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# Long-term fire frequency variability in the eastern Canadian boreal forest: the influences of climate vs. local factors

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### Abstract

**The influence of climatic and local nonclimatic factors on the fire regime of the eastern Canadian boreal forest over the last 8000 years is investigated by examining charred particles preserved in four lacustrine deposits. Herein, we compare the distribution of fire-free intervals (FFIs) and the synchronicity of fire events among sites, using Ripley's *K*-function to determine the extent of the role of local-scale vs. large-scale processes with respect to fire control. Between 8000 and 5800 cal. BP (calibrated years before present) the climatic and ecological conditions were less conducive to fire events than after this date. After 5800 cal. BP, the number of fires per 1000 years (fire frequency) progressively increased, reaching a maximum ca. 3400 cal. BP. There was a sharp decrease in fire frequency during the last 800 years. Between 8000 and 4000 cal. BP, comparable FFIs and synchronous fire episodes were determined for the study sites. During this period, the fire frequency was predominantly controlled by climate. After 4000 cal. BP, two sites displayed independent fire histories (different FFI distributions or asynchronous fire events), underlining the important influence of local factors, including short-term fuel wetness, characteristics of the watershed and landscape connectivity, in determining fire occurrence. We conclude that climatic changes occurred during the last 4000 years that induced a rise in the water table; this may explain the high spatial heterogeneity in fire history. Current and projected global climatic changes may cause similar spatial variability in fire frequency.**

*Keywords:* bivariate Ripley's *K*-function, boreal ecosystem, climatic change, fire history, Holocene, kettle lakes, Neoglacial, Quebec, sedimentary charcoal, spatial fire pattern

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## Introduction

Current global warming is expected to increase both the frequency and extent of fires across much of the world's boreal forests; this will have severe environmental and economic consequences (Flannigan *et al*., 2005; Tymstra *et al*., 2007). In Canada, an increase in extreme fire events during the last few decades largely supports this scenario (Gillett *et al*., 2004). However, it is important to stress that current predictions relating to fire frequency are mostly based on data collected over a relatively short time (Flannigan *et al*., 2005), i.e. <100 years. Such data do not allow fire frequency over longer time scales to be characterized. Indeed, longer temporal perspectives are often crucial in order to appreciate the ways in which natural processes respond to climatic variation (Cyr *et al*., 2009). The analysis of charred particles preserved in lake sediments overcomes this problem by providing a long record of fire frequency, thus allowing the interactions between climate, fire, and vegetation dynamics to be determined (e.g. Clark,

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1990; Gavin *et al*., 2007). In areas affected by frequent wildfires, long-term fire frequency reconstructions are required to provide guidance for future biodiversity conservation (Willis & Birks, 2006) and forest management strategies (Kuuluvainen, 2002; Bergeron *et al*., 2006). In general terms, knowledge of the past is a key to understanding the present-day and for planning sustainable management policies for forest ecosystems (Peteet, 2000; Botkin *et al*., 2007).

In the Canadian boreal forest, the occurrence and spread of fires at annual to millennial time scales, i.e., fire frequency, is linked to several regional and local factors including climatic variability, air mass circulation, wind speed, geomorphological context, fuel characteristics, and thickness of the organic layer of the soil (e.g. Payette & Gagnon, 1985; Johnson, 1992; Girardin *et al*., 2006). During the last 10 years, there has been an increasing understanding of the interactions between climatic change, fire frequency, and vegetation dynamics over long time scales. However, few studies have considered the influence of local-scale factors on fire frequency at the time scale of millennia (Clark, 1990; Lynch *et al*., 2004b; Hu *et al*., 2006). Local nonclimatic factors that affect fire frequency could influence vegetation patterns and result in high spatial variability at the landscape-scale (Asselin *et al*., 2006). The current challenge is to differentiate between the influences of climatic and local factors on fire frequency. Thus, understanding the roles of climatic and nonclimatic factors is key for forecasting how fire frequency will change in response to global warming.

Herein, we describe the spatial and temporal variations in fire frequency for the coniferous boreal forest of western Quebec's Abitibi region over the last 8000 years. The fire frequencies were reconstructed using high-resolution charcoal records obtained from four lakes separated by distances of $<40$ km. We compare the fire histories of the sites, as well as determining relationships between fire and the principal climatic oscillations during the Holocene. We hypothesize that if climate is the main driver of long-term fire frequency, the sites should display similar fire histories. However, if they have different fire histories, then local factors are likely to have exerted a strong influence and need to be identified.

## Study area

The study area currently experiences a continental climate with long cold winters and short warm summers. The mean annual air temperature is $0.8 \pm 1.0\,°C$ (La Sarre weather station: 1971–2000; 48°48′22″N 79°11′40″W) and annual precipitation varies between 800 and 900 mm, with ca. 25% falling as snow (Environment Canada, 1993). Lac (L.) aux Geais, Lac (L.) Profond, Lac (L.) Raynald, and Lac (L.) à la Loutre are kettle lakes within the fluvioglacial deposits (sand and gravel) that constitute the Harricana interlobate moraines; these lakes were chosen for their small area and the depth of their sediments (Table 1). The lakes are located along a 40 km transect, and contain evidence of local fires within an area of $<100\,km^2$ (Fig. 1).

