Ecological Applications, 23(4), 2013, pp. 904–923

Fire regime zonation under current and future climate over eastern Canada

Yan Boulanger,[1,4] Sylvie Gauthier,[1] David R. Gray,[2] Héloïse Le Goff,[1] Patrick Lefort,[3] and Jacques Morissette[1]

[1]*Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, 1055 du P.E.P.S., P.O. Box 10380, Station Sainte-Foy, Quebec, Quebec G1V 4C7 Canada*
[2]*Natural Resources Canada, Canadian Forest Service, Atlantic Forestry Centre, 1350 Regent Street, Fredericton, New Brunswick E3B 5P7 Canada*
[3]*Centre d'Étude sur la Forêt, UQAM, Succursale Centre-Ville, Montréal, Quebec H3C 3P8 Canada*

Abstract. Fire is a major disturbance in Canadian forests. Along with fuel and ignition characteristics, climatic conditions are seen as one of the main drivers of fire regimes. Projected changes in climate are expected to significantly influence fire regimes in Canada. As fire regime greatly shapes large-scale patterns in biodiversity, carbon, and vegetation, as well as forest and fire management strategies, it becomes necessary to define regions where current and future fire regimes are homogeneous. Random Forests (RF) modeling was used to relate fire regime attributes prevailing between 1961 and 1990 in eastern Canada with climatic/fire-weather and environmental variables. Using climatic normals outputs from the Canadian Regional Climate Model (CRCM), we delineated current (1961–1990) and future (2011–2040, 2040–2070, 2071–2100) homogeneous fire regime (HFR) zones. Heterogeneous response of fire regime to climate changes is projected for eastern Canada with some areas (e.g., western Quebec) experiencing very small alterations while others (e.g., southeastern Ontario) are facing great shifts. Overall, models predicted a 2.2- and 2.4-fold increase in the number of fires and the annual area burned respectively mostly as a result of an increase in extreme fire-weather normals and mean drought code. As extreme fire danger would occur later in the fire season on average, the fire season would shift slightly later (5–20 days) in the summer for much of the study area while remaining relatively stable elsewhere. Although fire regime values would change significantly over time, most zone boundaries would remain relatively stable. The information resulting from HFR zonations is clearly of interest for forest and fire management agencies as it reveals zones with peculiar fire regimes that would have been hidden otherwise using predefined administrative or ecological stratifications.

Key words: annual area burned; climate change, REDCAP, Random Forests; fire occurrence; fire regime; fire seasonality; North America; regionalization.

Introduction

Fire is a major disturbance in the Canadian boreal forest. Around 8000 fires burned approximately 1.8 million hectares of forest per year during the 1959–1997 period in Canada (Stocks et al. 2003). The fire regime, defined by several variables, including the annual area burned, the number of fires, their size, and the season during which they occur (Krebs et al. 2010), is known to be highly variable across Canada's forests (Stocks et al. 2003, Parisien et al. 2006, Boulanger et al. 2012). Fire regime largely shapes landscape diversity and productivity (Payette 1992) and strongly influences the carbon flux in boreal forest ecosystems (Bond-Lamberty et al. 2007, Amiro et al. 2009). Fire occurrence, event size, severity, seasonality, annual area burned, and ignition types, all have major impacts on vegetation dynamics and fire management. Interactions among these fire regime characteristics influence several post-fire ecological processes (e.g., landscape patchiness, post-fire succession, susceptibility to insect outbreaks). As such, the concurrent consideration of many fire parameters is important to our understanding the Canadian forest dynamic as a whole (Burton et al. 2008).

Dominant factors influencing fire regimes may be classified into three groups: (1) climate, (2) vegetation (as fuel), and (3) ignition (Parisien and Moritz 2009). Climatic conditions are seen as one of the main drivers of fire regimes (Flannigan and Wotton 2001, Girardin et al. 2009). The frequency and the intensity of precipitation events as well as the temperature regime prevailing during the fire season affect the probability of fire ignition, fire size, and fire seasonality and hence greatly shape broad-scale trends in fire regimes. In North America, interannual variability at sub-continental to continental scales in the fire regimes was related to synoptic cyclical patterns in the ocean and atmosphere

Manuscript received 30 April 2012; revised 22 October 2012; accepted 10 December 2012; final version received 7 January 2013. Corresponding Editor: B. P. Wilcox.
[4] E-mail: yan.boulanger@nrcan.gc.ca

resulting from the Pacific Decadal Oscillation (PDO), the El Niño/La Niña Southern Oscillation (ENSO), or the Arctic (AO)/North Atlantic Oscillation (NAO) (e.g., Skinner et al. 2002, Girardin et al. 2004, Le Goff et al. 2007). In order to estimate fire danger, various fire-weather-based moisture codes and fire behavior indices (such as the components of the Canadian Forest Fire Weather Index [CFWI]) were built from daily seasonal observations in temperature, precipitation, relative humidity, and wind speed (Van Wagner 1987, Girardin and Wotton 2009). On the other hand, vegetation flammability and spatial continuity have also been shown to influence fire size, annual area burned, and fire occurrence (Cary et al. 2006, Krawchuk et al. 2006). Obviously, ignition sources, either lightning or human, limit fire occurrence. In this latter case, the anthropogenic influence on the fire regime is rather complex as active fire suppression reduces fire activity (Martell and Sun 2008) while, at the same time, humans may cause additional ignitions in the vicinity of infrastructures (Wang and Anderson 2010). Humans may also affect fire seasonality by causing additional ignitions during periods when lightning ignitions are limited (Le Page et al. 2010). All these factors are likely to interact causing spatial and temporal variations in the relative influence of the environment on fire activity (Parisien and Moritz 2009, Parisien et al. 2011).

It is now clearly recognized that the climate is changing rapidly as a result of human activities (Solomon et al. 2007). Accordingly, one should expect significant alterations to the fire regime as a direct consequence of climate change. Several studies have shown that fire regime characteristics have already begun to change recently in response to climate change (Gillett et al. 2004, Turetsky et al. 2011). Although alterations should be greatly heterogeneous within the boreal forest (Flannigan et al. 2005), a general increase in the annual area burned and fire frequency is projected for Canada for the upcoming decades, notably as a result of increasing frequency, duration, and severity of summer drought conditions (Gillett et al. 2004, Flannigan et al. 2009, Girardin et al. 2010). Moreover, the projected lengthening of the fire season as well as a temporal shift in the prevalence of severe fire-weather conditions are also suspected to greatly influence future fire seasonality (Wotton and Flannigan 1993, Amiro et al. 2009, Le Goff et al. 2009). As a consequence, changes in the fire regime would greatly modify landscape patterns, energy fluxes and carbon budgets in the boreal forest. In addition, these shifts are likely to affect future forest and fire management strategies, particularly by influencing forest productivity (Bergeron et al. 2006, Raulier et al. 2013) and the strategic planning of fire detection and suppression efforts (Flannigan et al. 2009, Podur and Wotton 2010).

Factors affecting the fire regime may act at several spatial scales resulting in complex spatially correlated patterns in fire regime (Cyr et al. 2007, Parisien and Moritz 2009, Parisien et al. 2011). As a result, zones with a homogeneous fire regime (HFR) can emerge, depending on the observer's scale of perception (Boulanger et al. 2012). Until now, the current and future broad-scale spatial patterns in fire regime have been frequently generalized or modeled over large and static administrative or multi-purpose ecological zones (or a mix of both; e.g., Flannigan et al. 2005, Amiro et al. 2009, Wotton et al. 2010), assuming a sufficient degree of spatiotemporal homogeneity within these units. However, the ability of these stratifications to provide an optimal zonation for current (Boulanger et al. 2012) and future fire regimes is questionable. Independent zonation analyses may help to identify zones with peculiar fire regimes that would have been overlooked otherwise (Boulanger et al. 2012). Furthermore, such analyses should allow for a dynamic temporal delineation of HFR zones as a result of projected changes in the spatial patterns of factors affecting the fire regime. HFR zones are necessary in the context of growing interest to assess current and future fire regime variability at supraregional scales (e.g., Flannigan et al. 2005, Balshi et al. 2009*b*, Krawchuk et al. 2009, Parisien and Moritz 2009), notably for effective decision-making, monitoring, and prediction regarding forest management and fire operational strategies (Wotton and Stocks 2006, Podur and Wotton 2010). Furthermore, accurate delineation of HFR zones may improve our ability to estimate broad-scale patterns in current and future regional forest productivity, forest carbon budget (Amiro et al. 2009, Balshi et al. 2009*a*), and biodiversity.

Many studies have looked at predicted changes in the area burned, the number of fires, or several fire behavior characteristics under the predicted climate change (e.g., Bergeron et al. 2004*b*, Flannigan et al. 2005, Balshi et al. 2009*b*, Le Goff et al. 2009). However, very few have looked at modifications in several fire regime parameters simultaneously under climate change. Despite recent attempts to delineate homogeneous fire regime zones in Canada with regard to the current fire activity (Mansuy et al. 2010, Boulanger et al. 2012), none has proposed zonations based on projected fire regimes in response to climate change. The specific objectives of the work described here are to (1) define regions in eastern Canada with homogeneous fire regimes under current climatic conditions; (2) relate characteristics of the fire regime to various climatic and environmental variables in order to project future HFR zonations based upon climate model outputs for 2040, 2070 and 2100; and (3) compare current and future spatial patterns in fire regime as based on current and future HFR zonations. As we were interested in coarse-scale environmental control of fire regime, we relied on climatic normals to project future area burned, fire occurrence, and fire seasonality. Future climate normals estimated from general circulation models (GCM) are considered very stable (Stoner et al. 2009), giving robust estimates of future fire activity at the scale at which we are working (Moritz et al. 2012, Parisien et al. 2012).

Study area

The study area encompasses all forested (either continuous or discontinuous) areas of New Brunswick, Quebec (south of 57° N), and Ontario (excluding its southernmost part), Canada that were subject to significant fire activity during the 1961–1990 period. Unfortunately, fire data for Ontario north of 54° N are not available, so this area was excluded from our analyses (Fig. 1). According to the National Ecological Framework of Canada (Ecological Stratification Working Group 1996), these areas lie within the Boreal Shield, the Taiga Shield, the Hudson Plains, as well as the Atlantic Maritime ecozones. The study area shows a strong climatic and fire regime heterogeneity (Stocks et al. 2003). Typically, precipitation increases from west to east and from north to south. The climate of the easternmost part of the study area is influenced by periodic incursions of relatively moist and cool airflows from the Atlantic Ocean. Otherwise, most of the area south of the 54° N is under a continental climate, characterized by cold winters and warm summers with annual precipitation typically lower than 1000 mm on average. The northernmost part of Quebec is under a subarctic climate with low precipitation, a short growing season and cool summers. Snow cover generally lasts between four months in the southern and western parts, and up to seven to eight months in the northern and eastern parts. Basically, the southern portion of our study area is within the temperate deciduous forest while forest cover shifts north to south from mixed wood to continuous and finally to discontinuous coniferous up north (Rowe 1972). Wetlands characterized by extensive bogs and fens are common west of James Bay, in the Hudson Plains ecozone. New Brunswick and southeastern Quebec are within the Appalachian Mountains while the remainder of the study area is located within the Canadian Shield. Topography is generally smooth with low- to mid-altitude rolling hills. Most of the area south of the 51° N is under active fire suppression and supports varying levels of logging activities, agriculture and urban development. Otherwise, there is no active fire suppression, except near human facilities. In addition to wildfires and human activities, other natural disturbances (e.g., recurring insect outbreaks, windthrow) contribute to generating a complex landscape mosaic, mostly in the southern part of the study area.

Materials and Methods

Fire data

Fire data comes from the Canadian National Fire Database covering 1961–1990 (CNFDB). This period is defined as the "historical" period from which both fire and climate data were retrieved. We restricted our analyses to fires greater than 200 ha as data from smaller fires are known to be incomplete, especially those that occurred before 1980 and in remote areas. Fire data for New Brunswick is completely lacking from the CNFDB for fires that occurred before 1980. Therefore, perimeters of fires greater than 200 ha for New Brunswick for the 1961–1979 period were retrieved from microfilms owned by the New Brunswick Department of Natural Resources and Energy. Although there were many fires smaller than 200 ha in the study area, the area burned is very well represented by our database set; fires larger than 200 ha were responsible for 97% of the area burned across Canada between 1959 and 1997 (Stocks et al. 2003). A total of 1766 fires were in our database. In the original CNFDB, fires are represented as points, and an attribute file contains information on the final size and starting date. As polygon data delimiting the actual perimeter of the fire patches were not available for the whole time period covered here (with different period coverage for different jurisdictions), each fire was represented by a circle with a radius proportional to the area burned.

