Spatial Variability of Fire History in Subalpine Forests: From Natural to Cultural Regimes

Author(s): Christopher Carcaillet, Adam A. Ali, Olivier Blarquez & Aurélie Genries, Brice Mourier, Laurent Bremond

Source: Ecoscience, 16(1):1-12. 2009.
Published By: Centre d'etudes nordique, Universite Laval
DOI: http://dx.doi.org/10.2980/16-1-3189
URL: http://www.bioone.org/doi/full/10.2980/16-1-3189

ÉCOSCIENCE
16 (1): 1-12 (2009)

Spatial variability of fire history in subalpine forests: From natural to cultural regimes[1]

Christopher CARCAILLET[2], Adam A. ALI, Olivier BLARQUEZ & Aurélie GENRIES,
Centre de Bio-Archéologie et d'Écologie (UMR5059 CNRS), Université Montpellier 2 and Paléoenvironnements et Chronoécologie (PALECO EPHE), Institut de Botanique, 163 rue Broussonet,
F-34090 Montpellier, France, e-mail: Christopher.carcaillet@univ-montp2.fr
Brice MOURIER, Centre de Bio-Archéologie et d'Écologie (UMR5059 CNRS), Université Montpellier 2, Institut de Botanique, 163 rue Broussonet, F-34090 Montpellier, France, and
Laboratoire CARRTEL (UMR 42), Université de Savoie, 73376 Le Bourget du Lac, France.
Laurent BREMOND, Centre de Bio-Archéologie et d'Écologie (UMR5059 CNRS),
Université Montpellier 2, Institut de Botanique, 163 rue Broussonet,
F-34090 Montpellier, France, and Paléoenvironnements et
Chronoécologie (PALECO EPHE), Institut de Botanique,
163 rue Broussonet, F-34090 Montpellier, France.

Abstract: The goal of this study was to determine the effect of local and large-scale processes on fire frequency during the postglacial period in a subalpine ecosystem (Alps, France). Large-scale processes should produce homogeneous distribution of fire-free intervals and synchronicity of fire series, and dominance of local-scale processes, such as those triggered by differences in relief, slope aspect, human history, etc. should create heterogeneous fire regimes. Four ponds and peat were sampled at different elevations and exposures. Sedimentary charcoal was used as a fire proxy, and plant macroremains were used as a vegetation proxy. Synchronicity analysis was based on a transformed Ripley's *K*-function. Similar fire-free intervals during the early Holocene suggest that fire regimes were controlled at that time by large-scale natural processes such as climate and vegetation patterns and establishment. No fire was reconstructed before 9000 y cal BP. Infrequent fires occurred following establishment of the subalpine bio-climate belt. However, local-scale processes have dominated the pattern of fire intervals during the late Holocene, with more fires at lower elevation and on south-facing slopes. Although altitude, topography, and slope aspect certainly drove between-site differences during the early Holocene, these differences disappeared during the late Holocene, when fire frequency was related not to ecological features of the natural landscape but likely to human population density and activities, *e.g.*, need for pastures (woody fuel suppression). Fires were certainly controlled at first by climate and vegetation (*Pinus cembra*), but human practices have affected the fire regime for centuries. A new fire epoch might result from both the current global warming and on-going land-use abandonment, which has led to a significant fuel build-up in the Alps.

Keywords: cembra pine, disturbance, fire, forest, Holocene, mountain, paleoecology.

Résumé : Cette étude a pour objectif de déterminer le rôle des processus à petite et grande échelles sur la fréquence des feux durant le Postglaciaire dans un écosystème subalpin (Alpes, France). Nous postulons que les processus à grande échelle produisent une distribution homogène des intervalles entre les feux et une synchronisation des séries de feux, alors que les processus plus locaux (petite échelle), comme ceux qui sont induits par les différences de relief, d'exposition de versant, d'histoire sociétale, devraient créer des régimes de feux très hétérogènes entre les sites. Quatre dépressions lacustres et tourbières ont été échantillonnées à différentes altitudes et expositions. Les charbons sédimentaires ont été utilisés comme indicateurs de feux et les macrorestes végétaux comme indicateurs de la végétation locale. Les analyses de synchronisation ont été basées sur la fonction *K* transformée de Ripley. Durant l'Holocène, des intervalles de feux similaires suggèrent que les régimes étaient régis par des processus naturels à grande échelle comme ceux qui sont générés par le climat, la mise en place et la structure de la végétation. Aucun feu n'a été reconstruit avant 9000 ans cal BP, par la suite, des feux peu fréquents ont eu lieu lorsque le bioclimat de l'étage subalpin s'est établi. Cependant, les processus locaux ont dominé le patron des intervalles de feux durant la fin de l'Holocène, se manifestant par une plus grande fréquence de feux à basse altitude sur les versants sud. Bien que l'altitude, la topographie et l'exposition des versants ont certainement déterminé les différences entre les sites durant l'Holocène, ces différences se sont estompées à la fin de l'Holocène favorisant des chronologies de feux sans liens avec les paramètres écologiques du paysage naturel, mais probablement liées aux activités humaines et à la densité des populations nécessitant des pâturages (suppression du combustible). Les feux étaient certainement d'abord sous le contrôle du climat et de la végétation (*Pinus cembra*), mais les sociétés ont un effet sur la disponibilité du combustible, et par leurs pratiques, elles ont influencé le régime des feux durant des siècles. Une nouvelle ère d'incendies pourrait résulter à la fois du changement climatique planétaire en cours et de la poursuite de l'abandon des terres provoquant un fort accroissement de combustible dans les Alpes.

Mots-clés : feu, forêt, Holocène, montagne, paléoécologie, perturbation, pin cembra.

Nomenclature: Tutin *et al.*, 1968–1993.

---

[1] Rec. 2008-03-25; acc. 2008-09-15.
Associate Editor: Renzo Motta.

[2] Author for correspondence.

DOI 10.2980/16-1-3189

Introduction

The global warming currently underway is expected to change the spatial pattern of precipitation distribution and occurrence of drought events on the earth surface (IPCC, 2007). Fire regimes are also expected to be modified, with changes in fire area (Flannigan *et al.*, 2005; Tymstra *et al.*, 2007) or frequency (Flannigan *et al.*, 1998; Pausas, 2004; Schumacher & Bugmann, 2006). Because the relationships between plant cover and fire regimes are strong in many world ecosystems, controlling biodiversity, landscape structure, or biomass distribution (Bond, Woodward & Midgley, 2005), knowledge of the natural range of the fire regime is an important issue for land and natural resource managers (Bergeron *et al.*, 2006; Gavin *et al.*, 2007). European mountain regions are affected by large-scale processes resulting from land-use abandonment, with important consequences for fuel build-up and forest connectivity at the landscape scale (Walther, 1986; Motta, Morales & Nola, 2006; Chauchard, Carcaillet & Guibal, 2007; Gerlich *et al.*, 2007). These ecological changes, which are associated with an increase in the length of the summer dry spell in southern and central Europe in response to global warming (Pal, Giorgi & Bi, 2004), are likely to alter fire risk and fire patterns in the region (Pausas 2004; Schumacher & Bugmann, 2006). The natural range of fire regimes in the Alps is unknown due to centuries of vegetation suppression and intensive land-use that prevented wildfires while utilizing human fires for heathland clearing. However, paleoecological studies have demonstrated that fires have occurred in the Alps during the last millennia (Tinner *et al.*, 1999; Ali *et al.*, 2005a; Stähli *et al.*, 2006; Hajdas *et al.*, 2007) and as far back as the Lateglacial period (Ali *et al.*, 2006). Nonetheless, no quantified fire regimes have been proposed to date, despite the need for parameterized data to support future land management decisions, such as prescribed burning to manage biomass or biodiversity (Narayan, 2007). Furthermore, the processes that trigger fire occurrence remain to be elucidated. To date, the sole debate in paleofire ecology in Europe has concerned the relative contributions of climate, a black box of natural factors, and human practices, a black box of cultural factors, in controlling fire occurence (*e.g.*, Carcaillet, 1998; Pitkänen & Huttunen, 1999; Tinner *et al.*, 2005), which is a much too limited and simplistic approach to the issue. There are many other factors among the natural causes of changes in fire regimes, including the structure and quality of vegetation (Brown *et al.*, 2005; Higuera *et al.*, 2008) and the landscape pattern in terms of relief, fragmentation, and elevation (Gavin *et al.*, 2006). In addition, the synergy between cultural and natural fires is complex (Marlon *et al.*, 2008). Further investigation is thus needed to determine how climate, biomass, relief, and society have driven the fire regime.

The present study aims to reconstruct the variability of fire frequency and fire patterns within a mountain valley based on temporal high-resolution sedimentary charcoal analyses (Long *et al.*, 1998; Carcaillet *et al.*, 2001a). The fire frequency reconstruction will be completed using a Ripley *K*-function to estimate the degree to which fire events have been synchronous, indicating that large-scale processes have been acting on the fire regime. A lack of synchronicity among fire series would indicate that local-scale mechanisms such as vegetation diversity and structure, relief, and soil variability (Gavin *et al.*, 2006) or different land-use practices and history (Carcaillet, 1998) have played a greater role in determining the fire regime.

