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A comparison of charcoal measurements for reconstruction of Mediterranean paleo-fire frequency in the mountains of Corsica

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ABSTRACT

Fire-history reconstructions inferred from sedimentary charcoal records are based on measuring sieved charcoal fragment area, estimating fragment volume, or counting fragments. Similar fire histories are reconstructed from these three approaches for boreal lake sediment cores, using locally defined thresholds. Here, we test the same approach for a montane Mediterranean lake in which taphonomical processes might differ from boreal lakes through fragmentation of charcoal particles. The Mediterranean charcoal series are characterized by highly variable charcoal accumulation rates. Results there indicate that the three proxies do not provide comparable fire histories. The differences are attributable to charcoal fragmentation. This could be linked to fire type (crown or surface fires) or taphonomical processes, including charcoal transportation in the catchment area or in the sediment. The lack of correlation between the concentration of charcoal and of mineral matter suggests that fragmentation is not linked to erosion. Reconstructions based on charcoal area are more robust and stable than those based on fragment counts. Area-based reconstructions should therefore be used instead of the particle-counting method when fragmentation may influence the fragment abundance.

Introduction

Paleofire reconstructions require a robust method for analyzing high-resolution charcoal series in lake or peat sediments in order to separate continuous input of charcoal (background) from peaks corresponding to fire events. Separation methods have typically been based on numerical decomposition in which a time series of charcoal accumulation rates is detrended (Carcaillet et al., 2001a; Gavin et al., 2006; Higuera et al., 2009). The background series (Kelly et al., 2011) represents long-term shifts in fire regime (e.g., area burned, fuel characteristics) and taphonomic processes unrelated to fire occurrence (e.g. slope wash, sediment focusing: Bradbury, 1996; Whitlock and Millspaugh, 1996; Carcaillet et al., 2007). Charcoal pattern and behavior varies according to fire severity or burned area ("typology") and associated vegetation that act through the fuel structure and quality (Pitkänen et al., 1999; Higuera et al., 2005). Experimentation suggests that a peak of charcoal particles larger than 150 μm in diameter reveals stand to local fire events, due to limited charcoal transportation from the source area (Clark et al., 1998; Lynch et al., 2004).

Mediterranean regions are characterized by endemic yearly drought which stresses the vegetation and promotes frequent fires (Pausas, 1999; Keeley et al., 2011). Fire intervals in the dry biomes (e.g. Mediterranean, tropical dry forest or savannah) are frequently <100 yr, and can even be <30 yr. The role of fires in Mediterranean ecosystems is then crucial because they act directly on vegetation composition, distribution and dynamics (Bond et al., 2005) and indirectly on the global carbon budget (Andreae and Merlet, 2001). Mediterranean sedimentary charcoal records typically show high-frequency peaks during the Holocene, characterized by high accumulation rates of pollen-slide charcoal (e.g. Colombaroli et al., 2007) of sieved particles (e.g. Turner et al., 2008; Vanniere et al., 2008; Hallett and Anderson, 2010).

Three methods of charcoal quantification are commonly used for fire reconstruction. These are based on number, surface area or volume of macroscopic particles or fragments (Ali et al., 2009). These methods have been widely documented for charcoal records from boreal regions (Kelly et al., 2011). They generate robust fire reconstructions (Ali et al., 2009) but further research is needed to establish their limitations.

Due to the high frequency of fires, and fire typologies that may differ from those of boreal biomes, we expect Mediterranean records to

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differ from the better-studied boreal charcoal series (e.g. Kelly et al., 2011). Taphonomical processes such as fragmentation in the Mediterranean biomes could complicate fire reconstruction based on charcoal numbers, because fragmentation will increase particle abundance without changing their total area. Charcoal areas should be more conservative than particle counts, providing a more robust reconstruction of fire history. In particular for the Mediterranean biomes where runoff following drought is frequent and where the humus layer is thin or absent, charcoal fragmentation could be more important than in boreal biomes, where soils are generally covered by thick humus layers. The question of fragmentation can be tested by comparison with the mineral matter (hereafter "*MM*") contained in sediments that result from erosion of the catchment area. Co-variation between changes in total charcoal and *MM* would indicate that similar processes of sedimentation may be not related to fire history but to surface transportation during runoff and soil cover (Carcaillet et al., 2006).

Here, we analyze the different methods used to estimate sedimentary macro-charcoal abundance (number, area and volume), to reconstruct the local fire frequency and history in a montane Mediterranean area. The fragmentation rate of charcoal is analyzed by comparison of variation in charcoal abundance with input of terrestrial *MM* in the lake. We selected a mountain lake situated in a small watershed of the western Mediterranean basin, where the sediments accumulated without interruption at a ~constant rate for the last 18,000 yr. The sediments have previously been analyzed for pollen (Reille et al., 1997, 1999).

Materials and methods

Study site: Lake Creno

Lake Creno (42°12′18″N, 08°56′45″E) is located in western Corsica, on the southeastern part of the Rotondo massif (Figs. 1a–c). The lake lies in a small (22.6 ha ± 21%, measured using ArcGIS 10 and the digital terrain model of Fig. 1b) glacial basin at 1310 m asl on a broad crest on the northern slope of Monte San Eliseo (Fig. 1c). The local bedrock is monzonitic granite. Lake Creno covers 1.5 ha; its maximum water depth is 6.5 m; and it has no permanent inflow.

The lake is situated in the Corsican montane belt characterized by *Pinus nigra* ssp. *laricio* (hereafter *P. laricio* or Corsican pine), *Fagus sylvatica and Abies alba.* The understory is dominated by *Erica arborea* and *E. multiflora* (Gamisans and Jeanmonod, 1993). Today, the vegetation surrounding the lake and on the watershed is degraded. It is composed chiefly of *P. laricio*, with scattered *Fagus sylvatica, Quercus pubescens*, *Taxus baccata* and *Alnus cordata* in the surrounding understorey. The woody plants are generally browsed by livestock or pollarded (*Fagus sylvatica*).

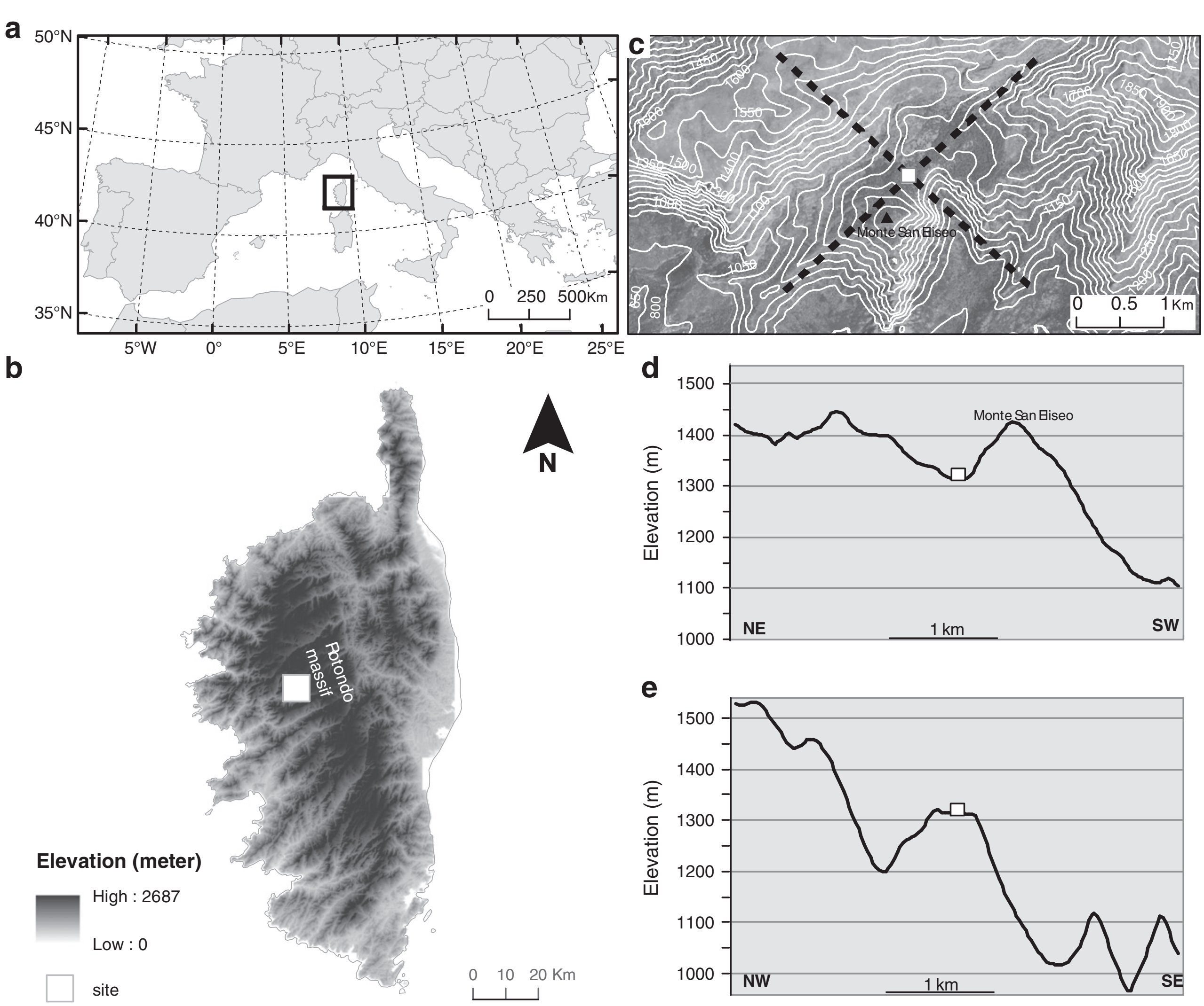


Figure 1. Location of Corsica (a) and the study site, Lake Creno (42°12′18″N, 08°56′45″E; 1310 m asl) (b). Topographic map of the study site (c), with two transects (black dashed lines), oriented northeast-southwest (d) and northwest–southeast (e). In c, the contour elevations (irregular spacing) are labelled (m asl). In c–e, the square marks the location of the lake.

The modern fire-return interval (FRI) has been estimated to be 60–70 yr in such montane areas covered by pine forests in Corsica (Mouillot et al., 2002). The lack of fire scars on the local trees, however, shows that fire has not occurred at this site for at least the last 200 yr.

