

Spatial attributes of fire regime in eastern Canada: influences of regional landscape physiography and climate

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Abstract The characterization of the fire regime in the boreal forest rarely considers spatial attributes other than fire size. This study investigates the spatial attributes of fires using the physiography of the landscape as a spatial constraint at a regional scale. Using the Canadian National Fire Database, the size, shape, orientation and eccentricity were assessed for 1,136 fires between 1970 and 2010 in Quebec's boreal forest and were summarized by ecodistrict. These spatial metrics were used to cluster 33 ecodistricts into

homogeneous fire zones and then to determine which environmental variables (climate, topography, hydrography, and surficial deposits) influence the spatial attributes of fires. Analyses showed that 28 out of 33 ecodistricts belonging to a given fire zone were spatially contiguous, suggesting that factors driving the spatial attributes of fire are acting at a regional scale. Indeed, the orientation and size of fires vary significantly among the zones and are driven by the spatial orientation of the landscape and the seasonal regional climate. In some zones, prevailing winds during periods conducive to fire events parallel to the orientation of the landscape may favour the occurrence of very large fires (>100,000 ha). Conversely, an orientation of the landscape opposite to the prevailing winds may act as a natural firebreak and limit the fire size and orientation. This study highlights the need to consider the synergistic relationship between the landscape spatial patterns and the climate regime over the spatial attributes of fire at supra-regional scale. Further scale-dependant studies are needed to improve our understanding of the spatial factors controlling the spatial attributes of fire.

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Introduction

Since the beginning of the Holocene, landscapes of the boreal forest in North America have been sculpted by

naturally occurring large fires (Rowe and Scotter 1973). In turn, the fire regime and its main attributes are influenced by complex interactions between the regional climate, the landforms and the susceptibility of fuels to drought (McKenzie et al. 2011). Despite a number of definitions and concepts (Krebs et al. 2010), the fire regime in boreal forest could be simply defined as a core group of attributes describing fires according to frequency, size, seasonality, severity, intensity and type (crown fires vs. surface fires). As a direct result of the heterogeneity of these attributes over time and space, wildfire creates mosaics of patches within the landscape. The analysis of spatial patterns created by fire in the landscape is fundamental to documenting the ecological processes of post-fire dynamics (Madoui et al. 2010). Understanding environmental factors that influence the fire regime attributes is also paramount for effective fire management and forest management (Jenkins et al. 2012).

Fire size, fire cycle and fire frequency are the most commonly documented attributes of the fire regime in the literature on the boreal forest (Parisien et al. 2006; Boulanger et al. 2013). Climate- and fuel-related factors that influence these attributes are relatively well understood and were integrated into fire danger rating systems decades ago (e.g., the Canadian Forest Fire Danger Rating System, Van Wagner 1987). Many studies have successfully linked the regional variability of the fire regime attributes to climate, topography and fuel (Collins et al. 2007; Parisien and Moritz 2009). In spite of recent technological advances that have enhanced the accuracy of fire mapping, the analyses of the spatial attributes of fires such as the orientation or the shape related to the landscape physiography, are under-documented in the literature compared with other fire regime attributes (Parisien et al. 2006; Barros et al. 2012). Whereas wind effects and daily weather conditions are well known and play a key role in the daily initiation and spread of fires (Linn et al. 2007; Sharples 2008), topography and slope, along with river systems, are fixed elements in the landscape that may influence the size and shape of wildfire (Heyerdahl et al. 2001; Flatley et al. 2011). Since the interactions between the top-down factors (climatic) and the bottom-up factors (topography) are known to vary from one ecosystem to another as well as depending on the spatial scale considered (Falk et al. 2011; Parisien et al. 2014), their

particular effects on the spatial attributes of the fire regime need to be further addressed in a specific geographical context. The regional variability of the boreal landscape in the province of Quebec (Fig. 1) offers a case study well suited for testing whether the fixed elements of the landscape could influence the spatial attributes of the fire regime at a regional scale. Several studies in the province of Quebec have described the distinct orientations of the topography associated with glacier meltwater flow from the centre toward the outer margins of the Labrador-Quebec ice sheet (Fig. 1b–d; Clark et al. 2000; Veillette 2004). The peculiar pattern that originates from the last glacier meltwater flow influences today's landscape of the boreal forest (Jansson et al. 2002). As a result of ongoing geomorphological processes, the shape and orientation of the surficial deposits and watercourses, in addition to the vegetation pattern, are influenced by the meltwater flow (Trenhaile 1990). Moreover, the surficial deposits, which are a major structuring element in the landscape of the boreal forest, could influence the composition and flammability of the vegetation and thus the regional variability of the fire regime, by virtue of their drainage and morphology (Robitaille and Allard 2007; Mansuy et al. 2010).

This study focuses on the spatial arrangement of the landscape as the main driver of the spatial attributes of fire, namely the orientation, size, eccentricity and shape of fires, in a very large study area that encompasses about 800,000 km² in the province of Quebec (Fig. 1a). The main hypotheses that steer our analysis are (1) large-scale landscape physiography elements such as surficial deposits, watercourses and topography, inherited from the last glacier meltwater flow, control the regional variability of the spatial attributes cited above, and (2) seasonal climate regime, including prevailing wind direction, also influences the spatial attributes of fire. To test these hypotheses, we used the polygon version of the Canadian National Fire Database (Canadian Wildland Fire Information System [CWFIS] 2012) that consists of all mapped fires ≥ 200 ha that occurred between 1970 and 2010 and the 33 Canadian ecodistricts as the units of reference. The method involved two steps: (1) to group the 33 ecodistricts into fire zones based on the spatial attributes cited above; and (2) to determine whether environmental variables can be used to

