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Short Paper

Comparing fire-history interpretations based on area, number and estimated volume of macroscopic charcoal in lake sediments

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ABSTRACT

Sedimentary charcoal particles from lakes are commonly used to investigate fire history. Fire-history reconstructions are based on measuring the surface area or counting the number of charcoal fragments in adjacent samples. Recently, the volume of charcoal particles was advised as a more accurate method for quantifying past charcoal production. Large charcoal datasets, used to synthesize global fire history, include these different types of charcoal measurements and implicitly assume that they provide comparable fire-history information. However, no study has demonstrated that this assumption is valid. Here we compare fire-frequency reconstructions based on measurements of charcoal area and number, and estimates of charcoal volume from two lake sediment records from the eastern Canadian boreal forest. Results indicate that the three proxies provide comparable fire-history interpretations when using a locally defined threshold to identify fire events.

Introduction

Since the studies of Clark (e.g., 1988), sedimentary charcoal records from lake sediments have been widely used to reconstruct past fire regimes. In combination with other paleo-environmental proxies, macroscopic charcoal is used to analyse climate–fire–vegetation linkages (e.g., Clark and Royall, 1995; Gavin et al., 2006), prehistoric human practices (e.g., Pitkänen and Huttunen, 1999; Wick and Möhl, 2006), and the contribution of biomass burning to the global carbon cycle (Clark et al., 1996; Pitkänen et al., 1999; Carcaillet et al., 2002).

Two main approaches have been used to estimate charcoal concentrations in lake sediments, identifying charcoal on pollen slides (<75-μm diameter) and identifying "macroscopic" charcoal particles >≈ 150-μm diameter. The first approach yields information on regional-scale fire history, up to hundreds of km from lakeshores and is time-consuming and inefficient for high-resolution studies (Carcaillet et al., 2001a). The sieving method is used to detect local-scale fires, i.e. ≈1 km from the lakeshores (Higuera et al., 2007). In both approaches, charcoal particles are quantified by area (e.g., Carcaillet et al., 2001b; Lynch et al., 2004a) or by counting (e.g., Long et al., 1998; Gavin et al., 2006). Some studies indicate that the number and the area of charcoal particles are significantly correlated (Tinner and Hu, 2003; Carcaillet, 2007), and thus the two methods should provide comparable fire-history interpretations.

Recently, Weng (2005) presented a simple equation to estimate charcoal volume based on area measurements, introducing yet another possible metric by which to quantify charcoal accumulation. Weng (2005) further suggested that charcoal volume is a better proxy of biomass burning than either charcoal area or number, because the latter are more sensitive to fragmentation processes resulting from transportation, sedimentation and laboratory treatments.

No study has tested whether number, area and volume measurements from macroscopic charcoal provide comparable fire-history reconstructions. This methodological consideration is crucial when inferring global-scale fire histories based on datasets that include diverse quantification methods (Marlon et al., 2008; Power et al., 2008). To address this issue we reconstruct fire history using these three charcoal quantification methods, namely number, area, and estimated volume, on lake sediments from two small, deep kettle lakes from the eastern Canadian boreal forest.

Materials and methods

Study sites

Lac Profond (L. Profond) and Lac Raynald (L. Raynald) are situated 200 km south of the James Bay in western Quebec, Canada (Ali et al.,

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2009). The lakes were chosen because of their small surface areas, large water depths (Table 1) and the absence of inlet and outlet streams. The lakes are located in the flat eastern boreal shield region, along the Harricana River (Table 1). Black spruce (*Picea mariana*) forest dominates the area with scattered balsam fir (*Abies balsamea*) and eastern white cedars (*Thuja occidentalis*) along the lakeshores and rivers, and jack pine (*Pinus banksiana*) woodlands on dry and sandy soils.

Sampling and charcoal quantification

Lake sediments were extracted with a Livingstone corer from the frozen lake surfaces in 2006. A Kajak-Brinkhurst (KB) gravity corer was used to accurately sample the sediment–water interface. Cores were sliced into continuous 1.0- (L. Raynald) or 0.5-cm (L. Profond) thick sub-samples, based on the expected resolution (*ca.* 15 yr) estimated by the total organic core length (L. Profond: 223 cm; L. Raynald: 472 cm). For charcoal analysis, 1 cm^3 was used from each sub-sample and soaked in a 3% $(NaPO_3)_6$ solution for a minimum of two days before wet-sieving through a 160-μm screen. The remaining particles were bleached in a 10% NaOCl solution to aid in distinguishing charcoal from dark organic matter. Peaks in charcoal fragments >160 μm are assumed to represent fires <1 km from the lakeshore (Lynch et al., 2004b; Higuera et al., 2007). Identification, counting and area measurements of charcoal particles were done under a 20× stereoscope coupled with a digital camera and image-analysis software (Regent Instruments Canada Inc.). The charcoal volume ($V_{charcoal}$) for each sample was estimated based on Weng's equation (Weng, 2005):

$$V_{charcoal} = \sum A_i^{3/2} \quad (1)$$

where A_i is the surface area (mm^2) of each charcoal particle (i) in a given sample (i.e., stratigraphic level). Charcoal measurements are reported both as charcoal concentration in area ($mm^2\ cm^{-3}$), number (# cm^{-3}) and volume ($mm^3\ cm^{-3}$), and as charcoal influx (CHAR) based on numerical age-depth models ($CHAR_a$: $mm^2\ cm^{-2}\ yr^{-1}$; $CHAR_\#$: # $cm^{-2}\ yr^{-1}$ and $CHAR_v$: $mm^3\ cm^{-2}\ yr^{-1}$). At each site, KB and Livingstone cores were cross-correlated using area charcoal concentrations ($mm^2\ cm^{-3}$).

