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Holocene fire regime changes from multiple-site sedimentary charcoal analyses in the Lourdes basin (Pyrenees, France)

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ABSTRACT

One lake and three peat bogs from the Lourdes glacial basin (France) were used for macrocharcoal analyses and fire frequency reconstruction over the entire Holocene (11700 years). The chronology was based upon thirty-three 14C AMS dates. Comparison of the distribution of both CHarcoal Accumulation Rate (CHAR) and fire return intervals showed that charcoal accumulation significantly differs between the lake and the peat bogs, but that frequency calculation overcomes the disparity between these site types. A composite frequency was built from the four individual records to assess regional versus local variability and fire regime controls by comparisons with regional fire activity, Holocene climatic oscillations and vegetation history. The millennial variability can be depicted as follows: relatively high frequency between 8000 and 5000 cal a BP (up to 5 fires/500 yrs), relatively low frequency between 5000 and 3000 cal a BP (down to 0 fires/500 yrs), and an increase between 3000 and 500 cal a BP (up to 4 fires/500 yrs). From 8000 to 5000 cal a BP, fire frequency displays strong synchrony between sites and appears to be mostly driven by increased summer temperature characterizing the Holocene Thermal Maximum (HTM). On the contrary, during the last 3000 years fire frequency was heterogeneous between sites and most probably human-driven. However, higher frequency at the millennial scale during the mid-Holocene strongly suggests that the perception of human-driven fire regime depends on the strength of natural controls.

1. Introduction

Fire is both a natural phenomenon and a human tool, used for example to clear and maintain open agro-pastoral areas since the Early Neolithic at least (Kaland, 1986; Tinner et al., 2005; Colombaroli et al., 2008). It is still used in Europe as a landscape management tool in grazed areas (Buffière et al., 1995; Ribet, 2009). Recent studies from the Alps, the Pyrenees and the Mediterranean area show that millennial variability in Holocene fire regimes is linked to climatic oscillations, particularly for the early to mid-Holocene (11700–5000 cal a BP; Vannière et al., 2011), but also that fire regimes are human-driven during the last 3000–4000 years (Tinner et al., 2005; Rius et al., 2009; Vannière et al., 2010). Thus, it appears difficult to understand human impact on fire regimes without placing it in the context of Holocene climatic and vegetation changes. Quantification of fire frequency from sedimentary macrocharcoal is a relevant method to study human impact on ecosystems throughout the Holocene (Conedera et al., 2009). However, this method is spatio-temporally limited (Olsson et al., 2010) and requires high resolution analysis. A second issue concerns the spatial significance of the results and of multi-proxy data comparison: what is the relevant scale of fire frequency reconstruction?

Theroretical and empirical efforts have been made to quantify charcoal production from biomass burning, both natural and anthropogenic (Fearnside et al., 2001; Eckmeier et al., 2007), and charcoal transport both during a fire (Clark et al., 1998; Pisaric, 2002; Lynch et al., 2004; Tinner et al., 2006; Higuera et al., 2007; Peters and Higuera, 2007) and after a fire (Whitlock and Millspaugh, 1996; Blackford, 2000; Ohlson and Tryterud, 2000). Comparing the results of those studies shows that experimental slash-and-burn for agro-pastoral purposes may produce more charcoal than experimental wildfire due to differences in fire intensity and severity, but there is no data about transport during the agro-pastoral fire experiments.

Experimental and natural wildfire studies show a considerable variability in the distance that macrocharcoal (>150 μm) is

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transported ranging from 80 m or less (Clark et al., 1998; Lynch et al., 2004) to 5 km (Tinner et al., 2006) and even 20 km (Pisaric, 2002). Theoretical work (Higuera et al., 2007; Peters and Higuera, 2007) demonstrated that macrocharcoal analysis is relevant at the local scale, ie 500 m–1 km around the coring site because long-distance transport does not dampen the strong relationship between local fires and their sedimentary macrocharcoal signature. However, those studies were mainly focused on North American boreal forests where natural fire events are potentially severe (crown fires). In any case, those ecosystems were weakly impacted by agricultural activity prior to relatively recent European settlement (Marlon et al., 2008).

The reproducibility of microcharcoal (<30 μm) analyses between mires has already been successfully tested (Innes et al., 2004). Regional, large-scale controlled fire activity deduced from microcharcoal might be consistently recorded at a very fine-scale in some cases. Nonetheless, it is unclear how representative a fire history from a single site is, both spatially and temporally. Multi-site macrocharcoal analysis conducted in an area which exceeds each site's charcoal source area may enable the assessment of whether or not large-scale fire history (mostly controlled by climate and vegetation change) is recorded at the local scale, and if so from which point anthropogenic fire-use blurred such a relationship.

In this paper, we compare charcoal records from three peat bogs and a lake in the Lourdes glacial basin (France). The aim was to examine synchronicity from secular to millennial scales and between-sites variability as a function of site type (peat bog/lake) and size. We also synthesise the inferred fire frequency from the four analyzed records as a composite to assess regional fire activity and local variability. Finally, we discuss the pattern of fire frequency in terms of potential controls.

