Holocene history of fire, vegetation and land use from the central Pyrenees (France)

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ABSTRACT

Located on a mountain pass in the west-central Pyrenees, the Col d'Ech peat bog provides a Holocene fire and vegetation record based upon nine ^{14}C (AMS) dates. We aim to compare climate-driven versus human-driven fire regimes in terms of frequency, fire episodes distribution, and impact on vegetation. Our results show the mid-Holocene (8500–5500 cal yr BP) to be characterized by high fire frequency linked with drier and warmer conditions. However, fire occurrences appear to have been rather stochastic as underlined by a scattered chronological distribution. Wetter and colder conditions at the mid-to-late Holocene transition (4000–3000 cal yr BP) led to a decrease in fire frequency, probably driven by both climate and a subsequent reduction in human land use. On the contrary, from 3000 cal yr BP, fire frequency seems to be driven by agro-pastoral activities with a very regular distribution of events. During this period fire was used as a prominent agent of landscape management.

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Introduction

Fire is a key agent of disturbance in a wide range of ecosystems from boreal biomes (Pitkanen, 2000; Tinner et al., 2006) to temperate European mountain zones (Carcaillet, 1998; Tinner et al., 1999, 2000), as well as in the Mediterranean area (Carrión et al., 2003; Noti et al., 2009; Gil-Romera et al., 2010; Vannière et al., 2011). On the millennial scale of the Holocene, controlling factors of fire regimes mostly depend on the bioclimatic characteristics (Marlon et al., 2006) and/or on the onset of human impact in these ecosystems (Abrams and Nowacki, 2008; Tinner et al., 2009). Climate controls fire regime by both ignition and fire spread-favouring conditions (composition, structure and moisture of biomass, e.g. Pausas, 2004) whereas humans change charcoal accumulation patterns through agro-pastoral activities type and intensity (Rius et al., 2009). At the global scale, fire regimes have been affected by humans for the last 250 yr: biomass burning sharply increased at 1750 AD before decreasing at 1870 AD due to land-use changes and fire management (Marlon et al., 2008). However, in Europe, charcoal analyses from single sites have recorded anthropogenic forcing of fire regimes at earlier dates. For example, Turner et al. (2008) showed that climate and fire had been disconnected since 1700 cal yr BP in Turkey. In central Switzerland, Mean Fire Interval (MFI) decreased by half 2000 yr ago due to increasing human impact (Stähli et al., 2006). In the Mediterranean basin, the regional-scale switch from a climate-regulated to a human-dominated biomass burning regime occurred between 4000 and 2000 yr ago (Vannière et al., 2010). In the Pyrenees,

evidence exists for linking fire and human impact from the Middle Neolithic period (Vanniere et al., 2001; Galop et al., 2002; Miras et al., 2007). Human use of fire during this period remains sporadic with a limited impact on vegetation. The threshold from which humans became the main controlling agent of fire occurrence seems to be the mid to late Holocene (i.e. the Bronze Age to Iron Age) with a clear succession of a sporadic use of fire during the Neolithic to systematic fire use from 4000 to 3000 cal yr BP (Rius et al., 2009). This shift from sporadic fire use to a predominantly anthropogenic driven fire regime was also observed in the Alps (Tinner et al., 2005). However, in the north-western central Pyrenees the natural occurrence of fire in ecosystems prior to the onset of agriculture at 7600 cal BP (Zapata et al., 2004; Galop, 2006), remains poorly known due to the lack of high-resolution fire studies. As a consequence, it is difficult to characterize natural versus anthropogenic fire regimes in terms of frequency, distribution of fire episodes, and environmental impact as it has recently been done in northern Italy (Kaltenrieder et al., 2010) or in southern Sweden (Olsson et al., 2010).

Here, we present a 10,500-yr-long charcoal and pollen record from the "Col d'Ech" peat bog (Lourdes basin, central Pyrenees, France) with the aim of 1) disentangling the different forcing factors controlling the fire regime, i.e. climate and human impact and 2) examining fire frequency and distribution during both non-anthropogenic and anthropogenic parts of the record.

Materials and methods

Environmental settings

The study site (43°4′58.74 N; 0°5′38.53 W, 710 m asl) is located in the west-central Pyrenees, southwest above Lourdes city (Fig. 1). This

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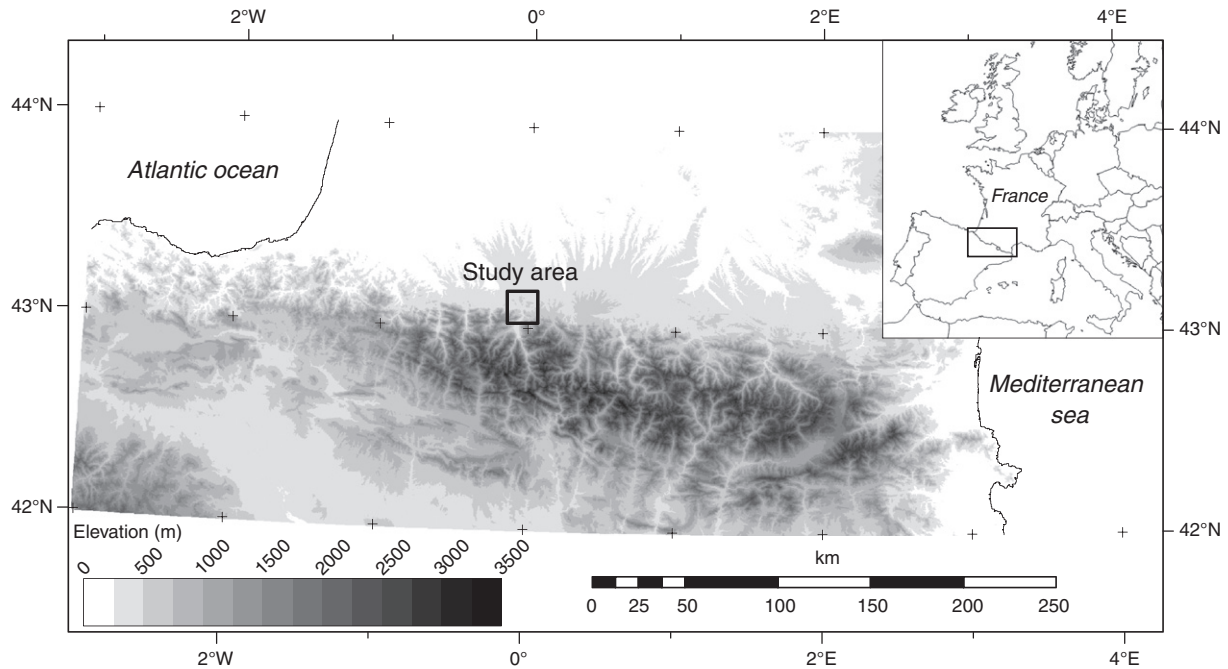E-mail address: damien.rius@univ-tlse2.fr (D. Rius).

