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# Long-term fire history in northern Quebec: implications for the northern limit of commercial forests

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## Summary

**1.** Fire frequency is expected to increase in boreal forests over the next century owing to climate change. In Quebec (Canada), the location of the northern limit of commercial forests (*c.* 51 °N) was established in 2000 taking into account mainly forest productivity and fire risk. The location of the limit is currently under debate and is being re-evaluated based on a more extensive survey of the territory. We characterized the natural variability of fire occurrence (FO) in the area surrounding the northern limit, and these results are a useful contribution to discussions on the re-evaluation of its location.

**2.** Regional FO over the last 7000 years was reconstructed from sedimentary charcoal records from 11 lakes located in three regions surrounding the northern limit (i.e. south, north and near the limit). Holocene simulated precipitation and temperature from a general circulation model (GCM) were used to identify the long-term interactions between climate and fire.

**3.** Fire histories displayed similar trends in all three regions, with FO increasing from 7000 calibrated years before present (cal. years BP) to reach a maximum at 4000–3000 cal. years BP, before decreasing during the late-Holocene. This trend matches the simulated changes in climate, characterized by drier and warmer conditions between 7000 and 3500 cal. years BP and cooler and moister conditions between 3500 and 0 cal. years BP.

**4.** Northern ecosystems displayed higher sensitivity to climate change. The natural variability of FO was narrower in the southern region compared with the limit and northern regions. An abrupt decrease in FO was recorded close to and north of the limit at 3000 cal. years BP, whereas the decrease was more gradual in the south.

**5.** *Synthesis and applications*. We reconstructed the natural variability in fire activity over the last 7000 years near the current location of the northern limit of commercial forests in Quebec. Fire occurrences were more sensitive to climate change near to and north of the limit of commercial forestry. In the context of predicted increase in fire activity, the lower resilience of northern forests advocates against a northern repositioning of the limit of commercial forests.

**Key-words:** boreal forest, climate change, fire–climate interaction, Holocene, natural range of variability, northern forests, palaeoecology, sustainable forest management

## Introduction

Since the United Nations Conference on Environment and Development (UNCED) in 1992, many forestry policies focused on sustainable forest management (SFM) have been proposed, such as forest certification (Stupak *et al.* 2011; Rist & Moen 2013). Sustainability requires some minimum conditions to be fulfilled, among which are minimum forest productivity and regeneration capacity. Forests need to be resilient, that is, to regenerate after

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natural or anthropogenic disturbances in such a way that stand density and productivity are comparable to pre-disturbance conditions. As boreal ecosystems are characterized by limited growing conditions and regular natural disturbances (Kneeshaw, Bergeron & Kuuluvainen 2011), adding anthropogenic disturbances may decrease resilience and create unsustainable conditions (Dussart & Payette 2002; Payette & Delwaide 2003).

In this context, since 2000, the northern limit of commercial forests in Quebec (Canada) has been established around 51 °N in the black spruce *Picea mariana* feather moss bioclimatic domain. This limit was mainly determined by taking into account the economic value of forests according to their productivity and fire cycle (MRNF 2000). North of the limit, productivity was deemed too low and fire cycles too short (<150 years) to allow for sustainable wood harvesting (MRNF 2000). The density of the boreal forest cover progressively decreases with increasing latitude and gives way to lichen woodlands beyond 52 °N. The fire cycle is shorter near the limit of commercial forests (*c.* 100 years) (Mansuy *et al.* 2010) than further south in the boreal forest (*c.* 360 years) (Bergeron *et al.* 2004), because climatic conditions, including recurrent blocking of air masses in the troposphere close to the limit of commercial forests (Skinner *et al.* 2002; Girardin *et al.* 2006), decrease surface fuel moisture and promote the occurrence of large wildfires (Johnson & Wowchuk 1993).

Over the last 50 years, 9% of the area occupied by closed-canopy spruce–moss forests in boreal Quebec has shifted to open lichen woodlands because of successive fires (Girard, Payette & Gagnon 2008). When the interval between successive fires is too short, black spruce trees do not have time to reach sexual maturity, as seed production usually begins after 30 years (Viglas, Brown & Johnstone 2013). Moreover, 50–150 years are needed before enough seedlings are produced to restock northern black spruce forests after fire (Viglas, Brown & Johnstone 2013). Climate change is likely to cause fire frequency to increase in Quebec's boreal forest (Bergeron *et al.* 2010), and thus, regeneration failure following successive fires could become more common. Therefore, the current location of the northern limit of commercial forests might be put into question with regard to the potential lack of resilience of the northern boreal forest under climate change.

