NRC Research Press

ARTICLE

A refinement of models projecting future Canadian fire regimes using homogeneous fire regime zones

Yan Boulanger, Sylvie Gauthier, and Philip J. Burton

Abstract: Broad-scale fire regime modelling is frequently based on large ecological and (or) administrative units. However, these units may not capture spatial heterogeneity in fire regimes and may thus lead to spatially inaccurate estimates of future fire activity. In this study, we defined homogeneous fire regime (HFR) zones for Canada based on annual area burned (AAB) and fire occurrence (FireOcc), and we used them to model future (2011–2040, 2041–2070, and 2071–2100) fire activity using multivariate adaptive regression splines (MARS). We identified a total of 16 HFR zones explaining 47.7% of the heterogeneity in AAB and FireOcc for the 1959–1999 period. MARS models based on HFR zones projected a 3.7-fold increase in AAB and a 3.0-fold increase in FireOcc by 2100 when compared with 1961–1990, with great interzone heterogeneity. The greatest increases would occur in zones located in central and northwestern Canada. Much of the increase in AAB would result from a sharp increase in fire activity during July and August. Ecozone- and HFR-based models projected relatively similar nationwide FireOcc and AAB. However, very high spatial discrepancies were noted between zonations over extensive areas. The proposed HFR zonation should help providing more spatially accurate estimates of future ecological patterns largely driven by fire in the boreal forest such as biodiversity patterns, energy flows, and carbon storage than those obtained from large-scale multipurpose classification units.

Key words: fire regime, boreal forest, ecozones, regionalization, MARS.

Résumé : La modélisation à grande échelle des régimes des feux est souvent fondée sur de vastes unités soit écologiques, soit administratives. Cependant, il est possible que ces unités ne permettent pas de détecter l'hétérogénéité spatiale des régimes des feux et soient par conséquent la source d'estimations spatialement inexactes de l'activité future du feu. Dans cette étude, nous avons défini des zones de régime des feux homogènes (RFH) pour le Canada sur la base de la superficie brûlée annuellement (SBA) et de l'occurrence des feux (OF). Nous avons utilisé ces zones pour modéliser l'activité future (2011–2040, 2041–2070 et 2071–2100) du feu à l'aide de la régression multivariée par spline adaptative (MARS). Au total, nous avons identifié 16 zones de RFH qui expliquaient 47,7 % de l'hétérogénéité dans la SBA et l'OF pour la période 1959–1999. Les modèles MARS élaborés sur la base des zones de RFH prédisaient une augmentation de 3,7 fois de la SBA et de 3,0 fois de l'OF en 2100 comparativement à 1961–1990 avec une très forte hétérogénéité entre les zones. Les plus fortes augmentations surviendraient dans des zones situées dans le centre et le nord-ouest du Canada. La majeure partie de l'augmentation de la SBA serait le résultat d'une forte hausse de l'activité du feu durant les mois de juillet et août. Les modèles, qu'ils soient fondés sur les écozones ou les RFH, prédisaient une OF et une SBA relativement similaires à la grandeur du pays. Cependant, de très fortes divergences spatiales ont été notées dans la classification des zones sur de vastes superficies. La classification des zones proposée sur la base des RFH devrait aider à fournir des estimations plus précises du point de vue spatial des patrons écologiques futurs largement déterminés par le feu dans la forêt boréale, tels que les patrons de biodiversité, le flux d'énergie et le stockage de C, que celles obtenues à partir d'unités de classification à usages multiples à grande échelle. [Traduit par la Rédaction]

Mots-clés : régime des feux, forêt boréale, écozones, régionalisation, MARS.

Introduction

Fire is one of the most important natural disturbances in Canada, where it burns nearly 2 million ha annually (1959–1997 period) (Stocks et al. 2003). Fire strongly shapes landscape diversity and productivity (Payette 1992), and it influences carbon flux in boreal forest ecosystems (Bond-Lamberty et al. 2007; Amiro et al. 2009). Fire regime, as defined by several quantifiable fire parameters (e.g., area burned, fire occurrence, fire cause, seasonality, fire size, etc.), is expected to change drastically over the forthcoming decades in Canada as a result of the more fire-conducive weather linked with climate change. Recent shifts observed in annual area burned (AAB) and fire seasonality in boreal North America (Gillett et al. 2004; Kasischke et al. 2010) are consistent with recent changes in climate patterns. Several authors project sharp increases in future AAB and in the number of fires (e.g., Flannigan et al. 2005; Balshi et al. 2009; Wotton et al. 2010) as a result of warmer temperatures and more frequent extreme droughts due to frequent blocking high-pressure systems with climate change. Moreover, a lengthening of the fire season coupled with changes in seasonal fire weather patterns are expected to shift peak fire activity to either sooner (Stocks et al. 1998) or later in the season (Le Goff et al. 2009; Boulanger et al. 2013). Such a shift in fire activity will greatly affect many interconnected ecological processes in the boreal forest, including the forest age mosaic, biodiversity patterns, and carbon balance (Amiro et al. 2001; Flannigan

Received 11 September 2013. Accepted 26 January 2014.

Y. Boulanger and S. Gauthier. Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, 1055 du P.E.P.S., P.O. Box 10380, Stn. Sainte-Foy, Quebec, QC G1V 4C7, Canada.
P.J. Burton. University of Northern British Columbia, 4837 Keith Ave., Terrace, BC V8G 1K7, Canada.
Corresponding author: Yan Boulanger (e-mail: yan.boulanger@nrcan.gc.ca).

et al. 2005; de Groot et al. 2009). These changes are expected to have a profound impact on fire and forest management strategies, notably by requiring a reduction in annual allowable cut volumes (Armstrong 2004; Savage et al. 2010; Raulier et al. 2013) and by substantially increasing the costs associated with forest protection and fire suppression (Wotton and Stocks 2006; Podur and Wotton 2010).

When modelling a given ecological process or pattern, one has to be assured that it is rather homogeneous at the scale (units) at which it is being modelled. This ensures more spatially accurate predictions of the process, an important element when assessing fire risk, for example. Studies modelling future fire regime characteristics are frequently conducted using models developed for coarse-resolution spatial units. Indeed, fire regime characteristics rely on climatic, biological, and physiographical conditions and on anthropogenic influences that may be synoptic in scale (Heyerdahl et al. 2001; Lefort et al. 2003; Macias Fauria and Johnson 2006; Parisien et al. 2006, 2011; Le Goff et al. 2007). Moreover, global climate model projections are generally coarse in scale, thus preventing fine resolution predictions of future fire regimes. As a result, many researchers have relied on administrative units (e.g., provinces and management zones), ecological units, or a combination of both (e.g., Wotton et al. 2010) to project future AAB or fire occurrence (FireOcc). However, such classifications may not always be the panacea in this context by failing to correctly capture the spatial heterogeneity of the ecological pattern (Boulanger et al. 2012). Therefore, one may question the ability of large ecological units to provide spatially accurate estimates of future fire regimes at a broad scale.

In a recent study (Boulanger et al. 2013), we delineated homogeneous fire regime (HFR) zones for eastern Canada under current and future climates. This work enables the delineation of zones where changes in the fire regime might be very important for the next decades and where the adaptation of the forest and fire protection sectors to the projected changes, at a regional scale, is necessary. A similar zonation analysis may be highly relevant to project future fire regimes at a broader, national scale. Indeed, since it better captures the spatial heterogeneity of the fire regime than existing ecological classifications (Boulanger et al. 2012), HFR zones should allow for more precise spatially explicit modelling of the effects of climate and climate change on fire regimes at a broad scale. It may thus help to more accurately outline future areas with high fire risk while providing an appropriate framework for future forest and fire management. In this study, we broaden the scope of the Boulanger et al. (2013) study by (*i*) expanding the delineation of empirical HFR zones and projection of future fire regime to all of Canada. Moreover, (*ii*) we aim to assess how future fire regime estimates based on HFR zones may differ from those assessed using a predefined land classification. Here, we are considering the National Ecological Framework for Canada (NEFC) as a case of predefined land classification.

Material and methods

Fire data

Fire data comes from the Canadian National Fire Database (CNFDB) spanning the years 1959 to 2011. We restricted our analyses to large fires, i.e., >200 ha, because data from smaller fires are known to be incomplete, especially those that occurred before 1980 and in remote areas. Although there were many fires smaller than 200 ha in the study area, the area burned is very well represented by this subset of the CNFDB because these large fires were responsible for 97% of the area burned across Canada during 1959–1997 (Stocks et al. 2003). With these constraints, a total of 14 955 fires were included in the analyses (Fig. 1). 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 periods covered for different jurisdictions), each fire was represented by a circle with a radius assigned to reproduce the reported area burned.

Predefined units: the ecozones of the NEFC

The NEFC classification scheme provides a comprehensive, integrated, and standardized approach to ecosystems that is national in scope (Ecological Stratification Working Group 1996). This multipurpose stratification consists of four hierarchically designed units: ecozone > ecoprovince > ecoregion > ecodistrict. The larger units of this scheme form a mosaic defined by the interaction of climate, human activity, vegetation, soils, and geological and physiographic features at regional scales (Ecological Stratification Working Group 1996). Although smaller units of the NEFC have been used in the past (e.g., Wotton et al. 2010), the modelling of the future fire regimes at the Canada-wide scale is frequently conducted using the largest unit of the NEFC, i.e., the ecozones (e.g., Flannigan et al. 2005; Kasischke and Turetsky 2006; Amiro et al. 2009). The popularity of the ecozones to model the fire regime is based on the implicit assumption that these units delineate rather homogeneous fire-related environmental conditions leading to a spatially homogeneous response of fire regime at the scale investigated. However, recent analyses (Boulanger et al. 2012) have shown that large units of the NEFC fail to capture the spatial heterogeneity of the recent fire regime. Thus, for sake of comparison with HFR zones, ecozones were used as predefined units to summarize fire regime data and to develop fire models driven by climate.