Figure 1. Elevation map of the Pyrenees mountain range with the location of the study area.

zone is characterized by a mountainous oceanic climate with mean annual precipitation of 1200 mm. Mean annual temperature T is 12.5°C (mean summer T = 18.5°C and mean winter T = 6°C, MeteoFrance Data, 1931–2006). Regional vegetation consists of Atlantic-type oak forest mainly dominated by *Quercus robur* with *Corylus* and *Betula*. Locally, the north-facing slopes (up to 900 m) are covered by a mixed beech–oak forest, which is the dominant vegetation of the bioclimatic stage in the area. The ombrotrophic Col d'Ech bog is 5.3 ha in size. It is a former glacial lake which is located on a small plateau dammed by a recessional moraine at the south and by a 200-m-high-south-facing calcareous slope at the north. The peat bog has been drained and is drying out today. It is surrounded by seven farms, most of them now abandoned, and by pasture areas. The strong shelter effect from this slope combined with dry calcareous soils results in the presence of *Q. pubescens* and some *Buxus sempervirens* stands (Dupias, 1985).

In the central Pyrenees, there are currently two fire seasons. The main one, in extent and number of occurrence, is winter (January, February, and March), during which fires are linked to pasture management (Métailié, 1981; Ribet, 2009). The second one occurs during summer (July, August) and is linked to both accidental and natural (lightning) fires (Préfecture des Hautes-Pyrénées, 2007).

Holocene human impact in the northern Pyrenees

Archaeological data shows occupation of the Pyrenees since the Palaeolithic period by hunter-gatherer population (Bahn, 1984; Valdeyron, 2008), but the introduction of agriculture and husbandry started around 7600 cal yr BP (Guilaine, 1994) from the Mediterranean basin at the east and from the south via the Ebro valley in Spain (Peña-Chocarro et al., 2005). The first pollen evidence of agro-pastoral activities are recorded during the Early Neolithic at. 7500–7200 cal yr BP in the Basque country (Galop, 2006) and at 6800–6500 cal yr BP in the Lourdes basin (Reille and Andrieu, 1995). During the middle-to-late Neolithic (6500–4300 cal yr BP) grazing activities extended towards high mountains zones (Galop, 2006), while signs of agriculture and human occupation are increasingly recorded on the piedmont (Rius et al., 2009).

During the Bronze Age (4300–2700 cal yr BP), there were two main phases of agro-pastoral expansion, at 4100 and 3300 cal yr BP (Carozza and Galop, 2008). The first phase was characterized by an increase of both signs of agriculture and grazing activities but clearances seems to remain small. On the contrary, the second phase of agro-pastoral expansion resulted in marked deforestation. Thus, these two phases may highlight the transition from an agro-sylvo-pastoral system («slash and burn» with forested fallows) to an agro-pastoral system (Galop et al., 2002).

The Iron Age (2700–2000 cal yr BP) and the Antiquity (2000–1500 cal yr BP) emphasize a progressive increase of the grazing pressure (Galop, 2005). The rapid development of mining activities (Monna et al., 2004) appears as a major driver of deforestation at these times.

The beginning of the Middle Ages (1500–500 cal yr BP) shows no increase in the agro-pastoral pressure but some diversification in cultivated crops (*Secale* cultivation) at 1500–1300 cal yr BP (Galop, 2000). Then, there are clear signs of agro-pastoral expansion from 1300–1100 cal yr BP corresponding to the Medieval growth (Bonnassie, 1989). Finally, from 1000 to 800 cal yr BP onwards the intensification of both agro-pastoral and mining activities leads to generalized deforestation at the Pyrenean range scale (Vanniere et al., 2001).

This intensification of the agro-pastoral pressure was slowed by the medieval crisis (700–600 cal yr BP) characterized by demographic collapse (Berthe, 1984). Following this period, the effect of economic and demographic recovery on land use is clearly detectable in the paleoecological records (Galop, 2001) and is characterized by marked deforestation. Human pressure progressively peaked during this expansion phase, from 500 to 100 cal yr BP. Finally, massive rural depopulation began during the first half of the last century and promoted land-use changes at unprecedented rates, in reforestation in particular (Galop et al., 2011).

Coring, lithology and chronology

The core was taken (APAGEO device) with a Russian peat sampler (GIK type, 100 cm length, 10 cm in diameter), which avoided sediment compaction. The bore holes were located at the centre of the peat bog. Two overlapping cores of 500 cm (0–500 and 50–550 cm) were

obtained. Gamma density (GD) measurements were made each 1 cm on the first 300 cm, and each 5 mm on the remaining 200 cm with a Geotek MSCL (Multi Sensor Core Logger) device. This parameter was used along with sedimentary units to construct a composite sequence (550 cm) from the twin cores. The chronology was based on nine Accelerator Mass Spectometry (AMS, Table 1) radiocarbon dates on bulk sediments from samples picked between 20.5 and 380.5 cm depth. Dating was performed on bulk sediments after removing rootlets, because the high organic content enabled us to do so, without reservoir effect (Blaauw et al., 2004). Calibration to cal yr BP was made using CALIB software (Stuiver and Reimer, 1993) version 6.0.1., based on the dataset IntCal09 (Reimer et al., 2009). To predict ages along the entire profile, we used a mixed-effect regression model (Heegaard et al., 2005). The section analysed for charcoal (0–370 cm) covers the last 10,500 yr (Fig. 2), i.e. almost the entire Holocene.

The sedimentary record (Fig. 2) consists of lacustrine silty clay (400–387 cm), a 2-cm-thick light grey clay layer (387–385 cm), dark brown organic silts (385–330 cm), brown fibrous peat (330–10 cm) and a terrigenous unit (10–0 cm).

Macroscopic charcoal analysis

Contiguous samples of 2.6 cm^3 were retrieved with a needleless syringe at 1 cm intervals, soaked in a 10% NaOH solution during 24 h, then in a 6% H_2O_2 solution during the same time in order to bleach non-charcoal organic material and thus make identification easier (Rhodes, 1998). Because we aim to reconstruct local fire history, charred particle quantification was made by sieving with a 150 μm mesh size. Both charcoal particle number and area concentrations were estimated under a binocular microscope at a 50× magnification with a reticule grid of 10×10 squares of $62.5 \cdot 10^{-3}$ mm² each. Ten increasing size classes were defined (31.25–62.5, 62.5–125,..., 187.5–250 10^{-3} mm², ...). Charcoal identification was restricted to the criteria usually defined in literature (Umbanhowar and McGrath, 1998; Enache and Cumming, 2006, 2007).

