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Fire frequency and landscape management in the northwestern Pyrenean piedmont, France, since the early Neolithic (8000 cal. BP)

Damien Rius,[1]* Boris Vannière[1] and Didier Galop[2]

([1]Laboratoire Chrono-Environnement, UMR 6249 CNRS, Université de Franche-Comté, UFR ST, 16 route de Gray, 25030 Besançon, France; [2]Laboratoire GEODE, UMR 5602 CNRS, Université Toulouse II-le Mirail, 5 allées Antonio Machado, 31058 Toulouse, France)

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Abstract: Both quantitative reconstruction of fire frequency from charcoal counts and pollen analysis were undertaken on a 312 cm sediment core from Gabarn peat bog. An 8000 yr cal. BP palaeofire record and vegetation history were established on the basis of nine ^{14}C (AMS) dates. As anthropogenic Inferred Fire Frequency (IFF) has seldom been studied, we test and discuss two different methods of frequency calculation. Our results shows a clear Holocene bipartition at *c*. 3500–4000 cal. BP characterized by a three times decrease in Mean Fire Interval (MFI): from 7000 to 4000 cal. BP, MFI = 530 yr; from 4000 to 400 cal. BP, MFI = 160 yr. In an Atlantic vegetation context, we hypothesize this fire regime with such episode frequency to be mainly controlled by human activities. This hypothesis is supported by comparisons with other European quantified palaeofire regimes (Swiss Alps, northern Italy) whether they are controlled by climate, man or both. Taking into account the pollen record, we interpret the Gabarn palaeofire record links with human pressure and land use. Our results suggest that the relationship between fire frequency and human pressure is not always linear. Fire frequency could also reflect land-use shifts and changing use of fire within agro-pastoral activities.

Key words: Macroscopic charcoal, fire frequency, fire regime control, pollen, land use, Pyrenees.

Introduction

In the Pyrenees Mountains, the role of anthropogenic fire in landscape management is attested by historical sources since the Middle Ages (Chevalier, 1956; Bonhote, 1992). Prescribed burning is still used nowadays to prevent pasture colonization by shrubs and trees when grazing pressure is too low (Métailié, 1981). Climate-induced fires are scarce because of the conjunction of wet summers and Atlantic vegetation type (Dupias, 1985; Jalut *et al*., 2000) with low specific flammability. For the past 30 years, in the department of 'Pyrénées-Atlantiques', 127 fires have occured per year, burning 1170 ha in a forested area of 211 111 ha (data from the French Ministry of Agriculture). Prescribed burning is nowadays the major cause of forest fires which can spread over wide areas during drought. For example, in February 2002, an uncontrolled pasture burn provoked a 5000 ha forest fire in the Basque country.

Vegetation history of the Pyrenees since the early Neolithic assessed by pollen studies (Jalut *et al*., 1988; Galop and Jalut, 1994; Reille and Andrieu, 1995; Galop, 1998; Jalut *et al*., 1998) provides much evidence of forest clearance followed by farming activities. In other European mountain zones such as the Alps, high-resolution palaeofire records combined with pollen data have widely improved our knowledge on Holocene man–fire–vegetation interactions (eg, Tinner *et al*., 1999, 2005; Gobet *et al*., 2003; Tinner and Lotter, 2006; Stähli *et al*., 2006). However, the use of fire as an agrarian tool is not clearly understood in the Pyrenees as only three low-resolution palaeofire studies have been performed to date (Vannière *et al*., 2001; Galop *et al*., 2002; Miras *et al*., 2007). These studies clearly attested that fire and agropastoral practices have been linked since Neolithic times in the area.

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*Author for correspondence (e-mail: damien.rius@univ-fcomte.fr)

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However the threshold beyond which human activity became the major control over fire regime remains poorly studied. Quantification of fire regime parameters, especially frequency, is needed to understand and characterize this shift. Here, we propose a quantitative reconstruction based upon robust methodological tools initially developed in a climate-driven fire regime context (Clark and Royall, 1996; Long *et al*., 1998; Gavin *et al*., 2003; Lynch *et al*., 2004a).

Therefore, the main objectives of the present study were:

(1) to test the reliability of fire frequency calculation method on the peat record of anthropogenic palaeofires from a temperate ecosystem
(2) to examine if our results fit with the human impact history revealed by other proxies such as anthropogenic indicators in the pollen diagram and archaeological data
(3) to assess the role of fire in land-use shifts since the early Neolithic with particular focus on the significance of fire frequency within an area where climate control of fire regime was assumed to be weak.

Material and methods

Environmental settings

The study site (43°10′18.03N; 0°33′19.85W, 310 m a.s.l.) is located in the western Pyrenees, on the Ossau valley piedmont (Figure 1a). The ombrotrophic Gabarn peat bog is located on a fluvioglacial terrace, southwest above the Ossau river palaeovalley, which is dammed by the glacier terminal moraine, 10 km west. The present river course is south of the site, at 230 m a.s.l. The peat bog is covered by *Calluna vulgaris* and belted by *Betula pendula*, *Alnus glutinosa* and *Quercus robur*. The immediate surroundings consist of corn cultivated fields, meadows and pastures. This zone is characterized by a humid oceanic climate with mean annual precipitation of 1400 mm with maxima during autumn and spring. Mean annual temperature is 13°C, mean summer temperature is 19.5°C and mean winter temperature is 7°C. Regional vegetation consists of Atlantic-type oak forest mainly dominated by *Quercus* (*Q. robur* and *Q. pyrenaïca*) mixed with *Corylus* and *Betula*. Heathlands (*Ulex nanus*, *U. gallii*, *U. europaeus*, *Erica cinerea*, *E. vagans*, *Calluna vulgaris*, *Pteridium aquilinum*) typical of the bioclimatic hill-stage (130–800 m) are well represented. Above the site, the north-facing slopes (up to 1400 m a.s.l.) are covered by a mixed beech-oak forest (*Fagus sylvatica*, *Q. robur*), which is the dominant vegetation type of the bioclimatic mountain stage in the area.

Archaeological settings

In the Ossau valley piedmont, archaeological data are scanty and few syntheses have yet been done (Carozza *et al*., 2005; Blanc *et al*., 2006). However, ten archaeological sites (Figure 1b) from the piedmont and the mid part of the valley provide a set of 18 radiocarbon dates (Blanc *et al*., 2006). Most of the dates were performed on charcoal and bones. Two sites have chronology estimated from ceramic typology (‘Gabarn d’escout’, ‘Précilhon dolmen’, see Figure 7). The best dated periods are late Neolithic (5500–4400 cal. BP), early and middle Bronze Age (4400–3300 cal. BP) and Iron Age (2900–2000 cal. BP). Most of the sites are dedicated to burial (*n*=7) while the others are dwelling sites (*n*=3) or both (*n*=1). Therefore, we have a sufficient archaeological coverage from the late Neolithic to the Iron Age, but we lack data on the early and middle Neolithic. The sum of probability distributions of archaeological radiocarbon dates and estimated chronology are plotted on Figure 7.

Field and laboratory methods

Coring and sediments

The core was taken using a Russian peat sampler (GYK type, 50 cm length; 8 cm in diameter). The coring point was located in the centre of the peat bog. The basal till was reached at 400 cm. The sedimentary record (Figure 2) consisted of alternate layers of dark and light brown fibrous peat (0–238 cm) with a layer of dark brown silty peat (119–130 cm), dark brown peaty silt (238–260 cm), dark brown organic clay (260–286 cm), dark grey clay (286–312 cm), light grey clay (312–370 cm) and light brown clay (370–400 cm). The first 5 cm were too fibrous and disturbed to be sampled and analysed. The bottom section (312–400 cm) was not analysed because of lack of pollen and charcoal.

