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Holocene variations of wildfire occurrence as a guide for sustainable management of the northeastern Canadian boreal forest

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Abstract

Background: Cumulative impacts of wildfires and forest harvesting can cause shifts from closed-crown forest to open woodland in boreal ecosystems. To lower the probability of occurrence of such catastrophic regime shifts, forest logging must decrease when fire frequency increases, so that the combined disturbance rate does not exceed the Holocene maximum. Knowing how climate warming will affect fire regimes is thus crucial to sustainably manage the forest. This study aimed to provide a guide to determine sustainable forest harvesting levels, by reconstructing the Holocene fire history at the northern limit of commercial forestry in Quebec using charcoal particles preserved in lake sediments.

Methods: Sediment cores were sampled from four lakes located close to the northern limit of commercial forestry in Quebec. The cores were sliced into consecutive 0.5 cm thick subsamples from which 1 cm^3 was extracted to count and measure charcoal particles larger than 150 microns. Age-depth models were obtained for each core based on accelerator mass spectroscopy (AMS) radiocarbon dates. Holocene fire histories were reconstructed by combining charcoal counts and age-depth models to obtain charcoal accumulation rates and, after statistical treatment, long-term trends in fire occurrence (expressed as number of fires per 1000 years).

Results: Fire occurrence varied between the four studied sites, but fires generally occurred more often during warm and dry periods of the Holocene, especially during the Holocene Thermal Maximum (7000–3500 cal. BP), when fire occurrence was twice as high as at present.

Conclusions: The current fire regime in the study area is still within the natural range of variability observed over the Holocene. However, climatic conditions comparable to the Holocene Thermal Maximum could be reached within the next few decades, thus substantially reducing the amount of wood available to the forest industry.

Keywords: Fire occurrence; Holocene; Boreal forest; Northern limit; Forest management

Background

The northern part of the boreal biome contains some of the largest remaining tracts of intact forest in the world (Bradshaw et al. 2009). However, forestry operations have expanded in a south-north fashion over the last few decades (Bouchard and Pothier 2011; Kivinen et al. 2012), and the cumulative impacts of natural disturbances and forest harvesting may affect the ecological integrity of boreal ecosystems. For example, closed-crown spruce-moss forests have shifted to open woodlands in eastern Canada under the combined action of wildfire and clearcut logging (Dussart and Payette 2002; Girard et al. 2008). To lower the probability of occurrence of such catastrophic ecosystem shifts, harvesting rate must decrease when fire frequency increases (Bergeron et al. 2006; Raulier et al. 2013), so that the total disturbance rate (harvesting + wildfire) does not exceed the maximum disturbance rate recorded during the Holocene.

Climate models predict a major rise in mean annual temperature across boreal regions, but only a slight – if any – precipitation increase (IPCC 2014). This could lead to dryer conditions, as higher evapotranspiration

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would offset the precipitation increase (Hély et al. 2010). Hence, forest fires will likely be more frequent and cover larger areas by the end of the 21st century (Goldammer 2013), meaning that the margin of manoeuvre for forestry operations will decrease.

In Quebec (eastern Canada), government authorities have established a northern limit to commercial forestry operations in the boreal forest (Jobidon et al. 2015). North of this limit, forest productivity is deemed too low, and fire frequency too high, to support a profitable forest industry. In a comparative study of Holocene fire regimes along a transect crossing the limit of commercial forestry, Oris et al. (2014b) noted that all regions were characterized by considerably higher fire occurrences during the Holocene Thermal Maximum (HTM; ca. 7000–3000 cal. years BP), followed by a sharp decrease in fire occurrence at the beginning of the Neoglacial period (ca. 3000 cal. years BP) in forests located close to and north of the limit, compared to a more gradual decrease south of the limit. They thus concluded that fire occurrence was more sensitive to climate change close to and north of the limit than further south. These regional patterns, however, hide important between-site variability (see Figure S2 in Oris et al. (2014b)), and additional studies are needed to verify if the same regional fire history can be reconstructed from other sites.