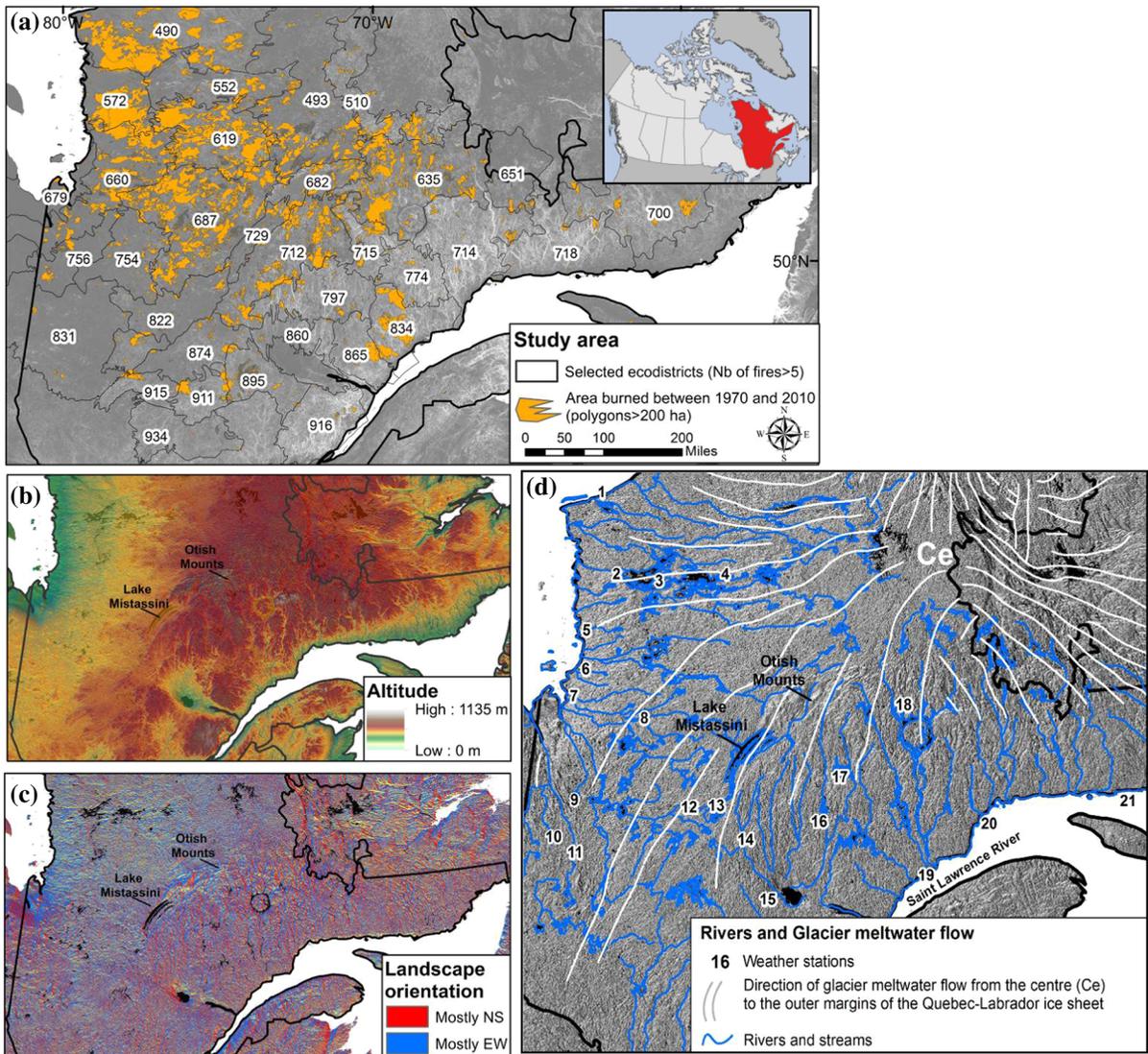


Fig. 1 **a** Study area location, fire polygons and the 33 selected ecodistricts in the province of Quebec, **b** the altitude, **c** the orientation of the landscape and **d** the direction of glacier

meltwater flow, the main rivers and the weather stations (note that weather stations were missing for 18 out of 33 of the ecodistricts)

differentiate the zones and can influence the spatial attributes of fire.

Materials and methods

Study area and physical environment

The study area encompasses about 800,000 km² and 33 Canadian ecodistricts located in the province of Quebec that experienced more than five fires between 1970 and

2010 (Fig. 1a). An ecodistrict is the smallest division (mean size ~25,000 km²) of the National Ecological Framework of Canada (Ecological Stratification Working Group [ESWG] 1995) and is characterized by distinctive regional ecological factors that include the climate, physiography, vegetation, soil, and water. The study area encompasses three bioclimatic domains: the black spruce-lichen domain north of 51°N, the black spruce-moss domain south of 51°N and the balsam fir-white birch domain south of 49°N. The climate is characterized by cold winters and warm summers.

Annual seasonal precipitation and temperatures vary widely among the ecodistricts. The elevation increases from east to west, from the James Bay lowlands to the highest peak of the Otish Mountains (1,100 m; Fig. 1b). West of Lake Mistassini and near James Bay, the topography is characterized by plains, but east of the study area is characterized by hills and plateaus interrupted by incised valleys oriented north–south (Fig. 1b). The most recent glacier meltwater flow, oriented east–west toward James Bay and north–south toward the St. Lawrence River, divides the central part of the province of Quebec (Fig. 1c, d). The surficial deposits are generally characterized by sandy tills, hummocky, sandy moraines, and drumlins or eskers with flutes (Mansuy et al. 2010). While glaciofluvial deposits are found in the valleys, shallow tills and rock outcrops cover the plateau summits. In contrast, the region south of James Bay is characterized by a high proportion of poorly drained organic deposits, which are typical of the Clay Belt region (Robitaille and Allard 2007). The fire cycle also varies significantly spatially, increasing from less than 100 years to more than 700 years along a north–south gradient (Mansuy et al. 2010). Fires are actively suppressed south of $\sim 51^\circ\text{N}$ (intensive protection zone) whereas no fire suppression activities occur in the northernmost part of the study area (extensive protection zone), except near human facilities (Mansuy et al. 2012). Since the area is relatively undisturbed by human activity, the degree of anthropogenic influences on the spatial attributes of fire was not examined in the study.