Sampling units and fire regime attributes

Fire sampling was conducted using a 60 × 60 km square cell grid (hereafter referred to as gridded cells, $n = 576$ cells). This size represents a compromise between capturing the local variation in the fire regime while being larger than all but one fire event (377 750 ha) in the study area. Using this spatial database, we computed the following fire regime variables over the 30-year period for each gridded cell: (1) the annual number of fires per 100 kha (FIREOCC); (2) the annual area burned (AAB); and (3) fire seasonality (median burn date, MBD) (Table 1). Fires that were ignited outside the study area but that had their areal buffer partly overlapping the gridded cells were considered for the calculation of AAB. We did not distinguish between anthropogenic and natural fires since it would have resulted in a large number of cells without either one of these fire types and because this information was lacking for many fires. Using the Earth Observation for Sustainable Development of Forests (EOSD) land cover classification (Beaubien et al. 1999), fuel area in each gridded cell was assessed as the sum of the 6.25-ha pixels covered by trees, shrubs, grasses, herbs, bryoids, or vegetated wetlands. The total area burned and total number of fires were expressed as a proportion of the area of fuel in the gridded cell. MBD was estimated as follows. In each cell, the date of ignition and final size were collected for each fire for the 30-yr period. By chronologically ordering fire events according to their ignition date, we determined the month and day on which cumulative area burned was 50% of the final area burned. Although much of the area burned by a given fire may occur within one or a few days, fires may burn over several days after ignition, even weeks for very large fires, before being totally extinguished. Unfortunately, because the great majority of fires did not have any "out" date within the CNFDB, final fire size was associated with the date of ignition. In areas where fires were rare, MBD would have been based on a few fire events (sometimes only one) within the time frame of our fire data. Therefore, MBD values were smoothed in each cell using a 180 × 180 km (3 × 3 cells) moving window. To do so, we used only cells that had at least one fire during the time period. In other words, cells with no fires were assigned a MBD value based on the 180 × 180 km moving window. Cells that had no fires within their moving window were discarded.

Explanatory variables

We aimed to model fire regime characteristics using 24 predictors classified into the following categories: weather/climate, fuel, human impact, and topography (Table 1). We did not include lightning as a predictor (c.f. Parisien and Moritz 2009) because lightning data were not available for both the historical period and the future scenarios. Furthermore, topography was added as an additional category because it was shown to influence fire activity at scales close to the size of one gridded cell (Cyr et al. 2007, Parisien et al. 2011). Even though many more explanatory variables were available for analyses, our objective was to select variables having the greatest influence according to previous studies on environmental control of fire regime. In each cell, vegetation was characterized according to its flammability potential. Previous studies (Cary et al. 2006, Krawchuk et al. 2006) have shown that areas with high volume of deciduous trees may strongly dampen fire occurrence and fire size and regions with extensive wetlands (e.g., bogs, fens) were less likely to burn. Therefore, we estimated (1) the percentage of coniferous forests (PctCon) and (2) the percentage of fuel area covered by wetlands (PctWet) from the EOSD land cover classification. Humans can strongly affect fire regime by either causing more ignitions or, conversely, by reducing the area burned through fire management and protection policies. As a surrogate for potential anthropogenic impact on fire regime, we estimated the total road length (km) per square kilometer (RoadDens) from the Atlas of Canada (Natural Resources Canada 2008). Topography was characterized using land roughness, as measured through the surface : area ratio (SurfAreaRatio; Jenness 2009), which measures the ratio between topographic surface area and horizontal projected area at a 500-m resolution.

Weather/climate data

The historical climate conditions were derived from the 1961–1990 Canadian Climate Normals database (Environment Canada 2007). Daily weather variables were simulated 50 times in each cell from the normals using the stochastic weather generator of BioSIM v10.0.6.20 (Régnière and Saint-Amant 2007). BioSIM simulates daily maximum and minimum temperatures (°C), precipitation (mm), mean daily relative humidity, and wind speed by matching georeferenced sources of

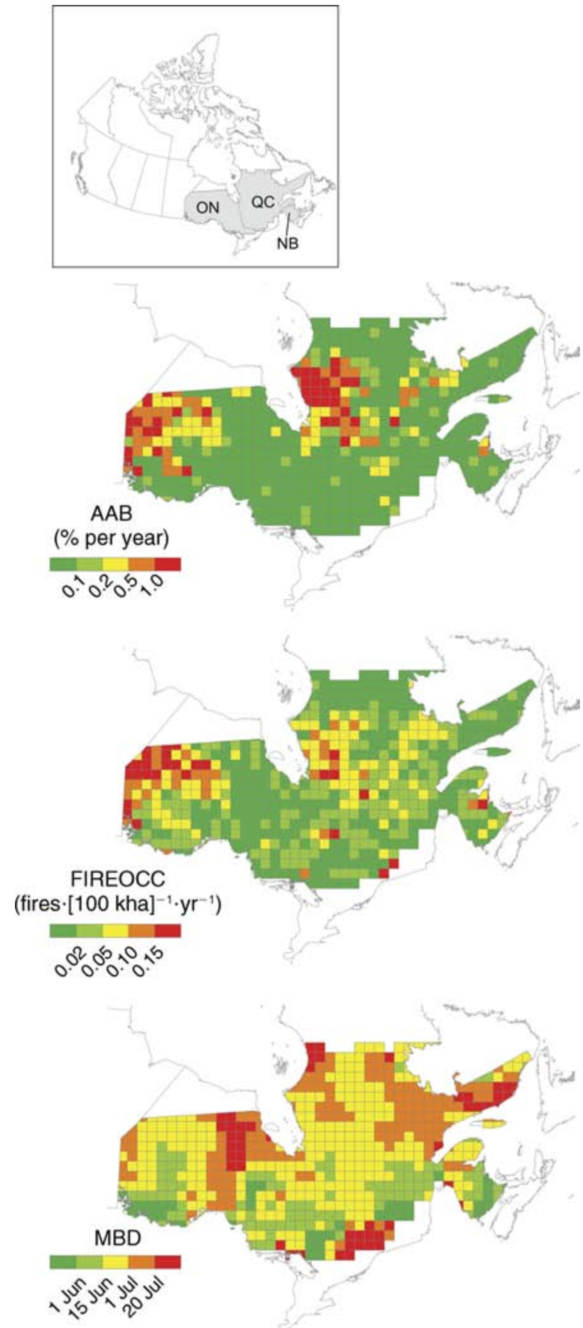

FIG. 1. Location of the study area (gray) as well as the annual area burned, number of fires, and fire seasonality at the 60-km grid-cell level as estimated from the Canadian National Fire Database (CNFDB) for the 1961–1990 period. Abbreviations are: ON, Ontario; QC, Quebec; NB, New Brunswick. AAB is the annual area burned; FIREOCC is the annual number of fires per 100 kha; median burn date (MBD) is the median month and day on which cumulative area burned was 50% of the final area burned.

TABLE 1. Name and description of the predicted and explanatory variables used in this study.

Variable name	Category	Description
AAB	fire regime	annual area burned (percentage of area of fuel)
FIREOCC	fire regime	fire occurrence (fires·100 kha^{-1} of area of fuel·yr^{-1})
NDayStartSsn†	fire regime	number of days from the beginning of the climatic fire season until 50% of area burned is reached
MBD‡	fire regime	median month and day when 50% of area burned is reached
FFMC	climate	mean fine fuel moisture code
FFMCmax	climate	mean maximum fine fuel moisture code
DMC	climate	mean duff moisture code
DMCmax	climate	mean maximum duff moisture code
DC	climate	mean drought code
DCmax	climate	mean maximum drought code
ISI	climate	mean initial spread index
BUI	climate	mean build-up index
BUImax	climate	mean maximum build-up index
FWI	climate	mean fire weather index
FWImax	climate	mean maximum fire weather index
Tmax	climate	mean maximum temperature during the fire season (°C)
WS		mean wind speed during the fire season (km/h)
DayFFMCmax		mean number of days after start of the fire season when the FFMC is at its maximum
DayDMCmax		mean number of days after start of the fire season when the DMC is at its maximum
DayDCmax		mean number of days after start of the fire season when the DC is at its maximum
DayBUImax		mean number of days after start of the fire season when the BUI is at its maximum
DayFWImax	climate	mean number of days after start of the fire season when the FWI is at its maximum
DayTmax		mean number of days after start of the fire season when temperature is at its maximum
MidDay	climate	middle day of fire season
RoadDens	human impact	road density (km road length /km^2 area)
SurfAreaRatio	topography	ratio of surface to area
PctWet	fuel	percentage of area covered by treed, shrubbed or herbaceous wetlands
PctCon	fuel	percentage of area covered by coniferous forests§

† Used in models

‡ Predicted as the sum of NDayStartSsn and the month and day of the beginning of the climatic fire season (as estimated from BioSIM).

§ As estimated from Earth Observation for Sustainable Development of Forests (EOSD) classification maps

weather data (the climate monthly normals) to a grid of geographical coordinates (the gridded cell centroid). First, BioSIM adjusts the local weather data (normals) for differences in latitude, longitude, and elevation between the source of weather data and each cell location by using climatic gradients. Local gradients are obtained from a multiple linear regression equation fitted to the monthly weather parameter observations from the 24 nearest stations in the normal database (Régnière and Saint-Amant 2008). Average elevation of each cell was estimated by intersecting the United States Geological Survey 120 arc-second digital elevation model (DEM) with the cell, and calculating the average elevation of the DEM values that fell within the cell. Data are then averaged with an inverse distance square algorithm among stations. Then, the BioSIM weather generator algorithm generates stochastic daily variation in temperature, precipitation, relative humidity, and wind speed. This algorithm produces realistic seasonal patterns in weather conditions notably by maintaining the temporal autocorrelation between daily variables that occurs naturally. Further details about the weather generator used by BioSIM can be found in Régnière and Saint-Amant (2007).

From the 50 simulated time series of daily weather generated in each cell, we derived the six standard components of the Canadian Forest Fire Weather Index (CFWI) System (Van Wagner 1987), i.e., fine fuel moisture code (FFMC), duff moisture code (DMC), drought code (DC), build-up index (BUI), initial spread index (ISI), and the composite fire weather index (FWI). The CFWI is a fire danger rating system whose components are based on daily solar noon measurements of temperature, relative humidity, wind speed, and 24-h accumulated precipitation. Consequently, temperature, relative humidity, and wind speed data from meteorological stations were adjusted to represent noon values before computing daily CFWI components (R. Saint-Amant, *unpublished manuscript*). The FFMC, DMC, and DC represent a numerical rating of water-holding capacity and drying time for fuel at increasing depth in the soil whereas the ISI and BUI are related to the fire behavior. FWI combines ISI and BUI as a measure of fire danger rating while the DSR is essentially a nonlinear transformation of the FWI. Both the mean and mean maximum values observed during the fire season for each component were estimated. Mean wind speed during the fire season was also estimated. Equations linking CFWI components to daily temperature, humidity, precipitation, and wind speed are highly nonlinear (Van Wagner 1987) and so CFWI estimations could be much affected by extreme weather values simulated by BioSIM. Preliminary analyses showed that most simulated estimates of the

CFWI components (both mean and maximum values) were highly correlated with observed values for the 1961–1990 period (Appendix A: Fig. A1). However, maximum ISI and wind speed values were constantly overestimated by BioSIM, so these components were dropped from subsequent analyses. The average starting time of the fire season was assessed as the first day after snow melt whereas the last day of the fire season was set as the first of three consecutive autumn days with sub-freezing temperature, or when there is a measurable snow cover. Because most of the area burned in the study area did so during a relatively short period of time (Appendix B: Fig. B1) or during events of severe fire danger (Flannigan and Wotton 2001), we computed the month and day each year where each of the CFWI components reaches its maximum annual value (except ISI as maximum simulated values tend to occur later than observed values; Fig. A1). The average midpoint of the fire season, i.e., the month and day halfway between the first and last day of the fire season (MidDay), was also estimated. These latter variables were computed from daily data generated from monthly normals using BioSIM.