We used high-resolution charcoal analysis to reconstruct the Holocene variability of fire occurrence from 4 small lakes located near the northern limit of commercial forestry in Quebec, ca. 100–200 km east of the lakes studied by Oris et al. (2014b). As wildfire dynamics are mainly controlled by regional climatic patterns in boreal forests (Flannigan and Wotton 2001; Ali et al. 2009; Boulanger et al. 2013), we expected to find a regional fire history similar to that reported by Oris et al. (2014b), despite inter-site variability. Having a clear understanding of the Holocene regional variability in fire occurrence is mandatory to adjust forest harvesting levels so that the total disturbance rate does not exceed the Holocene maximum. We show that fire occurrence at the northern limit of commercial forestry in Quebec was higher during warm and dry periods of the Holocene. According to predictions, climate warming over the next few decades will increase fire occurrence close to the maximum values recorded during the Holocene, thus substantially reducing the margin of manoeuvre of the forest industry.

Methods

Study area

The study area is located within the western black spruce-moss bioclimatic subdomain (Saucier et al. 1998), in northern Quebec, 50–100 km north of Chibougamau (Fig. 1). Mean annual temperature is −0.4 °C and mean annual precipitation is 961.4 mm (Environment Canada 2011). The regional climate history displayed a general progression from a cool early Holocene (<7000 cal. BP) to a warm and dry middle Holocene (Holocene Thermal Maximum: 7000–3500 cal. BP) followed by a cool and wet Neoglacial period (>3500 cal. BP), briefly interrupted (around 1000 cal. BP) by a Medieval Warm Period (Viau and Gajewski 2009). Forests of this region have been dominated by black spruce (*Picea mariana* (Mill.) BSP) throughout the Holocene (Garralla and Gajewski 1992; Payette 1993).

Sampling

Four lakes were selected close to the northern limit of commercial forestry (Fig. 1). The lakes are within 100 km of each other and have similar characteristics: size (<4 ha), absence of inlet or outlet, elevation (376–432 m a.s.l.), water depth (500–571 cm), and local vegetation (dominated by black spruce). Lake sediment cores were sampled in March 2009 at the deepest point of each lake. The water-sediment interface was sampled using a Kajak-Brinkhurst (KB) gravity corer (Glew 1991), and a Livingstone corer was used to sample deeper sediments (Wright et al. 1984). The cores were sliced into consecutive 0.5 cm thick subsamples to maximize temporal resolution. Subsamples were stored in plastic bags in the refrigerator until analysis.

Charcoal quantification

A volume of 1 cm^3 was taken from each subsample and soaked in a 3 % sodium hexametaphosphate – $(NaPO_3)_6$ – dispersing solution for 48 h before sieving through a 150 microns mesh. The material remaining on the sieve was washed with a 10 % sodium hypochlorite (NaOCl) solution to whiten organic matter particles and facilitate distinction of charcoal particles. Charcoal particles larger than 150 microns were counted and measured (area) under a dissecting microscope (20 ×) equipped with a digital camera coupled to an image analysis software (Winseedle, Regent Instruments Inc., Canada). Charcoal particles larger than 150 microns are rarely carried more than 1 km from the fire and are usually assumed to represent local fires (Wein et al. 1987), although long-distance transport (>30 km) of such particles has been reported (Oris et al. 2014a). We nevertheless elected to work with charcoal particles larger than 150 microns to ease comparisons with Oris et al. (2014b).

Age-depth models

Radiocarbon dates were obtained by accelerator mass spectroscopy (AMS) performed on samples from different levels of the sedimentary profiles (Table 1). Macroremains were rare (except for Aurélie lake), and most dates were obtained from bulk sediments (gyttja). All