Fire database

The fire database was compiled using the polygon version of the Canadian National Fire Database (CWFIS 2012). We limited our analyses to 1,136 fires ≥ 200 ha that occurred between 1970 and 2010 (Fig. 1a). The database contains fire perimeter and year of occurrence only. Data on the daily fire progression were not available. Fires that occurred prior to 1970 were deliberately omitted for the sake of standardizing the source and acquisition method. Fire perimeters were mapped from aerial photography and satellite imagery taken the same year as the fires and provided by Canadian fire management agencies including provinces, territories, and Parks Canada (CWFIS 2012). To allow for the comparison between ecodistricts, each fire polygon was assigned to an ecodistrict using its centroid.

Table 1 Description of the spatial attributes of the fire regime

Name (codes)	Description	Sources (software and authors)
Fire size (Size)	Mean area of each fire (ha)	ArcGIS 9.3
Shape index (Shape)	Index of complexity of fire shape: expresses the degree of divergence between a shape with a simple perimeter (a circle) from 1 to >1 and a complex shape (sawtooth)	Patch Analyst ArcGIS 9.3
Eccentricity (Ecc)	Expresses the degree of divergence between a perfect circle (equal to 0) and an elliptical shape (equal to 1)	R (Buliung and Rimmel 2008)
Orientation ^a (Orientation)	Azimuth (0° – 360°) of the axis consisting of the two most distant extremities. The azimuth is transformed into 4 cardinal directions: NS, SWNE, WE, NWSE for the hierarchical cluster analysis and the canonical redundancy analysis (see statistical analysis section)	ArcGIS 9.3 (Jenness 2005)

^a The orientations do not reflect the fire direction. For example, a NS orientation and a SN orientation are equivalent (the same holds true for all the orientations). The same tool is used to calculate the orientation of the surficial deposits and watercourses (Table 2)

Spatial attributes of fires

As in Parisien et al. (2006) and Rimmel and Perera (2009), the size (Size), shape index (Shape), eccentricity (Ecc) and orientation (Orientation) of each fire were calculated [Table 1; see also the Supplementary Material (hereinafter SM)]. Size refers to the area burned. Shape refers to the complexity of the fire pattern, with values increasing as the shape of the fire becomes more complex. Ecc refers to the elongation of the fire perimeter (from 0 = circle to 1 = straight line). Orientation refers to the geographical orientation of fires in relation to the true north from 0° to 360° . The values of the spatial attributes were calculated with different geometric tools using ArcGIS 10.0 (ESRI, Redlands, California, USA) and R (R Development Core Team 2013) and then averaged for each

Table 2 Description of the environmental variables used in the canonical redundancy analysis

Environmental variables (codes)	Description	Sources
Climatic		
Mean seasonal temperature (TEMP)	Mean daily values recorded between May 1 and August 31 interpolated for the centroid of the ecodistrict	BioSIM
Mean seasonal precipitation (PT)	Mean daily values recorded between May 1 and August 31 interpolated for the centroid of the ecodistrict	BioSIM
Extreme seasonal severity rating (SSR)	Extreme seasonal severity is defined by the values above the mean + 2 standard deviations between May 1 and August 31 interpolated for the centroid of the ecodistrict	BioSIM
Physical		
Orientation of deposits parallel to direction of glacier meltwater flow (D) ^a	Proportion of the 4 directions: NS, SWNE, WE, NWSE by ecodistrict	GEOGRATIS
Orientation of major watercourses (H) ^a	Proportion of the 4 directions: NS, SWNE, WE, NWSE by ecodistrict	GEOGRATIS
Orientation of topography (T) ^a	Proportion of the 4 directions: NS, SWNE, WE, NWSE by ecodistrict	GEOGRATIS
Mean elevation (ALT)	Mean elevation of the ecodistrict (meters)	GEOGRATIS

^a The orientations do not reflect the direction of watercourses, surficial deposits or topography. For example, a NS orientation can be equivalent to a SN orientation (the same holds true for all orientations). The orientation codes for surficial deposits have the notation NS_D (with D for deposit) if the NS orientation is dominant (the same holds true for each dominant orientation). The orientation codes for watercourses have the notation NS_H (with H for Hydro) if the NS orientation is dominant (the same holds true for each dominant orientation). The orientation codes for topography have the notation NS_T (with T for topography) if the NS orientation is dominant (the same holds true for each dominant orientation)

ecodistrict (Table 1). For analysis purposes (see below), the orientation values were also transformed in one of four cardinal directions: WE, NWSE, NS and SWNE. The proportion of the four cardinal directions was then compiled for each ecodistrict.

Environmental variables

To test whether landscape patterns can control the spatial attributes of fires (Kellogg et al. 2008; McKenzie and Kennedy 2012), we calculated the geographic orientation of the surficial deposits and major watercourses for each ecodistrict using the same tool used for fire orientation (Table 2). In the same way, the output values from 0° to 360° were converted to proportions in one of the four cardinal directions for each ecodistrict. Also, orientation was only determined for coarse-textured surficial deposits such as drumlins and eskers (Prest et al. 1967), which are more likely to burn in this area (Mansuy et al. 2010). The surficial deposit and hydrography data, both in polyline format, were obtained from Natural Resources Canada's GeoGratis Web site (NRCan 2012). In addition, the mean terrain orientation was calculated

and transformed into the four cardinal direction classes (i.e., east or west aspect corresponds to a NS orientation of landscape; north or south aspect corresponds to an EW orientation). The proportions of the four terrain orientation classes were calculated for each pixel and then averaged by ecodistrict. Mean elevation was calculated for each ecodistrict (Table 2). The topographic and elevation data were derived from a 1:50,000 scale digital elevation model with a resolution of 30 m pixels using ArcGIS 10.0.