Chronology

Chronology was based on nine Accelerator Mass Spectrometry (AMS) radiocarbon dates on bulk sediment. Calibration to year cal. BP was made using CALIB 5.0.1. (Stuiver and Reimer, 1993), based on the data set IntCal04 (Reimer *et al*., 2004). Dates are expressed as intercepts with 2σ ranges (Table 1). To estimate ages along the entire profile, we used a mixed-effect regression model according to the procedure standardized by Heegard *et al*. (2005). The deepest dated sample was 298 cm but pollen as well as charcoal data were recovered until 312 cm. Therefore we extended the age–depth curve over the undated 14 cm on the basis of the sedimentation rate estimated on the previous section (247–298 cm).

Macroscopic charcoal analysis

Contiguous samples of 1 cm^3 were retrieved at every 1 cm of the core, soaked in a 10% NaOH solution for 24 h for peat digestion, then in a 30% H_2O_2 solution for the same time to bleach non-charcoal organic material and thus make charcoal identification easier (Rhodes, 1998). As we aim to reconstruct local fire history, quantification of charred particles was made according to the sieving method (eg, Whitlock and Larsen, 2001; Carcaillet *et al*., 2001) with a 150 µm mesh size (Clark, 1988; Ohlson and Tryterud, 2000). Charcoal identification was restricted to the criteria usually defined in the literature (eg, Umbanhowar and McGrath, 1998; Enache and Cumming, 2006). Both number and area concentrations of charcoal particles were estimated under a binocular microscope at a 50× magnification with a reticule grid of 10×10 squares of 62.5×10^{-3} mm² each. Ten increasing size classes were defined (31.25–62.5, 62.5–125, …, 187.5–250 10^{-3} mm^2, …). Charcoal concentration (CHAC; mm^2/cm^3) was expressed as charcoal accumulation rate (CHAR; mm^2/cm^2 per yr) based on sedimentation rate estimated by the depth–age model.

Inferred fire frequency (IFF)

Fire frequency calculation procedure has been developed mainly on lacustrine sediment records (Clark, 1995; Clark and Royall, 1996; Clark *et al*., 1996; Long *et al*., 1998; Gavin *et al*., 2003; Lynch *et al*., 2004a, b) on the evidence of the dichotomy between two source components in the charcoal signal (Clark and Patterson, 1997) which are background charcoal (BCHAR) and peak component.

The background component includes (1) a low-frequency level corresponding to centennial-scale variability (Gavin *et al*., 2006), (2) re-deposition of secondary charcoal from the watershed and/or the littoral of the lake to the deep-water sediments (Whitlock and Millspaugh, 1996), and (3) distant fire charcoal production (Clark and Royall, 1996). Two mechanisms could transport secondary charcoal to the peat bog: surrounding soil erosion (but slopes around the basin are gentle) and secondary water transport. Since subaerial peat may better reflect atmospheric transport processes than lakes (Clark and Patterson, 1997), we should have a low

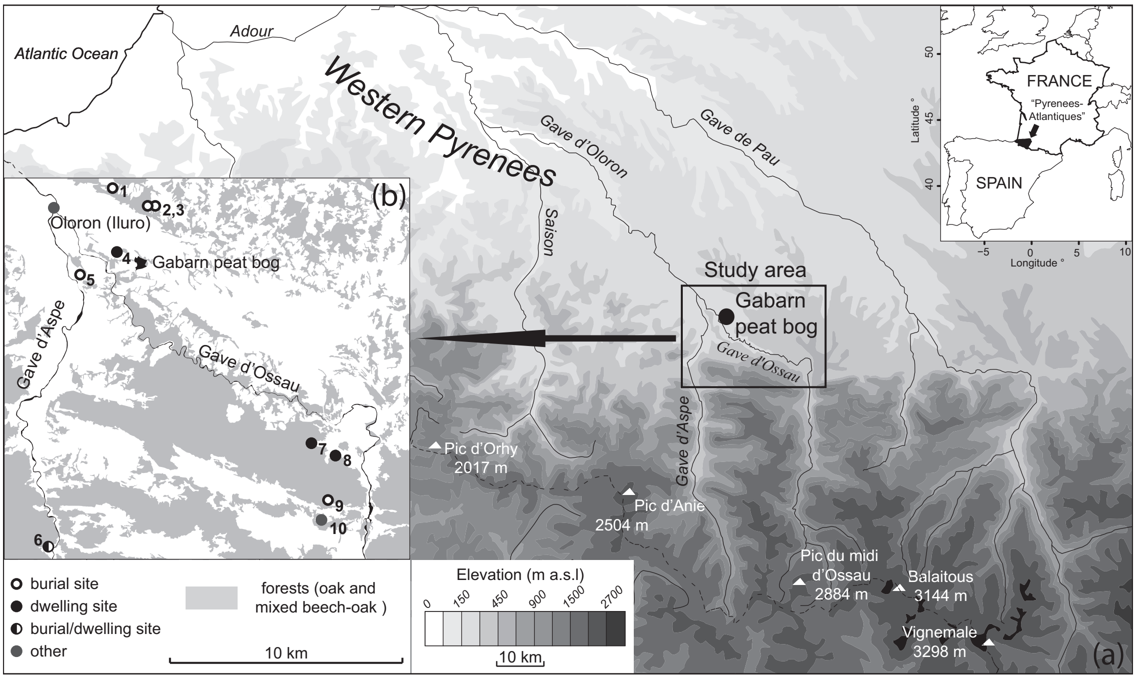

Figure 1 Geographical location of Gabarn peat bog in the French Pyrenees piedmont (a) and archaeological map (b) of dated archaeological sites plotted in Figure 7. 1, 'Precilhon' dolmen; 2,3, 'Peyrecor' dolmens; 4, 'Gabarn d' Escout'; 5, 'Soiex d'Oloron tumulus; 6, 'Apons' cave; 7, 'Malarode' cave; 8, 'Espalungue' cave; 9, 'Laplace' cave; 10, 'Accaüs' stone circle. Radiocarbon dates can be found in Blanc *et al.* (2006)