CHArcoal Concentration (CHAC; mm²·cm^{-3}) was expressed as CHarcoal Accumulation Rate (CHAR; mm²·cm^{-2}·yr^{-1}) based on sedimentation rate estimated by the depth–age model. The CHAR of particles >$562.5 \cdot 10^{-3}$ mm² (hereafter referred to as 'large charcoal fragments'), which can be regarded as a good indicator of local fires and could be compared with fire episodes detected and reconstructed fire frequency, is plotted on Figure 3.

Inferred fire frequency (IFF)

The calculation of Inferred Fire Frequency (IFF, Clark, 1995; Long et al., 1998; Gavin et al., 2003; Lynch et al., 2004) is based on the decomposition approach (Higuera et al., 2010) whose goal is to delineate the two source components in the charcoal signal (Clark and Patterson, 1997): background charcoal (BCHAR) and peak component.

The whole procedure was performed under the R open-source statistical environment (R Development Core team, 2009) and consisted of the following steps: 1) The CHAR record was resampled to equal-time intervals (as in Long et al., 1998) using a window corresponding to the mean sedimentation rate of the record (25 yr cm^{-1}), 2) The data were log-transformed (LogChar) to homogenize variance, 3) Background CHARcoal (BCHAR) was estimated with a Loess filter (250 yr moving window), allowing calculation of the Peak Component (PC = (log)CHAR − (log)BCHAR) as a residual, 4) A threshold value (Tv) within the range of values with the lowest sensitivity to the number of peaks detected was derived by plotting a frequency distribution histogram of peak component against a cumulative curve of peak number (Empirical Cumulative Distribution Function; ECDF). This is an essential step to separate noise-related variation from local fire episodes. All peaks above this Tv were considered as single fire episodes and, 5) Fire episodes frequencies were smoothed using a 500-yr moving window (K1D software, Gavin et al., 2006). The decomposition of the charcoal record is plotted on Figures 3 and 4. Finally (6), Mean Fire Interval (MFI) was calculated by dividing the difference in age between the first and the last fire episode by the number of fire intervals (*n* − 1, where *n* is the number of fire episodes) of a given period, while Fire Return Interval (FRI) is the difference in age between two fire episodes.

Pollen analysis

Subsamples for pollen analysis consisted of 1 cm^3 cubes taken at 5 cm intervals. Pollen preparation followed standard methods using treatment with 10% KOH (35 mn), HF (24 h), sieving at 150 μm, acetolysis (7 mn) and final mounting in glycerine (Faegri and Iversen, 1989). A minimum of 450 terrestrial pollen grains were counted in each sample. *Alnus*, Cyperaceae, aquatic taxa and fern spores were excluded from the pollen sum to avoid over-representation by aquatic and local taxa. All pollen types are defined according to Faegri and Iversen (1989) and Beug (2004), although some identification required the use of pollen atlases (Reille, 1992–98) or pollen collections from the laboratory GEODE (University of Toulouse II-Le Mirail). Figure 5 presents a percentage pollen diagram with major arboreal taxa, anthropogenic indicators and synthetic curves of cultivated crops and Anthropogenic Pollen Indicators (API).
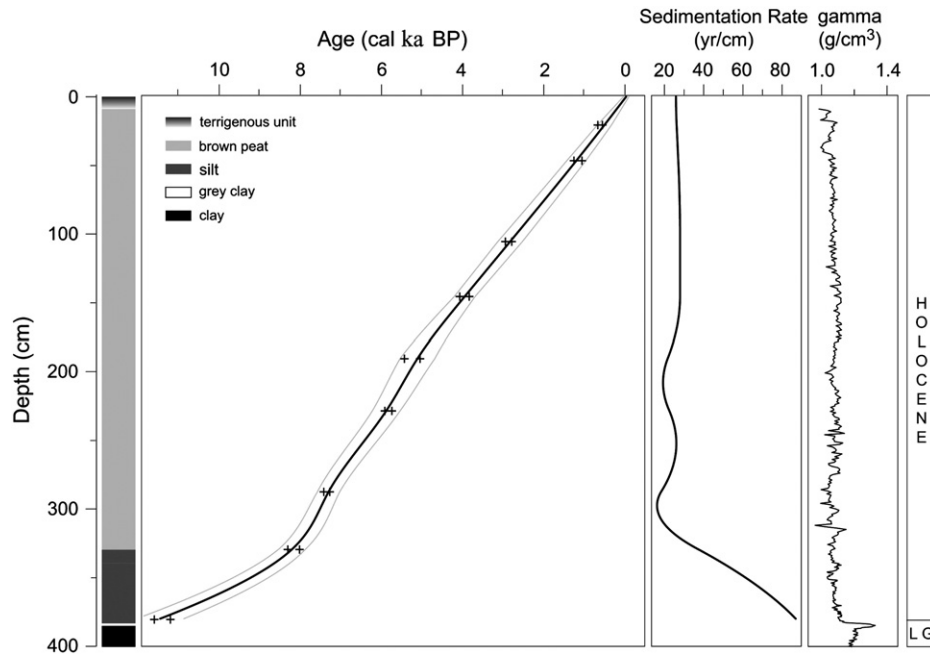
Results

Lithology and chronology

Lithology and radiocarbon dates show a single major shift in sedimentation during the Holocene. The shift is characterized by accumulation of silts that become more and more organic as the basin progressively filled up. This sedimentation change is only visible in the lithological log and is not reflected in gamma density measurements (Fig. 2).

This transition from silt to peat at 330 cm (~8200 cal yr BP, Table 1), which marks the final step of infilling of the lake basin, is characterized by an increase in sedimentation rate (between 370 and 300 cm mean sedimentation rate = 0.17 mm²·yr^{-1}, from 330 to 290 cm = 0.47 mm²·yr^{-1}).

Macroscopic charcoal record and fire frequency

Charcoal counts ranged from 0 to 3811 with a mean of 191 and a median of 92. The charcoal record emphasizes four main patterns (Fig. 3a).

Table 1
AMS radiocarbon dates from the "Col d'Ech" peatbog measured by the Poznan Radiocarbon Lab., Poland.

Sample depth (cm)	Lab. code	Type	AMS radiocarbon date, ^{14}C yr BP	Cal yr BP [2σ range] probability area	Δ ^{13}C values (‰)
EchO6 20.5	Poz-23135	Peat	645 ± 30	555–668	−33.1
EchO6 46.5	Poz-23136	Peat	1210 ± 30	1059–1256	−27.5
EchO6 105.5	Poz-22009	Peat	2770 ± 30	2788–2946	−27.9
EchO6 145.5	Poz-23137	Peat	3615 ± 35	3836–4071	−32.6
EchO6 190.5	Poz-23138	Peat	4550 ± 40	5049–5434	−27.4
EchO6 228.5	Poz-23139	Peat	5090 ± 40	5743–5917	−31
EchO6 287.5	Poz-23140	Peat	6420 ± 40	7274–7422	−28.1
EchO6 329.5	Poz-23141	Peat	7430 ± 50	8019–8308	−31
EchO6 380.5	Poz-27285	Bulk	9890 ± 50	11,202–11,597	−23.4

Figure 2. Lithology, age–depth model with expected age throughout the record (bold line), 95% confidence intervals (thin grey lines), 2σ range probability area (black crosses), sedimentation rate (yr/cm) and Gamma density (g/cm³). LG = Late Glacial.

