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Variation in local weather explains differences in fire regimes within a Québec south-eastern boreal forest landscape

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Abstract. Variation in natural disturbance regime within a landscape is important for species population dynamics, because it controls spatial arrangement of sites providing regeneration and survival opportunities. In this study, we examine the differences in fire regime and evaluate possible sources of its variation between the surrounding mainland and the islands of Lake Duparquet (44.5 km^2), a typical boreal lake in north-western Quebec, Canada. Dendrochronological reconstructions suggest that fires were frequent and of variable intensity on the islands, whereas fires were less frequent on the adjacent mainland, but were usually large and intense. Islands were significantly drier and warmer than the mainland, and maximum values of Fire Weather Index were significantly higher on the islands during both the early part of the fire season (May–June) and the whole fire season (May–September). The lightning density within the lake perimeter was significantly higher than in the surrounding mainland (0.63 *v.* 0.48 $year^{-1}$ km^{-2} respectively). This pattern was a result of the differences in lightning density during the first half of the lightning season. The study suggests that more fire-prone local weather and higher frequency of lightning strikes could cause a higher frequency of low-intensity fires on the islands, compared with the mainland.

Additional keywords: climate variability, fire hazard, fire history, fire weather, island ecosystems, natural disturbance, Quebec Clay Belt, red pine.

Introduction

Fire controls species regeneration cycles in the boreal forest (Bergeron and Charron 1994; Engelmark *et al.* 1994; Schimmel and Granstrom 1996; Asselin *et al.* 2001; Johnstone 2006). There are temporal, spatial, and severity-related aspects of this relationship. The temporal aspect relates to fire frequency (number of fires per time interval) or length of fire cycle (time required to burn the area equalling the study area; e.g. Johnson and Van Wagner 1985) in connection to the species lifespan or period where species seeds or spores maintain their vitality (Crow 1988; Niklasson and Drakenberg 2001). Spatial aspect relates to spatial arrangement of sites providing regeneration and survival opportunities (Sirois and Payette 1991). Finally, fire severity controls species mortality and site conditions during post-fire recruitment (Schimmel and Granstrom 1996; Bergeron *et al.* 2004; Greene *et al.* 2007). All of these factors show different degrees of variability across boreal landscapes. To better predict species behaviour in various temporal and geographical contexts, it is important to understand the sources of this variability.

The fire regime in natural boreal forest is driven by the interactions among factors including the weather, fuels, ignition pattern and topography. Strong atmospheric circulation anomalies are generally responsible for fire activity considered over large ($>10^3$ ha) areas (Flannigan and Harrington 1988), whereas the effects of fuel condition, fuel spatial distribution and topography are the most pronounced at finer spatial scales (Cumming 2001; Bilgili 2003). Differences in fire regimes

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among landscapes may be correlated with relative proportion of area under different fire hazards, i.e. relative amount of xeric and mesic sites (Heinselman 1981; Romme 1982). At the finest spatial scale, differences in fire return interval among sites of different forest types occupying specific positions within a landscape are an example of the interplay between fuel characteristics and topography controlling stand-scale fire activity (Hellberg *et al.* 2004; Wallenius *et al.* 2004; Drobyshev *et al.* 2008*a*).

It is reasonable to assume that topographical features not only modify the amount of precipitation and heat received and retained by a site (i.e. the local weather), but also can potentially contribute to the differences in the lightning-strike probability. Source of such differences may be a variation in the height of the site above the rest of the terrain. Differences in lightning-strike density would lead to the variation in ignition probability among sites and may enhance or mask other components of fire-related weather, e.g. air humidity or water conditions of the ground fuels. To better quantify the role of different factors driving natural fire activity, there is a need to separate the effects of water and heat availability and ignition and spread probabilities. However, few empirical studies (e.g. Cumming 2001; Wotton and Martell 2005) have attempted to systematically quantify the above-mentioned factors in different parts of the same landscape.

Most of the North American eastern boreal forest is subject to recurrent large and stand-replacing crown fires (Van Wagner 1983). However, results of dendrochronological fire histories reconstructions indicate that several forest types in this region have been regularly experiencing non-lethal fires. One example of such forests is mixed pine ecosystems with red pine (*Pinus resinosa*) and eastern white pine (*Pinus strobus*), both adapted to low-intensity surface fires (Ahlgren 1976; Cleland *et al.* 2004; Drobyshev *et al.* 2008*b*). The presence of red pine may, in fact, indicate that there are parts of the landscape where such a fire regime dominates. In a study of fire regime in the southern boreal forest in north-western Quebec, Dansereau and Bergeron (1993) demonstrated strong topographic controls over local fire histories and noted numerous multiscarred trees, indicative of non-lethal fire events. To further explore the possible impact of local topography on fire-related weather conditions in the same geographical region, we analyse features of fire regime and fire-related weather in the area of Lake Duparquet in a natural south-eastern boreal landscape. The impetus for our analysis was results from a previous study, which found a difference in fire regimes between islands ($<$1 ha to 10^2 in size) on the lake and the surrounding mainland (Bergeron 1991). Specifically, fires were frequent and of variable intensity and size on the islands, whereas fires were less frequent on the adjacent lakeshore but were usually large and intense, which is typical for this part of the North American boreal forest. To find the source of this variation, we tested two non-conflicting hypotheses relating local fire regime with site conditions. We hypothesised that (1) drought-related weather conditions, represented by indices of the Canadian Fire Weather system are more frequent or more intense on islands than on the mainland; and (2) lightning-strike frequency is higher within the lake perimeter compared with the mainland. To evaluate the influence of the local weather variation on the fire regimes, we utilised daily data (1990–2007) from four weather stations established on the islands and the surrounding mainland (Tables A1, A2). Lightning-strike location data (1996–2005) were examined to assess the variation in lightning activity between two locations. Additionally, we used dendrochronological dating of fire scars to evaluate the seasonal pattern of past fires and reconstruction of the Canadian Drought Code (Girardin *et al.* 2004) to put analysed fire regimes in a wider temporal perspective.