Natural ecosystems have evolved within ranges of conditions that can serve as references to assess the current ecological integrity of managed ecosystems and maintain their resilience (Landres, Morgan & Swanson 1999). As wildfire is the main disturbance controlling terrestrial boreal ecosystem functioning (Payette 1992), ecosystem-based forest management needs to be based on natural fire regimes (Bergeron *et al.* 2002). It has been suggested that management should not push forest ecosystems outside their natural range of variability (Bergeron *et al.* 2002; Cyr *et al.* 2009).

To assess the long-term stability of the current northern limit of commercial forests and its sensitivity to predicted increased fire activity, we investigated the long-term natural variability of the fire regime. More specifically, we compared fire histories recorded in the sediments of six lakes located near and north of the northern limit of commercial forests with similar data from five previously published records from lakes located further south in the boreal forest (Ali, Carcaillet & Bergeron 2009; Hély *et al.* 2010; Ali *et al.* 2012). Because northern ecosystems are known to change more rapidly under climate modifications (Payette, Fortin & Gamache 2001; Thuiller, Lavorel & Araújo 2005; Alsos *et al.* 2012), we expected that forests north of 51 °N would be more sensitive to climate change with, for instance, delayed, earlier or more abrupt decreases in fire occurrence observed north compared with south of 51 °N. We compared predicted fire frequencies (Bergeron *et al.* 2010) with the long-term Holocene variability to evaluate whether future wildfire activity could exceed the natural range of variability.

## Material and methods

### STUDY AREA

We examined the climate–fire relationship north, near and south of the northern limit of commercial forests in the James Bay Lowlands of northern Quebec (Canada) (Fig. 1). Eleven lakes were sampled along a vegetation gradient that extended from the black spruce – feather moss bioclimatic domain in the south to the spruce – lichen woodlands in the north. Four lakes were located north of the limit of commercial forests, five lakes were south of it, and two lakes were close to the limit. Dominant tree species along the transect were black spruce and jack pine *Pinus banksiana*. Climate averages recorded from the closest meteorological stations to the southern lakes [Matagami, 49°46′N, 77°49′W; 281 m above sea level (a.s.l.)] and to the northern lakes (La Grande Rivière, 53°38′N, 77°42′W; 194 m a.s.l.) are $-0{\cdot}7 \pm 2{\cdot}7$ °C and $-3{\cdot}1 \pm 1{\cdot}9$ °C (mean ± SE), respectively, for annual temperature. Annual precipitation averaged 905 in the south and 684 mm in the north, with 38% and 36% falling as snow, respectively (Series 1971–2000; Environment Canada 2011).

### SEDIMENT SAMPLING

Lacustrine sediment cores were extracted between March 2007 and March 2011 using a Livingstone corer, except for Lake Pessière where a Mackereth corer was used. The water–sediment interface was collected using a Kajak–Brinkhurst gravity corer, except for Lake Marie-Eve [named L-40 in Ferland *et al.* (2012)]. Sedimentary sequences from the five southernmost lakes have already been published (Carcaillet *et al.* 2001; Ali, Carcaillet & Bergeron 2009; Hély *et al.* 2010). All sequences were composed of gyttja, and their lengths ranged from 100 cm (Lake Garot) to 600 cm (Lake Geais) (Table 1).

Sediment accumulation chronologies were obtained from radiocarbon measurements of terrestrial plant macroremains and gyttja samples (see Table S1 in Supporting Information). The $^{14}C$ dates were calibrated using the CALIB program (Stuiver & Reimer 1993) based on the IntCal04 data set (Reimer *et al.* 2004). The age–depth models (see Fig. S1) were obtained using the