Analyses

Fire regime parameters were modeled at the cell level using Random Forests (RF) modeling. Random forests provide accurate predictions without overfitting the data (Prasad et al. 2006). RF has gained popularity in recent years for future projections of species distribution (Prasad et al. 2006) or insect outbreaks (Candau and Fleming 2011) according to climate change because it can handle nonlinear relationships, complex interactions, and highly collinear predictor variables (Prasad et al. 2006, Cutler et al. 2007). Such relationships are very likely between climate/environmental variables and fire regime attributes (Balshi et al. 2009*b*, Parisien et al. 2011). RF has outperformed several nonlinear modeling techniques such as multivariate adaptive regression splines (MARS), regression trees, and bagging trees used to model current and future tree species distribution in the eastern United States (Prasad et al. 2006).

RF is a machine-learning statistical method that fits multiple regression trees to a data set and then combines the predictions from all the trees (Cutler et al. 2007). First, several bootstrap samples (2000 in this study) representing about 64% of all the data are drawn from the data set. Remaining observations (36%) are called out-of-bag (OOB). For each bootstrap sample, a regression tree is fully grown. However, as opposed to a normal regression tree, the best predictor at each node is selected from among a random subset of all the predictors available. In this study, the number of variables randomly sampled as candidates at each split (mtry) was optimized from 1 up to the maximum number of variables included in the data set, in order to minimize the mean of squared residuals (MSE). Out-of-bag observations are used as training data at each bootstrap iteration to estimate MSE as follows:

$$\mathrm{MSE} = n^{-1}\sum_{1}^{n}\{y_i - \hat{y}_i^{\mathrm{OOB}}\}^2$$

where $\hat{y}_i^{\mathrm{OOB}}$ is the average of the OOB predictions for the ith observation. MSE is then used to compute the variation explained as

$$R^2 = \frac{\mathrm{MSE}}{\hat{\sigma}_y^2}.$$

Variable importance (Inc%MSE) is computed by estimating the normalized difference between MSE estimates obtained by first permuting the OOB data and then predictor variables. RF modeling was run separately for all fire regime attributes. Instead of relying on the modeling of MBD, we instead modeled NdayStartSsn, the number of days after the beginning of the fire season (as set by BioSIM) corresponding to MBD. Moreover, NDayStartSsn was modeled using a different set of predictors than AAB and FIREOCC that are thought to better reflect the variation in fire seasonality (Table 1). In fact, weather/climate variables for NDayStartSsn mostly referred to a specific time period within the year when CFWI components and temperature reached their maximum values, on average (Table 1).

Model validation

As OOB observations are not used for tree fitting, OOB estimates can be considered as cross-validated accuracy estimates (Cutler et al. 2007) and therefore they provided a "spatial" validation of RF models. We also wished to temporally validate RF models for each fire regime parameter. However, as fire data were available up to 2010 as of this writing, no full 30-yr normals period was totally independent from our baseline period, i.e., no period did not partly overlap the study period. Model accuracy was therefore assessed using climate normals and fire data for the 1981–2010 period, which represented the least overlapping normal period with the study period (1961–1990) among available normal periods. It has to be noted that several fires lacked an ignition date in the CNFDB for 2000–2010, especially in central and northern Quebec. Therefore, cells ($n = 121$ cells) where these fires had an influence on the calculation of MBD for the 1981–2010 period were removed for accuracy analyses of this attribute.

Future climate data

Future climate projections for temperature, precipitation, wind speed and relative humidity were obtained from the Canadian Climate Regional Model (CRCM 4.2.0, simulation run adjusted resolution = 45 km at 60° N; Caya and Laprise [1999]). CRCM driving data were taken from the Canadian Coupled Global Climate Model (CGCM3/T47) under the IPCC SRES A2 scenario (Nakicenovic et al. 2000). This is the "business-as-usual" scenario where global population steadily increases emissions of greenhouse gas. This scenario includes the effects of sulfate aerosol. Under this scenario, global carbon dioxide emissions should reach 30 Pg C/yr by 2100, which represents a three-fold increase compared with 1990. Future monthly normals at each weather station were directly assessed from changes observed between the current (1961–1990) and future weather conditions estimated in the CRCM cell where the weather station was located. Future climatic variables were estimated for three different periods, 2011–2040, 2041–2070, and 2071–2100, using BioSIM following the same approach as for the historic climatic variables.

Future fire regime

Projections of the future fire regime values under the projected climate conditions of 2011–2040, 2041–2070, and 2071–2100 were performed using the retained RF model obtained previously for each fire regime attribute. Future MBD was estimated from projected NDayStartSsn from RF models and the start of the fire season as estimated from CRCM projections. Although changes in environmental conditions other than climate are expected by 2100, topographical, anthropogenic, and fuel conditions were not altered for our projections. This is the "lesser evil" approach as there are great uncertainties in future anthropogenic and forest conditions, notably regarding road network and future range distribution of tree species in response to logging activities, climate change, and so on, in the next century. Such an approach was already used by numerous authors (e.g., Flannigan et al. 2005, Girardin and Mudelsee 2008, Wotton et al. 2010) to model future fire regimes. Furthermore, it is reasonable to consider that vegetation is at its equilibrium at the scale investigated (i.e., the 3600-km^2 cell). Significant vegetation change at large spatial scales, even under high disturbance rates (~1%/yr), should occur over a very long period. Consequently, we considered that vegetation or, more broadly, fuel composition (essentially the conifer content) within a cell should not change significantly within the temporal window investigated here (100 years) considering the system's inertia.

Homogeneous fire regime zonation

HFR zones were identified separately for the historic and future conditions through spatially constrained clustering analyses. These analyses aimed to connect spatially joined gridded cells into distinct regions having maximum internal similarity according to fire regime attributes. For each period, five different sets of HFR zones were then derived using dynamically spatially constrained agglomerative clustering and partitioning algorithms developed by Guo (2008). This method was favored over traditional spatially constrained hierarchical clustering techniques as it directly optimizes the production of spatially contiguous regions that have maximum internal similarity. We initially built a connectivity graph linking cells in a rook-type fashion. This method led to a few disconnected subgraphs, as some cells were surrounded by areas that did not burn or were located on islands. In order not to leave any unconnected cells, additional connections were created between the nearest cells pertaining to a given subgraph. Then, cells were clustered according to Ward's hierarchical clustering but with contiguity constraints to produce a spatially contiguous tree. Clusters (zones) were dynamically determined throughout an agglomerative algorithm using all edges between clusters, i.e., all links between cells pertaining to different candidate clusters, instead of first-order neighbors only as in traditional spatially constrained hierarchical clustering (Guo 2008). Using a heuristic, the trees were partitioned to optimize the delineation of spatially contiguous regions with minimum sum-of-squared deviations (SSD). The minimum zone size was fixed to four gridded cells covering 14 400 km^2 to avoid the production of very small zones. Zonations were completed for all four periods separately using predicted values of AAB, FIREOCC, and MBD obtained from RF models. In all cases, the three fire regime variables were scaled to have a 0 mean and 1 standard deviation. Each tree was partitioned successively to obtain 2–50 HFR zones giving a total of 49 different zonation solutions for each period. The "best" zonation for a given period, i.e., the most parsimonious solution, was selected by cross-validation as the one showing the smallest coefficient of variation of error. For each solution, 1000 cross-validations were performed using the mvpart function of the mvpart v1.4.0 package in R (R Development Core Team 2011). All zonation solutions were computed using REDCAP v2.0.1 (Guo 2011). Once the best zonation was selected for each period, fire regime and environmental conditions were summarized by averaging the values of all the cells in the HFR zone.

Comparing the zonation configuration between the historical and future periods

The difference in cell partitions between all zonations was estimated using the variation of information (VI) index (Meila 2007). This index measures the amount of information lost or gained when changing one zonation to another. If the VI equals 0, both zonations are similar whereas greater differences in zone affiliation result in higher VI values (max VI = log[n], where n is the total number of cells). We used the fpc package v2.0-2 (Hennig 2010) in R to estimate VI values.

Results

A total of 102 809 km^2 burned throughout the study area during the 1961–1990 period. For most of the study area, the burn rate was below 0.1% per year (Fig. 1). Highest AAB values were recorded in northwest Ontario and Quebec where several cells burned at a rate of more than 1% per year. Fire occurrence followed approxi-

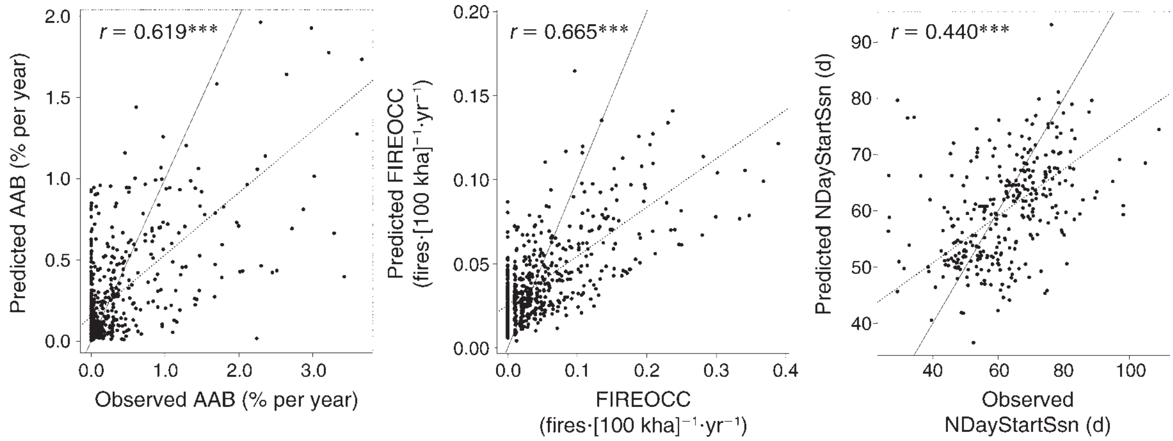

FIG. 2. Assessment of temporal model performance for the three fire regime parameters: AAB, FIREOCC, and NDayStartSsn Random Forests (RF) models built for the 1961–1990 normal period were used to project their values for the 1981–2010 normal period. Predicted values are plotted here against observed values for this period. The solid line shows a 1:1 slope; the dotted line is the major axis regression line between predicted and observed values. Pearson's r is also given. All correlation coefficients are highly significant ($P \ll 0.001$). NdayStartSsn is the number of days after the beginning of the fire season (as set by BioSIM) corresponding to MBD.

mately the same trend as AAB (Fig. 1). For the great majority of the study area, 50% of the area burned occurred before July 1 during the historic period (Fig. 1). Except for a small area in southern Quebec and Ontario where half of the area burned was reached after July 20, fires tended to occur later in the northern part of the study area.

RF modeling of AAB, FIREOCC, and NDayStartSsn

Pseudo-R^2 values (AAB = 0.477, FIREOCC = 0.411, NDayStartSsn = 0.481) as estimated from training data revealed rather high spatial predictive accuracy for RF models. However, models tended to underestimate AAB and FIREOCC in areas with exceptionally high fire activity (e.g., northwest Ontario and Québec,) whereas MBD was underestimated in small portions in the southernmost part of the study area (Appendix C: Fig. C1). Assessment of model performance on a temporal basis shows that predicted and observed AAB and FIREOCC values are highly ($P \ll 0.001$) correlated (r = 0.619 and 0.665, respectively) although, as for the spatial cross-validation analysis, fire activity was underestimated when exceptionally high during the 1981–2010 period (Fig. 2). Therefore, projections of fire activity in these areas may be conservative. Model performance was lower for MBD (r = 0.440) although predictions were significantly ($P \ll 0.001$) related to observed values (Fig. 2).

According to RF modeling, non-climatic variables had a high influence on AAB and FIREOCC (variables are defined in Table 1). For both fire regime parameters, road density and the surface to area ratio ranked among the most important variables (Fig. 3). Fuel variables PctCon and PctWet also ranked as important variables for AAB and FIREOCC. High road density, terrain roughness, and proportion of wetlands were an impediment for both fire regime attributes. On the other hand, a greater proportion of coniferous forest resulted in higher AAB and FIREOCC, especially at high PctCon values (Fig. 4). PctWet also had a great influence on NDayStartSsn (Fig. 3), with the latter constantly occurring later where wetlands are more abundant (Fig. 4), notably along the western side of James Bay (Fig. 1).

