Using tree-ring records to calibrate peak detection in fire reconstructions based on sedimentary charcoal records

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Research paper

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Abstract

We compared fire episodes over the past 150 years reconstructed using charcoal particles retrieved from well-dated sediment deposits from two small lakes in the eastern Canadian boreal forest, with dendrochronological reconstructions of fire events from the corresponding watersheds. Fire scars and age structure of living trees highlighted three fire events (AD 1890, 1941, and 1989). To explore the ability to detect these fire events based on sedimentary charcoal records, we explored the influence of two user-determined parameters of a widely used peak-detection algorithm (the CharAnalysis software): (1) the temporal resolution used to interpolate charcoal series and (2) the width of the smoothing window used to model background noise. The signal-to-noise index (SNI) is often used to evaluate the ability to detect peaks in sedimentary charcoal records, which can be related to fire events. SNI values >3 identify records appropriate for peak detection. Selecting standard settings in paleoecological studies (median temporal resolution of the entire sequence and 500- to 1000-year window width) yielded higher global SNI values but failed to detect most recent fire events. Instead, selecting a shorter reference period (the past ~150 years) to determine the temporal resolution to interpolate the charcoal series and a narrower smoothing window (100 years) best matched the tree-ring data despite lower SNI values (often <3.0). However, Holocene fire history differed markedly when reconstructed using different smoothing window widths (100–150 years vs >300 years). Consequently, we suggest using the smallest window width yielding a SNI >3. Practitioners must not necessarily focus on obtaining the highest possible SNI, usually related to wide smoothing windows. We also suggest that fire history reconstructions should focus on core sections presenting fairly constant sedimentation rates. Alternatively, sediments could be subsampled after age–depth models have been obtained.

Keywords

dendrochronology, fire history, fire frequency, paleoecology, sedimentary charcoal, ^{210}Pb chronology

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Introduction

In North American boreal forests, wildfires correspond to a key ecological disturbance by controlling vegetation dynamics (Payette, 1992; Senici et al., 2013) and altering the carbon cycle by emitting high quantities of greenhouse gases to the atmosphere (Balshi et al., 2009; Oris et al., 2013). Paleoecological reconstructions of past wildfire events allow predicting changes in fire regimes in response to climate change and anthropogenic activities. Over the past three decades, lacustrine charcoal records have widely been used to reconstruct past fire activity in diverse ecosystems (Ali et al., 2012; Asselin and Payette, 2005a; Clark, 1990; Power et al., 2008; Tinner et al., 1998). It is increasingly being recognized that such reconstructions must be based on well-dated sequences with clear charcoal signals obtained after statistical treatment (Higuera et al., 2010; Kelly et al., 2011). Moreover, in a best-case scenario, for recent periods (generally <300 years), charcoal signals must be compared with historical or tree-ring records to refine peak detection (Clark, 1990; Higuera et al., 2011; Long et al., 1998; Pitkänen et al., 1999; Whitlock et al., 2004) and to evaluate reconstruction accuracy. Whereas some 'false' fire events are detected or 'true' fire events not detected, studies in mountain and subalpine forests of western North America highlight relatively good matches between charcoal signals and dendrochronological data (Higuera et al., 2011; Whitlock et al., 2004). Such calibration procedures are, however, lacking for eastern Canadian boreal forests.

Fire reconstructions from lake sediments are highly influenced by user choices during statistical treatment (Blarquez et al., 2013; Carcaillet et al., 2001; Genries et al., 2012). To account for uneven sampling intervals resulting from variable sediment accumulation rates, charcoal records are interpolated to a constant temporal interval, typically the median temporal resolution of the entire record (e.g. Ali et al., 2009; Gavin et al., 2006; Higuera et al., 2010), which can vary considerably within and among lakes (Carcaillet et al., 2001; Genries et al., 2012). Additionally, temporal windows of varying widths can be used in the reconstruction of fire episodes by decomposing charcoal series into background noise that represents taphonomical and sampling effects, and

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high-frequency charcoal peaks that can be related to fire events. To our knowledge, the effect of choosing different temporal resolutions or window widths on fire reconstruction accuracy has not yet been verified with corroborative dendrochronological data in Canadian boreal forests.

In this study, we compared recent fire histories inferred from tree-ring and charcoal records for the watersheds of two small lakes located in the eastern Canadian boreal forest. The lakes were less than 5 km apart and were therefore likely to have been equally affected by regional climate. We aimed to (1) evaluate the accuracy of charcoal signals to infer recent local fire events and (2) discuss the impact of statistical treatment on fire detection in lacustrine charcoal records. Because most wildfires are typically large (>200 ha) in our study area (Lavoie and Sirois, 1998; Natural Resources Canada, 2013), they should display a clear signal both in tree-ring and sediment records. We hypothesized that for the recent period (i.e. the last 150 years), the two approaches would give comparable results. Nevertheless, the topography of the study area, characterized by flat landscapes covered by large peatlands and lakes that act as natural firebreaks, may induce spatial variability in fire ignition, severity, and propagation (Cyr et al., 2007; Mansuy et al., 2010; Senici et al., 2010), which could reduce the representativeness of fire history reconstructions based on single lacustrine charcoal records (MacDonald et al., 1991). It is also generally admitted that fire history deduced from lacustrine charcoal does not necessarily detect all fire events, as single charcoal peaks could be related to more than one fire (Clark, 1990; Higuera et al., 2007).

Material and methods

Study area

The study was conducted in the James Bay lowlands of northwestern Quebec. The dominant vegetation cover corresponds to the open boreal forest (lichen woodland) zone. Black spruce (*Picea mariana* (Mill.) B.S.P.) and jack pine (*Pinus banksiana* Lamb.), two fire-adapted species, dominate the landscape. Jack pine is often found on dry and sandy soils, while black spruce is more abundant on mesic sites. Lake Nano (LNA) and Lake Loup (LLP) were chosen due to their proximity and similar morphometries (Table 1). The study area is recurrently affected by large fires (>200 ha, Natural Resources Canada, 2013) with a fire cycle of ~100 years (Le Goff et al., 2007; Mansuy et al., 2010; Payette et al., 1989).

