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Spatial distribution of mean fire size and occurrence in eastern Canada: influence of climate, physical environment and lightning strike density

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Abstract. In Canada, recent catastrophic wildfire events raised concern from governments and communities. As climate change is expected to increase fire activity in boreal forests, the need for a better understanding of fire regimes is becoming urgent. This study addresses the 1972–2015 spatial distributions of fire cycles, mean fire size (FireSz) and mean fire occurrence (mean annual number of fires per 100 000 ha, FireOcc) in eastern Canada. The objectives were to determine (1) the spatial variability of fire-regime attributes, (2) the capacity of FireSz and FireOcc to distinguish homogeneous fire zones and (3) the environmental factors driving FireSz and FireOcc, with some emphasis on lightning strikes. Fire cycles, FireSz and FireOcc greatly varied throughout the study area. Even within homogeneous fire zones, FireSz and FireOcc were highly variable. FireSz was controlled by moisture content in deep layers of the soil and by surficial deposits, whereas FireOcc was controlled by moisture content in top layers of the soil and by relief. The lack of a relationship between FireOcc and lightning-strike density suggested that the limiting effect of lightning-strike density on FireOcc could be operating only under certain circumstances, when interacting with other environmental factors.

Additional keywords: boreal forest, fire cycle, fire regime, Quebec.

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Introduction

Wildfire constitutes one of the main drivers of boreal forest dynamics and processes in North America (Weber and Flannigan 1997; Ryan 2002). Human communities in boreal forests have learned to live with and adapt to fire hazards. However, there is increasing concern as fire activity is expected to increase in the near future in response to climate change (Bergeron *et al.* 2010; Flannigan *et al.* 2016; Boulanger *et al.* 2018). Recent catastrophic fire events in western Canada, such as the 2016 Fort McMurray Horse River fire, have forced fire-suppression agencies to question their capacity to cope with both current and future fire activity (Wotton *et al.* 2017). In eastern Canada, fire activity has decreased since the end of the Little Ice Age (*c.* 1850) in response to changes in atmospheric circulation patterns (Drobyshev *et al.* 2017). Despite important spatial variability in eastern Canada's fire regimes (Gauthier *et al.* 2015*a*; Portier *et al.* 2016), a series of uncontrollable large fires that occurred in 2013 in the James Bay region could be seen as the first sign of a trend reversal in fire activity (Héon *et al.* 2014; Portier *et al.* 2016; Erni *et al.* 2017).

Fire regimes are characterised by various components, such as fire size, cycle, return interval, occurrence, intensity and severity (Johnson and Gutsell 1994; Weber and Flannigan 1997). Fire cycle is defined as the time that is required to burn an area equivalent to the area of interest (Van Wagner 1978), whereas fire return interval is the time elapsed between fires at a given location. Each of these components is associated with particular ecological characteristics (Johnson 1992; Weber and Flannigan 1997; Ryan 2002). For instance, fire size affects habitat fragmentation and the capacity of trees to recolonise the area that has been burned from the burn edge (Galipeau *et al.* 1997). Fire return intervals determine successional pathways: short fire return intervals will favour early-successional, shade-intolerant species that reach reproductive maturity early in their development, whereas long fire return intervals will favour late-successional, shade-tolerant species (Johnson 1992; Bergeron

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et al. 2002). Consequently, for a given area burned, numerous small fires or rare large ones will have different ecological consequences. In the context of climate change, where the escape rate of wildfires is expected to increase (Wotton *et al.* 2017), a comprehensive understanding of the distribution of the main fire regime components is becoming increasingly crucial. A fire regime that is characterised by many small fires could be more challenging for fire-suppression agencies than one with fewer large fires.

The spatial variability of a fire regime depends upon various environmental and anthropogenic factors, such as climate (Balshi *et al.* 2009; Girardin *et al.* 2009), the physical environment (Mansuy *et al.* 2014; Rogeau and Armstrong 2017), and land cover (Lefort *et al.* 2004; Marchal *et al.* 2017). For instance, the Fire Weather Index System (Amiro *et al.* 2004) has been widely used in North American studies modelling fire activity (Balshi *et al.* 2009; Boulanger *et al.* 2013). The role of all these factors has been demonstrated with respect to fire regime components, such as the well-documented annual area burned, but it has not been as extensively studied in terms of fire size or occurrence (Lefort *et al.* 2004; Wotton and Martell 2005; Marchal *et al.* 2017). Although human-caused fires in Canada are most numerous in populated areas, lightning-caused fires are responsible for ~80% of the area burned (Stocks *et al.* 2002). Lightning is also a strong driver of inter-annual variability in area burned in western North America (Veraverbeke *et al.* 2017). Lightning-caused fires are ignited by cloud-to-ground lightning strikes that move electrical charges between a cloud and the ground (Burrows and Kochtubajda 2010; Orville *et al.* 2011). The charge of a lightning strike can be positive or negative, but no consensus exists in the literature as to which is more likely to start a fire (e.g. Flannigan and Van Wagner 1991; Wotton and Martell 2005). In addition, the relationship between lightning-strike density and the spatial variability of fire occurrence is still poorly documented in eastern Canada.

This study aimed to better understand the spatial distribution of fire regimes in the coniferous boreal forests of eastern Canada in terms of fire cycle, mean fire size (FireSz) and fire occurrence (mean annual number of fires per 100 000 ha, FireOcc) over the period 1972–2015. The first objective was to characterise the spatial variability of fire-regimes attributes, and more specifically to update estimates of fire cycles from 1972–2009 (Gauthier *et al.* 2015*a*) to 1972–2015. Second, we determined if homogeneous zones in terms of fire cycles (Gauthier *et al.* 2015*a*) were also homogeneous in terms of FireSz and FireOcc. Last, we determined which environmental factors were related to FireSz and FireOcc, using a spatially explicit modelling approach that has been proven to be effective in analysing the spatial variability of burn rates (Portier *et al.* 2018).

Methods

Study area

The study area covers 482 000 km^2 of sparsely populated coniferous boreal forest in Quebec, in eastern Canada (49–53°N, 79°30′–57°00′W, Fig. 1). Overall, this region experiences a lower area burned and is covered by less permafrost and peatlands than western Canada (Gauthier *et al.* 2015*b*; Boulanger *et al.* 2018). Black spruce (*Picea mariana* (Mill.) B.S.P.) is the dominant tree species, although balsam fir (*Abies balsamea* (L.) Mill.), jack pine (*Pinus banksiana* Lamb.), paper or white birch (*Betula papyrifera* Marsh.), and trembling aspen (*Populus tremuloides* Michx.) are encountered in smaller proportions. Mean annual temperatures range from −4.9°C in the north to 1.6°C in the south, whereas mean annual precipitation increases from 650 mm in the north-west to 1240 mm in the south-east. Thick and thin tills and organic surficial deposits are the most abundant parent materials, but bedrock dominates in the south-east (Fig. 2*b*). Topography varies from a rather flat, low-elevation relief (<3% slopes) in the west to higher elevations and gentle relief (3–5%) in the centre. Further east, relief is more pronounced (8–35%) with high elevation areas (>1000 m above sea level), but becomes gentler closer towards the north-eastern shore of the Saint Lawrence River (Saucier *et al.* 1998; Robitaille *et al.* 2015) (Fig. 2*a*, *c*).