To test whether climate regime can control the spatial attributes of fires at a regional scale over the last three decades, we used the average climatic conditions during the fire season (from May 1 to August 31) between 1970 and 2010 (the fire observation period in this study) to summarize the average climatic conditions at the ecodistrict scale. It was not possible to use the daily weather data during the fire spread because the information about the daily fire spread was not available in the fire dataset. Moreover, seasonal climate regime is frequently used to successfully model other fire regime attributes across Canada (see e.g., Parisien et al. 2010; Boulanger et al. 2013) and in the United States (Flatley et al. 2011). In

addition, the fire season used in this paper is particularly well linked to fire prone conditions in our study area (Girardin et al. 2004). Thus, we compiled the mean seasonal precipitation and seasonal temperature from May 1 to August 31. Climate data were averaged and interpolated to the centroid of each ecodistrict from data obtained from 21 nearby weather stations using BioSIM v10 (weather stations are shown in Table 1d; values are shown in SM 2). BioSIM is a Canadian software tool designed to assist in the application of temperature-driven simulation models used more than hundred times in forest ecology studies (fire and pest) to interpolate and simulate climatic data across North America (more details are available in SM 2). In addition to the precipitation and the temperatures, we derived the mean fire seasonal severity rating (SSR) of the Fire Weather Index (Van Wagner 1987). In order to capture the effect of the extreme fire-weather during the fire season, we used the extreme SSR values defined as mean + 2 standard deviations. The use of the SSR is justified by its strong correlation with the annual area burned (Girardin et al. 2004). Lastly, the orientation of the prevailing wind was calculated for each weather station during the period of extreme SSR using BioSIM (note that the wind direction cannot be extrapolated for the 18 ecodistricts that do not have weather stations; Fig. 1d).

Statistical analyses

The statistical analyses were completed in three steps with R 3.0 (R Development Core Team 2013). First, in order to determine if spatial attributes of fire were similar over large and contiguous areas, ecodistricts were clustered according to their mean fire attribute values. At this step, we standardized fire metrics, to a 0 mean and 1 standard deviation. The orientation values were transformed in cosine before being standardized. Ecodistricts were successively lumped into 2–33 groups using Ward's hierarchical clustering method and the "hclust" function in R. Ward's method is an alternative approach for performing cluster analysis. Basically, it looks at cluster analysis as an analysis of variance problem, instead of using distance metrics or measures of association (Ward 1963). The best clustering solution was determined as the one showing the smallest coefficient of variation of error after 1,000 cross-validations using the "mvpart" package (Segal and Xiao 2011) in R. Clusters (hereafter "fire zones")

were then mapped and their spatial pattern was interpreted.

Second, statistical differences among fire zones of the Size, Shape, and Ecc attributes were determined through a combination of analyses of variance (ANOVA; $P < 0.05$) and Tukey tests for multiple comparisons. The size was log-transformed to homogenize variance at this step. Pearson's Chi squared test (χ^2) was used to identify significant differences between the proportions of area burned in one of the four cardinal directions within each fire zone.

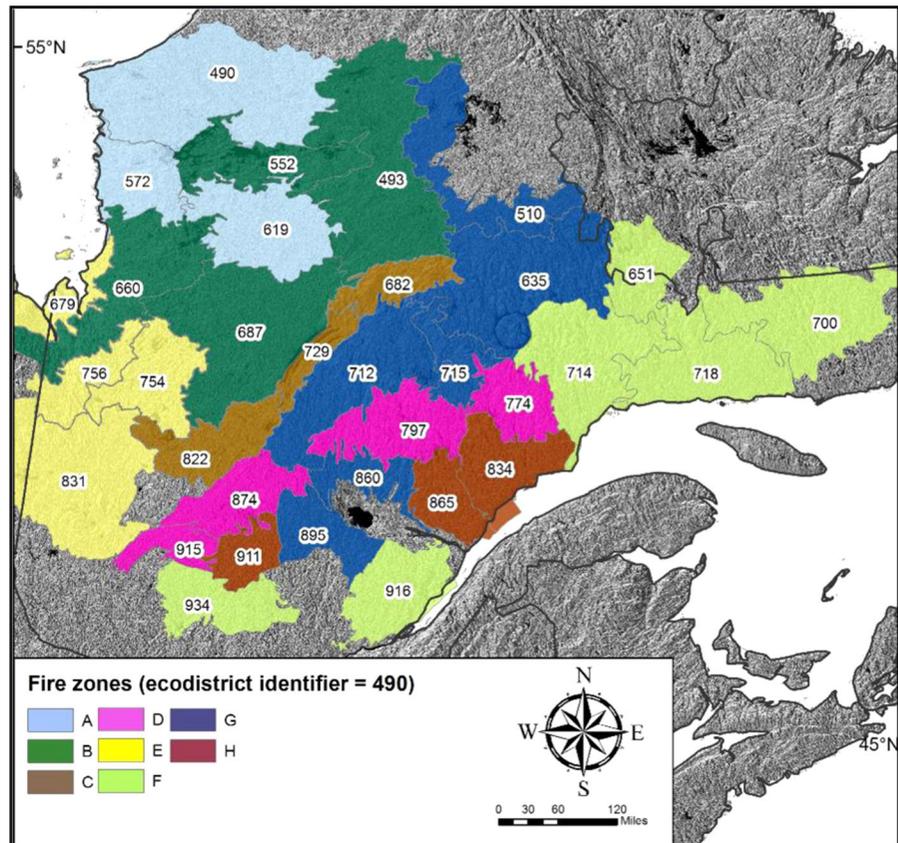
Third, a canonical redundancy analysis (RDA) was performed in R with the 'vegan' package (Oksanen et al. 2013) to test the control of the environmental variables on the spatial attributes. The response variables corresponded to the mean values of the spatial attributes of fires at the ecodistrict scale (Table 1). The Hellinger transformation was applied to the mean values of each spatial attributes. The Hellinger transformation is a method of data standardisation that is often used prior to analysis in ecology, especially when the sampling units are not all of the same size (Legendre and Gallagher 2001). The environmental explanatory variables (Table 2) included both climatic and physiographic variables. The mean values of the ecodistricts were used to represent the climatic variables (TEMP, PT and SSR). For the physiographic variables, we used the proportions of the deposits (D), the watercourses (H) and the aspect of the topography (T) in the four directions WE, NWSE, NS and SWNE, within the ecodistricts and the mean elevation (ALT). Significance and performance of the RDA were tested using 999 permutations. Wind direction could not be included in the RDA because weather stations were missing for 18 out of 33 of the ecodistricts (Fig. 1d). Instead, prevailing wind direction during extreme fire-weather conditions (see above) was compared a posteriori with fire spatial attributes at the fire zone level using data from individual weather stations.