From 10,500 to 8000 cal yr BP, there is only one distinguishable peak above a steady BCHAR with low variability (Fig. 3b). From 8000 to 3900 cal yr BP, CHAR and BCHAR show strong variability and remain high except during 7500–7000, 6500–6000 and 5000–3900 cal yr BP. It is during this mid-Holocene phase that charcoal accumulation reaches its highest values (4000 charcoal particles/sample, at 5500 cal yr BP).

Then, the phase between 3900 and 2900 cal yr BP is characterized by a charcoal accumulation almost equal to zero. Finally, from 2900 cal yr BP onwards, background accumulation is rather low but with high variability, and well-defined peaks.

Patterns of large charcoal-fragment accumulation follow CHAR until 6500 cal yr BP (Fig. 3d). From this point there is a general decrease to zero (reached 3900 cal yr BP). It is noteworthy that these millimetre-sized particles are absent during the 5600–5400 cal yr BP interval which encompasses the highest CHAR peak of the record. After 3900 cal yr BP large charcoal fragments again regularly contribute to CHAR until 1700 cal yr BP.

Forty-four fire episodes were detected along the record from 8450 to 475 cal yr BP (Figs. 3d and 4). There are no fires detected between 10,500 and 8500 cal yr BP. Three main phases of high fire frequency are recorded: 8500–6500 cal yr BP (up to 4.5 fires/500 yr, MFI = 155 yr) with an intermediate decrease between 7500 and 7200 cal yr BP (no fire episodes); 6000–5000 cal yr BP (up to 5 fires/500 yr, MFI = 160 yr) reaching the maximum of the record, and a last one 2900–400 cal yr BP (up to 3.5 fires/500 yr, MFI = 160 yr) with regular fire occurrences and a two-step increase in fire frequency at 2900 and 1700 cal yr BP. On the contrary, IFF emphasizes three main phases of low fire frequency between 6500 and 6000 cal yr BP (down to 1.3 fires/500 yr) and no fire episodes detected at all between 4900 and 4500 and between 3900 and 2900 cal yr BP.

Considering the whole record, the main high fire-frequency phases occur between 8500 and 5000 cal yr BP (i.e. the mid-Holocene) and during the last 3000 yr (i.e. the late Holocene). However, this last period shows slightly lower frequency than before with less variability (Fig. 6).

Vegetation history

Pollen analysis describes a Holocene vegetation succession which is in accordance with the previous work of Mardones and Jalut (1983) and

Reille and Andrieu (1995) in the Lourdes basin. The Col d'Ech pollen record yields some unprecedented results concerning both the dynamics of specific taxa such as *Betula* as well as human impact. Six local pollen assemblages zones (LPAZ) were defined using a stratigraphically constrained cluster analysis (Fig. 5); CONISS (Grimm, 1987).

– Zone Ech 1 (12,000–10,500 cal yr BP) corresponds to the onset of the Holocene with the rapid expansion of forest stands dominated by *Quercus*. However, the vegetation cover remains relatively open as evidenced by the steady presence of Poaceae.
– Zone Ech 2 (10,500–7250 cal yr BP). This zone marks the transition from an oak-dominated landscape to a more closed one as it is characterized by the development of *Corylus* synchronous with the decrease of Poaceae. To a lesser extent, *Ulmus* also develops in the forest stands of the area. In the middle of this zone, an increase of Cyperaceae followed by an increase of *Sphagnum* marks the transition from a lacustrine to a peat system around 8200 cal yr BP.
– Zone Ech 3 (7250–5500 cal yr BP) features abrupt changes in the local vegetation structure: a decrease of *Corylus* and an increase of Poaceae until 6600 cal yr BP follow the development of *Betula* at 6700 cal yr BP. Then a second increase of Poaceae is recorded towards the end of the zone. The development of grassland vegetation is also underlined by the regular occurrences of Cichorioideae throughout this period. *Cerealia*-type pollen appears at the beginning and at the end of the zone (at 7100 and 5600 cal yr BP respectively).
– Zone Ech 4 (5500–3600 cal yr BP) is mainly characterized by the increase of arboreal pollen percentages: *Quercus*, *Corylus* together with the local settlement of *Alnus* around the peat bog. This zone also emphasizes an increase in percentages of *Abies*, the first occurrences of *Fagus,* and high amplitude variations of *Betula*. Anthropogenic Pollen Indicators (API) slightly increase between 5000 and 4000 cal yr BP as shown by the regular occurrences of *Plantago* and *Plantago lanceolata*, Urticaceae*, Rumex* and *Cerealia*-type pollen.
– Zone Ech 5 (3600–2600 cal yr BP) starts with the main botanical event of the late Holocene which is the settlement of *Fagus* and the shift from a *Quercus*-dominated forest (with *Ulmus, Tilia, Fraxinus* and *Corylus*) to a mixed beech–oak forest, suggesting a shift to more humid conditions. The beginning and the end of this zone are characterized by high amplitude variations in percentages of *Betula* and to a lesser
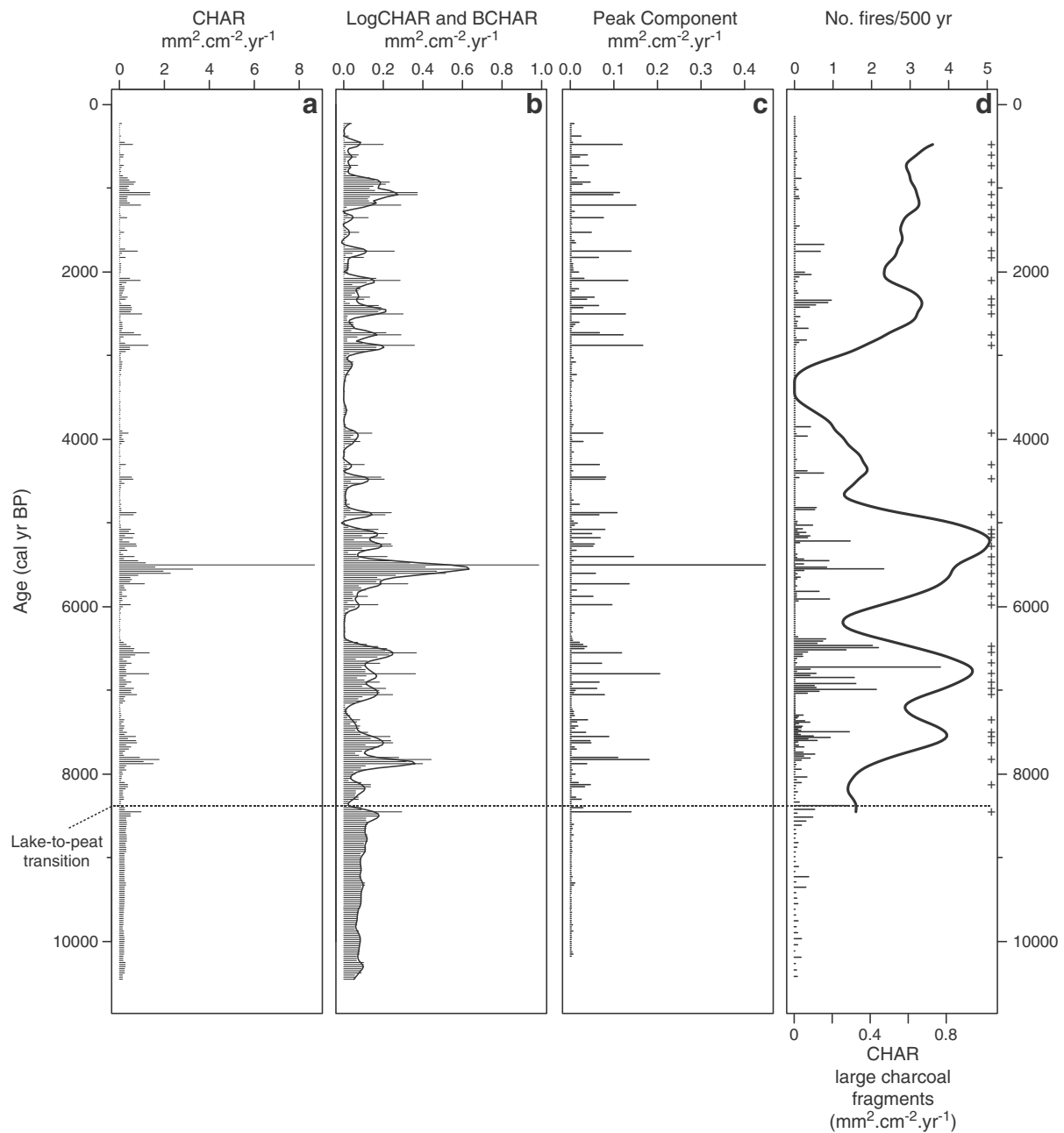
Figure 3. Inferred fire frequency (IFF) results: (a) raw CHAR, (b) LogCHAR (bars) and BCHAR (bold line), (c) Peak Component (logCHAR − log(BCHAR)), and (d) CHAR of large charcoal fragments with smoothed number of fires over a 500 yr window and detected fire episodes (black crosses).