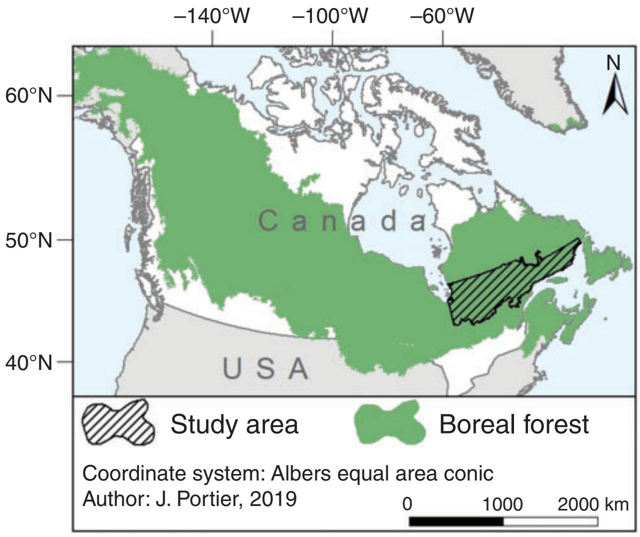

Fig. 1. Location of the study area within the North American boreal forest.

Data processing

Analyses were performed at two scales. Regional landscape units (LUs, $n = 75$, mean size = 623 000 ha) are a 'portion of the territory characterised by the recurrent organisation of the main permanent ecological factors of the environment and the vegetation' (Saucier *et al.* 1998, p. 3, in French), the permanent ecological factors being climate, natural and human disturbances, physical environment and vegetation. They form part of Quebec's ecological land-classification hierarchy (Jurdant *et al.* 1977) and have been used to perform analyses on the distributions of fire size and occurrence. Gauthier *et al.* (2015*a*) used 1972–2009 mean annual burn rates (the inverse of the fire cycle) to group LUs into homogeneous fire zones ($n = 11$, mean size = 4 327 000 ha; Fig. 3*a*). We used these zones as the basis for fire-regime description. The number of LUs contained in each homogeneous fire zone is presented in Table 1.

Explanatory variables were at scales commensurate with the spatial distribution of fire regimes over large regions. Therefore, climate was accounted for using long-term regional averages rather than strictly through the application of local

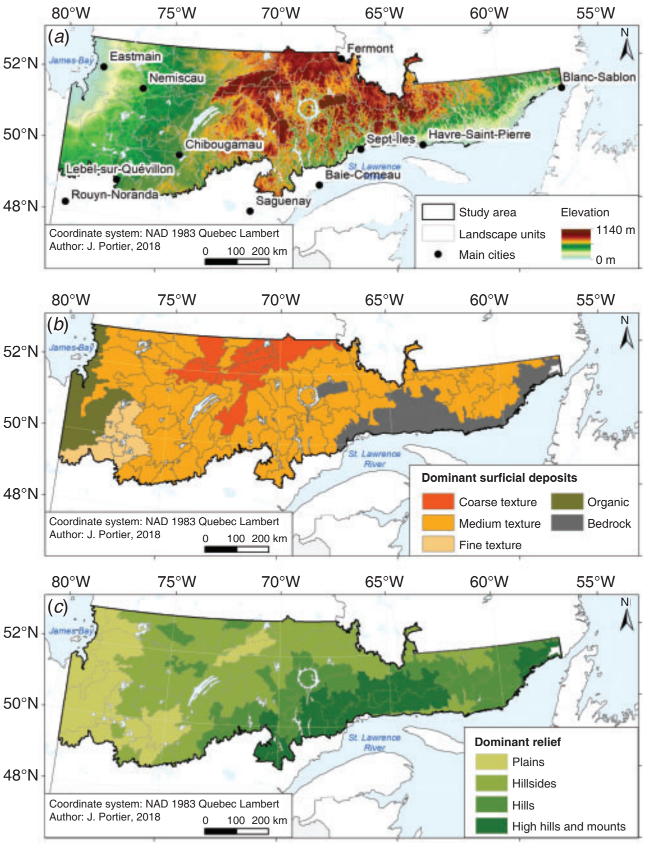

Fig. 2. (*a*) Elevation and main cities of the study area; (*b*) dominant surficial deposits (Lord and Robitaille 2013); (*c*) Dominant relief type (Saucier *et al.* 1998; Lord and Robitaille 2013).

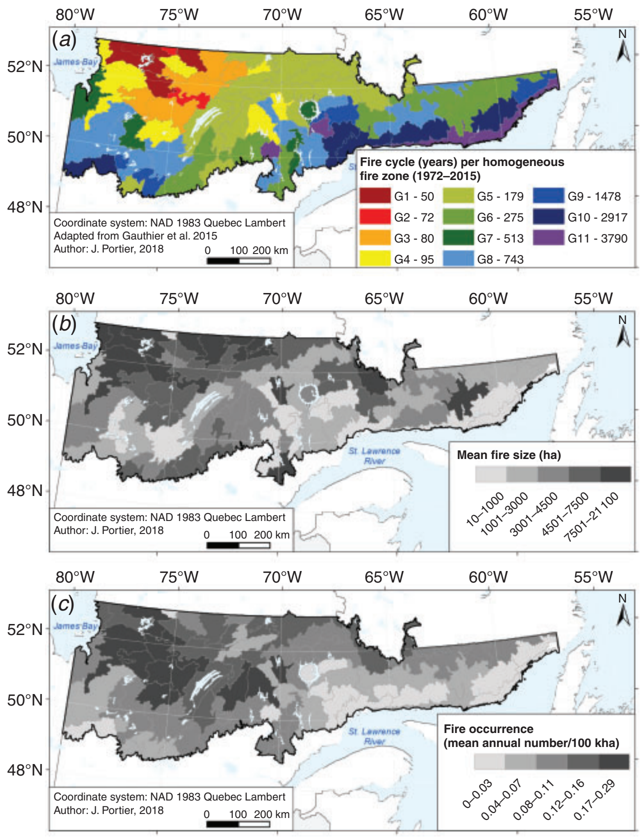

Fig. 3. (*a*) Fire cycles in years that were calculated for each homogeneous fire zone; (*b*) the mean fire size (FireSz) of each LU in hectares; (*c*) the mean annual number of fires per 100 000 ha (FireOcc) of each landscape unit (LU). Note: Fire cycle, FireSz and FireOcc were calculated over the period 1972–2009.

meteorological data. Land cover was not considered, given that the landscape at the LU scale is too heterogeneous for an averaged value to be relevant. Also, including land cover would require information about the vegetation that was locally present before each fire in each LU, which is not available. Description of the physical environment was approached through qualitative variables that summarised the dominant characteristics of each LU. Although the temporal extent of both climate and lightning datasets did not perfectly match that of the fire data, potential biases are considered negligible as we are modelling the spatial variability of FireSz and FireOcc.