The study area

The study area is located in the Hébércourt township, close to Lake Abitibi in north-western Quebec (Fig. 1). The study area is part of the Clay Belt of Quebec and Ontario. The regional geomorphology of the study region is shaped by a post-glacial lacustrine phase, which resulted in the formation of the Northern Clay Belt, i.e. varved clays left by proglacial Lake Barlow-Ojibway. The Clay Belt currently covers large areas of north-western Quebec and north-eastern Ontario (Vincent and Hardy 1977). Topography of the area is generally flat, characterised by low-elevation hills and a mean altitude between 250 and 400 m above sea level.

The continental climate of the area is characterised by cold winters and warm summers. A cold Arctic air mass dominates the area during the cold period and a dry tropical air mass tends to dominate during the summer months. The mean annual temperature is −0.7°C. Mean temperatures of January and July are −20.0° and 16.1°C respectively. The heat sum (degree-days above 5°C) reaches 1170, and growing-season frosts are common throughout the study area. Total annual precipitation is 905 mm, 35% of which is received during the growing season (Matagami weather station, 49°84′N, 77°84′W). Annual snowfall is estimated at ~30.0 cm (Environment Canada 2006).

Lake Duparquet is located at the southern limit of the boreal forest in the Missinaibi–Cabonga section. In the area, the dominating type of forest cover is formed by balsam fir (*Abies balsamea* (L.) Mill.), black spruce (*Picea mariana* (Mill.) B.S.P.), and white birch (*Betula papyrifera* Marsh.), accompanied by white spruce (*Picea glauca* (Moench) Voss) and trembling aspen (*Populus tremuloides* Michx.) (Rowe 1972). Mixed-pine stands with red, eastern white, and jack pines (*Pinus resinosa* Ait., *P. strobus* and *P. banksiana* Lamb.) with white cedar (*Thuja occidentalis* L.), black spruce, and white birch are common on the islands. The area of the lake is 44.48 km^2, of which 5.46% is covered by islands ($n = 179$). Minimum, average and maximum sizes of the islands are 0.003, 1.358 (±6.335 s.d.), and 74.036 ha respectively.

Material and methods

Records of local weather

Four weather stations were established in the study area in 1990: two were located on the islands of Lake Duparquet and two on the surrounding mainland (Fig. 1). The stations were located in forest clearings. Temperature and a relative humidity sensor (Campbell Scientific 207 probes, Edmonton, AB, Canada) were placed inside a Stevenson screen 1.5 m above the surface. Wind speed and direction were observed 10 m above ground using a 03001-L RM Young Wind Sentry Set. Rainfall was recorded by a tipping bucket. All sensors were connected to a Campbell