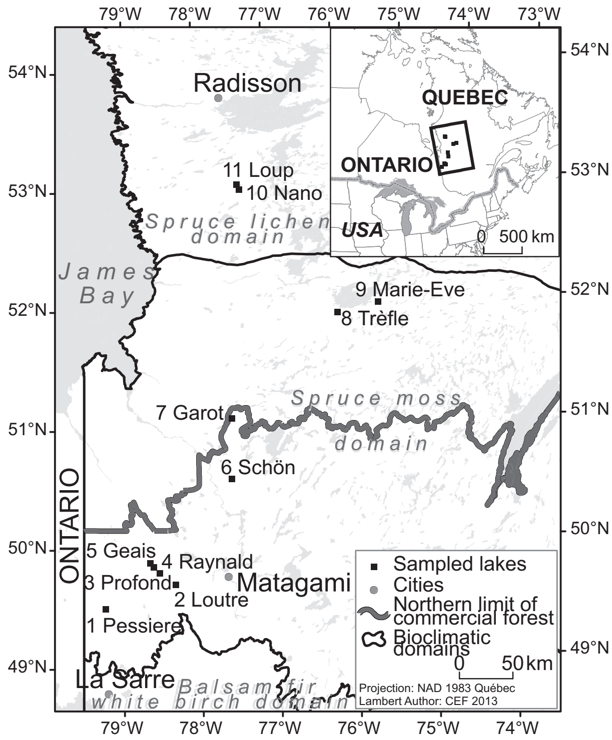


**Fig. 1.** Location of the study sites in northern Quebec.

MCAgeDepth program (Higuera 2008), which applies a Monte Carlo resampling technique to assess median ages and to generate confidence intervals around the fit, based on the probability distribution of each date that was provided by the CALIB program.

Three age–depth models displayed substantial sediment accumulation (*c.* 50 cm) over short periods of time (*c.* 100 years) (Fig. S1). This could be explained by peat and/or soil erosion from the shores into the lakes caused by major flooding events that have been observed elsewhere in boreal and subarctic Quebec (Payette & Delwaide 2004; Asselin & Payette 2006; Ali *et al.* 2008). Rapid changes in sedimentation accumulation rates represent an impairment of accurate charcoal analysis (Higuera *et al.* 2010), therefore sections of the cores showing disruptions in sediment accumulation were not used in the analyses.

### CHARCOAL QUANTIFICATION

To obtain fine-scale temporal resolution, sedimentary sequences were cut into 0·5- to 1-cm-thick slices, depending on total sequence length. Sediment samples (1 $cm^3$) taken from each slice were heated for 24 h in an aqueous 3 % $(NaPO_3)_6$ solution to facilitate deflocculation and then sieved through a 150-μm mesh. Peaks in charcoal particles larger than 150 μm were likely to represent local fire events (Higuera *et al.* 2007). Sieved samples were immersed in an aqueous 10% NaOCl solution to ease distinction of charcoal from bleached organic matter. The calculation of the number and size of charcoal particles was performed under a binocular microscope (×40) equipped with a camera and connected to a computer with image analysis software (WinSeedle 2009, Regent Instruments Canada Inc.). Charcoal area was transformed to a charcoal accumulation rate (CHAR; $mm^2\ cm^{-2}\ year^{-1}$) using the age–depth models.

### FIRE-HISTORY RECONSTRUCTIONS

Fire-history reconstructions were performed with the CHARANALYSIS 1.1 program (Higuera *et al.* 2009, freely available at http://sites.google.com/site/charanalysis/ ). To remove bias induced by the different sedimentation rates (median sample resolution varied between 12 and 37 years, with a mean of 20 years), a constant resolution of 20 years was used to interpolate the CHAR series into $CHAR_{interpolated}$ series for further charcoal analyses. The $CHAR_{interpolated}$ series were then decomposed by removing the low-frequency background signals ($CHAR_{back}$), corresponding to variation in charcoal production, the sedimentation process, mixing and sampling, to obtain residual high-frequency series ($CHAR_{peak}$). Finally, the $CHAR_{peak}$ series were separated into two subpopulations, which are referred to as $CHAR_{noise}$ and $CHAR_{fire}$, using a Gaussian mixture model according to a locally defined threshold. Each $CHAR_{peak}$ that exceeded the 99th percentile threshold was considered a local fire episode. The signal-to-noise index (SNI; Kelly *et al.* 2011) and goodness-of-fit (GOF) were, respectively, used to evaluate the effectiveness of the discrimination between $CHAR_{fire}$ and $CHAR_{noise}$ and to assess peak detection accuracy by comparing the empirical and fitted noise distributions.