extent by those of *Corylus*. API increase at the middle of the zone (at 3300 cal yr BP) with regular occurrences of *Plantago lanceolata*, Urticaceae, *Rumex* and isolated records of *Cerealia*-type pollen.

– Zone Ech 6 (2600–50 cal yr BP) is mainly characterized by the abrupt increase of API and a long-lasting decrease of arboreal pollen. It can be divided into two subzones. Zone Ech 6a emphasizes the progressive degradation of the vegetation cover. All the mixed beech–oak forest taxa decrease, especially *Fagus* and *Corylus*. Zone Ech 6b is the continuation of the previous one, with an even more marked decrease in percentages of arboreal pollen (*Fagus* in particular) and a significant increase of Poaceae percentages. Human impact became stronger as underlined by the continuous curve of cultivated crops, *Plantago lanceolata*, the regular occurrences of meadows taxa (Asteraceae, Cichorioideae, Brassicaceae), nitrophilous taxa (*Rumex acetosa* type, Urticaceae) and by the diversification of cultivated crops (regular occurrence of *Secale* from 800 cal yr BP).

Discussion

A complete Holocene fire record potentially encompasses the effects of climatic variations, biomass changes (type and structure), evolving sedimentary processes, and anthropogenic disturbances. All these potential forcing factors interact from local to regional scale.

Holocene climate changes and fire

Available pollen data and the first fire history studies undertaken in the northern slope of the Pyrenees (Vanniere et al., 2001; Galop et al., 2002; Miras et al., 2007) led us to assume pre-agricultural fire regime (i.e. pre-Neolithic) to be weak (Rius et al., 2009). This assumption was based on (1) the irregular and weak character of human activities before the Neolithic (7800 cal yr BP), (2) the assumed low flammability
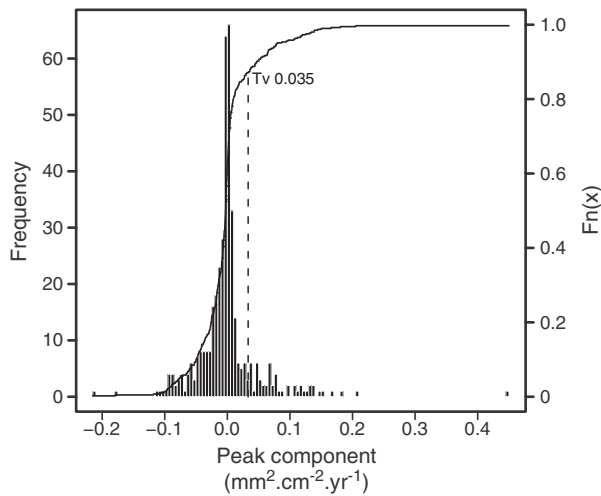
Figure 4. Histogram of sensitivity analysis for threshold-value selection. Noise-related variation and right-hand tail distribution, *i.e.* charcoal accumulation anomalies corresponding to local fire episodes, are separated by the threshold value (Tv, dotted line) chosen to identify local fire episodes. The separation between these two populations is where both the histogram and the cumulative curve emphasize a break and a plateau, respectively (Lynch et al., 2004).

of the forest stand types in the area (e.g. Clark et al., 1989) and (3) the scarcity of natural fire in present ecosystems.

Between 10,500 and 8500 cal yr BP, the relatively high values of CHAR with little variability which enable us to detect only one fire episode (at 8500 cal yr BP) may be explained by intra-lake processes such as charcoal particle transfer from the lake shore to the deep zone, reworking (Whitlock and Millspaugh, 1996) and a low sedimentation rate that concentrates and reduces the variability of CHAR. This may be the reason why the decomposition method is here ineffective in detecting any fires. However, the magnitude of CHAR suggest regular wildfire occurrence, probably linked with increasing biomass during the early Holocene. High fire activity during this period is recorded at the European scale (Power et al., 2008) and the occurrence of local fire is also supported by peaks in large charcoal fragments (Figs. 3 and 5).