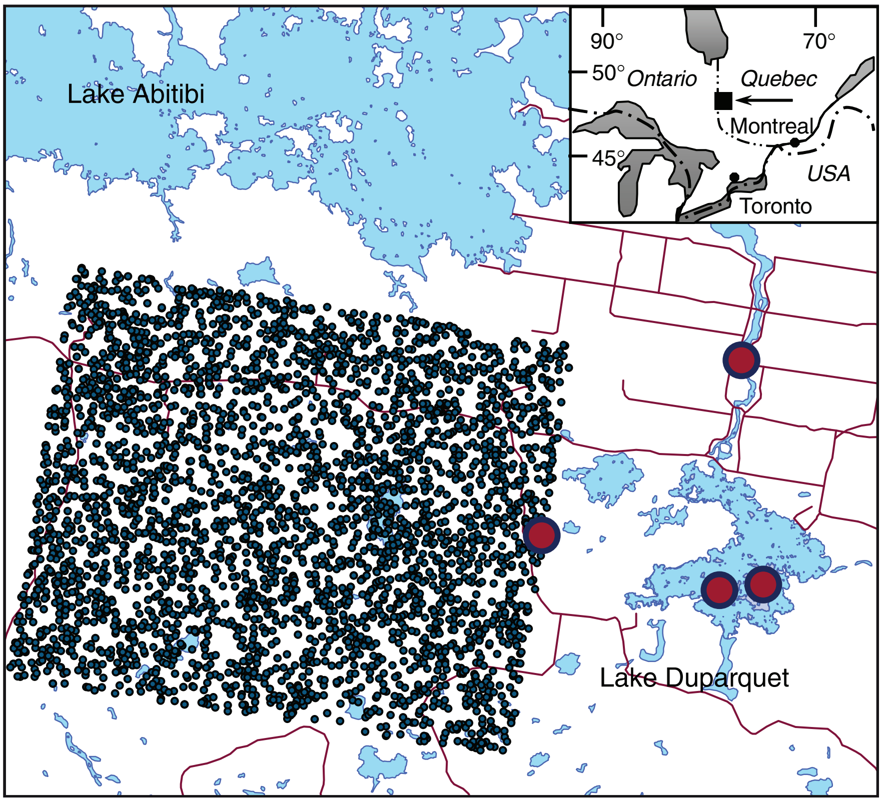

Fig. 1. Location of the study area, weather stations (large red circles), and the control area used in the analyses of lightning-strike distribution. Actual lightning-strike locations (small dark circles) demonstrate the shape of the control area. In the regional map (insert), the position of the study area is indicated by the arrow.

Scientific CR10 unit and observations were recorded hourly. Weather data for the months June to August for the period 1990–2007 were used in this study. The season covered by our analyses is the one corresponding to the fire season in the area (Harrington 1982).

Lightning-strike data were obtained from a network of lightning sensors operated by Hydro-Québec. The theoretical efficiency of lightning detection in the study area was above 80% and spatial resolution varied between 0.5 and 1 km (Cummin *et al.* 1998). The available attributes of the recorded strikes were latitude, longitude, date, time and lightning polarity. For the current study, we used timing and location data only (see discussion on the role of polarity in Larjavaara *et al.* 2005). The season analysed in the present study was 1 May–31 August over the period 1996–2005. Lightning-strike season was considered as a time between the earliest and the latest strikes recorded over the observation period. The middle of such a period was considered as the mid-season point. Analyses of strike densities were performed for early and late parts of the season as well as for the whole period. See further details on the lightning-strike dataset in Morissette and Gauthier (2008).

Statistical analysis

To assess the fire weather on the adjacent landscapes, we calculated components of the Fire Weather Index (FWI) System (Van Wagner 1987; Stocks *et al.* 1989) at each weather station using the daily noon values for temperature, relative humidity (RH), wind speed, and the last 24-h precipitation amount. The FWI System comprises three fuel moisture codes and three fire behaviour indices. The three moisture codes represent the moisture content of the fine fuels (Fine Fuel Moisture Code, FFMC), loosely compacted organic layer (Duff Moisture Code, DMC), and the deep layer of compact organic matter (Drought Code, DC). The three fire behaviour indices, derived from the moisture codes and the surface wind data, indicate the rate of initial fire spread (Initial Spread Index, ISI), total available fuel (Build Up Index, BUI), and the intensity of spreading fire (FWI). Maximum daily temperature, seasonal precipitation, RH, DC, FFMC, and FWI were the variables selected for analyses. To initiate the computational routine, we used a standard method for the locations with significant snow accumulation (Turner and Lawson 1978). The following initial values were assigned: FFMC = 85, DMC = 6, and DC = 15 (Van Wagner 1987). Station-specific values were averaged for each location type.

Differences in fire weather indices between mainland and island locations were assessed in a two-fold procedure. First, maximum and average values were tested in a pair-wise fashion. Second, frequency of extreme conditions (Flannigan and Harrington 1988) was compared between the islands and mainland. These conditions were RH $< 30\%$, DC > 350, FFMC > 86, and FWI > 23. For both analyses, we used the Wilcoxon matched pair test (Sokal and Rolf 1995). Based on our knowledge of recent fire activity in the area, we considered values of the indices for the whole fire season (May–September) and for its two parts – early season (May through July) and late season (August–September).

To evaluate differences in lightning-strike density, a predominantly forest-covered control area (720.77 km^2) was selected at the provincial border between Québec and Ontario (Fig. 1), covering 1996–2005. A sub-area equal to the size of Lake Duparquet was randomly selected and the number of strikes was recorded. This bootstrap procedure (Efron and Tibshirani 1993) was repeated 1000 times to generate a statistical distribution of the number of strikes and to contrast it with the value observed within the perimeter of Lake Duparquet.

Fire history and drought reconstruction

Seasonal information on the fire occurrence was compared between sites on the islands of Lake Duparquet and mainland sites, located at the lake perimeter and within 10 km of it. We used results of dendrochronological crossdating of scars and spatial reconstructions of fires published earlier (Bergeron and Brisson 1990; Dansereau and Bergeron 1993), which were supplemented by the additional seasonal dating of the fire scars. This consisted in identification of the scar position relative to early- and latewood within a ring. Scars located in the earlywood or preceding earlywood ('dormant earlywood') of a ring were interpreted as indicative of early-season fires. Scars located in the latewood portion of the ring indicated late-season fires. The main species used for crossdating was white cedar, together with a few samples from red and jack pines. We also used available dendrochronological reconstruction of the Canadian DC (Girardin *et al.* 2004) and contrasted it with the list of fire year for the islands of Lake Duparquet and surrounding mainland (Bergeron 1991). A bootstrap bias-corrected and accelerated (BCa) confidence interval method (95% CI; Mudelsee and Alkio 2007) was used to test for differences in the median of the frequency distributions of drought indices at times of fire and non-fire events on the islands and mainland over 1593–1987. The BCa intervals correct not only for possible systematic under- or overestimation (i.e. bias) but also for systematic deviations in scale (Efron and Tibshirani 1993), as is the case with the current data.