When the proglacial Objibway lakes suddenly disappeared ca. 8200 cal. BP (Barber *et al*., 1999), trees rapidly colonized the area without the vegetation passing through an initial tundra phase (Richard, 1980; Liu,

**Table 1** Main characteristics of L. aux Geais, L. Raynald, L. à la Loutre, and L. Profond

| | L. aux Geais | L. Profond | L. Raynald | L. à la Loutre |
|---|---|---|---|---|
| Latitude | 49°53′32.2″N | 49°51′40.1″N | 49°48′33.4″N | 49°42′42.1″N |
| Longitude | 78°39′18.4″W | 78°36′47.9″W | 78°32′09.0″W | 78°20′09.0″W |
| Elevation (m a.s.l.) | 280 | 270 | 250 | 274 |
| Local vegetation | *Picea mariana*, *Abies balsamea*, *Larix laricina*, *Betula papyrifera* | *Picea mariana*, *Abies balsamea*, *Betula payrifera* | *Picea mariana*, *Picea glauca*, *Abies balsamea*, *Larix laricina*, *Betula papyrifera*, *Pinus banksiana* | *Picea mariana*, *Larix laricina*, *Abies balsamea* |
| Hillslopes | Flat | Flat | Moderate | Flat |
| Lake surface (ha) | 3.6 | 0.6 | 1.5 | 2.1 |
| Water depth (m) | 10.15 | $>20$* | 10.28 | 10.63 |
| Length of organic core (cm) | 603 | 223 | 472 | 227 |
| Mean deposition time (SE) yr cm$^{-1}$ | 13.2 ± (0.35) | 18.3 ± (0.50) | 15.2 ± (0.30) | 36.6 ± (0.76) |

*Coring processes were performed at below water deep ca. 10 m.

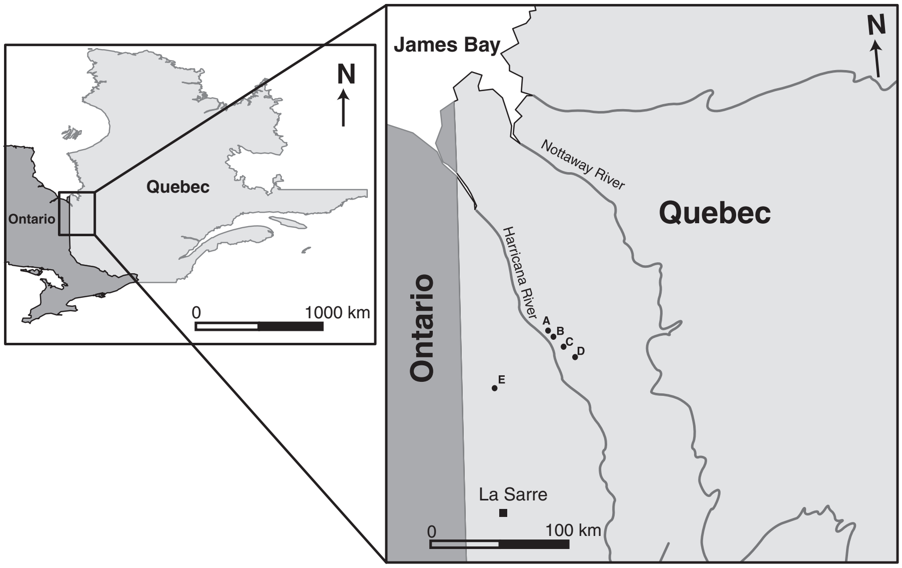


**Fig. 1** Location of the study sites. (A) L. aux Geais; (B) L. Profond; (C) L. Raynald; (D) L. à la Loutre; (E) L. à la Pessière (Carcaillet *et al.*, 2001a, b).

1990; Carcaillet *et al.*, 2001a). The vegetation history, as inferred from pollen and macroremains collected near the study area, indicates that *Picea mariana* (black spruce) has dominated the regional vegetation since at least 7000 cal. BP (Garalla & Gajewski, 1992; Carcaillet *et al.*, 2001a; Ali *et al.*, 2008). The fire history inferred from a lacustrine site located 50 km south of our study area indicates that wildfires were more frequent [fire-free interval (FFI) $<100$ years] in the coniferous boreal forest from 3300 to 1300 cal. BP, compared with the $>200$-year intervals between 7300 and 3300 cal. BP, and the $>400$-year intervals since 1300 cal. BP (Carcaillet *et al.*, 2001a: Lac (L.) à la Pessière, Fig. 1). In addition, fire frequency in the region has been decreasing since the end of the Little Ice Age, with a fire cycle $>300$ years (Bergeron *et al.*, 2004), in response to increasing summer moisture (Girardin *et al.*, 2006).

## Materials and methods

### *Sediment sampling and charcoal quantification*

Lake sediments were extracted using a modified Livingstone sampler (Wright *et al.*, 1984). A Kajak-Brinkhurst gravity (KB) corer (Glew, 1991) was used to collect sediment in a precise manner at the water–sediment interface. The cores were sliced into continuous 1.0 or 0.5 cm thick subsamples depending on the expected temporal resolution (ca. 15 years) and the core length. For charcoal analysis, a 1 $cm^3$ subsample was removed from each sample and soaked in a 3% $(NaPO_3)_6$ solution before wet-sieving through a 160 μm mesh (e.g. Carcaillet *et al.*, 2001b; Whitlock & Larsen, 2001). Typically, charcoal fragments larger than 160 μm are produced by fire events within 1 km of the shore of the sampled lake, allowing fire events to be reconstructed at the local-scale (Lynch *et al.*, 2004a; Higuera *et al.*, 2007). Charcoal particles were identified under a $\times 20$ stereo microscope and they were measured (area) with the aid of a digital camera connected to an IMAGE-ANALYSIS software system. Charcoal measurements are reported as charcoal accumulation rates (CHAR, $mm^2\,cm^2\,yr^{-1}$) based on numerical age/depth models. At each site, the KB and Livingstone cores were cross-correlated on the basis of charcoal concentration patterns.

### *Dating and age vs. depth models*

Chronologies were based on $^{14}C$ accelerator mass spectrometry measurements calibrated to dendrochronological years using the CALIB program (Reimer *et al.*, 2004) and are reported as intercepts with 2$\sigma$ ranges. Twenty-two dates were obtained, and a pool of terrestrial plant macroremains was used for dating when available (Table 2). A smoothing function was applied to assign ages to the samples based on the calibrated ages (Fig. 2).