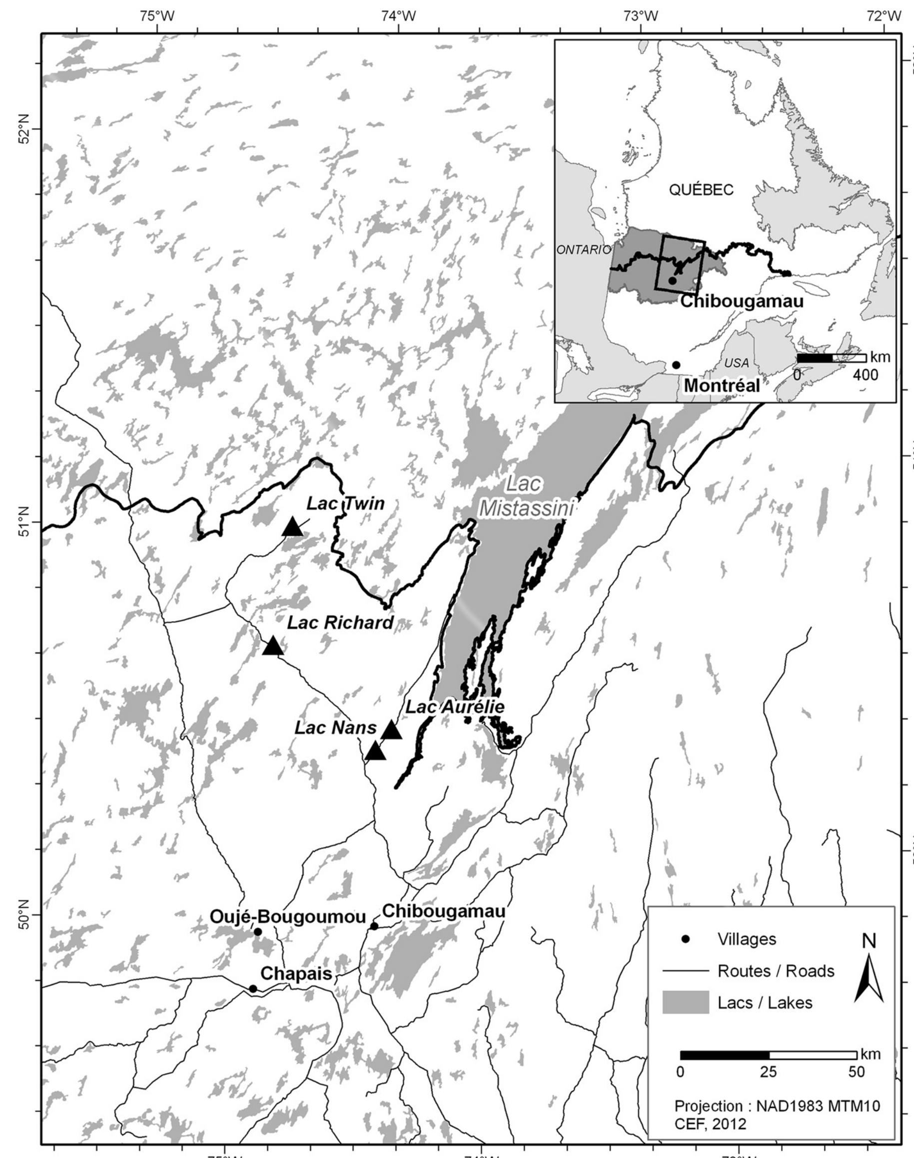

Fig. 1 Location of the 4 sampled lakes (triangles) at the northern limit of commercial forestry (thick black line). The dark gray area in the inset represents the western spruce-moss bioclimatic subdomain

dates were calibrated using the CALIB 6.0.1 program (http://calib.qub.ac.uk/calib/). Age-depth models were produced using MCAgeDepth software version 0.1 (Higuera et al. 2009; available for free at http://code.google.com/p/mcagedepth/) (Fig. 2).

Fire history reconstruction

Charcoal accumulation rates (CHAR) expressed in $mm^2 \cdot cm^{-2} \cdot yr^{-1}$ were calculated by multiplying charcoal concentration ($mm^2 \cdot cm^{-3}$) by sedimentation rate ($cm \cdot yr^{-1}$) for each subsample. To avoid possible influence of sedimentation variations within and between sites, a constant sedimentation rate (20 years, the average of the 4 lakes) was used to compare lakes and to compute the regional fire history (all lakes combined). Version 1.1. of the CharAnalysis software (Higuera et al. 2009; available for free at http://sites.google.com/site/charanalysis/) was used to remove background noise from the CHAR series with a LOWESS function. The remaining peak component was composed of two Gaussian subpopulations: (1) noise inherent to statistical analysis and part of the background noise that would not have been removed previously, and (2) fire peaks, each one representing the occurrence of one or more local fire events (Gavin et al. 2006). The noise subpopulation was removed from the fire peak subpopulation by applying a

