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

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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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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 ($\sim$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.,

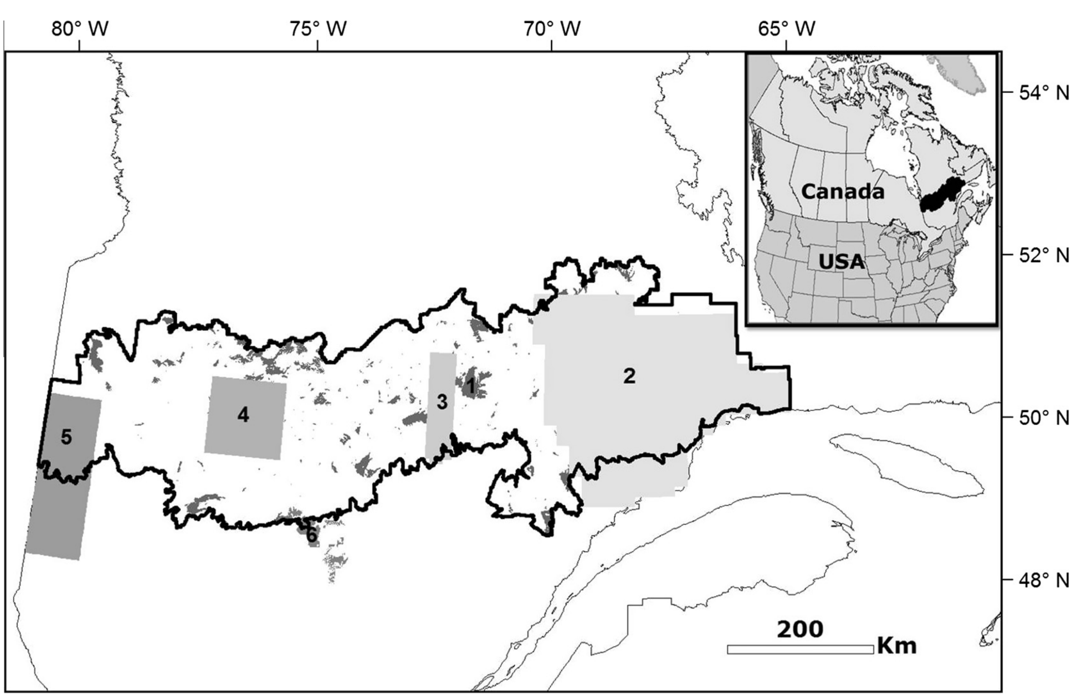


Fig. 1. Location of study area (outlined in dark black) and fire history maps (numbered grayed areas, refer to Table 2). Inventory plots used for the training of the TSLF models are not shown.

2010), to moderately hilly landscapes overlain by glacial–fluvial deposits and tills in the rest of the area. The central region has moderate elevation (339–535 m) with surficial deposits dominated by mesic glacial tills (Bélisle et al., 2011). The eastern section is characterized by till and rock deposits on a hilly to high hilled landscape (Bouchard et al., 2008).

The dominant forest types found in the study area vary along the precipitation gradient. Although black spruce stays dominant throughout the area, it shares its dominance with jack pine in the west, and with fire–averse balsam fir in the wetter east. Fire is the dominant disturbance across the study area, but its impact decreases in the wetter east. Spruce budworm (*Choristoneura fumiferana* Clemens) is a major periodic disturbance in the eastern half of the study area, especially in balsam fir dominated stands (Bouchard and Pothier, 2011).

2.2. Characterization of study units

For modeling purposes we partitioned the landscape into a square grid of 2 km^2 cells (cells of about 1414 m × 1414 m, and total of 108,477 cells). For ease of comparison with other studies and to increase our chances of past fire detection (Héon et al., 2014), we focused on the large fires (>200 ha) that accounted for 97% of the area burned between 1960 and 2000 in Canada (Stocks et al., 2003). Our grid corresponds to the minimum fire size of the Canadian Large Fire Database (200 ha), which provides the burned area in Canada from 1959 to 1999.

These 2-km^2 cells were characterized across the study area with a geospatial database based on forest maps produced by the Quebec Ministry of Natural Resources for its third inventory program (1992–2002), and climatic variables derived from the NCEP–NCAR Twentieth Century Reanalysis (20CR) project (Compo et al., 2011). The "Spatial information on Forest Composition based on Tessera" geospatial database – (SIFORT, Pelletier et al., 2007) is based on forest maps derived from the photointerpretation of false color infrared photos on a 1/15,000 scale, for the years 1990–1999. The map is divided into square tiles of 15 s in longitude by 15 s in latitude, each covering a mean area of approximately 14 ha. This database provides information for each grid centroid on stand composition, age, height, cover density, surficial deposit and drainage. Surficial deposits and drainage classes were combined into seven groups defined by their rock fraction and texture and linked to the drying potential of the surficial deposits (Mansuy et al., 2010).