Fires

Fire maps were obtained from the Ministère de la Faune, de la Forêt et des Parcs du Québec (MFFPQ) and compiled over the 1972–2015 period. The ignition source (human or lightning) of some fires was unknown. Given the low road and population density of the study area, all fires were retained in the analyses as we assumed most fires were lightning-ignited and that human impact was negligible. The fire database has been submitted to quality control and is considered complete and precise south of the limit of the commercial forest, which was established in 2002 (Gauthier *et al.* 2015*a*). North of the limit, burn boundaries were determined by remote-sensing techniques, so that fire size was estimated rather than precisely measured. Similarly, a few fires could not be dated precisely and fire dates were specified in 5-year intervals (Leboeuf *et al.* 2012), the middle year of which was used in the analyses. FireSz and FireOcc distributions of LUs are presented in Fig. 4. In total, 2079 fires were recorded.

Climate

Daily climate data over the 1971–2009 period were extracted with BioSIM 9 software (Régnière and Saint-Amant 2008) by Lord (2013) at forest-stand polygon centroids. BioSIM 9 compensates for the scarcity of weather stations by interpolating climate data from nearby weather stations, while adjusting for elevation, longitude and latitude (Régnière and Saint-Amant 2008). Lord (2013) aggregated the data at the land-district level (sub-units of LUs: ~2700 forest stand polygons per land district) and calculated monthly means for the whole period. Final climate variables were calculated over the fire-season months (mean from May to August) by averaging the land district data at the LU level with a weight that was based upon the land-district area.

Among variables of the Fire Weather Index System (Amiro *et al.* 2004), Drought Code (DC), Duff Moisture Code (DMC) and Fine Fuel Moisture Code (FFMC) were selected (Fig. 5). These indices have been shown to influence area burned and

Table 1. Main characteristics of the fire regime over the 1972–2015 period for each homogeneous fire zone

Homogenous fire zones and their corresponding fire cycles over the 1972–2009 period were reproduced from Gauthier *et al.* (2015*a*). The fire cycle data for the 1972–2015 period are from the present study. The 95% confidence intervals (CI) of fire cycles over the 1972–2015 period were obtained by bootstrapping after 1000 randomisations with replacement of all fires that occurred in the given zone and computation of the upper and lower percentiles of the 1000 resulting fire cycles. FireOcc is the mean annual number of fires per 100 000 ha. FireSz is the mean fire size, LU, landscape unit; N/A, not applicable

Fire zone	Percentage of study area covered by zone	Number of LUs	Fire cycle (95% CI) for 1972–2009 (years)	Fire cycle (95% CI) for 1972–2015 (years)	FireOcc	Total number of fires	FireSz (ha)	Median fire size (ha)	Size of largest fire (ha)
G1	4.7	4	44 (34–61)	50 (34–82)	0.17	162	13 087	867	406 446
G2	1.0	2	59 (46–81)	72 (50–116)	0.16	33	7096	1836	36 167
G3	8.3	7	67 (57–82)	80 (65–104)	0.18	305	6936	1065	194 484
G4	9.3	7	94 (85–105)	95 (68–131)	0.19	364	5886	593	494 341
G5	21.3	15	183 (155–221)	179 (128–258)	0.12	534	5379	546	459 250
G6	15.1	11	272 (239–312)	275 (203–397)	0.08	260	5306	331	225 826
G7	4.6	4	395 (343–463)	513 (357–756)	0.09	83	2142	283	34 436
G8	17.9	11	712 (636–816)	743 (576–989)	0.07	249	1703	183	29 741
G9	4.3	4	1 668 (1 286–2380)	1 478 (834–3429)	0.04	37	1613	152	19 384
G10	9.1	5	8 167 (5904–12 990)	2 917 (1499–9421)	0.02	34	2359	137	43 390
G11	4.3	5	N/A	3790 (1390–41 294)	0.02	18	211	52	1228

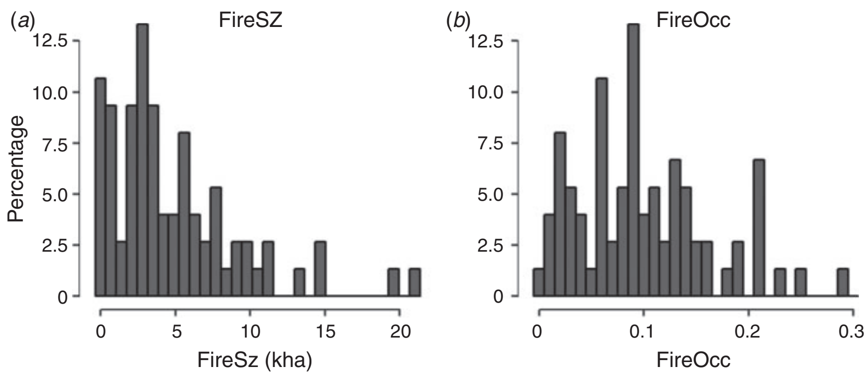

Fig. 4. Histograms of (*a*) the mean fire size (FireSz) (kha) and (*b*) the mean annual number of fires per 100 000 ha (FireOcc) of the landscape units (LUs).

fire occurrence (Girardin *et al.* 2009; Wotton *et al.* 2010). DC is a numerical rating of the average moisture content of deep organic layers and is derived from temperature and rain. DMC is a numerical rating of the average content of loosely compacted organic layers of moderate depth and is derived from temperature, relative humidity and rain. FFMC is a numerical rating of the moisture content of litter and cured fine fuels and is derived from temperature, relative humidity, wind and rain (Amiro *et al.* 2004).

Physical environment

Relief and surficial-deposit data were used as categorical variables to represent the physical environment. Initially, dominant relief and surficial deposits were available at the land-district level (Lord and Robitaille 2013) and categorised into classes (Portier *et al.* 2018). Dominant surficial deposits are representative of the drainage potential of the forest floor and were classified based upon their texture, i.e. coarse, medium or fine, as bedrock when the territory was mostly covered by bare bedrock at its surface, or as organic material (Portier *et al.* 2018). Dominant relief types were classified as plains, hillsides, hills, or high hills and mounts based upon slope and differences in elevation (Saucier *et al.* 1998). Dominant relief and surficial deposits of each LU were determined according to which category of relief and surficial deposits covered the highest proportion of the LU's area (Fig. 2*b*, *c*).

Lightning

In Canadian boreal forests, positive (Wotton and Martell 2005), negative (Flannigan and Van Wagner 1991) and total cloud-to-ground lightning strikes (Peterson *et al.* 2010; Veraverbeke *et al.* 2017) have all been shown to influence fire activity. Therefore, analyses were performed in turn using the three types of lightning strikes. Lightning variables were calculated from the Canadian Lightning Detection Network (CLDN) database over the 1999–2010 period (Burrows and Kochtubajda 2010; Orville *et al.* 2011). For each LU, the mean positive, negative and total annual cloud-to-ground lightning strike densities per 100 000 ha from May to September were compiled (Fig. 6).