Methods

STUDY SITES AND EXPERIMENTAL DESIGN

The 4 sites, Plan Bouchet, Lac du Lait, Lac du Thyl, and Lac du Loup, are situated in the same valley in the northern French Alps (Savoie; Figure 1; Appendix I). Plan Bouchet, the highest of the sites (2405 m asl), and the nearby Lac du Thyl (2038 m asl) are both located on the south-facing slope of Mount Brequin, whereas Lac du Loup is situated on the opposite slope (2032 m asl). Lac du Lait is located 25 km eastward (2180 m asl). Plan Bouchet is a peat fen, while the other sites are ponds. The ponds and fen were chosen because of their small size (< 1 ha) and restricted catchment areas (a few ha), features that were essential to ensure that charred particles in their sediments mainly originated from local fires (Millspaugh & Whitlock, 1995).

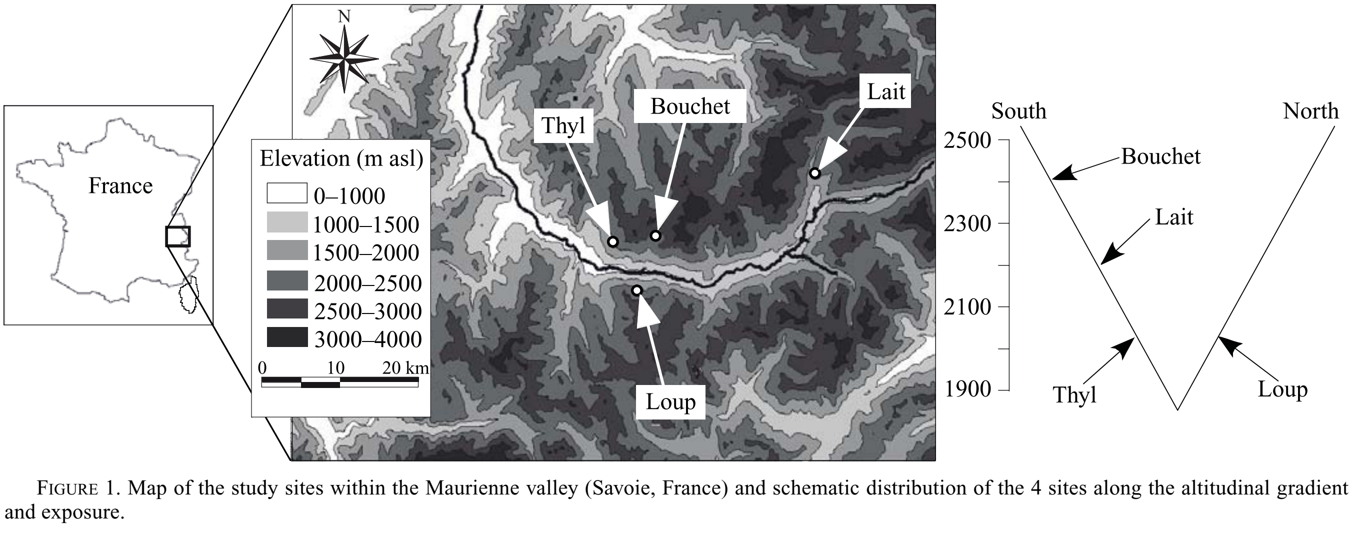

FIGURE 1. Map of the study sites within the Maurienne valley (Savoie, France) and schematic distribution of the 4 sites along the altitudinal gradient and exposure.

They are all located in the subalpine belt, although their present-day plant covers differ greatly: open mixed larch/cembra pine forest with ericaceous understorey for Lac du Loup and old grasslands for the 3 others.

Vegetation and soil are established on till, moraines, and periglacial landforms derived from Carboniferous parent material except at Lac du Lait, where they are derived from Permian micaschist. The subalpine grasslands are highly diversified but dominated by *Carex sempervirens, Carex curvulea*, and *Festuca rubra*. Owing to the decrease in pastoral activities in the last *ca.* 100 y (Delcros, 1994; Didier, 2001), patches of *Vaccinium ulliginosum*, *V. myrtillus,* and *Rhododendron ferrugineum* are expanding at all sites. The subalpine coniferous forests are dominated by *Pinus cembra* and *Larix decidua*, with scattered *Pinus uncinata*, *Picea abies*, and *Abies alba*. The forest understorey is characterized by *Vaccinium vitis-idaea* and *Juniperus sibirica* (south-facing slopes) and *V. uliginosum*, *V. myrtillus*, and *Rhododendron ferrugineum* (north-facing slopes). Under old-growth coniferous forests, soils are podzol-type, and under old-growth grasslands, they are cambisol-type (Mourier *et al.*, 2008).

SAMPLING

The cores were collected from the deepest part of the ponds when possible using a Russian corer (1000 × 75 mm). Since a Russian corer cannot collect the more recently accumulated material, the water–sediment interfaces were sampled using a Kajak–Brinkhurst gravity corer (Lac du Loup, Lac du Lait) or by peat-surface sampling using a saw.

DATING AND AGE/DEPTH MODEL

When possible, only terrestrial plant remains were dated. Samples were processed by AMS in ^{14}C laboratories in Saclay, France (SacA-), Poznan, Poland (Poz-), Tucson, Arizona (AA-), and Miami, Florida (Beta-). The ^{14}C dates were calibrated against dendrochronological years using the CALIB program (Stuiver & Reimer, 1993), version 5.1β, based on the IntCal04 dataset (Reimer *et al.*, 2004), and reported as intercept with 2 sigma and a probability range of $P = 1.0$. Calibrated years before present are labelled "cal BP" (Appendix II). For practical reasons, the chronologies are expressed in years before AD 2000, in the figures only. Dates used for the computation of the age/depth models were calculated using smooth distributions, based on the median probability age. The age/depth models are already published (Genries *et al.*, 2009a,b; Blarquez *et al.*, in press).

CHARCOAL ANALYSIS

For charcoal quantification, 1 cm^3 was extracted by sediment sieving (Carcaillet *et al.*, 2001b) every 0.5 cm (Plan Bouchet, Lac du Loup) or 1 cm (Lac du Thyl, Lac du Lait). In total, 330, 345, 495, and 489 samples were examined from the cores of Plan Bouchet, Lac du Lait, Lac du Thyl, and Lac du Loup, respectively. The samples were soaked in a 3% NaP_2O_4 solution for a minimum of 2 d to deflocculate any particles, then sieved through a 160-µm mesh. Particles larger than 160 µm were assumed to be of stand or local origin (Higuera *et al.*, 2007). A gentle manual water spray was used to aid the sieving process. The remaining particles were bleached in a 10% water solution of sodium hypochlorite (NaOCl) for as long as necessary (a few seconds to a few minutes) to distinguish charcoal from dark organic matter. The area of each charcoal fragment was estimated under a dissecting microscope at 40× magnification using an ocular grid with 100 squares, each of 0.0625 mm^2 (Carcaillet *et al.*, 2007). Fragments were then classified in size classes, which increased exponentially. We assumed that charcoal area would be a better proxy than fragment numbers because it is a more reliable estimator of charcoal volume or mass (Weng, 2005), which is a biomass burning proxy. The total surface area of charcoal in each sample was calculated by determining the median surface area of each size class and multiplying it by the number of particles in that class. Charcoal measurements are reported as charcoal area concentration ($mm^2 \cdot cm^{-3}$). The age/depth model derived from radiocarbon dating was applied to the charcoal series to estimate the charcoal accumulation rate (CHAR, $mm^2 \cdot cm^{-2} \cdot y^{-1}$), from which the fire reconstruction was obtained.

FIRE EVENT RECONSTRUCTIONS

Fire events were identified by breaking down the CHAR series into CHAR background and CHAR peak components using a tricube function with a time window of 1000 y (CHARSTER, version 0.8.3, unpubl. software, ©Dan G. Gavin 2005, University of Oregon). The CHAR peak component was obtained by subtracting the CHAR background from the CHAR series. The CHAR background represents variations in overall charcoal production, sedimentation, mixing, and sampling. Local fire episodes were inferred from the CHAR peak according to a given threshold, enabling us to split peaks into "fire" or "non-fire" (Higuera *et al.*, 2007). Each peak above the threshold was considered to be a local fire episode. To remove biases caused by sedimentation rate changes over the length of the cores, the CHAR peaks were first converted into 20-y equal time intervals corresponding to the mean deposition time per centimetre for the 4 lakes (Appendix I). To determine the optimal threshold we modeled the frequency distribution of CHAR peak as a zero mean-Gaussian distribution. The 95th percentile value of the fitting distribution was used to determine a range of threshold values. A sensitivity analysis was carried out to select the final threshold, chosen as the CHAR peak where fire-free interval distribution was least sensitive to changes in the threshold itself. Fire-free interval corresponds to the number of years between 2 adjacent fire episodes. The fire number per 1000 y was smoothed using a LOWESS to characterize fire frequency.

