Forest Ecology and Management 347 (2015) 30–39

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Lengthening the historical records of fire history over large areas of boreal forest in eastern Canada using empirical relationships

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ARTICLE INFO

Article history:
Received 18 December 2014
Received in revised form 2 March 2015
Accepted 5 March 2015
Available online 23 March 2015

Keywords:
Boreal forest
Fire history
Time since last fire
Succession
Decadal burn rate
Random forests

ABSTRACT

Fire plays an important role for boreal forest succession, and time since last fire (TSLF) is therefore seen as a useful covariate to devise forest management strategies, but TSLF information is currently either spatially or temporarily limited. We therefore developed a TSLF map for an extensive region in eastern Canada (217,000 km^2) by generalizing the empirical relationships that exist between regional historical records of fire (1880–2000) with forest inventory data and biophysical variables. Two random forest models were used to predict TSLF at the scale of 2-km^2 cells. These cells were first classified into TSLF $\leqslant$ 120 years and >120 years and TSLF was then estimated by decade for cells classified as younger than 120 years. Overall, both models showed a substantial agreement at the scale of both the study area and landscape units, but the accuracy remained fairly low at the scale of individual cells. Results show that the decades between 1920 and 1940 were characterized by widespread fire activity covering approximately 28% of the study region. Studies have reported a doubling of the burn rate from 1970 to 2000, but our longer-term analysis suggests that the 1970–2000 burn rate (4.3% $decade^{-1}$) is lower than the one detected between 1920 and 1940 (16.4% $decade^{-1}$) and provides a relevant context for interpreting the recent increases in area burned observed since 1970. These results highlight the importance of lengthening the historical records of fire history maps in order to provide a better perspective of the actual changes of fire regime.

1. Introduction

Boreal forests play a significant role in the global carbon budget (32% of global forest carbon stocks, Pan et al., 2011). In Canada, disturbances such as fire, insect outbreaks and logging influence the overall stability of the boreal forest carbon sink, but stand-replacing fires remain a key driver of carbon dynamics of the boreal forest (Wooster and Zhang, 2004; Stinson et al., 2011). It directly influences the age structure and vegetation mosaic of the landscape (Weber and Stocks, 1998) while its stochasticity in space and time (Morgan et al., 2001; McKinley et al., 2011) creates heterogeneous and complex landscapes (He and Mladenoff, 1999). Time since last fire (TSLF) is thus a primary determinant of the accumulation of stand biomass and soil organic carbon (Simard et al., 2007; Raymond and McKenzie, 2012), and is related to the abundance and diversity of animal and plant communities (Azeria et al., 2009; Bergeron and Fenton, 2012). Furthermore, TSLF can be used to characterize forest age structure when the mean lifetime of the dominant tree species is shorter than the fire return interval (Garet et al., 2012). Forest age structure is used as an indicator of economic, social and ecological sustainability (Didion et al., 2007; Cyr et al., 2009; Bouchard and Garet, 2014) and forest management strategies fundamentally manipulate the age structure to optimize trade-offs between timber supply, habitat and recreation values (Bettinger et al., 2009). Past fire activity has therefore a significant impact on how forest management and conservation plans are dimensioned to enhance sustainability.

However, forest managers usually have access to detailed archives of fires only for the last few decades, a constraint that limits their capacity to set management targets based on natural variability in forest ecosystem processes. Longer historical records help better define the range of natural variability of fire regime and thus of forest age structures (Cyr et al., 2009; Bergeron et al., 2010).

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http://dx.doi.org/10.1016/j.foreco.2015.03.011
0378-1127/

Knowledge of TSLF over a large spatial extent is therefore seen as useful for the planning of timber production and the conservation of biodiversity, as both types of activities require a good understanding of natural disturbances (Nalle et al., 2004; Bergeron et al., 2004a; Hauer et al., 2010; Savage et al., 2013; Börger and Nudds, 2014).

TSLF information can be acquired through direct measurements of burned areas from aerial photographs or satellite images, or through indirect methods in which fire history is reconstructed from dendroecological information (Frelich and Reich, 1995; Heyerdahl et al., 2001). All such methods are spatially or temporally limited. For instance, archived databases of area burned (Kasischke et al., 2002; Stocks et al., 2003) provide direct information over large areas but only for the past few decades. In contrast, tree or charcoal sampling and dating provide TSLF over century-level time scales but only cover limited spatial extents (Cyr et al., 2010).

Vegetation composition, cover density and stand structure of a specific forest area are known to be related to its TSLF. Across the North American boreal forest, the mean time since the last fire (MTSLF) exceeds 500 years (Bouchard et al., 2008) in the east and shortens to 100–150 years further west (Johnstone et al., 2010). This pattern creates an east–west gradient in within-stand age structure from uneven-aged to even-aged (Cumming et al., 2000; Bergeron et al., 2004a). In boreal forests, a shorter MTSLF promotes the dominance of fire-adapted jack pine (*Pinus banksiana* Lamb) or trembling aspen (*Populus tremuloides* Michaux) (Weir et al., 2000; De Groot et al., 2003), while a longer MTSLF promotes the dominance by black spruce (*Picea mariana* (Mill.) B.S.P.) and, in extremely long MTSLF, fire-averse balsam fir (*Abies balsamea* (L.) Mill.) (Bouchard et al., 2008). Forest composition and structure are available from regular forest properties mapping over large areas and could be used as an indirect method to enhance the current spatial coverage of TSLF information.