Table 1 Radiocarbon dates at different depths in the 4 sediment profiles

Site and depth (cm)	Conventional radiocarbon age ^{14}C BP ± 2 σ	Median probability (range of calibration) cal. years BP	Dated material	Laboratory number
Aurélie Lake				
43–44	2870 ± 30	3007 (2879–3136)	Macroremains	Poz-35983
111–112	3990 ± 35	4443 (4319–4568)	Macroremains	Poz-35984
163–164	4750 ± 35	5457 (5329–5586)	Macroremains	Poz-36014
220–221	6140 ± 40	7047 6931–7163)	Macroremains	Poz-36016
236–237	6490 ± 40	7396 (7317–7476)	Macroremains	Poz-36017
326–327	7460 ± 50	8279 (8185–8373)	Macroremains	Poz-36018
Nans Lake				
20–25	1200 ± 40	1075 (1180–970)	Gyttja	Beta-275126
30–35	1820 ± 30	1675 (1740–1610)	Gyttja	Beta-298239
50–51	3290 ± 40	3480 (3570–3390)	Gyttja	Beta-267031
100–101	4040 ± 40	4555 (4560–4550)	Gyttja	Beta-267032
130–131	4630 ± 40	5420 (5460–5380)	Gyttja	Beta-298237
150–151	4040 ± 40	4490 (4570–4410)	Gyttja	Beta-267033
150–151	4720 ± 40	5555 (5570–5540)	Gyttja	Beta-298238
170–171	5230 ± 40	5950 (6000–5900)	Gyttja	Beta-267034
212–213	7800 ± 40	8505 (8600–8410)	Gyttja	Beta-267035
Richard Lake				
0–5	560 ± 30	510 (530–490)	Gyttja	Beta-293916
20–25	1220 ± 30	1075 (1170–980)	Gyttja	Beta-293917
80–81	3800 ± 30	2325 (4230–420)	Gyttja	Beta-293911
97–98	4870 ± 40	5535 (5600–5470)	Gyttja	Beta-293912
131–132	6770 ± 40	7520 (7580–7460)	Gyttja	Beta-293913
149–150	6820 ± 40	7585 (7620–7550)	Gyttja	Beta-293914
159–160	7560 ± 40	8265 (8350–8180)	Gyttja	Beta-293915
Twin Lake				
24–25	2415 ± 30	2436 (2357–2679)	Gyttja	SacA16557
54–55	3615 ± 30	3923 (3848–4056)	Gyttja	SacA16556
74–75	4105 ± 30	4625 (4480–4806)	Gyttja	SacA16555
94–95	4340 ± 30	4906 (4851–5019)	Gyttja	SaA16554
114–115	4435 ± 30	5028 (4892–5264)	Gyttja	SacA16553
134–135	5245 ± 30	5988 (5931–6169)	Gyttja	SacA16552
164–165	6285 ± 30	7215 (7166–7267)	Gyttja	SacA16551
180–181	6910 ± 50	7742 (7654–7866)	Macroremains	Poz-32158
183–184	7625 ± 45	8419 (8368–8531)	Gyttja	SacA16550

Beta = Beta Analytic Inc; Poz = Poznan Radiocarbon Laboratory; SacA = Laboratoire de mesure du carbone 14

threshold corresponding to the 99th percentile of the noise distribution. General trends in fire occurrence were expressed as number of fires per 1000 years, smoothed with a 100 years moving window using K1D software version 1.2 (Gavin 2010). The composite record illustrating regional fire occurrence was obtained by averaging data from the 4 sites, with a 95 % bootstrap confidence interval.

Results

As expected, Holocene trends in fire occurrence (number of fires per 1000 years) varied between lakes (Fig. 3). At Nans Lake, fire occurrence was higher between 5000 and 3800 cal. BP and around 1000 cal. BP. At Richard Lake, fire occurrence was higher between 4600 and 3600 cal. BP and between 1400 and 800 cal. BP. Most fire events at Aurélie Lake occurred before 3400 cal. BP,