To assess fire synchronicity between the sites at centennial to millennial scale, we used the bivariate Ripley's *K*-function modified for 1 dimension, *i.e.*, time, where each site is a class (Gavin *et al.*, 2006). The *K*-function was transformed to an *L*-function to facilitate the interpretation of results. This process stabilizes the means and variances of the *K*-value outputs. Confidence envelopes of 95 and 99% were defined for the $L(t)$-values by randomizing 1000 fire events. $L(t)$-values > 0 suggest comparable patterns in fire occurrence among sites, while values near 0 and < 0 indicate independence and asynchrony among sites, respectively. All analyses were performed with KD1 software (unpubl. software ©Dan G. Gavin 2005, University of Oregon). The distribution of fire-free intervals per site was compared using a nonparametric Kruskal–Wallis test (KW test) for fire series > 2, and the median intervals were compared with a Kolmogorov–Smirnov test (KS test) for pairs of fire series.

Results

Post-glacial, organic-rich sediments began to accumulate *ca.* 13 000 cal BP in Plan Bouchet, *ca.* 14 600 cal BP in Lac du Lait, *ca.* 9000 cal BP in Lac du Thyl (no clay), and *ca.* 9500 cal BP in Lac du Loup. The age/depth models provide the following deposition time (median ± SE): 45.1 ± 6.7 $y \cdot cm^{-1}$ at Plan Bouchet, 51.2 ± 5.4 $y \cdot cm^{-1}$ at Lac du Lait, 9.4 ± 0.5 $y \cdot cm^{-1}$ at Lac du Thyl, and 45.9 ± 1.2 $y \cdot cm^{-1}$ at Lac du Loup (Appendix I).

FIRE HISTORY AND TEMPORAL VARIABILITY

Charcoal was found throughout the length of the core samples of all 4 sites, from the bottom to the topmost centimetres. Between 15 000 cal BP and 9000 cal BP, *i.e.*, from the Lateglacial until the early Holocene, the charcoal accumulation rate (CHAR) was very low (Figure 2). Since 9000 cal BP, the CHAR has increased abruptly or progressively depending on site (Figure 2). The CHAR remained elevated throughout the rest of the Holocene in the 4 series, but values varied tremendously, showing clear peaks more or less frequent according to periods and sites. The Plan Bouchet CHAR series remained low until *ca.* 3000 cal BP (Figure 2a). The Lac du Lait series rose both in terms of raw values and background until *ca.* 2000 cal BP and dropped abruptly afterward (Figure 2b). The Lac du Thyl values were high immediately after 9000 cal BP but then experienced a progressive decrease until 5900 cal BP. No charcoal was observed between 5900 and 3900 cal BP. The CHAR remained low, with 2 peaks between the end of the sedimentological hiatus recorded from 3900 to 1700 cal BP and the present (Figure 2c). The Lac du Loup values were generally low, except between 7000 and 5000 cal BP (Figure 2d), when background and peak magnitude and frequency were higher.

At Plan Bouchet 15 fires were reconstructed (Table I). Most of them occured between 2810 and 110 cal BP. Only 1 was determined to have happened during the early Holocene, at 8290 cal BP (Figure 2a). The largest number of fires was recorded at Lac du Lait, with 25 events between 8810 and 1310 cal BP (Table I). Two periods of fire-free intervals appear: the first between 8810 and 4950 (median: 280 y; mean ± SE: 429 ± 162 y) and the second between 4090 and 1310 cal BP (median: 230 y; mean ± SE: 313 ± 85 y). However, the early and late Holocene median fire-free distributions are not distinguishable (Table I). No fire event more recent than 1310 cal BP was detected, and the site is currently tree-less, dominated by a grass ecosystem (Figure 3s). At Lac du Thyl the fire chronology covers several periods: the first between 9000 and 6650 cal BP, with 13 fire events, and the second after 5830 cal BP, with only 2 fires, one at 990 and the other at 170 cal BP. This chronology is partly the result of a sedimentological hiatus (3900–1700 cal BP). However, no fires were detected during the 1900 y that preceded the hiatus, and the CHAR was very low, generally showing null values (Figure 2c). At Lac du Loup, the fire history shows 14 events between 7650 and 2150 cal BP. The highest concentration of fires is between 6550 and 5650 cal BP (8 events). There have been no fires since 2150 cal BP; during the same period, the herb accumulation rate increased and tree remains decreased, mainly dominated by *Larix decidua* (Figure 3i). Comparison of the fire-interval distributions before and after 4500 cal BP for Lac du Thyl and Lac du Loup indicates that the 2 sites experienced very different fire regimes triggered by different processes during the first and second parts of the Holocene (Table I; Wilcoxon test, $P < 0.05$).

SPATIAL VARIABILITY

The distribution structure of fire-free intervals is not significantly different among sites over the Holocene, *i.e.*, 9000–0 cal BP (Table II; KW test; $0.25 < P < 0.52$). This indicates that the median fire-free interval, ranging between 180 and 270 y (Table I), is rather homogeneous regardless of site characteristics and differences. However, the temporal patterns of fire events differ among sites at the millennial scale (Figure 3). From 9000 to 4500 cal BP, the distribution of fire intervals does not differ among the 3 sites (Table II; Plan Bouchet excluded because of only 1 fire), although Lac du Lait and Lac du Thyl are distinguishable (Table III). After 4500 cal BP, the fire-interval distributions differ greatly (Table II; KW test, $P < 0.05$). A sensitivity test shows that these significances are robust, except if the Lac du Loup series is excluded (Table II). This principally results from the indistinguishable fire-interval distributions between Lac du Loup and Lac du Thyl at 4500–0 cal BP (Table III).

The bivariate K-function shows that fires are independent between sites whether the period of comparison is 9000–0 cal BP, 9000–4500 cal BP, or 4500–0 cal BP (Figure 4). The only sites that show a synchrony of fire patterns are Lac du Lait and Lac du Loup, where significant P-values are reported for a short window of 600 y and a large window of 800–1600 y between 4500 and 9000 cal BP (P-values = 0.05; Figure 4f) and a window of 1700 y between 4500 and 0 cal BP (P-values = 0.05; Figure 4i). However, these synchronicities disappear with P-values of 0.01, suggesting a limited robustness of these observations (Figure 4f,i).

FIRE FREQUENCY AND VEGETATION PROXIES

Plant macroremains analysis was not possible on sediments of Plan Bouchet, because of their extremely dense composition, rich in Hypnaceae bryophytes and, above all, Cyperaceae roots and remains. The 3 other sites provide an abundance of tree remains of different taxa, depending on sites and Holocene periods. Plant macroremains accumulation rates are summed up in Figure 3 and compared with fire frequency, reconstructed and expressed in terms of $fires \cdot 1000\ y^{-1}$.

Lac du Lait began to accumulate terrestrial plant remains during the Lateglacial, *ca.* 15 000 cal BP, with Poaceae and Cyperaceae (data not shown). The first occurrence of woody taxa dates back to 14 660 cal BP with *Betula* seeds and catkin scales (Figure 3j). *Pinus cembra*