### *Fire reconstructions*

Fire events were identified by separating the CHAR series (charcoal influx) into CHAR background and CHAR peak components (e.g. Long *et al.*, 1998; Carcaillet *et al.*, 2001a; Gavin *et al.*, 2006), using a tricube function with a time window of 1000 years (CHARSTER

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**Table 2** Accelerator mass spectrometry $^{14}$C dating of L. aux Geais, L. Raynald, L. à la Loutre, and L. Profond

| Site and depth (cm) | $^{14}$C year BP | Range of calibration (cal. years BP; 2δ) | Materials | Lab. code |
|---|---|---|---|---|
| *L. aux Geais* | | | | |
| 98–99 | 1730 ± 40 | 1720–1540 | Gyttja | Beta-228813 |
| 261–262 | 2990 ± 40 | 3330–3060 | Gytta | Beta-228814 |
| 368–372 | 3110 ± 40 | 3400–3250 | Plant macoremains | Beta-228815 |
| 507–510 | 4590 ± 40 | 5440–5070 | Plant macoremains | Beta-228821 |
| 600–603 | 7100 ± 40 | 7990–7850 | Plant macoremains | Beta-228822 |
| *L. Raynald* | | | | |
| 52–54 | 1350 ± 50 | 1340–1180 | Plant macoremains | Beta-231638 |
| 121–122 | 2160 ± 40 | 2310–2040 | Plant macoremains | Beta-231639 |
| 202–206 | 2970 ± 40 | 3260–3000 | Plant macoremains | Beta-231640 |
| 300–305 | 3760 ± 40 | 4240–3990 | Plant macoremains | Beta-231641 |
| 439–441 | 5370 ± 40 | 6280–6010 | Plant macoremains | Beta-231642 |
| 461–465 | 6040 ± 40 | 6990–6790 | Plant macoremains | Beta-231643 |
| *L. à la Loutre* | | | | |
| 66.5–67 | 3450 ± 40 | 3830–3620 | Plant macoremains | Beta-231634 |
| 98–100 | 4070 ± 40 | 4800–4430 | Plant macoremains | Beta-231636 |
| 103.5–105 | 4480 ± 40 | 5300–4970 | Plant macoremains | Beta-231635 |
| 174.5–177 | 5430 ± 40 | 6300–6180 | Plant macoremains | Beta-231637 |
| 220–225 | 6900 ± 40 | 7830–7670 | Plant macoremains | Beta-228816 |
| *L. Profond* | | | | |
| 53–54.5 | 1230 ± 40 | 1270–1060 | Plant macoremains | Beta-228817 |
| 99.5–100 | 2170 ± 40 | 2320–2050 | Plant macoremains | Beta-231644 |
| 124.5–127 | 2760 ± 40 | 2950–2770 | Plant macoremains | Beta-228818 |
| 172–172.5 | 2850 ± 40 | 3070–2860 | Plant macoremains | Beta-228819 |
| 212.5–215 | 3460 ± 40 | 3840–3630 | Plant macoremains | Beta-231645 |
| 222–222.5 | 3720 ± 40 | 4220–3970 | Plant macoremains | Beta-228820 |

Radiocarbon dates. Dates have been calibrated using the CALIB 5.0.1 program (Stuiver & Reimer, 1993) and then rounded to the nearest 10 years.

unpublished program, version 0.8.3). The CHAR peak component was obtained by subtracting the CHAR background from the CHAR series. The CHAR background represents variations in overall charcoal production, sedimentation, mixing, and sampling. Local fire episodes were determined on the basis of the CHAR peaks, according to a defined threshold; this allowed us to divide peaks into 'fire' and 'nonfire' events (Higuera *et al*., 2007). Each peak above the threshold was considered to represent a local fire event. To remove any bias caused by sedimentation rate changes over the length of the cores, the CHAR peaks were first converted into 20-year equal time intervals corresponding to the average deposition time per centimeter for the four lakes (Table 1). This transformation allows to remove bias induce by the different sedimentation rates of the sites. To determine the optimal threshold we modeled the frequency distribution of the CHAR peaks as a zero mean-Gaussian distribution. The 95th percentile value of the fitted distribution was used to determine a range of threshold values. A sensitivity analysis was undertaken to select the final threshold (Clark *et al*., 1996), which was defined as the CHAR peak where the FFI distribution was least sensitive to changes in the threshold itself. The FFI corresponds to the number of years between two consecutive fire-events, modeled using a locally weighted regression with a 1000-year window. Composite fire frequency records were constructed from the averages of the four sites after rescaling the frequency of each site to the range 0–1. Using this technique, each site contributes equally to the composite record (Gavin *et al*., 2006).

### *Comparisons between sites*

To compare the fire histories of the sites, we examined median FFIs (mFFI) using the nonparametric two-sample Mann–Whitney test (MW-test), and overall FFI distributions using the nonparametric two-sample Kolmogorov–Smirnov test (KS-test) (Clark, 1989). In addition, we assessed the synchrony of fire episode occurrence between sites using a bivariate Ripley's *K*-