Meteorological stations are very sparse throughout the study region. We therefore used 1971–2000 daily minimum and maximum temperatures and precipitation obtained from the 20CR project. This climate dataset has a 2° × 2° spatial resolution and was specifically chosen because of its demonstrated link to tree growth in the eastern Canadian boreal forest (Girardin et al., 2012). Climatic variables (Table 1) were selected because of their demonstrated links to the fire regime (Le Goff et al., 2009; Mansuy et al., 2012) and downscaled with the BioSIM model (Régnière and St-Amant, 2008; Régnière, 2009). Altitude values, required to perform spatial interpolation with BioSIM, were obtained from the Shuttle Radar Topographic Mission Digital Elevation Model with 90 m resolution (van Zyl, 2001).

We aggregated the SIFORT geodatabase to our grid, with an average of 14 SIFORT tile centroids per 2-km^2 cell. Within each cell, the relative frequencies of species groups, age, height, cover density classes and surficial deposit groups were estimated with the SIFORT geodatabase and used as explanatory variables to estimate TSLF (Table 1). We removed cells for which more than 50% of the SIFORT tessera centroids were classified as water (7694 cells, 7.1% of total), wetlands and peatlands (8423 cells, 7.8% of total), heaths (4700, 4.3% of total), harvested land (9339 cells, 8.6% of total), insects-killed stands or wind throws (118 cells), and human infrastructure (38 cells), leaving 78,136 cells for analysis (henceforth referred to as the study dataset, corresponding to 72% of the total cell dataset and 89% of the forest area).

Table 1
List of explanatory variables considered for the training of the random forest models.

Variables	Description
Relative frequencies of vegetation attributes([a])	
Species composition groups	⩾75% stand cover = pure, <75% = mixed. Classified into black spruce (Pma), balsam fir (Aba), jack pine (Pba), intolerant hardwoods (Iha – aspen or birch), mixed (Mix), other conifers (Oco – conifers other than black spruce, balsam fir and jack pine) and no species composition but identified as a burned area (Brn), following Gauthier et al. (2010)
Stand age classes	0–20 years (age 0–20), 21–40 (age 21–40), 41–60 (age 41–60), 61–80 (age 61–80), 81–100 (age 81–100), ⩾ 101 (age ⩾ 101), young uneven-aged (Yua) and old uneven-aged (Oua)
Stand height classes	>22 m (height > 22), 17–22 m (height 17–22), 12–17 m (height 12–17), 7–12 m (height 7–12), 4–7 m (height 4–7), 2–4 m (height 2–4) and 0–2 m (height 0–2)
Stand cover density classes	The percentage of stands with density greater than 81% (cover > 81%), 61–80% (cover 61–80%), 41–60% (cover 41–60%) and 25–40% (cover 25–40%)
Physical variables	
Relative frequencies of surficial deposit groups ([a])	Based on a combination of soil stoniness and texture, linked to the drying potential of the surficial deposits (Mansuy et al., 2010): VAVC (very abundant, very coarse), MM (moderate, moderate), MAM (moderately abundant, moderate), MAC (moderately abundant, coarse), AC (abundant, coarse), ROC (rock) and ORG (organic) (Mansuy et al., 2010)
Elevation	The elevation for the centroid of 2 km^2 cells from SRTM DEM (90 m resolution) (van Zyl, 2001)
Slope	The slope for the centroid of 2 km^2 cells derived from elevation in ArcGIS 10.0 from the SRTM DEM
Climate	Derived from the 20CR project (Compo et al., 2011) and BioSIM
Temperature	The annual mean temperature (°C) for the period of 1971–2000
Total precipitation	The mean of annual total precipitation (mm $year^{-1}$) for the period of 1971–2000
Degree-days	The annual degree-days (above 5 °C) for the period of 1971–2000 (°C $year^{-1}$)
Growing season	The mean length of growing season (days for which the mean temperature is above 5 °C) for the period of 1971–2000 (days $year^{-1}$)
Potential evapotranspiration	The mean annual total Thornwaite's potential evapotranspiration (PET) (mm) for the period of 1971–2000 (Dunne and Leopold, 1978)
Aridity index	The mean annual aridity index for the period of 1971–2000 (mm), corresponding to the annual sum of the differences between monthly Thornthwaite's potential evapotranspiration and monthly precipitation
Drought code	Fire weather index corresponding to moisture content of the deep layer of compacted organic matter, 10–20 cm deep (Amiro et al., 2005)

[a] Derived from the SIFORT geospatial database.

2.3. Modeling TSLF

In our study region, the 200-year mean longevity of black spruce, the dominant tree species, is shorter than the reported >500-year mean fire return interval (Bouchard et al., 2008). In the absence of fire, black spruce trees die asynchronously, thereby generating complex uneven-aged structures of near-constant mean canopy age while TSLF increases. In such cases, mean canopy age underestimates TSLF (Garet et al., 2012). We therefore based our prediction of TSLF (large spatial scale) on the relative proportions of tree species, of tree age classes, of cover densities and of heights, and on values of specific climatic variables.

We trained our TSLF model using detailed information on TSLF available for parts of the study area either from fire history maps (Fig. 1, Table 2) or from forest inventory plots. Cells covered 50% or more by a known fire polygon were attributed the TSLF value of that fire, yielding an initial training dataset of 23,289 cells, or 29.8% of the studied dataset (Table 2). We discarded 9552 cells that were covered 50% or more by fires in the 1970–2000 fire maps produced operationally by the SOPFEU (the Quebec forest fire control agency, Société de protection des forêts contre le feu) (Table 2, Boulanger et al., 2013), since there was no need to model TSLF for that well-documented period. We did not consider fires that burned after 2000 because the SIFORT database provides updated data on forest vegetation up to 2000.