In the study area, deglaciation was followed by the Tyrrell Sea invasion ~8000 years ago (Dyke and Prest, 1987). After the initial tundra and aspen (*Populus tremuloides* Michx.) parkland phases, open spruce woodlands colonized the area (Richard, 1979). Increased landscape opening occurred over the last 3000 years likely due to postfire regeneration failure (Asselin and Payette, 2005b).

Tree-ring records of fire history: sampling and data analysis

Field sampling for dendrochronological analysis was carried out in September 2011. We sampled 36 and 31 cross sections from scarred living trees around LNA and LLP, respectively. Sampling took place within 200 m from the lakeshores (Figure 1). Before sampling, the organic matter and mineral soil were removed from around the base of trees (DesRochers and Gagnon, 1997). We took two cross sections from each tree: at the root collar to date establishment, and at 1.30 m above ground (breast height) to obtain a master chronology. When fire scars were observed 1.30 m above ground, a third cross section was collected at the upper limit of the scar. For each sampled tree, we recorded diameter at breast height (DBH), height, spatial coordinates, and orientation of the scars. Flame front direction can be inferred from fire scar orientation because scars form on the side of the tree opposite to the origin of fire (Arno et al., 1977; Dickinson and Johnson, 2001). Cross sections were mostly collected from jack pine, with some black spruce and eastern larch (*Larix laricina* (Du Roi) Koch.; Table 3).

Table 1. Location and characteristics of LLP and LNA.

	LLP	LNA
Latitude	53°03′18.55″N	53°01′25.54″N
Longitude	77°24′00.38″W	77°21′49.33″W
Elevation (m a.s.l.)	206	206
Local vegetation	*Pinus banksiana, Picea mariana, Larix laricina*	*P. banksiana, P. mariana, L. laricina*
Topography	Flat	Flat
Lake surface (ha)	1.6	0.4
Maximum water depth (m)	3	3.2
Core length (cm)	106	140
Median deposition time (years/sample)		
Entire sequence (~7000 years)	35	22
Recent deposits (~last 150 years)	6	10

LNA: Lake Nano; LLP: Lake Loup.

Cross sections were dried and sanded using successively finer grades (80–600 grit) until annual growth rings and scars were clearly visible (Schweingruber, 1988). A master chronology was established with tree-ring widths of the DBH cross sections (Holmes and Fritts, 1986; Stokes and Smiley, 1968). Tree-ring analysis was made under a binocular microscope according to standard dendrochronological methods (Niklasson et al., 2010; Stokes and Smiley, 1968). Pointer years or marker rings (narrow, wide, and incomplete rings) were identified visually and used for crossdating (Schweingruber et al., 1990). Tree-ring widths were measured using a LINTAB 5 µm (Rinn, 2004) with 0.001 mm precision along two radii opposite to the scars and separated by 120°. Crossdating was achieved using the TSAPWin 4.64 software (Rinn, 2003) and validated using the COFECHA 6.06 software (Holmes, 1983). For all scars, calendar date and seasonal position within annual growth-ring were recorded (Arno et al., 1977). Scars and stand age data were analyzed using the dplR package of the R software (Bunn, 2008). Fire history reconstructions based on dendrochronological and lacustrine charcoal records were carried out independently by different researchers in order to avoid any bias.

Sediment dating and age–depth models

Lake sediments were extracted in March 2011 using a modified Livingstone piston corer (Wright et al., 1984), and the water–sediment interface was collected with a Kajak–Brinkhurst (KB) gravity corer (Glew, 1991). To obtain an age–depth model for the younger unconsolidated sediments, ^{210}Pb measurements were performed from the uppermost 14 cm of the cores (Table 2). ^{210}Pb values were inferred by measuring the activity of the daughter product, that is, ^{210}Po, by alpha spectrometry assuming an equal concentration of the two isotopes. In all, 14 samples, each >100 mg in dry weight, were analyzed for each core (Table 2).

Radiocarbon dating of terrestrial plant macroremains and bulk gyttja samples allowed us to extend the chronologies downcore (Table S1). The ^{14}C dates were calibrated using the CALIB 7.0 program (Stuiver and Reimer, 1993) based on the IntCal04 dataset (Reimer et al., 2004). Age–depth models (Figure S1) were obtained using the MCAgeDepth program (Higuera et al., 2008),