Among weather/climate predictors, BUImax and FFMCmax were most influential for AAB and FIREOCC, respectively (Fig. 3). Generally, mean maximum value of CFWI components had a greater influence on AAB and FIREOCC than the mean of the components. However, mean wind speed and mean drought code were also important determinants of both fire regime attributes, and wind speed was important for FIREOCC (Fig. 3). Both AAB and FIREOCC increased sharply at DC values above 140. Generally, AAB and FIREOCC values increased along with CFWI predictors mostly in a quasi-sigmoidal or quasi-exponential fashion (Fig. 4). The occurrence of NDayStartSsn was mostly influenced by DayDCmax although DayFFMCmax was also highly influential (Fig. 3) when compared with the normal occurrence of other weather/climate events.

Future fire-weather conditions

According to the A2 scenario, mean temperature during the fire season would gradually increase virtually everywhere over the 21st century, mostly by 2–4°C by 2071–2100 (Appendix D: Fig. D1). The largest temperature increases would be observed in southern and western Ontario. Although western Ontario would experience drier conditions during the fire season by the end of the 21st century, precipitation would steadily increase elsewhere, especially in northern Quebec (Fig. D1). The length of the climatic fire season would also

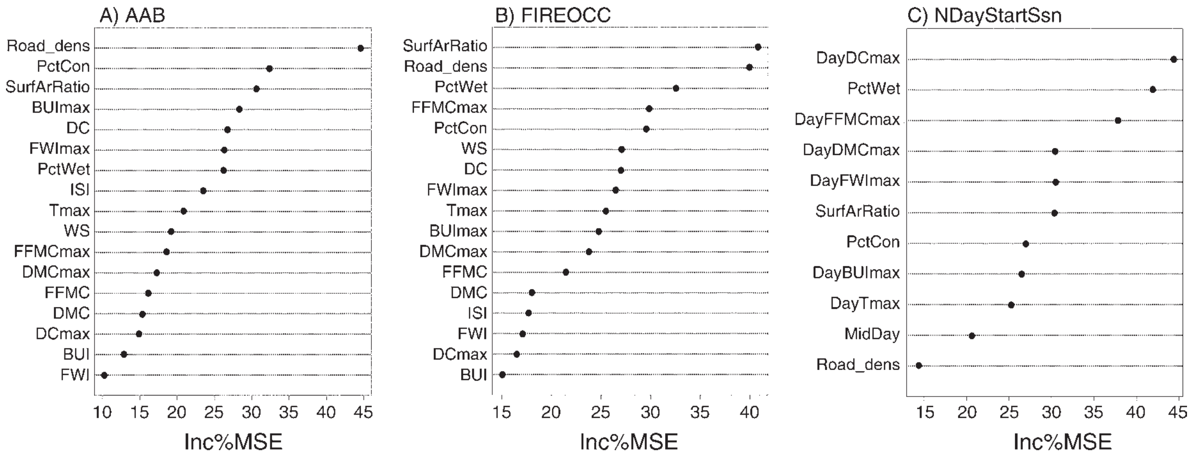

FIG. 3. Variable importance in RF models predicting AAB, FIREOCC, and NDayStartSsn. Variable importance is measured as the normalized difference (Inc%MSE) between the prediction error (MSE) measured when permuting the out-of-bag portion of the data and the MSE when permuting the given variable. Large Inc%MSE indicates high variable importance in the RF model. Variables are defined in Table 1.

increase ubiquitously to become longer by more than a month in most of the study area, with the greatest lengthening (>50 days) occurring in central and eastern Quebec. The beginning of the fire season would be earlier by 10 to 20 days on average by 2100 with the largest shift following approximately the same pattern as for the length of the fire season (Fig. D1). Further descriptions of future weather conditions are restrained to the most important predictor variables for fire regime parameters as assessed from RF modeling.

Despite an increase in precipitation over much of the study area, the most important CFWI components would steadily increase over time, with the exception of FFMCmax values, which would rise very slightly by 2100 (Appendix E). No significant changes were projected to mean wind speed. The largest period-to-period changes would occur by 2071–2100, especially in Ontario. Absolute increase in BUImax would be most important in areas that had already experienced the highest values during the historic period (Appendix E). Patterns of change in DC and FWImax would be roughly similar, except for northern Quebec where mean DC would decrease by 2040 and again by 2100. The largest increase for both CFWI components would occur in western and southern Ontario (Appendix E).

The occurrence of maximum DC values through the fire season would not change greatly until 2071–2100 (Appendix E). By the end of the 21st century, the occurrence of maximum DC values would be later in the fire season, especially in central Quebec and in Ontario where it would happen more than two weeks later (Appendix E). In contrast, maximum FFMC values would be observed sooner in Ontario during the 2011–2040 period when compared with 1961–1990. Afterward, peaks in FFMC values would be later in the fire season compared with the historic period, yet mostly by less than two weeks (Appendix E).

Historic and future fire regime zonation

The best zonations resulted in 21–29 HFR zones (Fig. 5, see also Appendix F) depending on the time period considered. A high portion of the total variability of the fire regime (R_a^2 between 0.763 and 0.849) was captured by these zonations (Fig. 5).

Zonation analyses revealed that predicted historic fire regime patterns were second-order nonstationary, i.e., both variance and mean were unstable spatially. Indeed, relatively high heterogeneity in fire regime was observed in western Ontario and the southernmost part of the study area, as seen by the large number of rather small zones (Fig. 5). In this latter area, HFR zones experiencing late-season fires intermingled with small zones with earlier MBD. In contrast, large homogeneous zones (e.g., zones 13, 16, 19) were delineated in eastern Ontario and central Quebec as a result of uniformly low fire frequency and AAB (Fig. 5). Other zones were outlined in northwestern Quebec and Ontario with frequent fires burning large areas. One small zone (10) located in New Brunswick, was delineated as a result of a particularly greater predicted fire frequency and AAB than their surroundings.

According to the VI index, the largest changes in zone configurations between two consecutive time periods would happen by 2011–2040, and thereafter the configuration would become more stable (Table 2). Nevertheless, fire regime would become more heterogeneous by 2071–2100, especially in Ontario where several zones were delineated by this time period (Fig. 5). A relatively large number of zones were delineated in western Ontario throughout the time period considered here. In contrast, relatively large zones depicting areas with homogeneous fire regime were outlined in central Quebec for all four periods.

The largest changes in fire regime would occur in Ontario, central and northeastern Quebec, as well as in

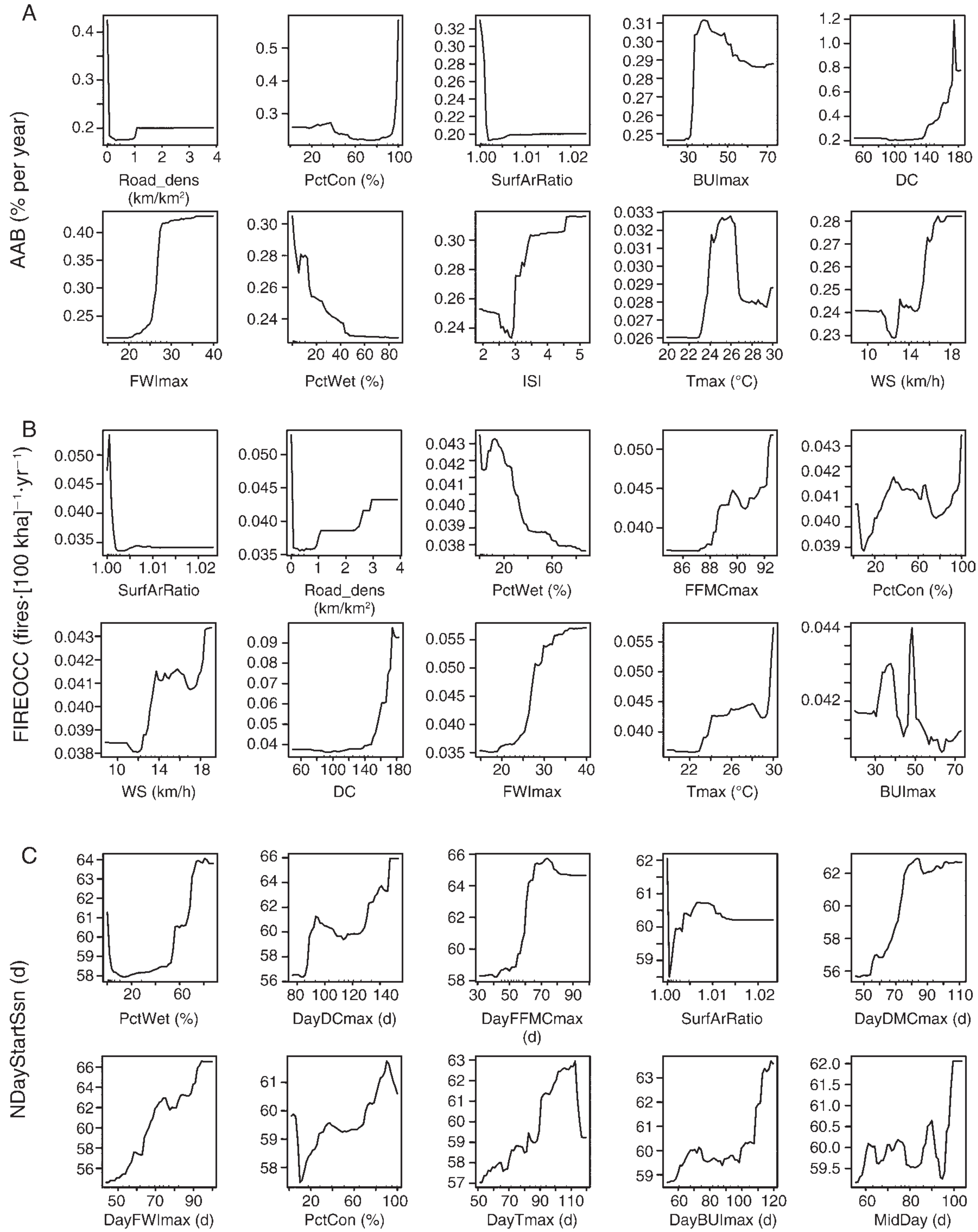

FIG. 4. Partial dependence plots of each predictor on the three fire regime attributes. The partial dependence of a given variable is the expectation of the Random Forests function with respect to all variables except the one under study (Cutler et al. 2007). Variables are ordered by their measured importance (see Fig. 3) on AAB, FIREOCC, and NDayStartSsn. Only the 10 most important variables for each fire regime attribute are shown. Variables are defined in Table 1.