Inventory plots of the Quebec Ministry of Natural Resources' third inventory program ($n = 6415$ plots) were also used to generate additional training information for our TSLF model. According to the two plot-level rules set by Bélisle et al. (2011), tree age and TSLF are equivalent 1 – if the plot is dominated by post-fire species (white birch, trembling aspen, jack pine, black spruce), and 2 – if the plot is even-aged, that is with no more than 20 years of age difference among the cored dominant trees. The TSLF of cells with more than one admissible plot was set as the mean age of cored trees within the oldest plot. This procedure enabled us to assign TSLF to 2218 additional cells (2.8%), for a total of 25,507 cells with a known TSLF (32.6% of the studied dataset).

Modeling TSLF involved the successive application of two separate models in which climatic variables and forest attributes were used as explanatory variables (Table 1). Since our TSLF modeling relies on forest succession, climatic variables were expected to influence its dynamics. Also, two models were needed because of the censored nature of TSLF data (e.g. Johnson and Gutsell, 1994), since although all forests have burned at some point in the past, there is a cut-off value beyond which TSLF cannot be evaluated. The first model was thus used to determine that TSLF cut-off value beyond which TSLF estimates acquired a greater uncertainty. Model uncertainty was rated using the improvement of the overall classification accuracy of burned/unburned cells (TSLF $\leqslant$ or > a cut-off value) as the cut-off TSLF value was gradually reduced from a maximum of 200 years. This initial analysis yielded a cut-off TSLF value of 120 years, a value more related to the oldest age class provided by the SIFORT database (Table 1) than to the maximal temporal depth common to all available fire history maps (Table 2). Cells of the training dataset with a TSLF value greater than 120 years were thus all categorized as "unburned" (TSLF > 120 years) for further model training. A second model was then used to estimate TSLF for cells for which the first model predicted a TSLF value below 120 years.

Both models were developed using random forests (RF), with the *randomForest* package (Liaw and Wiener, 2002) in R (Venables and Smith, 2013). This non-parametric method makes no assumptions about the distribution of the data and can model non-linear relationships. It has the ability to handle high dimensional input variables and rank variable importance. For both models, 1000 bootstrap samples were used to draw 63% (Cutler et al., 2007) of the training dataset to build classification or regression trees whose predictions were then combined. The remaining data (out-of-bag data) was used for cross-validation for each bootstrap iteration. The values of training parameters used in model development were: *ntree*, the number of trees to grow (1000), *mtry*, the number of the predictor variables sampled for each node (default parameters, classification: square root of the number of variables and regression: the number of variables/3), and *node size* (default parameters, classification: 1 and regression: 5). In the case of the first RF model used to form two groups based on a cut-off TSLF value, the final classification corresponded to the class most often selected by the classification trees. Accuracy was assessed with Cohen's kappa measure of agreement and the percent of correctly classified classes (PCC) through the construction of confusion matrices between the actual and predicted classes. The kappa measure corresponds to the classification accuracy adjusted for agreements that may occur due to chance alone (Cohen, 1960). A non-parametric method such as random forest is not affected by spatial autocorrelation as it does not require residuals to be independent and identically distributed, but the presence of residual autocorrelation could indicate among other things the omission of one or more important explanatory variables (e.g. Dormann et al., 2007). Furthermore, forest fire is a contagious process with potential inherent spatial autocorrelation. As a consequence we tested for the presence of residual autocorrelation with a global Moran's I index as a function of neighboring distance (Moran, 1950). To this effect, the Moran I index was computed with the cells having a value of 0 (incorrectly) or 1 (correctly classified).

For the second RF model used to estimate TSLF for cells where TSLF $\leqslant$ 120 years, taking the average of the bootstrap values (Cutler et al., 2007) led to biased predictions for values close to the bounds set at 30 and 120 years (i.e. corresponding to years of stand origin of 1970 and 1880). Different strategies were employed to avoid such biases, including a bias reduction technique proposed by Zhang and Lu (2012) (their model 3) or by taking the median instead of the mean as prediction. However, we found that biases were greatly reduced when bootstrap-predicted values were

Table 2
Sources used to generate the response variable for the training dataset for the random forest TSLF models.

No	Fire data source	Period	Area used in the study (km^2)	Location of region
1	Quebec's Société de Protection contre les Feux (SOPFEU)	1970–2000	19,104	Province of Quebec, Canada
2	Bouchard et al. (2008)	1800–2000	41,472	The eastern portion of study area (70–66.5°W to 49–51.5°N)
3	Bélisle et al. (2011)	1734–2009	228	The central part of study area (71°15′W–72°45′W and 49°36′N–50°59′N)
4	Le Goff et al. (2007)	1720–2000	232	The central portion of study area (75°W–76°30′W and 49°30′N–50°30′N)
5	Bergeron et al. (2004b)	1675–2000	4192	The western part of study area (78°30′W–79°30′W and 48°N–50°N)
6	Lesieur et al. (2002)	1923–2000	454	The south-central portion of study area (74°52′55″W–73°45′15″W and 47°57′13″N–49°08′22″N)

categorized into decades for each cell and the most frequent decade was selected as the predicted value. As a consequence of categorizing TSLF-predicted values by decades, accuracy of the second RF model was also assessed with the Cohen's kappa and the percent of correctly classified classes, instead of the coefficient of determination and root mean square error. We also tested for the presence of residual autocorrelation using the same methodology as described before (i.e. with cells being correctly or incorrectly classified).

