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Different regional climatic drivers of Holocene large wildfires in boreal forests of northeastern America

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Abstract

Global warming could increase climatic instability and large wildfire activity in circumboreal regions, potentially impairing both ecosystem functioning and human health. However, links between large wildfire events and climatic and/or meteorological conditions are still poorly understood, partly because few studies have covered a wide range of past climate-fire interactions. We compared palaeofire and simulated climatic data over the last 7000 years to assess causes of large wildfire events in three coniferous boreal forest regions in north-eastern Canada. These regions span an east-west cline, from a hilly region influenced by the Atlantic Ocean currently dominated by *Picea mariana* and *Abies balsamea* to a flatter continental region dominated by *Picea mariana* and *Pinus banksiana*. The largest wildfires occurred across the entire study zone between 3000 and 1000 cal. BP. In western and central continental regions these events were triggered by increases in both the fire-season length and summer/spring temperatures, while in the eastern region close to the ocean they were likely responses to hydrological (precipitation/evapotranspiration) variability. The impact of climatic drivers on fire size varied spatially across the study zone, confirming that regional climate dynamics could modulate effects of global climate change on wildfire regimes.

1. Introduction

Fire is the most important natural disturbance in the boreal forest biome, affecting vegetation dynamics, biodiversity (Granström 2001, Bond *et al* 2005), biogeochemical cycles and atmospheric aerosols (Stocks *et al* 1998, Kasischke *et al* 2005, Kelly *et al* 2016). Model-based predictions suggest that the severity of fire regimes will increase in the future in response to global warming (Turetsky *et al* 2011, De Groot *et al* 2013). Some scenarios even suggest that frequencies of large fires may increase sufficiently to push current fire suppression capacity beyond a tipping point (Amiro *et al* 2001, Balshi *et al* 2009, De Groot *et al* 2013, Lehsten *et al* 2016). Such changes could threaten human safety, impair the viability of some economic sectors (Simms 2016), and trigger substantial changes in vegetation structure and composition (Flannigan *et al* 2005, Remy *et al* 2016). However, robust prediction of the changes, evaluation of likely consequences, and formulation of appropriate adjustments to forest management strategies are hindered by paucity of understanding of the climate factors inducing large wildfires. The infrequent and random nature of these events, coupled with the short historical period covered by fire statistics (usually less than 100 years), further reduce the robustness of fire predictions. In this context, paleoecological investigations based on analysis of lacustrine sedimentary cores are valuable as they enable exploration of the relationships between fire size and climate in long-term perspectives (Ali *et al* 2012), and identification of the main climatic drivers of eclosion of large fire events.

During the last 7000 years, fires in boreal forest of northeastern Canada have mostly been larger in the continental region than in the region closer to the Atlantic Ocean (Remy *et al* 2016), hereafter referred to as the western and eastern regions of our study zone, respectively. According to previous studies (Balshi *et al* 2009, Ali *et al* 2012, Remy *et al* 2016) large fires in the western region have been triggered by long late fire-seasons, with warmer than today springs and dry summers. Thus, based on these results, we hypothesize that the fire season in the eastern region was mostly shorter, with colder springs and moister summers, than in the western one during the study period (Girardin and Wotton 2009, Boulanger *et al* 2013). However, around 1500 years cal. BP, fires in the eastern region became dramatically larger, more than those in the western region (Remy *et al* 2016). Two possible explanations for this are that the climate in western and eastern regions became similar, or climatic changes that favored large fire ignition specifically occurred in the eastern region.

The main objective of this study was to assess the spatial variation (if any) in drivers of large fires in coniferous boreal forests of eastern North America. A specific hypothesis tested is that periods of large-fires during the Holocene were associated with long late fire-seasons, with warm springs and dry summers, across the entire study zone and thus independently of regional characteristics. For this purpose we studied both past climate variations and fire size histories in three regions of boreal forests in Quebec-Labrador (western, central and eastern regions) displaying same or different relief, current climate conditions, fire activity and vegetation composition. We used macroscopic charcoal fragments previously extracted from lake sediments to reconstruct regional fire size histories during the last 7000 years. Then, we compared these fire reconstructions with simulated climate data obtained from a general circulation model (GCM) that we downscaled at regional scales to detect relationships between climate and fire size. The results highlight the importance of several climatic drivers of large fire occurrences linked to some regional characteristics during the Holocene, and we discuss their potential profound implications for future fire regimes across eastern Canada.

