Climate versus human-driven fire regimes in Mediterranean landscapes: the Holocene record of Lago dell'Accesa (Tuscany, Italy)

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B. Vannière [a], D. Colombaroli[b, d], E. Chapron[c, 1], A. Leroux[a], W. Tinner[b, e] and M. Magny[a]

[a]Chrono-Environment Laboratory, UMR 6249 CNRS-UFC, 16 route de Gray, F-25030 Besançon cedex, France

[b]Paleoecology, Institute of Plant Sciences, University of Bern, Altenbergrain 21, CH-3013 Bern, Switzerland

[c]Geological Institute, ETH Zürich, Universitätstrasse 16, CH-8092 Zürich, Switzerland

[d]Environmental Change Research, Department of Geography, University of Oregon, Eugene, OR 97403-1251, USA

[e]Paleoecology and Vegetation Dynamics, Department of Environmental Sciences, Institute of Terrestrial Ecosystems, ETH Zürich, Universitätsstrasse 22, CH-8092 Zürich, Switzerland

[1] ISTO, UMR 6113, CNRS Université d'Orléans, B.P. 6759, F-45067 Orléans cedex 2, France.

Abstract

A high-resolution sedimentary charcoal record from Lago dell'Accesa in southern Tuscany reveals numerous changes in fire regime over the last 11.6 kyr cal. BP and provides one of the longest gap-free series from Italy and the Mediterranean region. Charcoal analyses are coupled with gamma density measurements, organic-content analyses, and pollen counts to provide data about sedimentation and vegetation history. A comparison between fire frequency and lake-level reconstructions from the same site is used to address the centennial variability of fire regimes and its linkage to hydrological processes. Our data reveal strong relationships among climate, fire, vegetation, and land-use and attest to the paramount importance of fire in Mediterranean ecosystems. The mean fire interval (MFI) for the entire Holocene was estimated to be 150 yr, with a minimum around 80 yr and a maximum around 450 yr. Between 11.6 and 3.6 kyr cal. BP, up to eight high-frequency fire phases lasting 300–500 yr generally occurred during shifts towards low lake-level stands (ca 11,300, 10,700, 9500, 8700, 7600, 6200, 5300, 3400, 1800 and 1350 cal. yr BP). Therefore, we assume that most of these shifts were triggered by drier climatic conditions and especially a dry summer season that promoted ignition and biomass burning. At the beginning of the Holocene, high climate seasonality favoured fire expansion in this region, as in many other ecosystems of the northern and southern hemispheres. Human impact affected fire regimes and especially fire frequencies since the Neolithic (ca 8000–4000 cal. yr BP). Burning as a consequence of anthropogenic activities became more frequent after the onset of the Bronze Age (ca 3800–3600 cal. yr BP) and appear to be synchronous with the development of settlements in the region, slash-and-burn agriculture, animal husbandry, and mineral exploitation. The

anthropogenic phases with maximum fire activity corresponded to greater sensitivity of the vegetation and triggered significant changes in vegetational communities (e.g. temporal declines of *Quercus ilex* forests and expansion of shrublands and macchia). The link between fire and climate persisted during the mid- and late Holocene, when human impact on vegetation and the fire regime was high. This finding suggests that climatic conditions were important for fire occurrence even under strongly humanised ecosystem conditions.

1. Introduction

Fire is one of the most relevant agents of disturbance for it significantly affects vegetation cover, soils, and biodiversity at decadal to centennial scales (e.g. Moreno, 1998; Buhk and Hensen, 2006; Campo et al., 2006; Pausas, 2006; Shakesby and Doerr, 2006; Baeza et al., 2007). The role of fire for future ecosystem dynamics is underlined by the evidence that predicted climate warming will probably affect future fire dynamics (Piňol et al., 1998; Cramer, 2001; Moriondo et al., 2006; Running, 2006), given that fire severity and fire-surface extent are also climatically driven (Pausas, 2004; Keeley et al., 2006). However, many lines of evidence show that fire regime changes are not linearly linked to climatic change, for instance declines of fire frequency as a consequence of climatic warming are documented by long-term ecological and modelling studies from the Boreal biome (e.g. Bergeron and Archambault, 1993; Flannigan et al., 1998; [Tinner et al., 2006a] and [Tinner et al., 2006b]). On a longer-time perspective, fire hazard has generally increased due increases in population size since prehistory, changes in husbandry practices, and increases in human ignition sources (Clark et al., 1989; Tinner et al., 1999; Carcaillet et al., 2002).

Despite the relevant role of human activities during the past millennia and today (e.g. ignition or fire-suppression management; Terradas et al., 1998), fire regimes, defined in terms of severity, frequency, extent, in forested areas of the Mediterranean region and elsewhere are also linked to hydrologic conditions and seasonality that are in turn related to large-scale atmospheric circulation patterns (Heyerdahl et al., 2002; Veblen and Kitzberger, 2002; Trouet et al., 2006). For instance, besides a specific source of ignition, burning depends on the span and degree of the dry season (fuel flammability), but also on fuel availability, which often increases after wet years (Pausas, 2004; Pausas and Bradstock, 2007).

Fire–landscape interactions are still scarcely understood because of the complexity of fire ignition and propagation processes (Mouillot et al., 2003; Arora and Boer, 2005; Salvador et al., 2005; Cary et al., 2006; Heinl et al., 2006; Santoni et al., 2006). During recent decades fire-history studies from the Pacific Northwest of North America, as well as South America, Australia, and central and boreal Europe have progressively contributed to the present knowledge about Holocene fire–climate–vegetation–human interactions (e.g. Clark and Royall, 1996; Carcaillet, 1998; Pitkanen and Huttunen, 1999; Millspaugh et al., 2000; Long and Whitlock, 2002; Brunelle and Anderson, 2003; Brunelle and Whitlock, 2003; Lynch et al., 2003; Tinner et al., 2005; Black and Mooney, 2006; Gavin et al., 2006; Hu et al., 2006). Surprisingly, few data are currently available from the Mediterranean Basin (Carcaillet et al., 1997; Carrión, 2002; [Carrión et al., 2003] and [Carrión et al., 2007]; Sadori et al., 2004; Caroli and Caldara, 2006; Magny et al., 2006; Sadori and Giardini, 2006), most of them having low temporal resolution and/or precision. In fact, only a few studies have high enough precision and resolution (i.e. 10–20 yr, Birks, 1997) to address fire–vegetation linkages such as the role of fire in driving vegetational dynamics (e.g. [Colombaroli et al., 2007] and [Colombaroli et al., in press]). Therefore, most studies focus on long-term (millennial) trends to study linkages between fire and climate.

This paper aims to improve our knowledge about the linkages between Holocene fire regimes, climatic conditions, vegetation, and land-use history in the central Mediterranean. First, we present a high-resolution charcoal sequence from Lago dell'Accesa (Tuscany, Italy). We quantify the long-term charcoal accumulation anomalies along the temporal scale by means of inferred fire frequency (IFF), fire return interval (FRI), and mean fire interval (MFI), estimated according to events interpreted as local fire episodes (Clark et al., 1996; Long et al., 1998; Lynch et al., 2003; Whitlock and Anderson, 2003; Brunelle et al., 2005). We then compare these results with pollen data, lake-level reconstructions and archaeological data to understand to what extent the centennial variability of fires is controlled by climatic, environmental, and/or anthropogenic factors.

2. Study area

Lago dell'Accesa (42°59′17″N, 10°53′44″E, 157 m a.s.l.) is a small lake situated in the southern part of Tuscany (north-central Italy), 5 km from the town of Massa Marittima and 12 km from the Mediterranean Sea coast (Fig. 1a). Vegetation around Lago dell'Accesa is characterised by mixed evergreen/deciduous forests (e.g. *Quercus ilex*, *Q. pubescens*). Annual precipitation reaches ca 745 mm/yr, with a maximum during autumn and a marked summer drought. The average annual temperature is ca 13 °C, the mean temperature of the coldest month is 4.5 °C and that of the warmest month 22 °C (Rizzotto, 1981). The lake basin (ca 580×390 m) is of karstic origin and is fed by a sub-aerial and a sub-aqueous thermal spring (ca 20 °C; Fig. 1b). Its outlet marks the beginning of the Bruna River. The bathymetric map reveals a maximum depth of 37.5 m. The lacustrine profiles indicate a littoral sub-horizontal zone ca 5–20 m wide. Below, there is a steep slope, and finally a gentle slope that reaches the sub-horizontal deepest part of the lake basin (Fig. 1c). The catchment area of the lake covers ca 5 km^2 and is delimited by small hills culminating at ca 350 m a.s.l. The geology of the catchment area is characterised by Permian and Eocene schists and karstified Rhaetian dolomitic limestone (Merciai, 1933). In 1912, the lake level was artificially lowered to extend arable lands, and this diminished significantly the immerged littoral platform.

Several artifacts and archaeological remains have been found in the neighbourhood of the lake. The most important ones are situated on the eastern hill slope, where a necropolis and a settlement from the Etruscan period have been excavated. It is likely that the settlement was connected to the exploitation of the nearby metal deposits. This mining village lasted about a century, from ca 2600 to 2500 cal. yr BP (Lobell, 2002). Several other artifacts, such as potsherds, indicate that the area was continuously occupied by humans since the Neolithic. In historic times the lake water was used to wash minerals from the island of Elba or from regional and local mines (Rizzotto, 1981).

After an early rapid survey in 1984 (R. Drescher-Schneider, unpublished pollen data), and following investigations of the Holocene and Lateglacial littoral deposits in 2000 (Magny et al., 2006; Drescher-Schneider et al., 2007; Magny et al., 2007; Millet et al., 2007), a new coring campaign was organised in 2005 to obtain a continuous Holocene sedimentary sequence from the deepest part of the lake.