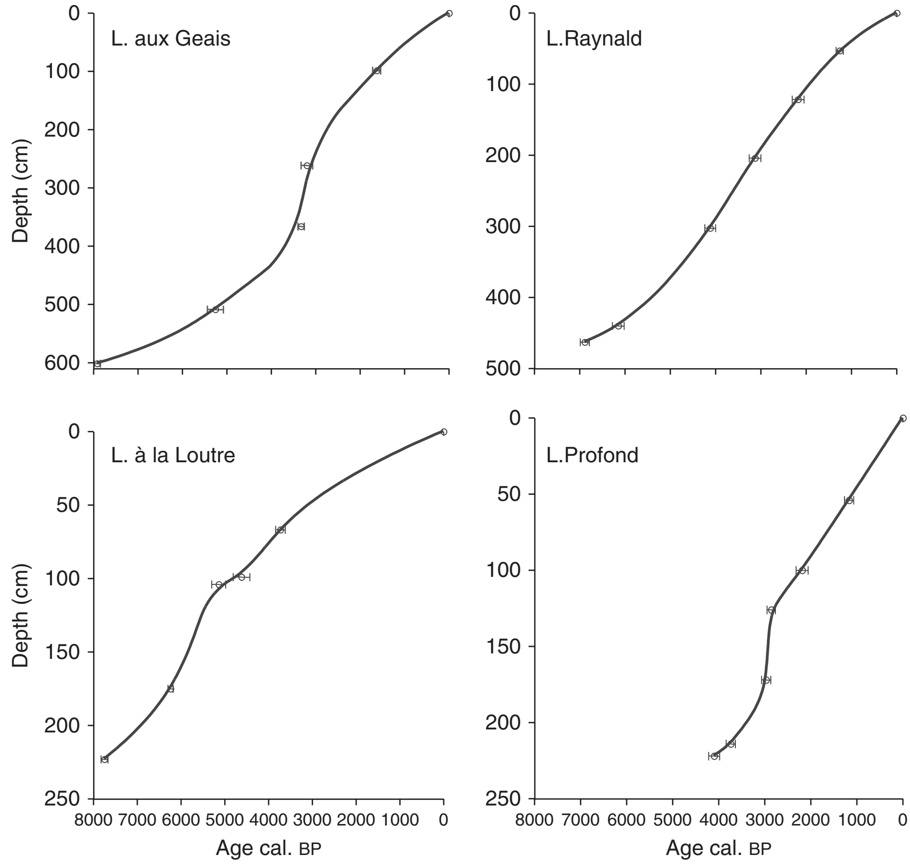


**Fig. 2** Age vs. depth models for L. aux Geais, L. Raynald, L. à la Loutre and L. Profond.

function (Ripley, 1977) modified to a single dimension (i.e. time, Doss, 1989), allowing us to evaluate the likelihood that fires occurred at several sites by chance (Gavin *et al*., 2006). The modified bivariate *K*-function allows several fire records to be compared in order to identify fire events occurring at the sites within a defined temporal window ($\pm t$ years). It should be noted that this analysis identifies fire event patterns at the centennial to millennial time scales, allowing similarities and differences to be determined. The *K*-function was transformed to an *L*-function to facilitate interpretation of the results (Gavin *et al*., 2006). This transformation stabilizes the means and variances of the *K* value outputs. The 95% and 99% confidence intervals for the $L(t)$ values were determined by randomization of 1000 fire-events. Each randomization consisted of shifting each record a random number of years and wrapping events from the end to the start of the recording period. $L(t)$ values $>0$ suggest comparable patterns in fire occurrences among the sites, while values near 0 and $<0$ indicate independence and asynchrony between sites, respectively. All analyses were performed with KD1 software (unpublished program, D. G. Gavin, University of Oregon).

When interpreting long-term fire history with respect to the relationships between local-scale and large-scale driving forces, several scenarios may be relevant; these relate to patterns of FFIs and fire event synchronicity:

*Scenario 1*. The sites exhibit the same distribution of FFIs and have synchronous fire episodes, indicating that large-scale processes, i.e. climate or biome transformation, are the main factors determining fire frequency.

*Scenario 2*. The distribution of FFIs is similar at all the sites, but the fires are asynchronous or independent. This scenario indicates that the actual timing of fire episodes is similar at all sites, but that local nonclimatic factors (landscape connectivity, fire ignition, local weather, topography, watershed size, etc.) override the influence of climate at one or all of the sites (Gavin *et al*., 2006; Long *et al*., 2007).

*Scenario 3*. The distribution of FFIs is dissimilar, but there are synchronous fire episodes. This scenario indicates that local factors cause more (or fewer) fire events at the different sites, in combination with large-scale processes, such as climate, that influence the regional fire dynamics (Gavin *et al*., 2006; Carcaillet *et al*., 2009).

 

*Scenario 4*. Finally, the FFIs can be different at each of the sites with asynchronous fire episodes. In this scenario, only local-scale factors influence the fire regime.

## Results

### *Deposition time and CHAR*

Charcoal series for L. aux Geais, L. Raynald and L. à la Loutre were examined from sediment cores representing the last 8000 years; the material from L. Profond covers only the last 4000 years. As a result, all cores were divided at 4000 cal. BP and comparisons between the sites were undertaken for the periods 8000–4000 cal. BP and 4000–0 cal. BP. L. aux Geais, L. Profond and L. Raynald had similar mean deposition rates, but the mean rate for L. à la Loutre was somewhat different (Table 1). Over the last ca. 8000 years, 600 cm of sediment was deposited at L. aux Geais, 498 cm at L. Raynald, and only 227 cm at L. à la Loutre (Fig. 2). The differences in sediment thickness highlight the low levels of deposition observed at L. à la Loutre. Only 222 cm of sediment was collected from L. Profond, since the water was so deep for our coring device (20 m) and we were unable to recover the proglacial clay horizon (Table 1). CHAR series reached maximums of $2.00\,\mathrm{mm^2\,cm^2\,yr^{-1}}$ at L. aux Geais, $2.70\,\mathrm{mm^2\,cm^2\,yr^{-1}}$ at L. Raynald, $0.25\,\mathrm{mm^2\,cm^2\,yr^{-1}}$ at L. à la Loutre, and $1.00\,\mathrm{mm^2\,cm^2\,yr^{-1}}$ at L. Profond (Fig. 3). L. aux Geais and L. Raynald experienced low CHAR between 8000 and 4000 cal. BP, unlike L. à la Loutre. L. Profond displayed a higher CHAR ca. 3000 cal. BP (Fig. 3).

