Charcoal dispersion and deposition in boreal lakes from 3 years of monitoring: Differences between local and regional fires

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Abstract To evaluate the influence of long-distance transport of charcoal particles on the detection of local wildfires from lake sediment sequences, we tracked three consecutive years of charcoal deposition into traps set within seven boreal lakes in northeastern Canada. Peaks in macroscopic charcoal accumulation ($>$150 μm) were linked to both local (inside the watershed) and regional wildfires. However, regional fires were characterized by higher proportions of small particles ($<$0.1 mm^2) in charcoal assemblages. We conclude that the analysis of particle size distribution is useful to discriminate "true" local fires from regional wildfires.

1. Introduction

Sediment-based fire history reconstructions can inform on long-term fire-climate-vegetation interactions in diverse ecosystems [*Aleman et al.*, 2013; *Ali et al.*, 2012; *Mooney et al.*, 2011]. This information is useful to guide future management decisions [*Bergeron et al.*, 2006; *Oris et al.*, 2014] or to understand biogeochemical cycles [*Bremond et al.*, 2010; *van Bellen et al.*, 2012]. An oft-used method to reconstruct spatially explicit fire histories involves the numerical analysis of continuous macroscopic charcoal ($>$120–150 μm) accumulation records (CHAR) with the so-called "decomposition approach" that aims at separating charcoal records into a "peak component" and a "background component" [*Clark and Royall*, 1996; *Long et al.*, 1998]. This method is based on the assumption that fire events can be inferred from the peak component because of the rapid settlement of wind-dispersed charcoal particles in lake sediments during a fire (primary deposition). However, the sediment charcoal record can be obscured by inputs from regional fires [*Clark and Royall*, 1996], as well as from secondary deposition as a result of surface runoff, sediment mixing, and redeposition within the lake [*Whitlock and Millspaugh*, 1996; *Whitlock and Anderson*, 2003] ("background" charcoal). The background component can spatially vary according to topography, lake characteristics, and differences in overall charcoal production between vegetation types, as well as temporally because of vegetation changes [*Umbanhowar and Mcgrath*, 1998; *Whitlock and Millspaugh*, 1996].

Theoretical models predict that charcoal dispersal distance decreases with increasing particle size and density [*Clark*, 1988; *Higuera et al.*, 2007]. The models have been validated by few empirical studies that have measured charcoal deposition following natural fires or prescribed burns, showing that the source area of large charcoal particles ($>$120–150 μm) is smaller than that of smaller particles [*Clark et al.*, 1998; *Gardner and Whitlock*, 2001; *Lynch et al.*, 2004]. Source areas strongly depend on injection height (i.e., the height of the smoke plume), which is influenced by fire intensity and the size of the area burned [*Peters and Higuera*, 2007; *Pisaric*, 2002; *Tinner et al.*, 2006].

Although theoretical dispersal models perform well for dispersal distances up to 200 m from the burn edge [*Peters and Higuera*, 2007], charcoal dispersal at distances $>$200 m is less well understood. Long-distance transport (5–20 km) has been reported [*Pisaric*, 2002; *Tinner et al.*, 2006], and charcoal peaks were recorded in lakes without their watersheds having burned [*Whitlock and Millspaugh*, 1996], suggesting that charcoal-source areas may be larger than previously assumed. In agreement with this, *Kelly et al.* [2013] found that although the maximum agreement between macroscopic charcoal-inferred fire frequency and area burned was reached for distances up to 1 km from lakeshore, it was robust up to 10 km. This can be explained by high-intensity fires developing a convection plume, which lifts charcoal particles higher, increasing the probability of long-distance dispersal and deposition in lakes downwind of the fire [*Peters and Higuera*, 2007; *Pisaric*, 2002; *Tinner et al.*, 2006].

An attempt to identify charcoal assemblages created by local fires was proposed by *Asselin and Payette* [2005], who suggested fitting a linear regression of the proportion of charcoal particle size against size classes (the charcoal size distribution (CSD) method). This method was based on previous observations that assemblages deposited nearer to burn edges contained higher proportions of large-sized charcoal particles than assemblages collected farther from burn edges [*Clark et al.*, 1998; *Lynch et al.*, 2004]. The slope of the linear regression could thus be used as an index of the site proximity from burn edge and should be less steep for a local fire compared to a regional fire or a nonfire year. Empirical studies would place the slope value threshold allowing to separate local fires from regional fires in circumboreal forests between −1.58 and −2.0 [*Asselin and Payette*, 2005; *Clark et al.*, 1998; *Lynch et al.*, 2004]. A further attempt to distinguish peaks caused by local and regional fires involves screening previously identified charcoal-area peaks using bootstrap resampling of charcoal-particle areas from samples around previously identified peaks [*Finsinger et al.*, 2014]. Peaks with total area significantly greater than expected by chance are deemed robust indicators of past local fire events. A stronger empirical basis is needed to fine tune these methods and to determine their potential for the detection of past local fire events.