HFR zones: sampling units and fire regime attributes

Readers may refer to Fig. S1[1] for a schematic representation of the methods. Fire sampling was conducted using a 60 km × 60 km square cell grid (hereafter referred to as a coverage of gridded cells). This cell size represents a compromise between capturing the local variation in the fire regime while being larger than all but nine individual fire events (0.08%) in the study area. HFR zones were built using fire data from the 1959–1999 period, the period for which fire data are most completed across the country. Using this spatial database, we computed the following fire regime variables over the 41-year period for each gridded cell: (*i*) the mean annual number of fires (>200 ha) (FireOcc); and (*ii*) the mean AAB (Table 1). Human- and lightning-caused fires were pooled for analyses while coalescent fires were considered as separate fire occurrences. Using the Earth Observation for Sustainable Development of Forests (EOSD; resolution 250 m × 250 m) land cover classification (Beaubien et al. 1999), fuel area in each gridded cell was assessed as the sum of the 6.25-ha EOSD pixels covered by trees, shrubs, grasses, herbs, bryoids, or vegetated wetlands. Both fire regime attributes were expressed as a function of the area of fuel in the gridded cell.

HFR zone delineation

HFR zones were delineated through a dynamic spatially constrained agglomerative clustering and partitioning algorithm (Guo 2008). We initially built a connectivity graph linking cells in a rook-type fashion, i.e., cells that share borders. Then, cells were clustered with spatial contiguity constraints according to the Ward's hierarchical clustering method.

Our goal was to produce a zonation that represents the best compromise between capturing most of the spatial variability in the fire regime and, at the same time, leading to fire weather/fire regime models with high predictive ability. In a recent study,

[1]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjfr-2013-0372.

Fig. 1. Map of the study area (gray) with ecozone boundaries. Occurrence of fires larger than 200 ha is also shown. Circle size is proportional to fire size. No fire data were available north of 54°N in Ontario (cross-hatched area). Ecozones are as follows: AM, Atlantic Maritime; BC, Boreal Cordillera; BP, Boreal Plains; BSE, Boreal Shield East; BSW, Boreal Shield West; HP, Hudson Plains; MC, Montane Cordillera; PM, Pacific Maritime; TC, Taiga Cordillera; TP, Taiga Plains; TSE, Taiga Shield East; and TSW, Taiga Shield West. The following ecozones were not considered in the analyses: AC, Arctic Cordillera; MP, Mixedwood Plains; NA, Northern Arctic; P, Prairies; and SA, Southern Arctic. Inset: Canadian provinces and territories (AB, Alberta; BC, British Columbia; MB, Manitoba; NB, New Brunswick; NL, Newfoundland and Labrador; NS, Nova Scotia; NWT, Northwest Territories; NU, Nunavut; ON, Ontario; PEI, Prince Edward Island; QC, Québec; SK, Saskatchewan; and YK, Yukon).

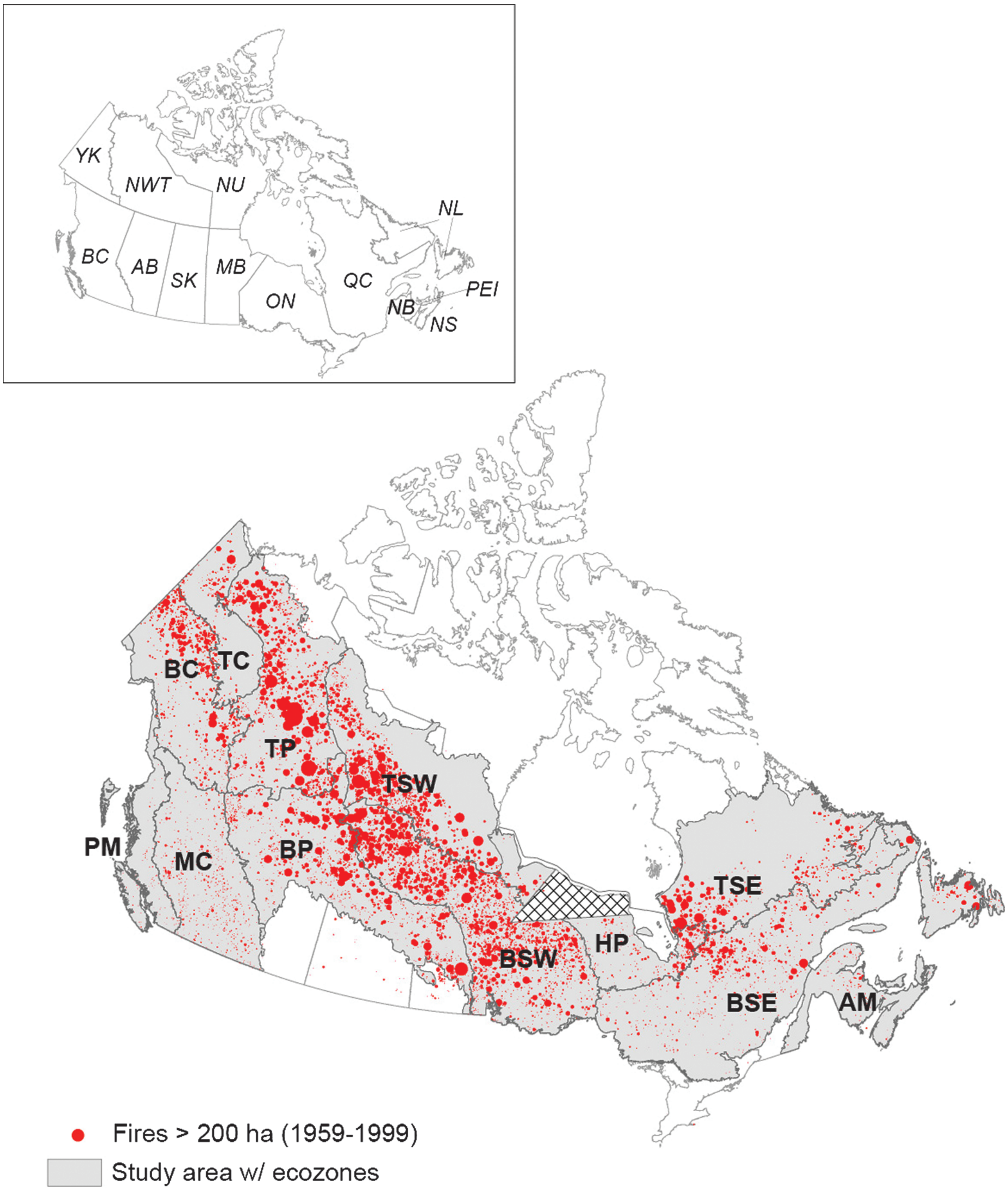


Table 1. Description of the predictors included in the MARS models.

Predictor	Description	Group of predictors
FFMC	Mean Fine Fuel Moisture Code	1, 3, 5
$FFMC_{max}$	Maximum daily value of the Fine Fuel Moisture Code	6, 7, 8
DMC	Mean Duff Moisture Code	1, 2
DMC_{max}	Maximum daily value of the Duff Moisture Code	6
DC	Mean Drought Code	1, 2, 3, 4, 5
DC_{max}	Maximum daily value of the Drought Code	6, 7, 8
ISI	Mean Initial Spread Index	2, 4
ISI_{max}	Maximum daily value of the Initial Spread Index	6, 7
BUI	Mean Build-up Index	3, 4
BUI_{max}	Maximum daily value of the Build-up Index	7
MSR	Monthly Severity Rating	5
DSR_{max}	Maximum daily value of the Daily Severity Rating	8
T	Mean temperature (°C)	1, 2, 3, 4, 5
T_{max}	Maximum temperature (°C)	6, 7, 8
WS	Mean wind speed ($m \cdot s^{-1}$)	All
Prcp_day	Mean daily precipitation (mm)	2, 4, 6, 7, 8

Note: Predictors were computed on a monthly basis and were assigned to one or several of eight different groups to avoid the inclusion of highly collinear predictors within a given MARS model. MARS, multivariate adaptive regression splines.

Boulanger et al. (2012) delineated 33 zones in Canada where fire regime for the 1980–1999 period was homogeneous. However, we decided to produce another zonation that would better fit the objectives of this study. First, HFR zones produced by Boulanger et al. (2012) were delineated using fire regime as characterized by both small and large fires recorded over a rather short time period (1980–1999). Furthermore, Boulanger et al. (2012) HFR zones were delineated at a finer scale thus preventing the comparison with ecozones. Finally, the vegetation may have a profound impact on the large-scale fire regime (Krawchuk et al. 2006) and may strongly interact with climate variables when predicting fire regime attributes (Parisien et al. 2012). As ecozones were also delineated based on large vegetation classes (Ecological Stratification Working Group 1996), this was one reason why these zones were frequently considered in the past to project future fire regime. Better fire regime models may thus be obtained using zones where both vegetation and fire regime are homogeneous.

Consequently, in addition to AAB and FireOcc retrieved from the 1959–1999 period, fuel attributes as represented by rather coarsely defined vegetation classes were added to the fire regime attributes in clustering analyses. In each 60-km cell, fuel was characterized by five attributes according to the EOSD classification, i.e., the area covered by (*i*) coniferous, (*ii*) mixed, and (*iii*) deciduous forests, as well as the area covered by (*iv*) wetlands and (*v*) any remaining nontree fuel components (shrubs, bryoids, and herbs). All fire and fuel attributes were scaled to have a mean of 0 and a standard deviation of 1.0 prior to zonation analyses. To still characterize mainly the fire regime, fuel attributes were given a lower weight (fixed at weight = 0.2) than fire regime attributes (weight = 1.0) in clustering analyses afterwards. This technique aims to distinguish areas with similar fire regimes but driven by different fuel × climate interactions. Preliminary analyses showed that adding fuel to HFR zones resulted in somewhat better fire predictive models (R^2 = +3% to +6%), while these zones were slightly less homogeneous (R^2 = –3%) than those using only fire data. Our method thus represents a compromise between having stronger zone-based climate-driven fire models given the current distribution of vegetation and slightly less homogeneous fire regime zones.