The $CHAR_{interpolated}$ series can be decomposed using several filtering methods (e.g. moving mode, moving median, moving average, lowess and robust lowess) and using various

**Table 1.** Main characteristics of the sampled lakes

| Region | Lake | Latitude | Longitude | Elevation (m a.s.l.) | Lake area (ha) | Water depth (m) | Core length (cm) | Mean deposition time ± SE (year $cm^{-1}$) |
|---|---|---|---|---|---|---|---|---|
| North | Loup | 53°03′18·1″ N | 77°24′01·9″ W | 206 | 1·6 | 3·0 | 106 | 69·0 ± 1·49 |
| | Nano | 53°01′25·5″ N | 77°21′51·3″ W | 206 | 0·4 | 3·2 | 140 | 54·0 ± 1·63 |
| | Marie-Eve | 52°01′47·4′′ N | 75°31′14·6′′ W | 296 | 16·5 | 8·7 | 290 | 24·0 ± 0·71 |
| | Trèfle | 51°57′54·7″ N | 76°04′52·0″ W | 270 | 6·8 | 5·4 | 150 | 48·0 ± 1·10 |
| Limit | Garot | 51°05′58·7″ N | 77°33′12·9″ W | 248 | 5·1 | 6·9 | 100 | 74·7 ± 3·00 |
| | Schön | 50°35′41·7′′ N | 77°34′06·1′′ W | 291 | 2·8 | 7·0 | 133 | 55·0 ± 0·12 |
| South | Geais | 49°53′32·2′′ N | 78°39′18·4′′ W | 280 | 3·6 | 10·2 | 603 | 13·2 ± 0·35 |
| | Profond | 49°51′40·1′′ N | 78°36′47·9′′ W | 270 | 0·6 | >20 | 223 | 18·3 ± 0·50 |
| | Raynald | 49°48′33·4′′ N | 78°32′09·0′′ W | 250 | 1·5 | 10·3 | 472 | 15·2 ± 0·30 |
| | Loutre | 49°42′42·1′′ N | 78°20′09·0′′ W | 274 | 2·1 | 10·6 | 227 | 36·6 ± 0·76 |
| | Pessière | 49°30′11·5″ N | 79°14′22·2″ W | 305 | 4·0 | 16·0 | 302 | 13·0 ± 0·11 |

smoothing-window widths. The choice is generally guided by maximizing the SNI and GOF. To obtain a robust fire reconstruction for each lake and to minimize potential bias related to the choice of a given filter, we used the method developed by Blarquez *et al.* (2013), which automatically produces several iterations of the numerical analysis, changing the filtering method and the smoothing-window width ($t = 100, 135, 170, \ldots,$ 1500 years). As a result, 205 reconstructions were obtained for each lake (41 smoothing-window widths x 5 filtering methods). A kernel density function (Mudelsee *et al.* 2004) was then applied to the 100 best reconstructions, that is, those with the greatest SNI and GOF, to calculate 100 fire occurrence (FO) scenarios for each lake. Finally, the median FO was calculated for each lake.

Regional fire occurrence (RegFO) was obtained by averaging the local median FO values for three regions: southern (49–50 °N), limit (*c.* 51 °N) and northern (52–53 °N). These were composed, respectively, of lakes 1–5, 6–7 and 8–11 (Fig. 1). Bootstrap confidence intervals (90%) were computed around the RegFO for each region, except for sites at the limit, which included only two lakes. A nonparametric Kruskal–Wallis test among 1000-year periods and Wilcoxon rank-sum tests among period pairs were used to identify significant changes in the RegFOs. The RegFOs were also inverted to estimate mean fire interval (MFI). To determine whether RegFOs of sites near the limit were more similar to those north or south of it, dissimilarity between RegFOs was calculated as one minus the samples' Spearman rank correlation between observations and used to conduct a hierarchical clustering.

### CLIMATE DATA

We applied the method developed by Hély *et al.* (2010) on climate simulations from the UK Universities Global Atmospheric Modelling Programme GCM (thereafter UGAMP) for each millennium throughout the Holocene (Hall & Valdes 1997; Singarayer & Valdes 2010). To increase the spatial resolution of the GCM simulation to ease comparison with our local proxy records, a downscaling method was used by applying the UGAMP temperature and precipitation anomalies to the Climate Research Unit climatology data set TS 2·1 with time series at 0·5° (Mitchell & Jones 2005). Within each 0·5° pixel, we used a normal distribution for temperature and a gamma distribution for precipitation (New *et al.* 2002) to obtain a 30-year time series where each specific monthly distribution was parameterized with the reconstructed monthly mean (Ramstein *et al.* 2007).