Here we present the results of 3 year long charcoal accumulation records (2011 to 2013) from traps located within seven boreal lakes in northeastern Canada. Large wildfires occurred in the study area during the monitoring period [*Ministry of Natural Resources* (*MRN*), 2012], including a fire that burned within the watershed of one of the studied lakes up to lakeshore (Figure S1 in the supporting information) and several very large fires (>100,000 ha) that did not reach any of the studied watersheds (Figure S2 in the supporting information). We aimed at investigating the influence of area burned and distance to burn edge on annual charcoal deposition. We expected that charcoal size distribution would differ for local and regional fires, with the latter having a higher proportion of smaller particles. We then applied the CSD method [*Asselin and Payette*, 2005] and the charcoal-area peak-screening method [*Finsinger et al.*, 2014] to Holocene charcoal records available for two of the studied lakes for which information on the twentieth century local fires was available from a previous dendrochronological study [*Brossier et al.*, 2014].

2. Study Area and Methods

2.1. Study Area

The seven study sites are aligned along a south-north transect that spans a vegetation gradient from the spruce-moss to the spruce-lichen bioclimatic domains across the James Bay lowlands (northern Quebec, Canada) (Figure 1 and Table S1 and Text S1 in the supporting information). Data from the Matagami (49°46′N, 77°49′W; 281 m above sea level (asl)) and the La Grande Rivière (53°38′N, 77°42′W; 194 m asl) weather stations, respectively recorded mean (±SD) annual temperatures of −0.7 ± 2.7°C and −3.1 ± 1.9°C and mean annual precipitations of 905 mm and 684 mm, with approximately one third falling as snow (Series 1971–2000 [*Environment Canada*, 2011]). Dominant winds are from the west in the study area [*Mansuy et al.*, 2014]. Black spruce (*Picea mariana* (Mill.) B.S.P) dominates the regional land cover, along with jack pine (*Pinus banksiana* Lamb.) on drier sites. Specific surface-weather conditions related to anomalous circulation patterns in the upper atmosphere decrease fuel moisture and promote the occurrence of large wildfires (>200 ha) [*Canadian Forest Service*, 2011; *Johnson and Wowchuk*, 1993], with a ~100 year period of time needed to burn an area equivalent to the study area [*Mansuy et al.*, 2010; *Payette et al.*, 1989]. Area burned is also related to rainfall frequency, temperature, relative humidity, and to the passage of cold fronts characterized by a surface wind shift from southwest to northwest [*Flannigan and Harrington*, 1988].