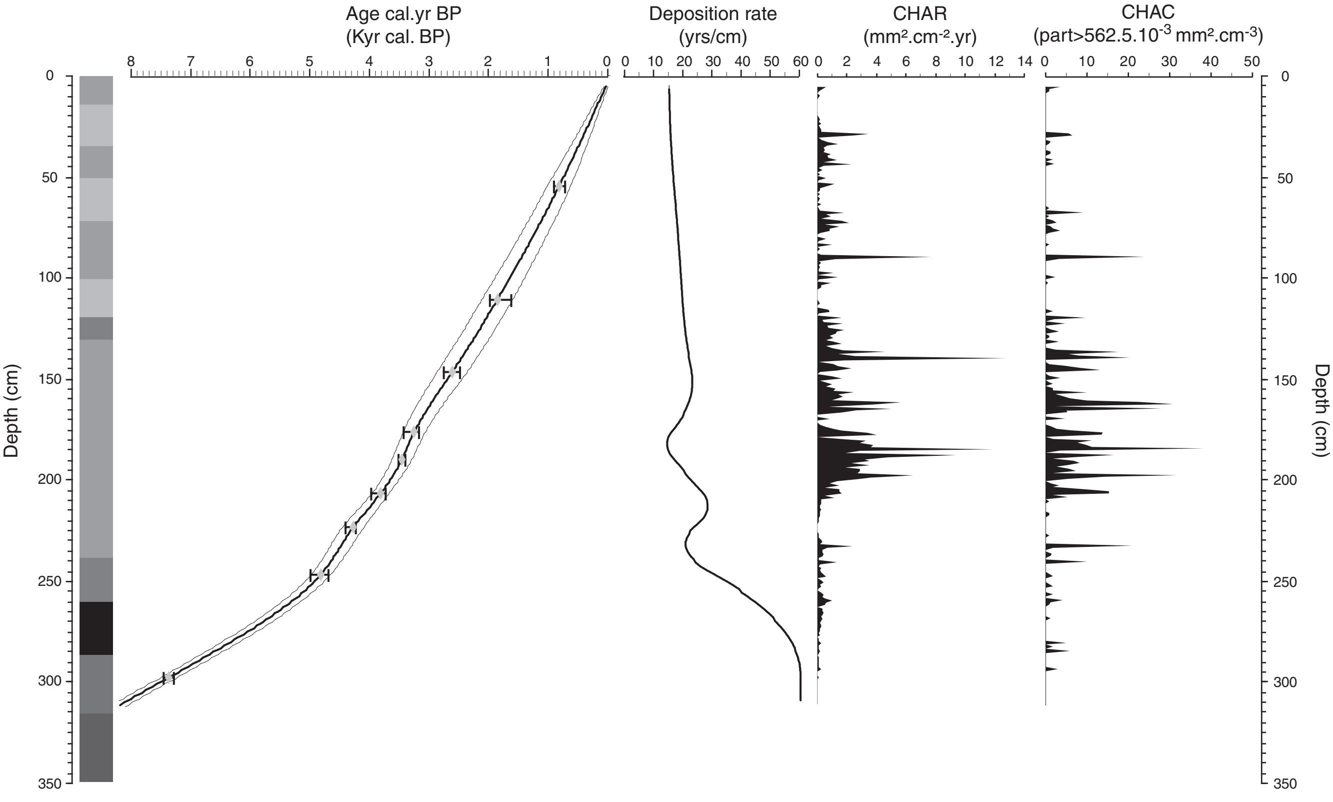

Figure 2 Lithology (see the Material and methods section for detailed description), age–depth model (constant variance) with expected age throughout the sequence (bold line), 95% confidence intervals (thin grey lines), estimated age of radiocarbon dates (grey diamonds) and 2σ range probability area (errors bars), estimated sedimentation rate (yr/cm), charcoal accumulation rate (CHAR, mm^2/cm^2 per yr) and charcoal concentration (CHAC) of large charcoal fragments (charred particles > 562.5 × 10^{-3} mm^2)

background level resulting from water transport particularly as there is no permanent river draining the peat bog. The charcoal analysis method may reduce the long-distance charcoal input, but some recent studies have emphasized long-distance atmospheric transport (> 5 km) of charred particles > 150 μm in length (Tinner *et al.*, 2006) as well as carbonized macroremains (Pisaric, 2002). Therefore, we may have a distant fire charcoal input in the background component (Peters and Higuera, 2007).

Table 1 AMS–radiocarbon dates from Gabarn (GB) peat bog

Sample depth (cm)	Lab. Code	Type	AMS radiocarbon date BP	Cal. Yr BP [2σ range] probability area	Cal. Yr BP in diagram
GB 55.5	Poz-7527	Peat	875 ± 35	710–910	824
GB111.5	Poz-7528	Peat	1860 ± 35	1714–1875	1860
GB147.5	Poz-7533	Peat	2515 ± 35	2471–2741	2622
GB177.5	Poz-7534	Peat	3025 ± 35	3081–3345	3261
GB190.5	Poz-13087	Peat	3245 ± 35	3391–3558	3459
GB207.5	Poz-13088	Peat	3500 ± 35	3650–3871	3825
GB224.5	Poz-13089	Peat	3880 ± 40	4158–4419	4291
GB247.5	Poz-13090	Peat	4240 ± 35	4626–4849	4825
GB298.5	Poz-15871	Clay	6420 ± 40	7274–7422	7394

The peak component is composed of a small population of high values, ie, local fires and a large population of small values derived from both analytical noise and random natural variability (Clark *et al*., 1996; Long *et al*., 1998; Gavin *et al*., 2006). It means that a peak could be (1) composed of more than one subsample or (2) a false positive (ie, residual peaks which are not representative of fire events, see Whitlock and Millspaugh, 1996; Higuera *et al*., 2005). We need to select a threshold value above which we can consider a peak as a single fire episode.

Background charcoal (BCHAR)

We could not calibrate the fire signal by means of tree ring data (Higuera *et al*., 2005) or by short core charcoal study (Tinner *et al*., 1998). Therefore, we tried two different options to estimate both BCHAR and peak component in order to obtain a robust estimation of fire episodes and IFF. Estimation of BCHAR was made (1) on log-transformed data (LogCHAR = log10 (resampled char value+1), Long *et al*., 1998), (2) on raw data series (RawCHAR = resampled char). All data series were smoothed with a locally weighted regression model (Lowess smoother) with 250 and 500 year moving windows in order to choose the one that best fit the low varying component (BCHAR). We consider the background estimation robust when the smoothed curves do not miss the peaks baseline nor follow the peaks too closely and when the residual peaks are composed of the smallest number of subsamples possible.

Peak component analysis and threshold value selection

We performed threshold value selection on both the difference and ratio-calculated peak component. Therefore, we used a sensitivity analysis (Clark *et al*., 1996; Lynch *et al*., 2004a, b) to select a threshold that identifies local fire episodes. We chose the threshold within the range of values with the lowest sensitivity to the number of peaks detected, by plotting a frequency distribution histogram of peak component against a cumulative curve of number of peaks. Then, all peaks above the selected threshold were considered as a single fire episode, except when a peak was composed of more than one subsample. In this case, instead of averaging the values (Lynch *et al*., 2004a, b), we selected the oldest value in order to date the peak as we consider it marks the beginning of charcoal accumulation corresponding to the single fire episodes.

The reliability of each option is discussed according to three criteria: accuracy of BCHAR, peak component estimation and comparison with CHAR. Both BCHAR estimation and sensitivity analysis were performed with ‘R’ software. Frequency curves were obtained by smoothing (K1D software; Gavin, 2006) a binary series of peaks (1= peak, 0= no peak) over 500 and 1000 year moving windows to allow comparison between the four results (log-difference, log-ratio, raw-difference, raw-ratio). Mean fire interval (MFI) is calculated by dividing the time-lag in years 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 lag-time in years between two fire episodes.

Pollen analysis

Subsamples for pollen analysis consisted of 1 cm^3 cubes taken at 4 cm intervals. Pollen preparation followed standard methods using treatment with HCL, 10% KOH, HF, acetolysis and final mounting in glycerine. 450 terrestrial pollen grains were counted in each sample. *Cyperaceae*, *Calluna*, aquatics and spores were excluded from the pollen sum to avoid over-representation by local taxa. All pollen types are defined according to Faegri and Iversen (1989), although some identification required the use of a pollen atlas (Reille, 1992–1998; Beug, 1961, 2004). Figure 5 presents a simplified pollen diagram with major arboreal taxa and anthropogenic indicators.

Results

Chronology

Mixed-effect modelling provided an estimation of the age–depth relationship with 95% confidence intervals and no outliers. The record covers the last 8200 years (Figure 2). The mean sedimentation rate of the record is 0.45 mm/yr (mean time resolution: *c*. 25 yr/cm). The deeper part (247–312 cm) is the weakest in terms of radiocarbon dates, but according to the lithostratigraphy and depth–age modelling, we can reasonably assume that there is no evidence of hiatuses, within a section whose sedimentation rate is the lowest of the record. The estimated sedimentation rate is 0.16 to 0.2 mm/yr (time resolution 50–60 yr/cm) on this section. The major change at 247 cm corresponds to the progressive beginning of peat formation within the basin. Both low CHAR and scarce anthropogenic pollen indicators suggest there is little evidence of human impact on this mechanism. The mean of total standard deviation (Tsd) of the model and the average confidence interval (95%) are 94 and *c*. 350 years, respectively.