The measure of the importance of a predictor variable (mean decrease in Gini coefficient when classification is used with RF and mean decrease in mean square error when regression is used instead) is the normalized decrease in classification accuracy or mean squared error for the out-of-bag data by including the predictor variable either as originally observed or as randomly permutated in the out-of-bag data. For both models, only the six most important variables ranked by RF were used in the model building process to develop robust models (Thompson and Spies, 2009). Colinearity among selected explanatory variables was checked through correlation analyses. More details on the RF algorithm can be found elsewhere (e.g. Cutler et al., 2007; Timm and McGarigal, 2012).

2.4. TSLF extrapolation to the entire study area

Both models were used to impute a TSLF value (either TSLF > 120 years or a decade of stand origin between 1880 and 1970) to each 2-km^2 cell of the studied dataset, except those used in the training dataset and those covered by the fires of the SOPFEU 1970–2000 fire history map (imputed dataset, 43,077 cells). The difference between the 95th and 5th percentiles of TSLF (individual years, TSLF ⩽ 120 years) generated through bootstrapping were used to provide a 90% confidence interval for each 2-km^2 cell. Half the width of these confidence intervals served to estimate margins of error of predicted values and their frequency distributions were computed by classes of predicted decade.

The three datasets (SOPFEU, training and imputed datasets) were combined to produce a TSLF map expressed in decadal classes for the entire study area. The burn rate per decade between 1880 and 2000 was then estimated for the study area from the areas belonging to each decadal TSLF and a survival analysis (Reed et al., 1998), considering that each decade might have a different burn rate (Fauria and Johnson, 2008). A survival analysis estimates the probability of an area having gone without fire for a given period of time (Johnson and Gutsell, 1994) and was required to correct for the effect of overlap in successive fires on burn rate estimates. Reed et al. (1998) have provided a recursive method to correct these past burned areas, accounting for the fact that the burn rate may change through time. The decadal burn rate was thus estimated in a recursive fashion, starting from 1980 to 1990 and correcting the area that had then burned by the inverse of its survival probability until the date of the 2000 TSLF map.

2.5. Relating forest composition with past disturbances at the landscape scale

The use of a nonparametric method such as random forests makes it much more difficult to interpret the results. The results were therefore synthesized to better understand how the 20th century landscape-scale burn rate estimated with the TSLF map is related to present forest composition. To this effect, TSLF was statistically upscaled to the 625 ecological districts within our study area (size between 65 km^2 and 2975 km^2) by computing the mean time since last fire (MTSLF). Ecological districts (Robitaille and Saucier, 1996) correspond to landscape units of similar topography, surficial deposits and drainage, and have been used for characterizing vegetation (Anyomi et al., 2013; Grondin et al., 2014). MTSLF for each ecological district was computed by fitting a Weibull distribution of TSLF with PROC LIFEREG (SASv9.2, SAS Institute Inc., Cary, NC, USA). Survival analysis allows computing MTSLF by considering censored data (TSLF > 120 years), for which an accurate estimation of TSLF was not available. Three ecological districts that completely burned between 1970 and 2000 were not considered in this analysis as a recent burn with no photointerpreted vegetation covered them.

Ecological districts were regrouped into homogeneous forest landscapes on the basis of the relative abundance of SIFORT grid cells by species composition (Table 1) using PROC FASTCLUS (SASv9.2, SAS Institute Inc., Cary, NC, USA). The optimum number of clusters (4) was detected with the first local maximum value of the cubic clustering criterion (CCC) by plotting its value as a function of an increasing number of clusters (Sarle, 1983). For each of these vegetation clusters, we computed the cell frequency with a TSLF value above or below 120 years and the variability of MTSLF values between districts of an individual cluster.

3. Results

3.1. Accuracy of TSLF models

For our first random forest model that classified 2-km^2 cells into two groups of TSLF (⩽ or >120 years), the six top-ranked predictor variables were the proportions of the four oldest stand age classes (61–80, 81–100, ⩾101 years, old uneven-aged, Table 1), the relative abundance of balsam fir, and the total precipitation (Fig. 2a). The Cohen's kappa (0.72) indicated a substantial agreement in the classification (Landis and Koch, 1977). The model was better able to predict unburned cells (TSLF > 120 years) (classification error of 8.3%) compared to burned cells (TSLF ⩽ 120 years) (error of 19.5%). Spatial autocorrelation of incorrectly classified cells was significant, which indicates clustering, and global Moran I index remained above 0.10 for distances inferior to 20 km. Clusters of incorrectly classified cells were therefore located at the boundaries or within individual fires (Supplementary material, Fig. A.1). A visual examination of the spatial distribution of these clusters did not indicate any latent spatial pattern that would have pointed to important processes not included in the RF model. The results of the classification suggest that 22,196 cells (52% of the imputed dataset) burned between 1880 and 1970 (TSLF ⩽ 120 years).