Zones (hereafter HFR_{fuel}) were dynamically determined using REDCAP v. 2.0.1 (Guo 2011) throughout an agglomerative algorithm using all edges between clusters, i.e., all links between cells pertaining to different candidate clusters (Guo 2008). Using a heuristic approach, the classification tree was partitioned to optimize the delineation of spatially contiguous regions with minimum sum-of-squares deviations. Minimal zone size was set to 200 000 km², which is approximately the size of the smallest ecozone with significant fire activity (Pacific Maritime: ~208 000 km²).

The classification tree was then partitioned successively from two zones until no tree pruning was possible given the zone's minimum size criterion. For each solution, 1000 cross-validations were performed using the mvpart v. 1.4.0 package in R 2.13.1 (R Development Core Team 2011). The "best" partition, i.e., the most parsimonious solution, was selected as the one showing the smallest variation in the error coefficient (Segal and Xiao 2011). As a complement, the amount of spatial heterogeneity (adj. R^2) in the fire regime (FireOcc and AAB pooled together) explained by the HFR_{fuel} zonation was computed and compared with the adj. R^2 calculated for the fire regime summarized simply by ecozones. In this latter case, the affiliation of a cell to a given ecozone was determined from the cell centroid. We further determined whether HFR_{fuel} zones were still "homogeneous" using 2000–2010 as a validation period by estimating the amount of variation in the fire regime (adj. R^2) explained by the zonation for this period. Similar validation analyses were also conducted for ecozones.

Analyses

Fire regime modelling

Models projecting fire occurrence and area burned were built on a monthly time step for the 1959–1995 period. We deliberately chose to use this slightly shorter period than the one used to build HFR_{fuel} zones (1959–1999) to a have a sufficiently long validation period (1996–2011) for fire models (see below). For the 1959–1995 period, monthly occurrence of large fires (mFireOcc) as well as monthly area burned (mAB) were related to monthly climate variables for each zone separately. First, daily weather data were retrieved for each zone (Environment Canada 2007). Weather data were then projected to the centroid of each zone (for both HFR_{fuel} zones and ecozones) from daily data obtained from nearby weather stations using BioSIM v. 10.0.6.20 (Régnière and St-Amant 2007). BioSIM projected daily maximum and minimum temperatures (°C), precipitation (mm), mean daily relative humidity (%), and wind speed ($m \cdot s^{-1}$) by averaging georeferenced sources of weather data (8 weather stations with daily weather data) to other georeferenced points (the zone centroid). Prior to averaging, weather data were adjusted for differences in latitude, longitude, and elevation between the source of weather data and each location by spatial regressions fitted on up to 69 nearby weather stations. Interpolation using this technique was necessary as some zones did not have long-record weather stations whereas other such weather stations were located at the extreme edges of the zone and were thus inappropriate for depicting synoptic variation of weather conditions in the zone. If the centroid fell outside of the zone's boundaries, we used the zone's centre of gravity as defined by ArcInfo instead (ESRI 2006).

From the daily time series of temperature, relative humidity, wind speed, and 24-h accumulated precipitation generated in each cell, we derived the following seven standard components of the Canadian Forest Fire Weather Index System (Van Wagner 1987): (*i*) Fine Fuel Moisture Code (FFMC), (*ii*) Duff Moisture Code (DMC), (*iii*) Drought Code (DC), (*iv*) Build-up Index (BUI), (*v*) Initial Spread Index (ISI), (*vi*) composite Fire Weather Index (FWI), and (*vii*) Daily Severity Rating (DSR). Prior to the computation of these components, wind speed, relative humidity, and temperatures as estimated using BioSIM were corrected for noon values (Van Wagner 1987). Corrections were made using weather data retrieved from

75 weather stations located in Canada for 2000–2008 from which hourly data were available. Another 25 weather stations were used as a validation data set. The sine wave function of Allen (1976) was used to estimate noon temperature from minimum and maximum temperatures projected by BioSIM. Maximum temperature was set to occur at 1600. Correlations between observed and estimated weather parameters were very high (R^2 = 0.9777) and were very slightly biased (mean absolute deviation (MAD) = 1.4 °C) (Rémi Saint-Amant, unpublished data). Other corrections were successfully made using the same weather data set to project noon wind speed (R^2 = 0.711, MAD = 4.7 km·h^{-1}) and noon relative humidity (R^2 = 0.790, MAD = 7.0%) using daily averages (Rémi Saint-Amant, unpublished data). 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 fire behaviour. FWI combines ISI and BUI as a measure of fire danger rating, whereas the DSR is essentially a nonlinear transformation of the FWI. Fire weather indices were computed for the climatically active fire season. The beginning of the fire season was computed following Van Wagner (1987) as follows: (*i*) if 75% of the days in January and February have snow and the maximum snow depth is at least 10 cm, the fire season begins 3 days after snowmelt; (*ii*) otherwise, the fire season begins after three consecutive days when the temperature at noon is above 12 °C. The end of the fire season was considered as either (*i*) the first day when snow accumulation started in the fall or (*ii*) after 3 days where the maximum temperature is below 5 °C. Only months with more than 23 days where the fire season is climatically "active" were selected for analyses. Both the mean and maximum monthly values for each fire weather component, temperature, and wind speed were estimated from the daily data. Mean daily precipitation for the month was also computed (Table 1).

We used multivariate adaptive regression splines (MARS) to model monthly fire regime parameters for each HFR_{fuel} zone separately. To account for months with less than 30 days of active fire weather, monthly fire regime attributes were standardized on a 30-day basis in models. MARS was shown to perform very well for the modelling of area burned and fire occurrence as a function of climate (Balshi et al. 2009; Bergeron et al. 2010; Terrier et al. 2013). MARS is a nonparametric regression technique that makes no assumption on the relationship tying dependent and independent variables (Friedman 1991). Models are built using basis functions that fit separate splines to distinct intervals of the predictor variables (Prasad et al. 2006).

Preliminary screening of data revealed that many fire weather attributes were highly collinear, regardless of the zone or the zonation considered. For the great majority of predictors, both monthly mean and maximum values were highly collinear (Pearson's *r* generally above 0.80). High collinearity (r > 0.70) was also observed among some fire weather components. Although MARS was shown to perform relatively well under high collinearity (Dormann et al. 2013), preliminary analyses using all variables showed that collinear variables were still selected in MARS models, which was leading to worse model validation results than when developing models without highly collinear variables (results not shown). To avoid such situations, eight different sets of predictors were developed (Table 1). Monthly mean and maximum parameters were included in separate sets, whereas we substituted some variables for other collinear variables (e.g., DMC for BUI, BUI and ISI for DSR) in other sets (Table 1). Model selection with MARS was performed for each of these eight sets of predictors for each zone. No interaction between predictors was allowed in the MARS models.

Further screening revealed that MARS models leading to very high pseudo-R^2 values were physically doubtful (e.g., decrease in area burned with more severe fire weather) even though they generally led to good model validation. To avoid such spurious relationships, the maximum number of terms (including intercept) in the pruned model (nprune) was sequentially decreased from its maximum to 1 (intercept-only model), i.e., from very flexible to more "rigid" relationships. Pseudo-R^2 values and partial plots were computed for each combination of nprune × sets of predictors (Table 1) for a given zone, and models were then ranked by pseudo-R^2 values. For a given zone, the model leading to the highest pseudo-R^2 while leading to "physically probable" (essentially, no strong decreases in mFireOcc or mAB with increasing values of a given fire weather component) relationships, as assessed from partial dependence plots, was selected. This procedure only affected model predictions and validation results very slightly (see below) and was deemed more appropriate to project future fire regime attributes than relying solely on the automatic model selection procedure. The same routine applied here to model mAB and mFireOcc in HFR_{fuel} zones was applied to ecozones. All MARS analyses were performed using the package earth v. 3.2-3 (Milborrow 2012) in R.

Model validation

Validation was conducted for MARS models predicting mFireOcc and mAB using fire and climate data for the 1996–2011 period. Instead of using a *k*-fold cross-validation procedure, we used this out-of-series period to assess whether our models were performing well in an already changing climate (Gillett et al. 2004). As for the calibration period, fire data for the validation period came from the CNFDB. Unfortunately, validation was not possible for zones overlapping Newfoundland and Labrador since fire data were missing for that time period. Moreover, the month during which ignition occurred was also missing for several fires within the CNFDB for this recent period. As a result, model validation was based on yearly data. Projected mFireOcc and mAB according to the 1996–2011 monthly climate data were pooled on a yearly basis and compared with observed yearly fire activity values for the same period. Pearson's *r* and the major axis slope coefficient were computed between yearly observed and predicted values estimated from HFR_{fuel}-zone-based models and separately for ecozone-based models.