Sampling, dating and the age–depth model

Five parallel overlapping cores were extracted from the deepest part of the lake in October 2009 using a Russian corer ($\o = 7.5$ cm, $L = 100$ cm). Coring was carried out during a period of drought. The longest sedimentary sequence measures 700 cm under ~600 cm of water column. This 700 cm long core was used for the charcoal analysis and loss on ignition (LOI) measurement. Two samples of the topmost water-saturated sediments (0–46 cm) were extracted with a Kajak–Brinkhurst (KB) sampler. The KB and Russian sediments were cross-correlated using charcoal concentrations (mm^2 cm^{-3}).

Dating of recent sedimentary layers on a centennial time scale was based on ^{210}Pb and ^{137}Cs measurements (Appleby and Oldfield, 1992). The CFCS (Constant Flux and Constant Sedimentation) model (Goldberg, 1963) assumes a constant ^{210}Pb flux and a constant sedimentation rate. In a logarithmic diagram, $^{210}Pb_{ex}$ should show a straight regression line whose slope allows calculation of an average sedimentation rate (details in Supplement Appendix 1). Using the average sedimentation rate W (mm yr^{-1}), the age T_m of the sediment layer can be calculated for each depth Z_m (cm):

$$\ln\left(\left({}^{210}\mathrm{Pb}_{ex}^{m}\right)\right) = \ln\left(\left({}^{210}\mathrm{Pb}_{ex}^{0}\right)\right) - \left(\frac{\lambda_{210}}{W}\right) \times Z_m, \tag{1}$$

$$\text{with}: \quad T_m = \frac{W}{Z_m}$$

This simple model gives an estimation of the average sedimentation rate. The peak of ^{137}Cs was identified in the recent sediments and used for dating the topmost sediments of the core, assuming that the depth of the maximum ^{137}Cs activity corresponds to the AD 1963 peak in atmospheric production (Robbins and Edgington, 1975).

Eleven accelerator mass spectrometry (AMS, Table 1) radiocarbon measurements were carried out at the Poznan Radiocarbon laboratory (Poland), to match with the previous chronology of Reille et al. (1999), which was based on 37 radiocarbon dates (Reille et al., 1999). The measurements were made on terrestrial plant macro-remains (e.g. needles, seeds). Each ^{14}C measurement was then calibrated with a 2 σ precision, in years before present (cal yr BP) using the CALIB program version 6.1 (Stuiver and Reimer, 1993) and based on the intcal09 dataset (Reimer et al., 2009).

The age–depth model was computed using the MCAgeDepth program (http://www.uidaho.edu/cnr/paleoecologylab/software; last accessed 12/12/2012), which applies a Monte Carlo resampling procedure to assess median ages and to generate confidence intervals (CI) around the fit, based on the probability distribution of each date. The resulting spline-based age–depth model, associated with the *CI* from the Monte Carlo simulations, is more robust than those constructed on the basis of ages inferred from the median value of calibrated dates or by the line-intersect method. This is because the model assumes a non-normal distribution of each ^{14}C date, which is weighted in accordance with its standard deviation (e.g. Telford et al., 2004). The age–depth model allows the assessment of deposition time.

Charcoal analysis and the fire-history reconstruction

One cm^3 of sediment was extracted every 0.5 cm along the 700 cm long core in contiguous samples. The sampling resolution was planned *a priori* based on the sedimentation rate that was assessed by analysing the depth distribution of ^{14}C dates (Reille et al., 1997, 1999). The aim was to obtain a time resolution < 30 yr sample^{-1}. In total, a series of 1400 contiguous samples was analyzed for the fire reconstruction.

Table 1
Accelerator mass spectrometry (AMS) radiocarbon dating. Terrestrial plant remains are needles of *Pinus laricio* or seeds of *Betula* sp.

Depth (cm)	Lab code	^{14}C yr BP	Calibrated age range, cal yr BP (2 σ)[a]	Dated material
90–95	Poz-36753	1415 ± 30	1287–1365	Plant remains
175–180	Poz-36754	3360 ± 35	3483–3689	Plant remains
240–245	Poz-36755	4705 ± 35	5321–5580	Plant remains
355–360	Poz-38609	7740 ± 60	8410–8627	Plant remains
370–375	Poz-36803	8150 ± 50	9004–9257	Bulk sediment
385–390	Poz-38612	8350 ± 60	9140–9491	Plant remains
435–440	Poz-36758	9630 ± 50	10,774–11,180	Plant remains
495–500	Poz-36759	11,250 ± 60	12,954–13,297	Plant remains
526–531	Poz-36802	12,850 ± 80	14,928–16,053	Bulk sediment
580–585	Poz-36760	13,130 ± 70	15,242–16,506	Bulk sediment
670–675	Poz-38611	14,430 ± 90	17,180–17,891	Bulk sediment

[a] Calibration via Calib 6.0 (INTCAL09; last accessed 16 December 2012).

The sediments were sieved through a 160 μm mesh and only charcoal particles > 250 μm^2 (macro-charcoal) were measured. They were assumed to be primarily of stand or local origin (Clark et al., 1998; Lynch et al., 2004). Identification, number and area measurements of charcoal particles were carried out using a 10× stereoscope coupled to a digital camera and image-analysis software. Charcoal measurements are reported both as charcoal concentration in area (mm^2 cm^{-3}), number (# cm^{-3}) and volume ($V_{charcoal}$, mm^3 cm^{-3}), which was estimated based on Weng's equation (Weng, 2005):

$$V_{charcoal} = \sum A_i^{3/2} \tag{2}$$

where A_i is the surface area (mm^2) of each charcoal particle in a given sample. The charcoal accumulation rate (*CHAR*) was calculated by multiplying charcoal concentration by the sedimentation rate inferred from the modelled sedimentation rate ($CHAR_a$: mm^2 cm^{-2} yr^{-1}; $CHAR_{\#}$: # cm^{-2} yr^{-1} and $CHAR_v$: mm^3 cm^{-2} yr^{-1}).

To identify fire events, we divided the CHAR series into CHAR-background and CHAR-peak categories using a locally weighted polynomial regression (LOWESS) with a time window of 600 yr, using Charanalysis software version 0.9 (Higuera et al., 2009; http://code.google.com/p/charanalysis/; last accessed 12/12/2012). We assumed that the variability in the *CHAR-peak* series varied on a time scale of > 500 yr, based on the theoretical study of Higuera et al. (2007) which recommended smoothing the raw series using a background greater than 10× the local *MFI* (median fire interval), together with and knowledge of the *MFI* in the local ecosystem (Mouillot et al., 2002). Furthermore, we found that using the 600 yr window maximized the signal-noise index (SNI) and goodness of fit between the empirical and modelled CHAR-noise distributions (CHAR-peack = CHAR-noise + CHAR-fire) (Higuera et al., 2009).

The CHAR-peak component was obtained by subtracting the CHAR-background, which represents the variation in overall charcoal production, sedimentation, mixing and sampling, from the *CHAR-series*. For each 600-yr overlapping window, a Gaussian mixture model was used to evaluate the mean and variance of the CHAR-noise distribution, enabling us to break down the CHAR-peak series locally into CHAR-fire and -noise. CHAR-fire exceeding the overall variation of CHAR-noise is probably caused by local fires. For each 600 yr window, CHAR-peaks exceeding the 99th percentile of the modelled CHAR-noise distribution were identified as fire events. A SNI for threshold values, at each interpolated sample, was estimated for testing the non-overlapping populations between CHAR-noise and CHAR-fire (Kelly et al., 2011).

Each peak exceeding the threshold have to be statistically significant in the variation of charcoal counts (*CHAR-series*) and present a minimum count of charcoal screening (Higuera et al., 2009). This "screening peak" calculates the probability that two charcoal measurements could arise from the same Poisson distribution. The screening is based on the original charcoal counts of each peak, hereafter $CHAR_{\#sp}$. Charcoal peaks are not considered as fire events if the likelihood that they match the same Poisson distribution is >5% as the minimum charcoal number preceding the peak (Higuera et al., 2007). This method is inapplicable to charcoal area and volume.

The dates of the reconstructed fire were used to calculate the *FRI*, here defined as the time between two consecutive events. The reconstructed fire history was smoothed using a LOWESS with a time window of 1000 yr, which emphasized the main trends of fire history. The fire frequency was then defined as the number of fires per millennium. The mean FRI (mFRI) over the sequence was estimated with a Weibull distribution.

To test whether erosion could explain the abundance of charcoal, we used the concentrations of MM that mirror the terrestrial input from the watershed. The MM was obtained through LOI analysis on each cm of the longest core, except from the upper 22 cm and the lower 26 cm that were characterized by too little sediment sampled. LOI (mg cm^{-3}) was based on dry matter (Heiri et al., 2001).

$$MM = 1 - \left(\frac{M_D - M_{LOI}}{M_D}\right) \times 100 \quad (3)$$

where M_D is the dry mass of sediment sample and M_{LOI} the mass of sediment sample after one hour of combustion at 550°C.

We estimated charcoal particles fragmentation throughout the 18,000 yr period represented by the core to determine whether the concentration patterns obtained by number and area ($C_{\#}$ and C_a) are similar in magnitude or, if not, if the differences were restricted to one period or were constant throughout the chronology. In these two alternatives (similar or different patterns) we assume that the fire frequency calculated by charcoal numbers, surface area or volume should provide similar fire histories (Ali et al., 2009). If the fire reconstructions differ, then temporal variability of the fragmentation rate would have varied, modifying the ratio between particle numbers and their surface or volume. To estimate particles the fragmentation, the fragmentation rate (ω) was assessed as follow:

$$\omega = C_{\#}/C_a \quad (4)$$

Results

The age–depth model and the chronology

The dating distribution (Table 1) is uniform with depth, resulting in an almost linear pattern apart from the top 50 cm, where there is little sediment compaction, and oscillation below 500 cm (Fig. 2). The ^{137}Cs peak in the KB core is at 6 cm below the water-sediment interface (data not shown), thus providing a mean accumulation rate of 1.3 mm yr^{-1} in the topmost centimeters, close to the value derived from $^{210}Pb_{ex}$ measurements (Fig. 2a insert). The sedimentation rate was 1.5 mm yr^{-1} within the top most sediment; older than 500 cal yr BP, the median value was 0.37 mm yr^{-1} (mean value: 0.45 ± 0.17 mm yr^{-1}) due to compaction and water extrusion. The sedimentation rate, which is associated with a large confidence interval between 14,500 and 12,000 cal yr BP, shows oscillating values from 0.2 to 0.8 mm yr^{-1} (Fig. 2b). The resulting median deposition time is 26.9 yr cm^{1} and, the median resolution is 13.4 yr sample^{-1} (sampling at each 0.5 cm).