3. Materials and methods

3.1. Mapping and coring

Bathymetric map and seismic profiles (Figs. 1b and c) were constructed with a high-resolution single-channel seismic system with a centre frequency of 3.5 kHz (Geoacoustic Equipment). The digital acquisition was achieved by an Octopus Marine 360 system and conventional GPS positioning. The acoustic data highlight a specific acoustic facies associated with the steep littoral environments, which progrades towards the centre of the lake. From these littoral environments, locally reworked sediment slumps produced lens-shaped bodies with a chaotic facies (Fig. 1c), intercalated in the acoustically stratified deposits characterising the deep basin. Below 23 m water depth the stratified basin fill has a dominating draping pattern and is made of several high-amplitude basin-wide reflectors (R1 to R7) that are locally associated with slump deposits or covering a former littoral facies. These geometries reflect the evolution of a dominating bio-induced sedimentation controlled by inputs from the springs and/or lake-level fluctuations. Unfortunately, gas in the deep basin limits the acoustic signal penetration to ca 5 m below the lake floor. Coring operations were directly guided by the quasi-3D image of subsurface sedimentary accumulation. Short (1 m) and long (8 m) sediment cores were retrieved from the best stratified and undisturbed parts of the deep-basin sedimentary infilling with the ETH short gravity corer and a 3 m long UWITEC piston system operating from a raft (Fig. 1c). This study refers to the overlapping twin cores AC05-P6, AC05-B* and AC05-BB*, which provided the temporally longest sedimentary sequence AC05-B.

3.2. Chronology

The chronology is based on 12 AMS ^{14}C ages measured on terrestrial plant macrofossils (Table 1). Macrofossils were selected from 70 sediment samples (volume ca 20 cm^3; mean thickness of 5 cm) which were sieved with a 100-µm mesh screen. After calibration of the ^{14}C dates (program Calib 5.0.2; Stuiver and Reimer, 1993; Reimer et al., 2004), one radiocarbon date was rejected (Poz-16244) on the basis of a reliability of stratigraphy test, as implemented in the program Oxcal 3.10 (Ramsey, 2001). The age–depth model is constructed with a cubic-spline interpolated method (Fig. 1d; Telford et al., 2004). The near-optimal number of degrees-of-freedom has been chosen to keep the interpolated chronological curve within the confidence interval of the generalised mixed-effect regression as proposed by Heegard (Birks and Heegaard, 2003; Heegaard et al., 2005) as well as to force the age–depth model to pass through the error range of the calibrated ages.

3.3. Sedimentology

Gamma density (GD) measurements were made on each 5 mm on the whole core with the Geotek Multi Sensor Core Logger. Bulk density is derived from gammaray attenuation measurements after calibration. Hand-made density measurements show a constant difference of 0.3 g/cm^3, which have been added to obtain the final results. The rapidity of this analysis allows measuring all the core sections sampled in the lake and then makes stratigraphic correlations useful for constructing the master sequence (ca 8 m) from the twin cores.

Rock-Eval® pyrolysis analyses offer an estimation of total organic carbon (TOC, wt%), mineral carbon (MINC, wt%), hydrogen index (HI, in milligrams of hydrocarbons per gram TOC) and oxygen index (OI, in milligrams of hydrocarbons per gram TOC). These parameters were determined from 25 samples with a model 6 device (Vinci Technologies; [Espitalié et al., 1985a] and [Espitalié et al., 1985b]). The 25 samples document major lithologic changes. MINC estimates the carbonaceous fraction of sediments. The TOC indicates the organic matter (OM) abundance. HI and OI index depends on OM origin and on oxygen conditions, which determine OM degradation in the water column and sediments (Talbot and Livingstone, 1989; Meyers and Lallier-Vergès, 1999). High HI values could be associated with well-preserved algal OM source, whereas OI increase is mainly due to degraded OM contribution from autochthonous productivity and allochthonous inputs (Disnar et al., 2003; Magny et al., 2006; Millet et al., 2007). The petrographic study involved the microscopic examination of samples after acid hydrolysis of organic remains (the residual preparation is named: palynofacies). Their chromatic and textural characteristics allow the distinction of two groups: material of phytoplanktonic origin (Lallier-Vergès et al., 1993) and material from soils and vascular plants (Sifeddine et al., 1996).

3.4. Pollen analyses

Sampling resolution (samples in cubes of 1 cm^3 and 1 cm thickness) on the whole sequence is 8 or 16 cm. The sediment samples were treated chemically (HCl, KOH, HF, acetolysis) and physically (0.5 mm sieving and decanting) following standard procedures (Moore et al., 1991). *Lycopodium* markers (Stockmarr, 1971) were added for estimation of pollen concentration (grains/cm^3). For identification of pollen types, we used keys (e.g. Moore et al., 1991; Beug, 2004) as well as the reference collection at the Institute of Plant Sciences in Bern. A total of 66 pollen samples were analysed under a microscope with a magnification of 400×. For calculation of pollen percentages, pollen of water and wetland plants as well as spores of pteridophytes were excluded from the pollen sum. The total pollen sum is >400 grains. The pollen and charcoals diagrams were plotted with Tilia 2 (Grimm, 1992). Local pollen assemblage zones (LPAZ) were defined according to the zonation method of optimal partitioning (Birks and Gordon, 1985), as implemented in the program Zone version 1.2 (Juggins, 1991). The number of statistically significant zones was determined according to the Broken-stick model, as implemented in the program BSTICK (Bennett, 1996).

3.5. Charcoal analyses

Microscopic and macroscopic charcoal sedimentary concentrations were estimated from 66 and 801 samples, respectively. Microscopic charcoal particles (>10 µm) mostly reflect regional fire history (e.g. MacDonald et al., 1991; Tinner et al., 1998; Carcaillet et al., 2001a; Gardner and Whitlock, 2001), whereas macroscopic particles (>100–150 µm) express local (e.g. Clark, 1988; Whitlock and Millspaugh, 1996; Gavin et al., 2003b; Lynch et al., 2004; Higuera et al., 2005) as well as micro-regional fire episodes that may mainly depend on fire size and intensity (Pisaric, 2002; [Tinner et al., 2006a] and [Tinner et al., 2006b]; Peters and Higuera, 2007).

Microscopic charcoal was counted in the pollen slides with a light microscope at 250× magnification following Tinner and Hu (2003) and Finsinger and Tinner (2005); charcoal concentration (#/cm^3) is calculated in proportion to the *Lycopodium* grains added to the samples. Influx values (#/cm^2/yr) derive from sedimentation accumulation rates (SAR) estimated with the age–depth model. For macroscopic charcoal quantification, data are based on the tallying of particles at 40× from contiguous 1-cm sediment samples of 2 cm^3 washed on a 150 µm mesh sieve after acid and peroxide treatments (Rhodes, 1998; Gardner and Whitlock, 2001; Whitlock and Larsen, 2001; Whitlock and Anderson, 2003). Only macro-charcoal particles with well-preserved ligno-cellulosic structure with thin and elongated shape were counted, as they indicate a rapid transport to the lake during and immediately after the fire episodes (Vannière et al., 2003). As in the case of microscopic charcoal (Tinner and Hu, 2003), counts of macroscopic charcoal particles usually give the same results as surface area estimation.

Charcoal counts for each sample were converted to macroscopic charcoal concentrations (CHAC) and then signal analysis was based on the decomposition method initially described by Long et al. (1998) and by use of the software CHARSTER v.0.8.3 (http://geography.uoregon.edu/gavin/software.html; by Daniel Gavin). The principal steps of the signal decomposition are the following. From the age–depth model the macroscopic charcoal raw data were re-sampled to interpolate them to a constant time interval. Then charcoal values were divided by the deposition time of the binned interval to obtain charcoal influx or charcoal accumulation rate (CHAR; #/cm^2/yr). To eliminate the slowly varying component or background signal of the charcoal record, influx values were smoothed with a robust locally weighted regression type (Lowess function) with a 500-yr time window that best fit the low frequency variation. Background charcoal influx (BCHAR) may be determined by several sedimentary processes on charcoal (e.g. the deposition of reworked particles from littoral sediment, Whitlock and Millspaugh, 1996). Alternatively, it may be also linked to fuel availability and characteristics (Vázquez et al., 2002; Marlon et al., 2006; Pausas and Bradstock, 2007) or regional fire activity (Whitlock and Larsen, 2001). However, the difference between charcoal influx and the background component defines the peak component (Clark et al., 1996; Lynch et al., 2003; Gavin et al., 2006). It is usually represented by two populations of values: the lowest ones are interpreted as analytical noise and the positive highest ones above the threshold values (TVs) are assumed to express fire episodes in the local or micro-regional area around the lake.

Two statistical distribution analyses were used to decompose the peak component and to choose the TV. First, sensitivity analysis allowed the identification of how the number of charcoal peaks varies with changing TV (Clark et al., 1996; Lynch et al., 2003). TV is in the range of values for which there is the lowest increase of residual peak number. Secondly, a Gaussian mixture model (Gavin et al., 2006; CHARSTER software) is used to analyse the histogram plot of the peak-component frequency distribution. This model helps to disentangle two overlapping subdistributions and to identify the upper limit of the main distribution, which may potentially be the upper limit of the analytical noise-related variation. The distribution of peaks along the sequence is evaluated by the smoothing sum of episodes in a defined moving time windows. IFF results from this time-series analysis of the peaks component (Long et al., 1998). The FRI and MFI are, respectively, estimated as the number of years between two episodes and between the first and the last fire episodes divided by the number of intervals between all the fire episodes.

4. Results

4.1. Sedimentary data

The age–depth model (Fig. 1d) indicates that the 8 m of sediments cover the last ca 11,700 years, with an average SAR of 0.7 mm/yr (i.e. a time resolution per sample of 14.5 yr/cm), spanning from a minimum of 0.4 mm/yr to a maximum of 1.7 mm/yr (or 25 and 6 yr/cm). The average confidence interval of the error of the generalised mixed-effect regression model is ca 340 yr. Major variations in sediment GD are associated with basin-wide high-amplitude seismic reflectors (R1 to R7; Fig. 1c). Reflector R5 is characterised by an inclination different from that of R6 and R7. At the same depth, SAR calculated from the age–depth model increases and reaches its maximum (Fig. 2). This specific basin-fill geometry suggests that deep-water sedimentation was affected by lake-level fluctuations. The 25 TOC values plotted versus GD show a significant correlation (Fig. 3); GD increases with decreasing TOC, so we assume that GD reflects the minerogenic component, as it has been also observed at Lago di Mezzano (Sadori et al., 2004). Consequently, estimated TOC values have been calculated for the whole sequence (Fig. 2: estimated TOC). Qualitative observations of palynofacies show that most OM particles derive from lacustrine production, with a minor contribution of allochthonous inputs from the shore-belt vegetation or soil OM. High TOC and HI values with low OI values indicate the accumulation of well-preserved autochthonous OM, while inverse OM characteristics involve high processes of OM degradation in well-oxygenated environments.