For our second random forest model that estimated TSLF for cells predicted as having a TSLF ⩽ 120 years with the first model, the six top-ranked predictor variables (Fig. 2b) were the proportions of intermediate age classes 41–60, 61–80, 81–100, the total precipitation, the potential evapotranspiration, and the percentage of stands originating from a burn. Total precipitation and potential evapotranspiration were only weakly correlated between themselves ($r = -0.19$, $p < 0.01$) and both variables were kept. TSLF values predicted by this second RF model and categorized by decade of stand origin, were unbiased (Fig. 2c) and correctly classified 85.5% of the time. This represents an "almost perfect" agreement with observed data (Cohen's kappa of 0.82, Landis and Koch, 1977). The cell-level margin of error was typically around 20 years, which is fairly high provided the time span covered (1880–2000) and no temporal trend was detected (Fig. 2d). The global Moran I index of incorrectly classified decades showed an approximately identical pattern with distance and values as the one for cells being incorrectly classified as having burned after 1880. Again, clusters of incorrectly classified decades did not show any spatial pattern over the whole study area that would have pointed to important variables missing in the RF model (Supplementary material, Fig. A.2).

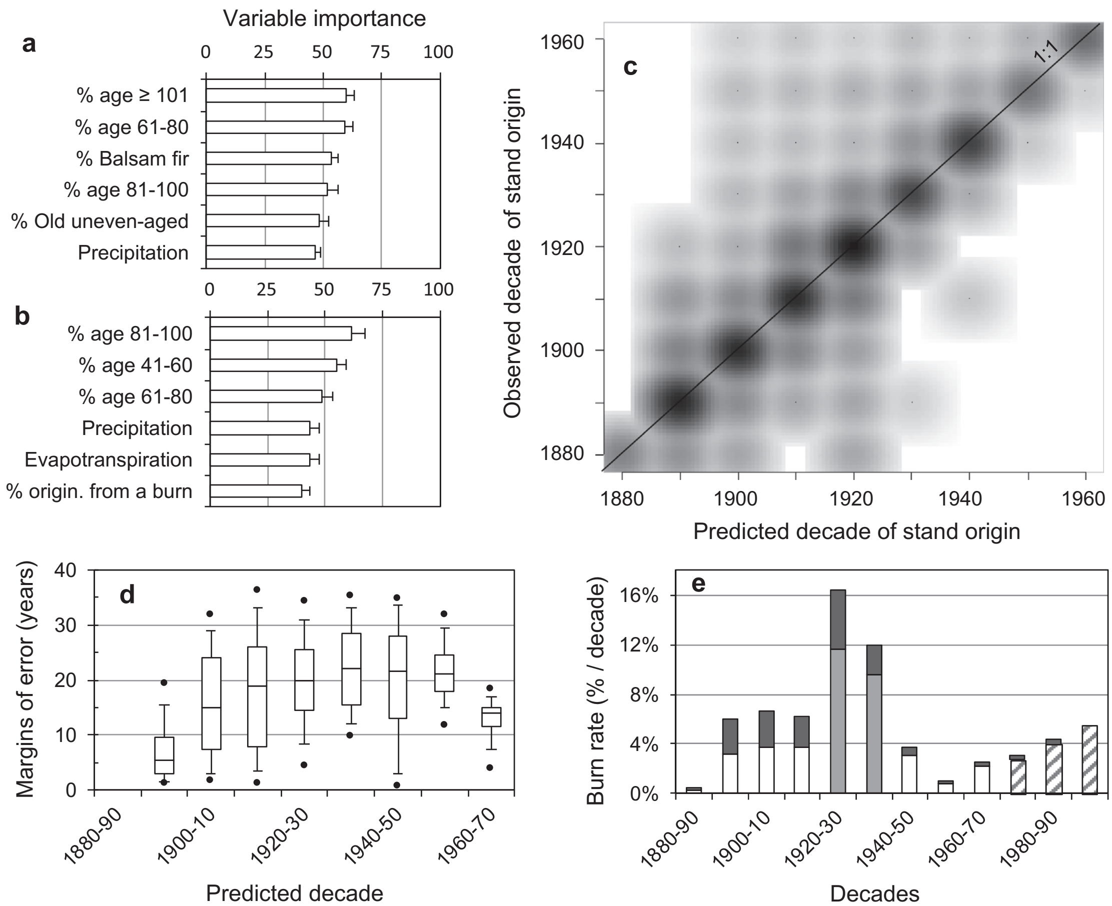


Fig. 2. For the top six variables (Table 1), ranked by the random forest models for the classification of 2-km^2 cells into TSLF $\leqslant$ 120 years and TSLF > 120 years, (a) normalized mean decrease in Gini coefficient, and (b) normalized mean decrease in mean square error in predicted cell-level TSLF for cells in which TSLF is predicted to be less than 120 years; (c) density plot of observed vs predicted year of stand origin for cells for which TSLF is predicted $\leqslant$120 years; (d) box-and-whisker plots of margins of error for predicted TSLF values grouped by decade class; (e) Decadal burn rates between 1880 and 2000 for the study region (dark gray: burn rate correction due to survival analyses, light gray: highest values of burn rate, hatching: burn rates between 1970 and 2000).