Macroscopic charcoal record

Charred particle counts (Figure 2) ranged between 0 and 2674 pieces per subsample with a mean of 180.5 and a median of 93. The first five size classes concentrate 95% of the total count, with a high area/number correlation (r^2 = 0.94). These first five classes are homogeneously distributed along the entire record. CHAC of particles $>562.5\times10^{-3}$ mm² (hereafter referred to as large charcoal fragments) matches the CHAR peaks more closely from 8000 to 2000 cal. BP than after (Figure 2). This, together with the constant input of

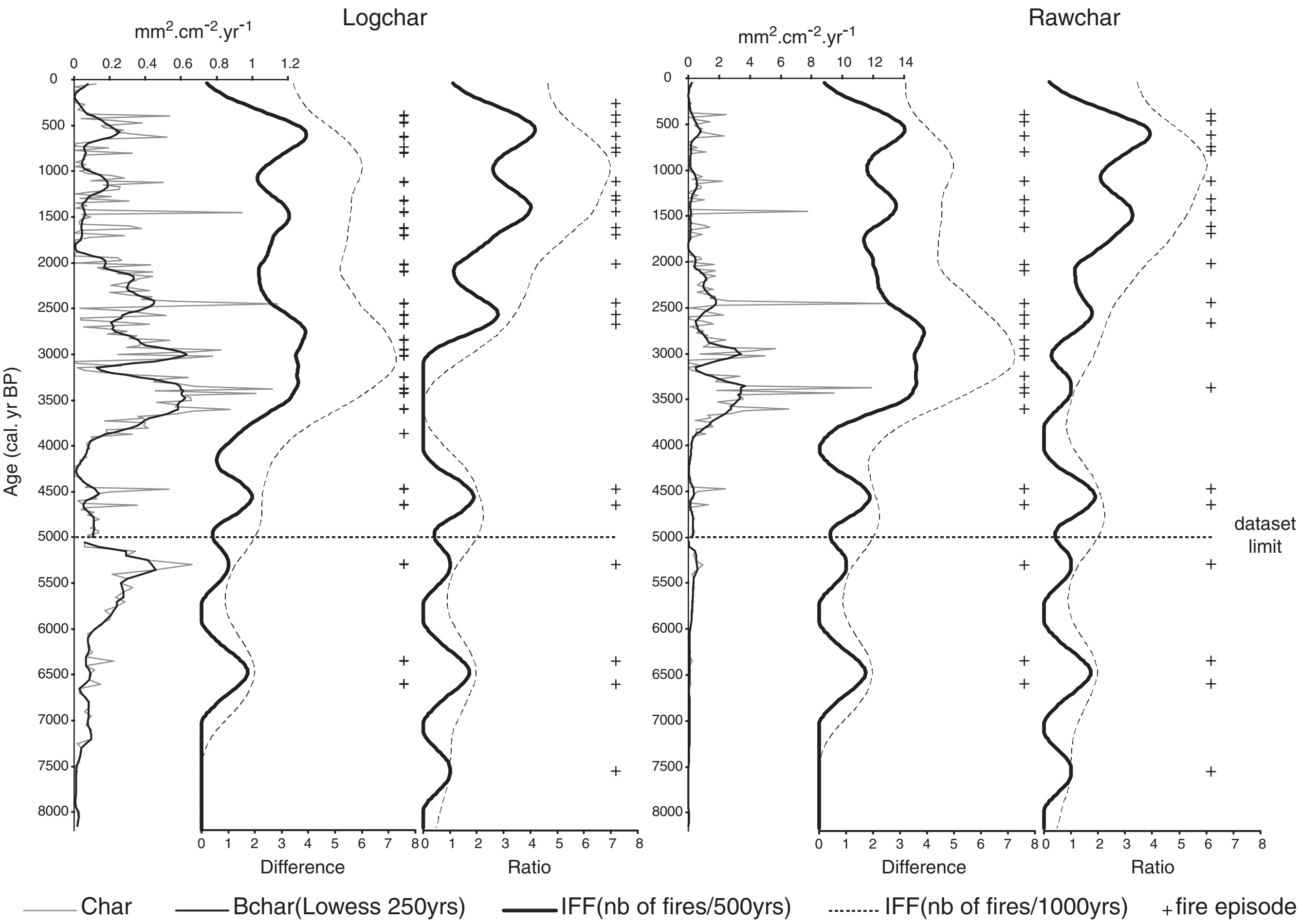

Figure 3 Inferred fire frequency (IFF) results from Logchar and Rawchar series

twig charcoal, particularly between *c*. 3905 and 2355 cal. BP is evidence of the robustness of CHAR as a record of local fire episodes, because this type of charred particles would likely not have been transported long distances nor redeposited after a fire without being broken (Vannière *et al*., 2003). The peaks are rather distinct, as they are composed of 2–5 subsamples. The CHAR record is separated into three phases: a period of low distinct peaks (mean 0.5 mm²/cm² per yr) with minor background during 0–2000 cal. BP, a period of large peaks (mean 1.9 mm²/cm² per yr) with high background during 2000–4000 cal. BP and a period of fewer low peaks (mean 0.2 mm²/cm² per yr) with no background during 4000–8200 cal. BP.

Inferred fire frequency

Background component estimation

Both CHAR and sedimentation rate (SR) emphasized a shift at *c*. 5000 cal. BP (Figure 2). From this point, SR rises to 40 yr/cm and does not fall back below this value. CHAR values also fall below 1 mm²/cm² per yr. Consequently, it was impossible to process the whole data for IFF calculation. The record was then separated into two data sets: the first one ranging from 0 to 5000 cal. BP and the second from 5000 to 8200 cal. BP. They were resampled to obtain uniform time intervals corresponding to each data set's respective mean SR, ie, 25 (50–5000 cal. BP) and 50 years (5050–8200 cal. BP). Resampling was made by dividing charcoal concentration by SR on the predefined time windows from a pseudo-annual series (Long *et al*., 1998).

A 250 yr moving window was selected because it modelled the peak baseline, did not underestimate peak amplitude and preserved both low and high peaks (Figure 3). Peak component is better individualized by difference (93 and 99 residual values >0) than by ratio (193 residual values>0). This estimation of BCHAR/peak component is also validated by the fact that residual peak distributions emphasize two subdistributions with clear threshold values that identify a number of episodes ranging from 20 to 28 (Figure 4).

Detected fire episodes and frequency

Difference calculated peak component and fire episodes show nearly the same results (28 fire episodes detected on LogCHAR, 25 on RawCHAR). IFF curves are in accordance with the tripartition of CHAR described above with minimum of 1 fire/500 yr (5350 cal. BP) and maxima around 5 fires/500 years (2800 cal. BP). MFI on the whole record are 248 (LogCHAR) and 258 years (RawCHAR) with six significant increases (ie, IFF increases > 1 fire/500 years) at *c*. 6500, 4600, 3350, 2800, 1550 and 600 cal. BP (Figure 4). MFI values show a clear bipartition: before *c*. 3500–4000 cal. BP MFI is 531 (LogCHAR) and 615 (RawCHAR) and after values fall to 158 and 160 years, respectively (Figure 6).

Ratio calculated frequency shows contradictory results (22 fire episodes detected on LogCHAR and 20 on RawCHAR). IFF curves are not in accordance with the tripartition of CHAR described above with a minimum of 1 fire/500 yr (5325 cal. BP) and maxima around 4 fires/500 yr (1000 and 600 cal. BP). MFI on the whole record are 346 (LogCHAR) and 376 years (RawCHAR) with five significant increases at *c*. 6500, 4600, 3400, 1550 and 600 cal. BP (Figure 4).