2. Material and methods

2.1. Study area

We used 13 charcoal records from lacustrine sediments located along a 500 km east-west transect within spruce woodlands (spruce-moss in the south and spruce-lichen in the north) of Quebec-Labrador (between 50 and 53°N, and 67 and 79°W; figure 1). Six of the lakes are located near the James Bay Lowlands in western Quebec (Oris *et al* 2014), four near Mistassini Lake in central Quebec (El-Guellab *et al* 2015) and three in eastern Quebec or Labrador (Remy *et al* 2016, figure 1; appendix A available at stacks.iop.org/ERL/12/035005/mmedia). These areas were rapidly colonized by trees after the last deglaciation, between *ca.* 8000 and 7000 years cal. BP (Richard 1995). Since then, the western and central regions have been mainly dominated by *Picea mariana* (Mill.) B.S.P. and *Pinus banksiana* Lamb. (Richard 1979, Gajewski *et al* 1993, Payette 1993), while the eastern region has been mainly dominated by *P. mariana* along with *Abies balsamea* (L.) Mill. and *Picea glauca* (Moench) Voss (Mott 1976, King 1986, Payette 1993). Mean annual temperature (from 1966 to 1996) are between −1.1 and −3.1 °C in western and central regions and are between −3.1 and −5.0 °C in eastern region (DesJarlais *et al* 2004). Mean annual precipitations (from 1966 to 1996) are between 710 and 989 mm in western region, 850 and 989 mm in central region, and 850 and 1129 mm in eastern region (DesJarlais *et al* 2004). In recent decades, fires in the eastern region have been less frequent than in the western and central one, but may have been episodically larger (Stocks *et al* 2003, Bergeron *et al* 2004, Bouchard *et al* 2008).

2.2. Fire-history reconstructions

Lakes with small surface areas and sufficiently long sediment cores to provide robust sedimentary records of fires at the local scale (i.e. at the watershed scale) were selected (appendix A). Sediment cores composed of gyttja were extracted between 2007 and 2013. To obtain fine-scale temporal resolution, they were cut into contiguous 0.5 to 1 cm thick slices depending on total sequence length (appendix A). Sediment accumulation chronologies were generated based on AMS radiocarbon dating of terrestrial plant macro-remains and/or total organic content extracted from gyttja samples. ^{14}C dates were calibrated using the Bchron R package based on the IntCal13.14C data set (Hua *et al* 2013, Reimer 2013). Age-depth models were obtained using Bayesian models (Parnell *et al* 2008). All dates were expressed in calibrated years before present (hereafter BP).

Charcoal samples from all lacustrine cores were obtained from previous studies (appendix A) in which a common protocol for extracting charcoal was applied. Particles were measured and the resulting data were transformed into charcoal accumulation rates (CHAR; mm^2 cm^{-2} yr^{-1}) based on numerical age-depth models to reconstruct past regional biomass burning (hereafter *RegBB*; no unit) and past regional fire frequency (hereafter *RegFF*; # of fires yr^{-1}) values. Individual CHAR series were homogenized to reduce