2.2. Recent Fire History

We obtained the area burned by fires that occurred in 2010–2012 from the geographic information system (GIS) fire database of the Ministry of Natural Resources [*MRN*, 2012]. This database is available for fires with an area of ≥14 ha and is derived from air photos and satellite imagery. Only 3% of all boreal Canadian wildfires exceed 200 ha in size, yet these fires account for 97% of the total area burned [*Stocks*, 1991]. We measured the perimeters of the 2013 fires on a composite of Landsat 8 images (available from U.S. Geological Survey at http://glovis.usgs.gov/) taken on 15 and 22 July and on 25 and 26 September 2013. We also calculated the shortest distance between the studied lakes and the edges of the 2010–2013 fires (Table S2 and Table S3 in the supporting information). We calculated yearly area burned within areas defined by various radii (ranging from 1 to 100 km) around all study sites (Text S1 and Table S4 in the supporting information).
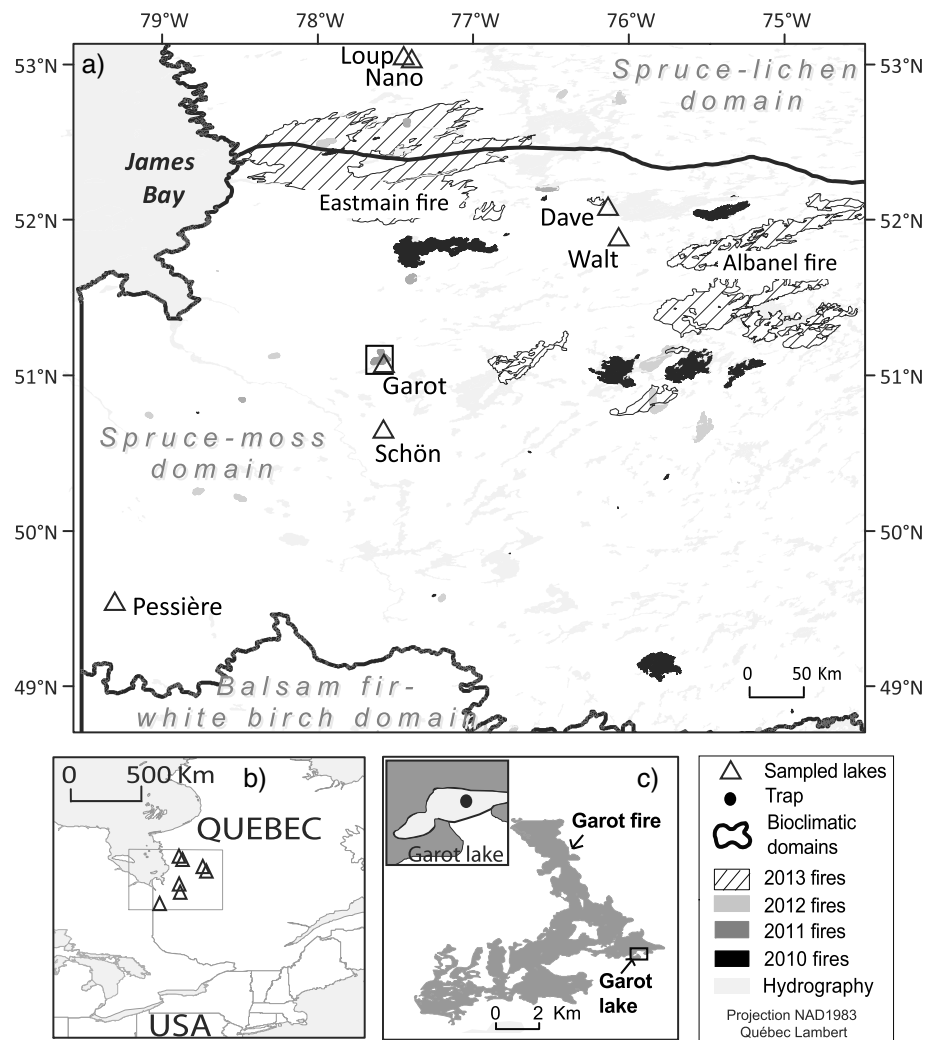
Figure 1. (a) Location of the studied lakes and of the fires having occurred in 2010–2013. (b) The location of the studied lakes in eastern North America is also presented. (c) A close-up of the Garot fire is also displayed.

2.3. Sampling Design

Our sampling design was inspired by that of *Giesecke and Fontana* [2008]. Lacustrine traps were installed in the center of the seven study lakes in September 2010, and trap content was collected once a year in September 2011, 2012, and 2013. Lacustrine traps consisted of two vertical plastic cylinders (length = 70 cm, diameter = 9 cm) inserted into two sampling bottles anchored to a weighted PVC plate (Uwitec Sampling Equipments), itself anchored at the lake's bottom (Figure S3 in the supporting information). Trap opening was placed about 1 m above the sediment-water interface and at least 1 m below the water surface to prevent the traps to be stuck in ice in winter. Once collected, trap contents were kept in a refrigerator at 4°C until analysis.

2.4. Macroscopic Charcoal Analysis

Trap contents were first gently sieved through a 150 μm mesh and then immersed in a 10% NaOCl aqueous solution to bleach organic matter and ease charcoal identification. The number and area of charcoal particles were measured under a binocular microscope (at magnification of 20) equipped with a camera and connected to a computer with an image analysis software (WinSeedle 2009, Regent Instruments Canada Inc.). We expressed charcoal particle abundance as accumulation rates by number or by area (CHAR, i.e., number of particles cm^{-2} yr^{-1} or mm^2 cm^{-2} yr^{-1}).

We transformed particle surface area into geometric mean diameters of charcoal particles by calculating the square root of particle surface area as suggested by *Clark and Hussey* [1996]. We then fitted a linear regression to the charcoal particle size distribution using a maximum of five evenly spaced classes ranging from −0.9 to 0.1 log mm (i.e., every 0.2 log mm). Thus, the model predicted the proportion of charcoal particles (response variable) for each size class. We expected the slope of the regression to be less steep for local fires that produce charcoal particle assemblages with a higher proportion of large particles [*Asselin and Payette*, 2005; *Clark et al.*, 1998; *Lynch et al.*, 2004].