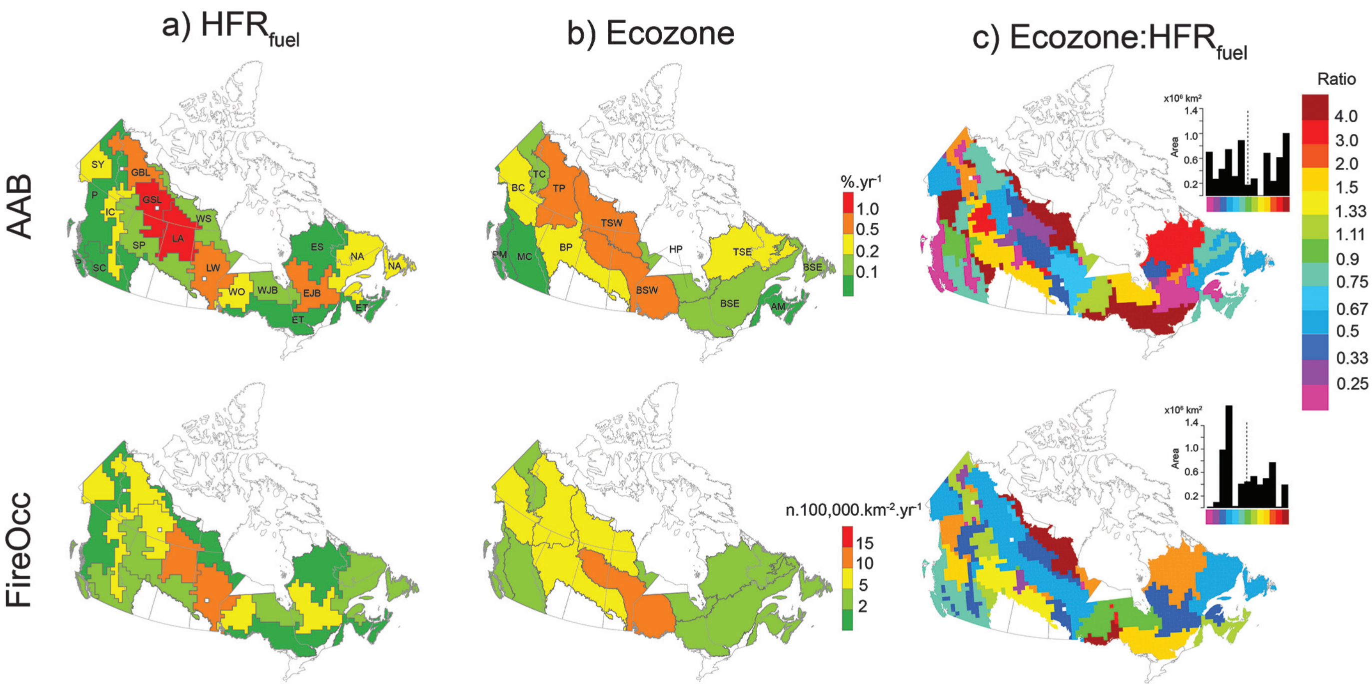
Future climate data

Future climate projections were obtained from the Canadian Regional Climate Model (CRCM 4.2.0; having an adjusted resolution of ~45 km at 60°N) (Caya and Laprise 1999). CRCM-driven data were taken from the Canadian Coupled Global Climate Model (CGCM3/T47) under the IPCC SRES A2 scenario (Nakicenovic et al. 2000). Future monthly values (normals) at each weather station were assessed directly as the differences between the baseline and future weather conditions estimated in the CRCM cell in which the weather station was located. Monthly normals were built at each zone centroid by adjusting CRCM data for climatic gradients in observed weather data using BioSIM as described above. We then used these difference-adjusted normals to simulate 30 years of future monthly fire weather values for each of three different future periods, i.e., 2011–2040, 2041–2070, and 2071–2100, as well as for the baseline period (1961–1990). Simulations were run 100 times for each period.

Future fire regime

Projections of future monthly fire regime values under the projected climate conditions for 2011–2040, 2041–2070, and 2071–2100 were performed using the MARS models obtained earlier for each zone. As the behaviour of MARS models is unknown beyond the range of climatic values observed during the calibration period (1959–1995), future values of climatic variables were clamped to this range when projecting future mAB and mFireOcc. As a result, projected fire regime estimates may be conservative. From the monthly projected values, AAB and FireOcc were computed for each of the 100 replicate periods of 30 years simulated for each normal period. Mean AAB and FireOcc were estimated from these

Fig. 2. Annual area burned (AAB) and fire occurrence (FireOcc) as averaged by (*a*) homogeneous fire regime (HFR_{fuel}) zones and (*b*) ecozones for the 1959–1999 period. See Fig. 1 for ecozone abbreviations. (*c*) Discrepancies in AAB and FireOcc, i.e., the ratio between values averaged by ecozones and HFR_{fuel} zones, are also mapped. Ratios > 1 indicate that values observed from ecozones overestimate values observed using HFR_{fuel} zones as spatial units. Discrepancies were assessed at the 60-km cell level. Insets: area (×10⁶ km²) covered by each ratio class. Zone names: EJB, Eastern James Bay; ES, Eastern Subarctic; ET, Eastern Temperate; GBL, Great Bear Lake; GSL, Great Slave Lake; IC, Interior Cordillera; LA, Lake Athabasca; LW, Lake Winnipeg; NA, North Atlantic; P, Pacific; SC, Southern Cordillera; SP, Southern Prairies; SY, Southwestern Yukon; WJB, Western James Bay; WO, Western Ontario; and WS, Western Subarctic.



100 simulations. Future fire regime values were compared with those estimated from climate data as simulated for the baseline period (1961–1990). The same procedure was repeated for ecozones. Differences in future AAB and FireOcc as estimated from both zonations were computed and mapped. Interpretation of future fire regime analyses mostly focused on values as projected from models derived from the HFR_{fuel} zonation. As a complement, future fire seasonality for each HFR_{fuel} zone was estimated by reporting the averaged area burned projected for each month of the fire season over a given 30-year normal period.

Results

Historical spatial patterns in fire regime according to the HFR zonation

Zonation analyses led to a total of 16 zones (Fig. 2). High fire activity was recorded in zones forming a band from western Yukon to northwest Ontario (Fig. 2). The highest AAB (1.55%·year^{-1}) and FireOcc (15.4 fires·(100 000 km^2)$^{-1}$·year^{-1}) were observed in the Lake Athabasca zone. Lower fire activity was recorded in the Pacific, Eastern Temperate, and both Subarctic zones.

Spatial heterogeneity in AAB and FireOcc for the 1959–1999 period was much better explained by our HFR zonation (adj. R^2 = 0.477) than by ecozones (adj. R^2 = 0.190). Furthermore, the HFR zonation explained much more of the variation in fire regime for the 2000–2010 validation period (adj. R^2 = 0.317) than did ecozone boundaries (adj. R^2 = 0.098). When compared with ecozones, HFR_{fuel} zone boundaries very seldom come close to matching the boundaries of ecozones except along the Montane Cordillera and the Hudson Plains (Fig. 2). Large differences between fire attributes, averaged by zones, were obvious between ecozones and the HFR_{fuel} zonation (Fig. 2). Discrepancies between classifications were most important for AAB, especially along the tree line, in northern British Columbia and in southern Quebec and Ontario. Differences in FireOcc between both classifications followed approximately the same spatial patterns as differences in AAB.

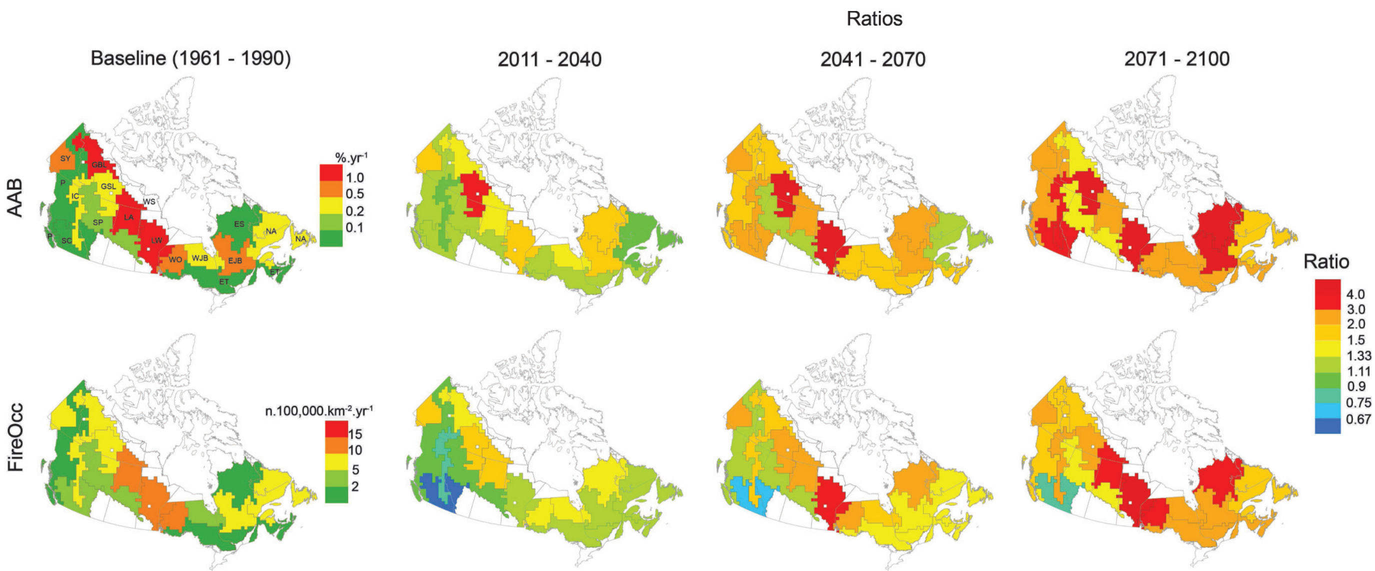
Fire regime modelling and model validation

Overall, the performance of MARS models in predicting both mAB and mFireOcc was high. Nonetheless, the Western Subarctic HFR_{fuel} zone and the Pacific Maritime and Taiga Shield West ecozones were excluded from fire regime projection analyses because MARS models performed very poorly for both attributes in those regions. The predictive ability of MARS models for the HFR zonation was relatively high for both mAB (mean pseudo-R^2 = 0.476) and mFireOcc (mean pseudo-R^2 = 0.535). Similar predictive ability was achieved using ecozones as spatial units (mAB: mean pseudo-R^2 = 0.482; mFireOcc: mean pseudo-R^2 = 0.553). Predicted values pooled for the entire study area on a yearly basis for the 1959–1995 period were very strongly correlated with observed values for both area burned and fire occurrence for the HFR_{fuel} zonation (r = 0.941 and 0.901, respectively) and for ecozones (r = 0.847 and 0.909, respectively) (Fig. S3[1]). Model validation shows high correlation between predicted and observed annual values (r between 0.430 and 0.646) for both mAB and mFireOcc models, either when developed from HFR_{fuel} or ecozones as spatial units (Fig. S2[1]). Nevertheless, models developed from HFR_{fuel} zones tend to slightly overestimate the AAB (major axis slope coefficient (b) = 1.241) while annual FireOcc is slightly underestimated for models developed from HFR_{fuel} (b = 0.839) and ecozones (b = 0.617).