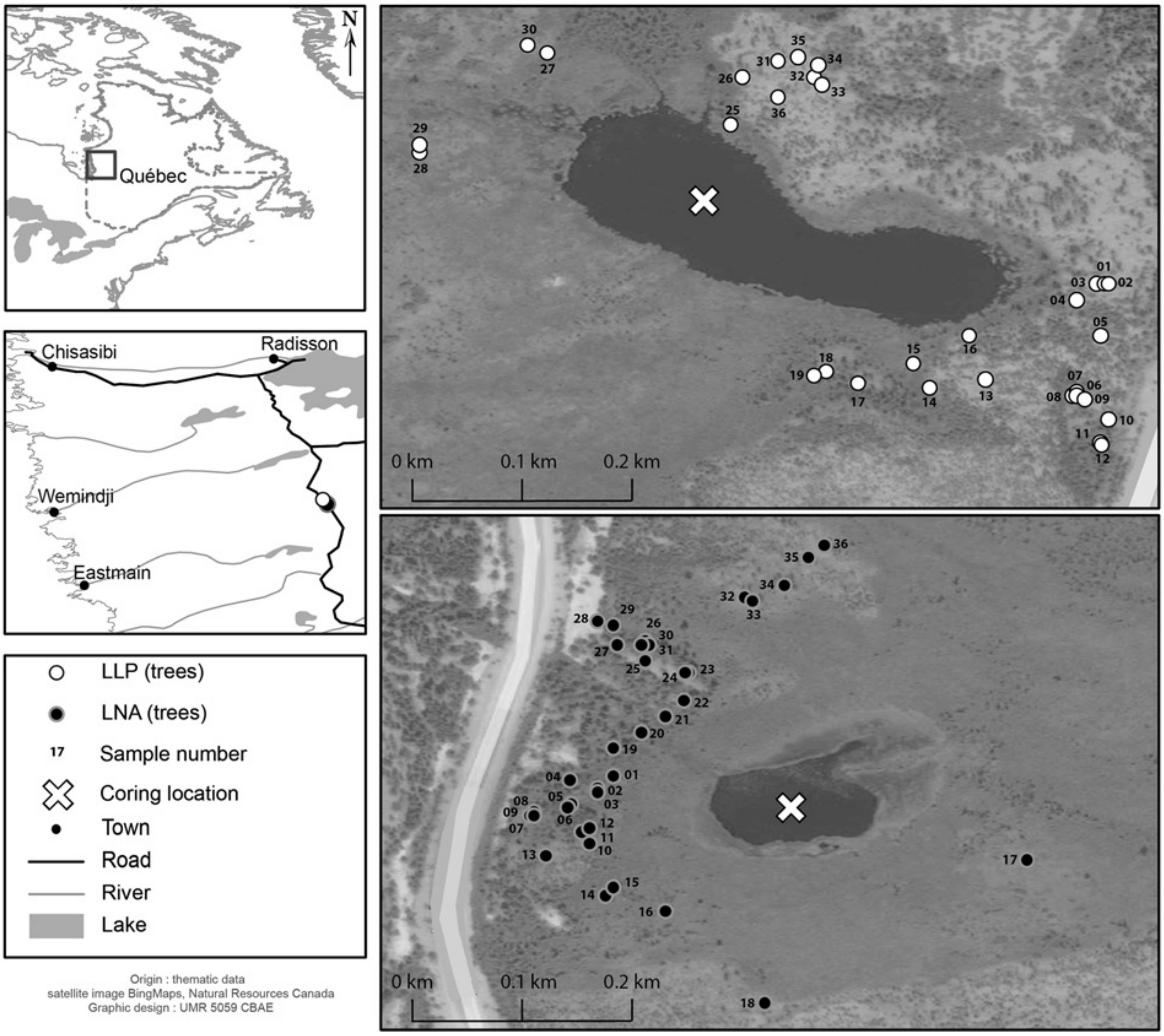

Figure 1. Location of the study area, lakes, and sampled trees.
LNA: Lake Nano; LLP: Lake Loup.

Table 2. ^{210}Pb activity of recent sediments from LLP and LNA.

Sample depth (cm)	LLP			LNA		
	Sample number	^{210}Pb activity (Bq/kg)	SD (%)	Sample number	^{210}Pb activity (Bq/kg)	SD (%)
0.5	265	798	3.7	251	203	7.8
1.0	266	799	3.0	252	206	7.0
1.5	267	796	3.4	253	135	13.4
2.0	268	800	3.4	254	145	8.8
2.5	269	688	4.2	255	89	7.6
3.5	270	586	3.7	256	49	9.0
4.5	271	447	4.1	257	36	14.2
5.5	272	299	3.7	258	17	15.7
6.5	273	222	3.9	259	16	13.9
7.5	274	80	5.0	260	15	10.7
8.5	275	106	7.1	261	13	10.9
10.0	276	78	8.2	262	10	10.5
11.5	277	41	6.1	263	12	9.9
13.5	278	27	7.6	264	12	11.6

LNA: Lake Nano; LLP: Lake Loup; SD: standard deviation.

which applies a Monte Carlo resampling technique to assess median ages and to generate confidence intervals (CIs) around the fit, based on the probability distribution of each date.

From charcoal particles to fire events

The sediment cores were sliced into contiguous 0.5-cm-thick samples. For charcoal analysis, a 1-cm^3 subsample was removed from each slice and soaked in a 3% $(NaPO_3)_6$ solution before wet sieving through a 150-µm mesh (Whitlock and Larsen, 2002). Charcoal pieces larger than 150 µm are mostly produced by fire events within 1 km of the lake shores, allowing fire events to be reconstructed at the local scale (Higuera et al., 2007; Lynch et al., 2004). Charcoal pieces were identified under a 20× stereomicroscope, and their area was measured with the aid of a digital camera connected to an image-analysis software (Regent Instruments Inc., Canada). Charcoal measurements are reported as charcoal accumulation rates (CHAR, $mm^2/cm^2/year$) based on age–depth models.

The CHAR series were interpolated to constant time steps ($C_{interpolated}$). We used two different temporal resolutions to explore the effect of the interpolation procedure on the detection of recent fire events: one corresponding to the median temporal resolution of the recent sediments (~ the last 150 years) and one corresponding to the temporal resolution for the entire sequence (~ 7000 years), respectively, called Run_{KB} and Run_{All} hereafter. To model the background series (C_{back}), corresponding to low-frequency variations in $C_{interpolated}$, we used a locally weighted regression robust to outliers under several window widths (100–150, 300, 500, 800, and 1000 years). This procedure allowed us to track the incidence of window width on the detection of local fire events. A 100-year smoothing window was used to approximate the temporal resolution of dendrochronological reconstructions. The C_{peak} series was obtained by subtracting C_{back} from $C_{interpolated}$. Global signal-to-noise index (SNI; Kelly et al., 2011), which indicates the suitability of a charcoal record for peak-detection analysis, was calculated for each run.