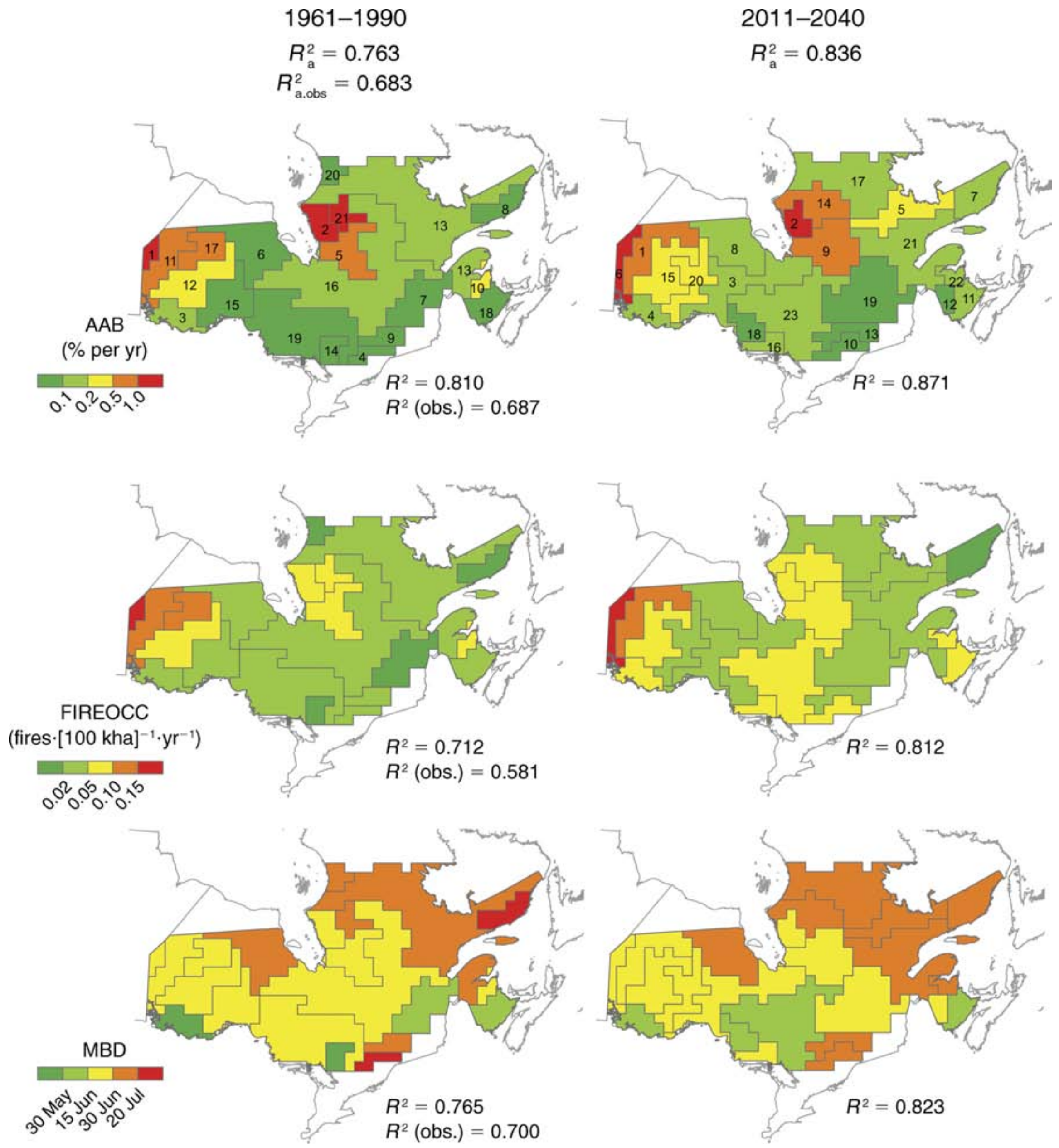

FIG. 5. Annual area burned, number of fires, and median burn date (MBD) averaged at the homogeneous fire regime (HFR) zone level for the historic (1961–1990) and future periods (2011–2040, 2041–2070, 2071–2100) considered in this study. Fire data were estimated for all periods, including 1961–1990 (zone values for the 1961–1990 periods refer to values predicted by Random Forests models, instead of observed values), from the RF model predicting the three fire regime parameters in the 60-km gridded cells. Numbers on the map are the zone numbers. The variability (R^2_a) of the fire regime captured by these zonations, as well as for each fire regime attribute (R^2) considered separately, is shown. The variability captured by the 1961–1990 period was also assessed on observed data (obs.).

southern New Brunswick (Fig. 6). Changes in these areas would be mostly driven by sharp increases in area burned and fire occurrence. Notably, the fire regime in south- and northeastern Ontario would shift from one with relatively few fires resulting in low AAB to one with frequent fires leading to more than 0.5% of annual area burned by 2071–2100 (Fig. 5). Similar shifts would occur in eastern and northern Quebec although changes in AAB and fire frequency would be smaller. Conversely, the fire regime would remain relatively unchanged in central and northwestern Quebec as well as in northwest Ontario although fires would tend to occur somewhat sooner in the latter area (Figs. 5 and 6).

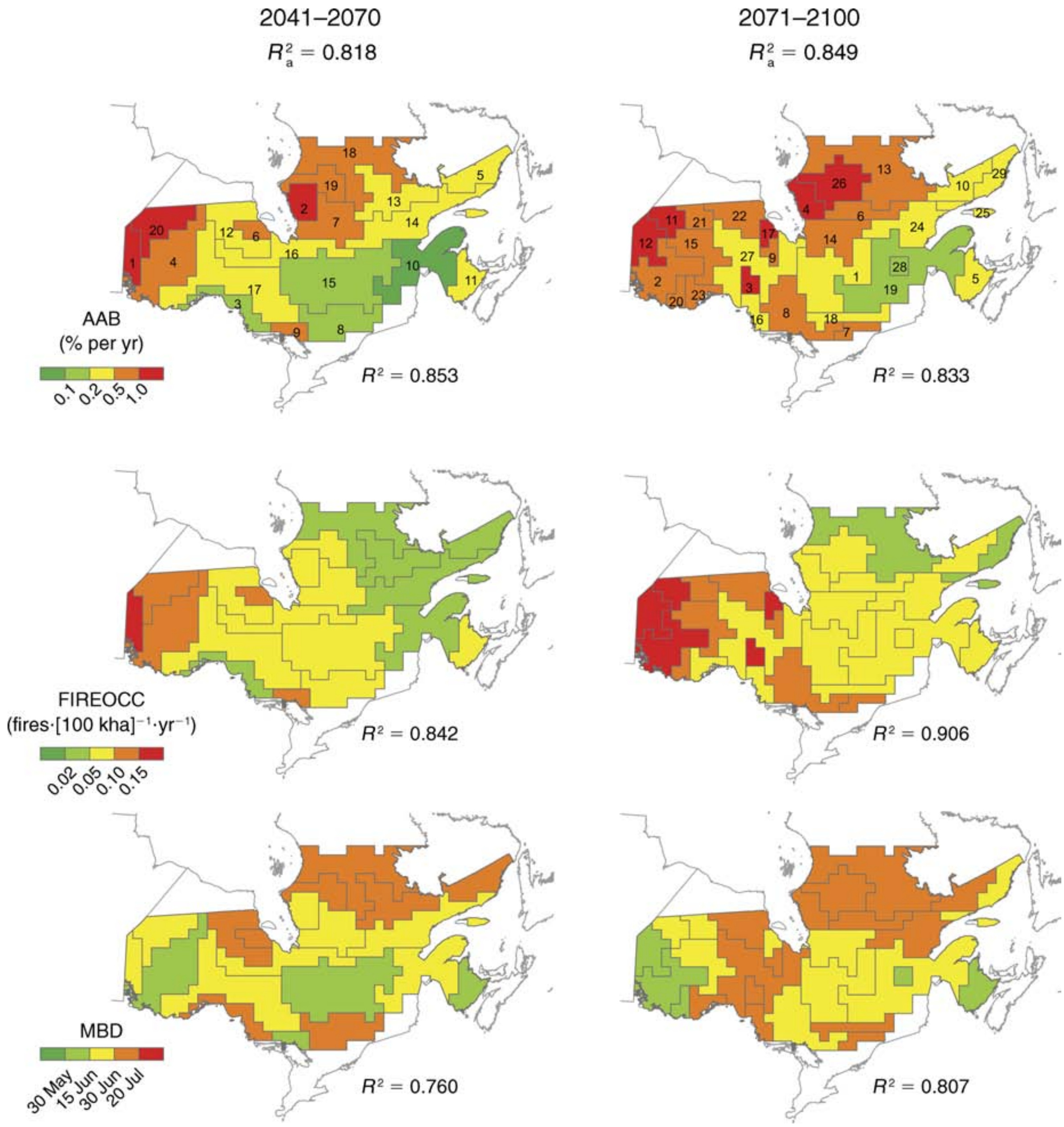

FIG. 5. Continued.

Overall, AAB and FIREOCC would increase mostly by 2041–2070 and then reach an increase of 143.8% and 119.4%, respectively, by 2071–2100 (Fig. 6) with only a very small part of the study area showing no important changes or a decrease. A sharp increase would occur in most of Ontario, and eastern Quebec (Fig. 6). These areas would experience more than four times the AAB and FIREOCC recorded during the historic period. Most of Ontario would be subject to an annual burning rate and FIREOCC of more than 0.5% and 0.1 fires/100 kha, respectively, by 2071–2100. When averaged by zones, FIREOCC and AAB would increase by two- to fourfold in southeastern Ontario, central and eastern Quebec as early as 2011–2040. Small zones in southern and northern Ontario and eastern Quebec (zones 6 and 9) were outlined in 2041–2070 as a result of relatively high AAB and FIREOCC compared with their surroundings, which contrast with the historic period (Fig. 5). Two small zones (3 and 17) were delineated by 2071–2100 in northeastern and central Ontario reflecting a particularly high fire activity. Large increases (more than fourfold) in AAB were also projected for northern Quebec and southern New Brunswick. In contrast, these two fire regime attributes would remain relatively

TABLE 2. Meila's variation of information (VI) criteria to assess differences in cell partition between the best zonation computed for a given time period.

Time period	1961–1990	2011–2040	2041–2070	2071–2100
1961–1990	0			
2011–2040	1.846	0		
2041–2070	2.162	1.616	0	
2071–2100	2.124	1.710	1.718	0

unchanged in northwestern Quebec and northwestern Ontario, and yet remain one of the highest of the study area.

No zones were clearly delineated throughout the 21st century as a result of sharp changes in MBD (Fig. 5). Nevertheless, rather large areas would experience a small shift (mostly 10–20 days) toward a later fire season in central Ontario and northern Quebec in 2071–2100 (Fig. 6). However, fires would tend to occur sooner concurrently in northwestern Ontario where fire activity is projected to be very high. Consequently, MBD, as weighted by fire occurrence over all the study area, would remain relatively unchanged by the end of the 21st century. Regional changes in MBD would mostly appear late in the 21st century as this fire regime attribute would remain relatively unchanged over most of the study area up to 2070 (Fig. 6).

DISCUSSION

Along with Boulanger et al. (2012), we are presenting one of the first zonations of the current fire regime of the eastern North American boreal forest solely based on fire regime characteristics. Although it is based on a relatively short time period, we think that our choice of zone size and methodology have allowed in an accurate characterization of current and also future regional fire regimes. This type of exercise allowed us to define multiple zones within areas that are usually considered uniform when researchers are using predefined zones (Boulanger et al. 2012). Indeed, we are confident that our HFR zonation better captured the heterogeneity in both the historical and future periods than classifications based on administrative or landscape physical characteristics (Boulanger et al. 2012). HFR zonation for the 1961–1990 period is in relatively good agreement with previous studies based on historical fire data. Zones in northwestern Ontario reflect the higher fire activity as documented by Bridge (2001). In Quebec, zones 2, 5, and 21 correspond to the higher fire frequency reported by Gauthier et al. (2009), Le Goff et al. (2007), and J. Héon and D. Arseneault (*unpublished manuscript*) when compared with neighboring areas (Bergeron et al. 2004*b*).

To our knowledge, this is the first study to concurrently model current and future large fire occurrence, annual area burned, and fire seasonality for northern North America. Admittedly, fire regimes can be described by more than these three attributes. However, there is no consensus on which of those attributes a fire regime should be used (Krebs et al. 2010) and selection of attributes is largely dependent of the research objectives. We chose our three attributes because they are very frequently used, mostly independently, in fire regime studies across the boreal biome. Future work focusing, for example, on the occurrence of fire events from different size classes (e.g., Kasischke and Turetsky 2006, Terrier et al. 2013), or on more detailed analyses of fire seasonality (Kasischke et al. 2010) would add further precisions to the characterization of the current and future fire regimes.

Our models provide additional evidence that the fire regime at the scale investigated is strongly linked to fuel composition, topography, and anthropogenic influences. High coniferous content generally promotes large fire occurrence and area burned as this fuel type appears more flammable than deciduous trees (Krawchuk et al. 2006). Moreover, our results also suggested that rough terrain impedes large fire occurrence and propagation as suggested earlier (Cary et al. 2006, Cyr et al. 2007) while area burned and fire occurrence were strongly and negatively linked to road density, which may be a surrogate for fire monitoring and suppression efforts (Martell and Sun 2008). Obviously, models predicted higher fire activity where fire-weather conditions were more severe. Moreover, RF modeling clearly demonstrated that the relationship between CFWI components and fire occurrence/area burned may be strongly nonlinear. Except for the drought code, mean maximal values of CFWI components were better predictors of fire occurrence and the annual area burned than their average counterparts. Indeed, fire events are known to occur more often during specific periods within the fire season when the fuel is particularly dry (Flannigan and Wotton 2001). As a result, fire seasonality was strongly affected by the occurrence of fire-weather extremes with half of the area burned being cumulated after the beginning of the fire season in areas experiencing later occurrence of fire-weather extremes.