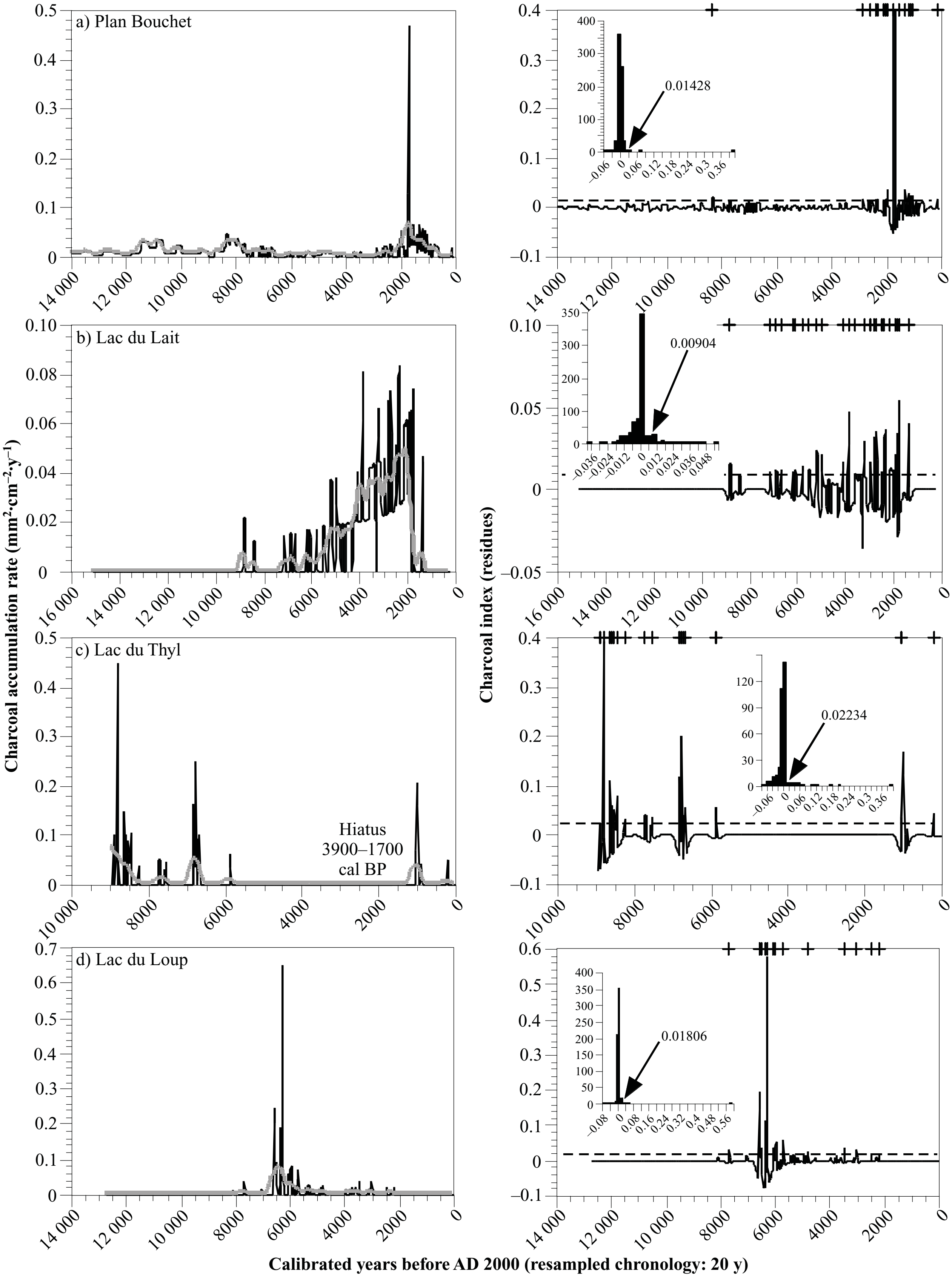

FIGURE 2. Reconstruction of fires based on the charcoal series (left, black curve) detrended from their background computed with a tricube function (left, grey curve). The fire event (+) results from charcoal peaks were significantly distinct from the detrended charcoal series (right). In inset, the frequency distribution of residuals: the arrow indicates the threshold value used to detect the fire events based on the 95th percentile value of the fitting distribution.

was the main conifer that accumulated remains (needles, male cone scales, etc.) through the Holocene. The first occurrences of *P. cembra* are at 10 180 cal BP (Figure 3d). A few needles of *Abies alba* and *Larix decidua* are observed after 5000 and 3500 cal BP, respectively, but at no time were they abundant (Figure 3g,p). The *Pinus cembra* remains disappeared 1000 y ago, after 2000 y of progressive decrease (Figure 3d). Cyperaceae and other non-aquatic grass species replaced the woody taxa 1000 y ago (Figure 3s). Fire frequency increased *ca*. 8000 cal BP and fluctuated between 2 and 4 fires·1000 y^{-1} between 7000 and 2000 cal BP, *i.e.*, during the period of greatest accumulation of *Pinus cembra* remains. The drop in fire frequency from about 4 fires·1000 y^{-1} *ca*. 2000 cal BP to 0 fire·1000 y^{-1} during the last millennium is synchronous with the development of subalpine grassland (Figure 3a).

Lac du Thyl experienced its highest fire frequency during the centuries following sediment inception, *i.e.*, from 9000 to 6000 cal BP, with 2 to 8 fires·1000 y^{-1}. Afterward, the frequency dropped until the last millennium, in which 1 fire·1000 y^{-1} was recorded (Figure 3b). This high fire frequency covers 2 types of plant assemblages, the first

TABLE I. Statistics of fire intervals. The interval between the sediment inception and the first fire event is not taken into account. The comparison of the 2 fire chronologies per site (*i.e.*, 9000–4500 *versus* 4500–0 cal BP) is based on Wilcoxon test. Asterisk (*) indicates significant *P*-values.

	9000–0 cal BP			9000–4500 cal BP			4500–0 cal BP			Test
	Median	Mean ± SD	*n*	Median	Mean ± SD	*n*	Median	Mean ± SD	*n*	*P*
Plan Bouchet	200	556 ± 1377	15	—	—	—	200	556 ± 1377	15	—
Lac du Lait	240	354 ± 392	25	280	429 ± 487	9	230	313 ± 339	16	0.27
Lac du Thyl	180	393 ± 497	17	100	234 ± 274	13	730	910 ± 744	4	0.02*
Lac du Loup	270	550 ± 630	14	180	322 ± 396	9	540	960 ± 805	5	0.03*

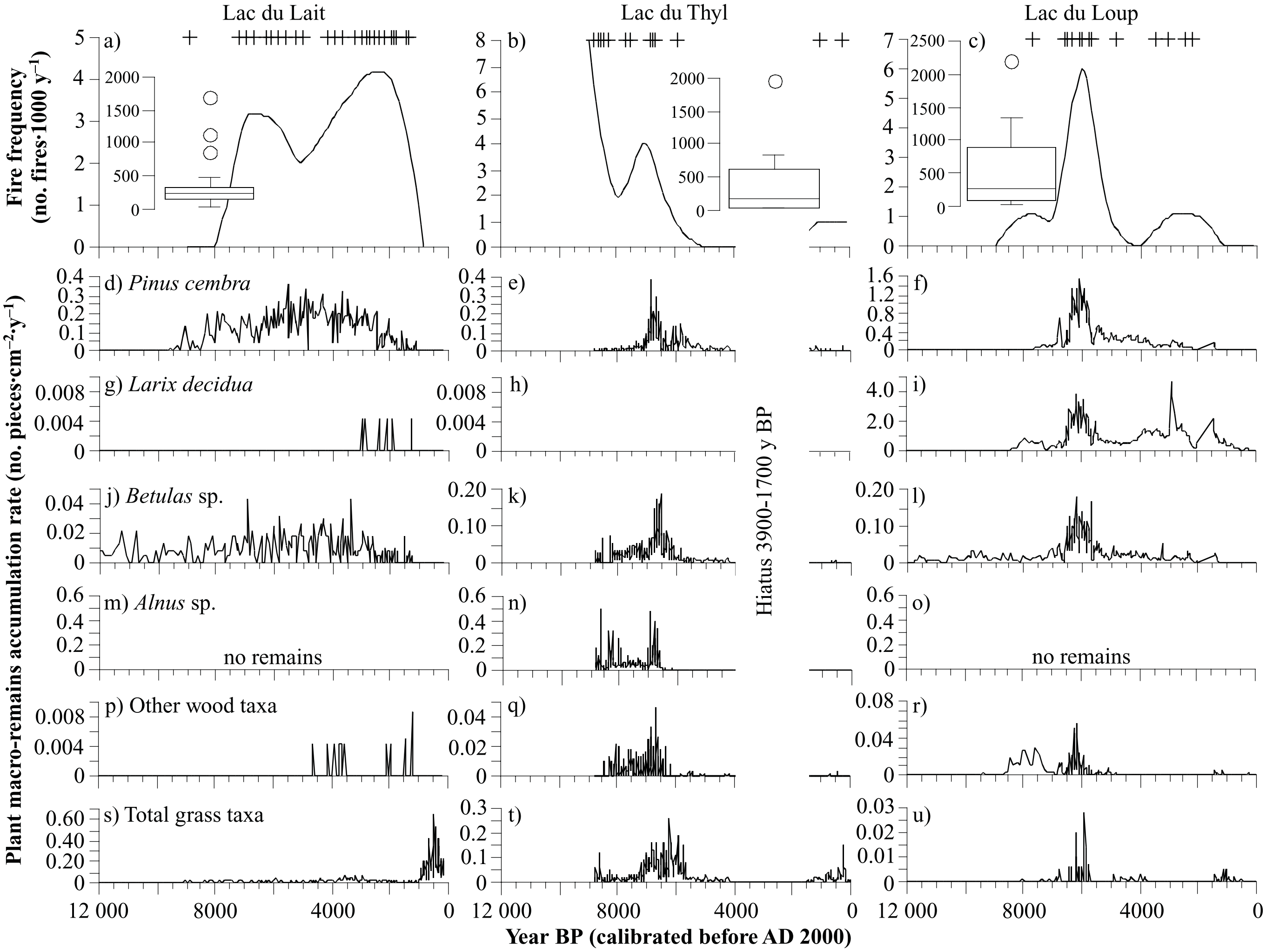

FIGURE 3. Fire series (+), fire frequency, and distribution of fire-free intervals (box-plot in inset) for Lac du Lait (a), Lac du Thyl (b), and Lac du Loup (c), compared to vegetation proxies (total plant macroremains): *Pinus cembra* (d,e,f), *Larix decidua* (g,h,i), *Betula* sp. (j,k,l), *Alnus* sp. (m,n,o), other woody taxa (p,q,r), and grass taxa (s,t,u).