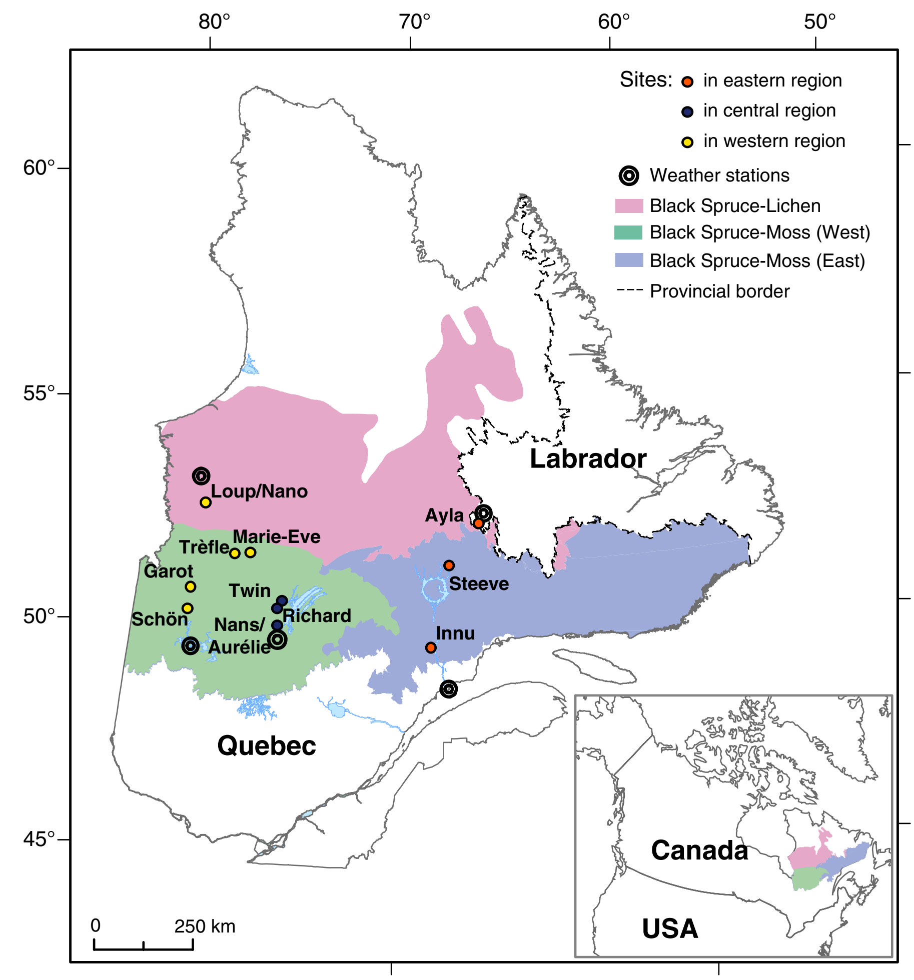

Figure 1. Locations of the study sites in the western, central and eastern regions of Quebec-Labrador.

the influence of sedimentation rate and potential taphonomic biasing factors linked to sequestration of charcoal in the sediments (Power *et al* 2008). Homogenized series were then pooled to build the *RegBB* by (i) rescaling initial CHAR values using min-max transformation, (ii) homogenizing the variance using Box-Cox transformation, and (iii) rescaling the values to Z-scores (Power *et al* 2008).

The dates of local fire events ($\leq$ 1–3 km from the lake shore; (Higuera *et al* 2007) were extracted from CHAR series using CharAnalysis v1.1 software (Higuera *et al* 2010a) available at https://sites.google.com/site/charanalysis/ (appendix B). The local fire frequency was calculated using the 'paleofire' R package (Blarquez *et al* 2014). The *RegFF* for each region was constructed by pooling individual lake smoothed series (Ali *et al* 2012, Kelly *et al* 2013). We assessed the significance of changes in both *RegFF* and *RegBB* by bootstrap resampling the pooled means 999 times (BCI; 90%).

For each region, we used the ratio between *RegBB* and *RegFF* (hereafter *FS index*; Ali *et al* 2012) to assess changes in fire size through time. The significance of changes in the *FS index* was derived from ratios between maximum and minimum values of *RegBB* and *RegFF*. The *RegBB* values are correlated to long-term changes in areas burned inferred from fire histories (Higuera *et al* 2010b, Ali *et al* 2012, Kelly *et al* 2013). Thus, we consider fire size to be related to the temporal trajectory of mean biomass burned per fire (*RegBB*), and modulated by the number of fires through time (*RegFF*). *FS index* values are indicative of mean areas burned per fire.

2.3. Climate data

We applied the method developed by (Hély *et al* 2010) to climate simulations from the UK Universities Global Atmospheric Modeling Program GCM (hereafter HadCM3; Hall and Valdes 1997) to compute the fire-season length centered on each millennium over the last 7000 years (Singarayer and Valdes 2010) in each region. For each millennium of HadCM3 dataset, we computed the twelve monthly temperature and precipitation anomalies as compared to those from the HadCM3 pre-industrial control (i.e. 1750 AD). To obtain spatial resolution more compatible with our palaeodata, we downscaled these Holocene datasets at 0.5° by applying HadCM3 temperature and precipitation anomalies to the modern 1971–2000 climate normals computed from the Climate Research Unit spatial grid TS 2.1 (Time Series at 0.5°; Mitchell and Jones 2005). Then, within each 0.5° pixel, we used the