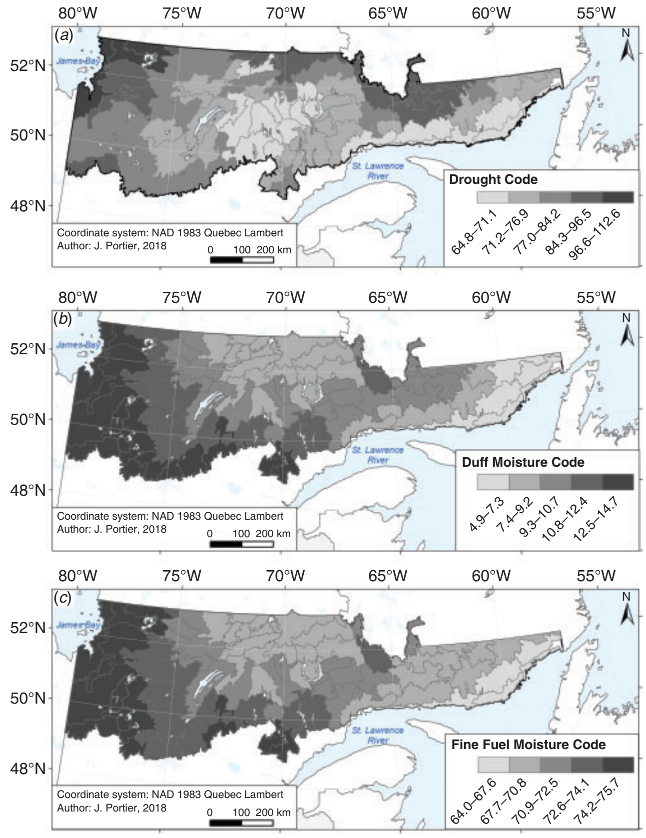

Fig. 5. (*a*) Drought Code (DC), (*b*) Duff Moisture Code (DMC) and (*c*) Fine Fuel Moisture Code (FFMC) calculated for the fire season months (mean from May to August) over the period 1971–2009.

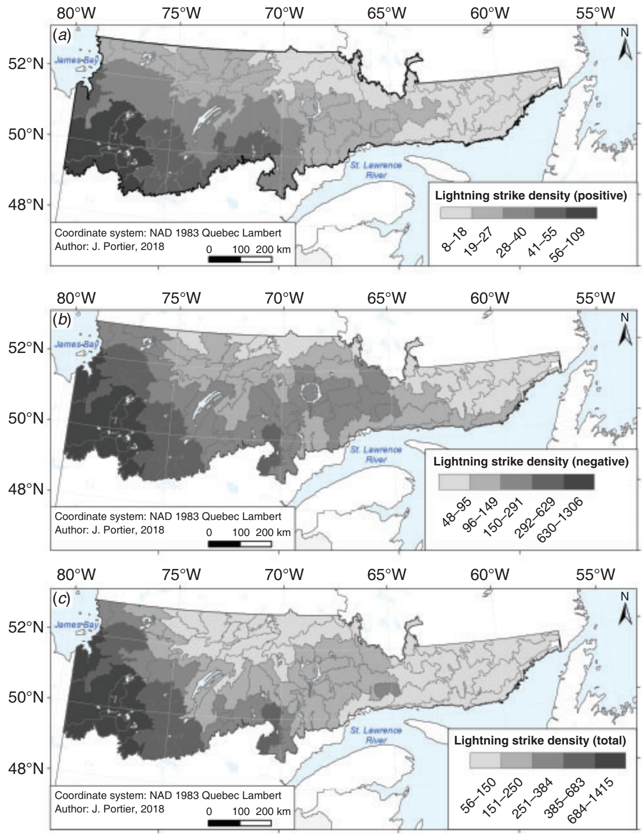

Fig. 6. (*a*) Positive, (*b*) negative and (*c*) total annual lightning strike density per 100 000 ha over the period 1999–2010.

Fire-regime description

Fire regime was described at the scale of homogeneous fire zones. As zone G11 did not experience any fires between 1972 and 2009, this area was not considered in the analyses of Gauthier *et al.* (2015*a*). Zone G11 had been added to our study because some fires occurred there since 2010. To update the estimates of Gauthier *et al.* (2015*a*), fire cycles were recalculated in each zone over the 1972–2015 period. Mathematically, fire cycles were computed as the inverse of the mean annual proportion of area burned (Johnson *et al.* 1998):

$$\text{fire cycle} = \frac{(2015 - 1972)}{\sum_{1972}^{2015} \frac{\text{area burned}}{\text{total area}}}$$

In addition, we calculated fire-regime components relative to distributions of size and occurrence of fires, including the mean size of all fires that had occurred between 1972 and 2015 (FireSz) and the mean fire occurrence (FireOcc). Except for the fire-cycle calculation, when a fire overlapped more than one fire zone, it was only considered in the zone that contained most of the area that had been burned by that particular fire. Detailed fire size and occurrence distributions were also extracted for each homogeneous fire zone and are presented in Appendix 1. All analyses were performed using R (ver, 3.4.2, R Foundation for Statistical Computing, Vienna, Austria, see https://www.r-project.org/).

FireSz and FireOcc at the LU level

FireSz v. *FireOcc*

Linear Discriminant Analysis (LDA) is a statistical method for determining the linear combinations of variables that maximise the separation of a dataset into known groups while minimising the variation within each group (Fisher 1936). LDAs were conducted to determine, between FireSz and FireOcc, which variable best explained the LUs belonging to homogeneous fire zones. This analysis aimed at understanding whether the spatial variability of burn rates could be best explained by FireSz or FireOcc. Zone G2 was removed from this analysis because it is relatively small compared with the other zones and contains only two LUs (Table 1). Zones G9, G10 and G11 were merged into zone G9_11 because they all experienced a very low number of fires during the study period (Table 1, Fig. 7).

Three LDAs were performed using the *lda* function of the *MASS R* package (ver. 7.3-49. B. Ripley, B. Venables, D. M. Bates, K. Hornik, A. Gebhardt and D. Firth, see https://cran.r-project.org/web/packages/MASS/MASS.pdf): one using FireSz as the explanatory variable, one using FireOcc and the third using both variables. The accuracy of each LDA was measured as the number of correct classifications, divided by the total number of observations.