Dating and chronologies

Chronologies were based on six ^{14}C AMS dates on plant macro-remains per lake (i.e., needles, seeds, twigs, and wood fragments; Table 2), calibrated to calendar years using CALIB 5.0.1 (Stuiver and Reimer, 1993) and the IntCal04 dataset (Reimer et al., 2004). Ages are reported as intercepts with 2σ ranges and age–depth models were based on a smoothing function fit to the calibrated dates.

Historic fire frequency

Statistical treatments of charcoal data

Charcoal records ($CHAR_a$, $CHAR_\#$ and $CHAR_v$) were decomposed into background ($C_{background}$), and peak (C_{peak}) components, and a locally defined threshold based on universally applied criteria was used to identify charcoal peaks likely related to the occurrence of one or more local fires (i.e., "fire events" within *ca.* 1 km). These methods are described in detail by Higuera et al. (2008, 2009) and summarized below. Prior to decomposition, charcoal data were interpolated to constant 15-yr time steps, corresponding approximately to the median temporal resolution of each record.

Low-frequency variations in a charcoal record, $C_{background}$, represent changes in charcoal production, sedimentation, mixing, and sampling, and were subtracted to obtain a residual series, C_{peak} (i.e., $C_{peak} = C_{interpolated} - C_{background}$). Consistent with theoretical evidence (Higuera et al., 2007) and previous work (e.g., Gavin et al., 2006; Higuera et al. 2008, 2009), we assume that C_{peak} is composed of two subpopulations: C_{noise}, representing variability in sediment mixing, sampling, and analytical and naturally occurring noise; and C_{fire}, representing charcoal input from local fires. For each sample, we used a Gaussian mixture model to identify the C_{noise} distribution. We considered the 95th, 99th, and 99.9th percentiles of the C_{noise} distribution as possible thresholds separating samples into "fire" and "non-fire" events, but chose the 99th percentile for simplicity and because between-record differences were similar based on all three threshold criteria. We estimated $C_{background}$ with a locally weighted regression using a 400- or 500-yr window. For each record, we chose the window width that maximized a signal-to-noise index and the goodness-of-fit between the empirical and modeled C_{noise} distributions (Higuera et al., 2009). We did not screen peaks based on the original charcoal counts of each peak, as in Higuera et al. (2008, 2009), because this procedure is specific to charcoal count data only. All statistical treatments were done using the program CharAnalysis, written by PEH and freely available at http://CharAnalysis.googlepages.com.

Reconstructing fire history

Fire history was described by plotting fire-free intervals (years between two consecutive fire events; FFI) over time and smoothing this series using a locally weighted regression with a

Table 1
Main characteristics of L. Profond and L. Raynald.

	Lac Profond	Lac Raynald
Latitude	49°51′40.1″N	49°48′33.4″N
Longitude	78°36′47.9″W	78°32′09.0″W
Elevation (m a.s.l.)	270	250
Hillslopes	Flat	Moderate
Lake surface (ha)	0.6	1.5
Water depth (m)	>20[a]	10.28
Length of organic core (cm)	223	472
Mean deposition time (SE) yr/cm	18.3 (±0.50)	15.2 (±0.30)

[a] Core was collected from a water depth *ca.* 10 m.

Table 2
AMS ^{14}C dating from, L. Profond and L. Raynald.

Site and depth (cm)	^{14}C yr BP (±σ)	Range of calibration (cal yr BP; 2σ)	Materials dated	Laboratory code
Lac Raynald				
52–54	1350 ± 50	1340–1180	Plant macroremains	Beta-231638
121–122	2160 ± 40	2310–2040	Plant macroremains	Beta-231639
202–206	2970 ± 40	3260–3000	Plant macroremains	Beta-231640
300–305	3760 ± 40	4240–3990	Plant macroremains	Beta-231641
439–441	5370 ± 40	6280–6010	Plant macroremains	Beta-231642
461–465	6040 ± 40	6990–6790	Plant macroremains	Beta-231643
Lac Profond				
53–54.5	1230 ± 40	1270–1060	Plant macroremains	Beta-228817
99.5–100	2170 ± 40	2320–2050	Plant macroremains	Beta-231644
124.5–127	2760 ± 40	2950–2770	Plant macroremains	Beta-228818
172–172.5	2850 ± 40	3070–2860	Plant macroremains	Beta-228819
212.5–215	3460 ± 40	3840–3630	Plant macroremains	Beta-231645
222–222.5	3720 ± 40	4220–3970	Plant macroremains	Beta-228820

1000-yr window (approximating the mean FFI). We used a non-parametric Kolmogorov–Smirnov test to evaluate the null hypothesis that any two FFI distributions, based on different charcoal metrics from the same site, did not differ statistically. Although the nature of the FFI distribution may have changed through time, we use this global test to evaluate if fire-history reconstructions based on the three different charcoal metrics provide statistically similar results.