Area, volume and number relationship

Charcoal concentration measured from number (# cm^{-3}) and area (mm^2 cm^{-3}) are poorly correlated ($r^2 = 0.28$, Fig. 3a) even without taking into account the outlier, i.e. the maximum area value ($r^2 = 0.49$, Fig. 3b), based on model 2 regression (i.e. simple linear regression using ordinary least squares and major axis and providing a 95% CI; Legendre and Legendre, 1998). One proxy cannot be used to predict the second. Consequently $C_{background}$ might differ for the area and the number used for the reconstruction of fire history.

The fragmentation rate (ω) based on the number/area ratio is high and variable from 11,500 to 7500 cal yr BP and from 5000 cal yr BP to present and, particularly low between 7500 and 5000 cal yr BP and during recent centuries (Fig. 3c). This variation shows that reconstructions of fire history would differ depending on the use of $CHAR_{\#}$ or $CHAR_a$.

The *MM* concentration, which is a proxy for soil erosion in the watershed, shows no correlation with the different measurements of charcoal abundances, i.e. number ($r^2 = 0.0035$), area ($r^2 = 0.0003$) and volume ($r^2 = 0.0002$; Fig. 4). These results indicate no linkage between the erosion and the pattern of charcoal abundance.

$CHAR_v$ presents a lower $C_{background}$ than $CHAR_a$ (Fig. 5), which is due to the mathematical transformation that reduces background and lowest values (Eq. (2)). In contrast, the $C_{background}$ obtained by detrending $CHAR_{\#}$ is probably over-estimated because of the fragmentation processes and presents several high magnitudes of $CHAR_{\#}$ values.

Fire reconstructions

The sum of total fires obtained is 47 for $CHAR_{\#sp}$ (sp = screening peak; Fig. 5a), 136 for $CHAR_{\#}$ (Fig. 5b), 94 for $CHAR_a$ (Fig. 5c) and 124 for $CHAR_v$ (Fig. 5d) over the last 18,000 yr. These fire numbers suggest under-estimation relative to $CHAR_{\#sp}$, and over-estimation relative to $CHAR_{\#}$. Furthermore, SNI is the lowest for reconstruction based on $CHAR_{\#}$ and $CHAR_{\#sp}$, and near the minimal acceptable threshold (median at 4.10 and 25th percentile of the distribution of the minimal threshold of 3.00, Figs. 6a and b) required for a reliable reconstruction. Higher *SNI* values are observed for reconstructions based on $CHAR_a$ and $CHAR_v$ (6.57 and 8.15, respectively) supporting the better reliability of these last reconstructions (Figs. 6c and d). The local distribution of *SNI* shows a greater confidence when ω is high, from 11,500 to 7500 cal yr BP and from 5000 to 200 cal yr BP (Fig. 3c), indicating that *SNI* becomes unreliable with high fragmentation rates, due to difficulties in distinguishing peaks and noise for $CHAR_{\#}$ and $CHAR_{\#sp}$. For this reason, the screening-peak method is recommended to separate peak from noise based on *CHAR* number.

Based on $CHAR_{\#sp}$, the reconstructed fire history begins at 12,500 cal yr BP and shows three oscillations with maxima at 11,300, 8200 and 5600 cal yr BP (Fig. 7), revealing a moderate amplitude of fire regime throughout the Holocene (0–5.9 fires ka^{-1}; $FRI_{max} = 160$ yr fires^{-1}). From 4500 to 1000 cal yr BP, the oscillation amplitudes were smaller. The main drop of fire frequency inferred from $CHAR_{\#sp}$ is from the highest frequency at ~2000 cal yr BP of 8.2 fires ka^{-1} (mean FRI = 122 yr fires^{-1}) to 0 fires ka^{-1} today.

The fire histories reconstructed with $CHAR_a$, $CHAR_v$ and $CHAR_{\#}$ differ from the one reconstructed from $CHAR_{\#sp}$ (Fig. 7). The frequency based on $CHAR_{\#}$ is too high, of similar order to the reconstruction based on $CHAR_V$. Three fires are reconstructed during the Late Glacial period, before 12,500 cal yr BP (mean frequency of 0.6 fires ka^{-1}; mFRI = 1670 yr fires^{-1}) for $CHAR_a$ and $CHAR_V$, and almost two others for $CHAR_{\#}$ (mean frequency of 1.0 fires ka^{-1}; FRI = 1000 yr fires^{-1}). A major increase in fire frequency between 12,500 and 11,200 cal yr BP is common to the three reconstructions, ranging from 1.7 to 10.6 fires ka^{-1} (FRI from 588 to 94 yr fires^{-1}) based on $CHAR_v$, from 1.2 to 12.0 fires ka^{-1} (FRI from 833 to 83 yr fires^{-1}) based on $CHAR_a$ and, from 1.8 to 13.4 fire ka^{-1} (FRI from 555 to 74 yr fires^{-1}) based on $CHAR_{\#}$ (Fig. 7). From 11,300 to 5500 cal yr BP, a short decrease and subsequent slight increase is recorded from $CHAR_a$ (ranging from 12.0 to 7.0 fires ka^{-1}; *FRI* from 83 to 143 yr fires^{-1}).

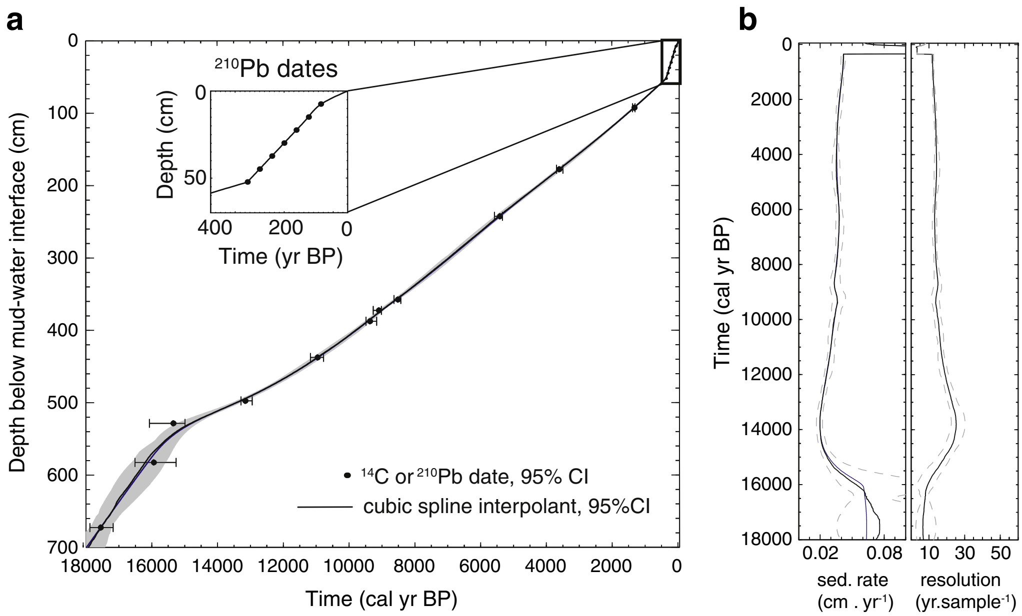


Figure 2. Age–depth model of Lake Creno (a) and the calculated sampling resolution based on the sedimentation rate as a function of time (b). Error bars in a are 2 σ; shaded gray area is the 95% CI of the age model. Dashed lines in b indicate the 95% CI.

However, four small-amplitude oscillations are observed with the $CHAR_v$ (mean fire frequency of 8.7 fires ka^{-1}; FRI = 114 yr fires^{-1}) and the $CHAR_\#$ records (mean fire frequency of 10.6 fires ka^{-1}; *FRI* = 94 yr fires^{-1}), revealing an extreme frequency of 14.3 fire ka^{-1} around 4700 cal yr BP (70 yr fires^{-1}). During the last 5500 yr two oscillations in the fire regime are reconstructed, showing a

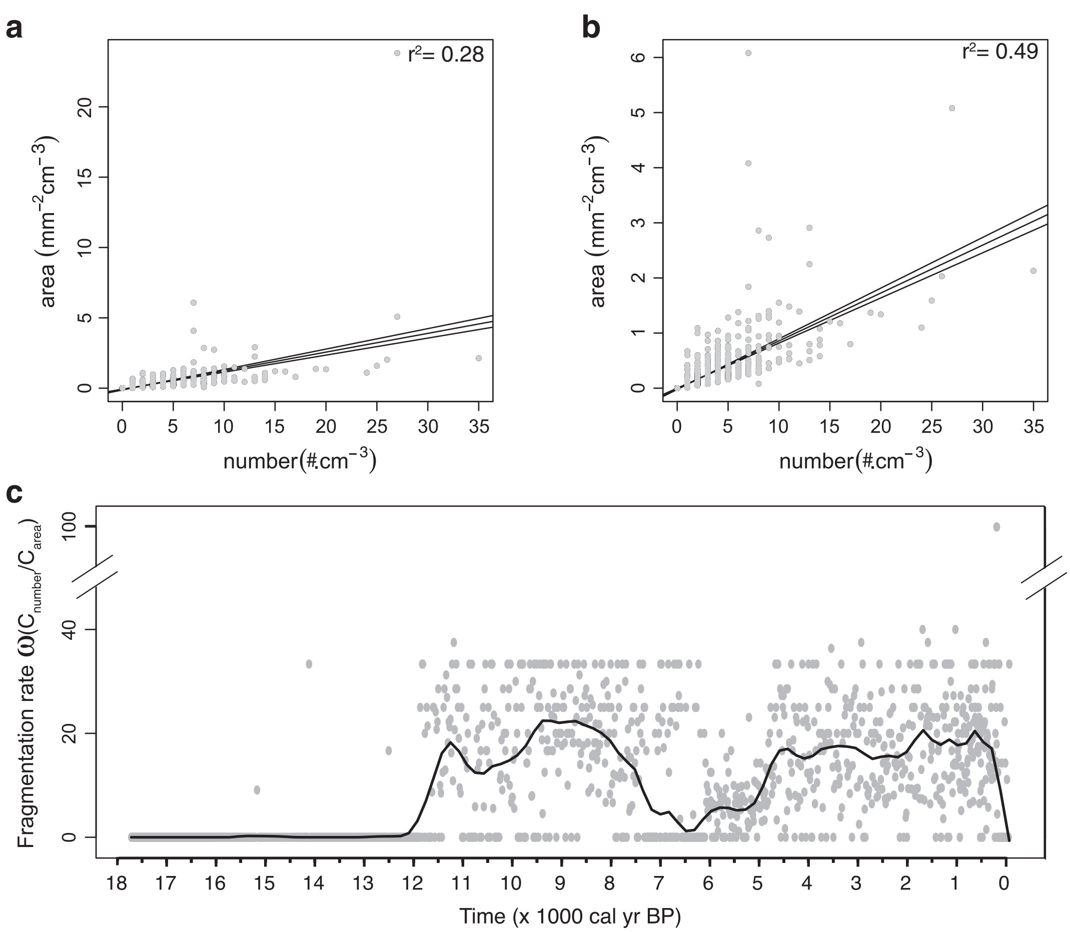


Figure 3. Correlation (and 95% CI) between charcoal concentration expressed in area and number with (**a**) and without (**b**) the outlier; and fragmentation rate (**c**, number/area ratio, ω) over the last 18,000 yr smoothed with a LOWESS (0.001, thick curve); high value = high fragmentation rate, and vice versa.