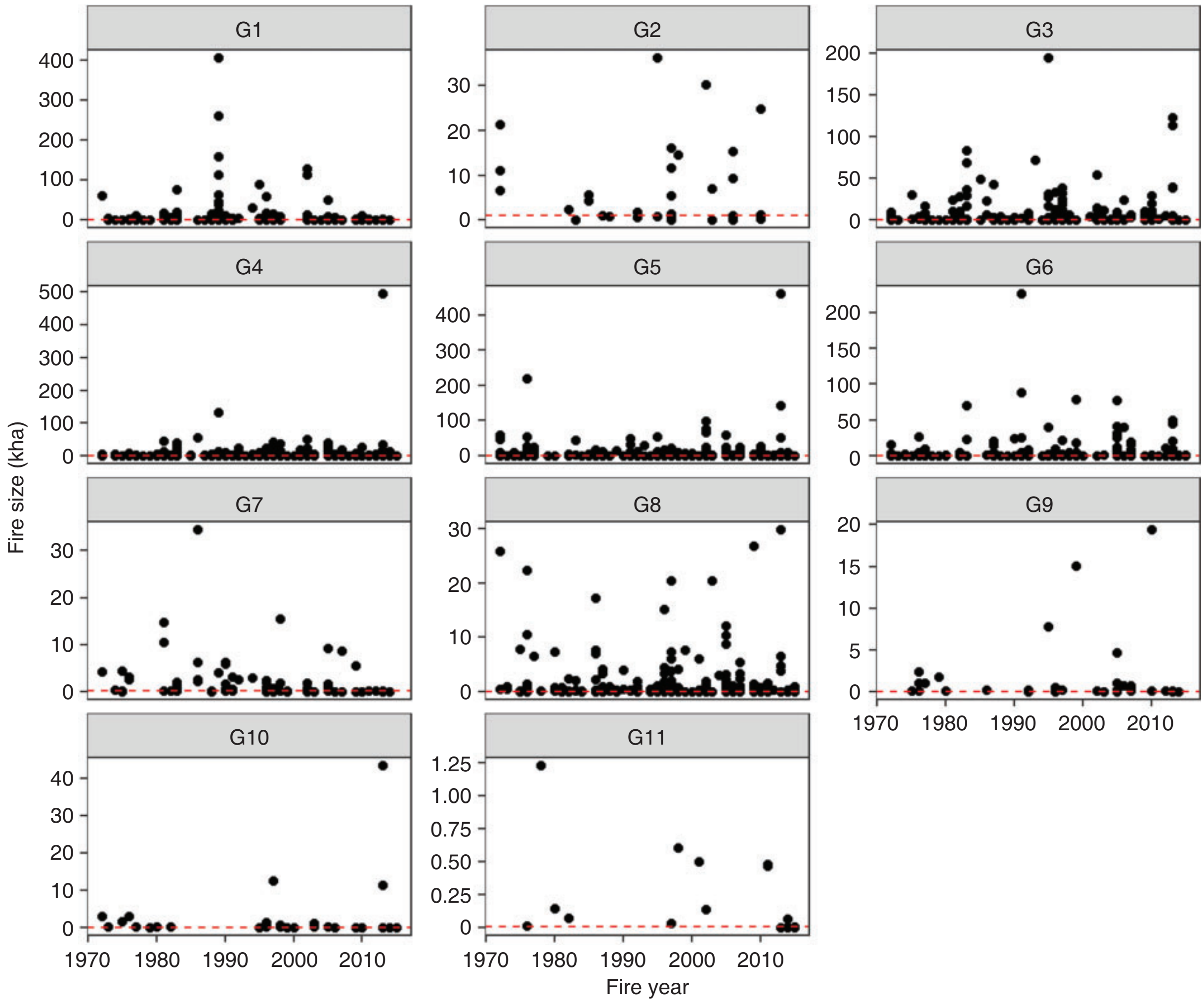

Fig. 7. Size of all fires that were recorded between 1972 and 2015 for each homogeneous fire zone. Each point represents a fire, while dashed horizontal lines represent the median fire size of each zone. The fire size axis is shown in 1000 ha, but the scale varies from one zone to the next as some tended to experience larger fires than others. This figure also allows the visualisation of extreme events with reference to the median size of each zone, as for instance the ~500 000 ha fire in zone G4.

Environmental factors controlling FireSz and FireOcc

In order to identify which environmental factors were responsible for FireSz and FireOcc, we constructed Generalised Linear Models (GLMs) using a Gamma distribution with a log-link function. The Gamma distribution was selected because both FireSz and FireOcc distributions were right-skewed (Fig. 4).

We tested different explanatory variables for FireSz and FireOcc. We had hypothesised that FireSz would increase with the dryness of the forest floor (DC and dominant surficial deposits) and that fires would be smaller in more-rugged, higher-elevation terrain (dominant relief). We further hypothesised that FireOcc would decrease with increasing moisture content of the top layers of the forest floor (DMC, FFMC) and that it would increase with lightning-strike density (positive, negative or total) and where the terrain is more rugged and at higher elevation (dominant relief). Interactions were constructed between lightning-strike density and climate variables because we expected a greater effect of lightning-strike density where climatic conditions were drier. Given that there was collinearity between some of the variables (DMC and FFMC; positive, negative and total lightning strikes), collinear variables were tested in different models.

Full GLMs containing all variables were submitted to a backward model-selection process using the Akaike Information Criterion (AIC) to determine what combination of variables best explained FireSz and FireOcc. All models within two AIC differences (ΔAIC) of the best model (model with the lowest AIC value) were retained. Among the most parsimonious models, the one with the lowest AIC value was retained as the final model. Final-model AICs were compared with null-model AICs to ensure overall improvement. GLMs were constructed using the *glm* function of the *stats R* package (ver, 3.4.2, R Foundation for Statistical Computing, Vienna, Austria, see https://www.r-project.org/).

Because they are spatially connected, LUs can face spatial autocorrelation issues in terms of both fire activity and environmental factors. We used the methodology of Portier *et al.* (2018) to address spatial autocorrelation using a Residuals Autocovariate (RAC) approach (Crase *et al.* 2012). Given that they are based on residuals, RAC models have the advantage over other autoregressive methods in letting the explanatory variables control for spatial autocorrelation in the response variable (Crase *et al.* 2012).

The first step was to assess whether GLM residuals were spatially correlated and, if so, to then identify at which distance (lag). We used lag one = 85 km, which is the distance at which 95% of the LUs had at least one neighbour (Portier *et al.* 2018). Lags one to five (85–425 km) were tested using a spatial correlogram that measured the strength of spatial autocorrelation in the residuals for each lag with Moran's *I* (Legendre and Legendre 1998). Confidence intervals on Moran's *I* were computed using a Bonferroni correction, where the corrected significance level α' of the *k*th lag equalled the significance level ($\alpha = 0.05$) divided by *k*, so that $\alpha' = \alpha \div k$ (Legendre and Legendre 1998). Spatial correlograms were built using the sp.*correlogram* function of the *spdep R* package (ver. 0.6-15, Bivand and Wong 2018).

When the correlogram revealed non-significant Moran's *I* values, the GLM was considered free of spatial autocorrelation and was retained as a final model. When residuals were spatially correlated, a RAC model was constructed from the GLM. An autocovariate was calculated for each lag at which Moran's *I* was significant (Portier *et al.* 2018). An autocovariate is an additional variable that is calculated for each observation from the spatial autocorrelation contained in the residuals, and represents the strength of the relationship between the residuals at a given location and residuals at neighbouring locations (Crase *et al.* 2012). It aims to reduce the bias resulting from spatial autocorrelation (Dormann *et al.* 2007; Crase *et al.* 2012) and can substantially improve model performance (Portier *et al.* 2018). Autocovariates were calculated using the *autocov_dist* function of the *spdep R* package (Bivand and Wong 2018). Finally, one RAC model was built for each autocovariate, each corresponding to a given lag. RAC models were compared to each other and with the final GLM, so the model with the lowest AIC value was retained as best model (Portier *et al.* 2018).