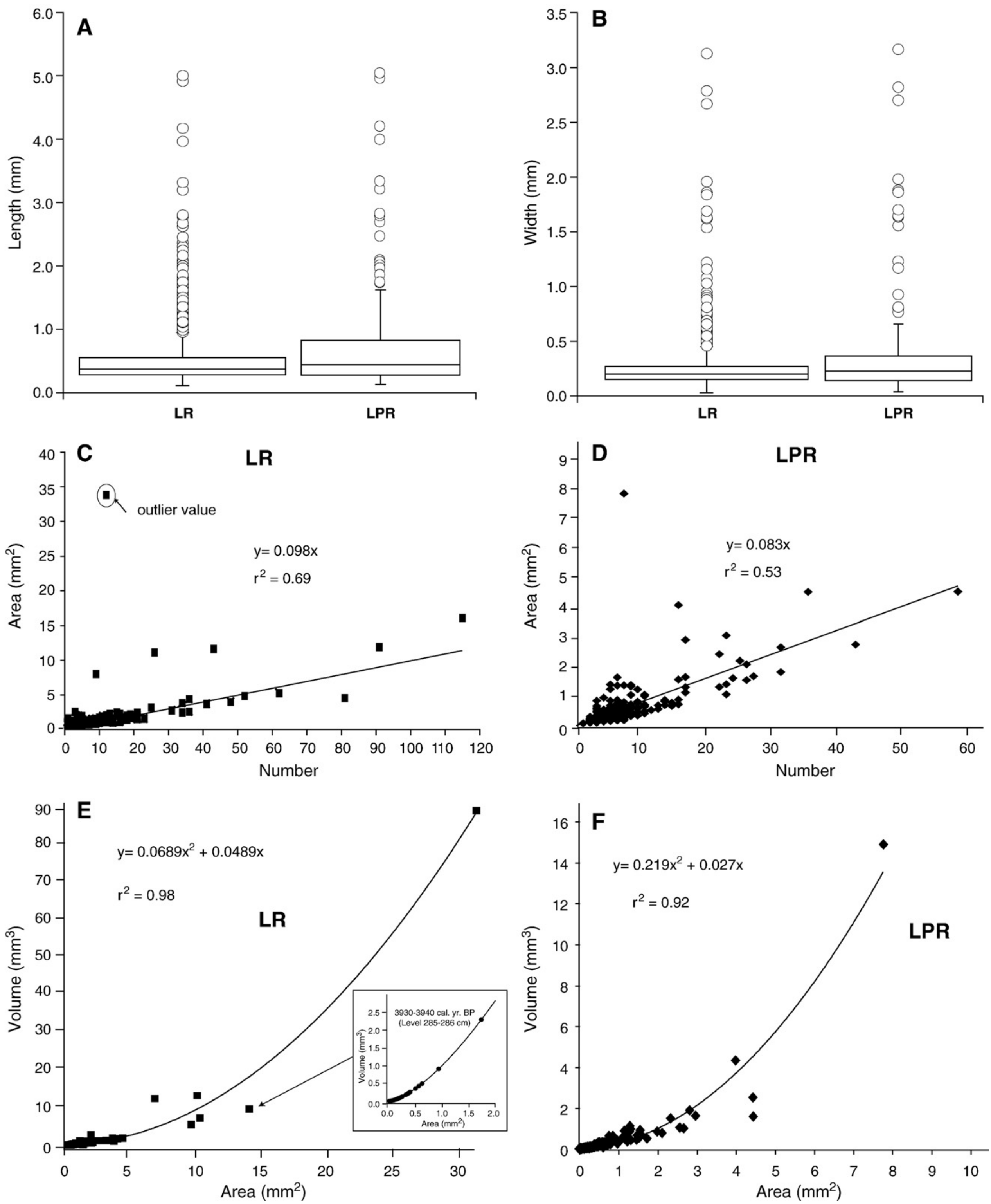

Figure 1. (A, B) Box-and-whisker plots displaying the variation of length and width of particles recorded in the sediments of L. Profond (LPR) and L. Raynald (LR). Boxes identify the 25th, 50th, and 75th percentiles, whiskers identify the 10th and 90th percentiles, and dots identify outlier values. (C, D) Number versus area of charcoal concentrations for the different levels analyzed at both sites. Area and number values are significantly correlated (r^2>0.5, p<0.0001). (E, F) Total area versus estimated volume concentrations for the different levels analyzed at both sites. Area and estimated volume values are significantly correlated (r^2>0.95, p<0.0001). The inset in (E) shows the geometric relationship between particle area and estimated volume at level 285–286 cm, based on Eq. (1).