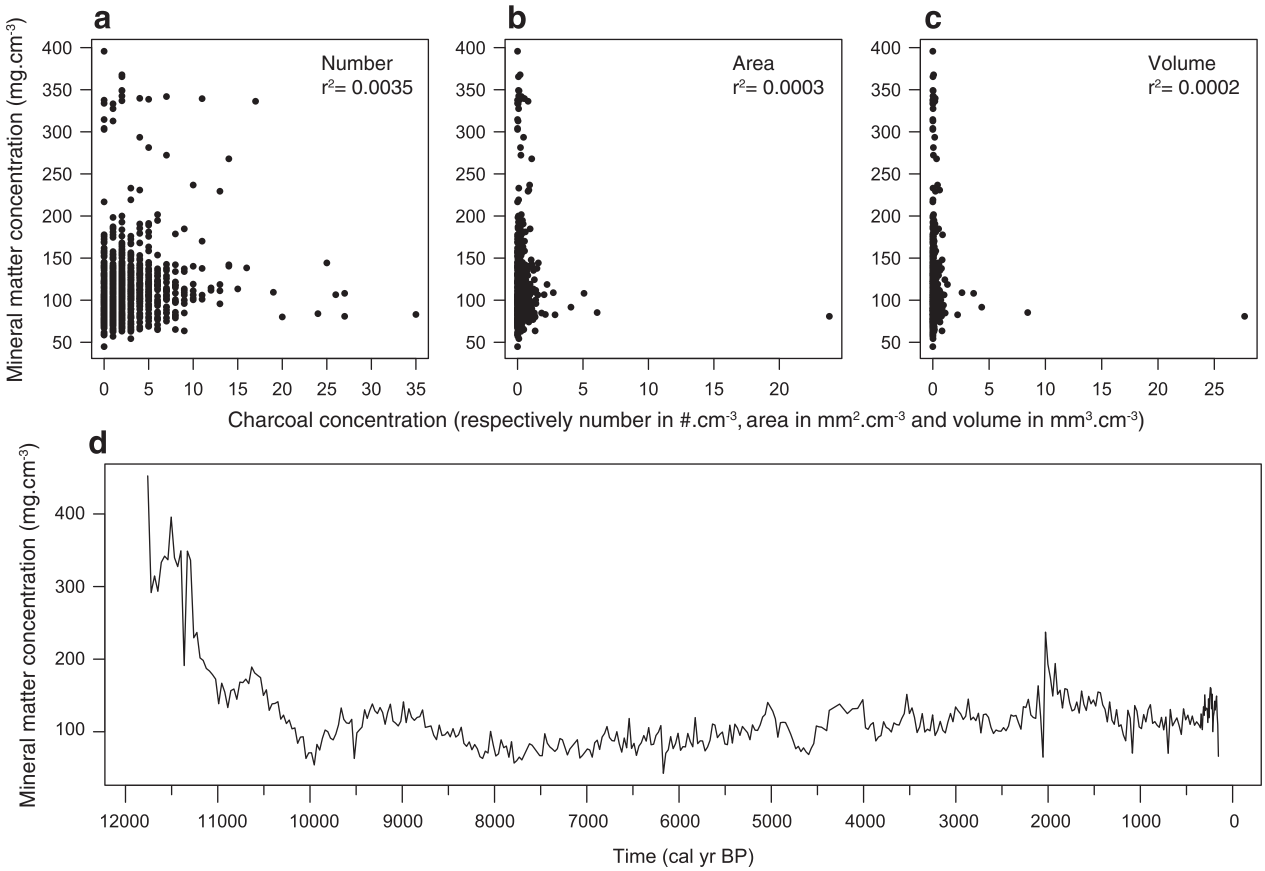


Figure 4. Mineral–matter concentration, an erosion proxy, measured by loss on ignition (residues) plotted against fire proxies (number (a), area (b) and volume (c) of charcoal particles). Mineral–matter concentration regards time (d). Data before 12,000 cal yr BP were not used because of insignificant concentrations of charcoal.

smaller range (from 8.4 to 13.4 fires ka^{-1}; FRI from 119 to 74 yr fires^{-1}) and a smaller decreasing value during the last millennium for $CHAR_v$ (from 13.4 to 9.2 fires ka^{-1}; FRI from 74 to 108 yr fires^{-1}) compared to $CHAR_a$ (from 7.0 to 12.2 fires ka^{-1}; FRI $=$143–82 yr fires^{-1}). A very slight decrease in the mean fire frequency is reconstructed with the $CHAR_\#$ record around 4500 cal yr BP attaining 10.4 fires ka^{-1} (FRI$=$ 96 yr fires^{-1}), and a net decrease is observed during the last millennium, from 12.1 to 6.4 fires ka^{-1} (*FRI* from 83 to 156 yr fires^{-1}).

The higher fire number for $CHAR_\#$, $CHAR_a$ and $CHAR_v$ is in part explained by the unscreened peak analysis, but also by the difference of influx when fragmentation is taken into account and different fires are reconstructed during the last 18,000 yr (Fig. 7, left). Indeed, $CHAR_\#$ influx displays different peaks of charcoals than in $CHAR_a$ or $CHAR_v$ influxes. The variant and abundant $CHAR_\#$ provides also different background estimation than for $CHAR_a$ and $CHAR_v$. Furthermore, several clear peaks that appear in the $CHAR_a$ and $CHAR_v$ reconstructions, are not considered as peaks with $CHAR_{\#sp}$, but as components of $C_{background}$ (Fig. 7, left).

Paleofire intercomparison

The two cumulative curves of fires inferred from charcoal numbers correspond to the extreme scenarios, with the fire maximum inferred from $CHAR_\#$ and the fire minimum from $CHAR_{\#sp}$ (Fig. 8). The distribution plotted from $CHAR_v$, lies above the one inferred from $CHAR_a$, which is the intermediate reconstruction (Fig. 8). $CHAR_a$, $CHAR_v$, and $CHAR_\#$ are very different from the one calculated from $CHAR_{\#sp}$, throughout the 18,000 yr (Fig. 8). However, cumulative fire distributions from $CHAR_a$ and $CHAR_v$ are similar between 18,000 and 10,000 cal yr BP and, their distributions display the same trend during the last 10,000 yr. The curve of cumulative fires inferred from $CHAR_{\#sp}$ displays three steps between 12,000 and 5000 cal yr BP and a~linear slope for the last 5000 yr (Fig. 8). The values of fire frequency reconstructed by *$CHAR_v$* are always above $CHAR_a$ because the detrending runs well with a low $C_{background}$ (better *SNI* value), even when more fires are detected.

Since 18,000 cal yr BP, the fire frequency inferred from area *vs* volume are, on the whole, better correlated (median $r=1.0$, $p<0.01$) than all the other combinations (0.5 for area vs number (#sp); 0.7 for area vs number (#); 0.7 for volume vs number (#); 0.5 volume vs number (#sp); 0.5 number (#sp) vs number (#); $p<0.01$, Fig. 9). Two periods are distinguished, from 18,000 to 11,000 cal yr BP and from 11,000 cal yr BP to present. In the first period, all pair-wise comparisons present high positive correlations, except between 15,500 and 14,000 cal yr BP for $CHAR_a$ vs $CHAR_\#$ and $CHAR_v$ vs $CHAR_\#$. The second period presents a majority of negative correlations with means r ranging from 0.2 to -0.3 ($p<0.01$), except for $CHAR_a$ vs $CHAR_v$ comparison with a mean r of 0.8 ($p<0.01$). The main differences between the fire reconstructions inferred from $CHAR_a$ vs $CHAR_v$ and the others are observed from 9400 to 2400 cal yr BP, when the series are frequently negatively correlated (Fig. 9), although the correlations are better after 2400 cal yr BP (mean $r=0.8$, $p<0.01$). The fire histories based on area and volume are well correlated. Fire reconstruction with number (#) and number (#sp) are poorly correlated with area and volume depending on time. The pair-wise comparison of $CHAR_\#$ and $CHAR_{\#sp}$ is the worst during the last 11,000 yr.