Future fire regime according to HFR

Overall, MARS models projected a 3.7-fold increase in AAB by the end of the 21st century, shifting from 0.40% for the baseline period to 1.5% by 2071–2100 (Table S1[1]). A similar strong increase (3.0-fold) would also occur for FireOcc, which would shift from 5.5 to 16.5 fires·(100 000 km^2)$^{-1}$·year^{-1} (Table S1[1]). Changes in AAB and

Fig. 3. Baseline (1961–1990) and ratio in projected annual area burned (AAB) and fire occurrence (FireOcc) for the future periods (2011–2040, 2041–2070, and 2071–2100) compared with the baseline period. AAB and FireOcc values were not projected for the Western Subarctic zone because multivariate adaptive regression spline models performed very poorly in this zone. See Fig. 2 for definitions of homogeneous fire regime zone abbreviations.



FireOcc would be rather spatially heterogeneous throughout the study area (Fig. 3). The great majority of zones would experience increases in both fire regime attributes throughout the 21st century, with the greatest shifts occurring during the 2071–2100 period (Table S1[1]; Fig. 3). As the exception, FireOcc in the Southern Cordillera zone would decrease slightly (–12.7%) by 2100 compared with the baseline period (Table S1[1]; Fig. 3). Large increases in AAB and FireOcc would mostly occur in zones where it is already high (>0.5%) during the baseline period. Zones located in central Canada (Great Slave Lake, Lake Athabasca, and Lake Winnipeg zones) would experience very short fire return intervals (<27 years or AAB > 3.7%) by 2071–2100 (Table S1[1]). Large shifts in AAB (>4-fold) are also projected for most of northern and central Québec (Eastern Subarctic and Eastern James Bay), while AAB would more than triple in the Interior and Southern Cordillera. Except for the Eastern Subarctic zone, zones with low fire activity during the baseline period (Southern Cordillera, Eastern Temperate, and Pacific zones) would remain relatively inactive (Fig. 3). The Southern Prairies zone would experience relatively small changes (+45.6% and +47.5% for FireOcc and AAB, respectively) in fire regime attributes through the end of the 21st century (Table S1[1]; Fig. 3).

The greatest contribution to the increase in AAB would result from a sharp increase in fire activity during the months of July and (or) August, especially for the 2041–2070 and 2071–2100 periods (Fig. S4[1]). Most of the increase in area burned would occur in July in the Great Slave Lake zone. The Lake Athabasca, Interior Cordillera, and Southwestern Yukon zones would experience large increases in area burned in both July and August. Several zones in eastern and central Canada (Lake Winnipeg, Eastern Subarctic, Eastern and Western James Bay, and North Atlantic) would also experience an increase in area burned in June in addition to July and August. Otherwise, area burned would remain relatively unchanged for the remainder of the fire season when compared with the baseline period, except for the Eastern Temperate zone where it would increase for July, August, and September. As a result, fire seasonality in some zones would shift slightly with the median cumulative proportion of yearly area burned occurring later in the summer. This is the case for the Eastern Temperate, Lake Winnipeg, Western James Bay, and Western Ontario zones (Fig. 4). These changes will be most important in 2071–2100. Proportionally, area burned in the spring would contribute less to the AAB in the future, when compared with the baseline period, in the Interior Cordillera zone. With respect to the other end of the fire season, the proportion of late summer fires will be less for future periods in the Great Slave Lake zone. Elsewhere, fire seasonality would remain relatively unchanged (Fig. 4).

Comparison of HFR zones with ecozones

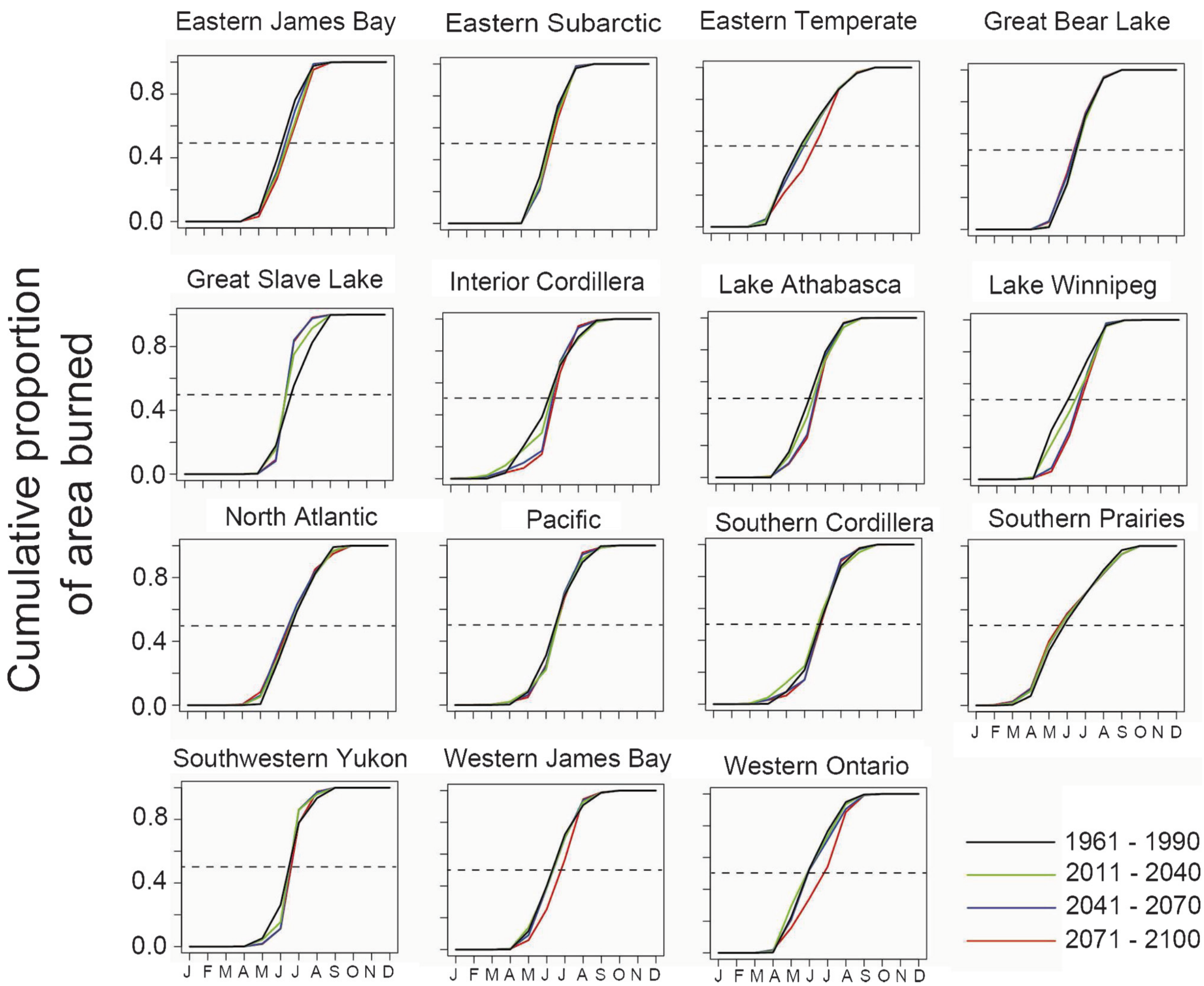
Very high spatial discrepancies were noted between projected values for both zonations over extensive areas. Ecozone-based models tend to overestimate fire regime values over very large areas, whatever the period considered. Discrepancies were more important for AAB. Projections based on ecozones greatly (2- to >4-fold) and constantly overestimated the increase in AAB and FireOcc in northern Quebec, most of Ontario, and the Boreal Plains as well as in northern British Columbia (Fig. 5). Fire regime attribute values were underestimated, sometimes more than 4-fold, on relatively smaller areas, mostly where fire activity is projected to be peculiarly high when compared with the surroundings (e.g., eastern James Bay, central British Columbia, southwestern Yukon, and most of Manitoba as well as central Quebec and Newfoundland).

Discussion

This study is the first to use HFR zones to project future fire regime conditions at the national level for Canada. In this study, we decided to define large-scale spatial units to characterize the nationwide fire regime. This is not trivial because there is considerable spatial variation in fire regime. Fire regime attributes may be spatially structured at various spatial scales, even at smaller spatial scales than the grain we used to define HFR_{fuel} zones (Cyr et al. 2007; Parisien and Moritz 2009; Parisien et al. 2011). For example, ignition, fuel, and topographic conditions may strongly affect fire ignition and area burned at the landscape or regional scale (e.g., Cary et al. 2006; Parisien and Moritz 2009; Parisien et al. 2011, 2012). Consequently, our analyses do not preclude that specific locations may experience a peculiar fire regime within a given HFR_{fuel} zone.

The rationale behind delineating large-scale spatial units was two-fold. First, our aim was to model nationwide fire regimes according to climate conditions. Since the temporal variation in these conditions is synoptic in scale, we assumed, like several

Fig. 4. Modelled fire seasonality as expressed by the cumulative proportion of yearly area burned for the baseline (1961–1990) and future periods (2011–2040, 2041–2070, and 2071–2100) for each zone. Dashed line represents the median (50%).