Results

Islands were significantly drier and warmer than the mainland (Table 1), although differences in maximum temperatures and minimum precipitation sums were generally non-significant. Mean values of both DC and FFMC were significantly higher on the islands during the early-season (May–July) and the whole season (May–September) (Table 1). Similarly, FWI were significantly higher on the islands during both the early part of the fire season (May–June) and the whole fire season (May–September).

Frequency of extreme values of fire indices showed pronounced seasonal patterns (Fig. 2). Frequency of low-humidity days (RH) had a tendency to decrease during the whole summer, with the highest values observed in May. Similar dynamics were recorded for the FFMC values. In contrast, high values of DC became more common in August. The temporal pattern of

Table 1. Differences in weather indices between mainland and island weather stations

In each cell, mean values for mainland (left value) and island (right value) stations are given together with P value (in italic) obtained through non-parametric Wilcoxon matched-pairs tests. Number of replications for each test is indicated in parentheses. Early season included May, June, and July; late season, August and September

Weather variables and indices	Differences in maximum values (minimum in case of subseasonal precipitation sums and RH)			Differences in means (subseasonal sums in case of precipitation)		
	Seasons			Seasons		
	Whole	Early	Late	Whole	Early	Late
Temperature (°C)	34.5–34.1, *0.441* (9)	33.4–32.1, *0.241* (10)	32.8–33.5, *0.953* (9)	15.4–16.6, *0.017* (10)	13.6–15.5, *0.007* (9)	14.6–15.9, *0.007* (9)
Precipitation (mm)	372.6–220.2, *0.043* (5)	74.1–62.6, *0.345* (6)	254–162, *0.063* (7)	389.6–246.1, *0.043* (5)	88.3–69.9, *0.249* (6)	266.9–183.1, *0.043* (7)
Relative humidity (RH)	18.1–19.7, *0.660* (14)	18.4–20.0, *0.638* (14)	32.7–32.5, *0.972* (14)	59.2–55.5, *0.363* (14)	54.2–51.6, *0.778* (14)	66.7–59.0, *0.650* (12)
Drought code (DC)	280.1–383.8, *0.080* (4)	235.9–285.9, *0.173* (5)	297.1–372.7, *0.063* (7)	140.3–211.7, *0.043* (5)	121.8–142.2, *0.249* (6)	216.5–288.2, *0.010* (7)
Fine fuel moisture code (FFMC)	94.1–91.5, *0.080* (5)	93.9–92.7, *0.463* (6)	90.2–90.6, *0.237* (6)	63.3–70.4, *0.043* (5)	71.2–73.8, *0.116* (6)	65.1–74.6, *0.018* (7)
Fire weather index (FWI)	24.9–31.4, *0.043* (5)	23.3–30.0, *0.028* (6)	21.0–29.9, *0.138* (6)	4.3–5.7, *0.138* (5)	5.9–7.4, *0.345* (6)	4.2–9.9, *0.028* (7)