Discussion

The fire reconstructions based on area and volume present the same trends, in contrast to the reconstruction based on number with screening peaks ($CHAR_{\#sp}$). As screening-peak analysis was not used for $CHAR_\#$, $CHAR_a$ and $CHAR_v$, we cannot base our interpretations of fire history on isolated fires. The trend of fire frequency must be taken

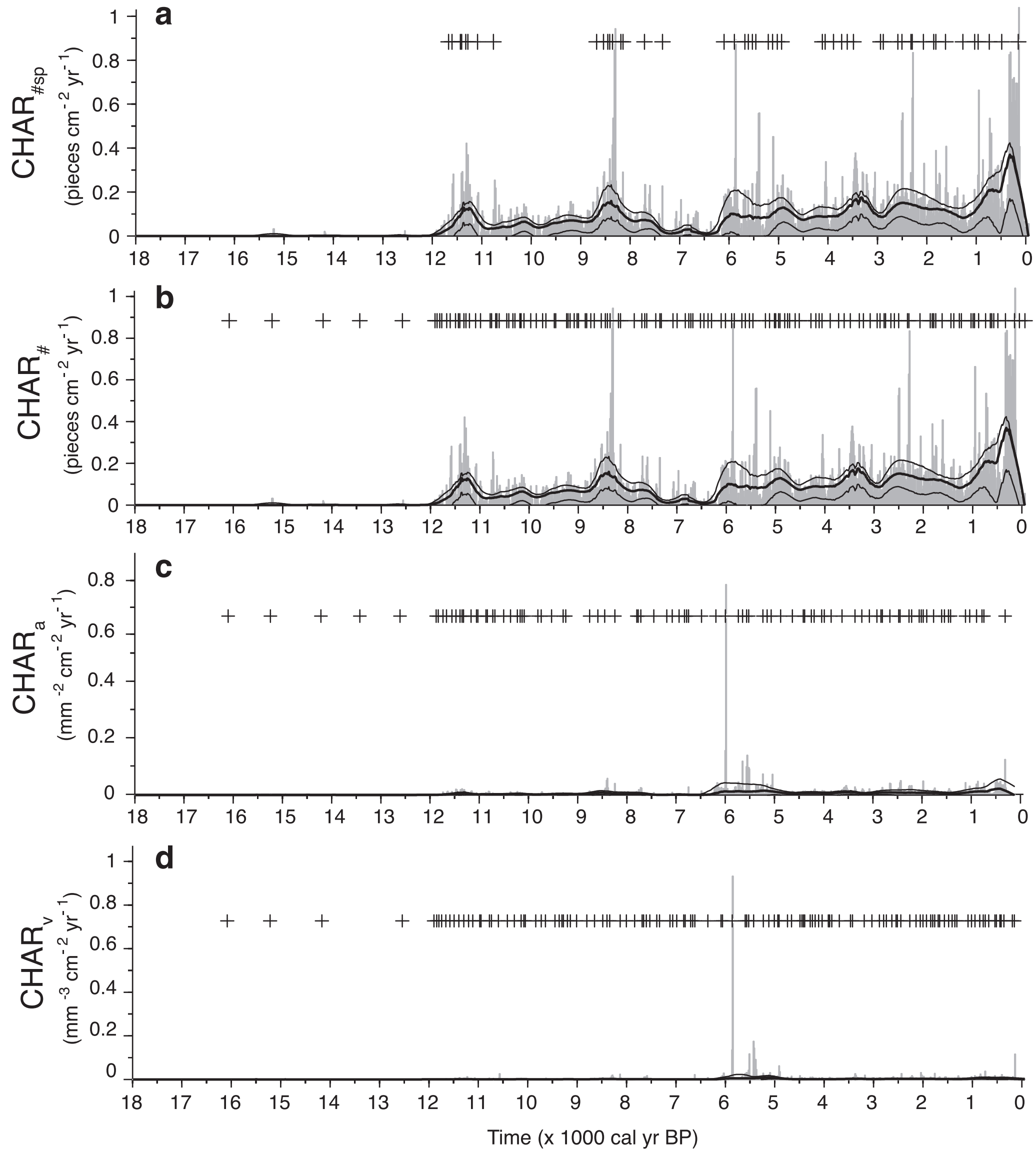


Figure 5. Background and peaks of charcoal accumulation rate ($C_{background}$) and CHAR-peaks for numbers (a with, and b without screening peaks), areas (c) and volumes (d).

into account for this study. Our main finding is that reconstructions based on numbers with or without screening peaks provide distinct fire histories from those based upon area or volume. Furthermore, we obtain extreme reconstructions from $CHAR_{\#sp}$ (minimal) and $CHAR_{\#}$ (maximal, Fig. 8), both showing poor SNI and extremely variable and high $C_{background}$ (Fig. 5) with several high-magnitude peaks (Fig. 7 left), which is in contrast to the reconstructions based on $CHAR_a$ and $CHAR_v$. Hence, the methods based on numbers with or without screening peaks do not provide secure reconstructions of fire frequency.

The key to understanding the differences between the series and the subsequent reconstruction is likely to be taphonomical processes, particularly the fragmentation rate that affects the number of particles and the resulting fire history. The area of charcoal measurements limits the taphonomic bias at this site because ω is intrinsically taken into account by the surface-area method. Using area for the reconstruction is therefore likely to generate charcoal accumulation estimates that better reflect the biomass burning history, because the use of particle number is more dependent on fragmentation processes than the surface area during aerial or run-off dispersal after fire, or within the sediment. It is misleading to interpret macroscopic charcoal series based on the number of fragments in terms of fire events in such Mediterranean ecosystems because they likely overestimate the fire numbers.

We thus advise the use of charcoal areas or estimated volume of charcoal for reconstruction of Mediterranean fire history, whereas for boreal reconstruction it seems that the three series are well correlated (Ali et al., 2009). Fragmentation in such Mediterranean ecosystems could occur during the fire, in the catchment area through run-off, or within the lake basin. The LOI, which allows deciphering of the linkages between erosion in the catchment area and the pattern of charcoal, reveals no correlation with charcoal concentration, either number, area or volume (Fig. 4). Erosion has thus no direct consequences on the charcoal pattern and subsequent fire history. The lack of correlation between $CHAR_a$ and $CHAR_{\#}$ thus results from taphonomical processes during the fire or within the lake. Whatever the cause of the fragmentation processes, the use of charcoal number instead of area can mislead the fire reconstruction.

Ecosystem properties and robustness of statistical values

The fire histories based on $CHAR_{\#}$ and $CHAR_{\#sp}$ are not robust because of, first, the moderate quality of the SNIs and, second, the total

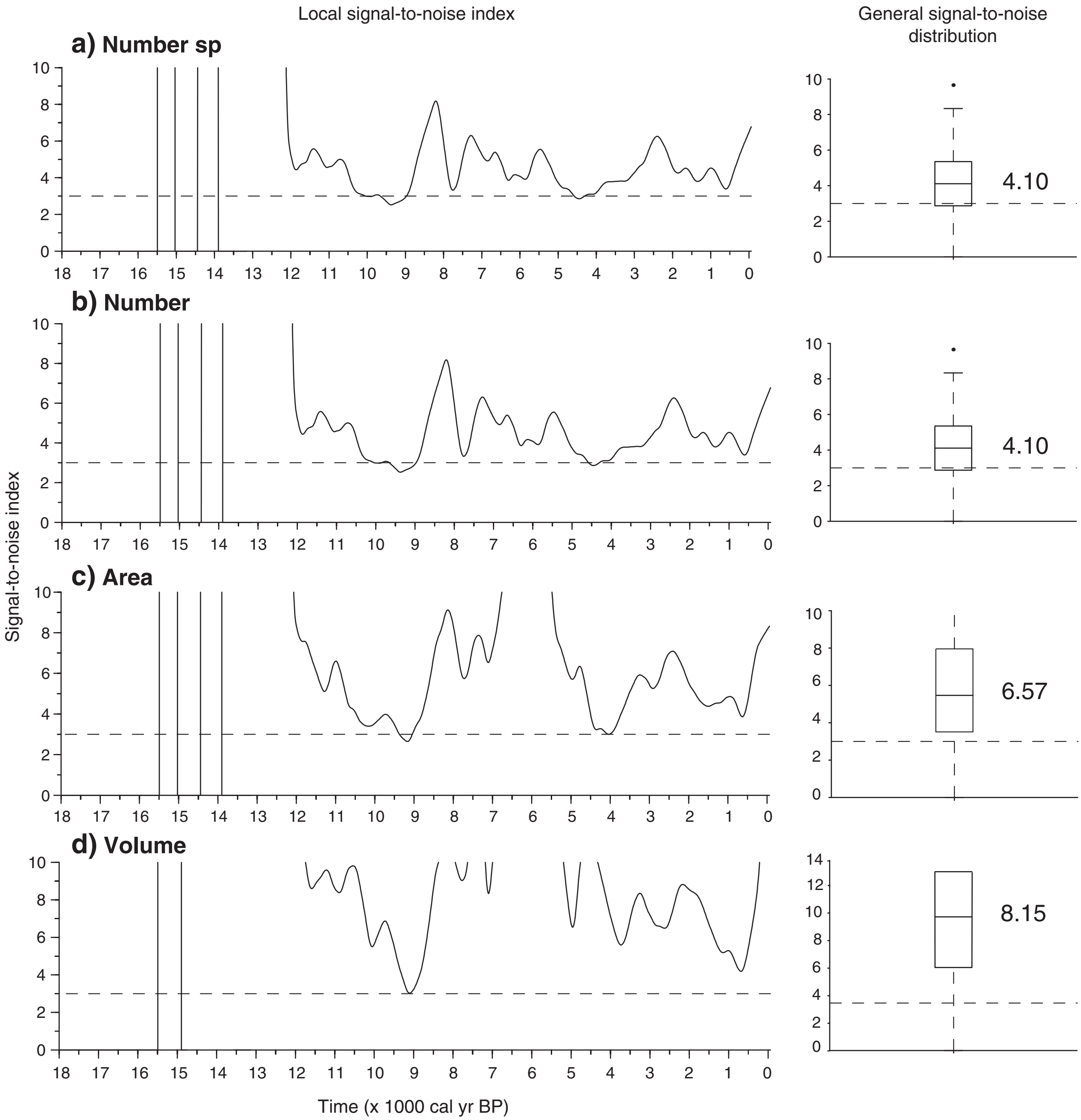


Figure 6. Local signal-to-noise index (*SNI*) distributions over time (left) and general SNI (right) for reconstructions based on $CHAR_{\#\ sp}$ (number with screening peak, number sp), $CHAR_{\#}$ (number without screening peak, number), $CHAR_a$ (area) and $CHAR_v$ (volume). Boxplots of general SNIs correspond to the second and the third quartiles; black line inside is the median, and bars represent extreme values. The dashed lines represent the threshold of a good detrending of CHAR-noise (SNI > 3).

fire numbers do not correspond to realistic reconstructions according to the modern fire record (Mouillot et al., 2002). The most realistic reconstruction is between these extremes, i.e. reconstructions based on charcoal area or volume. The main differences between fire histories from $CHAR_a$ and $CHAR_v$ appear during the last millennia when $CHAR_a$ analysis produces a stronger decrease of the frequency compared to the frequency reconstructed from $CHAR_v$. During the last 500 yr, the frequency based on $CHAR_v$ was 10.7 fires ka^{-1} (mFRI of 74 yr) whereas the frequency based on $CHAR_a$ was 4.6 fires ka^{-1} (mFRI of 183 yr).