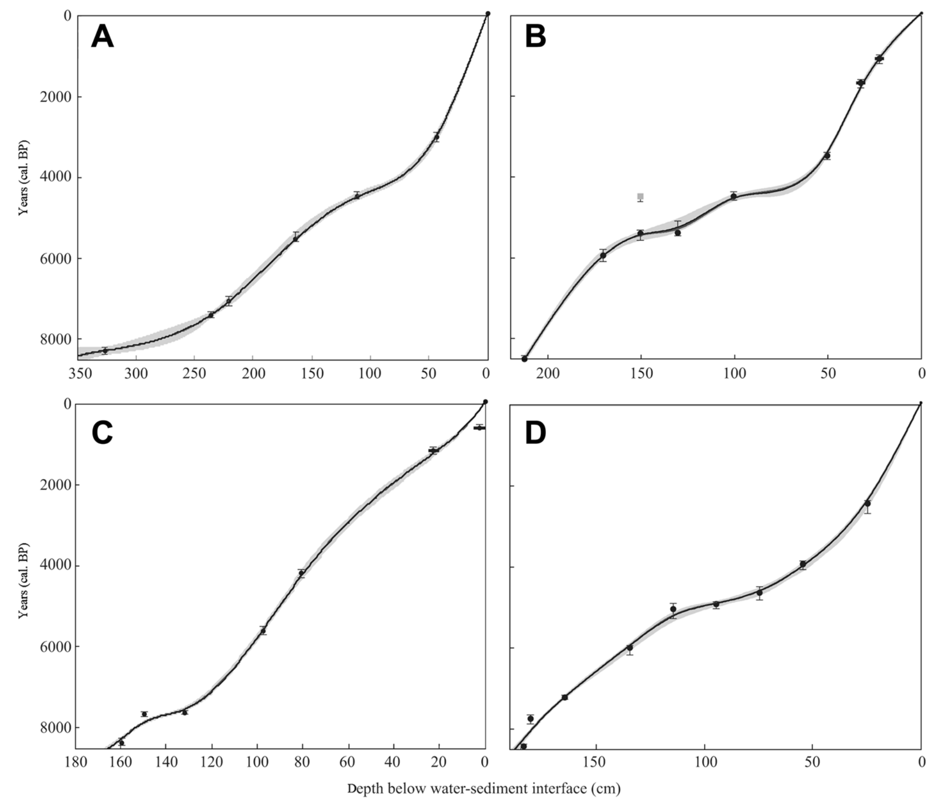

Fig. 2 Age-depth models (cubic spline interpolation) for lakes Aurélie (**A**), Nans (**B**), Richard (**C**), and Twin (**D**). Radiocarbon dates are shown (black dots) with 95 % confidence intervals (whiskers). One of the dates from the lake Nans profile was discarded (grey dot) as it was too young and was likely contaminated by more recent material during sampling

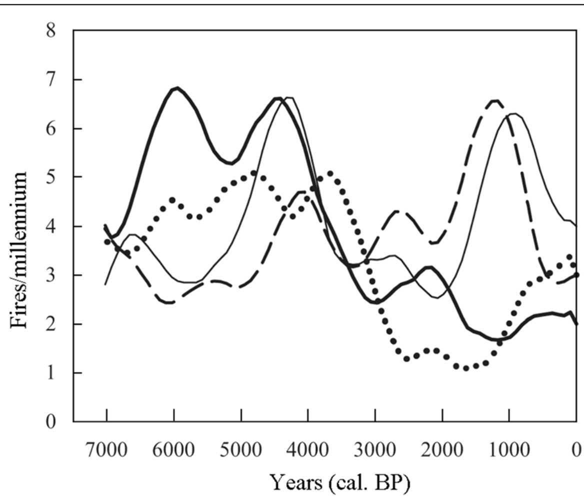

Fig. 3 Fire occurrence (number of fire events per 1000 years) for lakes Aurélie (thick full line), Nans (thin full line), Richard (dashed line), and Twin (dotted line)

and the highest occurrence was recorded between 6800 and 4000 cal. BP. At Twin Lake, fire occurrence was higher before 3200 cal. BP.

The composite curve of regional fire occurrence shows that fire occurrences were generally higher during the middle Holocene (ca. 7000–3500 cal. BP) than during the late Holocene (3500–0 cal. BP), where a brief increase of fire occurrence was nevertheless recorded around 1000 cal. BP (Fig. 4).

Discussion

The long-term fire history at the northern limit of commercial forestry in Quebec fluctuated during the last 7000 years under the influence of regional climate. Fire occurrence was higher between 7000 and 3500 cal. BP, especially between 5500 and 3500 ca. years B.P. This period corresponds to the Holocene Thermal Maximum, previously shown to have been warmer and drier in northern Quebec (Garralla and Gajewski 1992; Viau and Gajewski 2009) and in various locations across North America (Bartlein et al. 1998; Viau et al. 2006). A sharp decrease in fire occurrence occurred in the study area at the beginning of the Neoglacial period (3500–0 cal. BP), especially at lakes Aurélie and Twin, likely in response