Results

Clustering of ecodistricts

From the 33 ecodistricts, eight spatially homogeneous fire zones were distinguished based on fire spatial attributes (Fig. 2; see SM 3 for the statistical results of

Fig. 2 Results of the hierarchical clustering of the ecodistricts in eight distinct zones (from A to H) using Ward's method based on fire size, shape index, eccentricity and geographic orientation (the azimuth of the fires was transformed into four orientation classes and then calculated as a percent of area burned for each zone)



the clustering). Analyses showed that 28 out of 33 ecodistricts belonging to a given fire zone were spatially contiguous, thus suggesting that the environmental variables that regulate the spatial attributes of fires are expressed at a regional scale. In fact, four fire zones (D, E, F and H) and five ecodistricts (679, 911, 915, 916 and 934) are not spatially contiguous. The area of the fire zones is very variable, from $\sim 5,000 \text{ km}^2$ to more than $\sim 160,000 \text{ km}^2$.

Spatial attributes of fires by zones

The analyses of variance and Pearson's Chi squared test reveal that the Size and Orientation varied significantly among zones, while the Shape did not (Table 3). Ecc did not vary significantly among zones with most of the fires having an elliptical shape (values between 0.81 and 0.85). From the northwest to the southeast of the study area, Size and Orientation varied considerably among the fire zones (Table 3;

Fig. 3a, b). At the extreme northwestern limit of the study area, Zone A is characterized by the largest fire sizes (mean $>17,000 \text{ ha}$; max $\sim 400,000 \text{ ha}$) with a dominant EW fire orientation (43.65 %). At the eastern limit of the study area, Zone F is characterized by one of the smallest fire sizes (mean $< 5,000 \text{ ha}$) with a dominant NS (72.48 %) fire orientation. Between these two extremes, zones B and C have the same dominant NESW fire orientation (respectively 47.32 and 70.18 %) but a rather different mean fire size (7,907 vs. 4,225 ha respectively). Zone D is characterized by the smallest mean fire size (3,771 ha) with a dominant NWSE orientation (50.18 %). In the southeastern part of the study area, Zone E is also characterized by a small mean fire size ($< 5,000 \text{ ha}$) but without any dominant orientation. Zone G extends from north to south in the study area with a NS dominant fire orientation (55.6 %). Zone H is distinct with a very dominant NWSE fire orientation (73.08 %) and the second highest mean fire size (14,085 ha).

Table 3 Mean values of spatial attributes of fires by zone

Zones	Area (km ²)	Number of fires	Size (ha)	Shape	Eccentricity	Orientation			
						EW (%)	NESW (%)	NS (%)	NWSE (%)
A	99,780	227	17,717 ^a	2.53	0.82	43.65*	21.29	24.88	10.18
B	161,229	549	7,907 ^b	3.50	0.82	15.17	47.32*	17.46	20.05
C	35,835	76	4,225 ^c	3.44	0.85	0.15	70.18*	24.44	5.23
D	59,568	66	3,771 ^c	2.48	0.83	5.53	15.08	29.13	50.26*
E	139,661	71	4,499 ^c	2.54	0.83	2.92	10.56	48.98*	37.54
F	149,600	61	6,016 ^b	3.19	0.83	0.34	8.39	72.48*	18.79
G	137,371	333	7,240 ^b	3.55	0.82	4.68	22.21	55.16*	17.94
H	5,001	35	14,085 ^d	2.87	0.83	0.22	0.79	25.91	73.08*
Total	788,045	1,418	8,831	3.19	0.82	20.39	30.16	30.26	19.19

The azimuth of the fires was transformed into 4 cardinal directions and then calculated as a percent of area burned for each zone. Different lower case letters indicate significantly different values among zones, based on ANOVA ($P < 0.05$) for each variables tested

* The null hypothesis of equality of cardinal directions frequencies between the zones is rejected based on Pearson statistic ($P < 0.05$). See Table 1 for the explanation of the spatial attributes

Controls of environmental variables over spatial attributes of fire

Seven environmental variables associated with the orientation of surficial deposits (EW_D, NESW_D, NWSE_D and NS_D) and climate (TEMP, PT and SSR) were selected in the final RDA ordination. The remaining physical variables were not included in the RDA analysis as they were found to be correlated to the orientation of the surficial deposits (Pearson correlation >0.5 and variables variance inflation factors <10 (Borcard et al. 2011)). In addition, the choice to keep surficial deposits was motivated by their strong control over the variability of the fire regime in this study area (Mansuy et al. 2010, 2012). Moreover, as only Size and Orientation showed a significant difference among the fire zones, we plotted only these spatial attributes in the final RDA (Fig. 4). The two first axes of the RDA explained 88 % of the variance: 50 % for the first axis, and 38 % for the second axis (SM2). Size and Orientation showed significant relationships between climate and physiography landscape ($P < 0.05$). Along ordination axes 1 and 2, four clusters of ecodistricts can be clearly identified (Fig. 4a), which correspond to the zones distinguished earlier, namely A, B, C and H (Fig. 4b). In Zone A, very large fires oriented EW are controlled by EW_D. In Zones B and C, fire size and fire orientation are more under control of increasing TEMP and SSR rather than a distinct orientation of the surficial deposits. Fires oriented

NWSE in Zone H controlled by NWSE_D stand clearly apart from the other zones. The remaining zones (G, D, E and F) grouped in the centre of the Fig. 4b show less discernable control of environmental factors. Moreover, spatial attributes in Zone E appear more responsive to TEMP and PT than to landscape orientation.

Wind effects at the regional scale

Although it was not possible to integrate this variable into the RDA, the prevailing wind direction during extreme fire weather conditions shows a rather strong connection with the averaged fire orientation and size and the physiography of the landscape (see Figs. 3, 5 together). Indeed, in Zones A, B and C where the relief is relatively flat (west of Lake Mistassini; Fig. 1d), the prevailing winds are predominantly EW and NESW (Fig. 5) such as with the very large EW oriented fires that occur in these zones (Fig. 3). In Zones F, G and H, where the relief is more accentuated (east of Lake Mistassini), the wind direction is less constant and originates from the north and from the west and as well as from the east on the shore of the St. Lawrence River. In this situation we have smaller fires (except Zone G) mostly oriented NS or NWSE (Fig. 3). In Zone E, the wind blows from the NW for the coastal stations (stations 7 and 6) and from the south or the north for the inland stations. In this situation, fires are small with no particular orientation. It is difficult to draw conclusions for Zone D, which has only one weather station.