Then, the major sedimentary change of the «Col d'Ech» record between 8019 and 8308 cal yr BP (Table 1), is the lake to peat transition. The synchrony with the 8200 cal yr BP cold event (Alley et al., 1997) may indicate that climate forcing is responsible for that phenomenon. However, there are three other raised bogs in the immediate vicinity of the Col d'Ech: Biscaye, Le Monge and Lourdes. Those bogs are filled paleolakes where the transition from organic gyttja to peat was respectively estimated at 5950 ± 55 BP (6660–6930 cal yr BP), 9200 ± 60 BP (10,240–10515 cal yr BP) and at the beginning of the Late Glacial period (according to the pollen stratigraphy, Reille and Andrieu, 1995). The heterogeneity of these dates suggests that the infilling of those paleolakes is a local phenomenon and rules out regional forcing factors such as climate. Moreover, the infilling dynamic is clearly visible in the pollen data with the successive increase of Cyperaceae and *Spaghnum*, the latter evidencing the beginning of peat formation (Fig. 5).

Following this phase with no fire episodes detected, the mid-Holocene exhibits increased fire frequency from 8200 to 5000 cal yr BP. These results are in accordance with the high fire activity during the same period recorded in Lake Lourdes (Rius et al., 2011) and in the north-western Mediterranean area (Vannière et al., 2011) at the same latitude. This concordance between local and regional fire history suggest the predominance of a regional climate control (Ali et al., 2009). As shown by pollen-based temperature reconstructions (Renssen et al., 2009) and glacier level studies in the Alps (Nicolussi et al., 2005, 2009; Joerin et al., 2006, 2008), the mid-Holocene was a phase of increasing summer temperature (Holocene Thermal Maximum, HTM) at the regional to

continental scale (Renssen et al., 2009). The correspondence between high fire frequency and the HTM thus suggest that warmer conditions promoted increased fire frequency.

Some authors also state that increased fire frequency could be enhanced by increased moisture (Turner et al., 2008). However, this mechanism may be effective in fuel-limited environment, such as arid ecosystems, where the increase of moisture level results in increasing biomass and thus fuel build-up. This is obviously not the case in the western Pyrenees which are under oceanic influence.

From 5000 to 3000 cal yr BP onwards, the regional decrease of summer temperatures (Renssen et al., 2009) was synchronous with the establishment of *Fagus sylvatica* in the Pyrenean forests underlining a climate cooling (increasing precipitation and/or atmospheric humidity, Jalut et al., 1996) recorded at the western European scale (Magny et al., 2009). The absence of recorded fires during a millennium (3900–2900 cal yr BP, Fig. 5) suggests that increased moisture, promoting taxa such as *Fagus* with low specific flammability (Clark et al., 1989), could have inhibited fire occurrence. In contrast, the high level of fire frequency during the last 3000 yr seems disconnected from this long-term cooling trend and other controls must be investigated.

Land-use changes, fire regime and vegetation

During the early Holocene, the mode of subsistence of Mesolithic (11,700–7800 cal yr BP) people was hunting-gathering in small nomadic groups (Valdeyron, 2008), which implies weak environmental imprints. Besides, there is no pollen evidence for agro-pastoral activities until 7100 cal yr BP. We can thus reasonably assume that there was locally no fire used with agro-pastoral purposes before this date. In the same way, it seems unlikely that such a human occupation could have influenced sedimentary pattern (lake-to-peat transition) at the Col d'Ech.
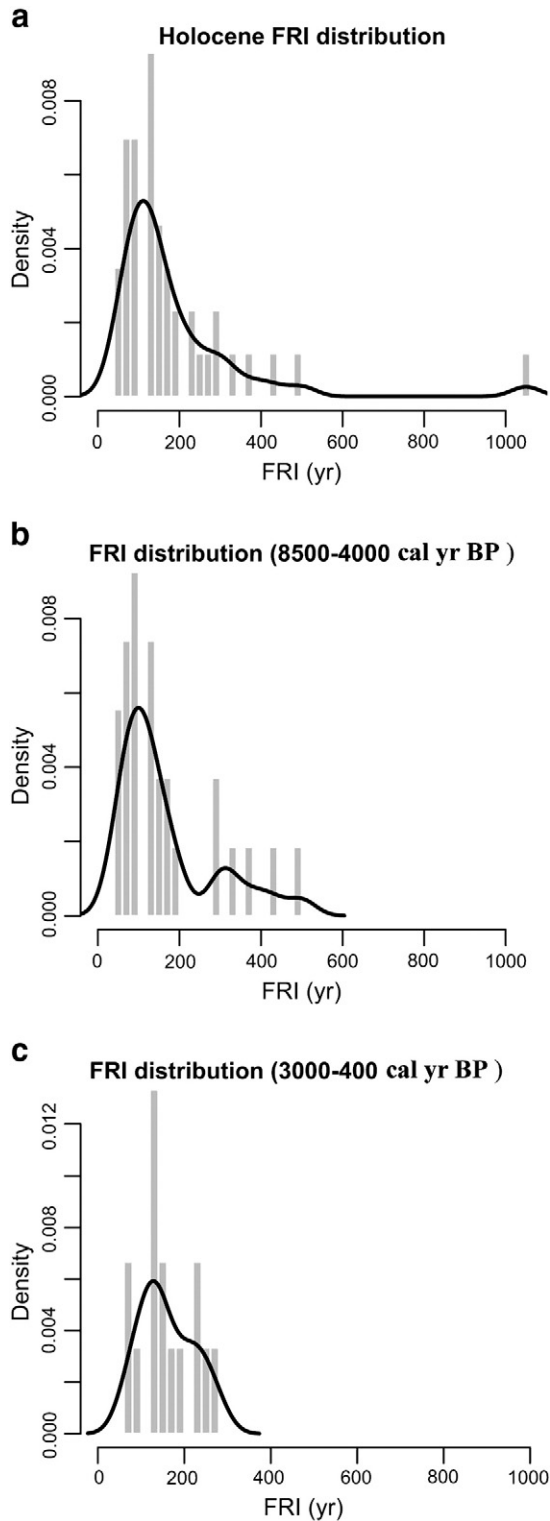
Therefore, between 8200 and 6000 cal yr BP signs of human impact are scarce (no *Cerealia*-type pollen is found before 7100 cal yr BP, and therer are only sparse and isolated occurrences of meadow taxa before 7250 cal yr BP), but the single and isolated occurrence of *Cerealia*-type pollen at 7100 cal yr BP (Early Neolithic, Fig. 5) is well correlated with AP decrease, between two fire episodes (at 7350 and 7050 cal yr BP). It may thus indicate the first local forest clearance for agriculture.

