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A landscape-level tool for assessing natural regeneration density of *Picea mariana* and *Pinus banksiana* following fire and salvage logging

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ABSTRACT

We present a landscape-level operational natural regeneration assessment tool, created by linking a validated forest regeneration model with forest inventory maps. Using basal areas obtained from temporary plots and seedbed distributions from field data, seedling densities are simulated for pure *Picea mariana* (Mill.) and *Pinus banksiana* (Lamb.) stands under burned intact, and traditional first winter and delayed salvage scenarios. These stands are grouped by age-class, pre-fire stand cover, surficial deposit, and drainage. Following this classification scheme, simulated seedling densities are transferred onto forest inventory maps for the Lake Matagami lowland ecological region (6a) in the boreal forest of Quebec (used as a case study to illustrate the potential of the tool). The final output of the model is an estimate of seedlings/m^2 following moderate to severe fire, and fire followed by 100% salvage in pure *P. mariana* and *P. banksiana* stands, however it is also capable of simulating partial salvage. Results are expressed as seedlings/ha, and illustrate that in our study area, only 35% of intact *P. mariana* and 6% of intact *P. banksiana* stands need to be planted following fire; however under the traditional 100% first winter salvage scenario, 100% of *P. mariana* and 74% of *P. banksiana* stands necessitate planting. If salvage logging is delayed until the second, third, or fourth winter following fire, planting will be required in 98%, 88%, and 66% of *P. mariana*, and 65%, 56%, and 56% of *P. banksiana* stands respectively. This type of tool allows managers and foresters to quickly assess reforestation needs following fire and salvage at the landscape level, and can be used to better plan the timing and location of salvage operations and subsequent silvicultural treatment application. In addition to being able to schedule operations faster, foresters will also be able to quickly identify regions where natural regeneration could be inadequate or excessive. Potential cost estimates of future interventions such as planting, aerial seeding, and pre-commercial thinning could be made. Foresters can also assess the current vulnerability of management units to fire and can identify regions at particular risk.

1. Introduction

Picea mariana (Mill.) BSP (black spruce) and *Pinus banksiana* (Lamb.) (jack pine) are two common conifer tree species in the boreal forest of North America (Charron and Greene, 2002; De Groot et al., 2004), and also the significant target species of the forest industry. These two species are well adapted to fire; *P. banksiana* is serotinous and *P. mariana* is semi-serotinous. Both possess aerial seedbanks that effectively distribute seeds following this disturbance (Gauthier et al., 1993; Enright et al., 1998; Greene et al., 1999). *P. banksiana* releases approximately 90% of its seeds in the first year following fire whereas *P. mariana* takes up to five years to release the same amount (Greene et al., 2013). Furthermore, smoldering combustion of the organic layer creates seedbeds that are more receptive (Miyanishi, 2001; Miyanishi and Johnson, 2002) to the seeds of these two species.

Fire is the dominant disturbance in the boreal forest of North America, burning approximately 2 million ha of forest in Canada annually between 1959 and 1997 (Stocks et al., 2002). 97% of total area burned is caused by large (>200 ha), high intensity, stand-replacing fires (Amiro et al., 2001; Flannigan et al., 2001; Stocks et al., 2002). The regional and continental-scale fire regime in the

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boreal forest is predominantly controlled by climate (Carcaillet et al., 2001). Fire frequency (Amiro et al., 2001; Flannigan et al., 2001, 2009; Bergeron et al., 2004, 2010; Soja et al., 2007; Wotton et al., 2010), fire season length (Wotton and Flannigan, 1993; Boulanger et al., 2013), and area burned (Flannigan et al., 2005) are expected to increase throughout the boreal forest as the climate warms in the future (IPCC, 2013).

Stand stocking can sometimes be inadequate following fire. Stands can be young when burned and therefore the trees are not mature enough to produce adequate seed (Viglas et al., 2013; Zasada, 1971; Viereck and Johnston, 1990; Gauthier et al., 1993), or pre-fire densities of mature trees can be low; conversely some fires can be so severe that they kill the seeds in the aerial seedbank (Pinno et al., 2013) regardless of pre-fire stand density or age. However, in terms of species composition there are usually no dramatic post-fire changes (Greene and Johnson, 1999; Ilisson and Chen, 2009; Boucher et al., 2014). Natural regeneration density, and by extension stand stocking, can be reduced even further by salvage operations due to the removal of the aerial seedbank (Greene et al., 2006, 2013; Splawinski et al., 2014), and seed mortality within remaining slash piles. It has an especially deleterious effect on *P. mariana* due to its extended abscission (seed release) schedule (Splawinski et al., 2014).

Salvage is typically applied within the first winter following fire to minimize degradation of burnt boles due to wood-boring insects, stain fungi, wood-decay fungi, and checking (cracking/splitting of wood due to wind, freezing, irregular drying, etc.) (St-Germain and Greene, 2009), due to easier accessibility to stands that are located far from an established road network, and less damage to the ground due to freezing and snow accumulation (O'Mahony et al., 2000). These stands can be regenerated artificially through planting (Saint-Germain and Greene, 2009) or, if access is restricted, through aerial seeding, however treatment application is costly. Conversely, when regeneration densities are excessive, pre-commercial thinning can be employed to control stand density, thereby maximizing growth and yield of residual trees and minimizing rotation period (Vassov and Baker, 1988).