We retrieved particle size distributions from previously published Holocene charcoal records available for two of the studied lakes (Loup and Nano Lakes; Figure S4 in the supporting information) [*Brossier et al.*, 2014; *Oris et al.*, 2014]. Charcoal accumulation rates (particles $cm^{-2} yr^{-1}$ or $mm^2 cm^{-2} yr^{-1}$) were analyzed with the CharAnalysis v1.1 software [available via http://sites.google.com/site/charanalysis/; *Higuera et al.*, 2009] (Text S1 in the supporting information). Following the above-mentioned method, we computed the slope of linear regressions of charcoal size distributions for samples that (i) were identified as fire events with the CharAnalysis software and (ii) contained more than 10 charcoal particles belonging to at least three size classes [*Clark et al.*, 1998]. We then used different slope values obtained from the charcoal assemblages recovered from the lacustrine traps to determine the appropriate threshold to identify local fire events. Specifically, a charcoal peak was rejected (i.e., considered not to be a "true" local fire) if the slopes of the charcoal size distributions of all the samples having contributed to that peak were steeper than the threshold used.

We also compared results based on different parameters of the charcoal-area peak-screening method [*Finsinger et al.*, 2014]. To screen the peaks, a bootstrap resampling of charcoal particle areas observed within a 900 year window centered on each charcoal area peak identified by CharAnalysis was used to obtain the range of likely charcoal areas for different counts. Significant charcoal area peaks were then defined as those that had a charcoal area significantly higher than the *p*th percentile threshold of the bootstrapped values. To test the sensitivity of the area-screening method, we used two different *p*th percentile thresholds $p = 0.95$ and $p = 0.90$.

To evaluate the sensitivity of the CSD and area-screening methods to changes in parameters, we focused our attention on local fire events (1890, 1941, and 1989 A.D.) identified by dendrochronological analysis [*Brossier et al.*, 2014]. We finally compared fire histories obtained from all methods by calculating fire return intervals (FRI).

3. Results

3.1. Recent Fire Occurrence

During the 3 year monitoring period, only one fire burned within the watershed of one of the study lakes (the 2011 fire at Garot Lake; Figure 1 and Figure S1 and Table S2 in the supporting information). The distance from this fire's edge to other study lakes was 54–212 km (Table S2 in the supporting information). In 2010, 2011, 2012, and 2013, shortest distances from burn to lake edge varied between 27–67 km, 0–157 km, 12–88 km, and 4–236 km, respectively (Table S3 in the supporting information). Although the 2013 Albanel fire burned only 4 km away from Dave Lake (Table S2 in the supporting information), it did not burn within the watershed. The large Eastmain fire was 32–57 km away from the shores of lakes Nano, Loup, Dave, and Walt (Figure S2 and Table S2 in the supporting information). During the monitoring period, most of the areas burned were >40 km from the study lakes (Table S4 in the supporting information).

3.2. Macroscopic Charcoal

Macroscopic charcoal accumulation rates displayed comparable trends when computed with particle number or area (Figure 2a and Figure 2b; Spearman's correlation coefficient $R^2 = 0.93$, $p < 0.0001$). At Garot Lake, CHAR values peaked 1 year after the local fire event. Whereas no fire occurred in the Nano Lake watershed during the monitoring period, macroscopic CHAR in 2013 was higher than peak CHAR values at Garot Lake (Figure 2a and Figure 2b). In 2013, CHAR was also higher than in previous years at Schön, Walt, Dave, and Loup Lakes but to a lesser extent than at Nano Lake (Figure 2a).