Future fire regime in eastern Canada

Our results indicated that fire regime in eastern Canada, mostly annual area burned and large fire occurrence, should undergo major regional changes in the current century. Larger shifts would occur in the last decades as reported before (e.g., Balshi et al. 2009*b*). Sharp and ubiquitous increases in temperature would greatly offset the increase in precipitation during the fire season as projected by the CRCM, resulting in a rapid worsening of fire-weather conditions and a general increase in area burned and large fire occurrence. However, as other authors (e.g., Bergeron et al. 2004*a*, Flannigan et al. 2005, Balshi et al. 2009*b*) have already pointed out, future changes in fire regimes would be rather heterogeneous across eastern Canada. Indeed, some zones located, e.g., in western Quebec or western Ontario would experience small alterations compared

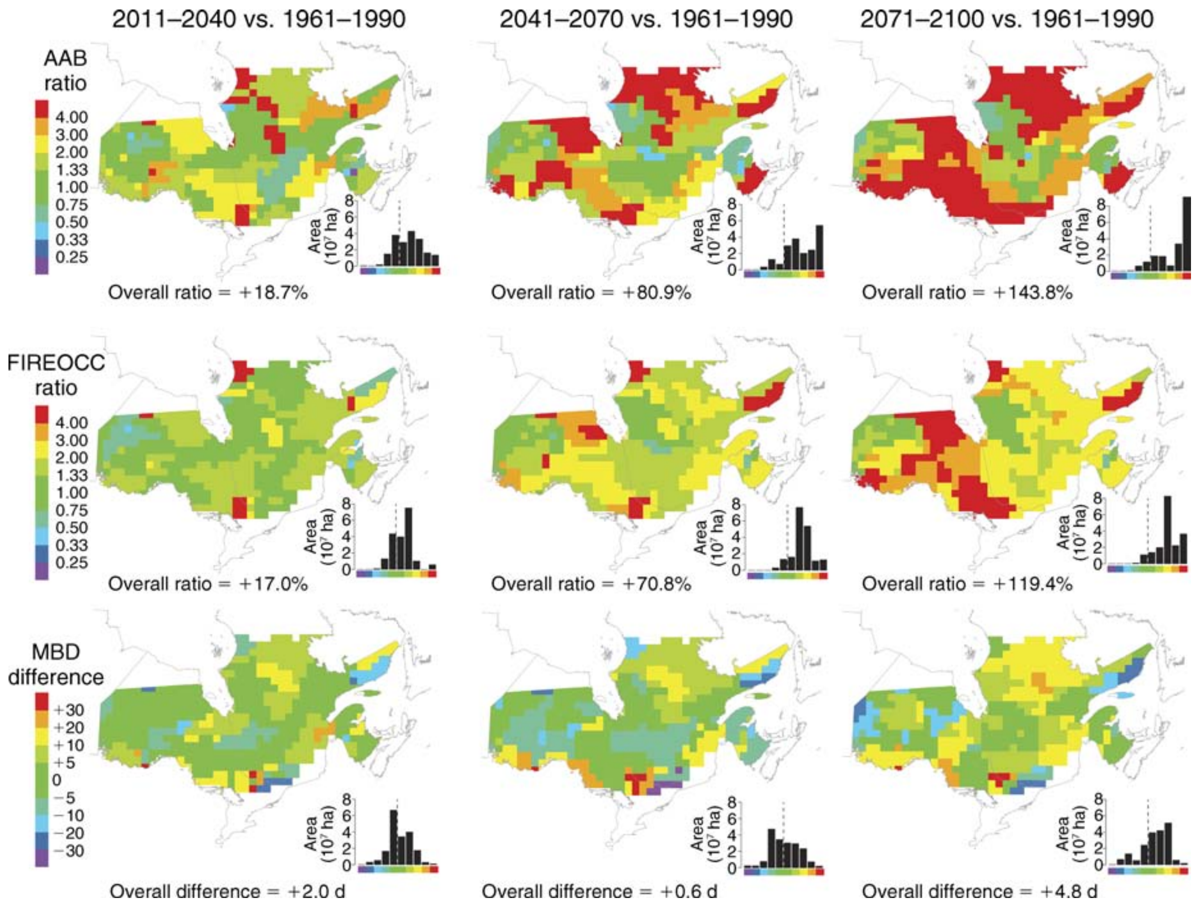

FIG. 6. AAB and FIREOCC ratio and MBD difference as estimated at the zone level between all future periods and the predicted historic interval (1961–1990). Insets show the area corresponding to each value.

with the historic period while others (e.g., southeastern Ontario) would face great shifts in many fire regime aspects. Regional trends in fire regimes predicted here are roughly similar to those reported previously (Bergeron et al. 2004*a*, 2010, Flannigan et al. 2005, Wotton et al. 2010). For instance, models predicted a general increase in annual area burned and the number of fires for most of Ontario while virtually no changes are forecasted for western Quebec. Remarkably, both annual area burned and the number of fires are predicted to dramatically increase in zones where fire activity was infrequent during the 1961–1990 period, e.g., northeastern and southeastern Ontario, to levels currently experienced by the most "fire-active" zones. Although much higher than during the 1961–1990 period, projected annual area burned for southeastern Ontario by 2071–2100 would fall well within the burn rate values experienced between ca. 1700 and 1900 (Bergeron et al. 2004*a*). Results also suggest that western Ontario and northwestern Quebec by 2071–2100 would still be among the most fire active zones in the study area.

Overall, our models predicted a 2.2- and 2.4-fold increase in the number of fires and the annual area burned, respectively, within the study area. These increases are within the range previously reported for this area though there is tremendous variation reported in the literature. Using a different nonlinear modeling technique (MARS), Balshi et al. (2009*b*) projected a 3.6- to 5.6-fold increase in annual area burned by the end of the 21st century, when compared to 1991–2000, for western Canada and Alaska, projecting very short fire return intervals (typically below 50 years) for the few cells located in western Ontario. Using the same global circulation model and SRES scenario as here, Podur and Wotton (2010) predicted an even larger shift (up to 820% by 2099 relative to 1992–2003) in annual area burned in Ontario although a much lower concurrent increase in fire occurrence (38% by 2099). Nevertheless, one must note that our models tend to underestimate the annual area burned and large fire occurrence in very fire-active areas; consequently, our estimates of future fire activity may be rather conservative in these zones. Smaller increases, typically below twofold, were also reported for both the number of fires and annual area burned (e.g., Flannigan et al. 2005, Girardin and Mudelsee 2008, Wotton et al. 2010).

For most of the study area, half of the burned area would be attained later in the season by 2071–2100. This contradicts earlier studies that suggested that extreme fire danger would occur more frequently early in the season (Stocks et al. 1998), resulting in larger annual area burned in late spring (Amiro et al. 2009). Even though weather conditions would be conducive to fire much earlier in the season, CRCM outputs suggested that maximal values of the important CFWI components, namely DC and FFMC, would occur later in the fire season, shifting the area burned to slightly later in the summer. It has to be noted that there are still uncertainties related to this shift as temporal changes in ignitions (mostly lightning activity) are highly uncertain. Nevertheless, a similar shift in fire occurrence was recently proposed for northwestern Quebec based on future fire severity rating (Le Goff et al. 2009). Recent observations in Alaska also suggested a shift in the fire season in the last decade toward late-summer fires as a result of climate change (Kasischke et al. 2010). It has to be noted that later occurrence of the most severe fire weather does not preclude the occurrence of large fires earlier or later in the season than during the historic period. Indeed, the CRCM projects a much longer fire season, mostly 35–50 days longer by 2071–2100, that would extend about equally earlier in spring and later in fall.

Refining current and future fire and forest management strategies

The fire regime characteristics of our historic zonation, and the characteristics of our predicted future zonations are clearly of interest for forest and fire management agencies as they reveal anomalous zones with high fire occurrence or large area burned, that were otherwise hidden in larger areas that are frequently used as the basis for zonation (Boulanger et al. 2012). The fire statistics may thus contribute to improving current and future fire management strategies and operational fire management planning, i.e., the deployment of fire management efforts and means across a territory. For example in Quebec, fire management efforts are distributed according to two main zones: intensive and extensive fire management zones, corresponding roughly to the territories situated south and north of the 51st parallel. However, delineation of fire regime zones inside the intensive fire management zone is of great relevance for the fire suppression strategic planning (for aerial detection planning as well as for the location of primary and secondary water bomber airports).

Although fire regime characteristics would change significantly over time, most zone boundaries would remain relatively stable over time with a few exceptions. This suggests that agencies should be able to adapt to and plan their efforts for novel fire conditions on a regional and rather long-term basis, without greatly modifying the areas under their jurisdiction. Nevertheless, they would have to quickly adapt to these novel conditions and immediately implement adaptive strategies as significant changes in the fire regime are projected in several areas as early as the 2011–2040 period. Indeed, several authors have suggested that future climate may lead to more frequent situations where fire management capacities are overwhelmed by numerous fires occurring simultaneously (Wotton and Stocks 2006, Podur and Wotton 2010). Although our aim was not to estimate the potential for such situations in the future, our results identify zones where an increase in fire activity is likely and where efforts should be focused. Keeping in mind that the increase in escaped fires (i.e., fires that escaped containment by initial attack) is greater than the increase in fire activity alone (Podur and Wotton 2010), some zones located within the intensive fire management area where large fires are currently uncommon, e.g., southeastern Ontario, might have to allocate more resources than today for future fire management. Furthermore, the shift in the fire season toward late summer, and the lengthening of the fire season are expected to have large impacts on the fire management budget and planning virtually everywhere (Wotton and Flannigan 1993, Wotton and Stocks 2006). As a result, the present protection system used in some zones may be unable to handle the increased fire load without better infrastructures and financial resources (Stocks et al. 1998, Wotton and Stocks 2006, Flannigan et al. 2009).

The zonation of fire regimes is also of great interest in discussions of sustainable forest management. It provides the information necessary to integrate forest fire as a forest management constraint where forest fire is a dominant ecological process in the landscape (Gauthier et al. 2009). Several authors (e.g., Armstrong 2004, Savage et al. 2010, Raulier et al. 2013) have suggested that fire risk should be incorporated into calculations of annual allowable cut in order to decrease the likelihood of a timber supply shortfall due to fire. This approach is a reasonable means to reach forest management objectives that better respect sustainable forest management principles (Armstrong 2004). The current and future fire activity in many zones under forest management suggested that fire risk is high enough to significantly reduce the probability that stands will reach commercial maturity before experiencing a fire (Armstrong 2004, Savage et al. 2010). Such changes may greatly affect forest productivity and have significant impacts on timber supply (Raulier et al. 2013). Savage et al. (2010) suggested that fire risk mitigation strategies should be implemented when AAB is above 0.45% in order to reduce the interannual variability of harvest volumes due to fire. Although current AAB suggested that such a strategy should be deployed in western Ontario and part of zone 5 in northwestern Quebec, future HFR zonations projected that virtually all Ontario would see its timber supply affected by fire by 2100 (see Appendix F: Table F3). As a consequence, future consideration in forest management planning, e.g., by using fire-smart forest management (Hirsch et al. 2001), should be undertaken in many zones in order to be able to cope with higher fire risk. Among these, a revision of the expectations in terms of timber supply from managed forests, notably by subtracting potential timber losses from the annual allowable cut, is required. Furthermore, the use of fire-adapted species such as jack pine in plantations may be a way to ensure good regeneration success after fire while the use of species that have a younger commercial maturity may mitigate future potential losses. In other zones where fire activity is moderate or low under both current and future climate conditions, traditional forest management that readjusts annual allowable cut levels following large fire years while mitigating timber losses using salvage logging may be enough to deal with the level of fire risk.

Other applications for current and future HFR zonations

We believe that large-scale assessments of forest and biodiversity patterns, energy flows and carbon storage would benefit from HFR zonation, particularly where fire is, or will become, the most important natural disturbance. For instance, future zonation may help to identify areas where forest composition, structure and processes might be altered under a changing fire regime. Significant projected shifts in fire regimes may influence the successional pathways of postfire regeneration, notably by favoring early-successional and fire-adapted species (e.g., jack pine, quaking aspen), prompting faster forest cover alterations than those assumed as a result of changes in temperature and precipitation only (Weber and Flannigan 1997). Such a shift should be very important in regions that currently experience long fire return intervals but where a dramatic increase in fire frequency and annual area burned is expected. Furthermore, the shift to more late-season fires as well as the general increase in the drought code imply that many more fires would occur during more severe drought conditions (Turetsky et al. 2011). Fires occurring during such drought periods have the potential to deeply burn the organic layer and greatly affect the postfire regeneration conditions by favoring species adapted to warm and thin-duff postfire conditions (Lecomte et al. 2006). Consequently, one may hypothesize that most black spruce forests located in Ontario and in a few zones in northern Quebec are vulnerable to such fire regime changes as stand conversion is much more likely under relatively short fire return interval and deeper organic soil combustion (Le Goff and Sirois 2004, Kasischke et al. 2010). Conversely, the productivity of black spruce stands located in the northern Clay Belt may benefit from a shorter fire return interval and more severe burning of the organic layer by reducing the hampering impact of paludification under a long fire cycle (Lecomte et al. 2006). Major shifts in forest cover could substantially influence biodiversity patterns, energy exchange, and surface albedo, as well as climate/disturbance feedback.