From climate simulations, the Drought Code (DC) index of the Canadian Forest Fire Weather Index System was calculated. The DC is a component of the Fire Weather Index (FWI; van Wagner 1987) that is used to assess fire risk based on weather conditions (de Groot *et al.* 2007). Richardson's weather generator (Richardson 1981) was applied to the simulated 30-year monthly temperature and precipitation time series to derive daily values needed to compute the DC.

A DC value of zero is indicative of water saturation, and values higher than 400 are indicative of extreme dryness that could result in deep burning of subsurface heavy fuels. We calculated the fire season length (FSL) under moderate fire danger, which is the cumulative number of days during the fire season with a DC value >80 units (Hély *et al.* 2010).

Departure from the mean Holocene FSL under moderate fire danger was also determined for spring (April–June) and summer (July–September). Simulated precipitation and temperature models are displayed as anomalies relative to the control period (0 cal. years BP) that was assumed to be representative of the present-day conditions. Climate averages used in this study came from a twelve-pixel grid corresponding to the area encompassing 70–80 ºW and 47–55 ºN. A Kruskal–Wallis test among 1000-year periods was also used to identify significant changes in the climate data.

## Results

### FIRE OCCURRENCE RECONSTRUCTIONS

The RegFOs displayed the same Holocene trend for all regions, with highest fire occurrence around 4000–3000 cal. years BP, relative to periods before and after (Fig. 2a,b,c) (see Fig. S2 for details of the 11 local FOs). The RegFO for the northern region gradually increased from *ca.* four fires per millennium at 7000 cal. years BP to *ca.* five fires per millennium at 4000 cal. years BP (Fig. 2a). It then significantly decreased to a low of *ca.* three fires per millennium around 2500 cal. years BP (Wilcoxon test, $Z = -8{\cdot}6673$, $P < 0{\cdot}0001$), before slightly increasing to present values close to those recorded 7000 cal. years BP. The RegFO near the commercial forest limit was stable at *ca.* four fires per millennium from 7000 to 5000 cal. years BP (Fig. 2b). It then increased to a maximum of *ca.* six fires per millennium around 3500 cal. years BP, before significantly decreasing to a low of *ca.* three fires per millennium around 1500 cal. years BP (Wilcoxon test, $Z = -16{\cdot}1420$, $P < 0{\cdot}0001$), and increasing again to present values close to those recorded at 7000 cal. years BP. The southern RegFO displayed relative stability between 7000 and 4000 cal. years BP at *ca.* five fires per millennium (Fig. 2c), before slightly increasing to a maximum of *ca.* six fires per millennium at 3000 cal. years BP. A significant decrease in RegFO subsequently occurred from 3000 cal. years BP to the present value of *ca.* four fires per millennium (Wilcoxon test, $Z = -10{\cdot}9447$, $P < 0{\cdot}0001$). The significant decrease in RegFO lasted 1500 years near or north of the limit of commercial forests, compared with 3000 years south of it.

Over the last 7000 years, median RegFOs were 4·4, 3·9 and 5·0 fires per millennium for the northern, limit and southern regions, respectively, and these values were significantly different (Kruskal–Wallis test, $H = 722{\cdot}57$, d.f. = 2, $P < 0{\cdot}0001$). RegFOs for all regions were higher than (or close to) the median until *c.* 3000 cal. years BP and lower afterwards. Using these periods [3000–0 and 7000–3000 cal. years BP] of relatively stable fire regimes, the conservative ranges of variability in RegFO are 3·9–4·8, 3·2–4·4 and 4·9–5·1 fires per millennium for the northern, limit and southern regions, respectively (Fig. 2d). These values correspond to MFI ranges of 256–208, 312–227 and 204–196 years for the northern, limit