A search was made in the Corsican pine forest surrounding the lake for fire scars that could be used to calibrate the fire reconstruction inferred from the charcoal series (*cf.* Clark, 1990; Higuera et al., 2005). No fire scars were found, although these forests contain a significant density of large trees, up to 200 yr old assessed by tree-ring counting, and intensive grazing causes the present absence of forest understorey. These observations suggest that no surface fires have spread within the catchment area for at least 200 yr. The reconstruction based on charcoal volume seems to simulate too short an *FRI* (~75 yr on average) during the last millennia, by comparison with the age of living trees and the absence of fire scars on these trees. The reconstruction based on charcoal areas appears the most realistic with a mFRI of ~185 yr, but the statistical scores are better in term of SNI for reconstruction based on volume (8.15 for $CHAR_v$ versus 6.57 for $CHAR_a$), a result recommended by Kelly et al. (2011). However, volume derived from charcoal area (Eq. (2); Weng, 2005) is not a direct observation but an equation modelling the common 3D form of charcoal particles. As this mathematical transformation is theoretical, it does not apply precisely to all particles, which present complex 3D

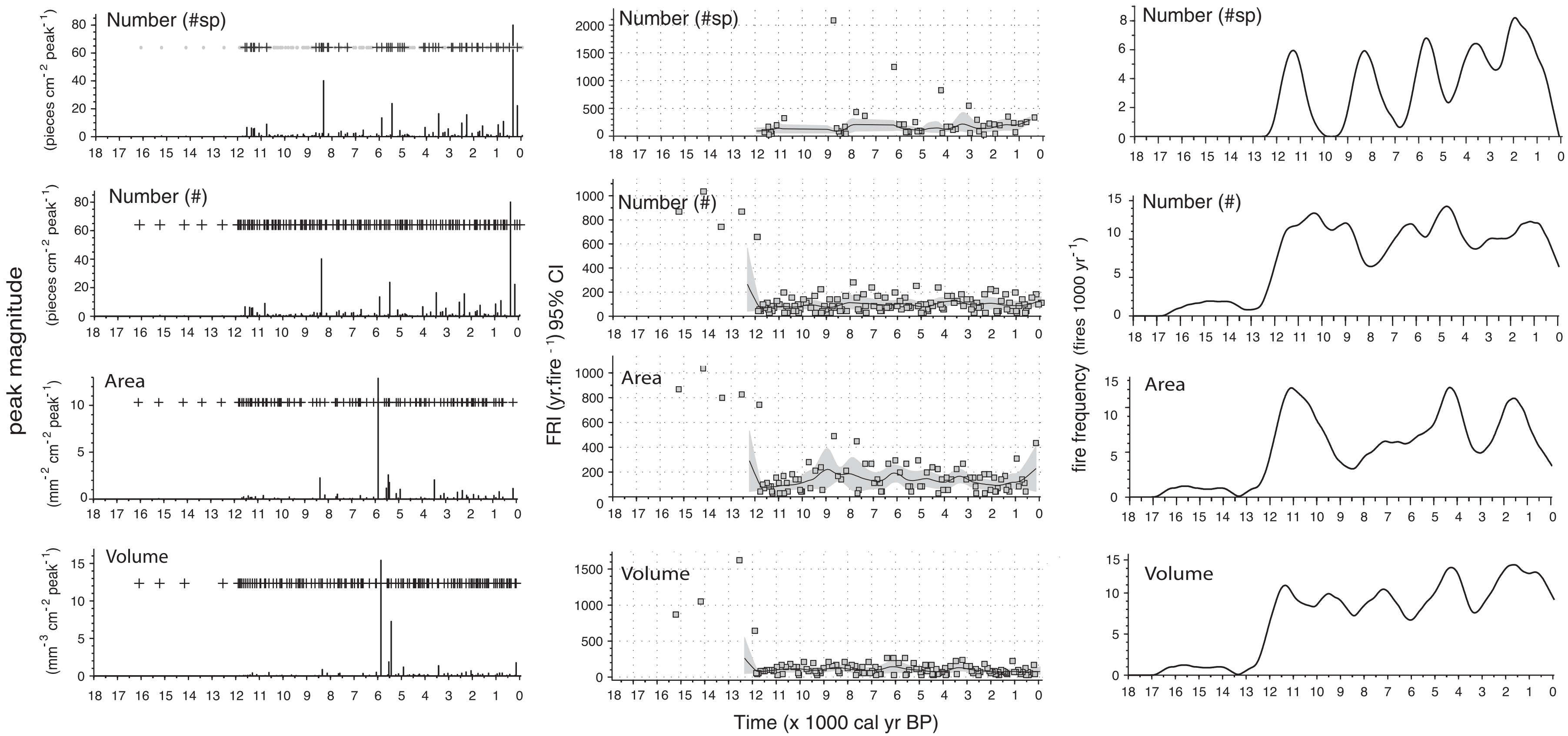


Figure 7. Peak detection (left) fire-return interval (*FRI*, middle, with a grey zone corresponding to 95% CI) and fire-frequency reconstructions (right) for $CHAR_{\#sp}$ (number (#sp) curve), $CHAR_{\#}$ (number (#) curve), $CHAR_{a}$ (area curve) and $CHAR_{v}$ (volume curve). All the crosses are fire events, all the gray points are not considered as fire events (only used for $CHAR_{\#\ sp}$, number (#sp) curve).

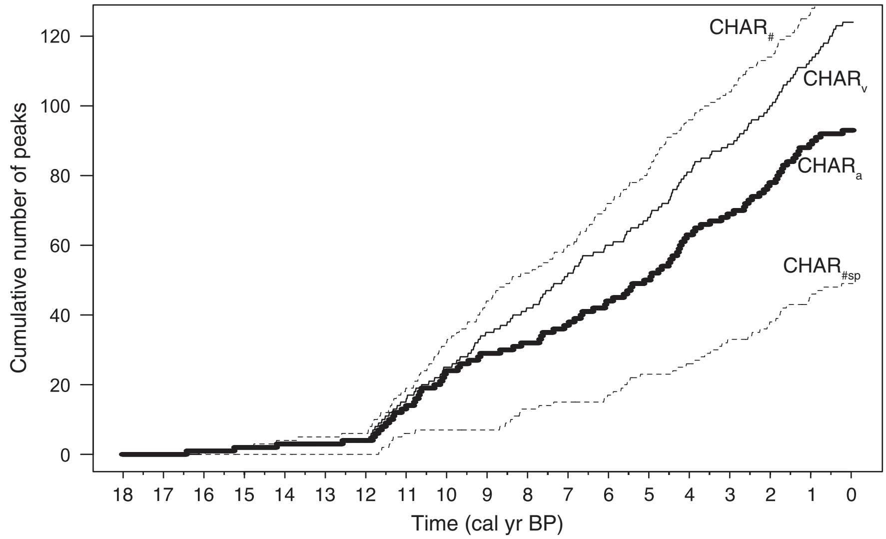


Figure 8. Cumulative number of fires obtained by $CHAR_{\#}$ (without screening peak, thin upper dashed line) and $CHAR_{\#\ sp}$ (with screening peak, thin lower dashed line), $CHAR_a$ (thick black curve, area) and $CHAR_v$ (thin curve, volume).

forms and contours (Clark and Hussey, 1996). For this reason, it is more reliable to reconstruct fire history from charcoal area, measured on each fragment.

Furthermore, a change of smoothing-window width modifies greatly the number of fires inferred from CHAR volume (120–135 fires, ~11% of uncertainty), in contrast to area (91–fires ~2% of uncertainty). Similarly, the fire numbers inferred from $CHAR_{\#}$ vary from 120 to 140 fires depending on the smoothing-window width (~14% of uncertainty), in contrast to $CHAR_{\#sp}$ (45–48 fires, ~6% of uncertainly). We cannot be confident in these latter reconstructions because they differ too greatly from the others (Fig. 8) and because the reconstructed frequency appears to be unrealistic. The number of fires is thus more stable based on $CHAR_a$, suggesting this method provides a more robust reconstruction, whatever the smoothing window.

A post-glacial Mediterranean montane fire history

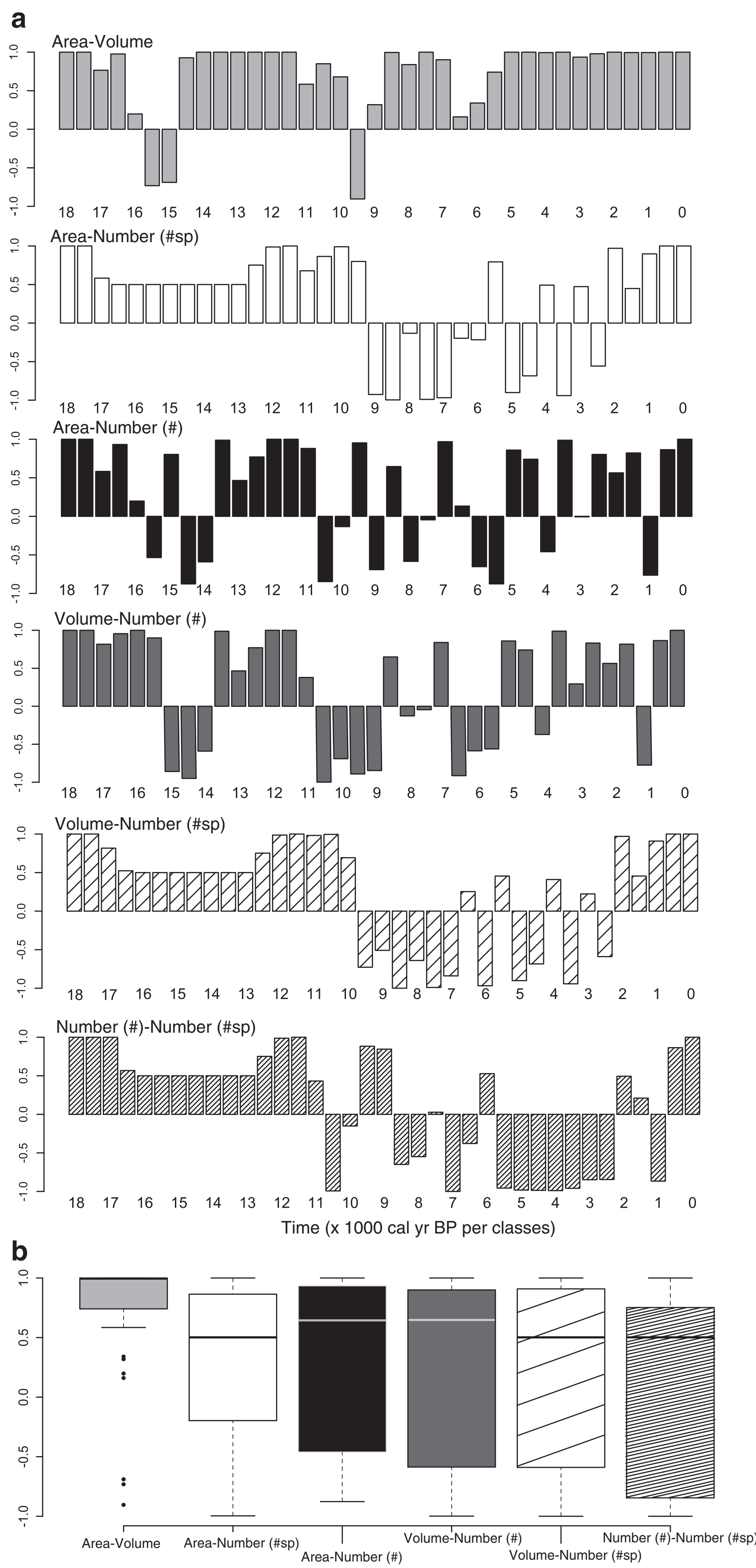
The fire frequency resulting from $CHAR_a$ measurements allows the reconstruction of a robust fire history at Lake Creno in the Corsican montane belt. The Late Glacial period, before 12,000 cal yr BP, was characterized by very few fires (mFRI = 1540 yr; frequency = 0.65 fires ka^{-1}), similar to values obtained during the 20th century within the northern forest tundra in eastern Canada (Payette et al., 1989), which is a shrub ecosystem with scattered woodland patches, or in the herb-tundra ecosystem in Alaska (Higuera et al., 2008, 2009). This suggests that the Late Glacial period was not favorable for fire ignition and spread, probably because forests were not established (Reille et al., 1997). However, a herb-dominated ecosystem including dwarf shrubs might burn, if lightning ignited the biomass and the climate was dry enough. It seems that these conditions were not met at Lake Creno before 12,000 cal yr BP, either in terms of climate or of fuel composition and structure. Whatever the charcoal assessment and the lack of charcoal background, only three fires were reconstructed during Late Glacial time.