TABLE II. Sensitivity test (Kruskall–Wallis test *P*-values) to estimate the robustness of among-sites comparison of fire-intervals. The interval between the sediment inception and the first fire event is not taken into account. Asterisk (*) indicates significant *P*-values. (Bo = Plan Bouchet; La = Lac du Lait; Th = Lac du Thyl; Lo = Lac du Loup).

	9000–0 cal BP	9000–4500 cal BP	4500–0 cal BP
Bo × La × Th × Lo	0.40	—	0.01*
Bo × La × Th	0.30	—	0.08
Bo × La × Lo	0.25	—	0.02*
Bo × Th × Lo	0.47	—	0.01*
La × Th × Lo	0.52	0.09	0.02*

TABLE III. Kolmogorov–Smirnov test *P*-values of paired-site comparisons of fire-free intervals distribution. The interval between the sediment inception and the first fire event is not taken into account. Asterisk (*) indicates significant *P*-values. (Bo = Plan Bouchet; La = Lac du Lait; Th = Lac du Thyl; Lo = Lac du Loup).

Sites	9000–0 cal BP	9000–4500 cal BP	4500–0 cal BP
Bo × La	—	—	0.50
Bo × Th	—	—	0.06*
Bo × Lo	—	—	< 0.01*
La × Th	0.29	0.03*	0.10
La × Lo	0.39	0.29	0.04*
Th × Lo	0.41	0.82	0.87

dominated by *Betula* and *Alnus* remains (seeds, catkin scales, strobiles) from 9000 to 7000 cal BP (Figure 3k,n) and the second, from 7000 to 5700 cal BP, with *Pinus cembra*, *Betula*, and *Alnus* (Figure 3e). The concentrations of other woody (*Vaccinium*, *Sorbus*, *Abies*, *Sambucus*, etc.) and grass taxa (Cyperaceae, *Potentilla*, etc.), which are elevated in this site, peaked during the period of high fire frequency from *ca*. 7000 to 5800 cal BP (Figure 3q,t). This last period corresponds to the decrease of *Pinus cembra*, the disappearance of *Alnus*, and the progressive disappearance of *Betula*. Very few remains of *Pinus cembra* and grass taxa are recorded from the period when fire frequency was null, from 5500 to 3900 cal BP. The ecosystem of the last 1700 y was characterized by grass remains and very rare *Pinus cembra* needles and by 2 fires (1 fire·1000 y^{-1}).

The vegetation proxies of Lac du Loup were dominated by the abundance of *Larix decidua*, which was rarely if at all recorded in the 2 other sites (Figure 3i). The *Larix decidua* accumulation rate remained high until *ca*. 1000 y ago, whereas *Pinus cembra* and *Betula* decreased progressively from 6500 to 2500 cal BP (Figure 3f,l). The other woody taxa, mostly *Pinus mugo/uncinata*, *Abies*, and *Vaccinium*, abounded between 8500 and 7500 cal BP (Figure 3r). The early Holocene from 8000 to 5700 cal BP was the richest period in terms of woody plants and had the highest fire frequency, peaking with 6 fires·1000 y^{-1}. Grass taxa were abundant during 2 sequences, the first during the highest fire-frequency period and the second during the last 1500 y, during which fires and trees were lacking (Figure 3u).

Discussion

Our analysis of 4 sedimentological sequences situated in the subalpine belt in the western Alps shows that fires occurred frequently during the Holocene, whereas they have been extremely rare or absent in the Alps under 20th century climate and vegetation cover conditions. This fact shows that mountain ecosystems have experienced significant changes during recent centuries. Until now, fire frequencies had never been reconstructed in the Alps, although paleofire evidence has been reported at different elevations or ecosystem belts based on soil or sedimentological charcoal concentration (*e.g.*, Carcaillet, 1998; Tinner *et al.*, 1999; 2005; Stähli *et al.*, 2006).

Here, we report the natural range of fire regimes over millennia for a subalpine ecosystem based on median fire interval. These medians are similar, at least during the first half of the Holocene (Table II), but the fire histories are dissimilar in terms of synchronicity (Figure 4). These observations indicate that large-scale natural processes have controlled the fire intervals but not their occurrence. The large-scale processes are the bio-climate of the subalpine belt, which differs greatly from the bio-climates within the mountain and alpine-tundra belts that are below and above the subalpine belt, respectively: both have differences in precipitation and in fuel load. However, the broad lack of synchronicity between sites indicates that the occurrence of fires does not depend on these factors (Figure 4). Between-site vegetation composition within the subalpine belt, topography, elevation, and slope aspect certainly affect fire ignition and spread. Furthermore, the occurrence of fire results from weather conditions, which include the lightning hazard and rapid moisture changes after thunderstorms, and the dominant species in the stand, which varies from site to site.

LATEGLACIAL CHARCOAL: FIRE OR NOT FIRE?

The CHAR observed during the Lateglacial, although low, is surprising since we know that the vegetation was not dominated by conifers but by herbs and broadleaf deciduous woody species, *e.g.*, *Betula*. It may have resulted from extremely low local fire severity in a treed-tundra environment, which would be similar to what happened in Alaska during the Lateglacial, when birch was abundant and fires occurred (Higuera *et al.*, 2008). However, transportation of charred particles from a known regional source area at lower elevation (Ali *et al.*, 2006) cannot be ruled out. This possibility is supported by the fact that very few remains of woody species accumulated during that time, and the vegetation that was there was certainly unproductive. Furthermore, the low CHAR values observed correspond to small and very rare charcoal fragments, whose occurrence could result from regional particle transportation. Mechanistic model-data comparisons do not exclude the possibility of such transportation (Higuera *et al.*, 2007). The numerical analyses did not show any fire events because the low CHAR results before 9000 cal BP contain too little charcoal and thus do not differ enough from the background. Their variance is too small to reconstruct fire events.

FIRE REGIMES LINKED TO RELIEF AND TOPOGRAPHY

The fire regime during the first part of the Holocene, between 9000 and 4500 cal BP, is interesting. Only 1 fire event is reported at 2405 m asl (Plan Bouchet), while several are reported between 2035 and 2180 m. However, the