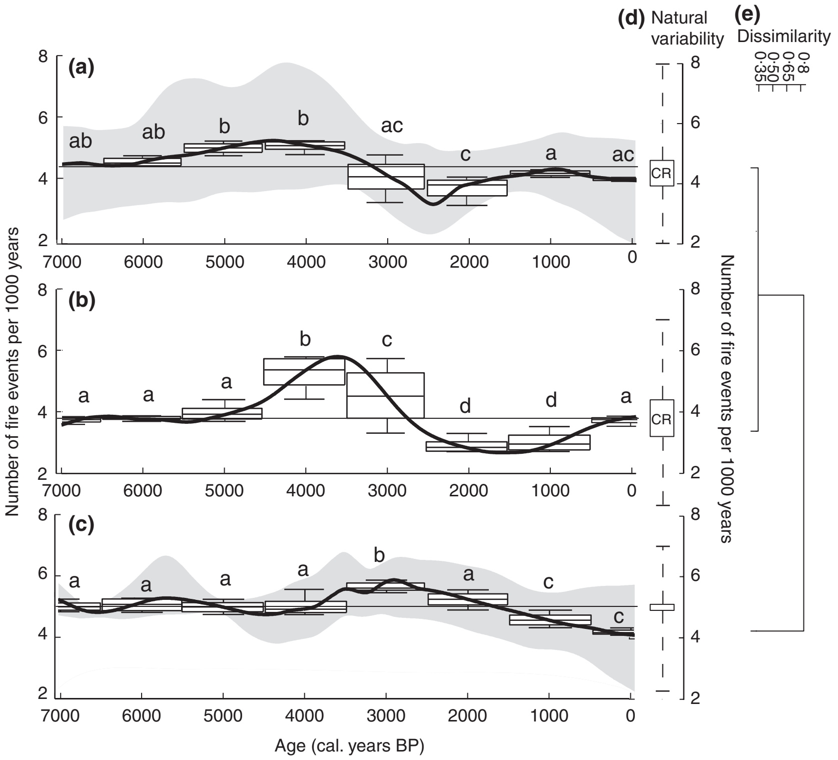


**Fig. 2.** Reconstructed fire occurrence based on the analysis of lacustrine charcoal deposits. RegFOs represent the average of median FOs from sampled lakes in the northern (a), limit (b) and southern (c) regions. Thick black lines correspond to smoothed values obtained using a LOWESS function (500-year window). Grey areas correspond to 90% bootstrap confidence intervals. The median value for each sequence is represented by a horizontal black line. Box-plots are shown for each millennium and significant differences between millennia are shown by different letters. Two ranges of natural variability in fire occurrence are presented (d). The conservative range (CR) corresponds to the range between mean RegFOs for the periods 3000–0 and 7000–3000 cal. years BP and is represented by a white box. The extended range corresponds to the minimal and maximal values of the 90% confidence interval for the northern and southern regions, and corresponds to the minimal and maximal values of all local FOs in the limit region over the last 7000 years. It is represented by dashed lines below and above the CR. Hierarchical clustering of the three regional fire histories based on dissimilarity coefficients is also shown (e).

and southern regions, respectively. The extended range of natural variability that corresponds to the minimal and maximal values of the 90% confidence interval for the northern and southern regions and to the minimal and maximal values of all local FOs in the limit region over the last 7000 years are 1·8–7·8, 1·5–7·0 and 1·8–7·0 fires per millennium for the northern, limit and southern regions, respectively. Hierarchical clustering based on dissimilarity indices established two groups of RegFOs: the northern and limit regions vs. the southern region (Fig. 2e).

### CLIMATE RECONSTRUCTION

Whereas summer temperature displayed relative stability, a gradual increase in spring temperature occurred from 7000 to 1000 cal. years BP (Fig. 3a). Temperature anomalies were positive from 7000 to 1000 cal. years BP in summer and from 3000 to 1000 cal. years BP in spring. A *c.* 0·7 °C decrease in annual and seasonal temperatures occurred between 1000 and 0 cal. years BP.

A general increase in precipitation anomalies occurred from 7000 to 1000 cal. years BP, before decreasing to present-day values (Fig. 3b). Summer precipitation anomalies were positive throughout the Holocene, whereas spring anomalies were negative between 7000 and 6000 and at 3000 cal. years BP.

The fire season length (FSL) was shorter between 5000 and 4000 cal. years BP and between 2000 and 1000 cal. years BP (Fig. 3c). The longest FSL was recorded at 7000–6000 cal. years BP and significantly differed from the minimum value reached at 1000 cal. years BP (Kruskal–Wallis test, $H = 29{\cdot}11$, d.f. = 7, $P = 0{\cdot}0001$). A slight, although not significant, increase in FSL occurred between 4000 and 3000 cal. years BP. FSL anomalies in spring and summer displayed the same trend during the Holocene (Fig. 3c), although spring anomalies were always lower than summer anomalies.