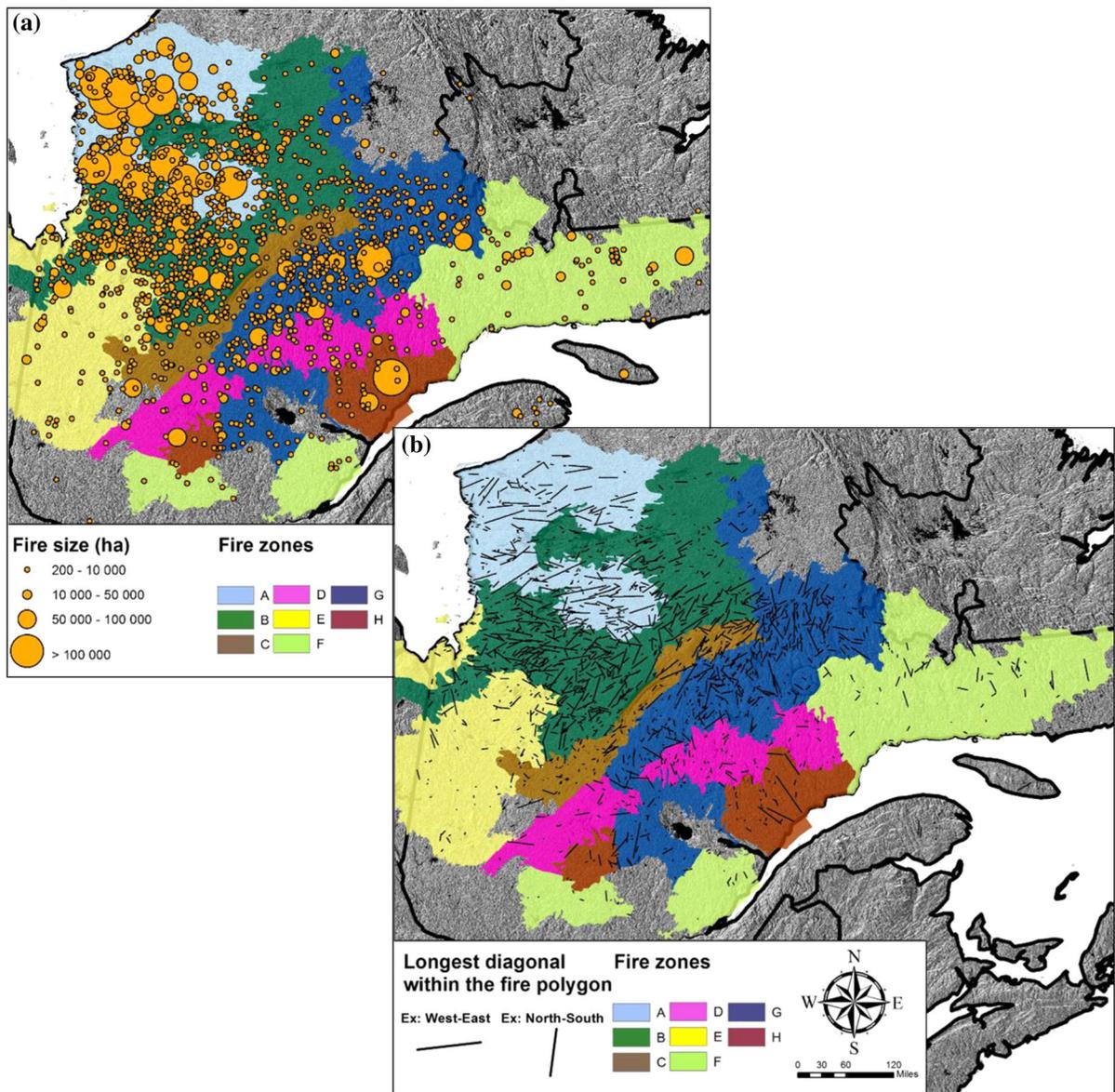


Fig. 3 **a** Fire polygons transformed into *circles* proportional to the fire sizes (ha). **b** Fire polygons transformed into the *longest diagonal* (within the *polygon*) showing the dominant orientation of fires

Discussion

Regional synergistic control over the spatial attributes of fires

Following a clustering analysis based on spatial attributes of fire, 28 out of 33 ecodistricts belonging to a given fire zone were spatially contiguous thus suggesting that the environmental variables that

regulate the spatial attributes of fires are expressed at a regional scale. With ecodistricts used as a reference framework, our results indicate that fire orientation and size vary regionally in response to landscape physiography and climate regime (McKenzie et al. 2011; Parks et al. 2012). However, our results differ from those of Parisien et al. (2006), who did not find a significant difference in fire orientation between the Taiga Shield and Boreal Shield ecozone. This