The first change in fire frequency occurred at the end of the Younger Dryas (~11,500 cal yr BP), indicating significant environmental transformation in terms of climate or fuel for fire spread. Indeed, this transition between Younger Dryas and Holocene was marked by record of arboreal pollen, which indicates an establishment of woodlands composed of *Pinus nigra* ssp. *laricio* (Reille et al., 1997). Thus, the fuel type could influence the charcoal record i.e. increase of charcoal count (Fig. 5), and the fire frequency (Fig. 7). The frequency peaked at 12.0 fires ka^{-1} at 11,200 cal yr BP showing that changes in both climate and fuel composition generated the most favorable environment over the last 18,000 yr for fire ignition and spread.

At the beginning of the Holocene (~11,500 cal yr BP), the frequency decreased rapidly reaching a minimum at 8300 cal yr BP, a time that also corresponds to the important cooling event in the North Atlantic area (Alley and Agustsdottir, 2005), with the establishment of unfavorable conditions for fire ignition. A similar decrease in fire frequency occurred in northern Europe around the 8.2 ka event (Carcaillet et al., 2012), suggesting large-scale processes in the fire history that overrode fuel availability as indicated by stable arboreal pollen abundance although the Holocene (Reille et al., 1999). The three following millennia were characterized by a plateau of ~5 fires ka^{-1}, i.e. one fire every ~200 yr on average. This suggests a stable climate and vegetation composition, although pollen analyses indicate some weak changes (Reille et al., 1999). However, at Lake Creno (1.5 ha), situated on a ridge crest (Fig. 1), the pollen record mirrors more the regional vegetation than the stand to local plant cover (Jacobson and Bradshaw, 1981; Jackson and Lyford, 1999). The pollen-based record of fire-sensitive deciduous trees (including *Quercus*) and *Pinus nigra* forest (Reille et al., 1999) is not consistent with the high fire frequencies reconstructed from charcoal volumes and number (FRI = 70–80 yr since 11,000 cal yr BP). The interval between two fires based on charcoal areas (FRI = 185 yr $fire^{-1}$) reconstruction is in better agreement with such vegetation that need more than 80 yr to recover and to sustain.

The last 5000 yr is depicted by two oscillations of frequency, peaking at ~4500 and ~1600 cal yr BP and, with two minima at ~3100 cal yr BP and today. Although climate oscillation could explain such changes in fire frequency, we cannot rule out a history resulting from human ignition (fire maxima) and fuel-wood suppression from the establishment of grassland for livestock (fire minima). Indeed, human remains from the early Holocene (~9.7 ka) have been discovered (Costa, 2004). Synanthropic pollen assemblages (Reille et al., 1999) indicate the first

Figure 9. Pair-wise analysis (correlation, Spearman test) for the comparison of fire-frequency histories calculated from $CHAR_{\#\ sp}$ (number (#sp)), $CHAR_{\#}$ (number (#)), $CHAR_a$ (area) and $CHAR_v$ (volume) reconstructions ($CHAR_a$ vs $CHAR_v$ in grey; $CHAR_a$ vs $CHAR_{\#\ sp}$ in white; $CHAR_a$ vs $CHAR_{\#}$ in black; $CHAR_v$ vs $CHAR_{\#}$ in dark grey; $CHAR_v$ vs $CHAR_{\#\ sp}$ in coarse hatching and $CHAR_{\#}$ vs $CHAR_{\#\ sp}$ in fine hatching) on moving windows of 1000 yr calculated every 500-yr time step from 18,000 cal yr BP to today. The six upper graphs (a) show the correlation value for each window (1 = perfect correlation; −1 = negative correlation; 0 = no correlation). The lowest figure (b) displays the range of correlation values during the 18,000 yr of fire history (boxplot corresponds to the second and the third quartile; black line inside is the median).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regional occurrence of human activities about 2000 yr ago and a subsequent collapse about 1600 yr ago.

We stress the need for stand- to local-scale vegetation reconstructions based on terrestrial plant macro-remains for interpreting these Holocene oscillations of fire frequency that cannot be compared with pollen records in a montane landscape due to differences between source areas of pollen and macro-charcoal. The 20th century regional *mFRI* for this ecosystem, based on observations and textual archives (Mouillot et al., 2002), indicates a fire regime that attains the upper limit of the Holocene fire record, i.e. 70 yr. The present-day lack of fire at Lake Creno is contradictory with the stand fire frequency reconstructed currently for Corsica and is outside the Holocene range of frequency. However, this area contributes to the fire cycle at the landscape scale, and represents a forest patch that escaped fire disturbances.

Mediterranean fire-history studies

Both quantitative and qualitative paleo-fire studies in the Mediterranean basin are based on the number of charcoal particles, counted and extracted by different methods. Charcoal particles could be counted in pollen slides (e.g. Colombaroli et al., 2007) at the same time as pollen, with low- to median-time resolution, and undergo the same chemical treatment in sample preparation. They could be counted in a slide separately from pollen analysis, with less chemical treatment such as HCl dissolution and gravity separation (e.g. Turner et al., 2010), depending on sediment composition. Studies do not decompose the charcoal curve into fire events (Connor et al., 2012), and it is known that only some peaks correspond to local fires and that background is a combination of both taphonomical processes in the catchment area or the lake basin and regional biomass areas (Higuera et al., 2011). Several thresholds of size particles were used for counting from few μm to few hundreds μm. Because these methods differ in time resolution (contiguous or not), in charcoal sizes that might result from methodological fragmentation (methodological bias) and, in the numerical treatment to transform charcoal curve into fire history, the fire reconstructions are not exactly similar and all comparisons need interpretation with cautions (Clark and Royall, 1995; Carcaillet et al., 2001b).

Studies are concerned by regional fire history and considered particles under a limit size (e.g. <180 μm in Turner et al., 2010 or <50 μm in Connor et al., 2012) or over a certain size (e.g. >10 μm in Colombaroli et al., 2007). Other studies are interested by local fire history and then considered charcoal particles over a larger size (>250 μm^2 for this study, or >150 μm in Rius et al., 2009). Vanniere et al. (2008) reconstructed regional (pollen-slide charcoal >10 μm) and local (sieved charcoal >100–150 μm) fire history on an Italian lake, histories that differ from 6000 cal yr BP. Regional fire-history reconstruction is misleading because of uncertainties on source of these particles: either a regional source of particles or catchment processes could explain the increase of micro-charcoal (Connor et al., 2012). Local fire history seems to be the less misleading interpretation because it requires fewer processes to play a part on charcoal transportation. But, the different protocols used for local fire-history reconstruction appear confusing in that different fire histories can be inferred from the same sediments.

Temporal variation of charcoal number is used to describe the change of fire frequency, without estimation of background or numerical detection of peaks (e.g. Turner et al., 2010). As shown in the present study, such an approach could be misinforming due to variation in the charcoal background that may be unrelated to the local fire history. To detect discrete fire events, statistical treatments are needed on continuous sampling, on large charcoal (i.e. >100 μm, Higuera et al., 2007) for local reconstruction, with detrending background and peaks taken into account or charcoal sources and charcoal reworking before deposition in the sediment (Clark, 1988; Clark et al., 1998; Lynch et al., 2004). For instance, some studies are based on the area of charcoal particles, passed on a mesh through a soft water jet (e.g. Rius et al., 2009), for a local reconstruction of fire history (charcoal particles >150 μm). This method of extraction is similar with this study, but the background is determined on classes of area of charcoals, log-transformed. The log transformation of data decreases the magnitude of *CHAR* that is a component of the fire severity, and is thus crucial for fire reconstruction. Even though it is likely more robust for statistical analyses, log-transformation of charcoal series is generally not advised.

The Mediterranean local fire histories of Rius et al. (2012) or Colombaroli et al. (2008), indicate 10 or 12 fires per 1000 yr (*FRI* ≤ 100 yr) respectively for a mixed oak vegetation in the Pyrenean foothills and Tuscany. This high frequency appears the same in these different locations, but the results may be excessive given the poor flammability of oak (Trabaud, 1976; Curt et al., 2011). An analysis based on charcoal area or detrending background from peak without log-transformation would have resulted in a lower fire number (as in this study between $CHAR_{\#}$ and $CHAR_a$ reconstructions) and different fire chronologies.

Conclusion

Our methodological analysis to estimate fire frequency indicates that measuring charcoal accumulation rates (CHAR) by area or by volume provides the same trend of fire history, if a locally defined threshold is used to infer fire occurrence. The reconstruction based on charcoal number, however, results in a completely different fire history (with or without screening peak) that is too sensitive to overestimation. The abundance and variations of the charcoal records varies between measurements. The analytical methods used to identify peaks in CHAR are sensitive to this variability between reconstruction based on $CHAR_v$ and $CHAR_a$. Consequently, comparisons between records using these three charcoal quantification methods should be done with special care to avoid possible misleading interpretations related to method. In this Mediterranean environment, characterized by high and variable $C_{background}$ caused by abundant fragmentation and lake charcoal input through both aerial and stream transportation, the surface area of charcoal should be favored for fire reconstruction. The volume of charcoal, directly estimated from area, does not bring more information and can generate a misleading interpretation because of great variation in the number of fire reconstructed, depending on the choice of the moving window used.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.yqres.2013.01.003.