## Discussion

### CLIMATE FORCING ON FIRE OCCURRENCES

RegFOs peaked in the mid-Holocene (4000–3000 cal. years BP), subsequently decreasing during the late-Holocene in all regions. Peatland fires in northern Quebec also have indicated a late-Holocene decrease in frequency (van

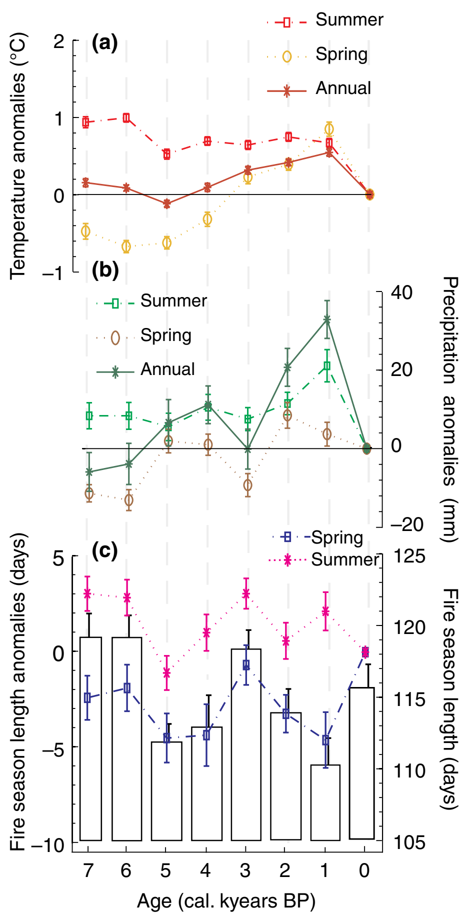


**Fig. 3.** Simulated annual and seasonal temperature (a) and precipitation (b) with standard error, obtained from the UGAMP model (anomalies relative to 0 cal. years BP) for the area encompassing 70–80 °W and 47–55 °N. Fire season length with standard error (c) over the last 7000 years assessed on the basis of the number of days with simulated monthly means of daily Drought Code higher than 80 (bars, scale on the right hand side). The lines correspond to fire season length anomalies in spring and summer (scale on the left hand side).

Bellen *et al.* 2012). These trends match the regional simulated long-term decrease in FSL over the last 7000 years (Fig. 3c). The decrease in FSL resulted from an increase in annual precipitation (Fig. 2b) together with a decrease in summer insolation (Hély *et al.* 2010; Ali *et al.* 2012). This Holocene climate corresponds to the July mean temperature and total annual precipitation reconstructions from pollen data for northern Quebec (50–70 °N, 65–80 °W) published by Viau & Gajewski (2009).

Maximum RegFO occurred earlier in the northern region than in the southern region (4000 vs. 3000 cal. years BP) (Fig. 2). Such a 1000-year time lag has already been observed between boreal mixedwood and coniferous forests (Carcaillet *et al.* 2001). It could be interpreted as earlier establishment of drought conditions in the north. However, no significant simulated climate change occurred at 4000 cal. years BP. Nevertheless, annual precipitation anomalies reconstructed from pollen data in northern Quebec (Viau & Gajewski 2009) suggest a period at 4000 cal. years BP that was drier than that exhibited in our simulations.

## VARIABILITY IN HOLOCENE FIRE ACTIVITY NORTH AND SOUTH OF THE NORTHERN LIMIT OF COMMERCIAL FORESTS

Over the last 7000 years, RegFO has been more variable north and near, than south of the northern limit of commercial forests. Higher variability in the northern region compared with the southern region underscores a greater sensitivity to climate. Moreover, whereas a gradual monotonous decrease in RegFO occurred between 3000 and 0 cal. years BP in the southern region, the shift towards lower RegFO was more rapid in the northern region, and it was followed by another shift to intermediate RegFO ca. 2000 cal. years BP (Fig. 2a,b). These last modifications in fire occurrence were not related to a significant change in simulated climate (Fig. 3), suggesting possible influence of other regional mechanisms. First, changes in the Pacific decadal oscillation and the mean position of the Arctic Front have previously been invoked as explanations for discrepancies in fire activity and tree-growth between the northern and southern regions in the last few centuries (Hofgaard, Tardif & Bergeron 1999; Le Goff *et al.* 2007). Although a decrease in fire activity in the southern region since *ca.* 3000 cal. years BP is likely to correspond to the Neoglacial period onset characterized by incursions of humid air masses from subtropical North Atlantic regions, northern sites could still be more strongly influenced by dry cold arctic air masses that favour fire ignition (Girardin *et al.* 2006). Secondly, changes in fire regimes could also lead to shifts in vegetation composition and structure, which could feedback on fire activity, thereby leading to a decrease in fire occurrence. Palynological investigations in the James Bay region, north of 53 °N, indicated an opening of the forest cover since the late-Holocene (Richard 1979; Asselin & Payette 2005). A possible explanation for this modification in forest structure could be the combined effect of higher fire occurrence and cooler climate, which would have inhibited post-fire regeneration (Payette *et al.* 1989). The inability of black spruce to regenerate under such environmental conditions could explain the transformation of some sites from spruce woodlands to lichen heath (Payette & Gagnon 1985; Asselin & Payette 2006). No such change in pollen-inferred vegetation history occurred in the southern studied region, where the forest cover seems more resilient to fire and climate changes than in the northern region (Carcaillet *et al.* 2001, 2010).