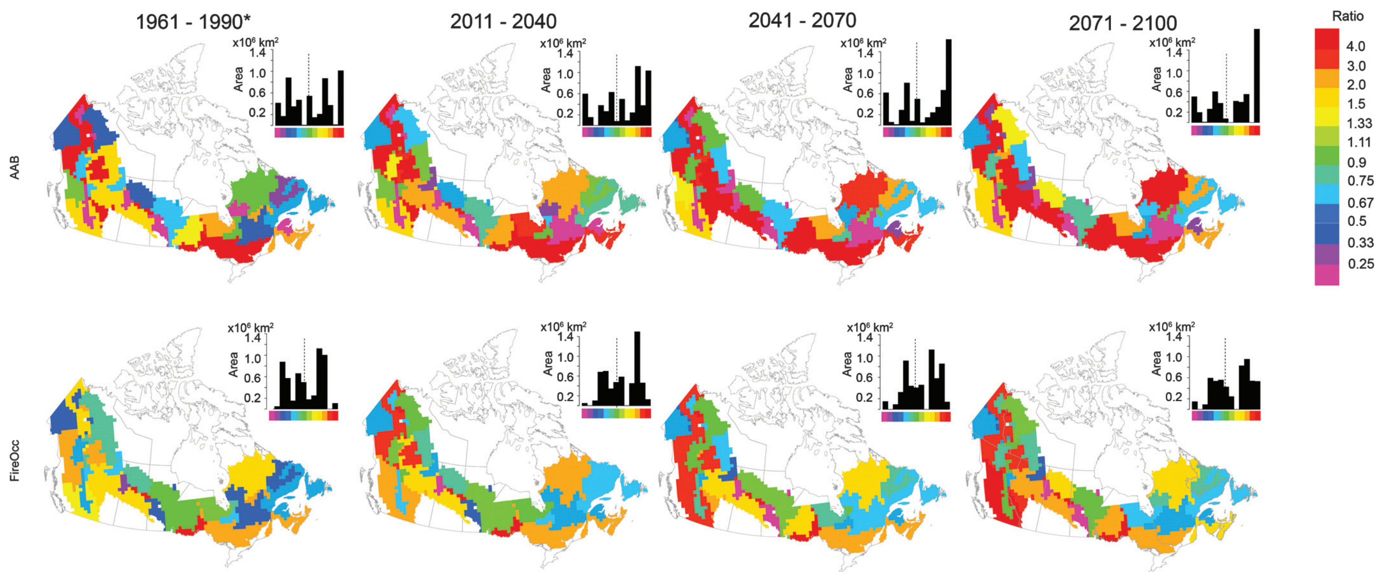


other authors (e.g., Skinner et al. 2002; Girardin et al. 2004; Le Goff et al. 2007), that fire regime would respond, at least in part, to a similar scale. Our models linking fire weather and fire regime attributes indeed showed very good predictive ability at the scale investigated. Second, the estimation of fire regime characteristics can be highly stochastic if it is assessed at small spatial scales (Metsaranta 2010). Indeed, one or very few events may greatly affect the estimation of fire regime attributes. Our HFR zones should thus allow for much more stable estimates of fire regime attributes, both in space and time.

It has to be noted that HFR zones represent a snapshot of the recent fire regime patterns resulting from recent climate and ignition conditions as well as fire and forest management strategies. In this context, one may argue that zone boundaries may have been different using another calibration period. Indeed, using static boundary zones implies that spatial patterns in fire-driving factors (e.g., climate) will be temporally stable over time. Temporal changes in the spatial pattern of these elements (either during the calibration period or for future periods) may affect zone boundaries to some extent, especially in areas with very low fire activity where one or very few fire events in some cells may change the local spatial variance pattern (Metsaranta 2010). However, any changes should be rather small as spatial patterns of the fire regime are rather stable at a large spatial scale (Reed 1998; Flannigan et al. 2005). Moreover, a recent analysis (Boulanger et al. 2013) in eastern Canada showed that future climate patterns should not affect to a great extent the actual boundaries of HFR zones. In this context, the use of large fixed-boundary zones may not be the panacea but still a rather good spatial framework to project future fire regimes.

HFR_{fuel}-zone-based models reveal that shifts in fire-conducive weather conditions along with projected climate change should cause a major increase in fire risk over Canada, with large areas experiencing dramatic increases in AAB and FireOcc. Overall, our models predicted a 3.7× and 3.0× increase in AAB and in the number of fires, respectively, within the study area by 2100 when compared with the 1961–1990 baseline period. With few exceptions (e.g., southeastern Ontario), our models project future large-scale patterns in area burned and fire occurrence for eastern Canada rather similar to those predicted in Boulanger et al (2013) although we used a different modelling technique (MARS vs. random forests) and different fire and climate data (monthly based vs. normals). Projected increases are within the range previously reported for the study area, though there is tremendous variation reported in the literature. Typically, increases below 2-fold are reported for both the number of fires and AAB throughout Canada (e.g., Bergeron et al. 2004; Flannigan et al. 2005; Girardin and Mudelsee 2008; Wotton et al. 2010). However, Balshi et al. (2009) projected a 3.6× to 5.6× increase in AAB by the end of the 21st century for western Canada and Alaska.

Fig. 5. Mapped discrepancies between homogeneous fire regime (HFR_{fuel}) zones and ecozones using zone-averaged projected annual area burned (AAB) and fire occurrence (FireOcc) values. Ratios > 1 indicate that values projected from ecozones overestimate values projected using HFR_{fuel} zones as spatial units. Discrepancies are assessed separately for the baseline and the three future periods at the 60-km cell level. Discrepancies were not estimated in areas overlapping the Western Subarctic zone and the Pacific Maritime ecozone because AAB and FireOcc models performed poorly in these zones. Insets: area (×10⁶ km²) covered by each ratio class.



Although virtually all zones would experience an increase in the number of fires and AAB, we project a spatially heterogeneous response of fire regime to climate change across Canada. The largest increase in fire activity, both in absolute terms and relative to the baseline period, would occur in northwestern and central Canada, as suggested by other authors (Balshi et al. 2009; Wotton et al. 2010). Within this latter rather large area, models predict a very high fire occurrence and area burned by 2071–2100, which indeed would be higher than what was experienced in the most fire-active zones between 1980 and 1999 (Boulanger et al. 2012), a period recognized for its intense fire activity (Kasischke and Turetsky 2006). Considering these increases, many zones would experience a fire activity that would fall well beyond their historical range of fire variability (Bergeron et al. 2004; Girardin and Mudelsee 2008), which may have large ecological and sociological impacts (Flannigan et al. 2005).

Our models projected that in some zones fire seasonality will shift with most of the area burned occurring later in the season by the end of the century. This contradicts earlier studies suggesting that extreme fire danger would occur more frequently early in the season (Stocks et al. 1998), resulting in a larger area burned in late spring (Amiro et al. 2009). Nonetheless, a similar shift in fire occurrence was recently proposed for northwestern Quebec based on future fire severity rating (Le Goff et al. 2009). Moreover, Boulanger et al. (2013) projected a shift in fire activity to slightly later in the summer for eastern Canada, considering similar shifts in the occurrence of maximal Canadian Forest Fire Weather Index annual values. Haughian et al. (2012) projected the potential for substantial increases in August fires in southern British Columbia. Recent observations in Alaska also suggest a shift in the fire season over the last decade towards late-summer fires as a result of climate change (Kasischke et al. 2010). This does not preclude, however, the occurrence of large fires earlier or later in the season than during the historic period.

Had we relied on ecozones to model fire regime, we would have failed to efficiently capture the spatial heterogeneity and changes in fire regime over a large portion of the territory. Indeed, our empirically derived zonation assessed the spatial heterogeneity in fire regime much more accurately than ecozones. A recent study (Boulanger et al. 2012) showed that even NEFC's smaller units (i.e., ecoprovinces) poorly capture spatial heterogeneity in the Canadian fire regime, at least for the 1980–1999 period. Ecozones and ecoprovinces may not represent reasonable proxies of variables that actually drive fire regimes at this scale, while ecoregions and ecodistricts (the finer divisions of the NEFC hierarchy) overfit the available fire regime data (Boulanger et al. 2012). For instance, the geological or physiognomic features used to delineate the NEFC's large-scale units may have little influence on fire regimes at these broad scales (Lefort et al. 2003; Cary et al. 2006).

If one assumes that the spatial heterogeneity in fire regimes observed during the 1959–1999 period will remain similar in the upcoming decades, future fire regimes as projected from our HFR_{fuel} zonation should provide much more spatially accurate estimates of future large-scale biodiversity patterns, energy flows, and carbon storage than those derived from multipurpose classification schemes. In the Canadian boreal forest, many of these patterns and processes are strongly fire driven (e.g., Bond-Lamberty et al. 2007) so their analyses benefit from a precise knowledge of the fire regime prevailing at the scale of concern. Indeed, shorter fire return intervals are associated with higher carbon losses and a decrease in carbon storage (Amiro et al. 2009; Brown and Johnstone 2011). In the light of the results presented here, total carbon emissions from fires should increase over the upcoming decades as a result of the concurrent increase in the area burned (Amiro et al. 2009).

HFR-based estimates of future fire regimes may help to better outline areas where forest composition, structure, and inherent processes might be altered. Significant projected shifts in fire regimes may influence the successional pathways of postfire regeneration, notably by favouring early successional and fire-adapted species (e.g., jack pine (*Pinus banksiana* Lamb.) and trembling aspen (*Populus tremuloides* Michx.)), prompting faster forest cover alterations than those resulting from changes in temperature and precipitation per se (Weber and Flannigan 1997). Zones located in central Canada (Great Slave Lake, Lake Athabasca, and Lake Winnipeg zones) would be an extreme case (but see the Limitations section below) since continuous forest cover may hardly be maintained under the projected fire return interval (<26 years). Indeed, these areas would experience a fire activity closer to what is currently or was historically experienced in ponderosa pine (*Pinus* *ponderosa* P. & C. Lawson) savannahs or aspen (*Populus* spp.) parklands (Weir et al. 2000). However, how succession would progress under such high fire activity requires considerable scrutiny. It has to be noted that fire regime attributes are projected on a 30-year basis. Shifts in forest composition may take much longer to materialize, i.e., to reach equilibrium. Nevertheless, important changes in forest structure and composition in areas that are currently experiencing relatively low burn rates (e.g., the Eastern Subarctic, Interior Cordillera, and North Atlantic zones) are very likely to affect regional patterns of biodiversity, notably by favouring species associated with early seral stages, while being detrimental to those associated with old-growth forests. Potential changes in forest composition may in turn influence insect outbreak dynamics (e.g., forest tent caterpillar and spruce budworm) by altering regional host abundance (James et al. 2007; Bouchard and Pothier 2008). HFR_{fuel} zones may thus provide an efficient framework for the management of large-scale biodiversity issues across Canada, at least in areas where fire is, or is projected to be, the most prevalent natural disturbance.