To test if the temporal trends in peaks between the different charcoal metrics (within a given record) were similar, we quantified the degree of synchrony between fire events deduced from the three charcoal metrics using a bivariate Ripley's *K*-function modified to one dimension (i.e., time, as by Gavin et al. (2006)). The modified bivariate *K*-function allows several fire records to be compared in order to detect synchrony of fire events within multiple temporal windows ($\pm t$ yr). If different charcoal quantification metrics do not significantly affect fire-history interpretations, then temporal trends in peaks should be synchronous at multiple time scales; alternatively, if different metrics result in different fire-history interpretations, then temporal trends should be independent. The *K*-function was transformed to an *L*-function, $\hat{L}_{AB}(t)$, to facilitate interpretation of the results by stabilizing the mean and variance of the *K* value outputs. Confidence intervals (95%) for $\hat{L}_{AB}(t)$ were constructed by shifting each record a random number of years and wrapping events from the end to the start of the record 1000 times. $\hat{L}_{AB}(t)$ values >0 suggest synchronous patterns in fire occurrences at time scales of $\pm t$, while values near 0 and <0 indicate independence and asynchrony in fire occurrences, respectively. All analyses were performed using a modification of the K1D program (unpublished program, D.G. Gavin, U. of Oregon) in Matlab software (Mathworks, Inc.).

Results and discussion

Charcoal particle size

Charcoal particles were parallelepiped in shape (Figs. 1A, B), with mean length-to-width ratio of *ca.* 2.30 ± 0.06. This suggests that fires burned mostly woody vegetation dominated by conifer species, rather than grassland vegetation or vegetation dominated by broadleaf species (Umbanhowar and McGrath, 1998). Lengths varied