## IMPLICATIONS FOR THE LOCATION OF THE NORTHERN LIMIT OF COMMERCIAL FORESTS

A scientific committee was created in 2005 by the Quebec Ministry of Natural Resources to re-evaluate the location of the northern limit of commercial forests based on a more extensive survey of the territory (MRN 2013).

Simulations of future climate from GCMs with various forcing scenarios (Meehl *et al.* 2007) have indicated that a warmer climate is expected in the study area, with a mean summer temperature increase of 4 °C between 1961 and 1999 and 2081 and 2100. The pattern of future summer precipitation is not as clear, with predicted increases and decreases (between −18% and +11%). All scenarios simulated an increase in spring precipitation, ranging from 8 to 41% (Bergeron *et al.* 2010). Climate change in the boreal zone of northeastern North America could thus trigger fire weather conditions more favourable to forest fire in the summer but not necessarily in the spring (Le Goff, Flannigan & Bergeron 2009; Bergeron *et al.* 2010; Ali *et al.* 2012). A warmer climate would favour seed viability, leading to denser stands (Gamache & Payette 2005; Meunier, Sirois & Begin 2007). Nevertheless, seedling mortality is sensitive to episodic, prolonged and/or repeated drought (Moss & Hermanutz 2009), and forest recovery is slower during dry post-fire years or on dry surface deposits (Mansuy *et al.* 2012). The $CO_2$ fertilization effect would increase plant productivity until a concentration threshold (Amthor 1995), whereas the increased temperature effect on productivity is still debated (Way & Sage 2008; Girardin *et al.* 2012).

To determine whether the current location of the northern limit of commercial forests could be sustained in the future under the ongoing climate change, we have presented the long-term natural variability of the fire regime, as it is increasingly used as a target to maintain resilience in managed forests (Landres, Morgan & Swanson 1999; Bergeron *et al.* 2002; Kuuluvainen 2002). The future mean fire interval inferred from the monthly drought code computed using GCM-scenario simulations is predicted to decrease from 500 to 222 years [95% confidence interval: 169, 313] by the end of the 21st century in the study area (Bergeron *et al.* 2010). This estimate lies within the natural range of variability of fire occurrence that has been recorded over the last 7000 years in all regions (Fig. 2d). However, higher fire occurrence in the northern region between 4000 and 3000 cal. years BP was followed by forest opening (Richard 1979; Arseneault & Sirois 2004; Asselin & Payette 2005), implying that northern forests are more sensitive to climate change and fire disturbance. Despite a potential global increase in productivity due to both $CO_2$ fertilization and warmer and longer growing season, landscape opening will likely continue in northern forests, even if future fire occurrence does not exceed the natural range of variability. Adding logging to fire could exacerbate the opening phenomenon (Payette & Delwaide 2003). To prevent jeopardizing ecosystem integrity and thus the possibility of sustainable ecosystem management, the northern limit should remain in its current position. Moreover, the Holocene fire regime near the current limit was more comparable to that in the northern region than in the southern region, suggesting that mitigation strategies would be best targeted around 51 °N, including lengthening of harvest rotations and increasing fire protection measures (Mansuy, Gauthier & Bergeron 2013). Although formal limits to commercial forestry might not exist elsewhere in the boreal zone, the transition from closed-crown forests to open woodlands is a circumboreal phenomenon (Payette, Eronen & Jasinski 2002). Fire-history reconstructions along south–north gradients such as the present one could help determine the potential northern extent of forest harvesting activities in other boreal ecosystems.

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## Supporting Information

Additional Supporting Information may be found in the online version of this article.

**Fig. S1.** Age-depth models of the sampled lakes.

**Fig. S2.** Fire occurrence recorded in the sampled lakes.

**Table S1.** Radiocarbon dates from lake sediments in the regions north and close to the limit.