Gaussian distribution for temperature and the Gamma distribution for precipitation (New *et al* 2002) to reconstruct 30 year time series in which each specific monthly distribution was parameterized with the reconstructed downscaled monthly mean and the modern variance computed from the 1971–2000 climate normals (Ramstein *et al* 2007). The weather generator presented by (Richardson 1981) was applied to the reconstructed 30 year monthly temperature and precipitation time-series to derive the daily values needed to compute the Drought Code index (hereafter DC index) of the Canadian Forest Fire Weather Index System (FWI; Van Wagner 1987). The DC index relates to deep humus dryness and is used to assess fire risks based on weather conditions with a 52 d lag (De Groot *et al* 2007). According to Hély *et al* (2010), the DC values computed from Canadian weather data (1981–2010) starts to be higher than 80 units in June in eastern North America when spring fires began to occur. Consequently, we calculated the fire-season length based on the cumulative number of days in months with mean DC index value >80 units, to which is added the number of days for the fire-season onset and termination computed as the number of days with DC value >80 units preceding and following the first or the last month with monthly mean DC value >80 units, respectively, based on interpolations of monthly mean DC values (Hély *et al* 2010). Spring fire onset (April-June), summer fire termination (July–October) and hence fire season length in spring, summer and over the year (spring and summer) were determined. The regional simulated climate and fire-season length datasets, expressed as anomalies relative to the control period (0 BP), represent average conditions computed from the three nearest 0.5° pixels to each sampled lake within the western, central and eastern regions of the study area.

Correlations between the reconstructed climate outputs and *RegBB*, *RegFF* or the *FS index* were computed using Pearson's correlation coefficients and assessing their significance using permutation tests (Robinson 2007).

3. Results

3.1. Fire histories

The Holocene *RegFF* and *RegBB* series for the western and central regions displayed the same trends, with fire occurrence peaking around 4000 BP and biomass burning peaking between 5000 and 3000 BP (figure 2). The *RegFF* gradually increased from *ca.* four or five fires per millennium at 7000 BP to approximately six per millennium at 4000 BP. It then decreased below *ca.* three fires per millennium around 2500 BP, before slightly increasing again to present values, close to those recorded during the early-Holocene period. Similarly, *RegBB* gradually increased from 0 at 7000 BP to 0.6 between 5000 and 3000 BP in the western region

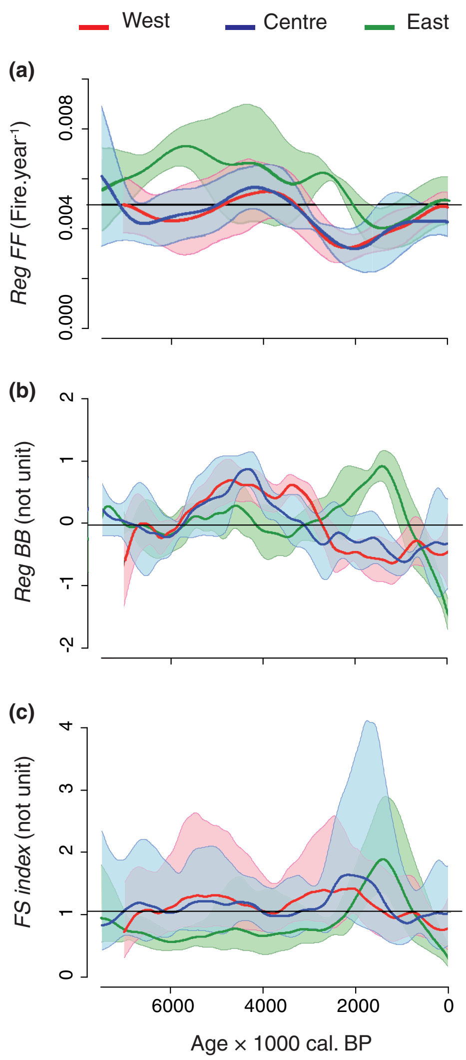

Figure 2. Reconstructed fire regime histories based on the analysis of lacustrine charcoal deposits for the western, central and eastern regions of the study area. (*a*) Fire frequency (*RegFF*), (*b*) Biomass burning (*RegBB*) and (*c*) Fire size (*Fire size index*) calculated for the 500 year bandwidth. The colored areas indicate 90% bootstrap confidence intervals. The black lines indicate the means of *RegBB*, *RegFF* and *FS index* throughout the last 8400 years in the three regions.

and to 0.9 in the central region around 4000 BP, before decreasing to present values, mostly lower than 0. In both of these areas, the *FS index* values oscillated around 1 before 3000 BP, then rose to 1.4 and 1.6 in the western and central regions, respectively, at *ca.* 2000 BP before decreasing back close to 1 until the present day. The derived *RegFF, RegBB* and *FS index* dynamics through the last 7000 years are independent of changes in sedimentation rates (appendix D).