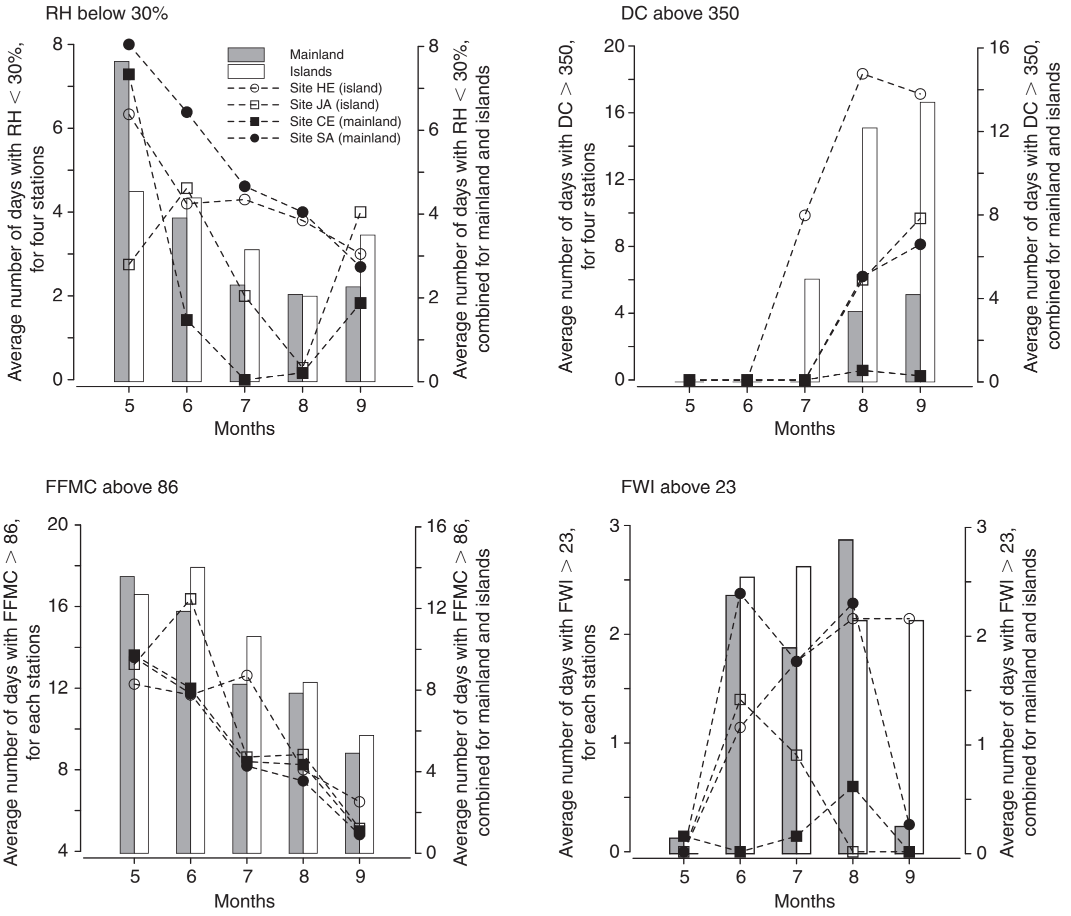

Fig. 2. Comparison of fire hazard indices between two island and two mainland locations. RH, relative humidity; DC, Drought Code; FFMC, Fine Fuel Moisture Code; FWI, fire weather index. Data – frequencies of days with values of fire indices above respective thresholds, averaged over 1990–2007. Lines with symbols show actual index dynamics for each weather station.

extreme values of FWI, integrating the seasonal dynamics of abovementioned indices, revealed, again, strong variation among weather stations with no clear seasonal pattern (Fig. 2).

Over 1996–2005, mid-May and mid-July were the most strike-prone periods on both the mainland and within the lake perimeter (Fig. 3). The earliest and the latest lightning-strike season occurred at Julian dates 131 and 263 respectively. The middle of the lightning-strike season (Julian date 212) was used to estimate strike density separately in two parts of the lightning season. Before the mid-season, the control area received, on average, 63.99% of strikes and the area within the Lake Duparquet perimeter 78.29% (difference significant at $P < 0.001$). In the early season, strike frequency within Lake Duparquet (0.36 $\text{year}^{-1}\,\text{km}^{-2}$) was above the maximum strike density for the control area generated in the bootstrap experiment (0.13 to 0.33 $\text{year}^{-1}\,\text{km}^{-2}$, Fig. 4). During the second part of the season, Lake Duparquet lightning-strike frequency was close to the average value for the control area (0.28 and 0.26 $\text{year}^{-1}\,\text{km}^{-2}$ respectively). The season-wide lightning density within the lake perimeter was significantly higher within the lake perimeter than on the surrounding mainland (0.63 *v.* 0.48 $\text{year}^{-1}\,\text{km}^{-2}$ respectively, $P < 0.001$).

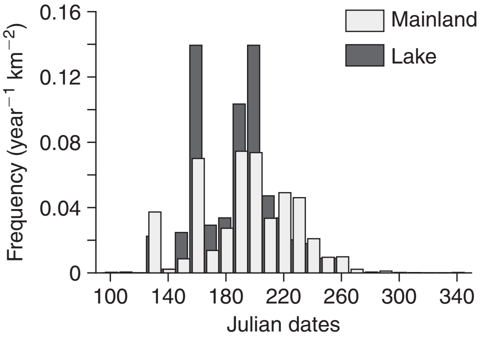

Fig. 3. Seasonal pattern of lightning-strike occurrence within the perimeter of Lake Duparquet and the neighbouring mainland area. Data are grouped into 10-day classes for both locations.

On a subset of Lake Duparquet islands, we dated 59 fire years occurring during the period 1591–1985. Out of these, 49 individual fire years (83.1%) were dated with seasonal resolution. The majority of fires were early-season fires, with respective fire scars located in the beginning of the earlywood. Only