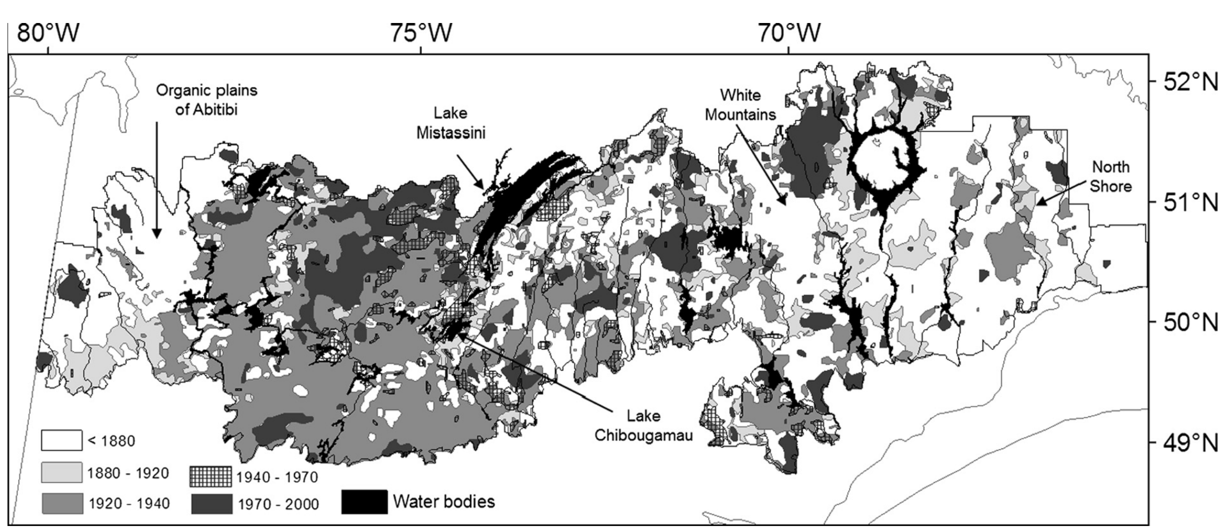


Fig. 3. Map of predicted time since last fire by decade class (between1880 and 2000). The map was generalized by aggregating 2-km^2 cells of identical period of fire activity (1880–1920, 1920–1940, 1940–1970 and 1970–2000) and by removing any object smaller than 4 km^2.

3.2. Temporal changes in the decadal burn rate during the 20th century

The decadal burn rate between 1880 and 2000 at the scale of the whole study area ranged from 0.5% to 16.4% decade^{-1} (Fig. 2e). More importantly, decades between 1920 and 1940 seemed characterized by a widespread fire activity corresponding to 28% of the study area. This period is surrounded by two periods of moderate to low fire activity (1880–1920 and 1940–1960). Most of the fire activity between 1880 and 2000 is concentrated in a region situated between the organic plains of Abitibi, where very

Table 3
Average proportions of tree species by vegetation cluster after a clustering analysis to explain the homogeneity of landscape units by vegetation composition. Species names are provided in Table 2. Bold numbers indicate the dominant species.

Mean of species cluster									
Cluster name	Abundance (%)	Aba	Pma	Iha	Pba	Mix	Oco	Brn
Pma–Pba	18	0.03	**0.42**	0.09	**0.35**	0.05	0.00	0.06
Aba–Pma	24	**0.50**	**0.37**	0.05	0.02	0.04	0.00	0.03
Pma	47	0.11	**0.69**	0.05	0.06	0.04	0.00	0.05
Brn–Pma	11	0.05	**0.28**	0.03	0.11	0.02	0.00	**0.51**

few fire events have occurred, and Lake Chibougamau (Fig. 3). Further east, the fire activity was moderate between Lake Mistassini and the White Mountains, and low on the North Shore.

3.3. Forest composition in relation to fire regime as derived from the TSLF map

At the scale of landscapes (ecological districts), cluster analysis indicated that dividing the study area into four regions or zonations based on regional vegetation composition was the optimal number to explain the heterogeneity in tree species composition. Except in one cluster, black spruce (co-)dominates in all clusters (Table 3). The cluster dominated by balsam fir has a median MTSLF of 217 years (Fig. 4b) and the highest proportion of 2-km^2 cells with a TSLF > 120 years (Fig. 4c) compared to the cluster dominated by black spruce and jack pine. The cluster dominated by black spruce has a closely equal proportion of cells with a TSLF ⩽ 120 or >120 years (Fig. 4c).