Between 6000 and 5000 cal yr BP, at the Middle to Late Neolithic transition, fire episodes are synchronous with *Cerealia*-type pollen occurrences (at 5700, 5550 and 5150 cal yr BP). Cultivation seem to have a large but temporary impact on the vegetation as underlined by the successive decrease/increase of AP percentages, (Fig. 5, transition between zones Ech 3 and Ech 4). This temporary impact is likely linked with non-permanent agriculture as underlined by the centennial to multi-centennial intervals between *Ceralia*-pollen type occurrences. *Betula* seems particularly favored by these temporary clearances (Fig. 5). This agricultural phase and its impact on vegetation fits well with previous results about Neolithic fire clearances in the north-western Pyrenean piedmont (Galop, 1998; Galop et al., 2002; Rius et al., 2009). However, the duration and the high fire frequency (up to 5 fires/500 yr) compared to the sporadic occurrences of *Cerealia*-type pollen suggests that climate remains the major control over the fire regime, all the more so as fire frequency is synchronous from local to regional scale (as discussed above). Consequently, human influence cannot be totally ruled out, but could be considered a secondary forcing factor.

After 5000 cal yr BP our results show sporadic human impact from Late Neolithic to Early Bronze Age (Fig. 5), but both pollen and CHAR patterns show no long-lasting effects on vegetation: fire frequency and CHAR gradually decrease from 5000 to 3900 cal yr BP (4 fires episodes in a millennia), while AP percentages remain steady. High-amplitude successive increases of *Betula* percentages (from 10 to 40–60%) alternate with decreases of both *Quercus* and *Corylus* which are synchronous with fire episodes. This suggests that the light-demanding *Betula* recolonized previously open spaces in the mixed-oak forest and was then
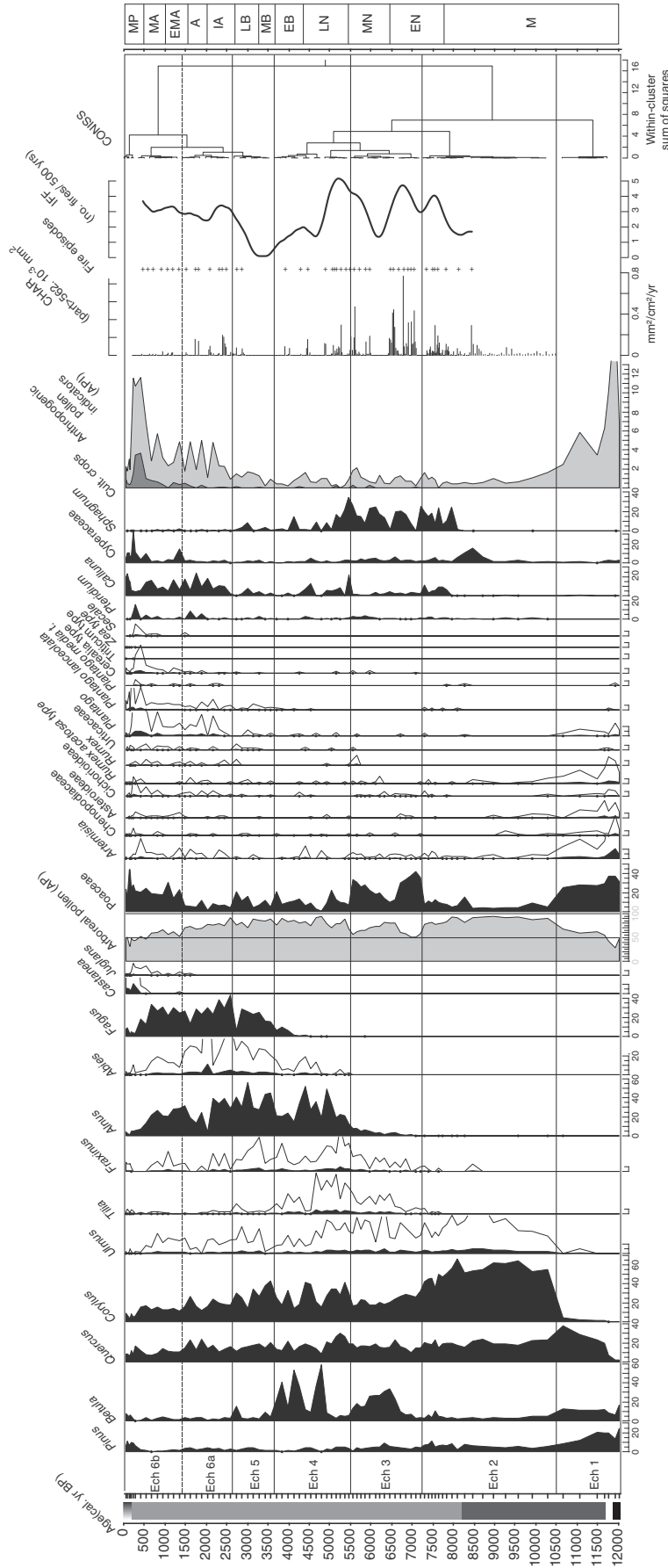
Figure 5. Percentage pollen diagram against reconstructed fire history from the Col d'Ech peat bog (see Fig. 2 for the legend of the lithological log). Synthetic pollen curves: Cultivated crops (*Cerealia*-type, *Triticum*-type, *Secale*), Anthropogenic pollen indicators (*Plantago major/media*-type, *Plantago lanceolata*, *Plantago* sp., *Artemisia*, *Urtica*, *Rumex* sp., *Rumex acetosa/acetosella*-type, Brassicaceae, Chenopodiaceae, Asteroideae, Cichoriodeae, *Centaurea cyanus*, *Polygonum aviculare*-type, *Trifolium*-type). Open curves represent 10× exaggeration. Reconstructed fire history: CHAR of large charcoal fragments (bars), detected fire episodes (crosses), Inferred Fire Frequency (IFF, bold line). Cultural periods are indicated in the right-hand chronological scale (M: Mesolithic, EN: Early Neolithic, MN: Middle Neolithic, LN: Late Neolithic, EB: Early Bronze Age, MB: Middle Bronze Age, LB: Late Bronze Age, IA: Iron Age, A: Antiquity, EMA: Early Middle Ages, MA: Middle Ages, MP: Modern period).

a

Holocene FRI distribution

b

FRI distribution (8500-4000 cal yr BP)

c

FRI distribution (3000-400 cal yr BP)

Figure 6. Density histograms of Fire Return Interval (FRI): (a) over the whole record, (b) between 8500–4000 cal yr BP and (c) between 3000–400 cal yr BP.

progressively outcompeted by other tree taxa. These clearances were probably performed for grazing activities as underlined by the slight increase of API without *Ceralia*-pollen type until 4250 cal yr BP. In the northwesten Pyrenean piedmont the Neolithic-to-Bronze Age transition is usually a period of decreasing agricultural activities (Galop et al., 2007; Carozza and Galop, 2008).