### *Fire event reconstruction*

In total, 26 fires were detected at L. aux Geais, 21 at L. Raynald, 15 at L. à la Loutre, and 13 at L. Profond (Fig. 3). The fire frequency reconstructions (number of fires per 1000 years) show that fires were most frequent at L. aux Geais ca. 2400 cal. BP, at L. Raynald ca. 4000 cal. BP, at L. à la Loutre ca. 5000 cal. BP, and at L. Profond ca. 3000 and 1000 cal. BP (Fig. 4a). The composite fire records from the four sites (Fig. 4a) indicate that between 8000 and 5800 cal. BP the study area was characterized by long FFIs (mFFI = 230 years). The periods between 5800 and 2400 cal. BP (mFFI = 110 years) and between 1400 and 600 cal. BP (mFFI = 90 years) were characterized by high fire frequencies (Fig. 4a). Several episodes of short FFIs were recorded between 4200 and 800 cal. BP (Fig. 4b). The last 800 years are characterized by long the longest periods of FFIs recorded during the Holocene (Fig. 4b, see inset).

### *Between-site analysis*

Over the last 8000 years, the mFFI was similar at L. aux Geais and L. Raynald (MW-test, $P<0.05$), but was somewhat different at L. à la Loutre (Table 3). L. aux Geais and L. Raynald had similar FFI distributions (Table 4). L. Raynald and L. à la Loutre had significantly different FFI distributions (KS-test, $P<0.05$). The bivariate *K*-function analysis revealed that the fire events at L. aux Geais, L. Raynald, and L. à Loutre were not synchronous between 8000 and 0 cal. BP (Fig. 5a). However, at the time scale of millennia, fire episodes at L. aux Geais and L. Raynald were synchronous (Fig. 5b, $P<0.05$). Independent fire episodes were also observed for L. aux Geais and L. à la Loutre (Fig. 5c) and for L. Raynald and L. à la Loutre (Fig. 5d). However, it is important to note that the *K*-function analysis could failed to detect changes in fire episode synchrony using a single core (Gavin *et al*., 2006). This problem was overcome when the cores were divided into two distinct periods.

*8000–4000 cal. bp.* L. aux Geais, L. Raynald, and L. à la Loutre have similar median and overall FFI distributions (Tables 3 and 4). The bivariate *K*-function analysis indicates synchronous fire episodes at centennial ($P<0.05$) to millennial ($P<0.01$) time scales for these sites, especially within a temporal window of 1100 years ($P<0.01$, Fig. 5e). L. aux Geais and L. Raynald have fire episode synchrony for temporal windows of 900, 1100 and 1500 years ($P<0.05$, Fig. 5f); L. aux Geais and L. à la Loutre for a temporal window <100 years ($P<0.01$, Fig. 5g); and L. Raynald and L. à la Loutre for a temporal window of 1100 years ($P<0.05$, Fig. 5h). These results suggest that between 8000 and 4000 cal. BP, large-scale processes, (climate or biome transformation), controlled the fire frequency at L. aux Geais, L. Raynald and L. à la Loutre (Scenario 1).

*4000–0 cal. bp.* Over the last 4000 years, L. aux Geais, L. Raynald, and L. Profond have similar mFFIs and fire event distributions, but these are significantly different from L. à la Loutre (Tables 3 and 4). The bivariate *K*-function analysis indicated that the four sites exhibit fire episode synchrony at the centennial to millennial time scales ($P<0.05$, Fig. 5i). These data indicate that L. à la Loutre experienced fewer fires than the other sites (Fig. 4), even though, like the other sites, climate was the main factor affecting long-term fire occurrence (Scenario 3). Local nonclimatic factors influenced the occurrence of fires at L. à la Loutre.

Highly significant synchrony ($P<0.01$) with respect to the occurrence of fires was found when pairs of sites were considered: a time window of 700 years for L. aux

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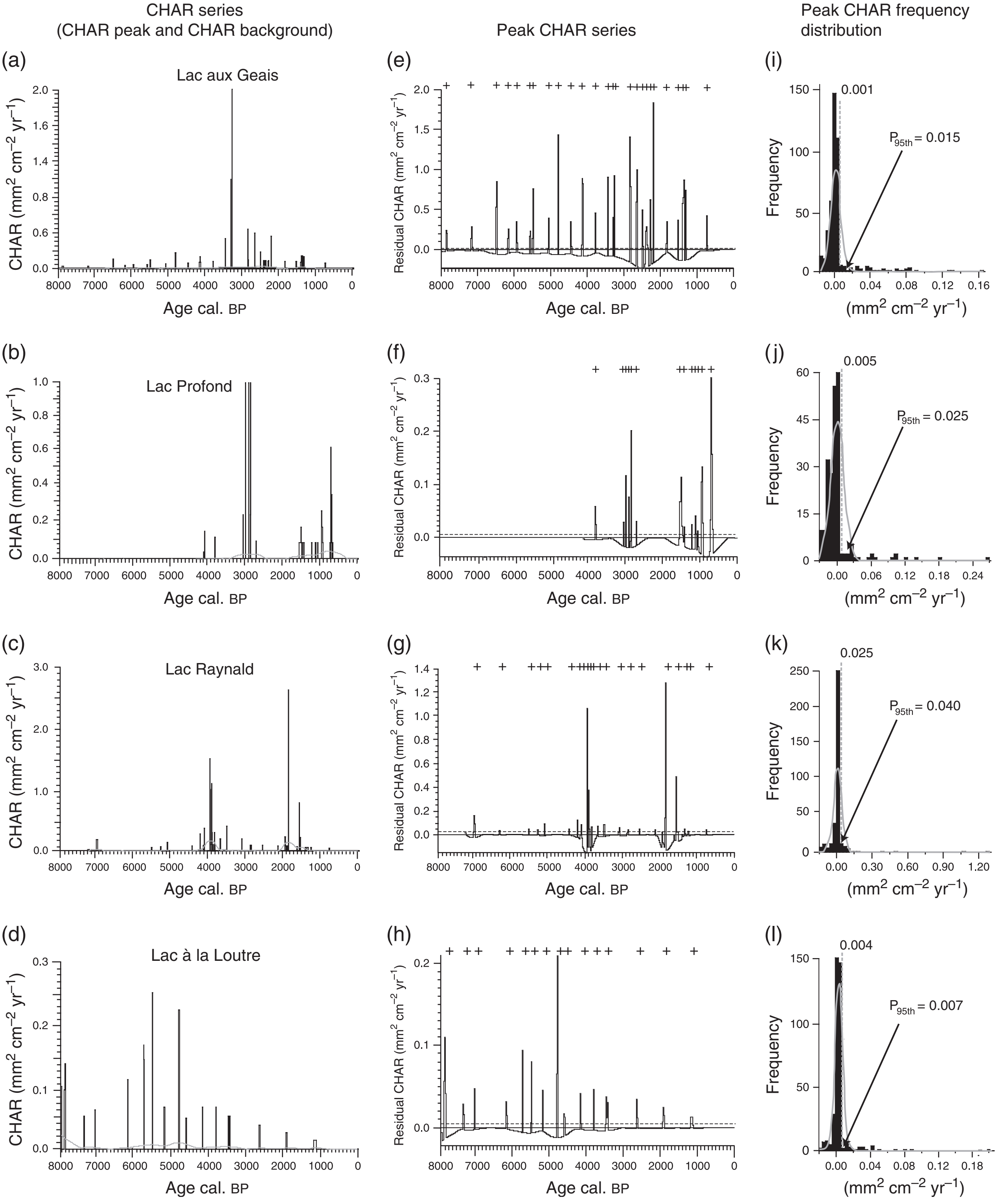