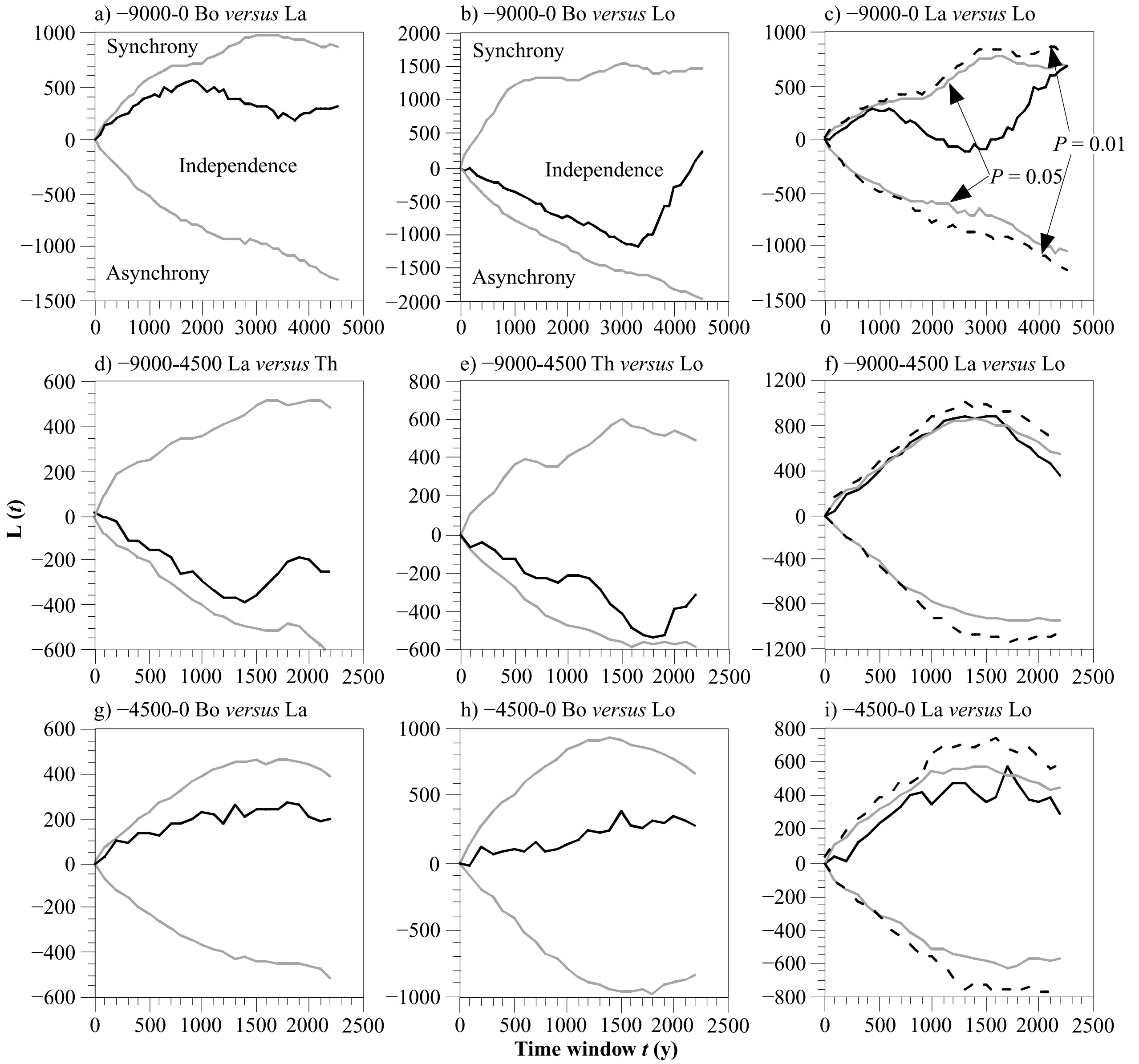

FIGURE 4. *L*(*t*)-function (transformed Ripley's *K*-function) is shown for lag of 4500 y over the whole period (here, 9000 y of fire history) and for a lag of 2200 y for each half-period (9000–4500 and 4500–0 cal BP). Confidence envelopes of 95% (grey lines) and 99% (dashed lines) are based on 1000 randomizing fire events. Bo = Plan Bouchet; La = Lac du Lait; Th = Lac du Thyl; Lo = Lac du Loup.

median fire interval ranged from 100 to 280 y at 2035 m and 2180 m asl, respectively, on the same slope aspect (south-facing), whereas it was 180 y at 2035 m on a north-facing slope that is wetter and colder during the fire season. The result is a fire pattern that appears to be controlled by altitude and aspect, *i.e.*, the median and the mean fire intervals decrease with altitude and with south- *versus* north-facing slopes.

TREE DOMINANCE ACTS ON THE SPATIAL VARIABILITY OF FIRE

After 4500 cal BP, the predictable fire pattern observed between 9000 and 4500 cal BP changed. Fire frequency increased at Plan Bouchet after 3000 cal BP, did not change significantly at Lac du Lait before total fire suppression 1300 y ago, and dropped abruptly at Lac du Thyl and Lac du Lait (Figure 3). These changes are associated with important transformations of vegetation cover. Unfortunately, the plant cover couldn't be reconstructed at Plan Bouchet. Lac du Lait experienced no significant changes of fire regime (Table I) during the period that its vegetation remained broadly unchanged, 8500 to 1500 cal BP (Figure 3). However, its fire regime altered after 1500 cal BP, when the treed ecosystem dominated by *Pinus cembra* and *Betula* disappeared, being replaced by a grass-dominated ecosystem. Lac du Thyl recorded a significant change in plant cover at the same time as fire frequency changed, *ca*. 6700 cal BP. The treed community that burned frequently and that was dominated by *Pinus cembra*, *Betula*, and *Alnus* was transformed into a fire-less grass community (Figure 3). Surprisingly, the Lac du Loup site, co-dominated by *Larix decidua* and *Pinus cembra*, experienced a progressive decrease in fire frequency 4500 y ago when *Pinus cembra* abundance decreased progressively.

Pinus cembra, which was the main dominant tree during the first part of the Holocene in the western Alps (Ali *et al.*, 2005a), appears to be a key functional species to explain fire-regime variability. When cembra pine did not dominate the plant communities, fire frequency was rather low. The local suppression or rarefaction of cembra pine and its substitution by grasses (Lac du Lait, Lac du Thyl) or by larch and grasses (Lac du Loup) triggered a reduction in the fire frequency and eventually its suppression. The abundance of *Pinus cembra* would have controlled the abundance of coarse and fine woody debris, resulting in a direct control on fire spread (Genries *et al.*, 2009a). Although the early Holocene fire regime is rather predictable, based on mountain landscape features (aspect, elevation) and abundance of cembra pine, the late Holocene is clearly less predictable: each site experienced its own fire history. Furthermore, the change in fire regime was asynchronous and varied from site to site, underlining that strong and efficient, strictly local processes controlled fire occurrence during the second half of the Holocene.

HISTORY OF FIRE-REGIME: FROM NATURAL TO CULTURAL PROCESSES

The first centuries of the Holocene, like the Lateglacial times, had very few fires. Fire was likely nonexistent in the subalpine belt of our study area, although evidence of a fire was obtained in a massif to the south based on charcoal from travertine (Ali *et al.*, 2005b). When the climate began to warm 11 000 cal BP (Davis *et al.*, 2003), trees started to increase in the subalpine belt, leading to the establishment of subalpine forests dominated by *Pinus cembra* between 9000 and 8500 cal BP. This seems to have led to a subalpine bioclimate associated with a pattern of fire regimes controlled by local-scale processes. This is consistent with fire-regime observations in Canadian plains (Carcaillet *et al.*, 2001a; Lynch, Hollis & Hu, 2004), Swedish foothills (Carcaillet *et al.*, 2007), and Alaskan boreal ecosystems (Higuera *et al.*, 2008), which show clear regional patterns of fire intervals varying with times and with vegetation zones. These subalpine reconstructions in the French Alps are consistent with those from the Canadian cordillera showing that local-scale processes resulting from mountain landscapes can experience different fire regimes and that these fires are not synchronized (Gavin *et al.*, 2006). However, unlike the study by Gavin *et al.*, which was based on only 2 sites, our study based on 4 sites provides evidence that natural processes can produce a clear pattern of fire regime, with fewer fires at higher altitudes close to the upper treeline and at sites on north-facing slopes, which are both colder and wetter. Our data demonstrate that changes in the fire regime varied greatly between sites, and that the early Holocene pattern controlled by altitude and aspect was altered by changes in vegetation composition and structure. This scenario suggests that intense local-scale modifications of ecosystems, such as those triggered by the expansion of farming practices from the Neolithic to the Middle Ages, were responsible for changes in fire regime. Indeed, although the Lac du Thyl site experienced an unexplained earlier transformation of the vegetation and fire regime at *ca.* 6500 cal BP (Middle Neolithic), the Plan Bouchet and Lac du Loup sites experienced significant transformation *ca.* 2800 and 2150 cal BP (Iron Age) and the Lac du Lait site at *ca.* 1500 cal BP (Middle Ages), although subtle changes had already begun to appear 3000 y ago (Late-Bronze Age). This between-site variability of fire history was previously reported based on soil charcoal dating in the same area (Carcaillet, 1998). A comparison of archeological data on the establishment and expansion of prehistoric societies in the region and paleofire reconstructions would help to clarify the effect of prehistoric occupations on fire history (Carcaillet *et al.* 2007); unfortunately, no quantitative archeological analyses are available for the valley, despite decades of sites excavation (Bocquet, 1997; Thirault, 2006ab) .

The practices of prehistoric societies have probably been the main factor controlling the fire regime in the Alps for the last several centuries or millennia, depending on site. These practices acted on the fire regime by increasing the frequency of fires through slash-and-burn activities to clear woody communities for pastures, for example, or by suppressing fires when pastures were established. The first prehistoric populations during the Neolithic and the Bronze Age seem to have been highly dispersed, with very low population density. This might explain why our sites did not experience the same fire history. Lac du Thyl was certainly the easiest site to reach due to its slope inclination and the best one for slash-and-burn agriculture due to its great soil thickness and lack of avalanches. Plan Bouchet and Lac du Loup were the worst sites for pastures, because of their elevation, the steep slopes leading to them, and the abundance of rock-fall and snow avalanches at these sites, which generated thin soils and greater risk for humans. Interest in such sites increased only later, when prehistoric population densities and needs increased.

Conclusion

During the first part of the Holocene, beginning with the Lateglacial, fire intervals appear clearly to have been controlled by large-scale natural processes such as climate and vegetation pattern. No fire was detected in our reconstructions before 9000 cal BP, while infrequent fires occurred after the subalpine bio-climate belt characterized by *Pinus cembra* was established. Local-scale processes became increasingly significant during this period, with more fires at lower elevation and on south-facing slopes. Altitude, topography, and slope aspect drove between-site differences for several millennia of the early Holocene, but during the late Holocene these differences disappeared, leading to a site chronology related not to ecological features of the natural landscape but to human practices and population density due to the need for livestock pastures. Fires were certainly controlled at first by climate and biomes, but social practices came to have an important effect on fire occurrence and synchronicity. Our study underlines the importance of investigating paleofires in light of current environmental changes, which act on fire risk and spread (Schumacher & Bugman, 2006), related to fuel build-up due to land-use abandonment and rural exodus (*e.g.*, Motta & Lingua 2005; Chauchard, Carcaillet & Guibal, 2007), global warming, and the increasing occurrence of drought in southern Europe (Pal, Giorgi & Bi, 2004). The current global changes could provoke a new fire epoch controlled by natural processes such as climate and vegetation.