C_{peak} was decomposed into two subpopulations: C_{noise}, representing variability in sediment mixing, sampling, and analytical and naturally occurring noise, and C_{fire}, representing significant charcoal peaks resulting from local fires (Clark et al., 1996; Gavin et al., 2003; Higuera et al., 2010). For each peak, we used a Gaussian mixture model to identify the C_{noise} distribution according to a locally defined threshold. To compare empirical and modeled C_{noise} distributions, we used the *p*-value from a Kolmogorov–Smirnov (KS) test (also called the goodness-of-fit (GOF)). A p-value > 0.05 suggests that the two populations are from the same distribution. We considered the 95th, 99th, and 99.9th percentiles of the C_{noise} distribution as a possible threshold separating C_{peak} into 'fire' and 'non-fire' events. However, a local 99th percentile threshold of the noise distribution was used to display the Holocene fire histories. A total of 10 runs (5 Run_{KB} and 5 Run_{All}) by sequence were performed (Table S2). To create a smoothed fire frequency, the total number of fires in consecutive 1000-year periods was summed and smoothed using a locally weighted function over 7000 years. All statistical treatments were performed using the CharAnalysis program 1.1 (Higuera, 2009, http://sites.google.com/site/charanalysis/). To compare the fire histories obtained from the different analytical treatments, we examined median fire-free intervals (mFFIs) using the nonparametric two-sample Mann–Whitney (MW) test, and overall FFIs distributions using the nonparametric two-sample KS test (e.g. Ali et al., 2009; Clark, 1989).

Results

Tree-ring records of fire history

Stand characteristics around each lake were comparable (Table 3). A total of 124 scars were found, from which 104 were identified as fire scars (45 at LNA; 59 at LLP). The 20 other scars (9 at LNA; 11 at LLP) did not have morphological characteristics typical of fire scars (Falk et al., 2011; Smith and Sutherland, 2001) and were thus discarded from analysis. Two and three fires were inferred based on the fire scars during the past 150 years in the LNA and LLP watersheds, respectively (Figure 2a and b). Fire scars and stand age indicated that the two sites were synchronously affected by two fire events in 1941 and 1989. As the eastern part of the LNA watershed was characterized by a large peat bog with few trees, sampling was concentrated in the western part. In the eastern part, only one tree was scarred in 1989 (Figures 1, 2a, and b). Fire scars were located in the latewood, indicating that wildfires occurred in summer. This was further supported

Table 3. Characteristics of dendrochronological samples from LLP and LNA watersheds.

	LLP	LNA
Number of trees	31	36
Pinus banksiana	29	27
Larix laricina	1	1
Picea mariana	1	8
Average DBH (cm)	17.45	15.89
Maximum DBH (cm)	31.35	24.51
Minimum DBH (cm)	10.00	7.00
Average height (m)	8.79	8.58
Maximum height (m)	15.20	12.60
Minimum height (m)	5.30	5.15

LNA: Lake Nano; LLP: Lake Loup; DBH: diameter at breast height.

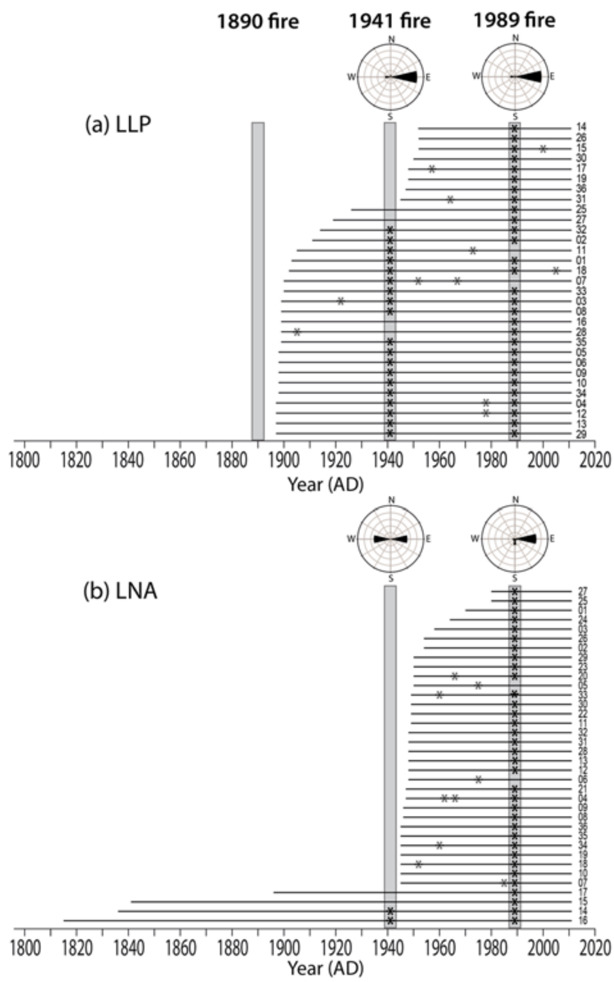

Figure 2. Tree-ring records of fire activity for (a) LLP and (b) LNA watersheds. Each horizontal line is an individual tree with sample number at the end, each gray asterisk is a scar (any type), and each black asterisk is a fire scar. Vertical gray bands indicate fire events. Scar orientation is presented in polar plots, each circular graduation corresponding to 20% of the samples.
LNA: Lake Nano; LLP: Lake Loup.