Future HFR zonations should help to identify areas where large-scale changes in the carbon budget are more likely to occur, especially in areas where fire is recognized as a dominant driver of the carbon balance (Bond-Lamberty et al. 2007). Shifting fire regime is likely to influence aboveground biomass, belowground carbon content and net carbon emission from forests (Amiro et al. 2009). Despite changes in stand productivity resulting from higher temperatures (Kurz et al. 2007), a shorter fire return interval will promote higher C losses and a decrease in carbon storage (Brown and Johnstone 2011). Likewise, late-season fires are more likely to result in larger carbon emissions and fuel loss through deeper burning of the soil organic layer and faster postfire soil decomposition (Kasischke and Johnstone 2005, Lecomte et al. 2006, Amiro et al. 2009, de Groot et al. 2009, Turetsky et al. 2011). In this context, it is likely that a great part of our study area will be subjected to increasing C losses as a result of a more active fire season with fires occurring during more severe drought conditions (Turetsky et al. 2011).

Limitations

We acknowledge that our analyses have some limitations. Our objective was to characterize and predict the fire regime, as averaged on a 30-yr basis, by relying on another regime, i.e., climate normals. Most studies (e.g., Flannigan et al. 2005, Balshi et al. 2009*b*) used either monthly or annual data to predict future changes in fire regime. Although our method was used with success earlier to estimate the relationship between fire regime and climate (e.g., Parisien et al. 2011, Moritz et al. 2012), we are aware that using averages blurs the interannual variability or short- to mid-term trends in both fire and climate regimes that influences ecological processes (Girardin et al. 2006). Indeed, one must note that fire activity steadily increased during the 1961–1990 period in Canada, mostly as a result of a concurrent increase in mean temperature (Gillett et al. 2004). Consequently, the climate conditions during the 1961–1990 period that we used as baseline were not "stable" but were rather already changing. Such trends cannot be detected using our modeling technique, possibly affecting model outputs. However, our models using climate normals predicted trends in fire regime attributes roughly similar to those computed on a monthly or annual basis in other studies. Furthermore, long-term climate norms are thought to be one of the most stable and robust approaches for predicting large-scale and long-term fire regimes (Moritz et al. 2012) as the GCM's ability to model the interannual variability of the future climate is highly uncertain (Stoner et al. 2009). As such, we endorse the point of view of Parisien et al. (2011) that the techniques complement each other though this assumption deserves further investigation using parallel data and modeling approaches.

Besides fire-weather/climate variables, our models assumed a "static" view of the environment for the future that is unlikely. Indeed, we did not account for potential changes in vegetation composition and spatial patterns prompted by fire itself or other natural (e.g., windthrow, insect outbreaks) or anthropogenic (logging) disturbances, nor in forest or fire management policies. All these changes may generate either negative or positive feedback on the subsequent fire regime attributes (Krawchuk et al. 2006). Despite this potential caveat, the great majority of authors projecting future fire regimes assumed no changes in vegetation pattern. Moreover, as mentioned earlier, we suspect that changes to fuel composition resulting from just natural disturbances should be very small for the time window considered given an assume level of the system's inertia. Nevertheless, future integration of these potential changes in vegetation patterns and anthropogenic influence may provide more accurate estimates of the future boreal fire regime.

Furthermore, many cells in the future will be subject to climate or fire-weather values that are beyond the range observed during the historic period. For instance, most of Ontario will experience higher annual BUImax values by 2071–2100 than the maximum values estimated for all the study area during the reference period of 1961–1990. In this context, the exact behavior of fire-weather variables with regard to fire regime attributes at such high values, especially its interaction with fuel, is uncertain and as such, must be interpreted with caution.

Conclusions

Our results clearly highlight the spatial variability of fire regimes in eastern Canada both under the current climate and that expected in the future. Zonation analyses revealed that zone boundaries would not change very much under climate change. However, analyses identified several zones where great shifts in the fire regime are likely. Overall, annual area burned and fire occurrence would dramatically increase, especially in Ontario whereas the fire season would shift toward more late-season fires, although the fire season would be extended in both spring and fall. Such shifts will likely have huge consequences for fire and forest management policies, biodiversity carbon fluxes, and more, suggesting a necessary adaptation to the projected changes in fire regime. In this context, we consider that HFR zonation provides a framework to help forest and fire management agencies adapt to novel fire risk conditions. In fact, these results suggest that zonation based on the disturbance itself may reveal significant differences that would otherwise be hidden when using predefined zones. In addition to fire, other major disturbances (especially insect outbreaks and storm damage) may have a profound impact on landscape structure and function and forest management (Dymond et al. 2010), and are likely to interact with fire (Fleming et al. 2002). Further work incorporating attributes from other disturbance agents in order to define current and future homogeneous disturbance zones should provide a more comprehensive and holistic framework with which to understand the dynamics of Canadian forests and regionally adapt disturbance and forest management policies to climate change.

Acknowledgments

The authors thank all provincial and territorial agencies and Parks Canada, as well as many Canadian Forest Service employees who contributed to the compilation of the National Fire Database. We thank Rémi Saint-Amant and Jacques Régnière (Natural Resources Canada) for providing the climate data generated by BioSIM. We also thank Catherine Boudreault, Martin Girardin, Eric Kasischke, Mike Wotton, and one anonymous reviewer for comments on earlier versions of the manuscript. This study was funded by Natural Resources Canada.

Literature Cited

Amiro, B. D., A. Cantin, M. D. Flannigan, and W. J. de Groot. 2009. Future emissions from Canadian boreal forest fires. Canadian Journal of Forest Research 39:383–395.

Armstrong, G. W. 2004. Sustainability of timber supply considering the risk of wildfire. Forest Science 50:626–639.

Balshi, M. S., A. D. McGuire, P. Duffy, M. Flannigan, D. W. Kicklighter, and J. Melillo. 2009*a*. Vulnerability of carbon storage in North American boreal forests to wildfires during the 21st century. Global Change Biology 15:1491–1510.

Balshi, M. S., A. D. McGuire, P. Duffy, M. Flannigan, J. Walsh, and J. Melillo. 2009*b*. Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. Global Change Biology 15:578–600.

Beaubien, J., J. Cihlar, G. Simard, and R. Latifovic. 1999. Land cover from multiple thematic mapper scenes using a new enhancement-classification methodology. Journal of Geophysical Research 104:909–920.

Bergeron, Y., et al. 2006. Past, current, and future fire frequencies in Quebec's commercial forests: implications for the cumulative effects of harvesting and fire on age-class structure and natural disturbance-based management. Canadian Journal of Forest Research 36:2737–2744.

Bergeron, Y., D. Cyr, M.-P. Girardin, and C. Carcaillet. 2010. Will climate change drive 21st century burn rates in Canadian boreal forest outside of its natural variability: collating global climate model experiments with sedimentary charcoal data. International Journal of Wildland Fire 19:1127–1139.

Bergeron, Y., M. Flannigan, S. Gauthier, A. Leduc, and P. Lefort. 2004*a*. Past, current and future fire frequency in the Canadian boreal forest: implications for sustainable forest management. Ambio 33:356–360.

Bergeron, Y., S. Gauthier, M. Flannigan, and V. Kafka. 2004*b*. Fire regimes at the transition between mixedwood and coniferous boreal forest in northwestern Quebec. Ecology 85:1916–1932.

Bond-Lamberty, B., S. D. Peckham, D. E. Ahl, and S. T. Gower. 2007. Fire as the dominant driver of central Canadian boreal forest carbon balance. Nature 450:89–92.

Boulanger, Y., S. Gauthier, P. J. Burton, and M.-A. Vaillancourt. 2012. An alternative fire regime zonation for Canada. International Journal of Wildland Fire. http://dx.doi.org/10.1071/WF11073

Bridge, S. R. J. 2001. Spatial and temporal variations in the fire cycle across Ontario. NEST TR-043. Ontario Ministry of Natural Resources, Northeast Science and Technology, South Porcupine, Ontario, Canada.

Brown, C. D., and J. F. Johnstone. 2011. How does increased fire frequency affect carbon loss from fire? A case study in the northern boreal forest. International Journal of Wildland Fire 20:829–837.

Burton, P. J., M.-A. Parisien, J. A. Hicke, R. J. Hall, and J. T. Freeburn. 2008. Large fires as agents of ecological diversity in the North American boreal forest. International Journal of Wildland Fire 17:754–767.

Candau, J.-N., and R. A. Fleming. 2011. Forecasting the response of spruce budworm defoliation to climate change in Ontario. Canadian Journal of Forest Research 41:1948–1960.

Cary, G. J., R. E. Keane, R. H. Gardner, S. Lavorel, M. D. Flannigan, I. D. Davies, C. Li, J. M. Lenihan, T. S. Rupp, and F. Mouillot. 2006. Comparison of the sensitivity of landscape-fire-succession models to variation in terrain, fuel pattern, climate and weather. Landscape Ecology 21:121–137.

Caya, D., and R. Laprise. 1999. A semi-implicit semi-Lagrangian regional climate model: the Canadian RCM. Monthly Weather Review 127:341–362.

Cutler, D. R., T. C. Edwards, Jr., K. H. Beard, A. Cutler, K. T. Hess, J. Gibson, and J. J. Lawler. 2007. Random forests for classification in ecology. Ecology 88:2783–2792.

Cyr, D., S. Gauthier, and Y. Bergeron. 2007. Scale-dependent determinants of heterogeneity in fire frequency in a coniferous boreal forest of eastern Canada. Landscape Ecology 22:1325–1339.

de Groot, W. J., J. M. Pritchard, and T. J. Lynham. 2009. Forest floor fuel consumption and carbon emissions in Canadian boreal forest fires. Canadian Journal of Forest Research 39:367–382.

Dymond, C. C., E. T. Neilson, G. Stinson, K. Porter, D. A. MacLean, D. R. Gray, M. Campagna, and W. A. Kurz. 2010. Future spruce budworm outbreak may create a carbon source in eastern Canadian forests. Ecosystems 13:917–931.

Ecological Stratification Working Group. 1996. A national ecological framework for Canada. Agriculture and Agri-Food Canada and Environment Canada, Ottawa, Ontario, Canada.

Environment Canada. 2007. Canadian climate normals or averages, 1971–2000. http://www.climate.weatheroffice.gc.ca/climate_normals/index_e.html

Flannigan, M. D., M. A. Krawchuk, W. J. de Groot, B. M. Wotton, and L. M. Gowman. 2009. Implications of changing climate for global wildland fire. International Journal of Wildland Fire 18:483–507.

Flannigan, M. D., K. A. Logan, B. D. Amiro, W. R. Skinner, and B. J. Stocks. 2005. Future area burned in Canada. Climatic Change 72:1–16.

Flannigan, M. D., and B. M. Wotton. 2001. Climate, weather, and area burned. Pages 351–373 *in* E. A. Johnson, and K. Miyanishi, editors. Forest fires: behavior and ecological effects. Academic Press, San Diego, California, USA.

Fleming, R. A., J.-N. Candau, and R. S. McAlpine. 2002. Landscape-scale analysis of interactions between insect defoliation and forest fire in central Canada. Climatic Change 55:251–272.

Gauthier, S., A. Leduc, Y. Bergeron, and H. Le Goff. 2009. Fire frequency and forest management based on natural disturbances. Pages 57–74 *in* S. Gauthier, M.-A. Vaillancourt, A. Leduc, L. De Grandpré, D. Kneeshaw, H. Morin, P. Drapeau, and Y. Bergeron, editors. Ecosystem management in the boreal forest. Presses de l'Université du Québec, Quebec, Quebec, Canada.

Gillett, N. P., A. J. Weaver, F. W. Zwiers, and M. D. Flannigan. 2004. Detecting the effect of climate change on Canadian forest fires. Geophysical Research Letters 31:L18211.