Charcoal particle areas varied from 0.023 mm^2 to 1.55 mm^2, but most were smaller than 0.4 mm^2 (Figure 2c). The distribution of particle areas at Garot Lake had a longer tail and higher median than at Nano Lake (Figure S5
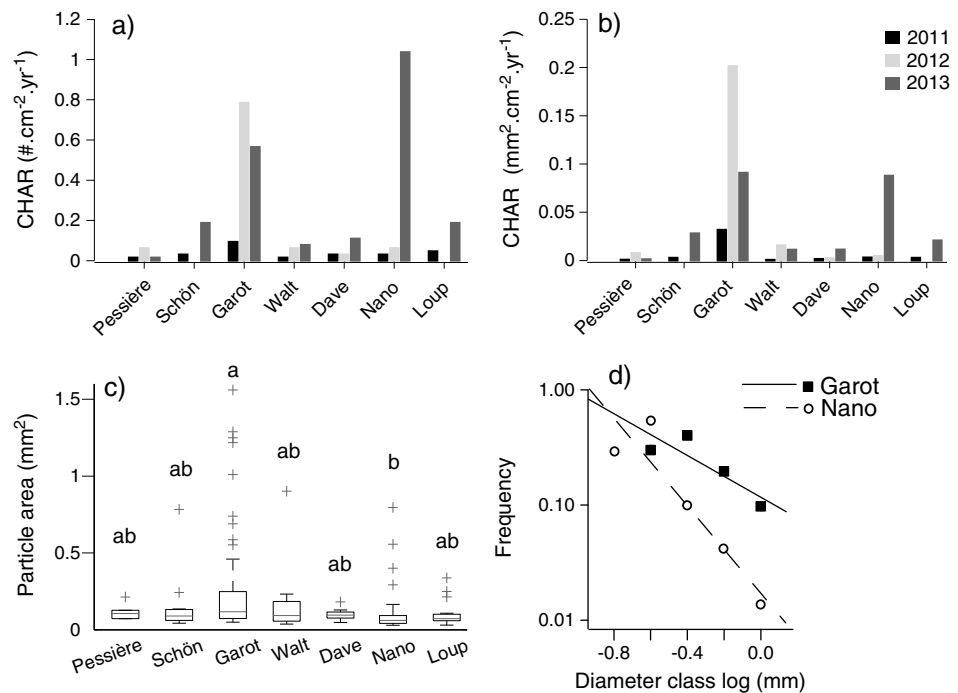
Figure 2. (a) Number and (b) total area of macroscopic charcoal particles deposited in lacustrine traps for each sampling year. (c) The box plots show the summed area of charcoal particles deposited in each lake during the three sampling years. Significant differences (Kruskall–Wallis test, d.f. = 6, H = 42.88, $p < 0.0001$) between lakes are shown by different letters. Only Garot and Nano Lakes have significantly different medians. Linear regressions on the size distributions of macroscopic charcoal particles (sum of the three sampling years) for (d) Nano (white circles and dashed line) and Garot (squares and straight line) Lakes are also shown.

in the supporting information). Due to the higher proportion of larger charcoal particles, the slope of the linear regression of particle size distribution was less steep for Garot Lake (slope = −0.90, R^2 = 0.76) than for Nano Lake (slope = −1.88, R^2 = 0.86) (Figure 2d).

3.3. Holocene Macroscopic Charcoal Records

The slope of the regression of macroscopic charcoal size distribution was calculated for samples corresponding to fire events recorded over 7000 years at Nano and Loup Lakes using CharAnalysis (Figure 3 and Table S5 in the supporting information [*Brossier et al.*, 2014]). To apply the CSD method, we used slope values obtained from charcoal assemblages recovered from traps and from local fire events (1890, 1941, and 1989 A.D.) detected by dendrochronological analysis [*Brossier et al.*, 2014]. At Nano and Loup Lakes, CharAnalysis detected two dendrochronological fires. We compared three different slope values as potential thresholds to detect true local fire events: (1) the slope of the charcoal size distribution at Garot Lake (−0.9), known to represent a local fire; (2) the slope of the charcoal size distribution at Nano Lake (−1.88), known to represent a regional fire; and (3) the median slope of the samples corresponding to the 1890 A.D. local fire detected by charcoal and dendrochronological analysis at Loup Lake (−1.77).