In the eastern region, the reconstructions indicated that fire occurrence peaked between 6000 and 2500 BP, whereas biomass burning peaked around 1500 BP (figure 2). *RegFF* increased gradually from approximately six fires per millennium at 7000 BP to *ca.* seven between 6000 and 2500 BP. Then, it decreased below four fires per millennium at 1500 BP before increasing again to present values, close to those recorded at 7000 BP. The *RegBB* value was equal to those in western and central regions at 7000 BP. It oscillated around 0 until 3000 BP and increased during the 3000–1500 BP period, reaching *ca.* 0.9 around 1500 BP. Then, it decreased rapidly to the present-day value, *ca.* 1.5; the lowest over the last 7000 years. *FS index* values of the eastern region stayed lower than 0.8 from 7000 to 2500 BP, and subsequently increased to *ca.* 1.9 at 1500 BP. This increase in *FS index* was not linked to a sudden increase in lacustrine sedimentation rates, but coincided with the largest peaks of charcoal area recorded in the three study lakes (appendix D). Finally, *FS index* values decreased to 0.3 at present-day.

3.2. Past climate

We have reconstructed Holocene climate data for eight periods centered on each millennium. Thus, although results are reported as temporal trends, climate data between two successive millennia must be interpreted with caution as there is no available data from this HadCM3 Holocene simulation experiment. During the last 7000 years, the fire-season length ranged between 164 and 175 d in the western studied region, and between 155 and 164 d in the central region (figure 3). In these regions, the fire-season started 2–3 d later in spring at 7000 BP than today. Between 6000 and 4000 BP, it began progressively earlier in spring and terminated earlier in summer-fall. During this period, the fire-season was slightly (two-three days) shorter than it is today. Then, between 3000 and 2000 BP, the fire-season extended in fall. At 2000 BP, the fire-seasons in the western and central regions were similar to the present-day seasons in terms of lengths (174 and 161 d, respectively) and time period in the year. However, the fire-season ended 8 and 4 d earlier in the two regions, respectively, and thus was markedly shorter at 1000 BP.

Overall, the fire-season in the eastern region was a third shorter (ranging from 105 to 135 d) than those of western and central regions during the Holocene (figure 3). At 7000 BP, the fire-season length was seven days shorter than today (*ca.* 130 d), mainly due to a later spring onset. The longest reconstructed fire-season was at 6000 BP, *ca.* 128 d, similar to the present-day length, and covering the same period in the year. Between 6000 and 4000 BP, the fire-season began progressively later and finished earlier. It was shortest at 4000 BP, when it began three days later and finished 12 d earlier than today. Then, between 3000 and 1000 BP the timings of fire-season length varied between 0–2 d later onset and 7–10 d earlier termination than today.

3.3. Fire-climate relationships

In the western and central regions, the *FS index* values were significantly higher during periods with warm springs and summers, and when the fire-season began early in spring (table 1). In the eastern region, the *FS index* values were not correlated with either spring or summer temperatures, and were significantly higher