The fire regime characteristics predicted for the upcoming decades may help forest and fire management agencies because they reveal zones with high fire occurrence or large area burned, that were otherwise hidden within larger areas. 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 resources across a territory. For example, HFR_{fuel} zones may help to localize specific areas where high fire occurrence may sporadically overwhelm fire management authorities in the future (Wotton and Stocks 2006; Podur and Wotton 2010). Several zones, especially in central Canada where fire occurrence may increase 4-fold, could need to allocate far more resources than they do today for future fire management.

Consideration of HFR zonation provides the information necessary to integrate forest fire as a forest management constraint where it is a dominant ecological process in the landscape (Armstrong 2004; Gauthier et al. 2009; Savage et al. 2010). At the current scale of analysis, our HFR zonation may give a first although still rather coarse view of future fire regimes to fire and forest management agencies. However, finer-scale delineations of HFR zones (Boulanger et al. 2013; Terrier et al. 2013) were recently done for eastern Canada and should help refine the projection of fire regime characteristics to a manageable scale in this context.

Limitations

We acknowledge that there are limitations to the work conducted here. Indeed, projections of future fire regimes were solely based on an intense-forcing climate scenario (A2). As such, these projections may be seen as a "worst case" scenario. Projections based on "milder" forcing scenarios (e.g., SRES A1B, B1, and B2) generally lead to less severe future fire activity (Girardin and Mudelsee 2008; Balshi et al. 2009). In this context, continuous yearly monitoring of fire statistics at the national scale is paramount for tracking any shifts in fire regime caused by the realized greenhouse gas emission scenario.

Our models and our zonation analyses assumed a "static" view of the nonclimate environment for the future, which is an unlikely situation. For instance, the delineation of HFR zones and our models did not account for temporal and spatial differences in fire management policies and (or) efficiency (Wotton and Stocks 2006). Indeed, the relative homogeneity of the fire regime within a given zone may not solely result from climate and fuel attributes but also from variable fire management policies within the zone. For example, some HFR_{fuel} zones overlap provincial extensive and intensive protection zones. As a result, effects of climate variables may not be stationary within a given HFR_{fuel} zone. Moreover, although HFR_{fuel}-based models show a fairly good predictive ability, part of the unexplained variation may result from changing fire protection efficiency throughout the calibration periods (Wotton and Stocks 2006). In any case, our models assume that fire management efficiency will remain spatially and temporally stable in the future and comparable with the calibration period. More important resource allocation for fire protection in the future may hamper the projected fire activity.

We did not account for potential changes in vegetation composition and spatial patterns prompted by fire or other natural (e.g., windthrow and insect outbreaks) or anthropogenic (logging) disturbances, nor changes in forest or fire management policies. All these changes may generate either negative or positive feedback for subsequent fire regime attributes, notably by altering energy exchange, surface albedo, and fuel flammability (Krawchuk et al. 2006). Future integration of these potential changes in vegetation patterns (as in Terrier et al. 2013) or fire management policies, notably through spatially explicit forest landscape simulation models, may provide more accurate estimates of the future boreal fire regime. Therefore, projections of future fire regime should be interpreted as a "what if" scenario, i.e., how today's fire regime (given the current fuel and forest/fire management policies) would look under climate conditions projected for the future.

Our models do not account for changes in lightning activity or other changes in fire weather during periods with high ignition probabilities. As such, some areas where lightning activity might change may experience fire activity different than predicted. Currently, CRCM models do not predict future lightning conditions. Future coupling of fire weather and ignition conditions (either natural or anthropogenic) would add much more predictive power to models projecting future fire activity.

Acknowledgements

The authors thank all provincial and territorial agencies, 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 Marc-André Parisien for comments on earlier versions of the manuscript. This study was funded by Natural Resources Canada.

References

Allen, J.C. 1976. A modified sine wave method for calculating degree days. Environ. Entomol. **5**: 388–396.

Amiro, B.D., Todd, J.B., Wotton, B.M., Logan, K.A., Flannigan, M.D., Stocks, B.J., Mason, J.A., Martell, D.L., and Hirsch, K. 2001. Direct carbon emissions from Canadian forest fires, 1959–1999. Can. J. For. Res **31**(3): 512–525. doi:10.1139/x00-197.

Amiro, B.D., Cantin, A., Flannigan, M.D., and de Groot, W.J. 2009. Future emissions from Canadian boreal forest fires. Can. J. For. Res **39**(2): 383–395. doi:10.1139/X08-154.

Armstrong, G.W. 2004. Sustainability of timber supply considering the risk of wildfire. For. Sci. **50**: 626–639.

Balshi, M.S., McGuire, A.D., Duffy, P., Flannigan, M., Walsh, J., and Melillo, J. 2009. Assessing the response of area burned to changing climate in western boreal North America using a Multivariate Adaptive Regression Splines (MARS) approach. Global Change Biol. **15**: 578–600. doi:10.1111/j.1365-2486.2008.01679.x.

Beaubien, J., Cihlar, J., Simard, G., and Latifovic, R. 1999. Land cover from multiple thematic mapper scenes using a new enhancement-classification methodology. J. Geophys. Res. **104**: 27909–27920. doi:10.1029/1999JD900243.

Bergeron, Y., Flannigan, M.D., Gauthier, S., Leduc, A., and Lefort, P. 2004. Past, current and future fire frequency in the Canadian boreal forest: implications for sustainable forest management. Ambio, **33**: 356–360. doi:10.1579/0044-7447-33.6.356.

Bergeron, Y., Cyr, D., Girardin, M.-P., and Carcaillet, C. 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. Int. J. Wildland Fire, **19**: 1127–1139. doi:10.1071/WF09092.

Bond-Lamberty, B., Peckham, S.D., Ahl, D.E., and Gower, S.T. 2007. Fire as the dominant driver of central Canadian boreal forest carbon balance. Nature, **450**: 89–92. doi:10.1038/nature06272.

Bouchard, M., and Pothier, D. 2008. Simulations of the effects of changes in mean fire return intervals on balsam fir abundance, and implications for spruce budworm outbreaks. Ecol. Model. **218**: 207–218. doi:10.1016/j.ecolmodel.2008.07.001.

Boulanger, Y., Gauthier, S., Burton, P.J., and Vaillancourt, M.-A. 2012. An alternative fire regime zonation for Canada. Int. J. Wildland Fire, **21**: 1052–1064. doi:10.1071/WF11073.

Boulanger, Y., Gauthier, S., Gray, D.R., Le Goff, H., Lefort, P., and Morissette, J. 2013. Fire regime zonation under current and future climate over eastern Canada. Ecol. Appl. **23**(4): 904–923. doi:10.1890/12-0698.1.

Brown, C.D., and Johnstone, J.F. 2011. How does increased fire frequency affect carbon loss from fire? A case study in the northern boreal forest. Int. J. Wildland Fire, **20**: 829–837. doi:10.1071/WF10113.

Cary, G.J., Keane, R.E., Gardner, R.H., Lavorel, S., Flannigan, M.D., Davies, I.D., Li, C., Lenihan, J.M., Rupp, T.S., and Mouillot, F. 2006. Comparison of the sensitivity of landscape-fire-succession models to variation in terrain, fuel pattern, climate and weather. Landsc. Ecol. **21**: 121–137. doi:10.1007/s10980-005-7302-9.

Caya, D., and Laprise, R. 1999. A semi-implicit semi-Lagrangian regional climate model: The Canadian RCM. Mon. Weather Rev. **127**: 341–362. doi:10.1175/1520-0493(1999)127<0341:ASISLR>2.0.CO;2.

Cyr, D., Gauthier, S., and Bergeron, Y. 2007. Scale-dependent determinants of heterogeneity in fire frequency in a coniferous boreal forest of eastern Canada. Landsc. Ecol. **22**: 1325–1339. doi:10.1007/s10980-007-9109-3.

de Groot, W.J., Pritchard, J.M., and Lynham, T.J. 2009. Forest floor fuel consumption and carbon emissions in Canadian boreal forest fires. Can. J. For. Res **39**(2): 367–382. doi:10.1139/X08-192.

Dormann, C.F., Elith, J., Bacher, S., Buchmann, C., Carl, G., Carré, G., Garcia Marquez, J.R., Gruber, B., Lafourcade, B., Leitão, P.J., Münkemüller, T., McClean, C., Osborne, P.E., Keineking, B., Schröder, B., Skidmore, A.K., Zurell, D., and Lautenbach, S. 2013. Collinearity: a review of methods to deal with it and a simulation a study evaluating their performance. Ecography, **36**: 27–46. doi:10.1111/j.1600-0587.2012.07348.x.

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

Environment Canada. 2007. Canadian climate normals or averages, 1971–2000. Available from http://www.climate.eatheroffice.gc.ca/climate_normals/index_e.html [accessed on August 23 2013].

ESRI. 2006. ArcGIS v9.2. Redland, CA, U.S.A.

Flannigan, M.D., Logan, K.A., Amiro, B.D., Skinner, W.R., and Stocks, B.J. 2005. Future area burned in Canada. Clim. Change **72**: 1–16. doi:10.1007/s10584-005-5935-y.

Friedman, J.H. 1991. Multivariate adaptive regression splines. Ann. Stat. **19**: 1–141. doi:10.1214/aos/1176347963.