The objective of this study was therefore to estimate TSLF for a 217,000 km^2 region of black spruce dominated boreal forest in eastern Canada through the integration of multiple sources of direct and indirect information. The specific objectives of this study were (1) to develop a TSLF map at a regional scale through the generalization of the empirical relationship existing between historical fire records with forest inventory and climate data, (2) to determine the accuracy and the temporal variation of the decadal burn rate from derived TSLF map, and (3) to identify how the burn rate estimated for the 20th century at the landscape scale with the TSLF map is related to present vegetation composition. To this effect, we first trained random forest models over specific areas of our study area with known TSLFs. Vegetation, geomorphological characteristics, and climate data were used as input data. We used bootstrap replications to build confidence intervals for the TSLF estimates, which were then extrapolated to the entire study area. Finally, MTSLF values were computed with survival analyses at the scale of landscape units (~100–3000 km^2) from the resulting TSLF map to visualize how they were related to the existing vegetation composition.

2. Methods

2.1. Study area

The study area is located in the eastern boreal forest of Canada (Fig. 1) and extends approximately from 49°N to 52°N and 66°W to 79°30′W corresponding to the portion of the black spruce – feather moss bioclimatic domain actually allocated to forest management and commercial harvest in the province of Québec (Robitaille and Saucier, 1996). The total extent of the study area is 217,000 km^2. This area is particularly rich in fire history maps (Fig. 1) and thus serving as a useful training area for testing the applicability of our methodology. The mean annual temperature for the study area varies from 0 °C to −2.5 °C (Bergeron et al., 2004b). Mean annual precipitation increases from 800 in the west to 1200 mm $year^{-1}$ in the east (Grondin et al., 2007).

Largely underlain by the Precambrian rocks of the Canadian Shield, the study area varies from organic deposits and a flat topography of the Clay Belt in the west, near James Bay (Cyr et al.,

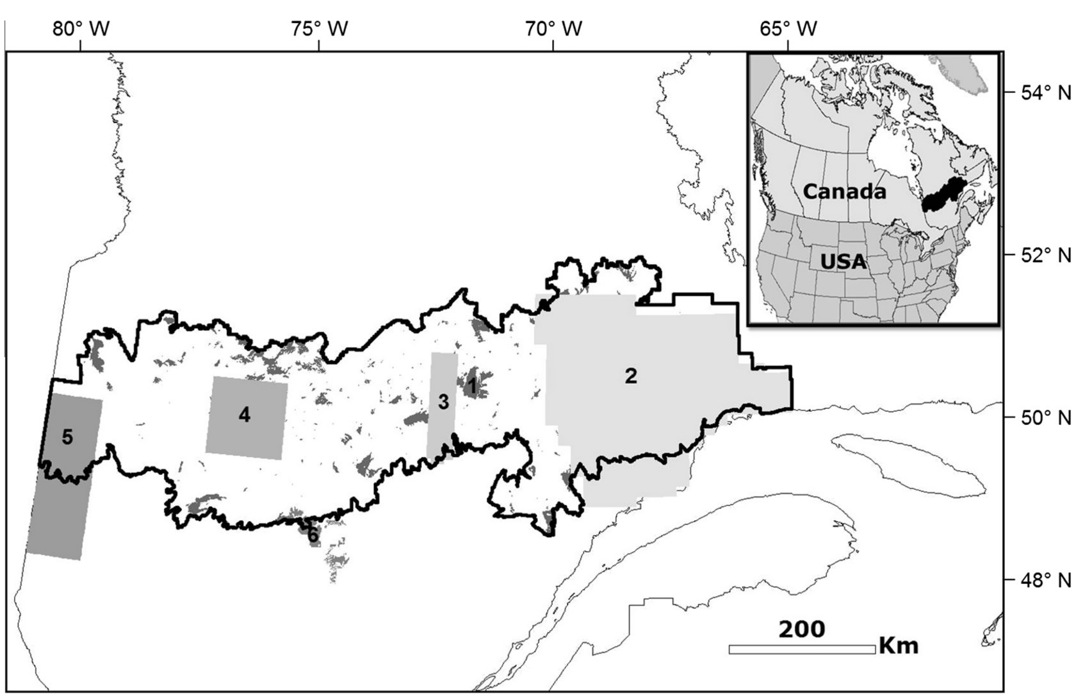

Fig. 1. Location of study area (outlined in dark black) and fire history maps (numbered grayed areas, refer to Table 2). Inventory plots used for the training of the TSLF models are not shown.