According to GD and Rock-Eval measurements, nine main sedimentary facies (MSF) describe this laminated organic and calcareous sequence (Fig. 2). MSF1 record spans ca 1500 years between ca 11,700 and 10,200 cal. yr BP; and the GD values are low and TOC percentage relatively high. Carbonate versus organic fine laminations may represent an annual signal. Several successive GD peaks record a sub-phase at 750–780 cm depth, i.e. ca 11,100–11,400 cal. yr BP. Increase of MINC percentages and decrease of TOC percentage characterise MSF2 (10,200–6300 cal. yr BP). OI values are up to 400 mg CO_2/g TOC. This tendency is briefly interrupted between 630 and 600 cm depth as shown by GD values. Compared with MSF1, the coarse laminations and sediments properties imply an important change in environmental conditions, as shown by the loss of the annual signal indicating more oxygenated water. MSF3 sediments conserve high GD values and associated low TOC percentages, but with weak variation in the carbonaceous fraction. At level 367 cm the highest SAR corresponds with the lowest HI value and an OI of ca 260 mg CO_2/g TOC. This marks an allochthonous contribution of OM as well as silicate material. The abrupt change in the MINC and HI curves above 295 cm depth and after 4500 cal. yr BP (MSF4) implies an evolution towards well-oxygenated water, an algal contribution to OM sedimentation, high OM degradation processes, and carbonate precipitation on the littoral platform in a context of a high lake level.

The sharp transition MSF4–MSF5 (240 cm; R4) documents a rapid evolution of lacustrine sedimentation and of the whole ecosystem at ca 3600 cal. yr BP. Granulometry increases, with more sand (Matter, 2005). Seismic data, along with the drop in GD and MINC values and the increase in TOC percentage reflect a lower lake-level, probably associated with allochthonous OM and silicate inputs. The finely laminated MSF6 sediments successively records alternating carbonaceous sedimentation, decrease of OM contribution, and IH increase and then decrease. The coarsely laminated MSF7 sediments parallel the GD curve and to the increase in MINC and OI values, which reflect the low contribution of highly degraded OM to sedimentation. The thin MSF8 section identified on the seismic profile between the high-amplitude reflectors R1 and R2 and by abrupt GD curve inflections is characterised by increased phytoplanktonic OM accumulation as well as coarse calcareous concretions visible to the naked eye, which contribute considerably to the GD decrease. Clay deposits in the top sequence (MSF9) are clearly marked by allochthonous OM inputs which suggest strong erosion on the watershed.

4.2. Pollen-inferred vegetation history and corresponding (low-resolution) microscopic and macroscopic charcoal data

In total, 66 pairs of pollen and microscopic charcoal samples at every 8 or 16 cm cover the whole sequence (Fig. 4, for more details see Colombaroli, 2007; Colombaroli et al., in press). Influx and pollen percentages have similar trends, so we present and discuss only the percentage values. *Pinus*, *Q. ilex*-type (t.), *Quercus pubescens*-t., *Corylus*, and Ericaceae are important pollen types in this Holocene sequence. The pollen record is subdivided into six statistically significant LPAZ. Interestingly, except for a few samples, the trend of microscopic and macroscopic charcoal curves are similar, and charcoal influx values are similar to the concentration values. Only around 350–400 and 580–630 cm depth, respectively, do minimum and maximum SAR values lead to modified charcoal input signals.

The diagram shows a first phase with a progressive decrease of herb pollen (LPAZ AC05-1; 11,700–10,400 cal. yr BP; from 60% to 20%), indicating an open landscape that developed into rather closed forests during this period. *Pinus* and *Q. pubescens*-t. pollen values reach 15% and 40%, respectively. Both microscopic and macroscopic charcoal influxes are at their maximum. Subsequently, the sequence is characterised by alternating phases with dominances of pollen of deciduous oaks (LPAZ AC05-2; AC05-4, and AC05-6) and pollen of evergreen oaks (AC05-3 and AC05-5), suggesting rather drastic shifts between evergreen and deciduous forest types.

During LPAZ AC05-2 (10,400–8600 cal. yr BP) values of tree pollen (mainly *Q. pubescens*-t.) are relatively stable around 80%, documenting the prevalence of deciduous forests. Charcoal influx decreases through the zone. High peaks in microscopic and macroscopic charcoal at the end of the zone are synchronous with an increase of pollen of shrubs and a decline of pollen of trees, suggesting a fire-linked transformation of the forested environments.

LPAZ AC05-3 (8600–7900 cal. BP) is characterised by the nearly instantaneous increase of pollen of *Q. ilex*-t., indicating the expansion of evergreen forests in the Accesa area. The subsequent decline of pollen percentages of *Q. ilex*-t. (from 60% to 30%; LPAZ AC05-4) is dated at ca 7900–7700 cal. yr BP and occurred together with an increase of pollen of herbs (Colombaroli et al., in press). Microscopic and macroscopic charcoal influx increase, suggesting that the decline of evergreen oak forests was associated with an increase of charcoal influx and thus of fire activity. In general, this pollen zone is characterised by relatively high non-arboreal pollen values (e.g. Poaceae) documenting rather open forested environments.

During LPAZ AC05-5 (6200–2800 cal. yr BP), tree pollen (mainly *Q. ilex*-t.) recovers (up to 80%), indicating the re-establishment of rather closed forests. Microscopic and macroscopic charcoal particles show different trends, with a pronounced minimum in the macroscopic charcoal and a peak at around 5000 cal. BP recorded only in the microscopic concentration and influx series. The increase of *Q. ilex*-t. pollen, however, is closely related to minimum charcoal values in both the microscopic and macroscopic series, again suggesting low fire activity when evergreen forests expanded. Towards the end of the zone AC05-5 (ca 3500 cal. yr BP), pollen percentages of *Q. pubescens*-t. slightly increase, whereas *Q. ilex*-t. decreases markedly (from 50% to 20%) together with pollen of all tree taxa. Again this shift from evergreen to deciduous vegetation is associated with an increase of charcoal influx and thus fire incidence.

After a break, the vegetational shift continues in LPAZ AC05-6 (from 2800 cal. yr BP), where pollen percentages of *Q. pubescens*-t. reach 50%, while pollen percentages of *Q. ilex*-t. become less than 10%. Pollen of Poaceae and *Corylus* decreases as well. Towards the end of zone AC05-6 pollen of all tree taxa declines with two major minima at around 1300 and 400 cal. BP (respectively, tree pollen reaches ca 50% and 35%). The first decline of tree pollen coincides with a maximum of macroscopic charcoal influx, while the second is synchronous with a peak in microscopic charcoal influx. Pollen (e.g. *Artemisia*, *Plantago*) and charcoal data suggest that during this last phase the landscape around the lake became more open, with large areas opened for agricultural purposes in part by the use of fire.

4.3. Macroscopic charcoal inferred fire frequency

Minimum and maximum macroscopic charcoal concentrations are 0.505 and 513.131 #/cm^3, respectively, which, taking into account SAR, leads to minimum and maximum influx values (CHAR) of 0.036 and 46.684 #/cm^2/yr. These values are similar to those from other coastal records from south-eastern Italy (Caroli and Caldara, 2006), eastern Australia (Mooney and Maltby, 2006), and the western USA (Long and Whitlock, 2002). They are higher than CHAR measured in lake or mire sediments from north latitude Mountains for instance from the Swiss Alps (Stähli et al., 2006), from the Rocky Mountains (USA; Brunelle et al., 2005), or from Alaska (Lynch et al., 2003). For the estimation of the background component (BCHAR) or CHAR tendency (see Section 3.5.) the re-sampling bin-width chosen was 25 yr and corresponded to the lowest SAR in the whole sequence (Fig. 5). BCHAR reached maximum values between 11,600 and 10,200 cal. yr BP, with a short period of decrease around 11,200 cal. yr BP. Then, with a progressive decrease, it reached low values at ca 9200 cal. yr BP and remained stable until 8000 cal. yr BP. Between 8000 and 5000 cal. yr BP BCHAR values are somewhat higher, with progressively lower maxima at ca 7400, 6900–6500, and 5700–5400 cal. yr BP. Micrococscopic charcoal particle influx clearly follows these oscillations (Fig. 5). During the second half of the Holocene BCHAR shows three phases with increased values around 3600–3100, 2600–2400, and 1500–1100 cal. yr BP. For this period microscopic charcoal influx remains very low, i.e. less than or around 10,000 #/cm^2/yr, except for the peak at ca 500 cal. yr BP.

The frequency-distribution analysis of residual peak values (difference between CHAR and BCHAR) with a Gaussian mixture model allows us to identify two clusters (Fig. 6). On the basis of the sensitivity analysis (as illustrated by the distribution curve of negative and positive residual peaks and the cumulative number of retained peaks under varying TVs) a TV of 0.7 #/cm^2/yr was selected. Seventy-five residual peaks are identified above this TV and are interpreted as local (to regional) fire episodes. We use the fire episodes to estimate the IFF per 500 and 1000 years (Fig. 5). For instance, over the entire sequence IFF varies between 1.1 and 6.2 episodes/500 yr. MFI for the entire Holocene is 152 yr and on an average oscillates between 80 and 450 yr. FRI reaches a minimum of 50 yr and a maximum of 525 yr (Fig. 7). In the whole sequence, eight significant MFI increases could be identified at ca 11,500–10,500, 9650–9450, 9000–8450, 8000–7400, 6500–5750, 5500–5100, 3600–3100, and 2000–1200 cal. yr BP. Two maxima up to 450 yr are recorded in FRI at ca 8100 and 4000 cal. yr BP.