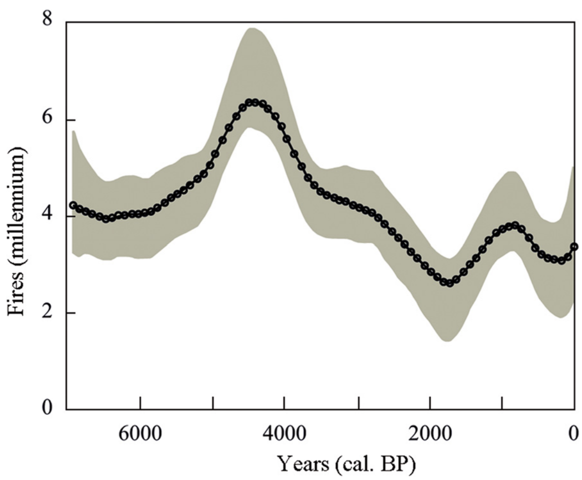

Fig. 4 Regional average of fire occurrence (number of fire events per 1000 years) combining the 4 sampled lakes. The 95 % confidence interval is shown in grey

to a cooler and wetter climate (Garralla and Gajewski 1992; Viau and Gajewski 2009). This general trend is similar to that found further west by Oris et al. (2014b), also at the northern limit of commercial forestry. A brief period of increased fire occurrence was noted in the study area around 1000 cal. BP, coinciding with the Medieval Warm Period (Gajewski 1988; Hunt 2006). The imprint of the Medieval Warm Period was not recorded at all sites, a specificity also noted further south and west in the spruce-moss forest (Ali et al. 2009; Oris et al. 2014b). This could be due to the short duration of this climatic period (a few centuries) making it less likely to affect fire regimes. Alternatively, local factors, such as topography, landscape connectivity, vegetation flammability, or weather could have been more important than regional climate to explain fire occurrence during that period (Gavin et al. 2006; Hu et al. 2006; Long et al. 2007; Ali et al. 2009).

Fire occurrence at the northern limit of commercial forestry in Quebec was variable between sites, but was generally higher during warm and dry periods of the Holocene, especially during the Holocene Thermal Maximum (7000–3500 cal. years BP), when fire occurrence was twice as high as at present. Current fire occurrence is still within the range of natural variability, probably because the amount of precipitation is still high enough to balance the effects of global warming. Fire return intervals (FRI) calculated from the composite chronology of fire occurrences presented here (ca. 167–333 years, based on 3–6 fires per millennium) are slightly higher than – but overlap with – those obtained from spruce-moss forests further south (Cyr et al. 2009: 111–267 years; Ali et al. 2009: 90–230 years) and west (Oris et al. 2014b; 196–312 years). The present-time FRI in our study area (ca. 333 years) is twice as long as that presented by Le Goff et al. (2007) for a particularly dry area located further west (132–153 years). It is however well within the range presented by Mansuy et al. (2010) for a wider study area encompassing both mesic and xeric sites (90–715 years). This is in line with reconstructions from northern Ontario (Canada) that showed significant differences between FRI values from xeric and mesic sites (Senici et al. 2013).

Predicted high temperatures for the middle of the 21st century could be close to those recorded during the Holocene Thermal Maximum (Plummer et al. 2006). If increased temperature is not accompanied by a marked increase in precipitation, the mid-Holocene scenario could be repeated and fire occurrence could increase at the northern limit of commercial forestry in Quebec. The extent to which forest managers will be able to replace wildfire by harvesting activities will be more limited (Bergeron et al. 2006, 2010; Raulier et al. 2013). Indeed, important fire suppression efforts have been deployed in the study area at times when fire activity was at its lowest levels of the past 7000 years.

Conclusions

We showed that fire occurrence was higher during warm and dry periods of the Holocene at the northern limit of commercial forestry in Quebec. Climate predictions for the middle of the 21st century point towards conditions similar to those that prevailed during the Holocene Thermal Maximum, when maximum fire occurrence was recorded. Because sustainable forest management implies that total disturbance (harvesting + wildfire) should not exceed the Holocene maximum, a substantial reduction of the amount of wood available to the forestry industry is to be expected over the next few decades.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

AE-G carried out the field and laboratory work, performed the analyses and drafted the manuscript. HA, SG, YB and AAA conceived of the study, participated in its design and coordination and helped to draft the manuscript. All authors read and approved the final manuscript.

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