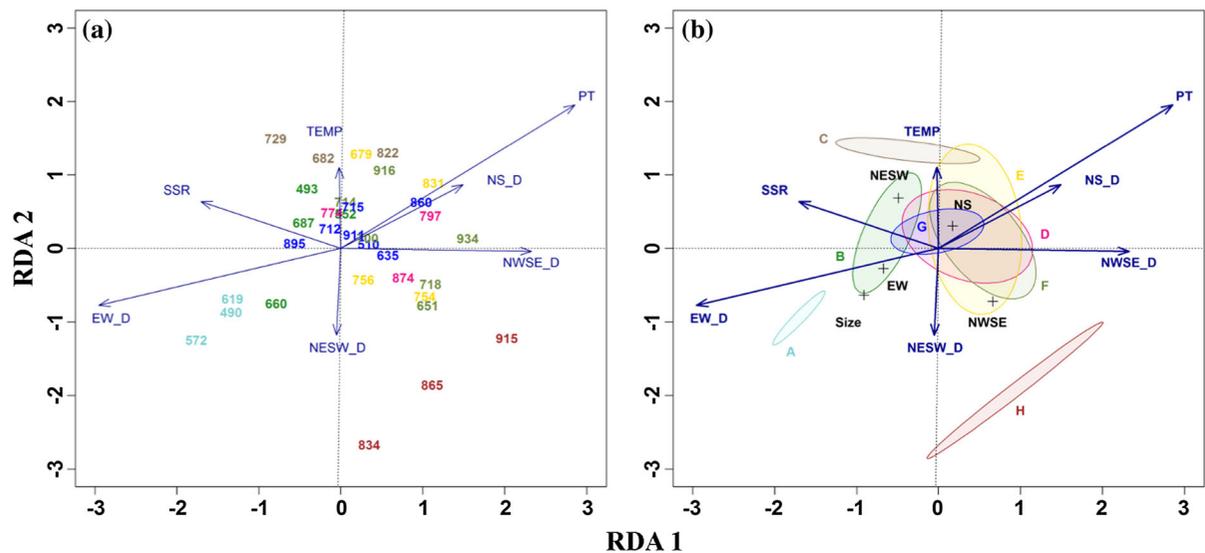


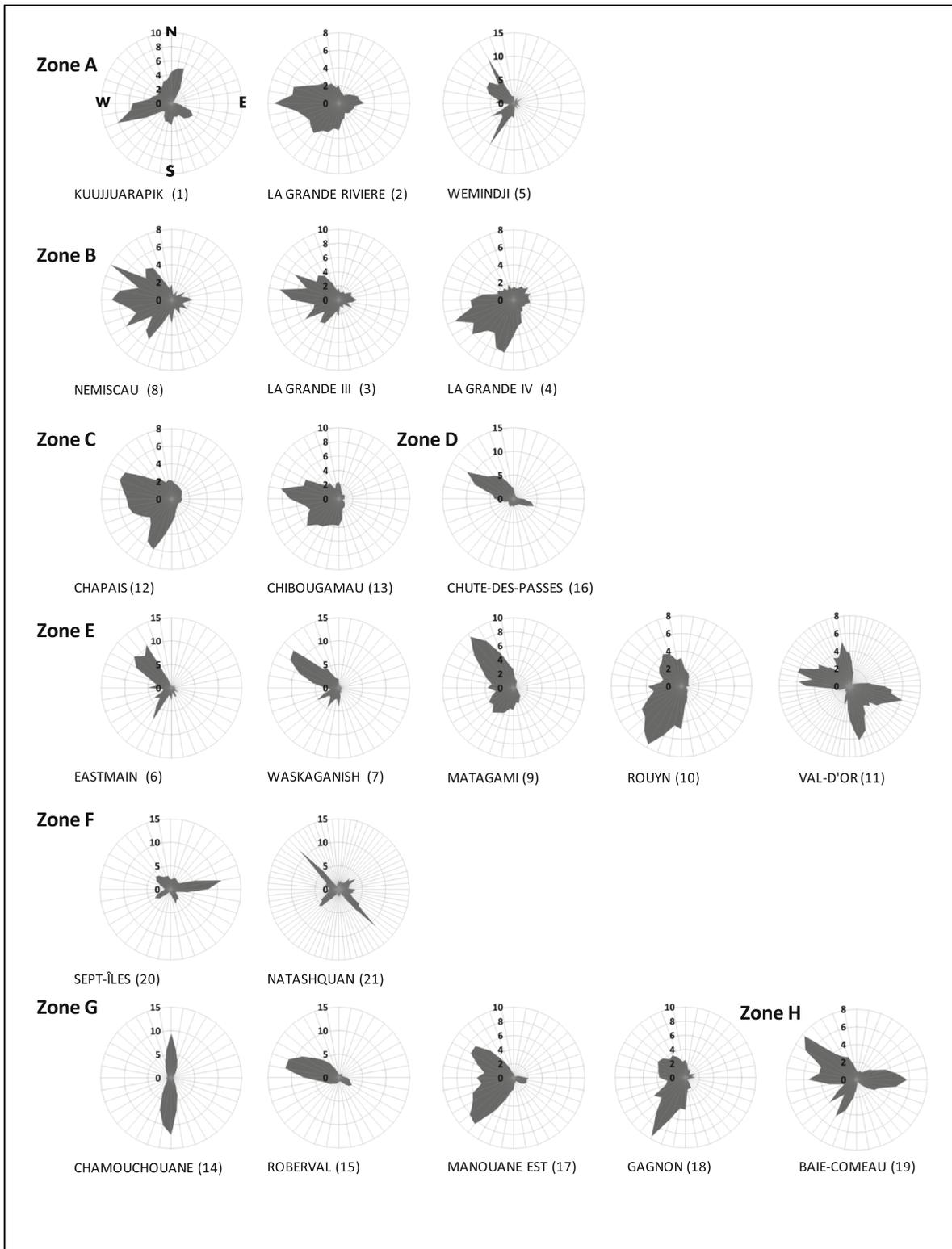
Fig. 4 Ordination based on the results of the canonical redundancy analysis with the 33 ecodistricts. **a** The ecodistricts and the selected environmental variables. **b** The zones with the fire attributes and the selected environmental variables. Colours

difference between our results and those of Parisien et al. (2006) stems from the fact that we used ecodistricts, which delineate smaller areas and can therefore be used to describe ecological and physical processes at the landscape level better than ecozones.