We also applied other techniques to estimate BCHAR and thus the residual peak component. For instance, we used different time windows for Lowess smoothing (300, 800) and log transformation of CHAR values. To identify charcoal episodes we also tried the ratio CHAR/BCHAR, and higher TVs (Clark et al., 1996; Long et al., 1998; Lynch et al., 2003;

Gavin et al., 2006; Marlon et al., 2006). The distribution of peaks always followed the same trend, but with lower total peak numbers (ca 35–50) that would result in rather long periods (1000–2000 yr) without any fire episode. However, residual peaks concentrate on three periods with many identified charcoal peaks between 9500 and 8000 cal. yr BP, a few spaced peaks between 6000 and 4000 cal. yr BP, and again many after 3800 cal. yr BP. Thus, by using these alternative (and more conservative) approaches, the MFI for the whole Holocene is significantly longer, with values of ca 230–320 yr (instead of 152 yr).

5. Discussion

5.1. Estimation of fire frequency and fire return interval

Quantification of fire signals by (sieved) macroscopic and (pollen-slide) microscopic charcoal display similar trends before 6000 cal. yr BP (Fig. 4), although some discrepancies appear in the signal amplitude around and after 8000 cal. yr BP. Differences in the spatial pattern of fire or taphonomic and sedimentary processes could be at the origin of these discrepancies. For instance, Carcaillet et al. (2001a) suggest that these differences could result from the regional source of small particles and/or high fragmentation during pollen-type chemical treatment. In contrast, quantitative comparisons between thin-section and pollen-slide charcoal series of the same core yielded no evidence of fragmentation during standard pollen procedures (Tinner et al., 1998; Tinner and Hu, 2003). Instead, statistical analyses of particle-size distributions (Tinner and Hu, 2003) showed that large particles (>0.2 mm) are eliminated by the pollen-slide method, which involves highly selective physical procedures such as sieving and decanting of sediments.

Unfortunately, the absence of historical fire data or studies of tree-ring scars from Lago dell'Accesa region raises some difficulties in the estimation of the TV by which a charcoal peak is identified as a local fire event (Gavin et al., 2003b; Lynch et al., 2004; Higuera et al., 2005). The major peaks detected would reflect the local space/time dynamics of fire (Fig. 5). The estimated MFI of ca 152 yr is in accordance with the study of Arora and Boer (2005), which simulated a FRI of 153 yr under quasi-natural conditions for the southern plain of Spain, and with modern data from Greece (100–150 yr, Hadjibiros, 2001). Shorter fire-return intervals have been estimated from recent observation for northern mountains and wetter places in Spain (Vázquez et al., 2002), where higher lightning frequency would favour fire ignitions (Arora and Boer, 2005). Combining modern observations and historical data, Moreno (1998) suggested a mean fire-return interval for Italy of ca 53 yr for the period 1980–1990. Even so, there is a high variability in Mediterranean countries (40 yr to even 2000 yr) related to the degree of land fragmentation and land-use. For the past 25 years, many scientists have agreed that fire frequency has increased (Moreno, 1998; Pausas and Vallejo, 1999; UNECE-FAO Report, 2002; Pausas, 2004; UNECE ICP-BFH Executive Report, 2004). The long-term fire-history study at Accesa shows that MFI could have reached an average of 80 yr during high fire-frequency periods, with two episodes separated only by ca 50 yr (Fig. 7). These results are comparable with the present-day variability observed in European Mediterranean countries and are linked with spatial landscape diversity (Moreno, 1998). Independent of ecological changes for the Holocene, the long-term MFI average of 152 yr appears closer to the assumed quasi-natural fire regime. The frequencies observed by these historical and modern ecological studies are in good agreement with the palaeo-IFF and MFI results. We thus conclude that the approaches used in this study are able to document important parameters of past Mediterranean fire regimes.

5.2. Early Holocene fire regime and climate seasonality

During the earliest Holocene (ca 11,700–10,500 cal. yr BP), our CHAR record suggests a high IFF, when the tree vegetation cover was rather open and lake-levels lowered twice (Fig. 7 and Fig. 5b). Dry climatic conditions during the summer (Rossignol-Strick, 1999; Drescher-Schneider et al., 2007) could have induced lower lake-levels as well as higher fire frequencies. In agreement, it has been suggested that high seasonality, summer drought, and frequent fires favoured the expansion of *Corylus* in northern Italy (Finsinger et al., 2006) and elsewhere in Europe (e.g. Huntley, 1993; Tinner and Lotter, 2001). High-amplitude fluctuations of reconstructed annual sea-surface temperatures support this evidence for stronger seasonality in the North Atlantic realm during the early Holocene (de Vernal and Hillaire Marcel, 2006). High seasonality during the early Holocene was probably a consequence of orbital parameters, inducing a minimum of winter solar radiation and a maximum of summer solar radiation in the Northern Hemisphere at ca 9 ka (Kutzbach and Webb, 1993). Such climatic conditions could explain the occurrence of laminated sediments at Lago dell'Accesa and could have advantaged fires, since dry summer conditions favour fire ignition and expansion. In agreement, charcoal series from around the Mediterranean basin in Sicily (Lago di Pergusa, Sadori and Giardini, 2006), Spain (Lake Siles; Carrión, 2002), and Turkey (Lake Van; Wick et al., 2003) also show high charcoal values during the early Holocene that were attributed to frequent fires. Similar results were obtained on the west coast of North America (Millspaugh et al., 2000; Gavin et al., 2003a; Whitlock et al., 2003; Whitlock et al., 2007; Anderson et al., 2008). These paleoecological findings are in agreement with modern observations from Liguria in northern Italy (Telesca et al., 2007) which reveal a high variability in the spatial distribution of forest fires (1997–2003) with largest fires (surface extension >400 ha) reflecting a cyclic pattern connected with seasonality.

Magny et al. (2006) deduced from their lake-level study that warmer climatic conditions, probably resulting from the restoration of the thermohaline circulation (Björck et al., 1996) and an orbitally induced summer-insolation maximum, led to an intensification of the hydrological cycle over the western Mediterranean area. The low lake level dated to ca 11,350–11,150 cal. yr BP and associated with a high IFF period is synchronous with relative sedimentary changes in core AC05-B (Fig. 2). Magny et al. (2006) associated this phase, which is accompanied by a slight decrease in tree pollen, with the Preboreal Oscillation (see Björck et al., 1997; Sangiorgi et al., 2002; Cacho et al., 2006). Both the pollen data from the central lake (this study) and littoral cores (Drescher-Schneider et al., 2007) record an expansion of deciduous thermophilous trees at ca 11,000 cal. yr BP. Later on, between 10,500 and 9000 cal. yr BP, lower IFF occurred in forested environments dominated by deciduous *Quercus* during a period with relatively high lake levels.

A drop in lake levels is recorded at 9000 cal. BP, when deciduous oaks started to decline and IFF increased, probably as a result of drier conditions in this part of the Mediterranean region (Magny et al., 2006). This period with drier conditions, more frequent fires, and lower lake levels spanned ca 500 yr and ended at ca 8500–8300 cal. yr BP. Chronologically, this period corresponds to the Sapropel 1 deposits and is synchronous with increased Nile River floods and possibly more humid conditions in the eastern Mediterranean (Ariztegui et al., 2000). This reconstruction is supported by stalagmite data from Corchia cave (northern Italy) that suggest increased of precipitation in the western Mediterranean during the deposition of Sapropel 1 (Zanchetta et al., 2007). Charcoal data available from Lago di Pergusa in upland Sicily (Sadori and Giardini, 2006) and from Lake Van in Turkey (Wick et al., 2003) also attest to high CHAR until 8400/8200 cal. yr BP. But the authors interpret pollen data from the same series as the indices of wet climatic conditions. In contrast, rather dry climatic conditions during the early Holocene at around 8400/8200 cal. BP are recorded in southern Spain (Reed et al., 2001). These differences may have resulted from the regional climatic setting. However, we have to take in account the relative sensibility of the different proxies and/or seasonality of climate (Carcaillet et al., 2001b; Wick et al., 2003; Magny et al., 2007). Actually, the fire-frequency and lake-level records are more sensitive to summer conditions (Magny, 1998). Wick et al. (2003) proposed that during the first part of the Holocene moisture increase was synchronous with dry spring–summer weather in Anatolia. Zanchetta et al. (2007) suggested that the precipitation increase observed at Corchia cave (central Italy) resulted from NAO oscillations that influenced winter-season rainfall.

5.3. Holocene fire regime, hydrological patterns, and ecological change

The Holocene expansion of *Q. ilex* forests started at about 8600 cal. yr BP, peaked at 8400–7900 cal. yr BP, and ended at about 7600 cal. yr BP. *Q. ilex* is a drought-adapted species with a high sensitivity to frost (Pigott and Pigott, 1993; Conedera and Tinner, 2000; Grund et al., 2005). Low lake-levels before 8300 cal. yr BP and high lake levels at around 8300–8100 cal. yr BP, however, indicate that this period was probably characterised by heterogeneous climatic conditions, most likely including changes in the precipitation regime. Transient humidity increases during this period are also suggested by high percentages of *Abies* and *Fagus* pollen (Drescher-Schneider et al., 2007; Colombaroli et al., in press). Dry (summer) climatic conditions, which prevailed between 9100/8400 and 8100/7700 cal. yr BP, possibly favoured fire ignition. Lake-level changes suggest that this situation was interrupted by a short humid period of 300–400 yr that resulted into less fire activity according to IFF and FRI estimations. Interestingly, during this period *Q. ilex* continued to expand. We therefore hypothesise that climatic changes (i.e. less dry conditions) would be enough to be recorded by lake-level and MFI increase but would be also moderated enough to maintain the *Q. Ilex*-t stands that had expanded during a dry period already at 8700–8600 cal. BP. Thus, it is conceivable that high FRI and low FFI could have directly advantaged evergreen oaks even during a relatively less dry period. The temporary lake-level changes and the low fire incidence fall into the range of the 8.2 kyr cal. BP cold event and could be the geo-ecological consequence of this global climatic event (Wick and Tinner, 1997; Tinner and Lotter, 2001; [Magny et al., 2003] and [Magny et al., 2006]; Alley and Agustsdottir, 2005).