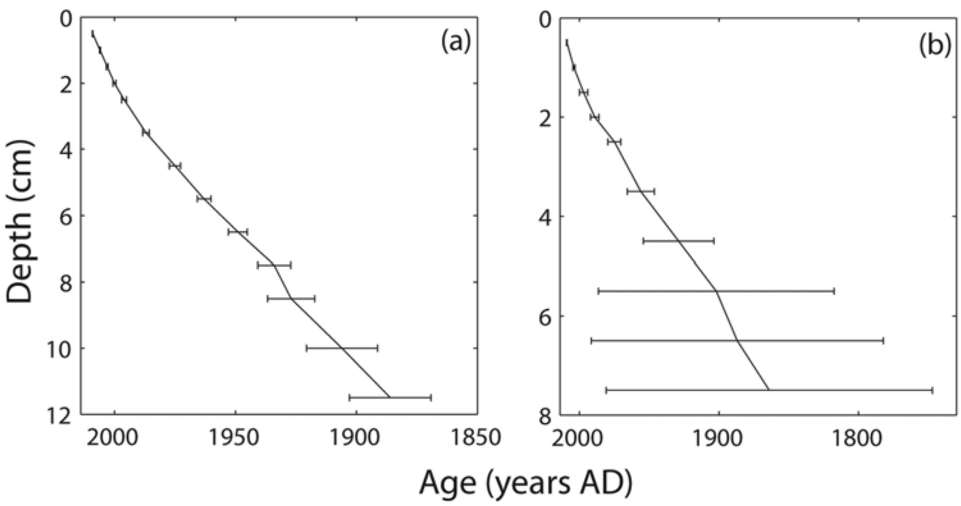

Figure 3. ^{210}Pb chronologies for (a) LLP and (b) LNA using the CRS model. Error bars represent one standard deviation. Note different scales on *x* and *y* axes.
LNA: Lake Nano; LLP: Lake Loup; CRS: constant rate of supply.

by the orientation of the fire scars indicating that the fire front came from the west, that is, the direction of prevailing summer winds in the study area (Figure 2).

Sediment chronologies

^{210}Pb chronologies allowed us to estimate sediment accumulation rates since *c.* AD 1864 (Figure 3). In LNA, larger standard deviations resulted from less ^{210}Pb excess above the background compared with LLP (with total ^{210}Pb concentration less than three times greater than background, Binford, 1990). ^{210}Pb background was reached at a depth of 7.5 cm at LNA with a value of 12 Bq/kg (Figure 3). Background was not reached in the LLP sediments. As both lakes were very close to one another, and as background ^{210}Pb concentrations are influenced by regional geology (Robbins and Edgington, 1975), the backgrounds in LNA and LLP were assumed to be the same. Therefore, we used the same background value for both sediment sequences. The resulting median temporal resolution of the younger sediments was about 6 and 10 years by sample at LLP and LNA, respectively. Radiocarbon dates allowed us to estimate sediment accumulation rates over ~7000 years (Table S1 and Figure S1). Median temporal resolution for the entire sequences was 35 and 22 years per sample at LLP and LNA, respectively.

Recent fire events

The number of detected fire events over the past 150 years changed markedly when different parameters were used (Figure 4; for detected fire episodes over 7000 years, see Figures S2–S5). Overall, the best concordance between the sedimentary charcoal series and the dendrochronological analysis was reached with Run_{KB} and narrow windows varying between 100 and 300 years (Figure 4). A maximum of three and two fires were detected against a minimum of one and no fire in LLP and LNA, respectively. At LLP, all three fires (AD 1890, 1941, and 1989) were detected with Run_{KB} along with a 100-year smoothing window (Figure 4a). At LNA, a maximum of two fires (AD 1890 and 1989) were detected when a 100-year smoothing window was used, but with both temporal resolutions (Figure 4c and d). However, these two fires were also detected using a 300-year smoothing window in Run_{KB} (Figure 4c). Using wide windows (>500 years) in Run_{All} generally failed to detect the recent fire events. For example, when we used a 1000-year smoothing window (Figure 4), the AD 1941 and 1989 fires were no longer detected in LLP and no fire was detected in LNA (Figure 4c and d). However, the AD 1989 fire was detected in LNA when a local 95th percentile threshold of the noise distribution was used (Figure 4c). Except when a 100-year window was used, local SNI values were generally high (>3.0).

Fire frequency over the last 7000 years

Except for the fire-episode reconstructions using a 100-year window, the fire frequencies displayed the same general trends (Figure 5), according to the different combinations used (window width × temporal resolution). The mFFIs and the distribution of the FFIs were usually not significantly different, except with a 100-year window (Table 4; Table S3), underlining comparable fire histories with most settings. The median and the distribution of FFIs at LNA were not significantly different between Run_{KB} and Run_{All}. At LLP, temporal resolution had an impact when narrow windows were used (100–150 years). Maximum fire frequency occurred at 1000 and 3000 cal. yr BP in Run_{KB} and Run_{All}, respectively. Nevertheless, all scenarios showed that fires were more frequent between 4000 and 0 cal. yr BP (Figure 5a and b). At LNA, all scenarios showed that fire frequencies decreased during the Holocene (Figure 5c and d).

When the window width increased, median SNI also increased (Figure 5). Using a 100-year smoothing window did not allow us to reach the SNI threshold (>3) allowing to accept secure output data. The median GOF was always higher than 0.05. However, a decrease in GOF values occurred when smoothing window width increased, especially in Run_{KB}.

Discussion

Our study compared fire episodes over the past 150 years reconstructed using charcoal pieces retrieved from lacustrine deposits from two sites of the eastern Canadian boreal forest with three fire events detected in the watersheds using dendrochronology. To explore the ability of the widely used CharAnalysis software to detect these fires, we explored the influence of the temporal resolution used to interpolate the CHAR series and the window width used to model background noise. As the dendrochronologically dated fire events could only be detected using specific combinations of methods and sites, the following discussion first focuses on the usefulness of a multi-site and multi-proxy approach to fire history reconstruction. Then, we discuss the influence of using various values of the different parameters central to the reconstructions.