Results

Fire regime

Fire cycles that were calculated over the 1972–2015 period in homogeneous fire zones (Table 1, Fig. 3*a*) updated the 1972–2009 estimates of Gauthier *et al.* (2015*a*). Although generally slightly longer, new estimates fell into the confidence intervals of the 1972–2009 fire cycles in nine out of eleven zones. Zones G7 and G10 experienced significantly longer and shorter fire cycles respectively (Table 1). In zone G7, only a few small fires occurred between 2010 and 2015 (Fig. 7) and FireSz dropped from 2500 ha in 1972–2009 to 80 ha in 2010–15. In zone G10, approximately one-third of the 35 recorded fires occurred in 2010–15 (Fig. 7). Overall, from zone G1 to G11, the fire cycle lengthened, FireSz was reduced and FireOcc decreased (Table 1, Fig. 3*a*, 7). Detailed distributions of fire size and number are presented in Tables A1 and A2 of Appendix 1.

Table 2. Accuracy of the linear discriminant analysis (LDA) in predicting the homogeneous fire zones

Accuracy is measured as the number of correct classifications, divided by the total number of observations. FireOcc is the mean annual number of fires per 100 000 ha. FireSz is the mean fire size

Predictors	Accuracy (%)
FireSz	34.3
FireOcc	46.6
FireSz + FireOcc	57.5

Importance of FireSz v. *FireOcc*

LDA showed that FireOcc was better able to discriminate homogenous fire zones than was FireSz. However, greater accuracy (57.5% correct classification) was obtained when both variables were considered together (Table 2). In this LDA, intra-zone accuracy was generally good (>36%, Table 3), except for zones G3 and G7. Homogeneous fire zones with short fire cycles were highly variable along the second linear-discriminant function and also in terms of FireSz and FireOcc (Fig. 8). The mean intra-zone coefficients of variation for FireSz and FireOcc were 65.8 and 40.0% respectively.

Environmental factors driving FireSz and FireOcc

Analyses revealed two concurrent models for FireSz and five for FireOcc. Selected models for FireSz and FireOcc respectively contained DC and dominant surficial deposits, and dominant relief, DMC and negative lightning-strike density (Table 4). Spatial correlograms showed no significant spatial autocorrelation in the model residuals for FireSz, whereas residuals were significantly spatially correlated at lag one for FireOcc (Fig. 9). For FireSz, the previously selected GLM was retained, given that correction for spatial autocorrelation was not required. Regarding FireOcc, an autocovariate corresponding to the first lag was calculated and added as a supplementary variable to build the RAC GLM. The autocovariate improved model fit by more than two ΔAIC, so the RAC GLM was retained as the final model for FireOcc (Table 5).

The FireSz final model revealed a positive effect of DC. LUs that were either dominated by surficial deposits with a fine texture, organic material or mostly covered by bedrock experienced smaller fires than LUs that were dominated by surficial deposits with a medium or coarse texture (Table 6*a*). FireOcc was higher in areas with high DMC values. The effect of FFMC in concurrent models was similar. LUs that were dominated by hills, plains and hillsides had a significantly higher FireOcc than those that were dominated by high hills and mounts. Although not significant, FireOcc tended to increase from LUs that were dominated by hills to those dominated plains and, finally, to hillsides (Table 6*b*). Contrary to what we expected, the effect of lightning-strike density on FireOcc was negative, although very close to zero. In concurrent models, this effect was also very close to zero and occasionally not significant.

Table 3. Confusion matrix of the Linear Discriminant Analysis (LDA) using both the mean fire size (FireSz) and the mean annual number of fires per 100 000 ha (FireOcc) as predictors

LU, landscape unit. Data in bold show the number of LUs that were correctly classified within each fire zone

		Fire zones								Total
		G1	G3	G4	G5	G6	G7	G8	G9–11	
Predicted fire zones	G1	**4**	0	0	1	1	0	0	0	6
	G3	0	**1**	1	1	0	0	0	0	3
	G4	0	3	**4**	1	0	0	0	0	8
	G5	0	2	2	**8**	2	0	0	0	14
	G6	0	1	0	2	**4**	0	1	0	8
	G7	0	0	0	0	0	**0**	0	0	0
	G8	0	0	0	2	4	3	**8**	1	18
	G9–11	0	0	0	0	0	1	2	**13**	16
Number of LUs		4	7	7	15	11	4	11	14	73
Accuracy (%)		100.0	14.3	57.1	53.3	36.4	0.0	72.7	92.9	**57.5**

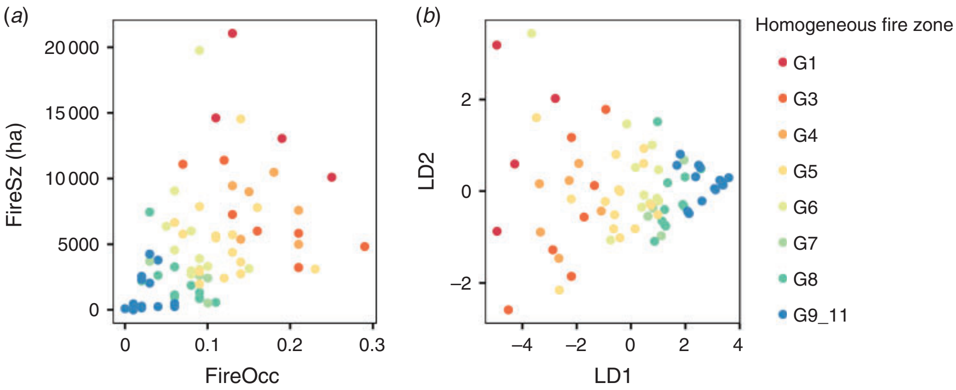

Fig. 8. (*a*) Distribution of landscape units (LUs) according to their mean fire size (FireSz) and mean annual number of fires per 100 000 ha (FireOcc). (*b*) Graphical representation of the Linear Discriminant Analysis (LDA) using both FireSz and FireOcc as predictors. Each point represents one LU.

Table 4. Generalised Linear Models (GLMs) with Gamma distribution within two Akaike Information Criteria differences (ΔAIC) of best model for (*a*) the mean fire size (FireSz) and (*b*) the mean annual number of fires per 100 000 ha (FireOcc)

Selected models are shown in bold. d.f., degrees of freedom; DC, Drought Code; FFMC, Fine Fuel Moisture Code; DMC, Duff Moisture Code

Models	AIC	ΔAIC	Cox and Snell pseudo-R^2	d.f.	Residual deviance	Dispersion parameter for Gamma family
(*a*) FireSz						
DC + Surficial deposit	**1358.6**	**0.0**	**0.27**	**66**	**59.1**	**0.64**
DC + Surficial deposit + summer precipitation	1360.5	1.9	0.27	65	59.1	0.65
(*b*) FireOcc						
Relief + FFMC + negative lightning + negative lightning: FFMC	−267.9	0.0	0.68	64	10.6	0.16
Relief + FFMC + total lightning + total lightning: FFMC	−266.9	1.0	0.67	64	10.7	0.16
Relief + DMC + negative lightning	**−266.5**	**1.4**	**0.65**	**66**	**12.6**	**0.18**
Relief + FFMC + negative lightning	−266.0	1.9	0.66	65	11.2	0.16
Relief + DMC + total lightning	−266.0	1.9	0.65	66	12.6	0.18