Acknowledgements

The Institut National des Sciences de l'Univers (INSU-CNRS, France) provided financial support for the CONSECOL program (headed by C. Carcaillet). We thank L. Bircker, D. Cyr, S. Ivorra, B. Vannière, L. Mercier, J. Poullenard, and F. Combet for field or laboratory assistance.

Literature cited

Ali, A. A., C. Carcaillet, B. Talon, P. Roiron & J. F. Terral, 2005a. *Pinus cembra* (arolla), a common tree in the inner French Alps since the early Holocene and above the present tree line: A synthesis based on charcoal data from soils and travertines. Journal of Biogeography, 32: 1659–1669.

Ali, A. A., P. Roiron, J. L. Guendon, P. Poirier & J. F. Terral, 2005b. Fire and vegetation pattern changes in the southern inner French Alps (Queyras Massif) during the Holocene: Charcoal and geomorphological analyses of travertine sequences. Holocene, 15: 149–155.

Ali, A. A., M. Martinez, N. Fauvart, P. Roiron, G. Fioraso, J. L. Guendon, J. F. Terral & C. Carcaillet, 2006. Incendies et peuplements à *Pinus mugo* Turra dans les Alpes occidentales (Val de Suse, Italie) durant la transition Tardiglaciaire–Holocène: une zone refuge évidente. Comptes Rendus Biologies, 329: 494–501.

Bergeron, Y., D. Cyr, C. R. Drever, M. Flannigan, S. Gauthier, D. Kneeshaw, E. Lauzon, A. Leduc, H. Le Goff, D. Lesieur & K. Logan, 2006. Past, current, and future fire frequencies in Quebec's commercial forests: Implications for the cumulative effects of harvesting and fire on age-class structure and natural disturbance-based management. Canadian Journal of Forest Research, 36: 2737–2744.

Blarquez, O., C. Carcaillet & B. Mourier, in press. Une forêt subalpine à mélèze dominant dans un vallon avalancheux: 9000 ans d'histoire révélés par l'analyse des macrorestes végétaux d'un lac de Maurienne. Travaux scientifiques du Parc national de la Vanoise.

Bocquet, A., 1997. Archéologie et peuplement des Alpes françaises du Nord au Néolithique et aux âges des métaux. L'Anthropologie, 101: 291–393.

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

Brown, K. J., J. S. Clark, E. C. Grimm, J. J. Donovan, P. G. Mueller, B. C. S. Hansen & I. Stefanova, 2005. Fire cycles in North American interior grasslands and their relation to prairie drought. Proceedings of the National Academy of Sciences, 102: 8865–8870.

Carcaillet, C., 1998. A spatially precise study of Holocene fire history, climate and human impact within the Maurienne valley, North French Alps. Journal of Ecology, 86: 384–396.

Carcaillet, C., Y. Bergeron, P. J. H. Richard, B. Fréchette, S. Gauthier & Y. T. Prairie, 2001a. Change of fire frequency in the eastern Canadian boreal forests during the Holocene: Does vegetation composition or climate trigger the fire regime? Journal of Ecology, 89: 930–946.

Carcaillet, C., M. Bouvier, B. Fréchette, A. C. Larouche & P. J. H. Richard, 2001b. Comparison of pollen-slide and sieving methods in lacustrine charcoal analyses for local and regional fire history. Holocene, 11: 467–476.

Carcaillet, C., I. Bergman, S. Delorme, G. Hörnberg & O. Zackrisson, 2007. Long-term fire frequency not linked to prehistoric occupations in northern Swedish boreal forest. Ecology, 88: 465–77.

Chauchard, S., C. Carcaillet & F. Guibal, 2007. Patterns of land-use abandonment control tree-recruitment and forest dynamics in Mediterranean mountains. Ecosystems, 10: 936–948.

Davis, B. A. S., S. Brewer, A. C. Stevenson, J. Guiot & Data Contributors, 2003. The temperature of Europe during the Holocene reconstructed from pollen data. Quaternary Science Reviews, 22: 1701–1716.

Delcros, P., 1994. Écologie du paysage et dynamique végétale post-culturale en zone de montagne. Études du CEMAGREF, série Gestion des Territoire n°13, Grenoble.

Didier, L., 2001. Invasion patterns of European larch and Swiss stone pine in subalpine pastures in the French Alps. Forest Ecology and Management, 145: 67–77.

Flannigan, M. D., Y. Bergeron, O. Engelmark & B. M. Wotton, 1998. Future wildfire in circumboreal forests in relation to global warming. Journal of Vegetation Science, 9: 469–476.

Flannigan, M. D., K. A. Logan, B. D. Amiro, W. R. Skinner & B. J. Stocks, 2005. Future area burned in Canada. Climatic Change, 72: 1–16.

Gavin, D. G., F. S. Hu, K. P. Lertzman & P. Corbett, 2006. Weak climatic control of forest fire history during the late Holocene. Ecology, 87: 1722–1732.

Gavin, D. G., D. J. Hallet, F. S. Hu, K. P. Lertzman, S. J. Pritchard, K. J. Brown, J. A. Lynch, P. Bartlein & D. L. Peterson, 2007. Forest fire and climatic change in western North America: Insights from sediment charcoal records. Frontiers in Ecology and the Environment, 5: 499–506.

Genries, A., L. Mercier, M. Lavoie, S. D. Muller, O. Radakovitch & C. Carcaillet, 2009a. The effect of fire frequency on local cembra pine populations. Ecology, 90: 476–486.

Genries, A., S. D. Muller, L. Mercier, L. Bircker & C. Carcaillet 2009b. Fires control spatial variability of subalpine vegetation dynamics during the Holocene in the Maurienne valley (French Alps). Écoscience, 16: 13–22.

Gerlich, M., P. Baur, B. Koch & N. E. Zimmermann, 2007. Agricultural land abandonment and natural forest re-growth in the Swiss mountains: A spatially explicit economic analysis. Agriculture, Ecosystems and Environment, 118: 93–108.

Hajdas, I., N. Schlumpf, N. Minikus-Stary, F. Hagedorn, E. Eckeier, W. Schoch, C. Burga, G. Bonani, M. W. I. Schmidt & P. Cherubini, 2007. Radiocarbon ages of soil charcoals from the southern Alps, Ticino, Switzerland. Nuclear Instruments and Methods in Physics Research B, 259: 398–402.

Higuera, P. E., M. E. Peters, L. B. Brubaker & D. G. Gavin, 2007. Understanding the origin and analysis of sediment-charcoal records with a simulation model. Quaternary Science Reviews, 26: 1790–1809.

Higuera, P. E., L. B. Brubaker, P. M. Anderson, T. A. Brown, A. T. Kennedy & F. S. Hu, 2008. Frequent fires in ancient shrub tundra: Implications of paleorecords for Arctic environmental change. PLoS ONE, 3: e0001744.

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Lynch, J. A., J. L. Hollis & F. S. Hu, 2004. Climatic and landscape controls of the boreal forest fire regime: Holocene records from Alaska. Journal of Ecology, 92: 477–489.

Long, C., C. Whitlock, P. J. Bartlein & S. H. Millspaugh, 1998. A 9000-year fire history from the Oregon Coast range, based on a high-resolution charcoal study. Canadian Journal of Forest Research, 28: 774–787.

Marlon, J. R., P. J. Bartlein, C. Carcaillet, D. G. Gavin, S. P. Harrison, P. E. Higuera, F. Joos, M. J. Power & I. C. Prentice, 2008. Climate and human influences on global biomass burning over the past two millennia. Nature Geoscience, 1: 697–702.

Millspaugh, S. H. & C. Whitlock, 1995. A 750-year fire history based on lake sediment records in central Yellowstone National Park, USA. Holocene, 5: 283–292.

Motta, R. & E. Lingua, 2005. Human impact on size, age, and spatial structure in a mixed European larch and Swiss stone pine forest in the Western Italian Alps. Canadian Journal of Forest Research, 35: 1809–1820.

Motta, R., M. Morales & P. Nola, 2006. Human land-use, forest dynamics and tree growth at the treeline in the Western Italian Alps. Annals of Forest Science, 63: 739–747.

Mourier, B., J. Poulenard, P. Faivre, C. Chauvel & C. Carcaillet, 2008. Distinguishing subalpine soil types using extractible Al and Fe fractions and REE geochemistry. Geoderma, 145: 107–120.

Narayan, C., 2007. Review of CO_2 Emissions Mitigation Through Prescribed Burning. European Forest Institute, Joensuu.

Pal, J. S., F. Giorgi & X. Bi, 2004. Consistency of recent European summer precipitation trends and extremes with future regional climate projections. Geophysical Research Letters, 31: L13202.1–L13202.4.

Pausas, J. G., 2004. Changes in fire and climate in the eastern Iberian Peninsula (Mediterranean basin). Climatic Change, 63: 337–350.

Pitkänen, A. & P. Huttunen, 1999. A 1300-year forest-fire history at a site in eastern Finland based on charcoal and pollen records in laminated lake sediment. Holocene, 9: 311–320.