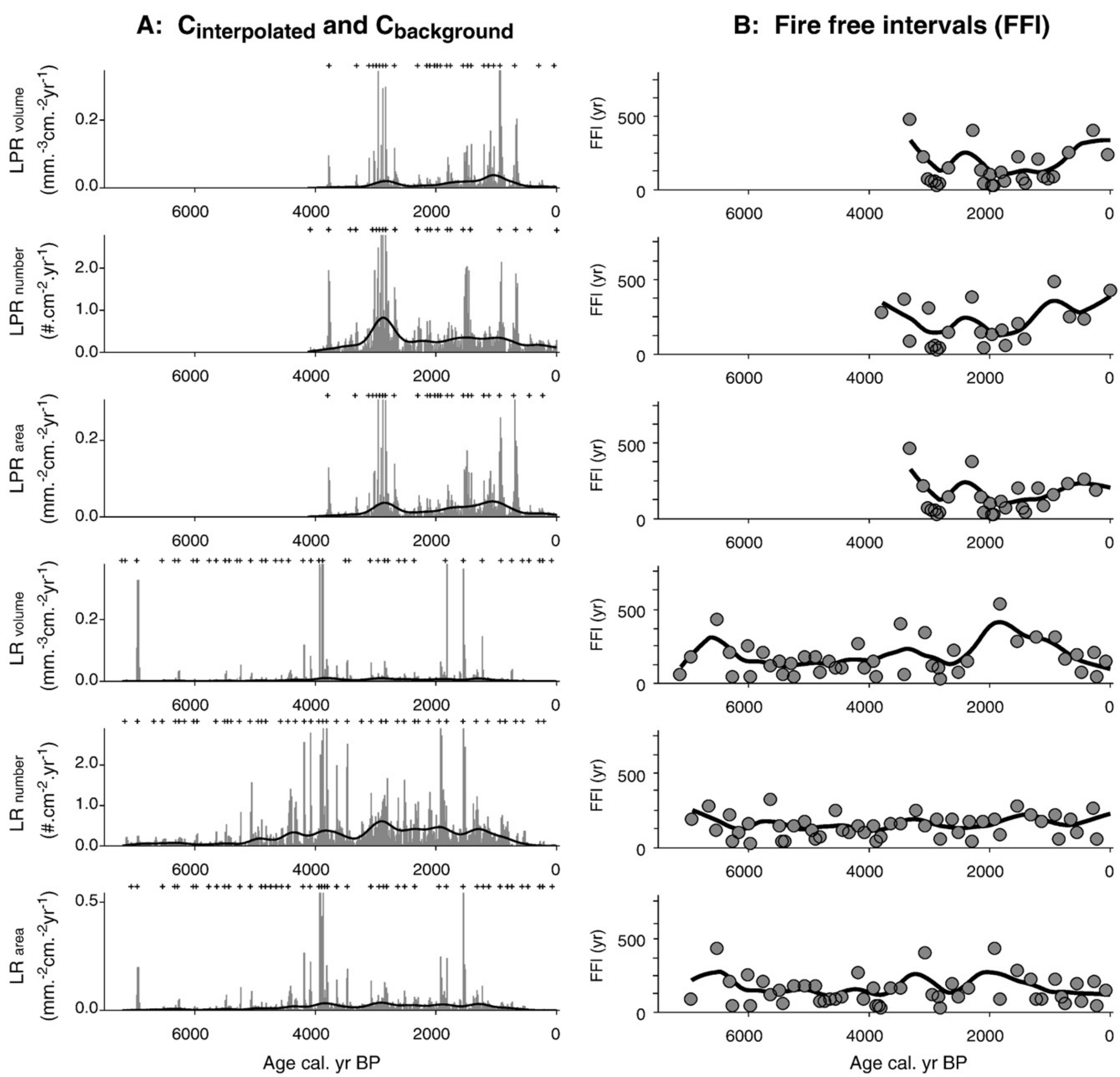

Figure 2. (A) Charcoal records for L. Profond (LPR) and L. Raynald (LR), including $C_{interpolated}$ (grey), $C_{background}$ (black), and reconstructed fire events ("+" symbols). Each charcoal quantification metric is identified by the subscript "area", "number", or "volume". (B) Corresponding fire-free-intervals (circles) over time, with a locally weighted 1000-yr averages (dark heavy lines).

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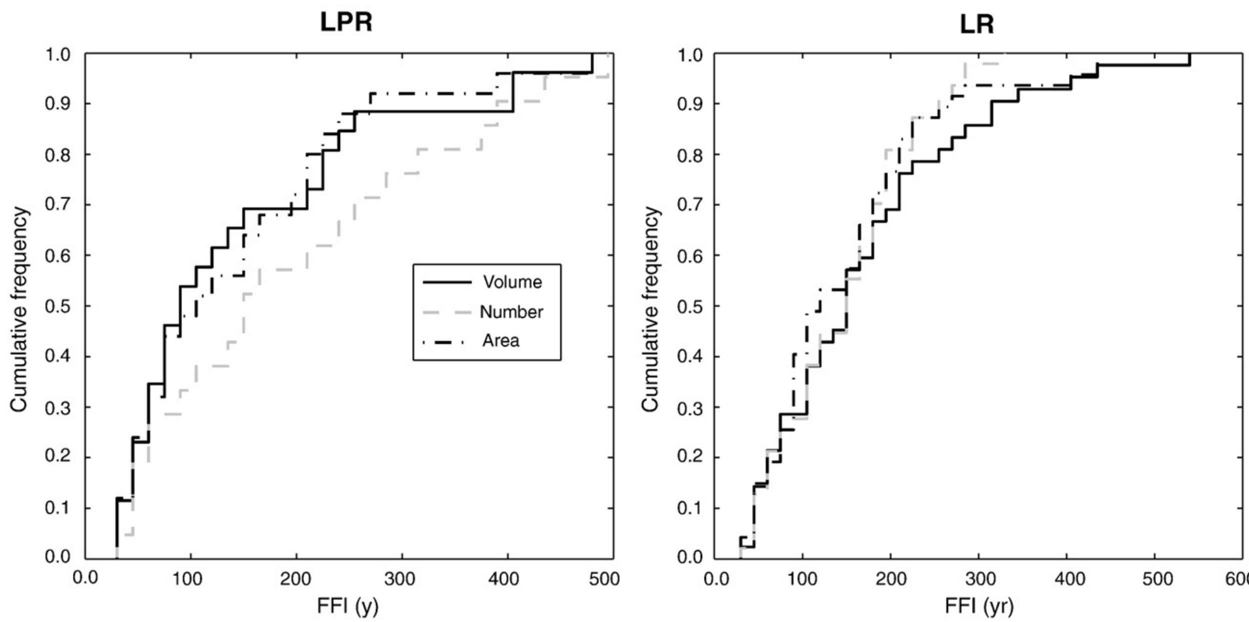

Figure 3. Empirical cumulative distribution functions (CDF) for fire-free interval values (FFI) from L. Profond (LPR) and L. Raynald (LR). Area, number, and volume quantification metrics provide comparable fire-free interval CDFs, as inferred from pairwise comparisons using a two-sample Kolmogorov–Smirnov test (p>0.49).

between 0.10 and 5.00 mm and widths varied between 0.03 and 3.00 mm (Figs. 1A, B). Charcoal particles likely originated from fires affecting local vegetation, but we cannot rule out the possibility of long-distance transport of particles, particularly in the smaller size classes, of several kilometres (Tinner et al., 2006; Higuera et al., 2007).

Area, number and volume relationships

Charcoal concentration measured by number (# cm^{-3}) and area (mm^2 cm^{-3}) were well correlated at both sites (r^2>0.5, p<0.0001; Figs. 1C, D). This result supports previous studies reporting strong correlations between the number and area of charcoal particles (Tinner and Hu, 2003; Carcaillet, 2007). Nevertheless, linear regressions linking these two descriptors differed between sites, indicating the difficulty in predicting total charcoal area of a sample with a single equation, as suggested by Tinner and Hu (2003) for pollen-slide charcoal. Taphonomic processes affecting charcoal fragmentation likely explain the site-specific relationships between charcoal number and area.