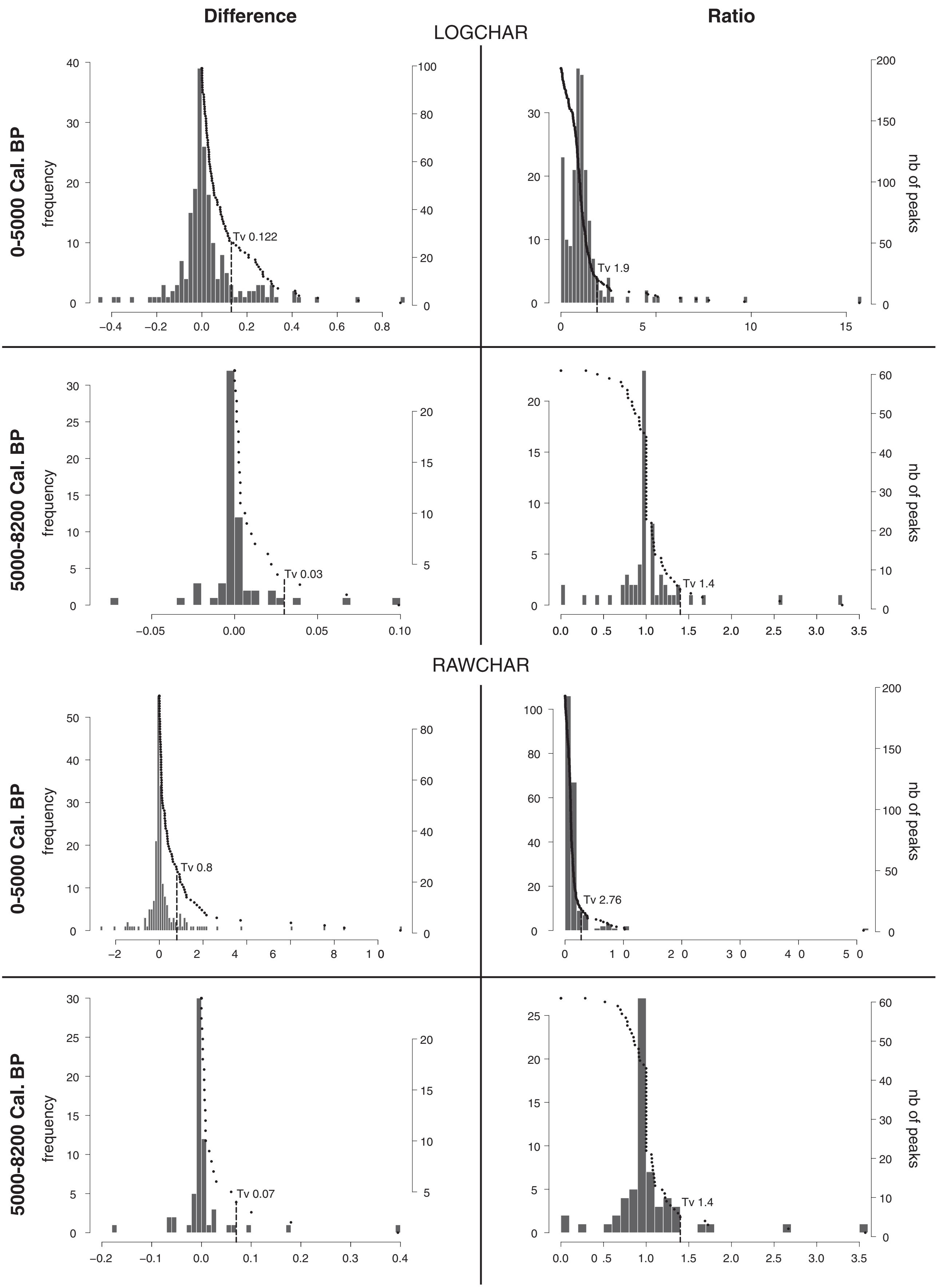

Figure 4 Histograms of frequency distribution of peak component with cumulative peaks number (black circles), performed on difference and ratio calculated peak component from Logchar and Rawchar series. Noise-related variation and right-hand tail distribution, ie, charcoal accumulation anomalies, are separated by the threshold-value (Tv, dotted lines) chosen to identify local fire episodes

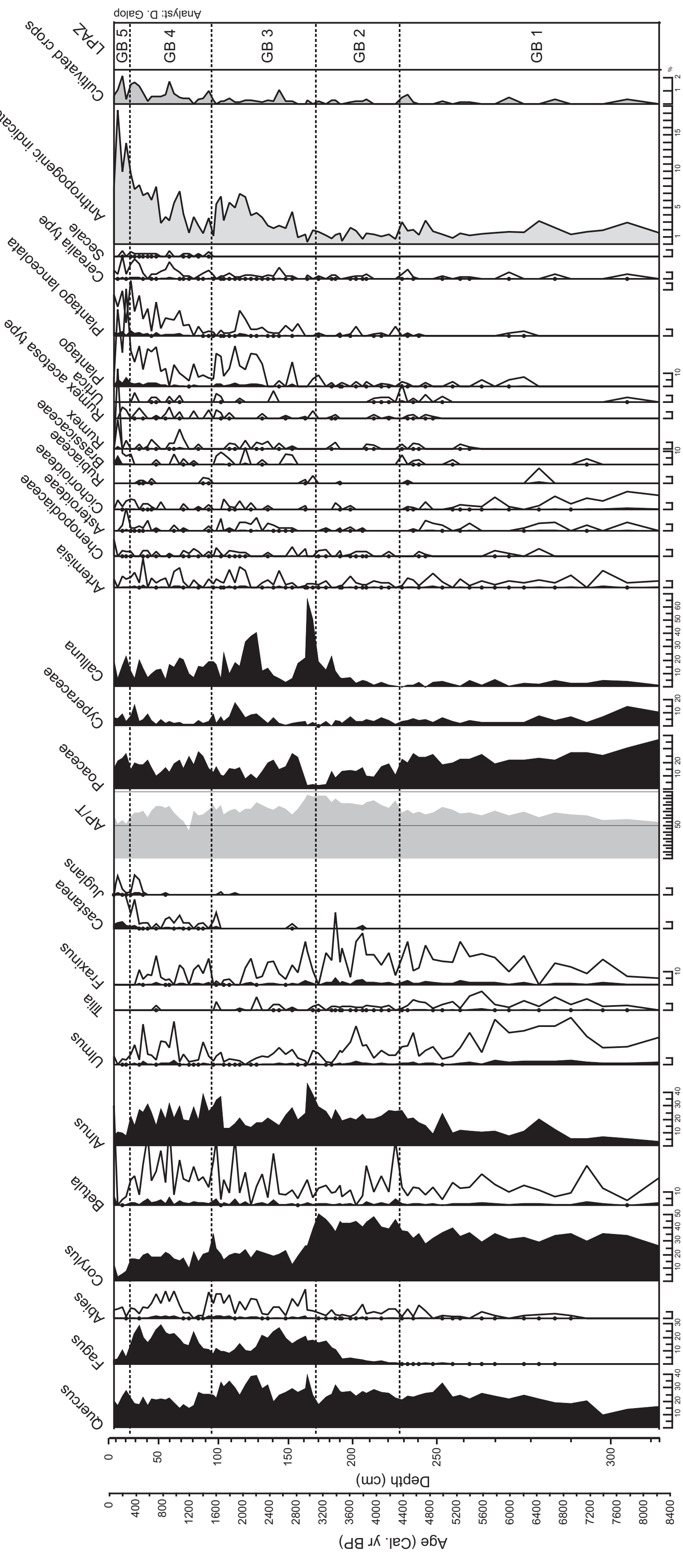

Figure 5 Simplified pollen diagram from the Gabarn peat bog record. Cultivated crops: *Cerealia*-type, *Triticum*-type, *Secale*; anthropogenic indicators: *Plantago major/media*-type, *Plantago lanceolata, Plantago* sp., *Artemisia, Urtica, Rumex* sp., *Rumex acetosa/acetosela*-type, Brassicaceae, Rubiaceae, Chenopodiaceae, Asteroideae, Cichoriodeae, *Centaurea cyanus, Polygonum aviculare*-type, *Trifolium*-type. Exaggerated curves are × 10