Gauthier, S., Leduc, A., Bergeron, Y., and Le Goff, H. 2009. Fire frequency and forest management based on natural disturbances. *In* Ecosystem management in the boreal forest. *Edited by* S. Gauthier, M.-A. Vaillancourt, A. Leduc, et al. Presses de l'Université du Québec, Québec, Canada, pp. 57–74.

Gillett, N.P., Weaver, A.J., Zwiers, F.W., and Flannigan, M.D. 2004. Detecting the effect of climate change on Canadian forest fires. Geophys. Res. Lett. **31**: L18211. doi:10.1029/2004GL020876.

Girardin, M.-P., and Mudelsee, M. 2008. Past and future changes in Canadian boreal wildfire activity. Ecol. Appl. **18**: 391–406. doi:10.1890/07-0747.1.

Girardin, M.-P., Tardif, J., Flannigan, M.D., Wotton, B.M., and Bergeron, Y. 2004. Trends and periodicities in the Canadian Drought Code and their relationships with atmospheric circulation for the southern Canadian boreal forest. Can. J. For. Res **34**(1): 103–119. doi:10.1139/x03-195.

Guo, D. 2008 Regionalization with dynamically constrained agglomerative clustering and partitioning (REDCAP). Int. J. Geogr. Inf. Sci. **22**: 801–823. doi:10.1080/13658810701674970.

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

Haughian, S.R., Burton, P.J., Taylor, S.W., and Curry, C.L. 2012. Expected effects of climate change on forest disturbance regimes in British Columbia. B.C. J. Ecosyst. Manage. **13**(1): 1–24.

Heyerdahl, E.K., Brubaker, L.B., and Agee, J.K. 2001. Spatial controls of historical fire regimes: a multiscale example from the interior west, U.S.A. Ecology, **82**: 660–678. doi:10.2307/2680187.

James, P.M.A., Fortin, M.J., Fall, A., Kneeshaw, D., and Messier, C. 2007. The effects of spatial legacies following shifting management practices and fire on boreal forest age structure. Ecosystems, **10**: 1261–1277. doi:10.1007/s10021-007-9095-y.

Kasischke, E.S., and Turetsky, M.R. 2006. Recent changes in the fire regime across the North American boreal region – spatial and temporal patterns of burning across Canada and Alaska. Geophys. Res. Lett. **33**: L09703. doi:10.1029/2006GL025677.

Kasischke, E.S., Verbyla, D.L., Rupp, T.S., McGuire, A.D., Murphy, K.A., Jandt, R., Barnes, J.L., Hoy, E.E., Duffy, P.A., Calef, M., and Turetsky, M.R. 2010. Alaska's changing fire regime — implications for the vulnerability of its boreal forests. Can. J. For. Res **40**(7): 1313–1324. doi:10.1139/X10-098.

Krawchuk, M.A., Cumming, S.G., Flannigan, M.D., and Wein, R.W. 2006. Biotic and abiotic regulation of lightning fire initiation in the mixedwood boreal forest. Ecology, **87**: 458–468. doi:10.1890/05-1021.

Le Goff, H., Flannigan., M.D., Bergeron, Y., and Girardin, M.-P. 2007. Historical fire regime shifts related to climate teleconnections in the Waswanipi area, central Quebec, Canada. Int. J. Wildland Fire, **16**: 607–618. doi:10.1071/WF06151.

Le Goff, H., Flannigan, M.D., and Bergeron, Y. 2009. Potential changes in monthly fire risk in the eastern Canadian boreal forest under future climate change. Can. J. For. Res **39**(12): 2369–2380. doi:10.1139/X09-153.

Lefort, P., Gauthier, S., and Bergeron, Y. 2003. The influence of fire weather and land use on the fire activity of the Lake Abitibi area, eastern Canada. For. Sci. **49**: 509–521.

Macias Fauria, M., and Johnson, E.A. 2006. Large-scale climatic patterns control large lightning fire occurrence in Canada and Alaska forest regions. J. Geophys. Res. **111**: G04008. doi:10.1029/2006JG000181.

Metsaranta, J.M. 2010. Potentially limited detectability of short-term changes in boreal fire regimes: a simulation study. Int. J. Wildland Fire, **19**: 1140–1146. doi:10.1071/WF10037.

Milborrow, S. 2012. earth: Multivariate Adaptive Regression Spline Models. R package version 3.2-3. Available from http://CRAN.R-project.org/package=earth.

Nakicenovic, N., Davidson, O., Davis, G., Grübler, A., Kram, T., Lebre La Roverere, L., Metz, B., Morita, T., Pepper, W., Pitcher, H., Sankovski, A., Shukla, P., Swart, R., Watson, R., and Dadi, A. 2000. Special report on emissions scenarios, summary for policy makers. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Parisien, M.-A., and Moritz, M.A. 2009. Environmental controls on the distribution of wildfire at multiple spatial scales. Ecol. Monogr. **79**: 127–154. doi:10.1890/07-1289.1.

Parisien, M.-A., Peters, V.S., Wang, Y., Little, J.M., Busch, E.M., and Stocks, B.J. 2006. Spatial patterns of forest fires in Canada, 1980–1999. Int. J. Wildland Fire, **15**: 361–374. doi:10.1071/WF06009.

Parisien, M.-A., Parks, S.A., Krawchuk, M.A., Flannigan, M.D., Bowman, L.M., and Moritz, M.A. 2011. Scale-dependent controls on the area burned in the boreal forest of Canada, 1980–2005. Ecol. Appl. **21**: 789–805. doi:10.1890/10-0326.1.

Parisien, M.-A., Snetsinger, S., Greenberg, J.A., Nelson, C.R., Shoennagel, T., Dobrowski, S.Z., and Moritz, M. 2012. Spatial variability in wildfire probability across the western United States. Int. J. Wildland Fire, **21**: 313–327. doi:10.1071/WF11044.

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

Podur, J., and Wotton, M. 2010. Will climate change overwhelm fire management capacity? Ecol. Model. **221**: 1301–1309. doi:10.1016/j.ecolmodel.2010.01.013.

Prasad, A.M., Iverson, L.R., and Liaw, A. 2006. Newer tree classification and regression tree techniques: bagging and random Forests for ecological prediction. Ecosystems, **9**: 181–199. doi:10.1007/s10021-005-0054-1.

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

Raulier, F., Le Goff, H., Gauthier, S., Rapanoela, R., and Bergeron, Y. 2013. Introducing two indicators for fire risk consideration in the management of boreal forests. Ecol. Indic. **24**: 451–461. doi:10.1016/j.ecolind.2012.07.023.

Reed, W.J. 1998. Determining changes in historical forest fire frequency from a time-since-fire map. Journal of Agricultural, Biological and Environmental Statistics, **3**: 430–450. doi:10.2307/1400575.

Régnière, J., and St-Amant, R. 2007. Stochastic simulation of daily air temperature and precipitation from monthly normals in North America north of Mexico. Int. J. Biometeorol. **51**: 415–430. doi:10.1007/s00484-006-0078-z.

Savage, D.W., Martell, D.L., and Wotton, B.M. 2010. Evaluation of two risk mitigation strategies for dealing with fire-related uncertainty in timber supply modelling. Can. J. For. Res **40**(6): 1136–1154. doi:10.1139/X10-065.

Segal, M., and Xiao, Y. 2011. Multivariate random forests. Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery, **1**: 80–87. doi:10.1002/widm.12.

Skinner, W.R., Flannigan, M.D., Stocks, B.J., Martell, D.L., Wotton, B.M., Todd, J.B., Mason, J.A., Logan, K.A., and Bosch, E.M. 2002. A 500 hPa synoptic wildland fire climatology for large Canadian forest fires, 1959–1996. Theor. Appl. Climatol. **71**: 157–169. doi:10.1007/s007040200002.

Stocks, B.J., Fosberg, M.A., Lynham, T.J., Mearns, L., Wotton, B.M., Yang, Q., Jin, J.-Z., Lawrence, K., Hartley, G.R., Mason, J.A., and McKenney, D. 1998. Climate change and forest fire potential in Russian and Canadian boreal forests. Clim. Change, **38**: 1–13. doi:10.1023/A:1005306001055.

Stocks, B.J., Mason, J.A., Todd, J.B., Bosch, E.M., Wotton, B.M., Amiro, B.D., Flannigan, M.D., Hirsch, K.G., Logan, K.A., Martell, D.L., and Skinner, W.R. 2003. Large forest fires in Canada, 1959–1997. J. Geophys. Res. **108**(D1): 8149. doi:10.1029/2001JD000484.

Terrier, A., Girardin, M.P., Périé, C., Legendre, P., and Bergeron, Y. 2013. Potential changes in forest composition could reduce impacts of climate change on boreal wildfires. Ecol. Appl. **23**: 21–35. doi:10.1890/12-0425.1.

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

Weber, M.G., and Flannigan, M.D. 1997. Canadian boreal forest ecosystem structure and function in a changing climate: impact on fire regimes. Environ. Rev. **5**: 145–166. doi:10.1139/a97-008.

Weir, J.M.H., Johnson, E.A., and Miyanishi, K. 2000. Fire frequency and the spatial age mosaic of the mixed-wood boreal forest in western Canada. Ecol. Appl. **10**: 1162–1177. doi:10.1890/1051-0761(2000)010[1162:FFATSA]2.0.CO;2.

Wotton, B.M., and Stocks, B.J. 2006. Fire management in Canada: vulnerability and risk trends. *In* Canadian Wildland Fire Strategy: Background Syntheses, Analyses, and Perspectives. *Edited by* K. Hirsch and P. Fuglem. Canadian Council of Forest Ministers. Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, Edmonton, Canada. pp. 49–55.

Wotton, B.M., Nock, C.A., and Flannigan, M.D. 2010. Forest fire occurrence and climate change in Canada. Int. J. Wildland Fire, **19**: 253–271. doi:10.1071/WF09002.