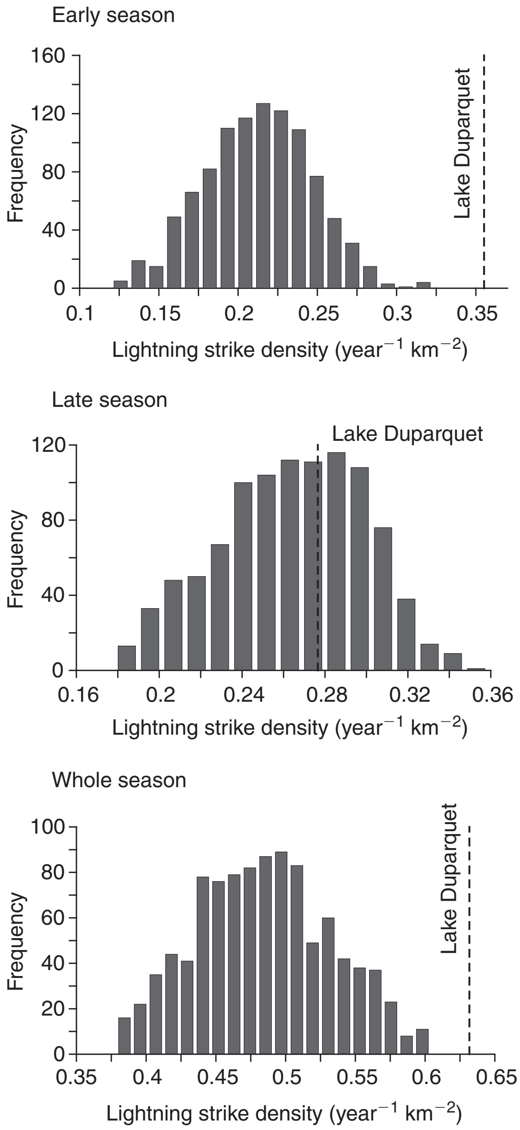

Fig. 4. Lightning-strike frequency within the perimeter of the lake Duparquet (44.5 km^2) and within a part of the control area of the same size on the mainland over 1996–2005. Data are results of Monte Carlo experiments ($n = 1000$) for early and late parts of the lightning-strike season, and for the whole year combined. Frequency is the number of occurrences with a given number of strikes (x-axis) over a 10-year period. Dashed line indicates respective numbers of strikes for Lake Duparquet. The middle of the lightning-strike season (Julian date 212) was defined as the mean of Julian dates for the earliest and the latest strikes (days 131 and 263 respectively).

two fires (4.1%) were dated as late-season fires, with scars positioned in the late earlywood or latewood.

On the mainland, 37 fire years were identified. Spatial reconstructions (Bergeron 1991; Dansereau and Bergeron 1993) revealed that 10 fires (which occurred in 1760, 1797, 1846–47, 1816, 1870, 1907, 1919, 1923, and 1944) were responsible for large areas burned in the vicinity of Lake Duparquet. For such large fires, conclusive seasonal information could be obtained only for 4 years. Fire in 1760 was an early-season fire (scars located in different parts of the

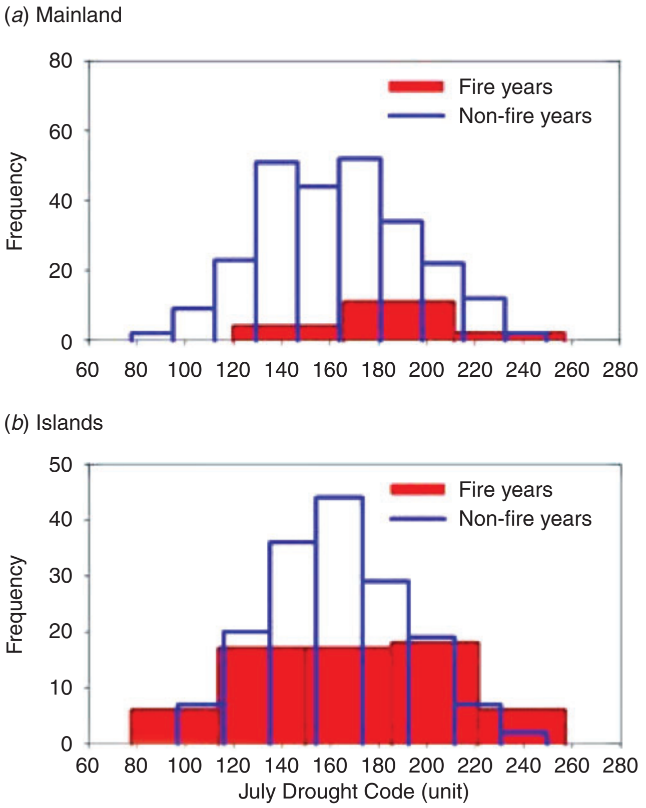

Fig. 5. Comparison of the dendrochronological reconstruction of the July Drought Code with the list of fire years for the islands of Lake Duparquet and surrounding mainland (Girardin *et al.* 2004). Data – distribution of drought code values for fire years (filled bars) and non-fire years (empty bars) for mainland and islands.

earlywood), and 1797, 1906, and 1923 were late-season fires (scars in latewood and on the border of early- and latewood). In the case of fires on the Lake Duparquet islands, the distribution of reconstructed DC values for the fire years did not differ from the bootstrap-generated distribution. Fire years on the mainland were significantly drier than an average year (Fig. 5).