Charcoal concentrations as measured by surface area (mm^2 cm^{-3}) and estimated volume (mm^{-3} cm^{-3}) were also well correlated, based on exponential relationships (r^2>0.95, p<0.0001; Figs. 1E, F). Similarity between volume and surface area measurements was expected, given that volume estimates are derived from measurements of charcoal surface area (Weng, 2005). The relationship between area and estimated volume is not direct, however, because values represent the sum of all charcoal pieces in a given sample, with each piece of charcoal having a unique volume estimate based on Eq. (1). When considering individual pieces of charcoal within a single sample (e.g., Fig. 1E inset), the expected direct geometric relationship is apparent. Summing individual area and volume estimates and then comparing across a record (i.e., Figs. 1E, F) does not produce a direct relationship because of the unequal influence of large versus small charcoal pieces in Eq. (1). Indeed, if this was not the case, then Weng's (2005) suggestion would be no different than a uniform transformation of the charcoal area series.

The most important aspect of the Weng method is that the estimated volume significantly reduces the impact of fragmentation processes in charcoal concentration (or influx). Even if this method is not commonly used, the mathematical and experimental demonstrations by Weng (2005) are clear and convincing. The principal limitation is that the estimated volume is strongly dependent on the fuel features (grass versus hardwood) and it is quite difficult in palaeoecology investigations to characterize this parameter due to potential short or longer-term vegetation changes. Nevertheless, based on Weng's (2005) findings, the use of the equation without accounting for fuel characteristics still provides a significant improvement in quantifying charcoal deposition.

Fire history

At L. Profond, peak analysis based on $CHAR_a$, $CHAR_\#$ and $CHAR_v$ identified 26, 22, and 27 fire events, respectively (Fig. 2A). At L. Raynald, peak analysis based on $CHAR_a$, $CHAR_\#$ and $CHAR_v$ identified 48, 48 and 41 fire events, respectively. At both sites, the FFI series display comparable long-term trends (Fig. 2B), and comparisons of FFI distributions using a KS-test (Fig. 3) fail to reject the null hypothesis of no difference between proxies within each site (p>0.49).

The patterns of peak frequencies based on the three different charcoal proxies within each site were synchronous from decadal through millennial time scales (p<0.05; Fig. 4). Synchronous patterns were also evident when only two proxies were compared within each site (e.g., number and area; data not presented). Synchronous patterns across a range of time scales indicate that interpretations of fire frequencies through time would vary little based on analysis of the three different charcoal proxies.

Conclusion

While volume may be the most precise estimate of charcoal accumulation for biomass burning (Weng, 2005), our results indicate that measuring charcoal accumulation rates by area, number or estimated volume all provide comparable fire-history interpretations when using a locally-defined threshold to infer fire occurrence. While the nature of the charcoal records varies between proxies, the analytical techniques used to identify peaks in CHAR are insensitive to this variability. Consequently, comparisons between records using