**Fig. 3** (a–d) Charcoal accumulation rates (CHAR peak and CHAR background) plotted against time for Lac aux Geais, Lac Profond, Lac Raynald, and Lac à la Loutre. The heavy grey line represents background values. (e–h) The CHAR peak component calculated by subtraction of the CHAR background from the CHAR series. The '+' symbols correspond to reconstructed fire events. Horizontal dashed lines correspond to the chosen threshold values. (i–l) Frequency distributions for the CHAR peaks with fitted curves derived from a zero-mean Gaussian model. The vertical dashed line indicates the selected optimal thresholds. The 95 percentile ($P_{95th}$) is the score below which 95% of CHAR peak frequency may be found.

 

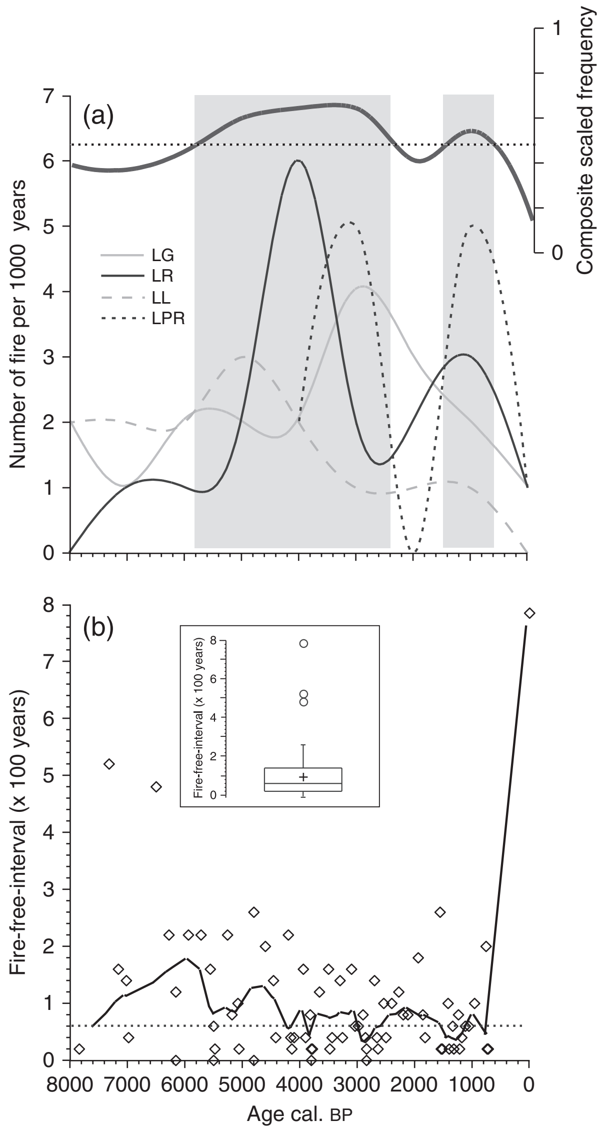


**Fig. 4** (a) Fire frequency expressed as the number of fire events per 1000 years with an 800-year moving window. The composite fire frequency record was constructed from the averages of the four sites after rescaling the frequency of each site to between 0 and 1. The horizontal dashed lines indicate the median value. The shaded areas (5800–2400 and 1400–800 cal. BP), correspond to periods when the composite scaled frequency was above the median value. (b) Fire-free interval (FFI) pattern of the four sites combined. The dark heavy lines correspond to the LOWESS smoothing fitted curves. The horizontal dashed lines indicate the median fire-free interval. The inset corresponds to the box plot of the FFIs over the postglacial. The box limits represent the 25th, the median and the 75th percentiles. The error bars indicate $\pm$ 2 SD from the mean value (+). The dots correspond to outlier values.