After ca 8000 cal. yr BP (Fig. 4 and Fig. 5) IFF increased while lake-levels reached very low stands (Magny et al., 2006), indicating that climate was again drier. For this (lake-level-inferred) dry period, time-series analyses from Lago dell'Accesa and Lago di Massaciuccoli (also in Tuscany) suggest that increasing fire frequency considerably reduced the abundance of *Q. ilex* (Colombaroli, 2007; [Colombaroli et al., 2007] and [Colombaroli et al., in press]). The little gap between maximum IFF and the lake-level drop may result from chronological uncertainties in both Accesa records (central and littoral sequences). Indeed, the central and littoral *Q. ilex* expansions and declines show a difference of about 400 yr (Magny et al., 2006; Drescher-Schneider et al., 2007). However, the littoral record clearly shows that the peak of evergreen oak (but not the onset of the expansion) is synchronous with the low lake level. The increase in charcoal influx is also recorded in the littoral sequence just after the 8.2 kyr deposit of lake marl (Magny et al., 2006).

During the *Q. ilex* expansion and dominance, the forests were relatively closed. Instead, between 7900 and 7700 and 6500 cal. yr BP, deciduous *Quercus* (probably *Q. pubescens*, see Drescher-Schneider et al., 2007) increased and shrub and herbs were more abundant

(Colombaroli, 2007; Colombaroli et al., in press). This change was associated with a significant increase of microscopic charcoal suggesting increased fire activities in the Accesa region. The situation appears more complex when consulting reconstructed local IFF (Fig. 7 and Fig. 5b), with a strong increase between ca 7900 and 7400 cal. yr BP, a subsequent minimum of IFF at 7200–6600 cal. yr BP, and finally a re-increase at 6500 cal. BP. Around 7700 cal. yr BP, lake-level rises at Lago dell'Accesa (Magny et al., 2007) suggest more humid conditions. However, it is likely that at least some of the fires were of anthropogenic origin. High-resolution pollen and charcoal series (contiguous analyses of every cm between 8400 and 6400 cal. yr BP, see Colombaroli, 2007; Colombaroli et al., in press) on the central lake cores suggest that increases of regional and local fire frequencies after 8000 cal. BP were at least partially connected to Neolithic agricultural activities around the lake at ca 7900–7700 cal. BP. This interpretation is mainly based on the close link between pollen indicative of agriculture (e.g. *Plantago lanceolata*, *Artemisia*) and the microscopic and macroscopic charcoal records. This more humid phase may correspond to the Central European cool-humid phase CE-4 (or "Frosnitz" in the Austrian literature), which lasted from 7500 to 7100 cal. yr BP (e.g. Haas et al., 1998; Nicolussi and Patzelt, 2000). Similar to the conditions at Accesa, a climatic shift to more humid conditions at ca 7000 cal. yr BP has been recorded in the south-western Mediterranean (Reed et al., 2001; Carrión, 2002). However, the period of lower IFF is relatively long (7200–6600 cal. yr BP, ca 600 yr) and is followed by a new phase of frequent fires. A more or less corresponding trend is recorded in lake-level change with a drop around 6400 cal. yr BP, when fire frequency increased. In agreement, a peat layer indicating a low lake-level is recorded at Lago di Mezzano ca 6700–6400 cal. yr BP (Ramrath et al., 2000). *Q. ilex*, however, as in the preceding periods, increases only significantly when fire frequency declines again at ca 5800 cal. yr BP. This close link between fire incidence and *Q. ilex* abundances continues during the next centuries with an IFF increase and a synchronous decline of *Q. ilex* around 5300 cal. yr BP and again a decrease of IFF and an expansion of *Q. ilex* at ca 4300 cal. yr BP. In agreement, recent paleoecological studies at nearby Lago di Massaciuccoli suggest that (late-successional) forests of *Q. ilex* are easily disrupted by fires and are usually replaced by macchia vegetation. This high fire sensitivity of mature *Q. ilex* stands has also been found at Croatian sites and in Sicily (Colombaroli, 2007).

5.4. Holocene fire regime and human impact

As pointed out above, pollen data from Lago dell'Accesa suggest that the decline of *Q. ilex* and the IFF increase between 8000 and 7600 cal. yr BP were synchronous with an increase of plants indicative of human activities, such as *P. lanceolata*, *Rumex acetosella*, Cichorioideae, Chenopodiaceae, *Apium*, *Artemisia*, and *Pteridium* (Drescher-Schneider et al., 2007; Colombaroli et al., in press). These taxa are often related to open habitats used for agricultural practices (Behre, 1981) and increase further around 4500–3800 cal. yr BP and during the Etruscan and Roman periods (Drescher-Schneider et al., 2007). In the central lake core these taxa are abundant already during the period 7700–6000 cal. yr BP (Fig. 4; for further details see Drescher-Schneider et al., 2007; Colombaroli et al., in press). The beginning of the Neolithic culture is only documented in Tuscany by occasional discoveries of Cardial pottery (from 8000 cal. yr BP; Malone, 2003). The middle Neolithic (ca 7500–5300 cal. yr BP) is attested by the excavated site of Piensa (Malone, 2003). But it is the late Neolithic (ca 5300–4500 cal. yr BP) that is probably the best represented in the region by cave settlements (e.g. around Pisa and Siena; Settis, 1985). During this period farming economies became more intensive. The use of fire in European Neolithic cultures for land-use and clearance is widely attested (Clark et al., 1989; Carcaillet, 1998; Tinner et al., 1999; Vannière and Martineau, 2005). Tinner et al. (2005) reported charcoal increases in lacustrine sedimentary sequences on the Swiss plateau at ca 6200 and 5500 cal. yr BP. They coincided with declines of pollen of fire-sensitive tree taxa at both sites. At the same time, higher fire activity is recorded at Lago di Massaciuccoli in northern Tuscany (Colombaroli et al., 2007; Fig. 8). It thus appears clear that besides climate, human impact was a driver of changes in both vegetational and fire regime for this period (8000–6000 cal. yr BP). The rather close link between lake levels and IFF (e.g. high lake stands and low IFF at 4800 and 4300) suggests that increased moisture availability diminished fire susceptibility of the ecosystems, probably favouring natural and anthropogenic ignition. However, similar findings (high lake levels before ca 4000 cal. yr BP) corroborate the lake-level-inferred climatic trends at other Italian sites (Giraudi, 1998; Sadori et al., 2004 L. Sadori, C. Giraudi, P. Petitti and A. Ramrath, Human impact at Lago di Mezzano (central Italy) during the Bronze Age: a multidisciplinary approach, *Quaternary International* **113** (2004), pp. 5–17.

For the Bronze Age, ca 4000–2900 cal. yr BP, no local settlement is known around the Lago dell'Accesa (Camporeale and Giuntoli, 2000). Nevertheless, human presence and land-use is attested by pollen. Around 3800–3600 cal. yr BP, lake levels were rather low (Fig. 5), and IFF increased toward maximum values at 3700–3200 cal. yr BP. Sedimentological analyses show that terrigenous inputs indicate erosion in the watershed. Environmental changes around the lake appear particularly marked. Increases in fire and erosion processes connected to drier climate and/or human impact are reported from other Italian sites (Caroli and Caldara, 2006; Sadori and Giardini, 2006; Fig. 8). It is likely that human populations increased during the Bronze Age and that land-use was more intensive. In agreement, human influences on sedimentation processes are also recorded in the Adriatic region during this period (3800 cal. yr BP; Oldfield et al., 2003; Rolph et al., 2004). However, the first important settlement around Lago dell'Accesa occurred during the Villanova culture (2900–2700 cal. BP; first Etruscan period). Tombs and houses belonging to miners testify to an occupation of the territory that spans from ca 2800 (tombs)–2600 (houses) to 2500 cal. yr BP (Camporeale, 2000; Camporeale and Giuntoli, 2000; Lobell, 2002). A slight IFF increase is contemporaneous with this nearby occupation (Fig. 7), when the lake level was rather high. After 1000 cal. yr BP only three peaks are recorded in the macroscopic charcoal series. Sediments were rich in rounded microscopic charcoal particles, which are most likely reworked from soils and mark strong erosional processes. Erosion was probably linked with agricultural activities that implemented another use of fire than before. This is in agreement with pollen data suggesting that most parts of the area where open and used as crop fields or pastures which were probably susceptible to erosion. Considering the available records, periods with increased fire activity were coarsely synchronous in Italy during the late Holocene (Fig. 8). Taken together, it is likely, that human activities contributed to increased fire frequencies during this period of demographic increase.

5.5. Climate versus human-driven Holocene fire regimes

Statistical analysis of the period 1997–2003 in Tuscany shows that the fire regime was determined by climate-related periodicities (Telesca and Lasaponara, 2006), though it is clear that in the Mediterranean region most fires are initiated by human activities (Moreno, 1998). Generally models show a large influence of climate and weather on landscape-fire-succession, although terrain complexity and fuel patterns are also relevant (Rollins et al., 2002; Cary et al., 2006). The importance of the precipitation regime on extreme fire occurrences is undoubted (Pausas, 2004; Trouet et al., 2006; Pausas and Bradstock, 2007), even in the modern humanised landscape. Fig. 9 presents a synthesis of millennial fire frequencies compared with lake-level trends. During the first part of the Holocene (11,700–ca

4000 cal. yr BP), the amplitude and rhythms of hydrological and fire regimes followed the same trend in millennial scales. During the second part of the Holocene (after ca 4000 cal. yr BP), the amplitude of IFF changes was always higher than that of the lake-level ones and was most likely related to interferences with human impact (e.g. slash-and-burn agriculture, animal husbandry, and mine exploitation), even if climate influence on fire regime was still significant. Similar results showing a close link between Holocene climatic changes, land-use, and the fire regime were obtained in Italian Switzerland (Tinner et al., 1999) and in Spain (Carrión, 2002; [Carrión et al., 2003] and [Carrión et al., 2007]). Unambiguous evidence also shows that fire was a natural component of ecosystems throughout the Holocene in the dry and continental Swiss central Alps (e.g. with MFI of 250 yr in mountain-pine forests; Stähli et al., 2006).