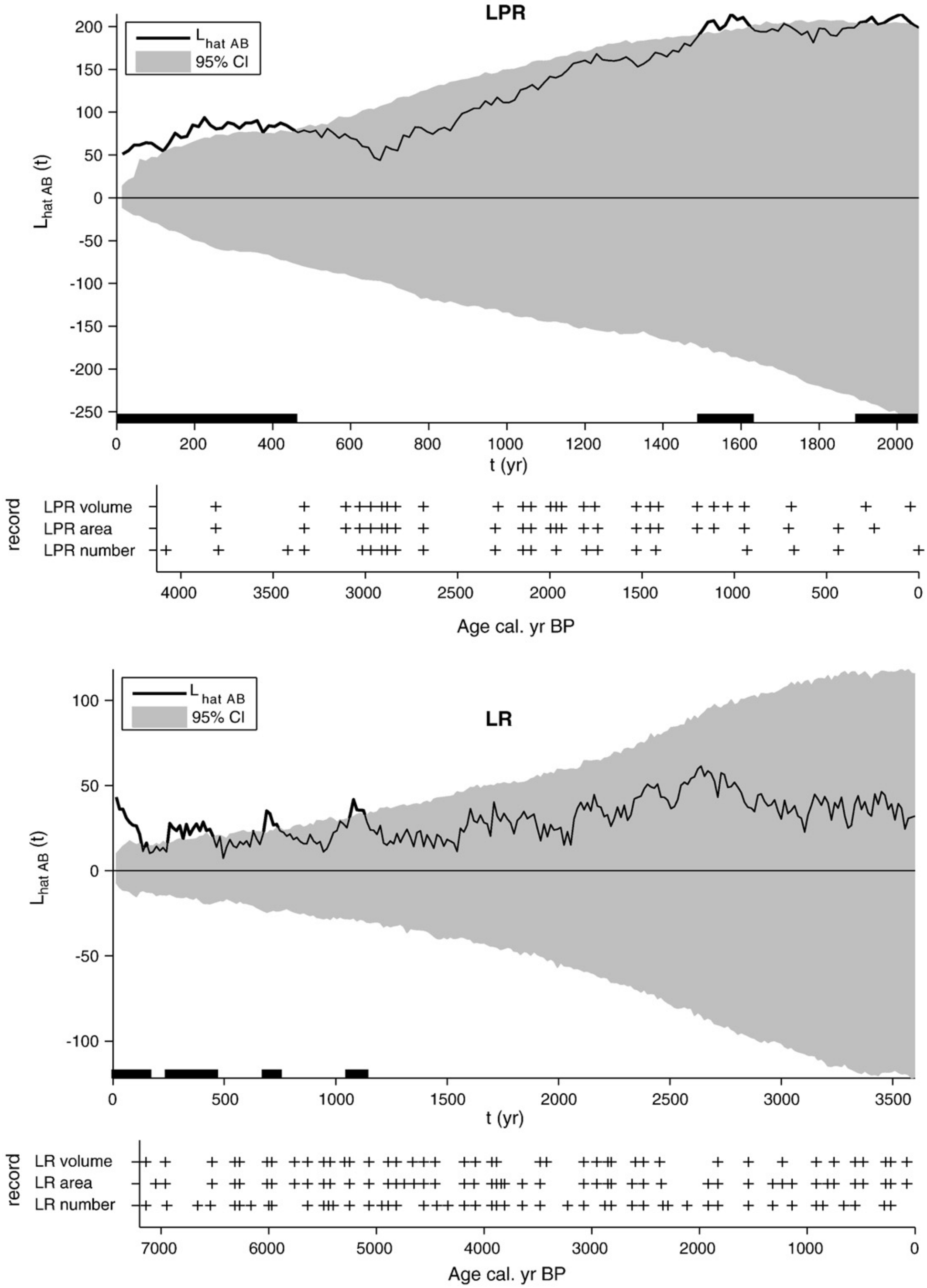

Figure 4. Bivariate *L*-function (black line, bold and non-bold) for reconstructed fire events based on different charcoal quantification metrics at L. Profond (LPR) and L. Raynald (LR). Grey areas correspond to 95% confidence intervals (CI) around $\hat{L}_{AB} = 0$ (i.e., independence), and bold lines identify $\hat{L}_{AB}$ values significantly greater than 0, indicating synchrony at time windows of $\pm t$. The "+" symbols in the lower panels correspond to reconstructed fire events from the three charcoal quantification metrics.

these three charcoal quantification methods can be done without misleading interpretations related to methodology. This opens the door for synthesizing peak-inferred fire occurrence from multiple records using different charcoal quantification methods (e.g., Marlon et al., 2009), so long as analytical techniques are insensitive to variation in the mean and variability both within and between charcoal series.

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References

Ali, A.A., Carcaillet, C., Bergeron, Y., 2009. Long-term fire frequency variability in the eastern Canadian boreal forest: the influences of climate vs local factors. Global Change Biology 15, 1230–1241.

Carcaillet, C., 2007. Charred particles analyses. In: Elias, S.A. (Ed.), Encyclopedia of Quaternary Science. Elsevier, Amsterdam, pp. 1582–1593.

Carcaillet, C., Almquist, H., Asnong, H., Bradshaw, R.H.B., Carrión, J.S., Gaillard, M.J., Gajewski, K., Haas, J.N., Haberle, S.G., Hadorn, P., Muller, S.D., Richard, P.J.H., Richoz, I., Rösch, M., Sánchez Goñi, M.F., von Stedingk, H., Stevenson, A.C., Talon, B., Tardy, C., Tinner, W., Tryterud, E., Wick, L., Willis, K.J., 2002. Holocene biomass burning and global dynamics of the carbon cycle. Chemosphere 49, 845–863.

Carcaillet, C., Bergeron, Y., Richard, P.J.H., Fréchette, B., Gauthier, S., Prairie, Y.T., 2001b. Change of fire frequency in the eastern Canadian boreal forest during the Holocene: does vegetation composition or climate trigger the fire regime? Journal of Ecology 89, 930–946.

Carcaillet, C., Bouvier, M., Fréchette, B., Larouche, A.C., Richard, P.J.H., 2001a. Comparison of pollen-slide and sieving methods in lacustrine charcoal analyses for local and regional fire history. The Holocene 11, 467–476.

Clark, J.S., Stocks, B.J., Richard, P.J.H., 1996. Climate implications of biomass burning since the 19th century in eastern North America. Global Change Biology 2, 433–442.

Clark, J.S, 1988. Stratigraphic charcoal analysis on petrographic thin sections: application to fire history in Northern Minnesota. Quaternary Research 30, 81–91.

Clark, J.S., Royall, P.D., 1995. Particle-size evidence for source areas of charcoal accumulation in Late Holocene sediments of eastern North American lakes. Quaternary Research 43, 80–89.

Gavin, D.G., Hu, F.S., Lertzman, K., Corbett, P., 2006. Weak climatic control of stand-scale fire history during the Late Holocene. Ecology 87, 1722–1732.

Higuera, P.E., Peters, M.E., Brubaker, L.B., Gavin, D.G., 2007. Understanding the origin and analysis of sediment-charcoal records with a simulation model. Quaternary Science Reviews 26, 1790–1809.

Higuera, P.E., Brubaker, L.B., Anderson, P.M., Brown, T.A., Kennedy, A.T., Hu, F.S., 2008. Frequent fires in ancient shrub tundra: implications of paleorecords for arctic environmental change. PLoS ONE 3, e0001744.