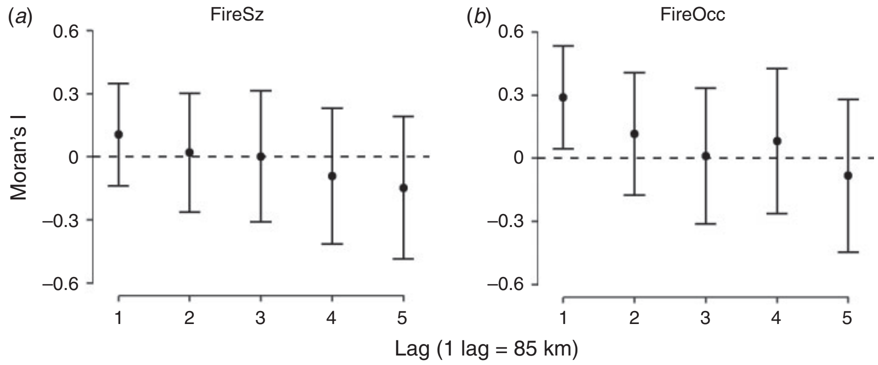

Fig. 9. Spatial correlogram calculated on the residuals of the final Generalised Linear Models (GLMs) of (*a*) FireSz and (*b*) the mean annual number of fires per 100 000 ha (FireOcc). The value of Moran's *I* at each lag is shown along with the associated Bonferroni-corrected confidence intervals.

Table 5. Final Generalised Linear Models (GLMs) and Residuals Autocovariate (RAC) GLMs for the mean annual number of fires per 100 000 ha (FireOcc)

AIC, Akaike Information Criterion; ΔAIC, differenced AIC from best model; d.f., degrees of freedom; DMC, Duff Moisture Code

Models	AIC	ΔAIC	Cox and Snell pseudo-R^2	d.f.	Residual deviance	Dispersion parameter for Gamma family
Relief + DMC + negative lightning + autocovariate (lag 1)	−272.8	0.0	0.69	65	11.2	0.16
Relief + DMC + negative lightning	−266.5	6.3	0.65	66	12.6	0.18

Table 6. Estimates of final models for (*a*) the mean fire size (FireSz) and (*b*) the mean annual number of fires per 100 000 ha (FireOcc)

DC, Drought Code; DMC, Duff Moisture Code

Variables		Estimate	s.e. estimate	*P*-value
(*a*) FireSz				
DC during fire season		0.04	0.01	<0.001
Dominant surficial deposit (reference level: organic)	Fine texture	0.53	0.91	0.57
	Bedrock	1.3	0.92	0.17
	Medium texture	1.79	0.86	0.04
	Coarse texture	2.31	0.9	0.01
(*b*) FireOcc				
DMC during fire season		0.23	0.03	<0.001
Negative lightning strike density		−0.002	0.0003	<0.001
Dominant relief (reference level: high hills and mounts)	Hills	0.87	0.15	<0.001
	Plains	1.14	0.18	<0.001
	Hillsides	1.27	0.14	<0.001
Autocovariate		14.16	4.86	0.005

Discussion

Fire cycles

The fire regime over the 1972–2015 period in the coniferous boreal forest of Quebec was spatially highly variable in terms of fire cycles, FireSz and FireOcc. Fire cycles ranged from 50 years in the north-west (low precipitation) to 2917 years in the south-east (high precipitation). In zones experiencing long fire cycles, such as G9 to G11, fires were highly infrequent but could still reach large sizes. In these cases, our study period might have been too short to calculate a fire cycle that was representative of the area and of the time period (Armstrong 1999; Li 2002). More robust estimates could be obtained by grouping zones into larger areas or by lengthening the time period. Except for zones G7 and G10, fire cycles were not significantly different from those calculated over the 1972–2009 period (Gauthier *et al.* 2015*a*). If this result tends to suggest that, since 2010, eastern Canada has not experienced an increased fire activity, the 6-year difference between both periods does not allow for robust inferences. In western Canada, area burned and the number of large fires have increased in the last decades, but this pattern is not as pronounced in eastern Canada (Hanes *et al.* 2019). Further analyses should be performed over longer time spans to test whether eastern Canada has reached the tipping point towards a climate change-triggered rise in fire activity, as suggested by Hanes *et al.* (2019). Indeed, many studies have warned that North American boreal forests will be facing greater fire activity in the near future (Balshi *et al.* 2009; Bergeron *et al.* 2010; Flannigan *et al.* 2016; Boulanger *et al.* 2018).

FireSz and FireOcc

FireSz and FireOcc generally decreased from zone G1 to G11. Nevertheless, the large intra-zone variability confirms that burn rates or similarly fire cycles cannot entirely capture and define a fire regime; rather, FireSz and FireOcc are equally informative (Lefort *et al.* 2004). For a given fire cycle, LUs could experience numerous small fires or rare large ones. The different ratios that were observed between FireSz and FireOcc in high fire-activity areas could result from the limiting effect of FireSz on FireOcc. The lack of fuel availability after a fire can limit subsequent fire ignition and spread, thereby providing some resistance to high burn rates (Héon *et al.* 2014; Parks *et al.* 2015, 2016). FireSz and FireOcc had a greater capacity to discriminate between homogeneous fire zones when they were used in combination rather than individually, but FireOcc performed better than FireSz. This could be a result of lower intra-zone variability for FireOcc than for FireSz.

Environmental factors responsible for FireSz and FireOcc

FireSz

Our results suggested that FireSz increased with fire season DC. Moisture content in deep layers of the soil can affect fire spread by controlling the quantity of dry fuel. For this reason, DC has been widely used as a predictor of area burned in boreal ecosystems (e.g. Drever *et al.* 2008; Girardin *et al.* 2009; Boulanger *et al.* 2013). Fire-suppression agencies should be particularly attentive to fire ignition in LUs that are characterised by high DC values, where greater efforts would be required to extinguish a fire (Amiro *et al.* 2004). Surficial deposits also influenced FireSz (Mansuy *et al.* 2014), which was greater in LUs that were dominated by surficial deposits with a high drying potential (medium or coarse texture) than in those exhibiting high water-retention potentials (fine texture or organic deposits). Soils that are well drained lead to drier forest floors that facilitate fire spread, whereas poorly drained ones typically exhibit high moisture contents that retard fire spread (Flannigan *et al.* 2016; Portier *et al.* 2018).

Our model on FireSz did not perform as well as expected, suggesting that other factors, such as land cover, were driving FireSz (Liu *et al.* 2013; Marchal *et al.* 2017). Lefort *et al.* (2004) also had difficulties in determining the environmental controls on FireSz at the LU level, suggesting that this scale might not be ideal to study this fire-regime component. Moreover, FireSz controls have been shown to change depending upon the size of the fires themselves (Flannigan *et al.* 2009; Liu *et al.* 2013). In Chinese boreal forests, small fires seemed to be controlled by fuel, whereas large fires mainly responded to weather (Liu *et al.* 2013). In western Canada, peatland abundance was related to the size of large fires only (Flannigan *et al.* 2009). For further research, analyses could be performed separately for different fire-size classes or by using other variables that are derived from the fire-size distribution. Further analyses could incorporate land-cover variables that are related to fuel type and availability (Marchal *et al.* 2017). Smaller entities than LUs, which are more representative of local conditions, could be used to this end.