However, in the temperate biome of central Europe and most regions of the Alps, fire incidence has been principally attributed to human activities. Before the Neolithic fire frequencies were very low (Carcaillet, 1998; [Tinner et al., 1999] and [Tinner et al., 2005]; Carcaillet et al., 2002; Gobet et al., 2003). It is also the same for Spain's Mountainous area ([Carrión et al., 2003] and [Carrión et al., 2007]). Our new charcoal records show that this was different in the fire-prone Mediterranean ecosystems around Lago dell'Accesa, where fire frequency was rather high during the entire Holocene with MFI between ca 450 yr, and less than 100 yr, with an average of 150 yr for the entire Holocene. During LPAZ AC05-1 and 2 MFI are, respectively, 130 and 158 yr, whereas MFI became longer (300 yr) during the period of *Q. ilex* dominance (LPAZ AC05-3). During the post-Neolithic periods, LPAZ AC05-4, 5 and 6, MFI reaches values close to the early Holocene ones of 131, 154, and 187 yr, respectively. Because of the high incidence of fire before the onset of the Neolithic, our results imply that fire can be considered an important natural component of Mediterranean ecosystems. This natural-fire component must be clearly separated from destructive anthropogenic fires that partly resulted in marked vegetational and environmental changes, such as the replacement of former *Q. ilex* forests by macchia shrubland.

6. Conclusion

This paper presents a continuous record of fire-regime changes for the last 11,700 yr from Lago dell'Accesa in Tuscany (Italy). The combined evaluation of charcoal-inferred fire regimes with hydrological, vegetational, and archaeological data reveals strong relationships among climate, fire, vegetation, and land-use and attests to the paramount importance of fire in Mediterranean ecosystems. The main findings are:

(1) The MFI for the entire Holocene was estimated to be 150 yr, with a minimum around 80 yr and a maximum around 450 yr. One hundred and fifty years could represent the quasi-natural MFI in Mediterranean ecosystem. The frequencies observed by historical and modern ecological studies are in good agreement with the palaeo-MFI results.

(2) The periods of maximum local fire activity are dated around 11,300, 10,700, 9500, 8700, 7600, 6200, 5300, 3400, 1800, and 1350 cal. yr BP.

(3) The macro-charcoal record suggests that before 4000 cal. yr BP, longer or shorter fire rotation intervals are principally related to hydroclimatic variations. Fire-activity maxima reflect drier climatic periods.

(4) At the beginning of the Holocene high climate seasonality favoured fire expansion in this region, as in many other ecosystems of the northern and southern hemispheres.

(5) Since the onset of Neolithic land-use at ca 8000 cal. yr BP humans have undoubtedly affected the fire regime, leading to higher fire frequencies. The use of fire as a tool was intensified during the Bronze Age (4000–3800 cal. yr BP), when the fire regime was clearly related to both climatic conditions and human activities.

(6) Charcoal-pollen time-series analyses clearly indicate that anthropogenically enhanced fire disturbance strongly promoted the establishment of shrublands and macchia in the Mediterranean area, particularly at the expense of the previously widespread *Q. ilex* forests.

(7) The anthropogenic phases with maximum fire activity corresponded to greater sensitivity of the vegetation and triggered changes in vegetational communities (e.g. decline of *Q. ilex* forests).

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Fig. 1. (a) Geographical location of Lago dell'Accesa (Tuscany, Italy) and reference sites in central Italy. (b) Bathymetric map of Lago dell'Accesa (isobaths: 5 m), location of seismic reflection profiles (white lines), extension of main seismic facies and locations of sediment cores. (c) High-resolution seismic profile illustrating of the basin-fill stratigraphy, main seismic facies, basin-wide reflectors (R1 to R7), and the location of piston core AC05-B. Reflector R1 shows an on-lap configuration in the deep basin, suggesting the occurrence of a turbidite deposit associated with a sediment slump reworking part of the NW slope. Reflectors R2, R3, and R4 have a slightly divergent configuration towards the NW, suggesting a main sediment supply originating from the springs. In addition, towards the SE a former littoral facies is buried bellow R3 and R4 along the SE part of the basin. Reflectors R5, R6, and R7 are comparatively less continuous, and R5 is characterised by a different inclination than R6 and R7. This specific basin-fill geometry suggests that deep-water sedimentation was affected by lake-level fluctuations. (d) Age–depth relationship of master core AC05-B based on ^{14}C age ranges (Table 1).

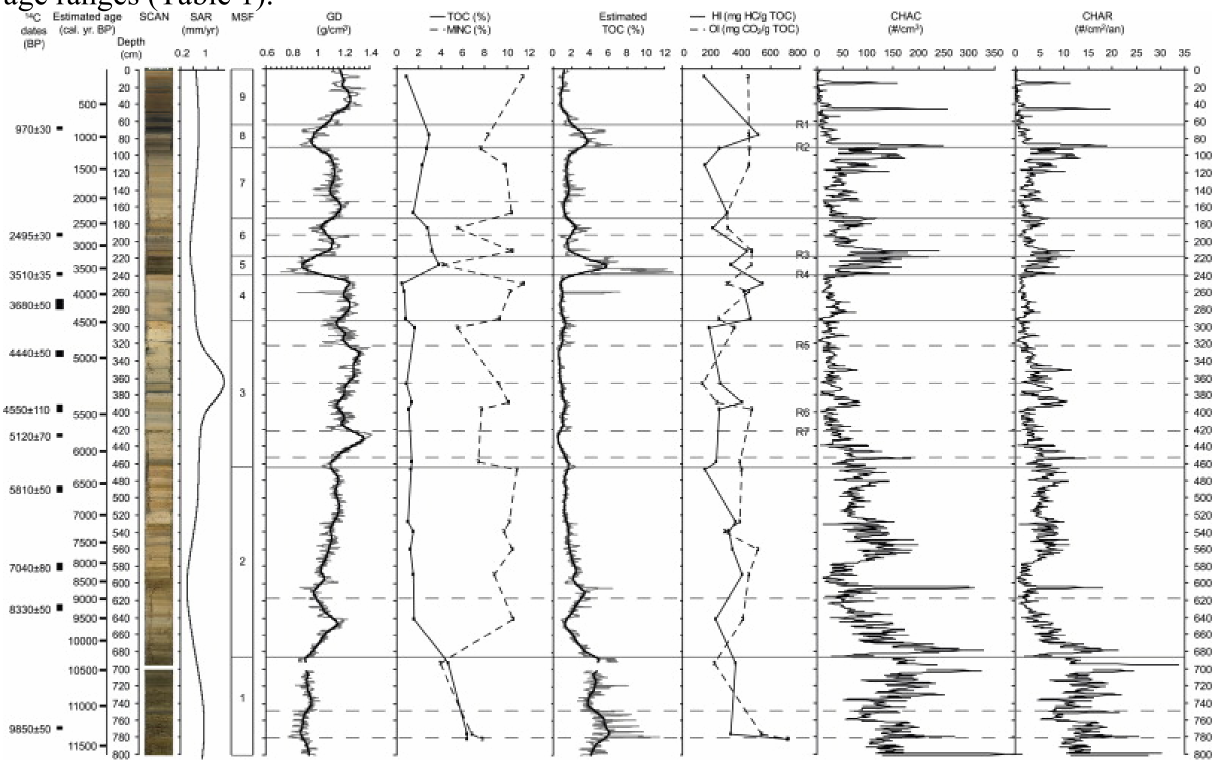

Fig. 2. Lithology, sedimentation accumulation rate (SAR), main sedimentary facies (MSF), gamma density (GD), total organic carbon (TOC), mineral carbon (MINC), TOC estimated from GD values (see Fig. 6), hydrogen index (HI), oxygen index (OI), macroscopic charcoal concentration (CHAC) and macroscopic charcoal accumulation rate (CHAR) high-resolution diagram (depth scale) from Lago dell'Accesa (core AC05-B). Estimated age and positions of AMS radiocarbon dates and seismic reference layers R1 to R7 (see Fig. 1c) are indicated. Changes in sediment bulk density match high-amplitude reflectors (R1 to R7) with use of a mean sediment Pwave velocity of 1.5 km/s. MSF1: laminated fine calcareous and organic silty clays; MSF2: laminated calcareous silt; MSF3 and 4: coarsely laminated calcareous clayey silt; MSF5: laminated fine organic silty clays; MSF6: laminated calcareous and organic silty clays; MSF7: coarsely laminated calcareous silt; MSF8: laminated fine calcareous and organic silty clays; and MSF9: laminated fine calcareous clays.

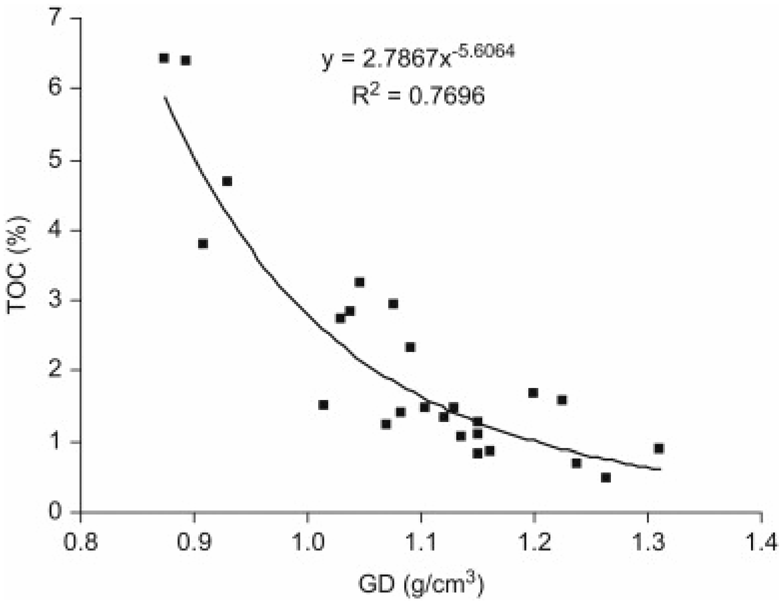

Fig. 3. Correlation diagram of total organic carbon (TOC) versus gamma density (GD) values.