Only four and six fire events passed the −0.9 slope-screening test at Nano and Loup Lakes, respectively. With this threshold, only one fire detected by dendrochronology (at 60 calibrated years before present, hereafter cal yr B.P.) was detected at Nano Lake and none at Loup Lake. With a slope threshold of −1.77, 23 and 20 fire events were identified at Nano and Loup Lakes, respectively. With the −1.88 slope threshold, 25 and 20 fire events were identified at Nano and Loup Lakes, respectively. The −1.77 and −1.88 slope threshold values screened one (out of two) and two (out of two) fire events detected by CharAnalysis and dendrochronology at Nano and Loup Lakes, respectively. With the $p = 0.95$ area screening test, 13 and 10 fire events were detected at Nano and Loup Lakes, respectively. With $p = 0.90$, 24 and 12 peaks were identified at Nano and Loup Lakes, respectively. One and two of the CharAnalysis/dendrochronological fire events were, respectively, detected at Nano Lake using the $p = 0.95$ and $p = 0.90$ area screening thresholds, while
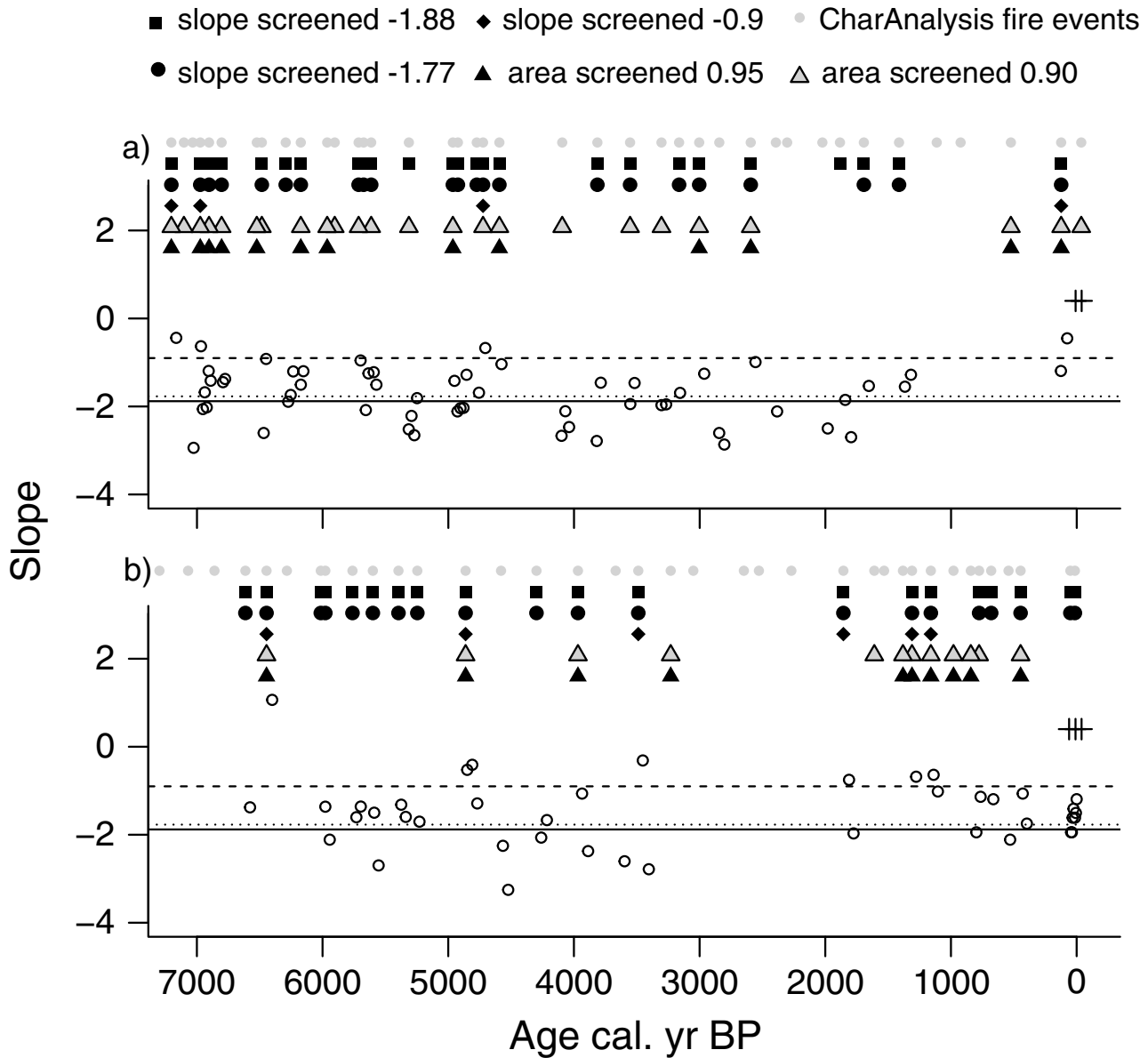
Figure 3. Slope values of linear regressions of charcoal size distributions obtained from each sample identified as a charcoal peak with CharAnalysis in (a) Nano and (b) Loup sediment sequences. Fires detected by dendrochronology are shown with crosses. Five different peak-screening methods were used to identify true local fire events. The straight, dotted, and dashed horizontal lines represent the slope thresholds of −1.88, −1.77, and −0.9, respectively.

none was detected at Loup Lake. Generally, all methods displayed the same trends at Nano Lake, with more frequent fire events detected between 7000 and 2500 cal yr B.P. (Figure 3a). At Loup Lake (Figure 3b), the −0.9 slope-screening test and both area-screening tests ($p = 0.95$ and $p = 0.90$) detected only a few fire events, leading to very long fire return intervals (Figure S6 in the supporting information). In summary, the −0.9 slope-screening and the $p = 0.95$ area-screening tests failed to detect most fires identified by dendrochronological analysis and yielded unrealistic (too long) FRI values. The −1.88 and −1.77 slope-screening tests and the $p = 0.90$ area-screening test retained similar numbers of fires and successfully detected most fires identified by dendrochronology. However, the $p = 0.90$ area-screening test produced longer FRI values for Loup Lake.