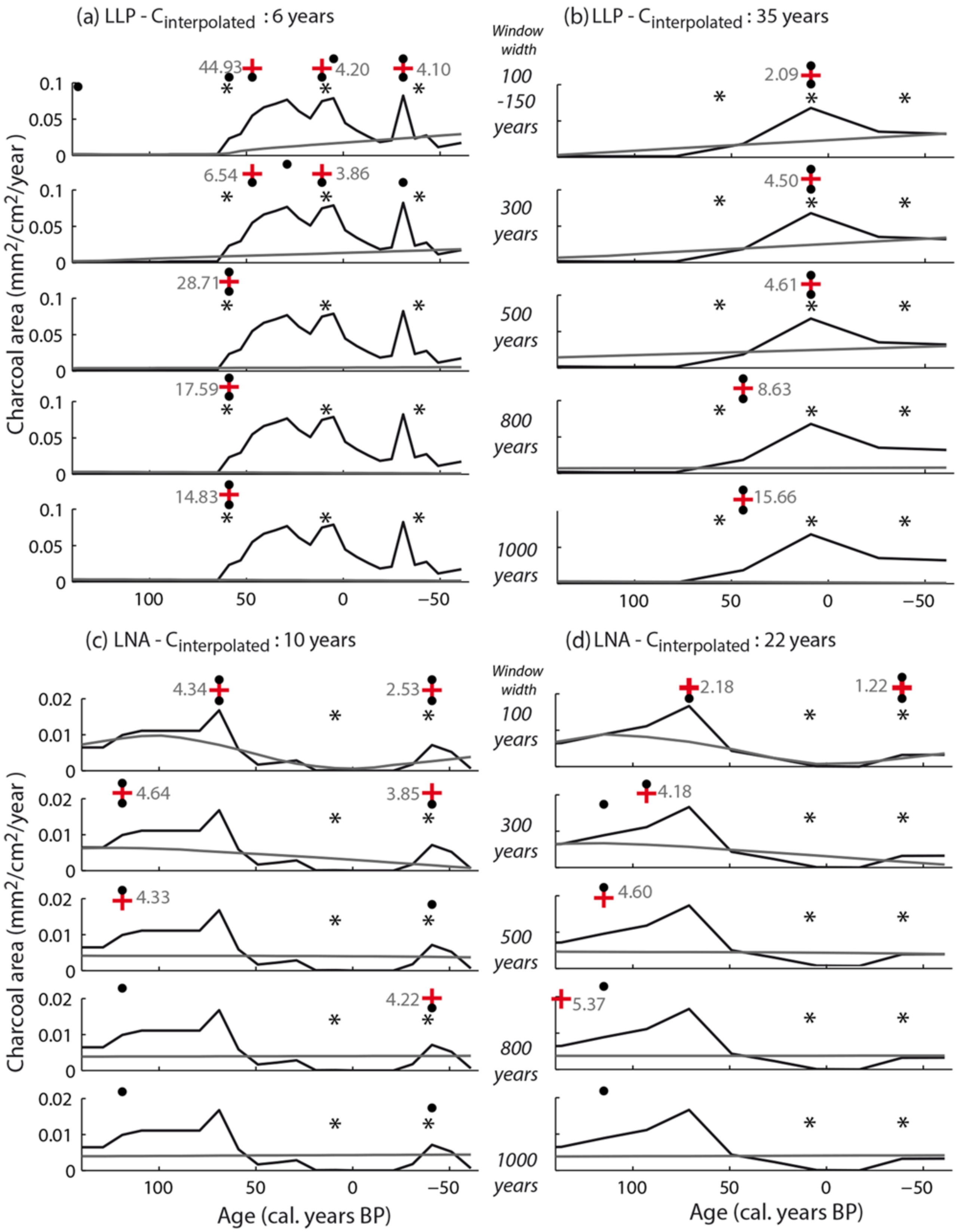

Figure 4. Interpolated charcoal accumulation rates ($C_{interpolated}$; black line), background noise (C_{back}; gray line), and detected fire events (+) for recent sediment deposits of (a and b) LLP and (c and d) LNA according to 10 model runs. Fires detected by dendrochronology are also shown with asterisks. Numbers above or beside detected fire events represent the local signal-to-noise index. Dots represent detected fires using 95th and 99.9th percentiles of the C_{noise} distribution as possible thresholds separating 'fire' and 'non-fire' samples. Two temporal resolutions were used for each lake to interpolate the CHAR series: (a and c) one corresponding to the median temporal resolution of the recent sediments (~last 150 years; Run_{KB}), and (b and d) one corresponding to the temporal resolution for the entire sequence (~7000 years; Run_{All}). Low-frequency variations (C_{back}) were computed using a robust LOWESS regression with 100-, 300-, 500-, 800-, and 1000-year windows, except for LLP where a 150-year window was used instead of 100-year window because of the model requirement that the lower value has to be at least three times greater than the median temporal resolution (35 years).
LNA: Lake Nano; LLP: Lake Loup.

