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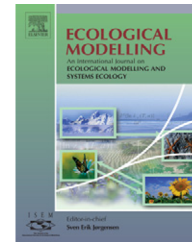

Simulations of the effects of changes in mean fire return intervals on balsam fir abundance, and implications for spruce budworm outbreaks

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ABSTRACT

In boreal forests of eastern Canada, the end of the little ice age (ca. 1850) coincided with a lengthening of mean fire return intervals, which has been hypothesized to increase the abundance of late-successional forests dominated by balsam fir. This increase could have generated unusually severe eastern spruce budworm (*Choristoneura fumiferana*) outbreaks from 1910 onward. The aim of this paper is to simulate the effect of various changes of fire return intervals on regional-scale balsam fir abundance, and to examine potential effect on spruce budworm outbreaks. We developed a regional-scale succession model based on empirical information on fire return intervals, fire sizes (using a reverse Weibull function) and post-fire successional trends (using a logistic growth function), based on an extensive dataset collected in a 65,000 km^2 section of the boreal forest located in eastern Quebec. The simulations indicate that lenghtening the fire return intervals from 300 to 500 years, or from 100 to 300 years, can increase mean balsam fir basal area by 1.3–5.7 m^2/ha at the regional scale, or increase the proportion of stands dominated by balsam fir by 3.5% to 25%. However this increase takes place very gradually, corresponding with the time needed for the forest age-class structure to reach a new equilibrium following the change in fire rate. Overall, we estimate that it is unlikely that an increase in balsam fir abundance following a change in fire return intervals around 1850 was sufficient to explain the change in outbreak patterns observed in the early 20th century.

1. Introduction

Even if fire is one of the main natural disturbances in the boreal zone, its importance varies regionally and temporally, mainly due to climatic factors. Spatially for example, the eastern part of the North-American boreal forest has lower mean fire return intervals (MFRIs) due to different meteorological patterns (Johnson, 1992). Temporally, the period 1750–1850 (little ice age) has been associated with higher fire frequencies due to dryer conditions throughout North-America (Johnson et al., 1998; Bergeron et al., 2006).

In eastern Canadian boreal forests, fires generally promote the establishment of stands initially dominated by pioneer species such as black spruce (Picea mariana), pines (*Pinus* spp.), and relatively shade-intolerant hardwoods (*Populus* spp., *Betula* spp.). In general, these species are gradually replaced by balsam fir (*Abies balsamea*)/black spruce mixtures during post-fire succession (Bergeron, 2000; Lesieur et al., 2002; Bouchard et al., 2008). Other than time since fire, the degree of replacement by late-successional species will also be influenced by other factors such as site characteristics (Gauthier et al., 1996; Messaoud et al., 2007) and

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post-fire legacies (Asselin et al., 2001), but nonetheless, at the regional scale, regions with longer MFRIs are generally associated with a higher abundance of balsam fir, and regions with shorter intervals with a higher abundance of pioneer species. Temporal changes in forest composition can also be observed following a change in MFRIs. These changes will take place gradually over several decades, which has been demonstrated both by paleoecological reconstructions (Carcaillet et al., 2001) and landscape modeling (Starfield and Chapin, 1996; He and Mladenoff, 1999). This delay occurs because climate change is rarely instantaneous (Starfield and Chapin, 1996), and also because the forest age-class structure needs a certain time to reach a new equilibrium after the change in fire rates (He and Mladenoff, 1999; Yemshanov and Perera, 2002).

The abundance of late-successional stands dominated by balsam fir in the forest mosaic will in turn have an influence upon important ecosystem processes such as spruce budworm (SBW) outbreaks, one of the most destructive forest insects in North-America, which tends to have a major impact in balsam fir-dominated landscapes (MacLean, 2004). Even though balsam fir is not the only host species of the SBW, it is the species which is most likely to die during an outbreak (Erdle and MacLean, 1999), and the devastating SBW outbreaks that have been reported in eastern Canada essentially took place in balsam fir-dominated stands and landscapes (Blais, 1983; Morin, 1994; Bergeron and Leduc, 1998; MacLean, 2004; Bouchard et al., 2006; Morin et al., 2007). Therefore, a change in MFRI is expected to have an impact not only on the regional balsam fir abundance, but also on SBW outbreak impacts (Bergeron and Leduc, 1998). This hypothesis has gained particular support among SBW researchers working in the eastern Canadian boreal forest, where it was postulated that a lengthening of the fire cycle following the end of the little ice age (around 1850), increased balsam fir abundance and generated particularly severe SBW outbreaks from 1910 onward (Bergeron and Leduc, 1998; Jardon et al., 2003; Bouchard et al., 2006; Simard et al., 2006).