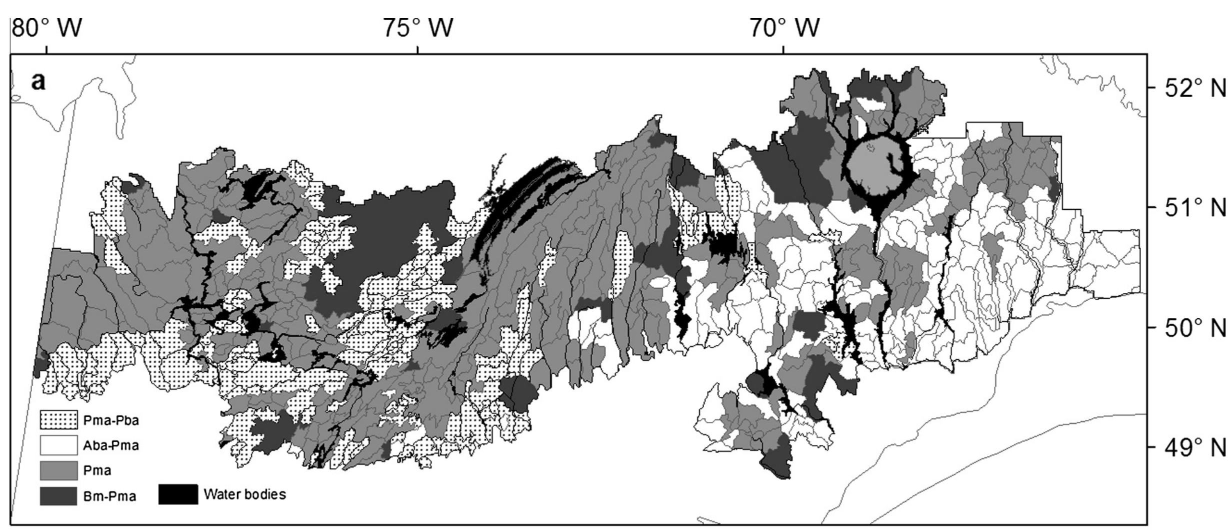
4. Discussion

4.1. Estimation of TSLF over a large spatial extent with random forest models

In this study, we modeled TSLF over an area covering 217,000 km^2. Cyr et al. (2010) used a similar approach (Bayesian Belief network) to estimate the proportion of old-growth forest (stands older than 150 years) over 6500 km^2 in central Canada (Ontario), with a similar accuracy but at the scale of forest stands (areas of approximately 20 ha). Empirical methods such as random forests or Bayesian belief networks are useful to characterize the errors incurred by the extrapolation of TSLF from local observations (sample area or sample plots) that is otherwise done manually (Fig. 2c and d). Notably, ambiguities remain apparent when trying to spatially distinguish individual fires that have occurred between 1920 and 1940 (map provided as supplementary material, Fig. A.3).

4.2. Interpretation of TSLF predictors

The proportions of stand age classes per cell (Table 2) were strong predictors of TSLF for TSLF ⩽ 120 years (Fig. 2a and b). Probability of predicting a TSLF > 120 years increased with an increase in the proportion of older stands, in the abundance of balsam fir and in precipitation. Such a result is in accordance with the mean longevity of black spruce in the eastern part of the study area (c. 200 years, Garet et al., 2009) and the time required for balsam fir to gradually reach the canopy (c. 200 years, Bouchard et al., 2008, their Fig. 4). Other variables that we expected to be related



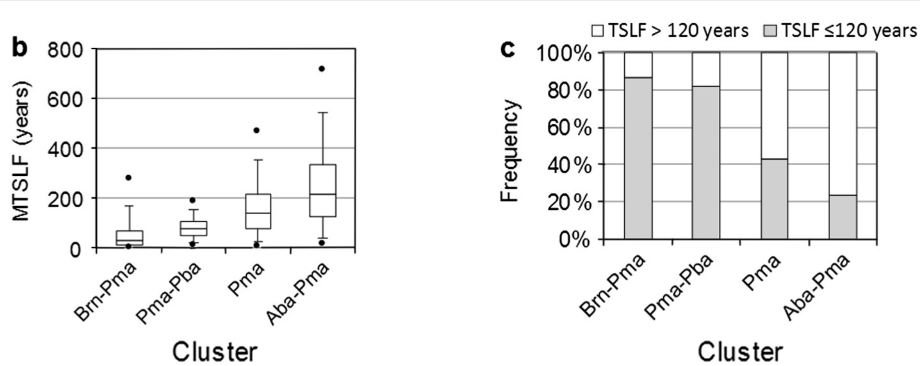


Fig. 4. (a) Vegetation map of landscape units (ecological districts) derived from a cluster analysis based on species abundance. Average proportions of species and names for each cluster are presented in Table 3; (b) box-and-whisker plots of mean time since last fire by ecological district across the vegetation clusters; (c) frequency of 2-km^2 cells with a TSLF value above or below 120 years by vegetation cluster.

to the fire regime and thus to TSLF were not selected by the RF models as strong predictors. For instance, we expected the relative abundance of open spruce woodlands, a forest type that apparently results from deficient post-fire forest recovery (Lavoie and Sirois, 1998; Girard et al., 2008; Mansuy et al., 2012), to help in the estimation of TSLF. This lack of relationship may point to a relative importance of other factors such as drought events and surficial deposits that contribute to their abundance (Mansuy et al., 2012). Or alternatively, the causal relationship between fire and open spruce woodlands may operate at a finer spatial scale than that used in the present study. In fact, surficial deposits are known to be related to fire regime because of their drying potential (Mansuy et al., 2010) but the study area is dominated by only two surficial deposit groups (75%) that correspond to thick and thin undifferentiated tills with moderate (MM) to abundant (MAM) stoniness with a moderate drying potential. Finally, we also expected elevation to help in the estimation of TSLF (Kasischke et al., 2002), especially in the White Mountains and the North Shore (Fig. 4), but at the scale of the study area, elevation is correlated with precipitation ($R^2 = 0.41$, $p < 0.001$) and precipitation was selected as strong predictor in the RF models (Fig. 2a and b).