4. Discussion

We presented charcoal accumulation data in lakes from a region submitted to a regime of large, high-severity, stand-replacing wildfires [*MRN*, 2012]. The originality of our study resides in the monitoring of charcoal

accumulation in lakes during natural fires (i.e., traps were installed prior to fires) and collected during three consecutive years. Variability in size and distance of wildfires in our study area allowed us to discuss implications for the detection of local fire events in sediment records. The occurrence of particles with larger diameters in macroscopic charcoal assemblages was a good indicator of short dispersal distances and could be used to detect true local fire events as was previously assumed based on theoretical models and empirical studies [*Asselin and Payette*, 2005; *Clark*, 1988; *Clark et al.*, 1998; *Lynch et al.*, 2004].

4.1. Identifying True Local Fire Events From Macroscopic Charcoal Assemblages

Charcoal accumulation rates reported here were comparable to those recorded over the Holocene period in boreal lakes located south of our study area [*Ali et al.*, 2012; *Hély et al.*, 2010]. At Garot Lake, maximum macroscopic CHAR occurred 1 year after a 1684 ha local fire (2011), and high CHAR were also recorded during the following year (2013). A similar delay was observed after the 1988 Yellowstone fire, with a significant increase of charcoal accumulation during the 5 years following the fire [*Whitlock and Millspaugh*, 1996]. This could possibly be explained by a stronger influence of secondary deposition from surface runoff after the spring snowmelt, wind erosion of burned snags, or redeposition at lake bottom [*Bradbury*, 1996; *Whitlock and Millspaugh*, 1996].

A 2387 ha fire occurred in 2013, only 4 km away from Dave Lake, but outside the watershed. Studies have shown a relationship between macroscopic charcoal accumulation and the relative position of lakes with respect to fire (downwind versus upwind) [*Gardner and Whitlock*, 2001; *Whitlock and Millspaugh*, 1996]. Although Dave Lake was downwind of this fire, no macroscopic charcoal peak was recorded. Other parameters such as fire intensity or severity, wind strength, and lake area can influence the deposition of charcoal particles into a lake [*Gardner and Whitlock*, 2001]. Thus, even if the fire was close to the watershed, conditions were not reached to allow its detection from lake sediments.

Interestingly, a macroscopic charcoal peak was recorded at Nano Lake in 2013, although the distance to the closest fire (the large Eastmain fire) was 32 km (Tables S2 and S3 in the supporting information). Long-distance dispersal can occur because of the formation of a high convection plume above a fire, with intense and turbulent winds [*Clark*, 1988; *Peters and Higuera*, 2007]. Our data thus support theoretical modeling, indicating that the contribution of long-distance dispersal to CHAR peaks increases with fire size [*Peters and Higuera*, 2007]. Previous studies also evidenced long-distance (>5–20 km) transport of macroscopic charcoal particles [*Pisaric*, 2002; *Tinner et al.*, 2006]. *Whitlock and Millspaugh* [1996] noted a charcoal peak in lakes located 7 km downwind of the 1988 Yellowstone fire, but charcoal accumulation decreased beyond 13 km from the burn edge. However, both the Yellowstone area [*Whitlock and Millspaugh*, 1996] and the Swiss Alps [*Tinner et al.*, 2006] display higher topographic heterogeneity than the eastern Canadian boreal forest and may thus not provide the best analogs for comparing charcoal dispersal distance. Our data show that long-distance transport is possible up to 32 km, but maybe not much further as no charcoal peak was recorded at Loup Lake, only 4 km north of Nano Lake.

Macroscopic charcoal peaks in lacustrine deposits could thus represent fire events having occurred several kilometers outside the watershed (extralocal to regional scales), consequently inflating the local scale fire history. Hence, identifying charcoal peaks based on common peak-identification methods is not sufficient to guard against the occurrence of peaks produced by extralocal or regional fires [*Gavin et al.*, 2006; *Higuera et al.*, 2010]. Distinguishing local from regional fires is especially important for studies aiming at describing the incidence of fires on local vegetation dynamics as inferred from plant macrofossils [*Genries et al.*, 2012; *Senici et al.*, 2013]. If the goal is to obtain a regional fire frequency to compare with climatic data, the distinction between local and regional fires could be thought of as being less problematic as all fires having occurred within a region have to be included in this kind of analysis. However, if the same regional fire is recorded in several lake sediment profiles, the regional fire frequency can be overestimated.