Due to limited understanding of post-salvage regeneration processes, managers and foresters currently lack the tools needed to assess reforestation needs following fire and salvage at the landscape level. We know of only two other spatial models that examine regeneration following fire in the boreal forest. The first, Valeria et al. (2011) is conceptual in nature, does not include salvage logging, and model projections are expressed as: good, average, low natural regeneration or not predicted. It qualitatively estimates the capacity of the expected regeneration in boreal forests following fires based on the scientific literature and research conducted by the Natural Sciences and Engineering Research Council of Canada (NSERC) – Université du Québec en Abitibi-Témiscamingue (UQAT) – Université du Québecà Montréal (UQAM) Industrial Chair in Sustainable Forest Management (SFM Chair) and the Canadian Forest Service (CFS) over fifteen years. The second, the Canadian fire effects model (CanFIRE) is based primarily on fire behavior, and simulates stand-level physical and ecological effects of fire (de Groot, 2012). It also does not include a salvage-logging component, and natural regeneration is calculated as a function of pre-fire stand density and age, and fire severity, and not seed production. Conversely, existing empirical stand-level models and tools (ex. Splawinski et al., 2014, 2015) although important, are limited to the local scale, and thus prove impractical when the goal is to quickly assess regeneration needs over large burned areas. Indeed, the stand-level tool presented by Splawinski et al. (2015) requires some fieldwork in order to estimate regeneration density.

The development of landscape-level assessment tools that can be used remotely to project regeneration density following fire and salvage is undoubtedly necessary. Such tools will improve the planning and execution of salvage operations both spatially and temporally, and subsequent silvicultural treatment application through the identification of regions and individual stands where natural regeneration density will be inadequate or excessive. Foresters can then estimate the potential cost of future interventions such as mechanical site preparation, planting, aerial seeding, and pre-commercial thinning. They can also assess the vulnerability of management units to the current fire regime, and can identify regions at particular risk.

The primary goal of this study is to illustrate how a tool that can project natural regeneration density can be used to define whether artificial regeneration will be required following a fire, and to help in assessing optimal salvage location and timing in order to increase regeneration success. This will be accomplished by using the Lake Matagami lowland ecological region (6a) in the boreal forest of Quebec as a case study. The objectives are therefore fourfold: (1) to outline how provincial forest datasets can be used to determine the parameters required by Splawinski et al. (2014) natural regeneration model, (2) to use the model along with Quebec forest inventory maps and temporary plots to simulate natural regeneration densities in pure *P. mariana* and *P. banksiana* stands following moderate to severe fire and salvage logging (traditional first winter salvage and delayed salvage) at the landscape-level (here we use Lake Matagami lowland ecological region (6a) in the boreal forest of Quebec as a case study); (3) develop recommendations on silvicultural practices based on simulated seedling densities; and (4) transfer simulated results onto GIS forest inventory maps.

2. Methodology

2.1. Case study area

The Quebec Ministry of Forests, Wildlife and Parks (formerly the Ministry of Natural Resources) employs a hierarchical ecological classification system that sub-divides territories based on ecological factors from the continental to local scale. The Lake Matagami lowland ecological region (6a) is located in the western part of the managed continuous boreal forest of Quebec, and represents part of the western portion of the spruce–moss bioclimatic domain (Fig. 1) (Blouin and Berger, 2005; Bergeron et al., 1998). It covers an area of 48,231 km^2, and is dominated by *P. mariana*, *P. banksiana*, and balsam fir (*Abies balsamea* (L.) Mill.) forest, interlaced with bogs, rivers, and lakes (Blouin and Berger, 2005; Bergeron et al., 1998). The regional climate of the western portion of the spruce–moss bioclimatic domain is sub-polar sub-humid continental, with approximately 825 mm of total precipitation per year; the growing season lasts four to five months and average annual temperature ranges from 0 to −2.5 °C (Blouin and Berger, 2005; Bergeron et al., 1998). The landscape of ecological region 6a is dominated by glaciolacustrine clays and sands, Cochrane tills, glacial tills, and organic surficial deposits; underlain by crystalline rock of granitic and volcanic origin (Blouin and Berger, 2005; Bergeron et al., 1998). Our study area makes up 43,572 km^2 or 90% of ecological region (6a). Forest inventory data in the remaining area was not available for simulation.

2.2. Simulation model

The regeneration model developed by Splawinski et al. (2014) simulates natural regeneration densities (seedlings/m^2) of *P. mariana* and *P. banksiana*, following fire and salvage at the stand level in the first 6 years following fire, here defined as the establishment phase. Data from provincial forest inventories and the field will be used to define model parameters. Simulated seedling