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References

Ali, A.A., Higuera, P.E., Bergeron, Y., Carcaillet, C., 2009. Comparing fire-history interpretations based on area, number and estimated volume of macroscopic charcoal in lake sediments. Quaternary Research 72, 462–468.

Alley, R.B., Agustsdottir, A.M., 2005. The 8 k event: cause and consequences of a major Holocene abrupt climate change. Quaternary Science Reviews 24, 1123–1149.

Andreae, M.O., Merlet, P., 2001. Emission of trace gases and aerosols from biomass burning. Global Biogeochemical Cycles 15, 955–966.

Appleby, P.G., Oldfield, F., 1992. Application of ^{210}Pb to sedimentation studies. In: Ivanovich, M., Harmon, R.S. (Eds.), Uranium Series Disequilibrium. Clarendon Press, Oxford, pp. 731–778.

Bond, W., Woodward, F., Midgley, G., 2005. The global distribution of ecosystems in a world without fire. The New Phytologist 165, 525–538.

Bradbury, J.P., 1996. Charcoal deposition and redeposition in Elk Lake, Minnesota, USA. The Holocene 6, 339–344.

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.
Carcaillet, C., Bergeron, Y., Richard, P.J.H., Frechette, B., Gauthier, S., Prairie, Y.T., 2001b. Change of fire frequency in the eastern Canadian boreal forests during the Holocene: does vegetation composition or climate trigger the fire regime? Journal of Ecology 89, 930–946.
Carcaillet, C., Richard, P.J.H., Asnong, H., Capece, L., Bergeron, Y., 2006. Fire and soil erosion history in east Canadian boreal and temperate forests. Quaternary Science Reviews 25, 1489–1500.
Carcaillet, C., Perroux, A.S., Genries, A., Perrette, Y., 2007. Sedimentary charcoal pattern in a karstic underground lake (Vercors massif, Alps, France): implications for paleo-fire history. The Holocene 17, 845–850.
Carcaillet, C., Hôrnberg, G., Zackrisson, O., 2012. Woody vegetation, fuel and fire track the melting of the Scandinavian ice-sheet before 9500 cal yr BP. Quaternary Research. http://dx.doi.org/10.1016/j.yqres.2012.08.001.
Clark, J.S., 1988. Stratigraphic charcoal analysis on petrographic thin sections: application to fire history in northwestern Minnesota. Quaternary Research 30, 81–91.
Clark, J.S., 1990. Fire and climate change during the last 750 a in northwestern Minnesota. Ecological Monographs 60, 135–159.
Clark, J.S., Hussey, T.C., 1996. Estimating the mass flux of charcoal from sedimentary records: effects of particle size, morphology, and orientation. The Holocene 6, 129–144.
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.
Clark, J.S., Lynch, J., Stocks, B.J., Goldammer, J.G., 1998. Relationships between charcoal particles in air and sediments in west-central Siberia. The Holocene 8, 19–29.
Colombaroli, D., Marchetto, A., Tinner, W., 2007. Long term interactions between Mediterranean climate, vegetation and fire regime at Lago di Massaciuccoli (Tuscany, Italy). Journal of Ecology 95, 755–770.
Colombaroli, D., Vannière, B., Emmanuel, C., Magny, M., Tinner, W., 2008. Fire-vegetation interactions during the Mesolithic-Neolithic transition at Lago dell'Accesa, Tuscany, Italy. The Holocene 18, 679–692.
Connor, S.E., Araùjo, J., van der Knaap, W.O., van Leeuwen, J.F.N., 2012. A long-term perspective on biomass burning in the Serra da Estrela, Portugal. Quaternary Science Reviews 55, 114–124.
Costa, L.J., 2004. Nouvelles données sur le Mésolithique des îles Tyrrhéniennes (Corse et Sardaigne). Gallia Préhistoire 46 (1), 211–230.
Curt, T., Schaffhauser, A., Borgniet, L., Dumas, C., Estève, R., Ganteaume, A., Jappiot, M., Martin, W., N'Diaye, A., Poilvet, B., 2011. Litter flammability in oak woodlands and shrublands of southeastern France. Forest Ecology and Management 261, 2214–2222.
Gamisans, J., Jeanmonod, D., 1993. Catalogue des plantes vasculaires de la Corse, Compléments au Prodrome de la flore corse. In: Jeanmonod, D., Burdet, H.M. (Eds.), Conservatoire et jardin botanique, Genève, pp. 1–391.
Gavin, D., Hu, F., Lertzman, K., Corbett, P., 2006. Weak climatic control of stand-scale fire history during the late Holocene. Ecology 87, 1722–1732.
Goldberg, E., 1963. Geochronology with lead-210 radioactive dating. International Atomic Energy Agency, Vienna, pp. 121–131.
Hallett, D.J., Anderson, R.S., 2010. Paleofire reconstruction for high-elevation forests in the Sierra Nevada, California, with implications for wildfire synchrony and climate variability in the late Holocene. Quaternary Research 73 (2), 180–190.
Heiri, O., Lotter, A.F., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. Journal of Paleolimnology 25, 101–110.
Higuera, P.E., Sprugel, D.G., Brubaker, L.B., 2005. Reconstructing fire regimes with charcoal from small-hollow sediments: a calibration with tree-ring records of fire. The Holocene 15, 238–251.
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 south-central Brooks Range, Alaska. Ecological Monographs 79, 201–219.
Higuera, P.E., Gavin, D.G., Bartlein, P.J., Hallett, D.J., 2011. Peak detection in sediment-charcoal records: impacts of alternative data analysis methods on fire-history interpretations. International Journal of Wildland Fire 19 (8), 996–1014.
Jackson, S.T., Lyford, M.E., 1999. Pollen dispersal models in Quaternary plant ecology: assumptions, parameters, and prescriptions. The Botanical Review 65, 39–75.
Jacobson, G., Bradshaw, R.H.W., 1981. The selection of sites for paleovegetational studies. Quaternary Research 16, 80–96.
Keeley, J.E., Pausas, J.G., Rundel, P.W., Bond, W.J., Bradstock, R.A., 2011. Fire as an evolutionary pressure shaping plant traits. Trends in Plant Science 16, 406–411.
Kelly, R.F., Higuera, P.E., Barrett, C.M., Hu, F., 2011. A signal-to-noise index to quantify the potential for peak detection in sediment-charcoal records. Quaternary Research 75 (1), 11–17.
Legendre, P., Legendre, L., 1998. Numerical ecology, 2nd English edition. (eds. Elsevier Science) BV, Amsterdam, pp. 853.
Lynch, J.A., Clark, J.S., Stocks, B.J., 2004. 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.
Mouillot, F., Rambal, S., Joffre, R., 2002. Simulating climate change impacts on fire frequency and vegetation dynamics in a Mediterranean-type ecosystem. Global Change Biology 8, 423–437.
Pausas, J.G., 1999. Mediterranean vegetation dynamics: modelling problems and functional types. Plant Ecology 140, 27–39.
Payette, S., Morneau, C., Sirois, L., Desponts, M., 1989. Recent fire history of the northern Quebec biomes. Ecology 70, 656–673.
Pitkänen, A., Lehtonen, H., Huttunen, P., 1999. Comparison of sedimentary microscopic charcoal particle records in a small lake with dendrochronological data: evidence for the local origin of microscopic charcoal produced by forest fires of low intensity in eastern Finland. The Holocene 9, 559–567.
Reille, M., Gamisans, J., deBeaulieu, J.L., Andrieu, V., 1997. The late-glacial at Lac de Creno (Corsica, France): a key site in the western Mediterranean Basin. The New Phytologist 135, 547–559.
Reille, M., Gamisans, J., Andrieu-Ponel, V., de Beaulieu, J.L., 1999. The Holocene at Lac de Creno, Corsica, France: a key site for the whole island. The New Phytologist 141, 291–307.
Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Buck, C.E., Burr, G.S., Edwards, R.L., Friedich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Ramsey, C., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E., 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0–50,000 years cal BP. Radiocarbon 51, 1111–1150.
Rius, D., Vannière, B., Galop, D., 2009. Fire frequency and landscape management in the northwestern Pyrenean piedmont, France, since the early Neolithic (8000 cal. BP). The Holocene 19, 847–859.
Rius, D., Vannière, B., Galop, D., 2012. Holocene history of fire, vegetation and land use from the central Pyrenees (France). Quaternary Research 77 (1), 54–64.
Robbins, J.A., Edgington, D.N., 1975. Determination of recent sedimentation rates in Lake Michigan using Pb-210 and Cs-137. Geochimica et Cosmochimica Acta 39 (3), 285–304.
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.
Telford, R.J., Heegaard, E., Birks, H.J.B., 2004. The intercept is a poor estimate of a calibrated radiocarbon age. The Holocene 14, 296.
Trabaud, L., 1976. Inflammabilité et combustibilité des principales espèces des garrigues de la région méditerranéenne. Œcologia Plantarum 11, 117–136.
Turner, R., Roberts, N., Jones, M.D., 2008. Climatic pacing of Mediterranean fire histories from lake sedimentary microcharcoal. Global and Planetary Change 63 (4), 317–324.
Turner, R., Roberts, N., Eastwood, W.J., Jenkins, E., Rosen, A., 2010. Fire, climate and the origins of agriculture: micro-charcoal records of biomass burning during the last glacial–interglacial transition in Southwest Asia. Journal of Quaternary Science 25, 371–386.
Vanniere, B., Colombaroli, D., Chapron, E., Leroux, A., Tinner, W., Magny, M., 2008. Climate versus human-driven fire regimes in Mediterranean landscapes: the Holocene record of Lago dell'Accesa (Tuscany, Italy). Quaternary Science Reviews 27, 1181–1196.
Weng, C.Y., 2005. An improved method for quantifying sedimentary charcoal via a volume proxy. The Holocene 15, 298–301.
Whitlock, C., Millspaugh, S.H., 1996. Testing the assumptions of fire history studies: an examination of modern charcoal accumulation in Yellowstone National Park, USA. The Holocene 6, 7–15.