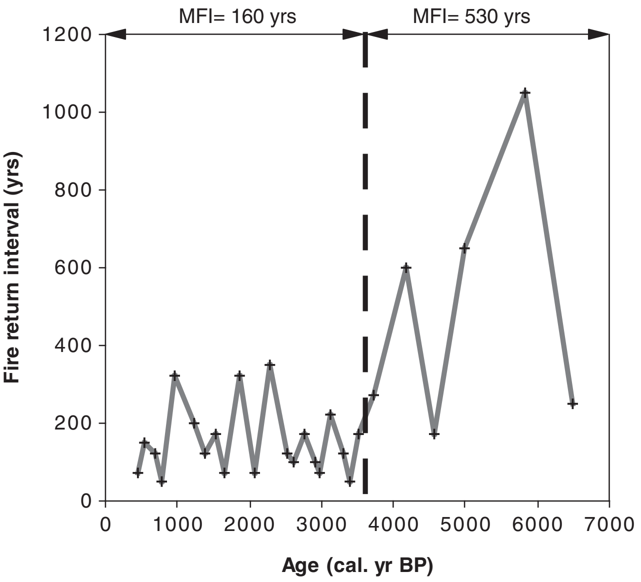

Figure 6 Fire return interval (FRI) calculated on Log CHAR (difference) series

Global trends are the same in all methods for Neolithic, Middle Ages and Modern periods (1500–0 cal. BP). However, the 4000–3000 cal. BP period, ie, the Bronze Age, emphasizes a huge discrepancy between difference and ratio calculated IFF corresponding to the highest BCHAR phase of the whole record.

Pollen record

Five local pollen assemblages zones (LPAZ) were defined.

During zone GB1 (8200–4300 cal. BP), vegetation cover is dominated by *Corylus*, *Quercus* and Poaceae. There are no major trends apart from the increasing percentages of *Corylus* at the end of the zone. Anthropogenic pollen indicators (API) and *Cerealia* pollen type are scarce but more frequent towards the end of the zone.

Zone GB2 (4300–3100 cal. BP) starts with the main botanical event of the record which is the beginning of the continuous *Fagus* curve. It also corresponds to the phase of *Corylus* dominance. Secondary woodland regeneration seems strong as other sprouters such as *Betula*, *Alnus*, *Ulmus* and *Fraxinus* also reach higher percentages than before. *Cerealia* pollen type occurrences are more regular but still discontinuous, anthropogenic indicators (Asteroideae, Cichorioideae, *Rumex*) are low, while Poaceae percentages decrease, indicating low human-related activities.

Zone GB3 (3100–1500 cal. BP) is characterized by the sharp decrease of *Corylus* and the first maximum of *Fagus* (*c*. 2550 cal. BP) and the recovery of *Quercus* stands. From *c*. 2800 cal. BP, *Cerealia* pollen type become more frequent and almost continuous while human activity indicators and Poaceae percentages increase.

In zone GB4 (1500–300 cal. BP) *Fagus* percentages rise to a second maximum (*c*. 800 cal. BP), while *Quercus* and *Corylus* remain quite steady. Grazing and meadows indicators are more regular than in the previous zone, while the *Plantago lanceolata* curve becomes continuous. Agricultural activities increase, as emphasized by more frequent occurrences of *Cerealia* pollen type and the first pollen of *Secale*.

Eventually, GB5 (300–75 cal. BP) is the zone where *Quercus* becomes dominant again in forest vegetation. The *Cerealia* pollen type curve is continuous and reaches its maximum, as do anthropogenic indicators.

Discussion

Frequency calculation robustness

The major expected problem in dealing with anthropogenic palaeofire series lies in the high frequency variability of CHAR linked with land-use changes. In our case, we assumed that this variability derives both from anthropogenic activities (involving different fuel types) and the natural occurrence of fire.

Whether we use LogCHAR or RawCHAR, discrepancies in results depend on whether we use difference or ratio (Figure 4). Indeed, the ratio method detects the same fire episodes as the difference method except for the Bronze Age (3000–4000 cal. BP), however this is the period where CHAR is the highest and could not be considered a fire-free period. We do not only lose information but also gain some doubtful peaks such as the 7550 cal. BP peak which is not obvious in CHAR. This section is the least robust of the age–depth model (two dates) and the SR is the highest of the record (60 yr/cm). It means that the chronological control is too weak to accept it as an undisputable fire episode even if it can be correlated with the early isolated occurrences of Cerealia type pollen (7500 cal. BP; Figure 7).

The ratio method does not work for several reasons. First, peat charcoal records seem to have relatively high variable BCHARs compared with lake charcoal ones (eg, in Carrión *et al*., 2003; Brunelle *et al*., 2005). This may be linked to (1) the lower surface runoff contribution in peatbog compared with lakes, (2) redeposition within lakes (Whitlock and Larsen, 2001) that homogenizes the BCHAR level. As this mechanism is negligible within peat bogs we observe that BCHAR has more abrupt variability within peat records. We assume that the ratio method needs a relatively steady level of BCHAR. If not, the resulting peak component estimation is too coarse to produce a robust IFF estimation. This assumption is supported by the difficulty in selecting an appropriate Tv (Figure 5), especially for the 0–5000 cal. BP window. For this period, there are two breaks in the slope of the cumulative curve. However, even the selection of the highest one as a Tv does not provide a correct frequency estimation of the high CHAR of the Bronze Age (Figure 4). This derives from the fact that the Bronze Age is the period with both highest BCHAR and highest within BCHAR variability. Therefore we tried to model it with a larger time window (500 yr) to minimize this effect. Then, 2 (logratio) and 3 (rawratio) episodes were detected during the Bronze Age against 6 (logdif) and 7 (rawdif). The ratio calculated peak component seems to be inaccurate to perform IFF calculation in our case.

These results suggest that log-transformation is particularly accurate for the anthropogenic palaeofire record as it stabilizes variance and standard error (untransformed series (variance = 3.07, se = 1.57), log-transformed series (variance = 0.05, se = 0.17)). As a result, the potential bias resulting from fire spatial pattern and practice type are reduced. It also minimizes the risk of underestimating fire frequency by eliminating low peaks between higher ones.

Therefore we chose to interpret fire regime/agropastoral activies linkages from the difference LogCHAR series. The comparison with large charcoal fragments (Figure 7) reveals that all fire episodes detected perfectly match large charcoal fragments peaks until *c*. 2000 cal. BP. Fire frequency quantification hence robustly reflects local-scale fire episodes (Clark *et al*., 1998). The looser correspondence at the end of the record suggests that the increasing human impact during the last 2000 years may have occurred at a broader scale.