Higuera, P.E., Brubaker, L.B., Anderson, P.M., Hu, F.S., Brown, T.A., 2009. Vegetation mediated the impacts of postglacial climate change on fire regimes in the southcentral Brooks Range, Alaska. Ecological Monographs 79, 201–219.

Long, C.J., Whitlock, C., Bartlein, P.J., Millspaugh, S.H., 1998. A 9000-year fire history from Oregon Cost Range, based on a high resolution charcoal study. Canadian Journal of Forest Research 28, 774–787.

Lynch, J.A., Hollis, J.L., Hu, F.S., 2004a. Climatic and landscape controls of the boreal forest fire regime: Holocene records from Alaska. Journal of Ecology 92, 477–489.

Lynch, J.A., Clark, J.S., Stocks, B., 2004b. Charcoal production, dispersal, and deposition from the Fort Providence experimental fire: interpreting fire regimes from charcoal records in boreal forests. Canadian Journal of Forest Research 34, 1642–1656.

Marlon, J.R., Bartlein, P.J., Carcaillet, C., Gavin, D.G., Harrison, S.P., Higuera, P.E., Joos, F., Power, M.J., Prentice, I.C., 2008. Climate and human influences on global biomass burning over the past two millennia. Nature Geoscience 1, 697–702.

Marlon, J.R., Bartlein, P.J., Walsh, M.K., Harrison, S.P., Brown, K.J., Edwards, M.E., Higuera, P.E., Power, M.J., Anderson, R.S., Briles, C., Brunelle, A., Carcaillet, C., Daniels, M., Hu, F.S., Lavoie, M., Long, C., Minckley, T., Richard, P.J.H., Scott, A.C., Shafer, D.S., Tinner, W., Umbanhowar Jr., C.E., Whitlock, C., 2009. Wildfire responses to abrupt climate change in North America. Proceedings of the National Academy of Sciences 106 (8), 2519–2524.

Pitkänen, A, Huttunen, P., 1999. A 1300-year forest-fire history at a site in eastern Finland based on charcoal and pollen records in laminated lake sediment. The Holocene 9, 311–320.

Pitkänen, A., Turunen, J., Tolonen, K., 1999. The role of fire in the carbon dynamics of mire, eastern Finland. The Holocene 9, 453–462.

Power, M.J., Marlon, J., Ortiz, N., Bartlein, P.J., Harrison, S.P., Mayle, F.E., Ballouche, A., Bradshaw, R., Carcaillet, C., Cordova, C., Mooney, S., Moreno, P., Prentice, I.C., Thonicke, K., Tinner, W., Whitlock, C., Zhang, Y., Zhao, Y., Ali, A.A., Anderson, R.S., Beer, R., Behling, H., Briles, C., Brown, K.J., Brunelle, A., Bush, M., Camill, P., Chu, G.Q., Clark, J., Colombaroli, D., Connor, S., Daniels, M., Daniau, A.-L., Dodson, J., Doughty, E., Edwards, M.E., Fisinger, W., Foster, D., Frechette, J., Gaillard, M.-J., Gil-Romera, G., Gavin, D.G., Gobet, E., Haberle, S., Hallett, D.J., Higuera, P., Hope, G., Horn, S., Inoue, J., Kaltenreider, P., Kennedy, L., Kong, Z.C., Larsen, C., Long, C., Lynch, J., Lynch, B., McGlone, M., Meeks, S., Mensing, S., Meyer, G., Minckley, T., Nelson, D., New, J., Newnham, R., Mohr, J., Noti, R., Oswald, W., Pierce, J., Richard, P.J.H., Rowe, C., Sanchez Goñi, M.F., Shuman, B.J., Takahara, H., Toney, J., Turney, C., Umbanhower, C., Vandergoes, M., Vanniere, B., Vescovi, E., Walsh, M., Wang, X., Williams, N., Wilmshurst, J., Zhang, J.H., 2008. Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data. Climate Dynamics 30, 887–907.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, G., Manning, S., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. INTCAL04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP. Radiocarbon 46, 1029–1058.

Stuiver, M., Reimer, P.J., 1993. Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. Radiocarbon 35, 215–230.

Tinner, W., Hu, F.S., 2003. Size parameters, size-class distribution and area-number relationship of microscopic charcoal: relevance for fire reconstruction. The Holocene 13, 291–296.

Tinner, W., Hofstetter, S., Zeugin, F., Conedera, M., Wohlgemuth, T., Zimmermann, L., Zweifel, R., 2006. Long-distance transport of macroscopic charcoal by an intensive crown fire in the Swiss Alps—implications for fire history reconstruction. The Holocene 16, 287–292.

Umbanhowar, C.E., McGrath, M.J., 1998. Experimental production and analysis of microscopic charcoal from wood, leaves and grasses. The Holocene 8, 341–346.

Weng, C., 2005. An improved method for quantifying sedimentary charcoal via a volume proxy. The Holocene 1, 298–301.

Wick, L., Möhl, A., 2006. The mid-Holocene extinction of silver fir (*Abies alba*) in the Southern Alps: a consequence of forest fire? Palaeobotanical records and forest simulations. Vegetation History and Archaeobotany 15, 435–444.