2. Material and methods

2.1. Study area

The surroundings of Lourdes (43°3′53″ N, 0°02′44″ W) have a complex geomorphologic structure of glacial origin. The "Gave de Pau" glacier originated in the axial part of the Pyrenean range (Fig. 1), 52 km south, and had its terminal basin in the actual location of Lourdes. At its maximum extent (45–50 ka BP, Mardones and Jalut, 1983; Herail et al., 1986; Reille and Andrieu, 1995) it was divided into five glacial branches from the west to the east (Fig. 1): 1) directed westwards the first one is where the actual "Gave de Pau" river course is (ca 350m asl) 2) the second one above, also directed westwards, is occupied by Lake Lourdes and Lourdes peatbog at its western shore, 3) the third glacial tongue was oriented northwest and is occupied by the palaeolake of "Biscaye", whose peaty valley is now colonized by deciduous forest, 4) the fourth one was headed northeast and was partly filled by the palaeolake of "le Monge" whose peat bog is now covered by a commercial zone, 5) and the last one was headed eastwards.

Three of the coring sites are located in piedmont glacial depressions: Biscaye peat bog, Lake Lourdes, and Lourdes peat bog, but the depression of Lake Lourdes and peat bog is perched in a small catchment. The fourth one is another peat bog of glacial origin: the "col d'Ech" peat bog (710m asl) which is located south above Lake Lourdes. The three peat bogs are raised, ombrotrophic bogs where charcoal input is mainly atmospheric (Clark and Patterson, 1997) with no fire related sedimentation as reported by Buckman et al. (2009). The main characteristics of the sites and distance between coring points are indicated in Table 1.

The Lourdes basin is at the limit of the western and central Pyrenees under temperate oceanic influence: mean annual precipitation of 1200 mm with maxima during Autumn and Spring, mean annual temperature is 12.5 °C (Mean summer T° = 19 and Mean winter T° = 6 °C, 1931–2006, MeteoFrance Data). Regional vegetation consists of Atlantic-type oak forest mainly dominated by *Quercus* (*Q. robur and Q. pyrenaica*) with *Corylus* and *Betula*. The north-facing slopes (below 900m) are covered by a mixed beech–oak forest, which is the dominant vegetation type of the bioclimatic stage in the area. The col d'Ech peat bog has slightly different environmental settings that the three other sites : it is located under a 900m high south-facing calcareous slope. The strong shelter effect from this slope results in the presence of *Q. pubescens* and some *Buxus sempervirens* stands.

In the contemporary environment, there are two fire seasons in the central Pyrenees. The main one in extent (January, February, March) and number of occurrences, is winter, during which fires are linked to pasture management. The second one is summer (July, August) and features both anthropogenic and natural (lightning) fires (Préfecture des Hautes-Pyrénées, 2007).

2.2. Coring, sedimentology and chronology

The three peat bog cores were mechanically taken (APAGEO device) with a Russian peat sampler (GIK type, 100 cm long, 10 cm in diameter) which avoided sediments compaction. Lake Lourdes was cored with an Uwitec platform with a 3m long and 6.3 cm in diameter piston corer.

The chronology for this study was derived from thirty-three 14C AMS radiocarbon dates (Table 2). For the peat records, bulk sediments were dated after removing rootlets, because the high organic content enabled us to do so without reservoir effect (Blaauw et al., 2004). Charcoal was dated for the lacustrine record in order to avoid hard-water effect. Calibration to year cal. BP was made using CALIB software (Stuiver and Reimer, 1993) version 6.1.0., based on the data set IntCal09 (Reimer et al., 2009). Dates are expressed as intercepts with 2σ range (Table 2). To predict ages along the entire profile, we used mixed-effect modeling according to the procedure standardized by Heegaard et al. (2005), except for Lourdes peat bog because of too few dates ($n = 5$). Indeed, the mixed-effect-model encompassed only three of five radiocarbon dates (calibration ranges at 2σ). We then used a cubic spline with the most linear interpolation possible that best fitted the calibration ranges. We estimated the 95% confidence interval following a similar procedure to the other depth-age models (Heegaard et al., 2005). One date was rejected (in italic in Table 2) in Lake Lourdes. The measure was not robust because of low carbon content in the dated sample and it yields an inverted date with regard to its stratigraphic position (Table 2).

2.3. Macroscopic charcoal analysis

Contiguous samples of 2.6 cm^3 were retrieved with a needleless syringe at every cm of the core, soaked in a 10% NaOH solution during 24 h for peat disaggregation, then in a 6% H_2O_2 solution during the same time to bleach non-charcoal organic material and thus make charcoal identification easier (Rhodes, 1998). As we aimed to reconstruct local fire history, charred particle were isolated using wet sieving (Carcaillet et al., 2001; Whitlock and Larsen, 2001) with a 150 μm mesh size (Clark, 1988; Ohlson and Tryterud, 2000). Charcoal identification was restricted to the criteria usually defined in literature (Umbanhowar and McGrath, 1998; Enache and Cumming, 2006). Both charcoal particles 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 10^{-3} mm^2 each. Ten increasing size classes were defined (31.25–62.5, 62.5–125, …, 187.5–250 10–3 mm^2, …). Charcoal concentration (mm^2 cm^{-3}) was