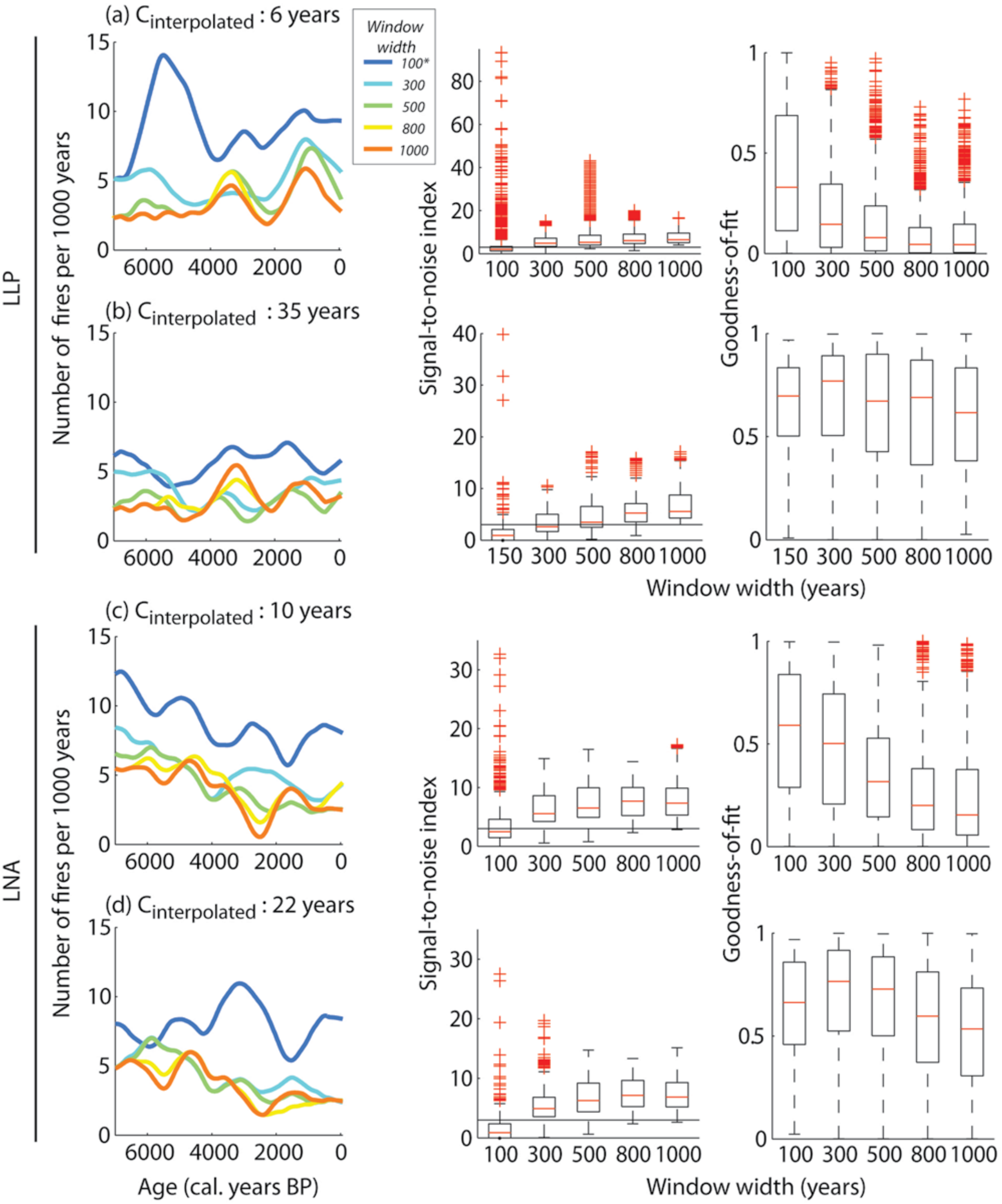

Figure 5. Fire frequency, global signal-to-noise index, and goodness-of-fit for (a and b) LLP and (c and d) LNA over 7000 years according to 10 model runs. Run_{KB} and Run_{All} are displayed in (a and c) and (b and d), respectively. A local 99th percentile threshold of the noise distribution was used. The horizontal bar corresponds to a signal-to-noise index value of 3.0. The goodness-of-fit is a *p*-value from a Kolmogorov–Smirnov test comparing the empirical and modeled C_{noise} distributions. A large *p*-value suggests that the two populations are from the same distribution. *A 150-year window for LLP was used instead of 100-year window because of the model requirement that the lower value has to be at least three times greater than the median temporal resolution (35 years).
LNA: Lake Nano; LLP: Lake Loup.

Multi-site and multi-proxy reconstructions

The fire event that occurred in AD 1890 at LNA was clearly identified in the charcoal record, but not in the tree-ring record. This oversight may be due, on the one hand, to the fact that cross sections were sampled from scarred living trees. Dendrochronological analyses indicated that the AD 1941 fire was likely severe in that particular area (Héon, 2010), which resulted in the establishment of a new cohort of trees (Agee, 1996; Smirnova et al., 2008). Thus, even if some trees survived the AD 1890 fire, they likely burned later during the AD 1941 fire. In the boreal forest, large fires include a mosaic of stands that have burned at different degrees of severity (Madoui et al., 2010). Such variation could explain why

Table 4. Two-sample comparisons of median fire-free intervals (Mann–Whitney (MW) test) and fire-free interval distributions (Kolmogorov–Smirnov (KS) test) for LLP and LNA using different smoothing windows for a fixed temporal resolution equivalent to that of (a) recent deposits (Run_{KB}) and (b) different temporal resolutions for fixed smoothing windows.

	LLP		LNA	
	MW test	KS test	MW test	KS test
(a) Window width				
$Run_{KB\ 100–300}$	<0.0001	<0.0001	0.0008	0.0002
$Run_{KB\ 100–500}$	<0.0001	0.0004	0.0001	0.0000
$Run_{KB\ 100–800}$	<0.0001	0.0001	<0.0001	0.0001
$Run_{KB\ 100–1000}$	<0.0001	0.0001	<0.0001	0.0001
$Run_{KB\ 300–500}$	0.5289	0.2401	0.2470	0.6631
$Run_{KB\ 300–800}$	0.1941	0.0836	0.3435	0.5861
$Run_{KB\ 300–1000}$	0.0977	0.0607	0.2696	0.3815
$Run_{KB\ 500–800}$	0.5199	0.9971	0.8541	0.9905
$Run_{KB\ 500–1000}$	0.3833	0.8511	1.0000	0.9995
$Run_{KB\ 800–1000}$	0.8730	1.0000	0.8487	1.0000
(b) Temporal resolution				
100_{KB-All}	<0.0001	<0.0001	0.3051	0.1896
300_{KB-All}	0.0687	0.2795	0.1540	0.3144
500_{KB-All}	0.0701	0.1461	0.8204	0.9903
800_{KB-All}	0.4191	0.5924	0.3428	0.3398
1000_{KB-All}	0.5257	0.7413	0.6376	1.0000

LNA: Lake Nano; LLP: Lake Loup.
p-values of the tests are reported. KB indicates recent sediments, All indicates entire sequence.

the AD 1890 fire was detected at LLP, where the AD 1941 fire was likely not severe enough to erase traces from the preceding event. However, we cannot exclude that the AD 1890 fire did not reach the lakeshore at LNA. Indeed, charcoal fragments can travel up to tens of kilometers from the flame front (Gardner and Whitlock, 2001; Whitlock and Millspaugh, 1996).