FireOcc

LUs with higher DMC and FFMC experienced a higher FireOcc, confirming that drought conditions in the top layers of the soil influence the number of lightning-caused fires (Krawchuk *et al.* 2006; Wotton *et al.* 2010; Liu *et al.* 2012). Although lightning strikes are responsible for 80% of the area burned in Canada (Stocks *et al.* 2002), the effect of lightning-strike density on FireOcc was close to zero. Our results suggest that lightning-strike density is sufficiently high throughout the study area not to limit FireOcc, even if it might affect the inter-annual variability in fire activity as it does in western North America (Veraverbeke *et al.* 2017). Relief affected FireOcc (Liu *et al.* 2012; Rogeau and Armstrong 2017), but contrary to what we expected, LUs that were dominated by rugged terrain with steep slopes experienced lower FireOcc than those that were dominated by flatter, less-rugged terrain.

Counter-intuitive results that were obtained for lightning strikes and relief could result from complex interrelations between fires, physical environment, climate and lightning. First, the effect of relief could be confounded with that of climate: LUs that are dominated by plains or hillsides are the driest (high DMC and FFMC), whereas LUs that are dominated by high hills and mounts were mostly located in humid areas. In addition, high-elevation areas have shorter fire seasons because of lower temperatures and delayed snowmelt, leading to lower fire frequencies (Westerling *et al.* 2006; Rogeau and Armstrong 2017).

Second, lightning-strike density might play a larger role in rugged terrain, as it does on islands (Drobyshev *et al.* 2010). Rugged terrain has a high degree of variability in land cover, including bare bedrock, steep slopes with low vegetation cover, or depressions that maintain a high level of moisture, all of which are unfavourable to fire ignition (Rogeau and Armstrong 2017) and spread (Portier *et al.* 2018). Therefore, a lightning strike is less likely to start a fire in this environment than in continuous terrain. This could also explain why high hills and mounts experienced the lowest FireOcc.

Third, lightning-strike density varies throughout the fire season (Morissette and Gauthier 2008; Burrows and Kochtubajda 2010), so its effect on FireOcc might not be well detected using mean values. For instance, lightning-strike density during dry weather conditions has been shown to positively affect FireOcc (Peterson *et al.* 2010).

Conclusion

We showed that a region under a given fire cycle could experience a high degree of variability in both FireSz and FireOcc. Ecologically, different combinations of FireSz and FireOcc can produce very different landscapes in terms of composition, fragmentation and biodiversity. In Quebec, ecosystem management aims at reproducing natural landscapes, and bases its management strategies on fire cycles. Distributions of size and occurrence of fires should also be taken into account in order to better reproduce natural landscapes.

Second, at the LU scale, eastern Canada's FireOcc was driven by climate and relief, but was not limited by lightning-strike density. Fires can more easily start and spread in boreal forests than in highly fragmented landscapes (e.g. islands, mountains) or temperate forests with less flammable fuel. Analysing the effect of lightning-strike density at a smaller scale while controlling for local conditions could help our understanding of whether lightning-strike density could be limiting in some particular climate and relief contexts.

Third, FireSz and FireOcc were partly controlled by the moisture content of the soil, which is extremely sensitive to temperature. With climate change, drier fuels are expected to occur more frequently in the near future (Balshi *et al.* 2009; Flannigan *et al.* 2016; Wotton *et al.* 2017), leading to increases in FireSz and FireOcc. In fact, even small changes in moisture conditions could lead to many more escaped fires and result in fire-suppression agencies being unable to cope with future demands (Podur and Wotton 2010; Wotton *et al.* 2017).

Conflicts of interest

The authors declare that they have no conflicts of interest.

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Appendix 1

Table A1. For each homogeneous fire zone, distributions over the 1972–2015 period of fire size and fire size from which a certain percentage of the cumulative area burned is observed

Fire zone	Distribution of fire size (25, 50 and 75 percentiles) (ha) (fire size from which percentage of the cumulative area burned is observed, ha)		
	25%	50%	75%
G1	200	867	4899
	(53 719)	(111 005)	(168 290)
G2	572	1836	11 191
	(9090)	(17 758)	(26 425)
G3	186	1065	5412
	(18 455)	(38 759)	(59 063)
G4	100	593	3467
	(16 404)	(33 822)	(51 241)
G5	114	546	2365
	(21 924)	(46 233)	(70 541)
G6	77	331	2357
	(19 963)	(41 216)	(62 469)
G7	95	283	2221
	(4081)	(8316)	(12 551)
G8	38	183	914
	(5373)	(11 222)	(17 072)
G9	72	152	1018
	(4601)	(9597)	(14 592)
G10	17	137	538
	(7181)	(14 529)	(21 876)
G11	4	52	388
	(271)	(521)	(771)

Table A2. For each homogeneous fire zone, distributions over the 1972–2015 period of fire size and fire number among different fire size classes in percentage of total number of fires and of total area burned

Bold values are the fire size classes where 50% of the total number of fires or of the total area burned is cumulatively reached

Fire zone	Percentage of number of fires per size category (percentage responsible for total area burned per size class)					
	0–10 ha	10–100 ha	100–1000 ha	1000–10 000 ha	10 000–50 000 ha	≥50 000 ha
G1	3.70	12.96	**36.42**	28.40	11.11	7.41
	(0.00)	(0.04)	(1.05)	(7.90)	(16.16)	(**74.84**)
G2	0.00	6.06	36.36	**30.30**	27.27	–
	(0.00)	(0.06)	(2.89)	(19.50)	(**77.54**)	(–)
G3	1.31	15.74	31.48	**35.41**	13.44	2.62
	(0.00)	(0.11)	(1.72)	(19.51)	(**42.53**)	(36.13)
G4	2.75	22.25	**33.24**	28.02	12.64	1.10
	(0.00)	(0.16)	(2.28)	(17.13)	(**46.09**)	(34.34)
G5	1.69	20.97	**38.20**	27.72	9.36	2.06
	(0.00)	(0.20)	(2.94)	(16.37)	(**33.78**)	(46.72)
G6	0.77	27.69	**36.54**	23.08	9.62	2.31
	(0.00)	(0.25)	(2.60)	(14.33)	(**40.07**)	(42.75)
G7	7.23	18.07	**39.76**	30.12	4.82	–
	(0.01)	(0.35)	(6.25)	(**50.94**)	(42.44)	(–)
G8	6.83	32.53	**36.55**	19.68	4.42	–
	(0.01)	(0.81)	(8.75)	(**40.66**)	(49.77)	(–)
G9	5.41	32.43	**35.14**	21.62	5.41	–
	(0.02)	(1.03)	(6.39)	(34.80)	(**57.77**)	(–)
G10	20.59	23.53	**32.35**	14.71	8.82	–
	(0.03)	(0.29)	(3.25)	(12.50)	(**83.43**)	(–)
G11	33.33	**27.78**	33.33	5.56	–	–
	(0.45)	(5.35)	(**61.81**)	(32.39)	(–)	(–)