Girardin, M.-P., A. A. Ali, and C. Hély. 2010. Wildfires in boreal ecosystems: past, present and some emerging trends. International Journal of Wildland Fire 19:991–995.

Girardin, M.-P., Y. Bergeron, J. C. Tardif, S. Gauthier, M. D. Flannigan, and M. Mudelsee. 2006. A 229-year dendroclimatic-inferred record of forest fire activity for the Boreal Shield of Canada. International Journal of Wildland Fire 15:375–388.

Girardin, M.-P., M. D. Flannigan, J. C. Tardif, and Y. Bergeron. 2009. Climate, weather and forest fires. Pages 79–102 *in* S. Gauthier, M.-A. Vaillancourt, A. Leduc, L. De Grandpré, D. Kneeshaw, H. Morin, P. Drapeau, and Y. Bergeron, editors. Ecosystem management in the boreal forest. Presses de l'Université du Québec, Quebec, Quebec, Canada.

Girardin, M.-P., and M. Mudelsee. 2008. Past and future changes in Canadian boreal wildfire activity. Ecological Applications 18:391–406.

Girardin, M.-P., J. Tardif, M. D. Flannigan, B. M. Wotton, and Y. Bergeron. 2004. Trends and periodicities in the Canadian Drought Code and their relationships with atmospheric circulation for the southern Canadian boreal forest. Canadian Journal of Forest Research 34:103–119.

Girardin, M.-P., and B. M. Wotton. 2009. Summer moisture and wildfire risks across Canada. Journal of Applied Meteorology and Climatology 48:517–533.

Guo, D. 2008. Zonation with dynamically constrained agglomerative clustering and partitioning (REDCAP). International Journal of Geographical Information Science 22:801–823.

Guo, D. 2011. REDCAP: a zonation toolkit (version 2.0.0). User manual. Department of Geography, University of South Carolina, Columbia, South Carolina, USA.

Hennig, C. 2010. fpc: Flexible procedures for clustering. R package version 2.0-2. http://CRAN.R-project.org/package=fpc

Hirsch, K., V. Kafka, C. Tymstra, R. McAlpine, B. Hawkes, H. Stegehuis, S. Quintilio, S. Gauthier, and K. Peck. 2001. Fire-smart forest management: a pragmatic approach to sustainable forest management in fire-dominated ecosystems. Forestry Chronicle 77:357–363.

Jenness, J. 2009. Surface area and ratio for ArcGIS (surface_area.exe). Jenness Enterprises, Flagstaff, Arizona, USA.

Kasischke, E. S., and J. F. Johnstone. 2005. Variation in postfire organic layer thickness in a black spruce forest complex in interior Alaska and its effects on soil temperature and moisture. Canadian Journal of Forest Research 35:2164–2177.

Kasischke, E. S., and M. R. Turetsky. 2006. Recent changes in the fire regime across the North American boreal region—spatial and temporal patterns of burning across Canada and Alaska. Geophysical Research Letters 33:L09703.

Kasischke, E. S., et al. 2010. Alaska's changing fire regime—implications for the vulnerability of its boreal forests. Canadian Journal of Forest Research 40:1313–1324.

Krawchuk, M. A., S. G. Cumming, M. D. Flannigan, and R. W. Wein. 2006. Biotic and abiotic regulation of lightning fire initiation in the mixedwood boreal forest. Ecology 87:458–468.

Krawchuk, M. A., M. A. Moritz, M.-A. Parisien, J. Van Dorn, and K. Hayhoe. 2009. Global pyrogeography: the current and future distribution of wildfire. PLoS ONE 4:e5102.

Krebs, P., G. B. Pezzatti, S. Mazzoleni, L. M. Talbot, and M. Conedera. 2010. Fire regime: history and definition of a key concept in disturbance ecology. Theory in Biosciences 129:53–69.

Kurz, W. A., G. Stinson, and G. Rampley. 2007. Could increased boreal forest ecosystem productivity offset carbon losses from increased disturbance? Philosophical Transactions of the Royal Society B 363:2261–2269.

Lecomte, N., M. Simard, N. Fenton, and Y. Bergeron. 2006. Fire severity and long-term ecosystem biomass dynamics in coniferous boreal forests of eastern Canada. Ecosystems 9:1215–1230.

Le Goff, H., M. D. Flannigan, and Y. Bergeron. 2009. Potential changes in monthly fire risk in the eastern Canadian boreal forest under future climate change. Canadian Journal of Forest Research 39:2369–2380.

Le Goff, H., M. D. Flannigan, Y. Bergeron, and M.-P. Girardin. 2007. Historical fire regime shifts related to climate teleconnections in the Waswanipi area, central Quebec, Canada. International Journal of Wildland Fire 16:607–618.

Le Goff, H., and L. Sirois. 2004. Black spruce and jack pine dynamics simulated under varying fire cycles in the northern boreal forest of Quebec, Canada. Canadian Journal of Forest Research 34:2399–2409.

Le Page, Y., D. Oom, J. M. N. Silva, P. Jönsson, and J. M. C. Pereira. 2010. Seasonality of vegetation fires as modified by human action: observing the deviation from eco-climatic fire regimes. Global Ecology and Biogeography 19:575–588.

Mansuy, N., S. Gauthier, A. Robitaille, and Y. Bergeron. 2010. The effects of surficial deposit—drainage combinations on spatial variations of fire cycles in the boreal forest of eastern Canada. International Journal of Wildland Fire 19:1083–1098.

Martell, D. L., and H. Sun. 2008. The impact of fire suppression, vegetation, and weather on the area burned by lightning-caused forest fires in Ontario. Canadian Journal of Forest Research 38:1547–1563.

Meila, M. 2007. Comparing clusterings—an information based distance. Journal of Multivariate Analysis 98:873–895.

Moritz, M. A., M.-A. Parisien, E. Batllori, M. A. Krawchuk, J. Van Dorn, D. J. Gantz, and K. Hayhoe. 2012. Climate change and disruptions to global fire activity. Ecosphere 3(6):49.

Nakicenovic, N., et al. 2000. Special report on emissions scenarios, summary for policy makers. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Natural Resources Canada. 2008. Atlas of Canada: 1,000,000 national frameworks data, road network. Earth Sciences Sector, Canada Centre for Remote Sensing, Ottawa, Ontario, Canada.

Parisien, M.-A., and M. A. Moritz. 2009. Environmental controls on the distribution of wildfire at multiple spatial scales. Ecological Monographs 79:127–154.

Parisien, M.-A., S. A. Parks, M. A. Krawchuk, M. D. Flannigan, L. M. Bowman, and M. A. Moritz. 2011. Scale-dependent controls on the area burned in the boreal forest of Canada, 1980–2005. Ecological Applications 21:789–805.

Parisien, M.-A., V. S. Peters, Y. Wang, J. M. Little, E. M. Bosch, and B. J. Stocks. 2006. Spatial patterns of forest fires in Canada, 1980–1999. International Journal of Wildland Fire 15:361–374.

Parisien, M.-A., S. Snetsinger, J. A. Greenberg, C. R. Nelson, T. Schoennagel, S. Z. Dobrowski, and M. A. Moritz. 2012. Spatial variability in wildfire probability across the western United States. International Journal of Wildland Fire 21:313–327.

Payette, S. 1992. Fire as a controlling process in the North American boreal forest. Pages 144–169 *in* H. H. Shugart, R. Leemans, and G. B. Bonan, editors. A systems analysis of the global boreal forest. Cambridge University Press, Cambridge, UK.

Podur, J., and M. Wotton. 2010. Will climate change overwhelm fire management capacity? Ecological Modelling 221:1301–1309.

Prasad, A. M., L. R. Iverson, and A. Liaw. 2006. Newer classification and regression tree techniques: bagging and random forests for ecological prediction. Ecosystems 9:181–199.

R Development Core Team. 2011. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.r-project.org/

Raulier, F., H. Le Goff, S. Gauthier, R. Rapanoela, and Y. Bergeron. 2013. Introducing two indicators for fire risk consideration in the management of boreal forests. Ecological Indicators 24:451–461.

Régnière, J., and R. Saint-Amant. 2007. Stochastic simulation of daily air temperature and precipitation from monthly normals in North America north of Mexico. International Journal of Biometeorology 51:415–430.

Régnière, J., and R. Saint-Amant. 2008. BioSIM 9: user's manual. Information report LAU-X-134. Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, Québec, Quebec, Canada.

Rowe, J. S. 1972. Forest regions of Canada. Fisheries and Environment Canada, Canadian Forest Service Headquarters, Ottawa, Ontario, Canada.

Savage, D. W., D. L. Martell, and B. M. Wotton. 2010. Evaluation of two risk mitigation strategies for dealing with fire-related uncertainty in timber supply modelling. Canadian Journal of Forest Research 40:1136–1154.

Skinner, W. R., M. D. Flannigan, B. J. Stocks, D. L. Martell, B. M. Wotton, J. B. Todd, J. A. Mason, K. A. Logan, and E. M. Bosch. 2002. A 500 hPa synoptic wildland fire climatology for large Canadian forest fires, 1959-1996. Theoretical and Applied Climatology 71:157–169.

Solomon, S., D. Qin, M. Manning, M. Marquis, K. Averyt, M. B. Tignor, H. L. Miller, and Z. Chen, editors. 2007. Climate change 2007: the physical science basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK.

Stocks, B. J., et al. 1998. Climate change and forest fire potential in Russian and Canadian boreal forests. Climatic Change 38:1–13.

Stocks, B. J., et al. 2003. Large forest fires in Canada, 1959–1997. Journal of Geophysical Research 108(D1):8149.

Stoner, A. M. K., K. Hayhoe, and D. J. Wuebbles. 2009. Assessing general circulation model simulations of atmospheric teleconnection patterns. Journal of Climate 22:4348–4372.

Terrier, A., M. P. Girardin, C. Périé, P. Legendre, and Y. Bergeron. 2013. Potential changes in forest composition could reduce impacts of climate change on boreal wildfires. Ecological Applications 23:21–35.

Turetsky, M. R., E. S. Kane, J. W. Harden, R. D. Ottmar, K. L. Manies, E. Hoy, and E. S. Kasichke. 2011. Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. Nature Geoscience 4:27–31.

Van Wagner, C. E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Forestry Technical Report 35. Canadian Forestry Service, Ottawa, Ontario, Canada.

Wang, Y., and K. R. Anderson. 2010. An evaluation of spatial and temporal patterns of lightning- and human-caused forest fires in Alberta, Canada, 1980–2007. International Journal of Wildland Fire 19:1059–1072.

Weber, M. G., and M. D. Flannigan. 1997. Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes. Environmental Reviews 5:145–166.

Wotton, B. M., and M. D. Flannigan. 1993. Length of the fire season in a changing climate. The Forestry Chronicle 69:187–192.

Wotton, B. M., C. A. Nock, and M. D. Flannigan. 2010. Forest fire occurrence and climate change in Canada. International Journal of Wildland Fire 19:253–271.

Wotton, B. M., and B. J. Stocks. 2006. Fire management in Canada: vulnerability and risk trends. Pages 49–55 *in* K. Hirsch, and P. Fuglem, editors. Canadian wildland fire strategy: background syntheses, analyses, and perspectives. Canadian Council of Forest Ministers, Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Alberta, Canada.

Supplemental Material

Appendix A

Comparison between observed values and those simulated by BioSIM for the 1961–1990 period for predictors used in Random Forests modeling (*Ecological Archives* A023-046-A1).

Appendix B

Area burned as a function of day of the year in each homogeneous fire regime zone delineated for the historical period (1961–1990) (*Ecological Archives* A023-046-A2).

Appendix C

Spatial validation of Random Forests models for AAB, FIREOCC, and MBD (*Ecological Archives* A023-046-A3).

Appendix D

Mean temperature and precipitation during the fire season, as well as the fire season length and the beginning of the fire season for all periods under study as projected by the Canadian Regional Climate Model (CRCM) under the SRES A2 scenario (*Ecological Archives* A023-046-A4).

Appendix E

Observed values for the historic period (1961–1990) for the most important climate variables used to project AAB, FIREOCC, and MBD, as well as projected changes according to the CRCM SRES A2 scenario (*Ecological Archives* A023-046-A5).

Appendix F

Fire regime characteristics for HFR zones produced for the 1961–1990, 2011–2040, 2041–2070, and 2071–2100 periods (*Ecological Archives* A023-046-A6).