At LNA, the AD 1941 fire could not be detected in any model run, although it was likely a severe stand-replacing fire (Héon, 2010). According to the chronological setting of LNA, this fire should have been recorded at a depth of 4–5 cm in the KB core, where no charcoal was counted. We first interpreted this absence of charcoal particles as a result of an important spatial variability in charcoal deposition into the lake (Gardner and Whitlock, 2001; Whitlock and Millspaugh, 1996). However, a second attempt to extract charcoal from this level was successful. Unfortunately, samples accidentally dried between the first and second counts, thus preventing us to include the results of the second count into the series. We concluded that the charcoal detected in the second count could be due to increased concentration of particles after water loss, but we cannot exclude the above-mentioned sample effect.

The only way we could clearly identify all fire events was using, when it was possible, two proxies (dendrochronology and sedimentary charcoal) and a minimum of two sites. Hence, whenever possible, multi-proxy and multi-site studies should be favored.

Temporal resolution

Using the temporal resolution of the recent sediments (Run_{KB}) allowed us to detect almost all the fire events recorded by dendrochronological analysis (Figure 4). Re-sampling the records to a constant sedimentation rate allowed us to minimize the influence of changes in sediment accumulation through time, a technique frequently used to analyze time series (Carcaillet et al., 2001; Genries et al., 2012). However, the usual procedure of using the median temporal resolution of the entire sequence (Ali et al., 2009; Gavin et al., 2006) generally failed to detect recent fire events (Run_{All}). The important difference in temporal resolution between the entire sequence and the upper part, 29 and 12 years in LLP and LNA, respectively, could explain the difficulty to detect recent fire events when using the median temporal resolution from the entire sequence to interpolate the CHAR series. This also confirms that the optimal sampling interval for detecting individual fires should be <0.12–0.20 times the mFFI (Clark, 1988; Higuera et al., 2007). Indeed, the mFFI of the recent fire events in our study area was 49.5 years, corresponding to an optimal sampling interval <5.9–9.9 years, which matched the Run_{KB} ones. A solution to minimize the problem of changing sedimentation rates through time could be to separate the sediment sequences according to changes in temporal resolution, and to analyze the sections separately, being cautious in the interpretation of low-resolution sections. However, that would imply to use more sequence extremities in the statistical treatment, which are admitted to introduce a bias, as each level in the analysis depends on the preceding ones. An alternative subsampling procedure could be to take into account changes in sediment accumulation rates along the core. To do this, more efforts should be made to establish at which resolution a sediment core should be subsampled. For example, sediment records are increasingly being subsampled after the age–depth models are established, and each sediment slice may represent as close as possible to a defined sediment accumulation threshold (Finsinger et al., 2013; Hicks et al., 2004; Joosten and Klerk, 2007). Such a procedure, although being potentially more time-consuming and expensive, should be used when subsampling lacustrine sediment cores if the resolution of the proxy records is deemed to be critical.

Our analyses underlined that if the main goal is to obtain a general trend in fire activity, using a temporal resolution equivalent to the entire sequence does not seem problematic (Figure 5). Nevertheless, when the difference in median temporal resolution per sample between recent and complete sequence is high, discrepancies appear between fire reconstructions. At LLP, the highest fire frequency was recorded at 1000 cal. yr BP and at 4000 cal. yr BP in Run_{KB} and Run_{All}, respectively (corresponding to 6- and 35-year temporal resolutions, respectively, Figure 5a and b). However, the general trend in fire history was preserved, with more fire activity after 4000 cal. BP, regardless of the temporal resolution used.

Window width

The temporal window used to model C_{back} strongly affected the number of fire events detected. The C_{back} component can vary over time (from centennial to millennial timescales) because of changes in overall charcoal production, sedimentation, mixing, and sampling (Long et al., 1998). The estimation of the C_{back} component is generally guided by maximizing the SNI and the GOF. Usually, the wider the temporal window (500–1000 years), the higher the SNI (Ali et al., 2009; Gavin et al., 2006). Our results displayed the same trend. However, wide windows (500, 800, and 1000 years) failed to detect the recent fires. In addition, narrow windows (100–150 years) displayed a completely different Holocene fire history and had low global SNI (<3). Low SNI could be explained by the fact that the smoothing window used to model the background noise should be 2–5 times the mean to fully separate C_{back} from C_{peak} (Higuera et al., 2007).

Conclusion

Fire history reconstructions based on lacustrine sedimentary charcoal are made difficult by the various taphonomical processes involved in charcoal deposition into lakes. The use of rigorous and up-to-date numerical techniques may not prevent the underestimation of fire occurrence, notably for recent periods, even when maximizing the SNI. Hence, only considering settings with the highest SNI should not necessarily be the standard procedure. Variation in sample resolution (sedimentation rate) is the main impairment that practitioners must carefully consider when analyzing and interpreting CHAR series. Reconstructions of fire events should ideally focus on core sections presenting fairly constant sedimentation rates and resampling CHAR series to a constant sedimentation rate must be conducted with caution. Several combinations of smoothing windows and temporal resolutions can be used to draw a consensual fire history. We showed that using wide smoothing windows (>300 years) under various temporal resolutions (6–10 vs 22–35 years per sample) yielded comparable fire histories. Nevertheless, we cannot totally rule out the possibility that the fire history based on the narrowest smoothing window (100–150 years) was false, even if the median SNI over the last 7000 years was low. Here, the best compromise was obtained when using a 300-year smoothing window that provided relatively good SNI values (>3), allowed us to detect most recent fire events, and displayed a fire history similar to those obtained with wider smoothing windows (500, 800, and 1000 years). Thus, using the widest smoothing window, which allows us to detect the recent fire events and satisfy the statistical needs (maximizing SNI and GOF), must be the ultimate goal. Consequently, fire reconstructions based on lacustrine sedimentary charcoal analysis must be coupled with dendrochronological reconstructions to minimize false fire identification, notably for the recent period.

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