Previous studies have suggested that peak magnitude could be used as an indicator of fire proximity [*Duffin et al.*, 2008; *Pitkänen and Huttunen*, 1999]. However, peak magnitude has also been related to other parameters such as fire size, intensity, and severity [*Colombaroli and Gavin*, 2010; *Duffin et al.*, 2008; *Higuera et al.*, 2005; *Pitkänen and Huttunen*, 1999]. Comparing CHAR at Nano and Garot Lakes indicated that the sum of particles was higher at Nano (regional fire) than at Garot (local fire) the year of the fire (2013 for Nano and 2011 for Garot). Hence, peak magnitude could not be used as a proxy to infer fire proximity to the lakeshores. Large

and severe regional wildfires could produce higher peaks than local fire events, underlining the difficulty to interpret peak magnitude data in palaeofire reconstructions.

More than 80% of the macrocharcoal particles in the trap installed at Nano Lake were <0.1 mm^2 compared to ~50% at Garot Lake. Large charcoal particles are usually dispersed at shorter distances compared to smaller ones [*Clark*, 1988; *Patterson et al.*, 1987; *Radke et al.*, 1991]. Analyzing charcoal size distributions may help differentiate local and regional fire peaks. Previous studies on charcoal size distribution reported that distributions with a slope less steep than −1.58 to −2.0 could indicate local fires [*Asselin and Payette*, 2005; *Clark et al.*, 1998; *Lynch et al.*, 2004]. Here we showed that most fires detected by dendrochronological analysis at Loup and Nano Lakes were also identified using slope thresholds of −1.88 and −1.77. The −0.9 threshold failed to detect local fires recorded by dendrochronological analysis and lead to FRIs (median = 2250 and 1374 years at Nano and Loup Lakes, respectively), considerably longer than current FRIs in our study area (about 100 years [*Payette et al.*, 1989]). Consequently, the optimal slope threshold to identify local fire events probably lies between −1.88 and −1.77.

The area peak-screening method with p = 0.9 allowed us to detect local fire events detected by dendrochronological analysis at Nano Lake and yielded results similar to those obtained with the −1.77 and −1.88 slope thresholds. However, at Loup Lake, the area peak-screening method displayed FRIs considerably longer than current FRIs in our study area (somehow like the −0.9 slope threshold) and failed to detect the local fires detected by dendrochronological analysis.

Charcoal-area peak-screening methods remove fire events initially detected by CharAnalysis that may correspond to distant wildfires. The two methods (CSD and area screening) strongly depend on the proportion of large particles in the charcoal assemblages. Therefore, local fires could go unnoticed if (1) a wildfire failed to produce high proportions of large particles due to in situ biomass structuring, (2) large charcoal particles were not included in lake sediments because of taphonomical processes and bathymetric characteristics of the lake, or (3) charcoal counts were too low. This is illustrated by the fact that the local fires identified by dendrochronological analysis at Loup Lake (1890 A.D. fire) produced charcoal distributions with a median slope of −1.77, compared to −0.9 at Garot Lake. The area peak-screening method seems to be more sensitive to the variability in the proportion of large charcoal particles, but could better account for changes in local vegetation as it uses variable thresholds instead of a fixed threshold as for the slope-screening method.

4.2. Implications for Fire History Reconstructions

Our study displayed long-distance dispersal of macroscopic charcoal particles (>150 μm) in boreal ecosystems during large and severe fire events. Consequently, macroscopic charcoal peaks recorded in lacustrine deposits could be related to both local and regional fire events. For studies aiming to reconstruct local fire events, a particular effort must be done to characterize particle size distributions, knowing that low proportions of larger particles (>0.1 mm^2) indicate regional wildfires. We showed that screening area-based CHAR peaks using either the slope of the particle size distribution [*Asselin and Payette*, 2005] or the peak-screening test [*Finsinger et al.*, 2014] can help identify true local fire events. The slope threshold we identified (between −1.88 and −1.77) is in line with those reported in previous studies conducted in the circumboreal forest (between −2.00 and −1.58 [*Asselin and Payette*, 2005; *Clark and Hussey*, 1996; *Clark et al.*, 1998; *Lynch et al.*, 2004]). Among the two percentile thresholds for the area-screening test, the p = 0.90 value seems preferable. Few studies have empirically validated the theoretical models of charcoal transport and deposition [*Clark et al.*, 1998; *Gardner and Whitlock*, 2001; *Lynch et al.*, 2004; *Ohlson and Tryterud*, 2000; *Whitlock and Millspaugh*, 1996]. Validation studies from a variety of biome/fuel types are highly needed. Also, as charcoal production could vary according to forest type or fire type [*Duffin et al.*, 2008; *Umbanhowar and Mcgrath*, 1998], studies in other forest ecosystems would allow to fine-tune the charcoal-area-screening tests.

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