Our findings suggest a synergistic relationship between the landscape spatial patterns and the seasonal climate regime over the spatial attributes of fire at very a large scale (Hellberg et al. 2004; Mermoz et al. 2005; Flatley et al. 2011) that works effectively to delineate and explain our zonation (Fig. 3). Specific to our study area, size and fire orientation seem to be under the control of the regional orientation of the glacier meltwater flow that left its mark on today's landscape from EW in Zone A to NS in Zone F (counter-clockwise). Under this peculiar regional pattern and between zones A and F, fixed attributes of the landscape such as surficial deposits and watershed can influence the spread and size of the fire (Barros et al. 2012). In addition, regional climatic gradients act as top-down controls on spatial attributes of fire as well as on fire frequency (Parisien et al. 2006; Cyr et al. 2007). In top of that, prevailing wind directions during extreme fire-weather conditions may also drive or exacerbate the orientation and size of the fires (Viegas 2004). As an example, large fires oriented EW in Zone A might result from the

assigned to the ecodistricts are used to identify the zones (Fig. 2). The environmental variables are identified by blue arrows. The variables describing the spatial attributes of fires are identified by black crosses. (Color figure online)

synergistic effect of dry summer climate and flat topography, with EW prevailing winds parallel to physiography orientation as well as large rivers oriented EW (Fig. 1d; Parisien and Sirois 2003). In fact, large unidirectional fires occur more frequently where the general physiography of the landscape (surficial deposits, rivers) is parallel to the prevailing wind direction during extreme fire weather conditions (Linn et al. 2007). From a strictly climatic point of view, annual large fires in the northwestern part of the study area are well known to be connected to high-pressure systems in the upper atmosphere, specifically at the level of 500 hPa, which would create ideal dry conditions for triggering fire in the summer (Skinner et al. 1999, 2006). High fire risk in these areas could also be associated with a high proportion of dry sandy coarse surficial deposits such as elongated esker or drumlin type morphology (Mansuy et al. 2010). On the other hand, small fires oriented NS or NWSE in the southeastern rugged region of the study area may respond directly to a drastic change in landscape physiography as well as in climate regime less prone to fire. Incised valleys specific to these areas may act like natural firebreaks that constrain fire propagation and fire size (Parks et al. 2012). Although it is complex to fully separate the climate regime controls and the topography effects, it is likely that the maritime



◀ **Fig. 5** Directions of prevailing winds during extreme fire weather conditions for each weather station grouped by fire zones. The first station shows the cardinal direction. Extreme fire weather conditions are defined by the SSR > mean + 2 standard deviations. Wind daily direction was recorded between 1981 and 2010 from May 1 to August 31 with BioSIM. Weather stations were missing for 18 out of 33 of the ecodistricts. The numbers in *brackets* identify the stations in Fig. 1d

influence of the Gulf of St. Lawrence could also moderate fire activity in the coastal regions (Bouchard et al. 2008) and affect the size of fires. In the more rugged context, it is also true that the effect of topography on spatial attributes of fires may possibly supersede the effect of wind and climate (Sharples 2008). Finally, in zones with small fires and no particular orientation in the landscape (zone E), the correlation between fire attributes, wind direction and landscape pattern is less obvious. In fact, Zone E corresponds to the Clay Belt lowlands, which are covered by glaciolacustrine deposits with no particular orientation or morphology (Veillette 1994) and with lower fire risk (Mansuy et al. 2010).

Limitations of the study

Our results can only be interpreted at the regional scale and not at the fire scale. Indeed, it was not possible to completely isolate the top-down controls (climate regime) from the bottom-up influences (e.g., topography) on the spatial attributes of fires. Interactions among factors suggest that separating top-down and bottom-up controls may be very difficult even in a controlled artificial landscape (Parisien et al. 2010). Although we did not look directly at the spatial attributes of fire in relation to forest cover, it is true that fuel type and continuity may influence the patterns of fires (Schoennagel et al. 2004) and when integrated with climate model land-cover data could improve the prediction of fire activity (Parisien et al. 2014). Climate-only models are effective for describing fire regime in highly weather-limited ecosystems such as the boreal forest (e.g. Flannigan et al. 2001). Besides, it is reasonable to assume that the topography and the climate regime may also impose constraints on the vegetation, in which case the combustible is expected to follow the same orientation as the landscape. Analyse in our study area show that size and fire orientation varied significantly among fire zones, which encompasses little variability in fuel types,

mostly spruce lichen woodland and boreal spruce (from fuel types map, CWFIS 2012). But it remains that the control of the landscape on the fire regime is often due to a complex relationship between vegetation and physiography rather than the physiography per se (McKenzie et al. 2011; Wu et al. 2013). Looking at the anthropogenic activities in our study area, it is also reasonable to assume that fire suppression does not have a major effect on fire attributes. In the region north of 51°N, fire suppression efforts are limited to protecting human infrastructures within a radius of action that takes in large tracts of highly combustible forest (MRNQ 2013). Furthermore, although intensive management exists south of 51°N, Gauthier et al. (2005) showed that these operations are not very effective at limiting the area burned during summer droughts conducive to large fires.

Future research

This study which encompasses about 800,000 km² shows some significant results at a supraregional scale. Meanwhile, further research is necessary to support these conclusions at the operational level with potential implications for fire and forest management (Hirsch et al. 2001; Finney et al. 2007). To overcome the scale issue in the landscape analysis related to the fire regime, scale-dependent studies should address the effect of fuel (type and continuity) linked to the feedback between landscape pattern and ecological process (Cyr et al. 2007; Kellogg et al. 2008; Falk et al. 2011). However, the synergistic interactions between the spatial arrangements of the landscape and the climate regime need to be further addressed to assess the underlying controls on patterns of fire, which in turn influence vegetation composition and dynamic (McKenzie et al. 2011). Finally, given that the ecological and physical (geomorphologic) patterns occurring in the province of Quebec may not be representative of other boreal forest regions, the next step should be to determine whether the interaction between the spatial attributes of fires and landscape physiography, which are identified in this study, can be confirmed at different locations in other boreal ecosystems. Multiple propagated fire simulation scenarios, with controlled environmental factors, seem to be an interesting approach to achieving these objectives.

Conclusion

The study of the spatial attributes of fire related to the landscape physiography is a challenge depending on both landscape structure and scale of measurement (Kellogg et al. 2008; McKenzie et al. 2011). At the scale of the province of Quebec, this study is the first one to show that the orientation of fires varies significantly from one region to another, as do fire frequency and fire size—two major elements of the fire regime. This study highlights the role played by the orientation of surficial deposits as a major structuring element in the boreal landscape with particular control over the size and orientation of the fire. These results are consistent with the role of surficial deposits on the current (Mansuy et al. 2010) and multi-millennial fire frequency in Canada (Senici et al. 2013). Further scale-dependent studies are needed to include fire orientation as a common attribute of the fire regime in the boreal forest.

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