Fire frequency and fire regime control

Fire regime control is a sensitive topic in a local context of agropastoral decrease accompanied by increase in fuel (colonization by shrubs and bushes), unauthorized agrarian practices of

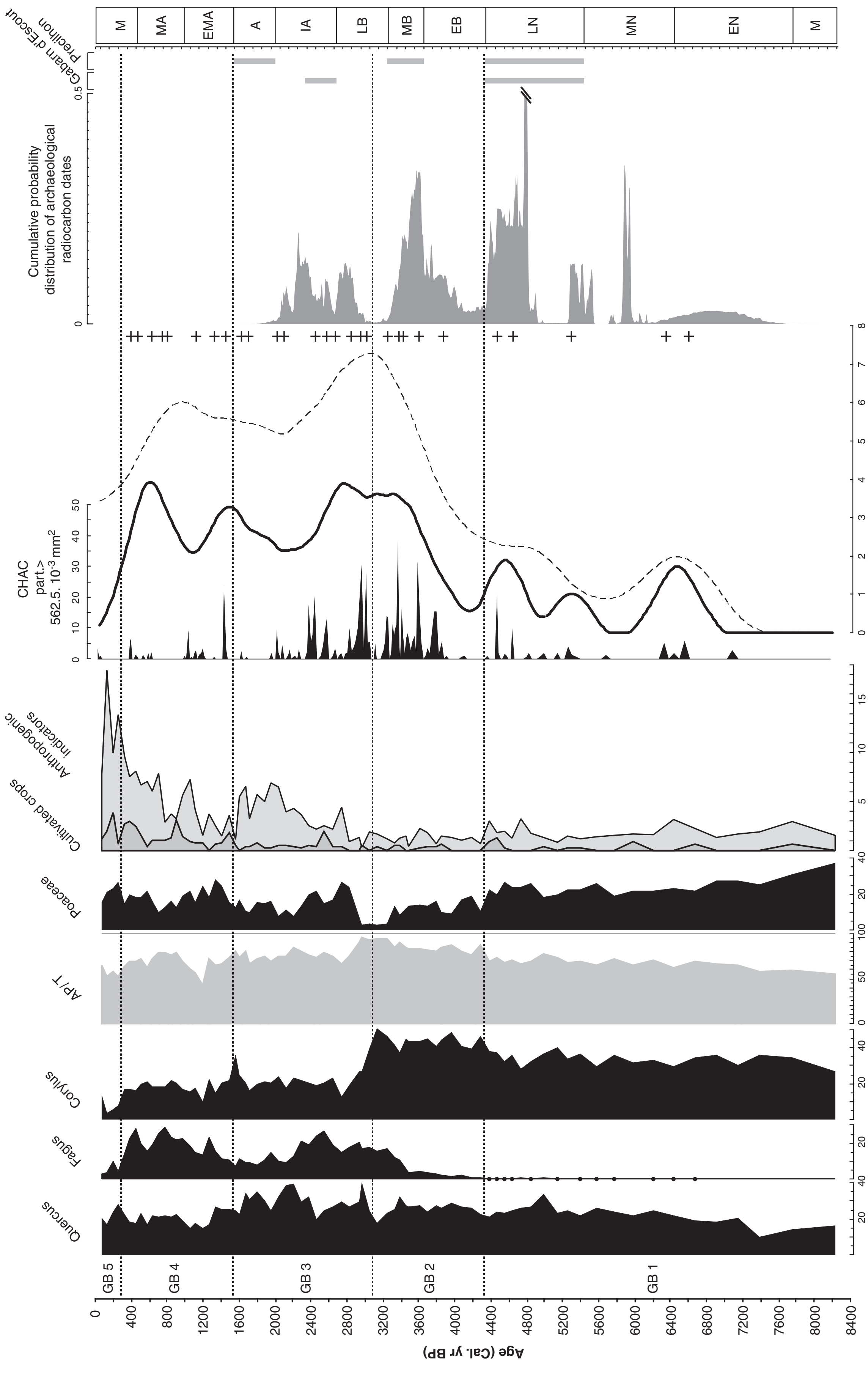

Figure 7 Simplified pollen diagram, charcoal concentration of large charcoal fragments (CHAC), IFF curves (bold line, episodes/500 yr; dashed line, episodes/1000 yr) from the Gabarn peat bog record, and cumulative probability of archaeological radiocarbon dates. Anthropogenic periods are indicated in 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; M, Modern period

burning and in a global context of warming. Fire ignition can be anthropogenically triggered but spread will be partially controlled by climatic conditions (example in Introduction). Fuel loading is controlled by vegetation type (trees, shrubs, herbs) but also by human activities (Stocks and Kaufmann, 1997) because fuel is specifically prepared for burning: biomass consumption and conversion to charcoal could be enhanced by anthropogenic fires (Fearnside *et al*., 2001; Eckmeier *et al*., 2007). Then, although the idea of clearly disentangling anthropogenic from climatic and vegetation controls appears rather elusive and simplistic, we discuss what seems to be the major controlling factor in our case and then the potential linkage with landscape management.

Taking into account forest stand composition through the Holocene with a closed landscape dominated by mixed Atlantic deciduous forest, both IFF maxima (*c*. 5 fires/500 yr, mean= 1.63/500 yr) and MFI (whole record = 230 yr; 400–4000 cal. BP= 158 yr) can be regarded as high for such a temperate ecosystem. Indeed, North American studies showed IFF maximum values ranging from 5 fires/1000 yr in the coniferous forest of the Rocky Mountains (Brunelle *et al*., 2005) to 6 fires/200 yr in the coniferous forest of Vancouver Island (western Canada, Gavin *et al*., 2003). Compared with a closer geographic area, Holocene MFIs are higher in subalpine coniferous forests in the central Swiss Alps (440 and 505 yr, Stähli *et al*., 2006), and lower in Mediterranean climate-driven fire regimes (150 yr, Tuscany, Vannière *et al*., 2008). In the first case, MFI was lowered by increasing human impact from *c*. 2000 cal. BP. In the second case, from *c*. 4000 cal. BP the MFI value is in accordance with those of Mediterranean ecosystems where fire-adapted vegetation and climatic conditions control fire regime, resulting in high frequencies. Such frequency values in an Atlantic context seem too high to be only climate-driven. The shift in fire regime occurring between *c*. 4000 and 3500 cal. BP, which is obvious in FRI values (Figure 6), is synchronous with archaeological evidence of occupation (Figure 7). We assume that increasing demographic pressure led to shortened fire return interval from this point. FRI reaches a threshold which suggests that man becomes the main control factor over the fire regime. This sharp increase in fire frequency at *c*. 4000 cal. BP has also been observed in Mediterranean dry ecosystems, although the triggering factor remains in question (southern Spain, Carrión *et al*., 2003).

The few Pyrenean palaeoclimatic reconstructions were obtained in the Mediterranean Pyrenean range (Jalut *et al*., 2000) or in the Spanish Pyrenees on a short timescale (Buntgen *et al*., 2008). Therefore, it is difficult to discuss the potential local climate control over fire regime. However, compared with the mid-European palaeoclimatic data (eg, Magny, 2004; Mayewski *et al*., 2004), it seems that the correlation between climate and fire (ie, high lake-level phases and low IFF values) is closer during the early Holocene (eg, between *c*. 6500 and 5000 and *c*. 4000 cal. BP) than after the shift in FRI and MFI values (Figure 6). We need further detailed local climate reconstructions to discuss the linkage but this could be another line of evidence for the anthropogenic fire regime shift at *c*. 4000 cal. BP.

Apart from the fire frequency values, there are two other indications of the anthropogenic triggering of fire regime: (1) pollen data do not show major vegetation shifts towards fire-adapted taxa, suggesting there is little evidence of vegetation control over fire regime, (2) the major phases of IFF increase and MFI decrease are correlated with anthropogenic pollen indicators (Figure 7), stressing the potential link between fire and land use.