Geais and L. Raynald (Fig. 5j); a time window of 1300–1700 years for L. aux Geais and L. à la Loutre (Fig. 5k); and a time window of 700 years for L. Raynald and L. à

**Table 3** Two-sample MW-test comparisons of median fire-free intervals (FFIs) for L. aux Geais, L. Raynald, L. à la Loutre, and L. Profond

| Sites | 8000–0 cal. BP | 8000–4000 cal. BP | 4000–0 cal. BP |
|---|---|---|---|
| LG–LR | 0.950 | 0.922 | 0.663 |
| LG–LL | 0.010* | 0.743 | 0.009* |
| LG–LPR | – | – | 0.482 |
| LR–LL | 0.011* | 0.710 | 0.008* |
| LR–LPR | – | – | 0.249 |
| LL–LPR | – | – | 0.022* |

*The sites display different median FFI ($P$-value $<0.05$).

**Table 4** Two-sample KS-test comparisons of fire-free interval (FFI) distributions for L. aux Geais, L. Raynald, L. à la Loutre, and L. Profond

| Sites | 8000–0 cal. BP | 8000–4000 cal. BP | 4000–0 cal. BP |
|---|---|---|---|
| LG–LR | 0.847 | 0.427 | 0.735 |
| LG–LL | 0.073 | 0.789 | 0.042* |
| LG–LPR | – | – | 0.758 |
| LR–LL | 0.030* | 0.502 | 0.022* |
| LR–LPR | – | – | 0.106 |
| LL–LPR | – | – | 0.006* |

*The sites display different FFI distribution ($P$-value $<0.05$).

la Loutre (Fig. 5m). However, when L. Profond was compared with each of the other sites, independence or asynchrony was apparent (Fig. 5l, n and o). This result emphasizes that, even if the FFI of L. Profond was similar to the other sites, local nonclimatic factors (fire ignition, local weather, topography, watershed size, etc.) overrode the influence of climate (Scenario 2).

## Discussion

In the black spruce boreal forest of western Quebec, fire frequency was not constant during the Holocene (Fig. 4a). Between 8000 and 5800 cal. BP, the study area was characterized by long FFIs, gradually increasing between 5800 and 3400 cal. BP, followed by a decreasing trend up to the present, although shorter fire intervals were recorded at $\sim$ 1200–800 cal. BP (Fig. 4b). Our data indicate that between 8000 and 4000 cal. BP global factors (climate or biome transformation) were the major influence on fire frequency at L. aux Geais, L. Raynald, and L. à la Loutre (Fig. 5). During the last 4000 years, local factors significantly influenced fire occurrences at L. Profond and L. à la Loutre.

### *Climatic variations and the fire frequency*

Current and long-term variations in fire frequency in the eastern *P. mariana* boreal forest are affected by

 