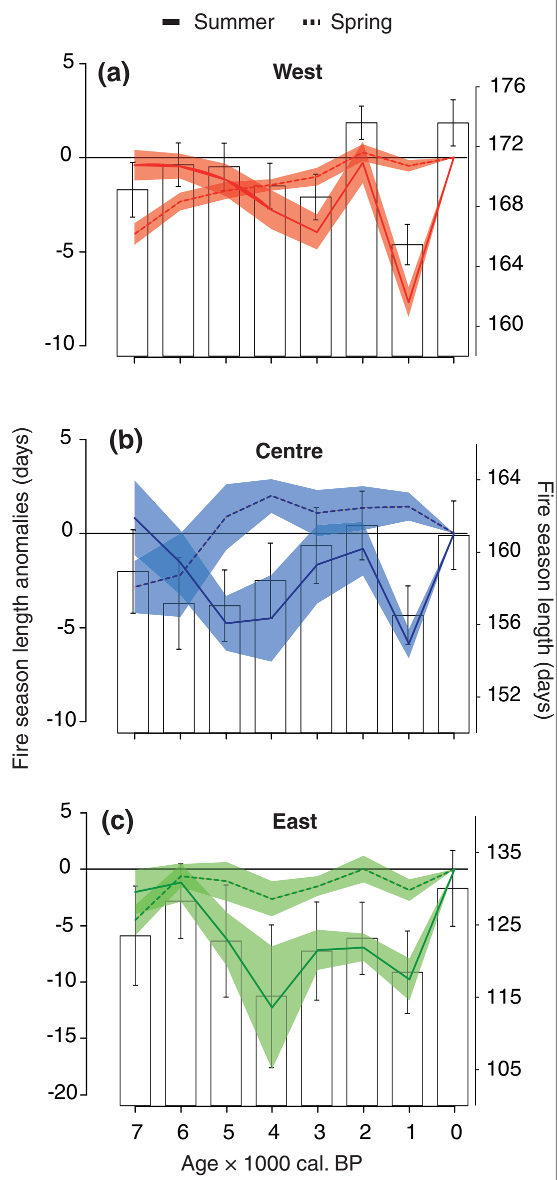

Figure 3. Fire season lengths (histograms with standard errors) based on numbers of days with simulated monthly daily Drought Code means higher than 80 (moderate wildfire risks). Holocene departure (in number of days, anomalies relative to 0 BP) of fire-season start (spring from April to June) and end (summer from July to October) are indicated by dashed and solid lines, respectively.

during periods when fire-seasons ended relatively early in fall. In the western and eastern parts, *FS index* values were significantly higher during moist periods.

4. Discussion

Our findings clearly show that fire histories during the last 7000 years were similar in the western and central regions, but differed in the eastern region (figure 2). These results suggest that fire regime in oceanic region (east) was driven by different climatic factors than in continental regions (west and centre). Three main chronological periods can be distinguished in the fire size dynamics during this period: 7000 to 3000 BP, when there were larger fires in the west and center than

Table 1. Pearson's correlation coefficients between past fire size and main climatic variables, fire occurrence and biomass burning for the three regions. Fire season is split into two periods: 'spring' from April to June and 'summer' from July to October. Significant correlation coefficients are marked in boldface type and asterisks indicate P values ($^{*}P < 0.1$, $^{**}P < 0.05$, $^{***}P < 0.01$) determined by permutation tests (sample size: $n = 8$ millennia).

		West	Centre	East
Temperature	Spring	**0.316*****	**0.416*****	0.099
	Summer	**0.560*****	**0.216*****	0.047
	spring and summer	**0.797*****	**0.499*****	0.113
Precipitation	Spring	**0.633*****	0.161	0.086
	Summer	**0.530*****	0.091	**0.764*****
	spring and summer	**0 642*****	0 02	**0 637*****
Fire season length	Spring	**0 174***	**0 228****	−0 031
	Summer	−0 037	**0 236****	**−0 504*****
	spring and summer	0 067	**0 516*****	**−0 461*****
RegBB		0 318	0 036	**0 836****
RegFF		−0 401	−0 65	**−0 832***

in the east; 3000 to 1000 BP, when the largest fires were recorded in all three regions; and the last 1000 years, when fires were again larger in the west and center than in the east. Detected regional climatic effects on the fire regimes during these three periods are discussed below.

4.1. 7000–3000 BP

Between 7000 and 3000 BP, fires were mostly larger in the western and central regions than in the eastern one (figure 2), probably partly because the fire-seasons were longer and drier (figure 3 and appendix E). Other influential factors presumably included the flatter relief and dominance of more fire-prone conifers (which favor the spread of fires), notably *Pinus banksiana* Lamb., in the western and central regions than in the eastern region (Hély *et al* 2001, Blarquez and Aleman 2015, Remy *et al* 2016). In the eastern region, fires were smaller but more frequent, possibly due to the more pronounced variations in relief, which reportedly increased lightning frequencies (Foster 1983, Reap 1986). The environmental conditions were more favorable for fire ignition and frequency in the eastern region before 5000 BP.