Discussion

Understanding such variation may help explain the distribution of different species and their communities within the landscape and provide crucial information for sustainable forest management. Analysis of locally collected weather data suggests islands were both generally warmer and drier than the mainland, which resulted in higher maximum values of FWI observed on the islands during the early part of the fire season (May–July) (Table 2). Although none of the other two fire weather indices (DC, FFMC) or RH showed significant differences between the mainland and the islands, the mean values of DC and FFMC tended to stay significantly higher on the islands, pointing to conditions of generally higher fire hazard on the islands. It is worth noting that the humus depth on islands analysed in this study is often heterogeneous and relatively thin (<18 cm, a nominal value used for DC calculation; Wotton 2009), which translates into an even higher actual fire hazard than predicted

Table 2. Differences between mainland and island fire regimes – summary of previously published and current results

Fire occurrence (FO) is the number of fires per unit area per year (after Bergeron 1991). FWI, Fire Weather Index; DC, Drought Code, as defined in 'Statistical analysis' section

Variable	Result	Period	Reference
Number of fire years	Islands (56) > lake shore (37)	1593–1987	Bergeron 1991
Fire cycle (FC)	Island (74, 112) > lakeshore (63, 99)	1593–1870, 1870–1987	Bergeron 1991
Trend in FC	Increase in FC for both locations since 1870s	1593–1987	Bergeron 1991
Fire occurrence	FO is higher on islands than on mainland	1593–1987	Bergeron 1991
Fire seasonality	Early-season fires dominate in both locations	1593–1987	Present study
Fire intensity	Generally lethal intensity on mainland, variable intensity on islands	1593–1987	Bergeron 1991
Local weather	Islands are drier and warmer than mainland, maximum FWI are higher on islands than on mainland during May–July and May–September	1990–2007	Present study
Lightning strike (LS) seasonality	Mid-May and mid-July are main LS seasons in both locations	1990–2007	Present study
LS frequency	Significantly higher LS frequency within lake perimeter during the first half of LS season	1996–2005	Present study
Historical fire regime	Reconstructed DC values for the fire year on islands did not differ from non-fire years, whereas they were significantly drier in case of mainland fire years	1593–1987	Present study

by DC values. Our data indicate that it is the maximum and average values of the fire weather indices, and not the frequency of extreme fire-prone weather, that differentiate between the two locations. This result points to the importance of fuel moisture, represented in our analyses by DC and FFMC. Apparently, the organic layer on the islands is generally drier than on the mainland. This effect is due to lower precipitation at the islands (Table 1). Our result supports hypothesis 1, explaining fire regime differences by variation in drought-related weather. We did not observe clear seasonal differences in the onset of fire season between the mainland and the islands: timing of the fire season onset and its duration were similar at both location types, as was suggested by the temporal pattern of fire-prone episodes (Fig. 2). This implies that it is not the temporal pattern of dry episodes, but rather changes in the absolute values of fire weather indices that differentiate between the two locations.

Both on the mainland and on the islands, early-season fires were the most common type of fire events. However, most of the large mainland fires dated with seasonal resolution were late-season fires, suggesting that more extreme fire weather conditions tend to develop towards the end of the fire season. Supporting this assumption, the frequency of DC extreme values showed a clear increase on the mainland over August–September (Fig. 2). In a centurial perspective, dendrochronological reconstruction indicated that the mainland fire years were significantly drier than non-fire years, the effect being non-significant for island fire year (Fig. 5). A similar temporal pattern of major fires, occurring at the end of the fire season, has been observed in many parts of the boreal zone, including mixed pine forests of Upper Michigan (Drobyshev *et al.* 2008*b*), boreal forests in Alaska (Kasischke *et al.* 2002) and eastern European pine forests (Drobyshev *et al.* 2004).

Strong and significant differences in lightning-strike density were present in the studied landscape, with the islands receiving a higher number of strikes than the control area on the mainland. Assuming that the lightning strikes above the lake surface land exclusively on the islands, the islands receive a one order of magnitude higher strike frequency than the mainland. This supports hypothesis 2, suggesting that differences in strike density, translated into differences in probability of effective ignitions, could be a factor behind the higher frequency of fires on the islands compared with mainland forests (Bergeron 1991).

We explain increased strike frequency on the islands by more pronounced variation in the topography, particularly a larger difference in the heights of the topographic features in a lake-island system, leading to the formation of a heat island (Westcott 1995; Soriano and de Pablo 2002). An association of increased lightning frequency with higher parts of the landscape has been shown for the western US (Reap 1986; but see Caprio and Swetnam 1993). Although several continent- and region-wide studies have demonstrated large spatial variation in strike densities (Orville and Huffines 2001; Orville *et al.* 2002; Sonnadara *et al.* 2006; Morissette and Gauthier 2008), little is still known about the pattern in lightning-strike variation at finer spatial scales ($\sim 10^1$–10^3 km^2). For example, an increased lightning-strike frequency was noted along shorelines (Golde 1977), an effect that might contribute to the pattern found in the current study. Similarly, a study in the longleaf pine ecosystems of Florida and South Carolina has shown that the probability of a tree being struck by lightning increased as a function of tree height, lightning preferentially causing mortality of the largest trees in the stand (Outcalt 2008). We observed a large proportion of strikes during May and July, which was different from the regional pattern in which the highest monthly frequency of strikes was associated with the 3 summer months (Morissette and Gauthier 2008). The source of these differences is unclear, given the fact that our strike data were a part of the larger dataset used in abovementioned study. This discrepancy may suggest considerable subregional variation in strike seasonality within Québec.