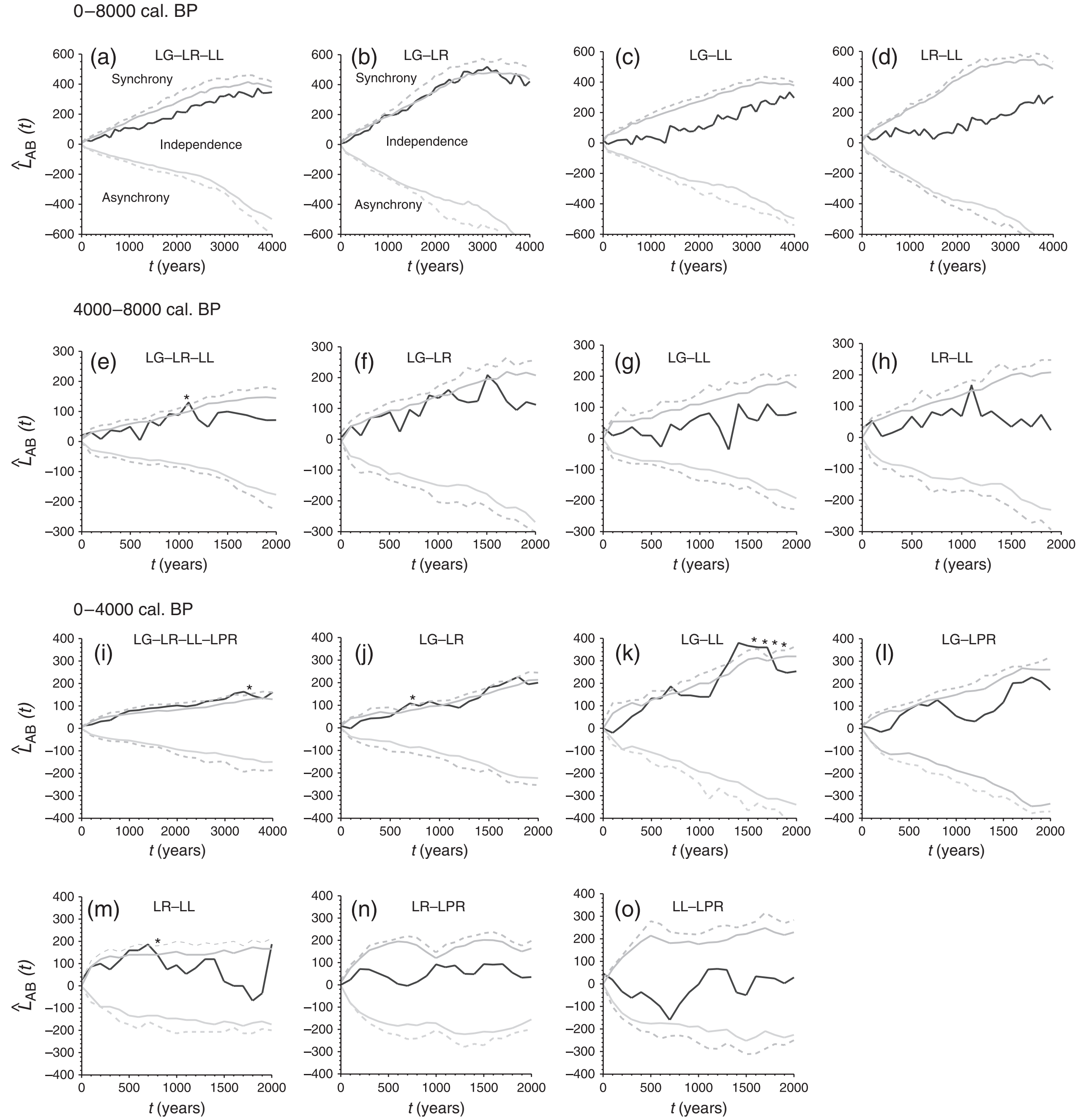


**Fig. 5** Bivariate *L*-function analyses performed on the fire episodes detected at L. aux Geais (LG), L. Raynald (LR), L. à la Loutre (LL) and L. Profond (LPR). Functions were performed for three time periods (0–8000, 4000–8000, and 0–4000). Heavy and dashed grey lines correspond to 95–99% confidence intervals, respectively, based on 1000 randomizations of shifting records relative to each other. *Highly significant synchrony with respect to fire episodes ($P < 0.001$).

interactions between the atmosphere, i.e. air mass circulation and geo-potential height anomalies ($>500$ hPa), and anomalies in sea surface temperatures (SST) or sea level pressures across the Arctic, the Pacific, and the Atlantic oceans (Girardin *et al*., 2004a, b; Skinner *et al*., 2006; Le Goff *et al*., 2007). These interactions involving the El Niño-Southern-Oscillation , the Pacific Decadal Oscillation (PDO), the North Atlantic Oscillation (NAO) and the Arctic Oscillation , affect air mass circulation and moisture/drought balance across North America, which influence the fire regime with respect to fire frequency, severity, and the extent of burned areas each year (Skinner *et al*., 1999, 2006; Girardin *et al*., 2004a, b; Le Goff *et al*., 2007). In eastern Canada, dendroclimatological investigations have determined that the climate became wetter following the Little Ice Age, i.e. ~1850 AD (Bergeron & Archambault, 1993) and climatic reconstructions based on Global Circulation Models have suggested that the climate will become wetter under the moderate scenario of a doubling in $CO_2$ levels (Bergeron & Flannigan, 1995; Flannigan & Wotton, 2001; Flannigan *et al*., 2001). This increase in moisture is probably related to northward displacement of the polar jet stream, favoring the incursion of humid air masses from the Atlantic Tropical zones (Bergeron & Archambault, 1993; Hofgaard *et al*., 1999; Girardin *et al*., 2004b). This northward displacement is induced by a warming of the SST along the North Pacific coast (Girardin *et al*., 2004b), blocking the incursion of dry Arctic air masses that create appropriate conditions for wildfires. This costal sea surface warming was induced by a cooling of SSTs in the central Pacific, corresponding to a negative PDO (Mantua *et al*., 1997).

During the last 8000 years, the study area experienced a shift in fire frequency around 5800 cal. BP, with a gradual increase in fire activity up to 3000 cal. BP (Fig. 4). After this period, environmental conditions became gradually less favorable for fire ignition or spread, although high fire activity is recorded up to ~800 cal. BP (Fig. 4). It is important to emphasize that any changes in vegetation (biome transformation) that occurred during this period would have altered the fire frequency. In fact, pollen and macrofossil analyses suggest that, during the Holocene, the regional vegetation was dominated by *P. mariana* (Garalla & Gajewski, 1992; Carcaillet *et al*., 2001a, b; Ali *et al*., 2008).

Our data suggest that the period between 5800 and 3000 cal. BP was characterized by ocean–atmosphere interactions that favored fire ignition. We hypothesize that anomalies in the atmosphere and SSTs and pressures in the Pacific and Atlantic, allowed the incursion of dry Arctic air masses, conducive to fire ignition, into the study area. Today, the positive influences of the PDO and NAO with respect to fire activity are clear in the study zone (Girardin *et al*., 2004a; Le Goff *et al*., 2007). In North America, it is important to note that after the Hypsithermal of the Holocene (ca. 6000 cal. BP), July temperatures gradually but gently decreased (Viau *et al*., 2006). This climatic change toward colder conditions probably promoted the southward displacement of the polar jet stream, thus allowing more incursions of dry Arctic air masses into Central and Eastern Canada.

### *Climate vs. local factors driving fire frequency*

Our data show that between 8000 and 4000 cal. BP, climate was the major driving force affecting fire frequency at the different sites (L. aux Geais, L à la Loutre, and L. Raynald). By 4000 cal. BP, L. aux Geais and L. Raynald had comparable fire histories (similar FFI and synchrony in fire occurrence), while L. à la Loutre and L. Profond had different FFIs or asynchrony in fire occurrence. This variability highlights the fact that local factors, such as ignition, local weather during fire events, landscape connectivity, and watershed size, were the major factors affecting the fire frequency of these two sites over centennial to millennial time scales. Similar results highlighting the importance of local factors on fire frequency have been observed in southern British Colombia (Gavin *et al*., 2006), western Oregon (Long *et al*., 2007) and Alaska (Hu *et al*., 2006).

One apparent driving force (but probably not the only one) that may explain the decrease in fire event synchrony after 4000 cal. BP is the climatic change that initiated the Neoglacial period, during which the climate became wetter and colder. This increase in moisture levels resulted in a rising water table (A. A. Ali *et al*., unpublished data) and higher lake levels (Payette & Filion, 1993; Lavoie & Richard, 2000a). We hypothesize that this climatic shift promoted the establishment of local weather conditions that affected fire ignition, propagation and extent.

## Conclusion

Our results demonstrate that, in the eastern Canadian coniferous boreal forest, both climate and local factors influence fire frequency. Between 8000 and 4000 cal. BP, the climate was the principal force affecting fire frequency. During the last 4000 years, local factors have played significant roles in the spatial distribution of wildfires. This result is important for improving our forecasts of the impact of ongoing climate change on future fire frequency and the effects on ecosystems dynamics. Consequently further lacustrine sites must be investigated to enhance our understanding of climate/fire linkages.

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