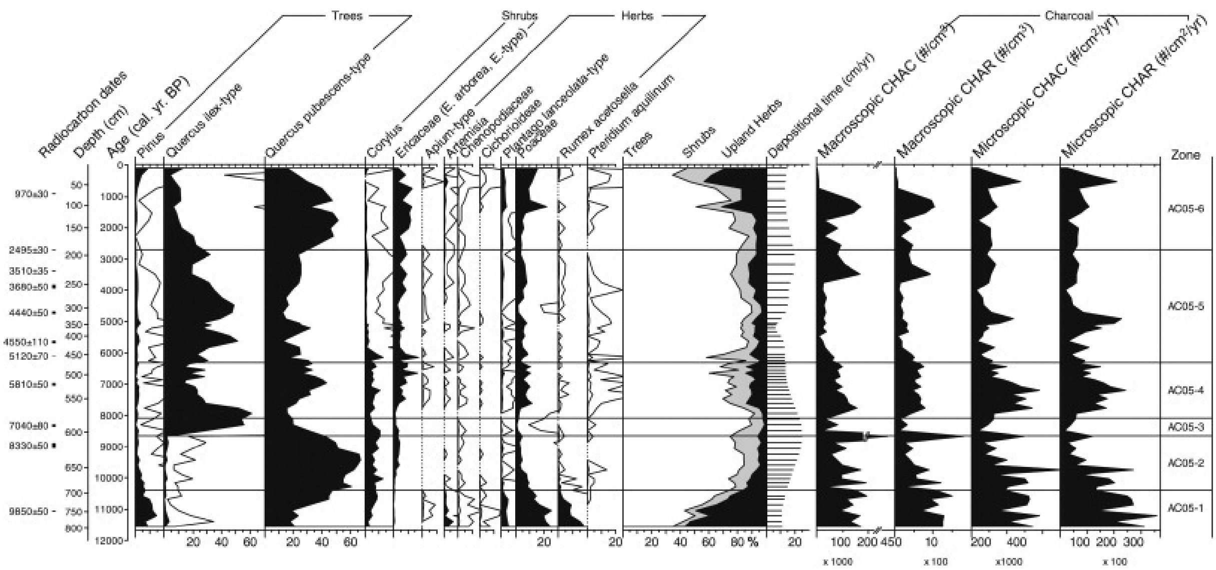

Fig. 4. Age scale diagram of pollen and charcoal data from Lago dell’Accesa (core AC05-B). The simplified pollen diagram is in percentages. Microscopic charcoal and macroscopic charcoal are shown in concentration (CHAC) and influx (CHAR). Sedimentary depths and positions of AMS radiocarbon dates are indicated.

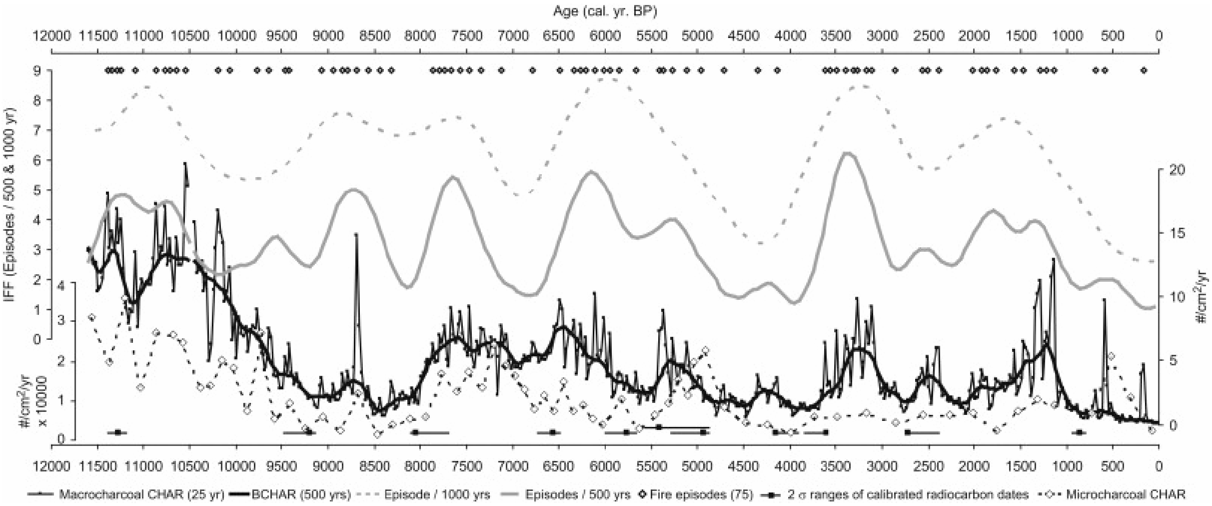

Fig. 5. Macroscopic charcoal accumulation rate (CHAR; re-sampled at 25 yr constant time interval) with background (BCHAR); locally weighted regression with a time window of 500 yrs) from Lago dell'Accesa AC05-B master core. The "◊" symbols represent identified charcoal episodes for a threshold values (TV) of 0.7. Inferred fire frequencies (IFF) with a 500- and 1000-yr smoothing window were calculated for residual peak distributions. Low-resolution microscopic charcoal particles influx are plotted for tendency comparison. Horizontal black bars indicate 2 S.D. ranges of radiocarbon dates on plant macrofossils.

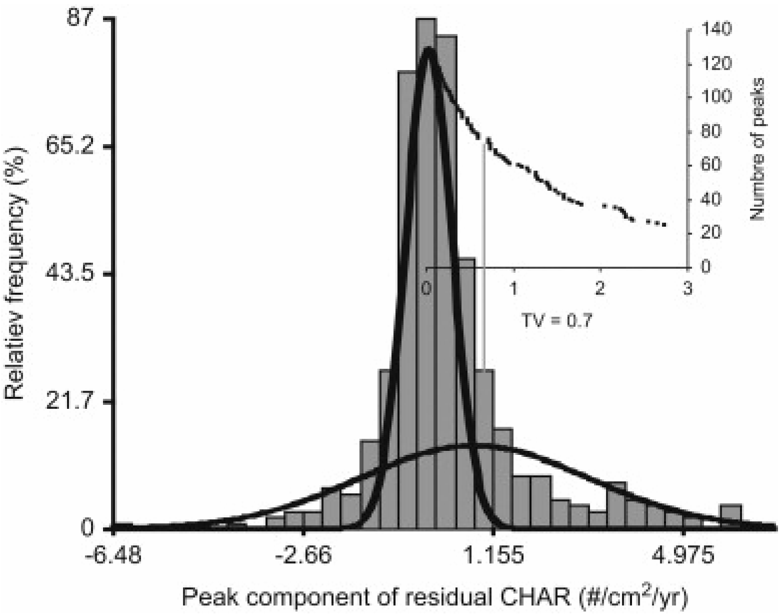

Fig. 6. Frequency distribution of the CHAR residuals with fitted curves from a Gaussian mixture model (here two sub-distributions with, respectively, a mean of −0.12 and 0.793, a variance of 0.217 and 5.41, explaining 53.8% and 46.2% of the values distribution; Gavin et al., 2006). The upper limits of the first distribution (95%; 0.645) can be considered the upper limit of "noise"-related variation. Insets show how the numbers of identified peaks vary with changing thresholds. The left *y*-axis shows the frequency of the peak component values (re-sampled data), and the right *y*-axis shows the numbers of fire episodes. The vertical dotted line shows the threshold value (0.7) chosen to identify charcoal peaks most likely due to local fire episodes.

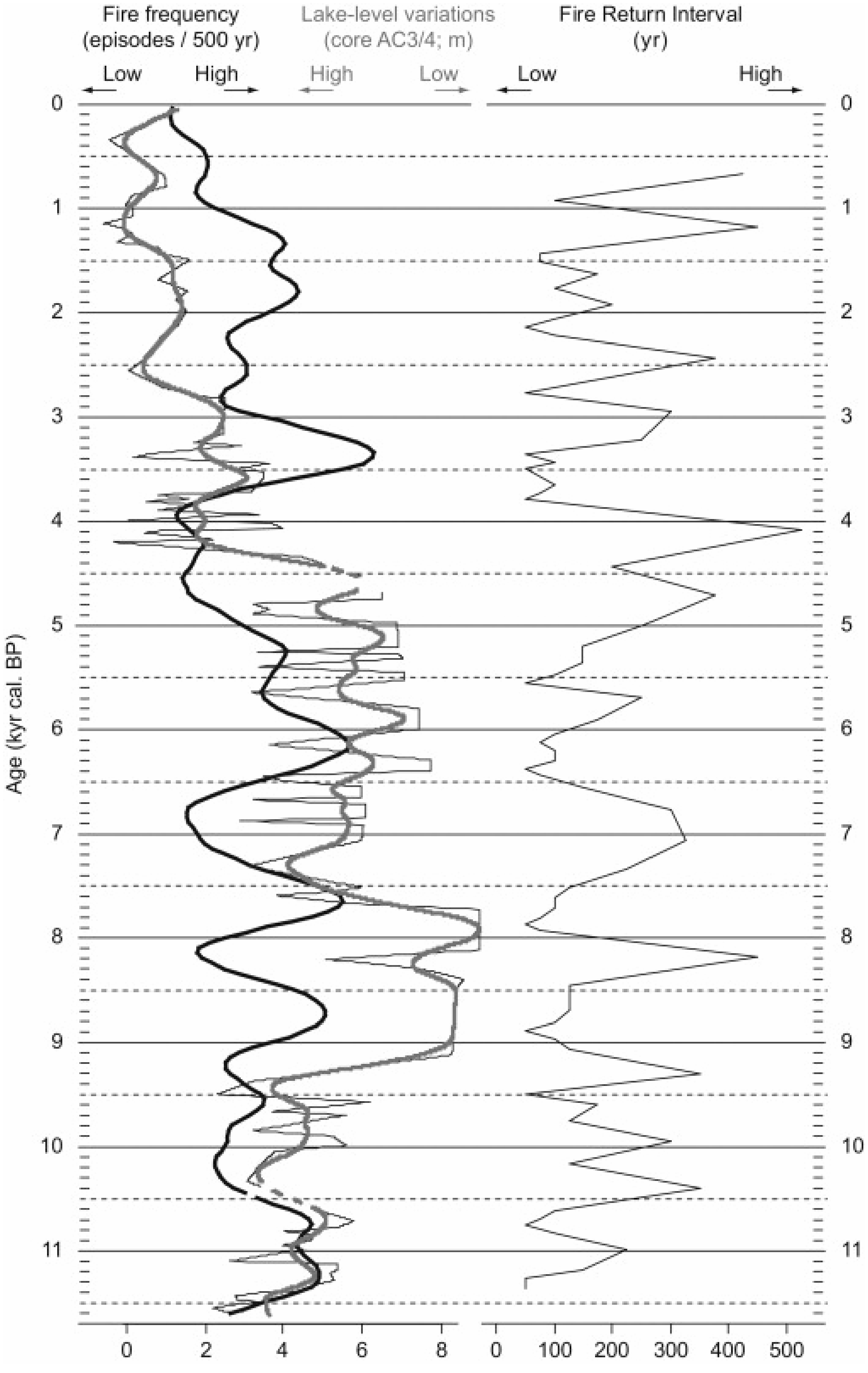

Fig. 7. Comparison between fire frequency per 500 yr (core AC05B), fire return interval (FRI; core AC05B), and lake-level reconstruction (raw data and tendency on a 500 yr running time window; littoral cores AC3/4; Magny et al., 2007) from Lago dell'Accesa.