The relative contribution of drought- and ignition-related factors in fire regime differences remains unclear. Apparently, both act synergistically (e.g. Podur *et al.* 2003) to result in more variable and generally less intense fire regimes on island locations. Mechanistically, a higher probability of island fires would result in more effective reduction in fuel loads and disruption of fuel continuity in these locations. Smaller and more poorly connected fuel loads would, in turn, translate into a higher frequency of low-intensity non-lethal fires. In eastern North America, such low-intensity fires have been recently suggested as the dominant type of fire events in pre-European mixed-pine forests of Upper Michigan (Drobyshev *et al.* 2008*b*) and, generally, as an important feature of the fire regime in red pine-dominated forests.

An important feature of the islands' fire regime is the very low (often negligible) probability of fire spread into the island from the surrounding landscape. In contrast to the ecosystems with a large variation in fuel connectivity during the fire season (as, for example, in mire-dominated landscapes; e.g. Hellberg *et al.* 2004; Drobyshev *et al.* 2008*a*), the lake surface, being a perfect fire break during the whole fire season, can only be crossed by fire through transport of hot particles by convection columns under conditions of extreme fire hazard. Dendrochronological reconstructions show that fire years on the mainland and on the islands rarely coincide (Bergeron 1991; Dansereau and Bergeron 1993), suggesting that this mechanism is unlikely. Therefore, lightning provides the only ignition source on the islands. Our results demonstrate that an increase in topographically controlled lightning frequency can easily overcompensate for close-to-zero probability of fire occurrence due to fire spread from neighbouring parts of the landscape. The high degree of spatial independence of the island fire regime from the one in the surrounding mainland is helpful when analysing long-term changes in fire activity. In contrast to most of the areas where dendrochronological reconstruction of past fire activity is done, island and mainland fire regimes can most closely approximate two spatially independent entities still representing the same landscape.

Comparison of reconstructed DC values for known fire years suggests that fires on the islands break out over a wider range of weather conditions, compared with mainland fires observed during a narrower range of significantly drier seasons (Fig. 5). Mainland fires generally spread over a mesic matrix of mixed coniferous forest and apparently occur during conditions of extreme fire hazard. As such conditions are rare, it is not surprising that our 17-year-long observational record might be too short to represent such events. It is therefore likely that increased lightning-strike frequency on the islands is also associated with a higher actual ignition probability in these locations. In this paper, we explain higher fire occurrence on the islands by variation in the physical environment between the islands and the mainland. In doing so, we assume that forest use by Amerindians had a negligible effect on past fire histories in the studied boreal forests. The nomadic lifestyles of Algonquins, aboriginal people in the studied area, and their typical fire use practices to clear land around campsites and trails (Lewis 1982), warranted this assumption.

What is the application of our results (Table 1) to the development of forest conservation activities? In line with conclusions from other studies (Krawchuk *et al.* 2006), our results point to the important role of landscape variability in regulating natural disturbance regimes. Such variability extends the range of fire regimes and allows for regeneration of species not adapted to the dominant mode of fire disturbance in this part of the North American boreal forest, i.e. large and intense stand-replacing fires. For example, red pine, eastern white pine and common juniper (*Juniperus communis* L.) commonly found on the Lake Duparquet islands do not naturally occur on the surrounding mainland. Their exclusion from the mainland vegetation is associated with the dominance of lethal fires (Diotte and Bergeron 1989; Bergeron and Brisson 1990; Flannigan 1993). The role of the lake-island systems as species refugia calls, therefore, for protective management of such stands, which may have important ecological functions in a much coarser spatial context than their own dimensions.

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Appendix

Table A1. Data used for weather analyses

Variable	Years with valid observations		
	Whole season (May–September)	Early season (May–July)	Late season (August–September)
Temperature	1990–96, 2002, 2007	1990–96, 2002, 2003, 2007	1990–96, 2002, 2007
Precipitation	1990–93, 1995	1990–95	1990–93, 1995–96, 2007
Relative Humidity (RH)	1990–93, 1995–2000, 2002–03, 2007	1990–93, 1995–2000, 2002–03, 2007	1990–2000, 2002, 2007
Fine Fuel Moisture Code (FFMC)	1990–93, 1995	1990–95	1990–93, 1995–96, 2007
Drought Code (DC)	1990–93, 1995	1990–95	1990–93, 1995–96, 2007
Fire Weather Index (FWI)	1990–93, 1995	1990–95	1990–93, 1995–96, 2007

Table A2. Geographical locations of the weather stations
Station code as on Fig. 2

Station	Station code	Location	Coordinates	Period covered by the data
Mont Sabrais	SA	Mainland	48.470°N, 79.437°W	1990–98, 2000–04, 2006–07
Herons	HE	Island	48.462°N, 79.256°W	1990–2001, 2004, 2007
Jacques	JA	Island	49.778°N, 79.265°W	1990–94
CETEC	CE	Mainland	48.582°N, 79.302°W	1990–2002