High fire frequency and biomass burning during the Holocene were significantly associated with warm and/or dry summers, but cold springs (appendix C). In the western and central regions, fire frequency and biomass burning both peaked during the mid- to late Holocene period (between 5000-3000 BP) without any increase in fire size (figure 2). According to paleoclimate reconstructions based on pollen data and the modern analog technique, this period corresponds to the Holocene Thermal Maximum, characterized by warm and dry conditions in northern Quebec (Viau and Gajewski 2009) and in various other locations across North America (Bartlein *et al* 1998, Viau *et al* 2006). The simulated climate data used here confirm this climatic scenario in spring with a gradual increase of temperature and DC relative to before, but not in summer (appendix E and F). We therefore assume that between 5000 and 3000 BP higher precipitation and temperature during spring led to increases in combustible biomass (appendix F). We conclude that series of consecutive days in spring and summer may often have been warm enough to favor fire ignition and spread, but fuel dried insufficiently for fires to spread over large areas, as the springs would have been generally too cool and the fire-seasons in summer too brief (table 1, figure 3; appendix E) (Ali *et al* 2012).

4.2. 3000–1000 BP

The decrease in fire frequency between 3000 and 1000 BP (figure 2) has been already observed by other studies in northern boreal forests and previously attributed to a cooler and wetter annual climate corresponding to the Neoglacial period (Gavin *et al* 2006, Ali *et al* 2009, 2012, Oris *et al* 2014, El-Guellab *et al* 2015). It has also been putatively linked to an abrupt decrease in solar activity around 2900–2800 BP (van Geel *et al* 2000, Wanner *et al* 2008). However, the largest fires were recorded in all regions of the study area during this period (figure 2), more specifically around 2500–2000 BP in the western and central regions, and around 1500 BP in the eastern region.

In the western and central regions, large fires were significantly dependent upon warmer springs and summers, relative to those in the preceding period (figure 3; appendix F), and upon the abundance of fire-prone coniferous species such as *Picea* sp. (mainly *Picea mariana*) and *Pinus banksiana* (Blarquez and Aleman 2015, Remy *et al* 2016). These findings are similar to conclusions from previous studies on boreal forests of North America (Balshi *et al* 2009, Turetsky *et al* 2011, Ali *et al* 2012, Blarquez *et al* 2015). However, such large fires in the western region occurred despite an increase in precipitation during the fire-season (table 1, appendix F). Intra-seasonal variations in precipitation distribution coupled with warm springs and summers may explain the low impact of precipitation on fire size (Ali *et al* 2012). We suggest that, like today, weather patterns creating long-lasting blocking events of high-pressure ridges inducing droughts lasting several days to several weeks during the fire-season (Harrington and Flannigan 1987, Flannigan and Harrington 1988, Skinner *et al* 1999, Girardin *et al* 2006) could have favored the occurrence of large fires during the course of fire-seasons.

In the eastern region, the largest fires during the whole 7000 year s study period (and the highest increase in fire size in any part of the study zone) occurred between *ca.* 2000 and 1000 BP (figure 2), contributing to an increase in the abundance of *Pinus banksiana* in regional vegetation (Remy *et al* 2016). The fire frequency was approximately as low as that recorded around 2500 BP in western and central regions, but the biomass burning was substantially higher (figure 2). In addition, fires were not significantly linked to the same climatic conditions that induced large wildfires in other regions (table 1 and appendix F). More specifically, warm and/or dry springs and summers do not seem to have triggered these large wildfires. However, reconstructions of past water table levels in ombrotrophic peatlands based on testate amoeba communities analysis indicate there was high interannual to interdecadal hydrological variability (precipitation *versus* evapotranspiration) between 2500 and 1500 BP in the eastern region (appendix G; Magnan and Garneau 2014). To limit uncertainties associated with autogenic influences of peatlands on water table depth results, these paleoclimate data reconstructions correspond to means recorded from four sites (two batches of two sites distanced by 450 km) and pooled into 500 year bins. This epoch between 2500 and 1500 BP corresponds to the Roman Warm Period in Eurasia and to high moisture shifts recorded in Greenland and North America, although the nature and causes of those are not yet clearly understood, especially in North America (Seidenkrantz *et al* 2007, Holmquist *et al* 2016). Such hydrological variability cannot be captured and confirmed (or refuted) with the available HadCM3 climate data due to the 'snapshot' format of these simulated data, causing an absence of information between each millennia. However, it could at least partially explain the reconstructed fire regime, as it could have resulted in series of moist years favorable to fine fuel production interspersed by one or several drier years with relatively low precipitation and/or very high temperature and/or strong winds, all of which cause high evapotranspiration (Li *et al* 2000) and thereby inducing few but large wildfires (Zumbrunnen *et al* 2008, appendix D). Palaeohydrological reconstructions in ombrotrophic peatlands in the western region (based on means results of three sites situated on a *ca.* 10 km radius) indicate there was less variability in the atmospheric moisture balance between 3000 and 1000 BP (period of largest fires in western and central regions) than in the eastern region (appendix G; van Bellen *et al* 2011). Thus, large wildfires in the western and central regions seem to have been mainly induced by high temperatures in spring and summer coupled with intra-seasonal variability in precipitation, while high interannual to interdecadal variability in precipitation may have been the major climatic driver of the development of large wildfire events in the eastern region. The latter hypothesis is corroborated by the eastern region's uneven topography, which favors fire ignition in dryness zones (mostly altitudinal tops and south slopes; Romme and Knight 1981, Parisien and Moritz 2009) but limits the spread of fire over large areas, implying that conditions were sometimes dry over large areas, as currently observed during some fire years in others regions (Kasischke *et al* 2002, Stocks *et al* 2003).

