Berger, 2004) may have mitigated fire severity and facilitated the establishment of a dense post-fire regeneration. More research is needed, however, to isolate the influence of potential vegetation on black spruce post-fire recruitment dynamics.

4.1. Management and research implications

Our work showed that fire severity, residual trees left after logging and vegetation type are key in explaining post-fire recovery of black spruce-dominated forests. The climate-induced increase of fire activity (Bergeron et al., 2010; Flannigan et al., 2013) poses challenges to foresters, especially since clearcutting is a dominant, large-scale ongoing disturbance that has already rejuvenated a large portion of the boreal forest landscape in eastern Canada; (Boucher et al., 2017b). Given their expected increase in frequency, fire disturbance has the potential to reduce the ability of boreal forest ecosystem to maintain ecological and economical services, mainly with regards to dense black spruce stands. Considering the slight impact of fire suppression activities on burned area during extreme fire years, forest managers should instead of allowing more efforts on fire controls, pay attention to (1) ensuring adequate retention of mature trees that are well distributed during clearcutting operations, in order to seed burned stands sufficiently, (2) integrating the use of dNBR index or other remotely sensed indices at an operational scale to monitor fire severity and evaluate its impact on boreal forest ecosystems at the landscape scale, and (3) refining black spruce post-fire regeneration models to identify areas prone to regeneration failure, to optimize planting operations and to maintain long-term forest productivity.

One obvious limitation of our study is that it was conducted over a single fire that burned during the particular conditions of a single year. Thus, research efforts should be dedicated to develop robust models to predict black spruce post-fire regeneration for multiple environmental conditions in Canada. New studies should focus on fires located in landscapes characterized by various stand ages, disturbance histories (insect, fire, and logging), ecophysiological stressors, fire seasons, fire years, and climatic and physiographic gradients that characterize the boreal forest. Nonetheless, our study was designed to explore the major drivers of black spruce regeneration in eastern Canada. Among these determinants, we found that the satellite-based evaluation of fire severity is a promising approach for a better estimation of post-fire black spruce regeneration.

Acknowledgements

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2017.05.026.