The aim of this study is to simulate the effect of a change in MFRIs on regional-scale balsam fir abundance. Specifically, we examine whether the 60 years period between the change in fire return intervals following the end of the little ice age (ca. 1850) and the documented change in outbreak pattern (ca. 1910) was long enough to convert the regional-scale forest composition. If not, this suggests that the change in outbreak pattern observed from 1910 may be due to other causes. Hence, even if Sections 2 and 3 of this study deal exclusively with post-fire succession modelling, the main objective of the study is to use this information to help interpret past changes in population dynamics of the SBW.

2. Ecological processes and model structure

Empirical data for this study come from studies of fire return intervals and post-fire succession carried in eastern Quebec, and detailed in Bouchard et al. (2008) (Fig. 1). The dataset consists of a fire map constructed for the 1800–2000 period, and of 3204 forest inventory plots that were established by the provincial Ministry of Natural Resources during the 1970–2000 period. Information on MFRI were derived from the forest map, whereas information on forest succession were obtained by attributing TSFs to individual plots based on the map (Bouchard et al., 2008). So as to reflect natural forest dynamics, plots located on areas affected by forest management were removed from the dataset. A study was conducted specifically on the effect of past SBW outbreaks, which were very minor in this region compared with most other eastern boreal forests (Bouchard and Pothier, submitted for publication). The dataset thus represents a nice opportunity to study a relatively budworm-free forest dynamics (Bouchard et al., 2008).

The present study consists of (1) a fire sub-model based on a map of severe stand-replacing fires that occurred in the reference area during the 1800–2000 period, (2) a balsam fir abundance sub-model based on data from the same reference area, and (3) an integration of these two sub-models in simulation experiments. The simulations were conducted on a fictive landscape of 120×120 cells, each cell representing an area of $4\,km^2$, for a total of $57{,}600\,km^2$. The cell size (grain) was determined based on the objectives of the study (i.e. a regional-scale assessment) and on available calibration data for the forest composition sub-model, which consists in forest inventory transects of length ranging between 1 and 2 km (refer to Section 2.2.1 for more details). The model was developed within SELES (Fall and Fall, 2001), a raster-based simulation environment. It is noteworthy that even if we use SELES to facilitate future implementation of the model in a spatially explicit context (c.f. Fall et al., 2004; James et al., 2007), the present version of the model is aspatial.

2.1. *Fire sub-model*

2.1.1. *Mean fire return intervals*

The mean fire return interval, expressed in years, represents the time needed for fires to burn an area equal to the size of the study area, which is considered in the context of this study as being equivalent to the concept of fire cycle (Van Wagner et al., 2006). The MFRIs calculated for the reference area vary between 250 and about 600 years (Bouchard et al., 2008). MFRIs of 300 and 500 years were simulated in the present study, and we added a 100 years MFRI, which is outside of the contemporary range of natural variability for the whole reference area, but may have been closer to the conditions prevailing during the little ice age in parts of the reference area (Cyr et al., 2007). The observed return interval was calculated for each simulation as the total area of the study area (in km^2) divided by the mean annual area burned (km^2/year).

2.1.2. *Fire size*

The spatial extent of each fire event was determined by adjusting a reverse Weibull function to the observed fire size distribution for the reference area. We used the reverse Weibull because the negative exponential distribution, which is often used to model fire size distributions (c.f. Cumming, 2001; Fall et al., 2004; Belleau et al., 2007), was not sufficient to describe the observed pattern, and a more flexible model was required. The cumulative density function of a reverse Weibull