Fire regime and land use

Agropastoral fires are not selective in terms of slope inclination, exposure, fuel loading and soils in the same way as natural fires are. Therefore, time and space variability may not depend only on climate and vegetation (fuel) but also on agrarian/pasture potentiality and human occupation. Second, we have little idea to what extent agropastoral fire charred particle production differs from that of a natural fire, because fuel differs in nature (wood/shrub/herb), moisture and loading. Unfortunately, comparison between charcoal formation during slash fires and grazing area fires is not available. But we can reasonably assume that combustion of grass would yield less charcoal and smaller charred particles than wood because charcoal morphology and size could reflect burned material (Umbanhowar and McGrath, 1998; Jensen *et al*., 2007).

The Neolithic (GB1) fire regime is characterized by sporadic local-scale fire episodes (CHAC Figure 7) co-occurring with anthropogenic pollen indicators (eg, the isolated fire episodes at *c*. 5300 cal. BP), and low fire frequency variability, oscillating between 0 and 2 fires/500 yr (Figure 7). Fire seems to be restricted to temporary clearances with agropastoral purposes. The close chronological correspondence between fire episodes and *Cerealia* pollen type occurrences suggests that it might be farming linked to shifting cultivation activities. During the first phase of fire frequency increase (6600–6350 cal. BP) the impact on forest cover is probably weak as it is not recorded in the pollen record. Archaeological data during this period are sparse (one radiocarbon date with low probability) and human occupation was probably mobile (Blanc *et al*., 2006), which could explain the weak impact on the forest cover. Then, between *c*. 4650 and 4400 cal. BP, fire clearances on vegetation cover are recorded by simultaneous fire episodes, a decrease of both *Quercus* and *Corylus* and an increase of Poaceae. This corresponds to the first important Neolithic human impact phase at the broad north-Pyrenean scale (Galop, 2006) with fires recorded in the eastern and central Pyrenees (Vannière *et al*., 2001; Galop *et al*., 2002). At the local scale, the nearest studied site (Estarres pollen record) provided a synchronous date of 4310 ± 70 BP (4627–5262 cal. BP at 2σ range; Jalut *et al*., 1988) for the first appearance of *Cerealia*.

The transition between late Neolithic and early Bronze Age is a period of agricultural decrease (beginning of zone GB3), which is also recorded in the whole north Pyrenean piedmont (Carozza and Galop, 2008). CHAR and IFF values clearly match this decrease in human activities. Reduced land-use pressure combined with fire absence leads to regeneration of sprouters (*Corylus* and *Betula*), as emphasized by the immediate increase of their percentages after the last fire (*c*. 4475 cal. BP).

From *c*. 3900 cal. BP, the Bronze Age fire regime is difficult to interpret because of regular but weak agropastoral activities matching increasing fire frequencies (max=7 fires/1000 yr). Previous works (Vannière *et al*., 2001; Galop *et al*., 2002) suggest the Bronze Age is a period of low charcoal accumulation linked with land-use decrease or abandonment during the middle Bronze Age, particularly in sites above 500 m a.s.l. (Galop *et al*., 2007; Carozza and Galop, 2008). Gabarn (300 m a.s.l.) local history confirms this hypothesis. Fire episodes are probably local, as emphasized by high amplitude peaks, high contribution of large charcoal fragments (Figure 7) and archaeological evidence of nearby occupation of sites. The co-occurrences of fire episodes and *Cerealia* pollen type indicate local agricultural clearances. However, the impact on vegetation cover is not recorded until *c*. 3400 cal. BP with *Quercus* decrease and then *Corylus* at *c*. 3200 cal. BP. Since the abandonment of the early Bronze Age, hazel became dominant and regular slash fires could have helped to maintain *Corylus* stands (Tinner *et al*., 2000) and then blurred the local vegetation dynamics.

During the late Bronze Age and Iron Age, fire–vegetation–land use interactions evolve towards a non-linear relationship. Indeed, synchronous evidence of occupations with high fire frequency corresponds to clearances (late Bronze Age, beginning of Middle

Ages) in arboreal taxa (*Quercus*). Increase in API and cultivated crops are immediately posterior as fire frequency decreases. It seems that after the clearance phase, agropastoral activities reach a threshold, from which the role of fire in landscape management changes. A hypothesis would be that decreases in frequency, CHAR and BCHAR stress the shift of fire use as a clearing tool to its use as an agropastoral landscape management tool (stubble and pastoral fire). Such shifts have already been observed in the central Pyrenean piedmont (Galop *et al*., 2002).

The end of the Iron Age and Antiquity (2100–1600 cal. BP, zone GB3) reflects a spatial expansion of anthropogenic activities. After a 350 yr fire-free period, increases in IFF and fire episodes detected are synchronous with API increases (*c*. 2000 and 1500 cal. BP) and *Quercus* clearances. The steady level of *Cerealia* pollen type suggests that this increase in human impact occurred at a larger scale. The low contribution of large fraction to CHAR peaks would confirm this spatial interpretation, but another could be that IFF reflects the increasing need for pastures or meadows: CHAR peaks, BCHAR and frequency may be lower compared with the Bronze/Iron Age transition because fire affects spaces already open to prevent their colonization so that fuel loading is less important. Surprisingly, the Roman foundation of the Iluro villa (Figure 1b) in the middle of the first century AD (Blanc *et al*., 2006) a few kilometres west from Gabarn seems to have no effect on fire frequency as there are no fire episodes detected between 2025 and 1700 cal. BP. This could indicate that Roman colonization was not accompanied by forest clearance because it occured in an already open territory.

During the Middle Ages and Modern times (1600–0 cal. BP) fire regime is characterized by high fire frequencies (3.2 and 3.9 fire episodes/500 yr) but low amplitude peaks and a fire-free period lasting from 1125 to 800 cal. BP. The IFF maxima at *c*. 1500 and 600 cal. BP are correlated respectively with the diversification in cultivated crops (first occurrences of *Secale*) and with the expansion of the husbandry activities phase to its maximum. The sharpest clearance of the record beginning at *c*. 1350 cal. BP does not correlate with detected fire episodes. As the clearance is undisputable we assume that clearances were probably made without burning, ie, remaining wood may be exploited. CHAR and pollen data underline the probable definitive shift of fire use as a management tool because: (1) charcoal peaks of lower amplitudes and with little contribution of large charcoal fragments (Figures 2, 7), which could indicate either non-local fires or low-intensity fires affecting grasses (Jensen *et al*., 2007) in pasture areas, are synchronous with the late Middle Ages increase of non-agricultural anthropogenic pollen indicators, (2) discrepancy between important clearances and fire episodes detected.

Conclusions

Even if a single palaeofire record is not enough to establish the best method to infer anthropogenic fire frequency, our results clearly show that processing charcoal counts to fire frequency (IFF, MFI) and detected fire episodes is an essential step to understand human–fire–vegetation interactions. These fire regime quantifications are very useful to analyse the linkages between fire and human impact intensity and fire within land use. Our main results are as follows.

(1) The MFI for the past 7000 years is *c*. 230 yr, with a threefold decrease at *c*. 4000–3500 cal. BP. This shift is assumed to be linked with increasing anthropogenic control over fire regime.

(2) The relationship between fire frequency and human impact is not always linear. We assume this discrepancy to be linked with fuel loading, and above all with type of land use.

(3) The six main phases of fire frequency increase are at *c*. 6500, 4600, 3350, 2800, 1550 and 600 cal. BP, corresponding to the major phases of human impact recorded in the Pyrenees.

(4) Fire regime significantly differs between early phases of human impact (Neolithic) and more intensive land-use phases (from Iron Age) in terms of frequency, peak amplitude, large fraction contribution, reflecting changes in fire use.

(5) The role of fire in landscape management is linked with agro-pastoral activities throughout the record with decreasing importance during the last 400 years.

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