4.3. Impacts of spatial scale on TSLF modeling

Houghton (2005) suggested as a rule of thumb that the spatial scale to be used for estimating standing biomass should be equivalent to that of fire disturbances. The spatial scale used in the present study (2 km^2) probably helped circumvent some of the problems encountered at a finer scale when relating stand age to TSLF, notably (1) the variability of fire severity linked to past fire dates (Miller et al., 2012) that affects the post-fire species composition (Barrett et al., 2011; Johnstone et al., 2010), (2) the errors linked to the photointerpretation of cartographic attributes of stand species composition, structure and age at the scale of forest stands (<10 ha) (Waldron et al., 2012; Bernier et al., 2010), (3) the interaction between cartographic stand age and succession when TSLF exceeds the longevity of pioneering post-fire species (Garet et al., 2012; Cyr et al., 2010) and (4) local neighborhood effects (*sensu* Frelich and Reich, 1999) observed at the scale of stands that blur the relationship existing between TSLF and species composition (e.g. Chen and Taylor, 2012). Indeed, at the coarser scale used here, it is not the exact stand age or the presence-absence of forest species that are indicators of TSLF but rather their different abundances (Fig. 2a and b).

4.4. Temporal changes in regional burn rate

A period of widespread fire activity over the whole study area was detected between 1920 and 1940 (Fig. 3) during which slightly more than 28% of the area has burned (6.1 Mha, Fig. 2e), corresponding to a burn rate of 16.4% decade^{-1}. This contrasts with the 4.3% decade^{-1} burn rate estimated between 1970 and 2000. The high mid-century peak in burn rate had already been observed by Grondin et al. (2014), and is apparent on account of the remarkably high proportion of stands aged between 60 and 80 years (22%). Such fire activity has also been identified by dendroecological studies carried out between Lake Mistassini and the organic plains of Abitibi (Lesieur et al., 2002; Le Goff et al., 2007), and to a lesser extent in other parts of the study area (Bergeron et al., 2004b; Bouchard et al., 2008; Girardin et al., 2013). This 6.1 Mha of burned area between 1920 and 1940 is not covered by the data of the Canadian forest fire statistics (e.g. Kurz and Apps, 1999, their Fig. 3 for "Boreal East") and provides a historical reference against which to compare, at least regionally, the recent increase in burn rate between 1980 and 2000 (Fig. 2e) that has been associated with climate change in the Canadian boreal region (e.g. Kasischke and Turetsky, 2006).

The methodology developed above to estimate regional TSLF may also help refine past estimates of fire-related carbon emissions from Canada's forests. Past assessments have been based on historical observational records. However, incomplete fire detection has been acknowledged (Podur et al., 2002; Stocks et al., 2003), especially before 1975 (Murphy et al., 2000). This situation may have led to incorrect century-long assessments of carbon budgets, at least for eastern Canada (Kurz and Apps, 1999; Chen et al., 2000; Mouillot and Field, 2005).

4.5. Management and conservation implications

The results discussed above show the importance of lengthening the historical records of fire history maps in order to provide a better perspective on the actual changes of fire regime and to better understand the relationship between fire activity and climate (Fauria and Johnson, 2008; Le Goff et al., 2007). The derived TSLF map has revealed the regional differences in fire regime and forest age class structures, which should be taken into account to devise region-specific forest ecosystem management strategies for maintaining regional-scale heterogeneity. In addition, the statistical model presented in this study to derive TSLF is also a new tool that forest managers can use to estimate regional TSLF. Estimates of long-term fire history can also help forest ecologists forecast fire regime under future climate scenarios and understand the impacts of climate warming on the forest.

5. Conclusion

We have devised an approach for modeling and mapping TSLF at a relatively coarse resolution (cells of 2 km^2) over a large spatial extent (>200,000 km^2). The training of the models used over existing fire history maps showed that at this resolution, TSLF is essentially and not surprisingly related to the observed proportions of stand age classes. Such a relationship is modulated by the climate gradient that occurs over the study area (precipitation, evapotranspiration) and by the abundance of fire-averse tree species such as balsam fir. When TSLF is categorized into decades, the accuracy is excellent at the scale of both the study area and landscape units but remains fairly low at the scale of individual cells. At least regionally, our results suggest that the burn rates during the 20th century were characterized by a widespread fire activity that occurred between 1920 and 1940, more important than the recent increase observed between 1980 and 2000. This highlights the need for lengthening the historical records of fire over large spatial extents to provide a better appraisal of contemporaneous changes in the burn rate (e.g. Bergeron et al., 2010). Our approach could be adapted and transferred to the other ecological systems where there is evidence of succession trends following TSLF (Pausas et al., 2008; Baeza et al., 2011; Higuera et al., 2011).

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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.2015.03.011.

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