4.3. 1000 BP to present-day

During the last 1000 years, the fire regimes of the three regions became similar (in terms of fire frequency, size, and biomass burning) to those recorded just after the deglaciation, with frequent but relatively small fires (figure 2). This change was likely caused by a slight shift of the fire-season timeframe towards earlier termination around 1000 BP, but without high intra-seasonal or interannual variations in precipitation (figure 3 and appendix E). This stable climatic pattern would have led to more years with optimal conditions for fire ignition, but also more frequent rainfall during the entire fire-season, which would have inhibited fire spread and, to some degree, efficient fire ignition.

Current regional fire-season lengths are similar (in the western and central regions) or longer (in the eastern region) than those recorded during the period of large wildfire events (figure 3), mainly due to a reduction in summer precipitation (appendix F). However, no significant changes in the fire regime were recorded during the last 1000 years (figure 2). In the western and central regions, the fire-season may have only begun to lengthen since the industrial era, but this possibility cannot be evaluated because the control period, which is the pre-industrial period, has been assumed to be equivalent to the modern period (1971–2000) in our simulations. Another possibility is that the lower summer temperatures which prevailed during the last 1000 years, according to our simulations, decreased the fire size, independently of the reduction in precipitation (appendix F), by limiting evapotranspiration late in the fire-season, and thus restricting the development of large wildfire events. This possibility is supported by pollen-based climate reconstructions in eastern North America indicating that summer temperatures have declined continuously, although not progressively, since ca. 1000 BP (Viau *et al* 2012). However, in the eastern region, temperatures during the fire season, which was cooler than in other regions during all of the Holocene periods, do not seems to have affected fire sizes (table 1). Consequently, the less frequent dry years due to a decrease in interannual hydrological variability since 1000 BP seems to be the best explanation for the rarity of large fire events in the eastern region, despite a decrease in summer precipitation in this region during this period (appendix G).

5. Conclusion

The largest fires recorded in boreal forests of eastern Canada during the last 7000 years occurred between 3000 and 1000 BP, but their causes varied spatially. In continental regions, warm summers and early fire-season onsets seem to have provided optimal conditions for large wildfires, as already shown by Ali *et al* (2012). However, closer to the Atlantic coast, large wildfires occurred during periods of high variability in atmospheric moisture balance, independently of temperatures over the entire fire-season. Thus, climatic variables that have most strongly influenced fire size differed between continental and oceanic regions. The predicted climatic changes for the next decades across eastern Canada seem to include trends towards both sets of conditions (warmer summers and increases in interannual precipitation-evaporation variability) that promote large fires (Bergeron *et al* 2010, Seager *et al* 2012, IPCC 2014). Thus, their frequency seems likely to increase. Focusing on climate conditions during the large-fire period from 3000 to 1000 BP with higher temporal resolution data and better understanding of associated atmospheric circulation patterns could help efforts to predict consequences of future climate changes on sizes and frequencies of fires in boreal forests more robustly.

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