The 3900–2900 cal yr BP fire-free period is concomitant with a decrease of agricultural indicators and a slightly progressive increase of API. This trend is consistent with the phenomenon of grazing overcoming agricultural activities at the regional scale for sites above 500 m asl (Galop et al., 2007; Carozza and Galop, 2008). However, the absence of recorded fires for 1000 yr together with clear signs of reforestation (AP percentage increase) underlines that grazing pressure was probably moderate. It is also probable that the climate cooling phase occurring during these period (see above) may have impacted agropastoral activities in climate change-sensitive habitats such as pile dwellings (Magny, 2004) or mountains zones (Galop et al., 2007).

Finally, the shift from a sporadic fire use to anthropogenic control over the fire regime can be assessed from 2900 cal yr BP, at the Bronze-to-Iron Age transition, when the shift from agro-sylvo-pastoral to agro-pastoral system was achieved. The first increase of fire frequency (up to 2.5 fires/500 yr, Fig. 5) between 2900 and 1700 cal yr BP is synchronous with a sharp increase in API percentages, AP decrease and sparse occurrences of *Cerealia*-type pollen. This might indicate a first phase of landscape opening with the probable dominance of grazing over agricultural activities. Those fire clearances are characterized by punctual *Fagus* decreases and by temporary recovery of secondary taxa such as *Pteridium* and *Corylus* during fire-free intervals (2000–1750 and 1750–1500 cal yr BP). The dynamic of the later taxa suggest moderate land use that enables temporary encroachment and also the use of fire as a "cleaning tool" (Rius et al., 2009), i.e. the use of fire to prevent colonization and maintain spaces open and available for grazing and/ or cultivation. Those anthropogenic disturbances favoring *Pteridium* after fires are well-known in Western Europe (Iversen, 1956; Valsecchi et al., 2010).

In a second step (1700-200 cal yr BP, Fig. 5) which begins at the transition between Antiquity and Early Middle Ages, the *Cerealia*-type curve becomes continuous and a general increase of API (*Plantago* and *Plantago lanceolata* in particular) is synchronous with a second increase in fire frequency (up to 3–4 fires/500 yr) and a marked decrease trend in AP percentages. These results suggest an accentuation of previously observed trends, with evidence for more permanent agriculture and diversification in cultivated crops. The increase and the regularity of fire occurences results in the suppression of temporary recovery as underlined by the flat trend of *Corylus* percentages and the quasi-disappearance of *Pteridium*. The abrupt decrease of AP from 700 cal yr BP and in *Fagus* in particular indicates an intensification of land use (Galop and Jalut, 1994; Valsecchi et al., 2010) corresponding to the Medieval growth (Galop, 2000): all the watershed of the peat bog was probably cleared and used, even the north-facing slopes (where *Fagus* is preferentially established) which are supposed to be less favourable for agro-pastoral activities.

Climatic versus anthropogenic fire frequency

Inferred fire frequency (IFF) and mean fire interval (MFI) provides a tool to understand the role of fire within the ecosystem linked with climatic, biomass, and/or anthropogenic controls (Whitlock et al., 2010). Multiproxy comparison with pollen, archaeological data, independent climatic proxy, can help us to disentangle those forcing factors from each other.

Here the MFI is 155 yr for the 8500–4000 cal yr BP period, 160 yr between 3000 and 400 cal yr BP, and 230 yr for the entire record. There is no significant difference between those values which means that human impact probably did not enhanced fire frequency. This feature was also observed by Vannière et al. (2008) in northern Italy. The signature for anthropogenic control here lies in the temporal distribution of fire-return interval (Olsson et al., 2010).

Indeed, the distribution of Fire Return Intervals (FRI, Fig. 6) shows scattered return intervals with a highly right-skewed distribution between 8500 and 4000 cal yr BP (Fig. 6b) and a distribution centred around 200 yr between 3000 and 400 cal yr BP (Fig. 6c). We assume

the scattered distribution of FRI between 8500 and 4000 cal yr BP to be linked with 1) the combined influence of natural and anthropogenic forcing factors over fire regime especially during the last two millennia of this phase, and 2) with the instability of climate and above all with the randomness of climate control over fire regime (Olsson et al., 2010) in a not-fire-prone ecosystem all the more so as local factors (hydrography, topography, vegetation patchiness and type) modulate the fire-climate relationship (Carcaillet et al., 2001; Heyerdahl et al., 2001). Indeed, even under increased temperature and seasonal drought during the HTM, the concomitance of all favourable factors to fire-ignition and spread in such a bioclimatic context (i.e. seasonal drought, biomass accumulation, vegetation moisture) appears highly stochastic (Enache and Cumming, 2009).

The bell-shaped distribution of FRI from 3000 to 400 cal yr BP could be interpreted as the strong predominance of a forcing factor freed from other controls. As discussed above, this forcing factor seems to be human activities related to agriculture.

This high fire frequency with regular episodes sustained by agro-pastoral activities becoming progressively permanent seems to have an impact on forest cover. It has been demonstrated in the Eastern Pyrenees that repeated prescribed burning in actual conditions has an effect in reducing encroachment by shrubby vegetation comparable with those of wildfires (Montané et al., 2009). Therefore, we suggest that fire played a prominent role in landscape opening during the last 3000 yr. However, fire itself cannot be considered as the only factor of forest clearances. Indeed, it is more likely to see this long term decreasing trend in arboreal pollen percentages as the consequence of the combined effect of regular fires, permanent agro-pastoral activities and probably increasing demographic pressure. It also underlines that the Bronze-to-Iron Age transition (Carozza and Galop, 2008; Bal et al., 2010) and the Iron Age in particular were key turning points in anthropogenic fire use.

Conclusions

The "col d'Ech" fire and vegetation record emphasize climate-driven and human-driven fire frequency phases which differ in timing and pace of fire episodes and in their impact on vegetation. Comparison among quantitative reconstruction of fire frequency, vegetation and climate history is a key for understanding the complex mechanisms controlling past fire regimes. Our main results are as follows:

(1) The mid-Holocene high fire frequency (8500–5000 cal yr BP) is controlled by climate under the Holocene climatic optimum. Sporadic agricultural activities also have an impact on fire frequency especially between 6000 and 5000 cal yr BP.

(2) The mid-Holocene fire frequency, before the onset of permanent agriculture, is higher than expected in such a bioclimatic context.

(3) High fire frequency during the last 3000 yr is mainly controlled by agro-pastoral activities.

Finally, these results also suggest that the current massive reforestation due to land abandonment, combined with the actual warming, may have an increasing impact on fire frequency.

Acknowledgments

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