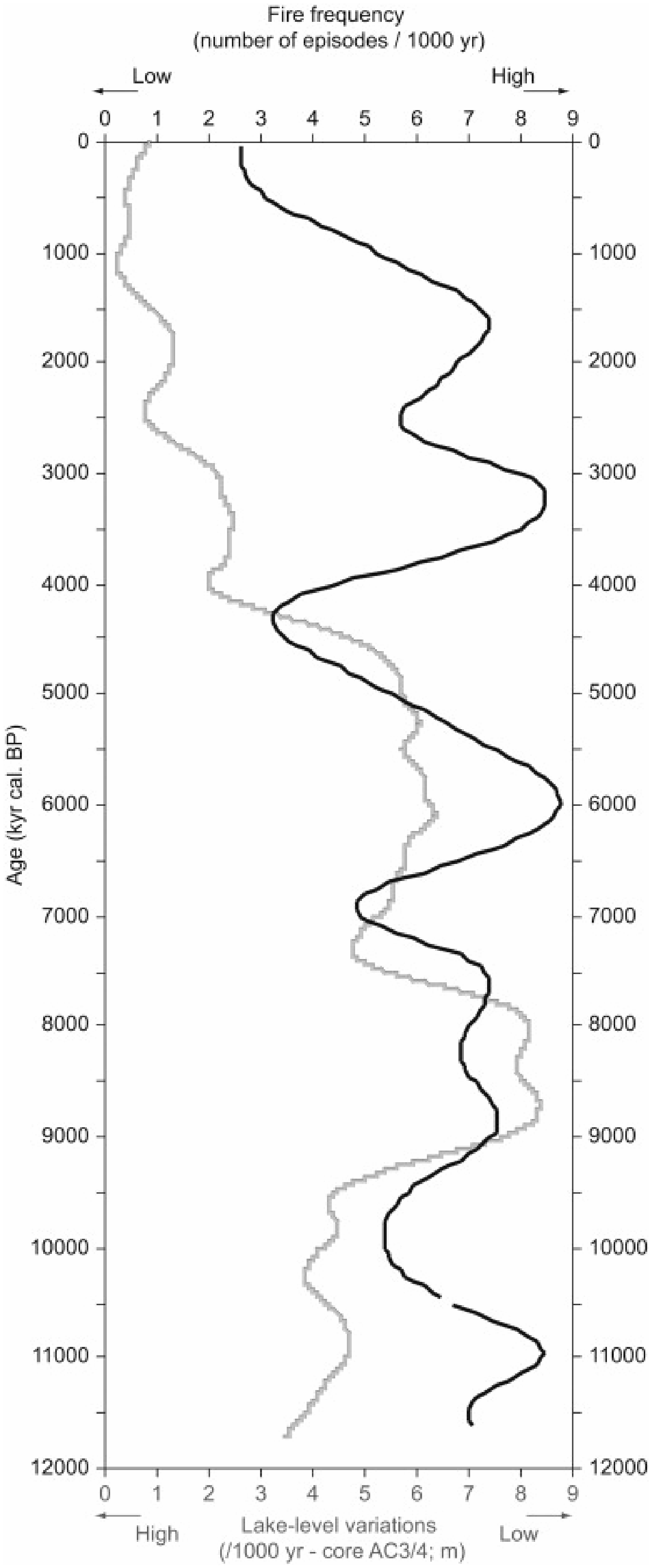

Fig. 8. Comparison (grey bands) of sedimentary charcoal series (CHAR: charcoal accumulation rate) from (1) Lago dell'Accesa, this paper, (2) Lago di Massaciuccoli, north-central Italy, Colombaroli et al. (in press), (3) Lago di Mezzano, central Italy, Sadori et al. (2004), (4) Battagla, south-eastern Italy, Caroli and Caldara (2006), and (5) Lago di Pergusa, Sicily, Italy, Sadori and Giardini (2006). Black boxes identified high charcoal input in sedimentary sequences and black points indicate slight charcoal input.

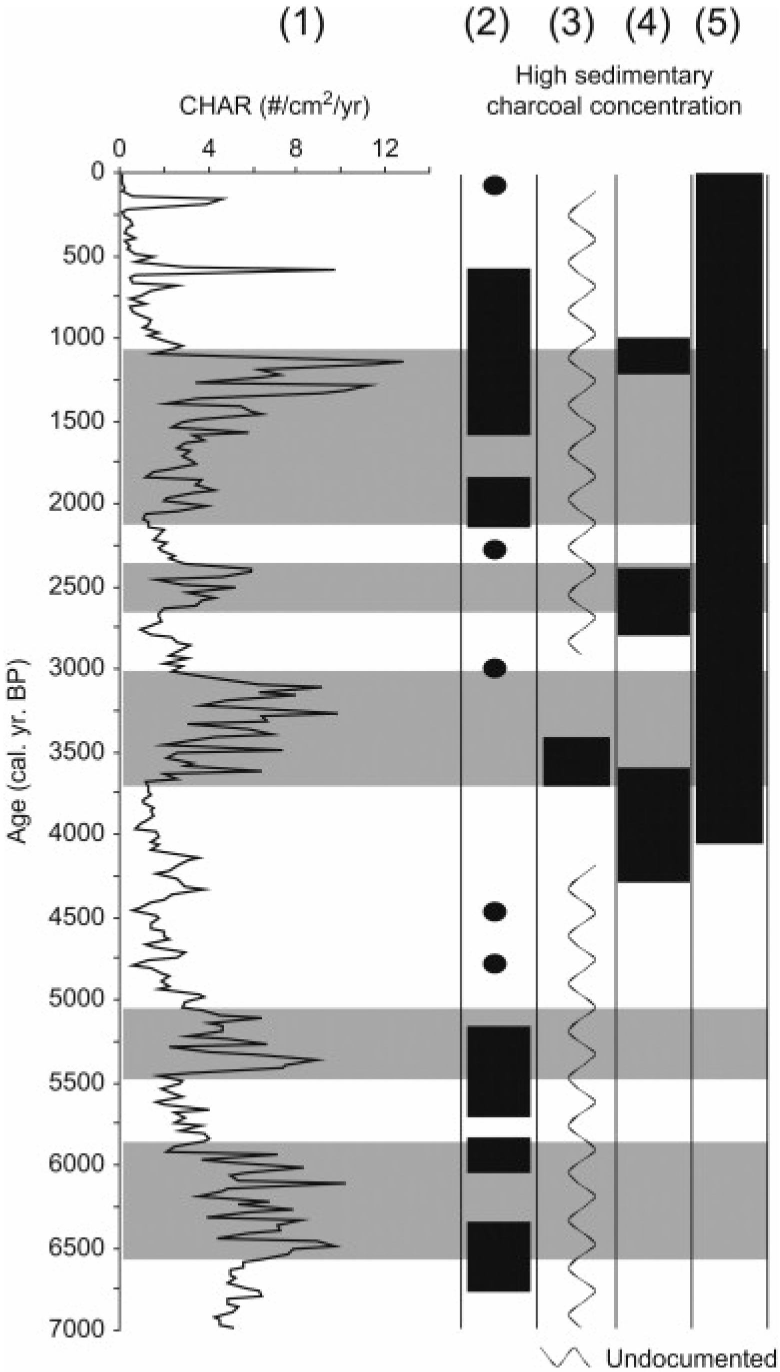

Fig. 9. Comparison between fire frequency per 1000 yr (core AC05B), lake-level reconstruction smoothed with a 1000 yr window (cores AC3/4; Magny et al., 2007) from Lago dell'Accesa.

Table 1.

AMS radiocarbon dates from cores AC05 of Lago dell'Accesa (Tuscany, Italy) used for chronology

Sample ID	**Lab. code**	**Material**	**AMS radiocarbon date BP**	**Master core depth (cm)**	**Cal. yr BP 95% limits**[a]
P7-60	POZ-14759	Wood	970±30	66.5–67.5	795–933
B1.2 99	POZ-12334	Wood	2495±30	191–192	2378–2732
C16-33	POZ14758	Wood	3510±35	237–238	3693–3876
B1.4 35.5	POZ-16242	Charcoal	3680±50	267.5–277.5	3879–4151
B1.5 7.5	POZ-16243	Bud scale	4440±50	328–333	4873–5285
BB1.4 57.5	POZ-16248	Bud scale	4550±110	392–397	4874–5572
BB1.5 4.5	POZ-16249	Bud scale	5120±70	425.5–426.5	5661–5997
BB1.5 67.5	POZ-16250	Bud scale	5810±50	486.5–491.5	6493–6734
B1.7 22.5[b]	*POZ-16244*	*Wood*	*3840±100*	*532–537*	*3933–4520*
B1.7 67.5	POZ-16245	Wood	7040±80	577–582	7697–7998
B1.8 32.5	POZ-16247	Leaves	8330±50	625–630	9141–9472
B1.9 68	POZ-11448	Wood	9850±50	768–769	11191–11389

[a] Calibrated with CALIB Rev 5.0.2 (intcal04.14c; Stuiver and Reimer, 1993; Reimer et al., 2004).
[b] Rejected data.