Reimer, P. J., M. G. L. Baillie, E. Bard, A. Bayliss, J. W. Beck, C. Bertrand, P. G. Blackwell, C. E. Buck, G. Burr, K. B. Cutler, P. E. Damon, R. L. Edwards, R. G. Fairbanks, M. Friedrich, T. P. Guilderson, K. A. Hughen, B. Kromer, F. G. McCormac, S. Manning, C. Bronk Ramsey, R. W. Reimer, S. Remmele, J. R. Southon, M. Stuiver, S. Talamo, F. W. Taylor, J. van der Plicht & C. E. Weyhenmeyer, 2004. IntCal04 terrestrial radiocarbon age calibration, 0–26 cal kyr BP. Radiocarbon, 46: 1029–1058.

Schumacher, S. & H. Bugmann, 2006. The relative importance of climatic effects, wildfires and management for future forest landscape dynamics in the Swiss Alps. Global Change Biology, 12: 1435–1450.

Stähli, M., W. Finsinger, W. Tinner & B. Allgöwer, 2006. Wildfire history and fire ecology of the Swiss National Park (Central Alps): New evidence from charcoal, pollen and plant macrofossils. Holocene, 16, 805–817.

Stuiver, M. R. & P. J. Reimer, 1993. Extended ^{14}C database and revised CALIB radiocarbon calibration program. Radiocarbon, 35: 215–230.

Thirault, E., 2006a. Le Néolithique d'une vallée alpine: la Maurienne. Enjeux, avancées, perspectives. Pages 241–250 *in* Alpis Graia. Archéologie sans frontières au col du Petit-Saint-Bernard. Actes du Séminaire de clotûre, Aoste, 2–4 mars 2006. Aoste: Programme Interreg IIIA ALCOTRA 2000–2006.

Thirault, E., 2006b. Bessans/La Teha (Savoie): présence néolithique à haute altitude (2250 m) sur les itinéraires transalpins. Bulletin de la Société Préhistorique Française, 103: 797–799.

Tinner, W., P. Hubschmid, M. Wehrli, B. Ammann & M. Conedera, 1999. Long-term forest fire ecology and dynamics in southern Switzerland. Journal of Ecology, 87: 273–289.

Tinner, W., M. Conedera, B. Ammann & A.F. Lotter, 2005. Fire ecology north and south of the Alps since the last ice age. Holocene, 15: 1214–1226.

Tutin, T. G., N. A. Burges, A. O. Chater, J. R. Edmonson, V. H. Heywood, D. H. Moore, D. H. Valentine, S. M. Walters & D. A. Webb, 1968–1993. Flora europaea. Vols. 2–5, Vol. 1 2nd Edition. Cambridge University Press, Cambridge.

Tymstra, C., M. D. Flannigan, O. B. Armitage & K. Logan, 2007. Impact of climate change on area burned in Alberta's boreal forest. International Journal of Wildland Fire, 16: 153–160.

Walther, P., 1986. Land abandonment in the Swiss Alps: A new understanding of a land-use problem. Mountain Research and Development, 6: 305–314.

Weng, C., 2005. An improved method for quantifying sedimentary charcoal via a volume proxy. Holocene, 15: 298–301.

APPENDIX I. Site descriptions and sedimentological characteristics (mean ± SE).

Site name	Plan Bouchet	Lac du Lait	Lac du Thyl	Lac du Loup
Type	Peat, fen	Lake, with peat belt, floating peat and open waters	Peated pond	Lake, with a peat belt and open waters
Elevation (m asl)	2405	2180	2038	2032
Exposure	South	South	South	North
Latitude	45° 14' 49" N	45° 18' 59" N	45° 14' 26" N	45° 11' 15" N
Longitude	06° 33' 58" E	06° 48' 49" E	06° 29' 59" E	06° 32' 16" E
Core length (cm)	165	344	494	292
# ^{210}Pb dating	no	no	17	15
# ^{14}C dating	6	7	12	12
Chronological range (cal BP)	0–14 500	200–26 000	0–1700 and 3900–8900 (hiatus: 1700–3900)	0–12 700
Deposition time (y·cm^{-1})	45.1 ± 6.7	51.2 ± 5.4	9.4 ± 0.5	45.9 ± 1.2
Sampling resolution (cm)	0.5	1	1	0.5
Time resolution (y·sample^{-1})	23	51	9	23

APPENDIX II. AMS radiocarbon dating of lakes and peat. Depths are expressed in terms of distance below the water-table surface. The median is the value used for computation of age/depth models.

Depth below the lake/peat surface (cm)	Lab code	^{14}C y BP	Dated material	Median value Cal y before AD 2000 [½ range y]
LAC DU THYL (PEATED LAKE), 2038 m				
67.5–69.5	AA-64296	673 ± 90	*Carex* S, degraded *Pinus* N	691 [124]
82.5–84.5	AA-64297	2451 ± 61	Degraded *Pinus* N, broad leaves, *Carex* S	2584 [180]
109.0–111.0	Beta-216570	3890 ± 40	Bulk sediment	4341 [132]
146.5–150.5	AA-64298	1693 ± 47	*Carex* S, bark	1670 [197]
150.0–157.0	Beta-216569	4230 ± 40	Bulk sediment	4794 [117]
160.0–165.0	Poz-15222	3960 ± 35	*Pinus cembra* N, *Betula* S, *Carex* S	4458 [114]
177.0–180.0	Poz-15223	4390 ± 40	*Pinus cembra* N, *Betula* S, *Rubus*. sp. S, broadleaves, *Carex* S	5106 [203]
192.5–194.5	AA-64299	4971 ± 47	*Pinus cembra* N, *Betula* S, broadleaves, *Carex* S	5794 [146]
246.5–250.5	Beta-201498	5520 ± 40	*Pinus cembra* N, *Carex* S	6390 [60]
347.5–349.5	AA-64300	6153 ± 43	*Pinus cembra* N, broadleaves, *Carex* S, insect	7101 [117]
448.5–450.5	AA-64301	7389 ± 42	*Pinus cembra* N, *Carex* S, broadleaves, insect, bark	8246 [145]
544.5–549.5	Beta-201499	8010 ± 40	*Pinus cembra* N, *Carex* S, broadleaves, insect	10 936 [140]
LAC DU LOUP (LAKE), 2032 m				
170.0–174.0	Poz-22999	1490 ± 35	*Larix decidua* NS, *Pinus cembra* N	1407 [103]
202.0–205.0	Poz-18280	1985 ± 30	*Larix decidua* N, *Pinus cembra* N, *Betula* SSc	1935 [60]
223.0–225.0	SacA-8347	2630 ± 30	*Larix decidua* N, *Pinus cembra* N, *Betula* L	2754 [31]
240.0–242.0	SacA-6901	3385 ± 30	*Betula* SL, Ericaceae L	3630 [71]
260.0–262.0	SacA-8348	4850 ± 35	*Larix decidua* N, *Pinus cembra* N, *Betula* L	5567 [85]
278.0–281.0	SacA-6902	4790 ± 30	*Betula* SL, Ericaceae L	5531 [62]
300.0–303.0	SacA-6900	5040 ± 30	*Larix decidua* N, *Pinus cembra* N, Ericaceae L	5783 [119]
340.0–342.0	SacA-6899	5640 ± 40	*Larix decidua* N, *Pinus cembra* N, Ericaceae L	6405 [90]
360.0–366.0	SacA-8349	5795 ± 35	*Larix decidua* N, *Pinus cembra* N, *Abies alba* N, *Betula* L	6584 [88]
373.0–378.0	SacA-8350	7785 ± 40	*Larix decidua* N, *Pinus mugo* N, *Pinus cembra* N, *Abies alba* N, *Betula* L	8544 [89]
380.0–385.0	Poz-18282	8160 ± 50	*Larix decidua* N, *Pinus cembra* N, *Betula* SSc	9135 [127]
409.0–419.0	Poz-23000	9420 ± 60	*Larix decidua* N, *Pinus cembra* N, *Betula* S, leaf fragments	10 754 [310]
LAC DU LAIT (LAKE), 2180 m				
104.0–110.0	AA-65523	216 ± 42	*Carex* S	212 [212]
196.0–200.0	AA-65524	1496 ± 41	Poaceae L, *Pinus cembra* N, *Abies* N	1410 [106]
297.0–299.0	AA-65525	4911 ± 44	*Pinus cembra* N, *Betula* S, *Carex* S	5658 [71]
346.0–347.0	Beta-210811	8060 ± 40	Bulk sediment	8930 [160]
385.0–387.0	Poz-19291	11 770 ± 60	Bulk sediment	13 607 [311]
403.0–404.0	AA-65526	12 813 ± 82	Bulk sediment	15 169 [308]
421.0–423.0	Beta-210812	16 790 ± 90	Bulk sediment	19 896 [294]
PLAN BOUCHET (FEN), 2405 m				
29.0–30.0	Poz-14258	1230 ± 30	Poaceae L, Cyperaceae S, Caryophyllaceae S	1165 [97]
69.0–70.0	Poz-14259	2045 ± 30	Poaceae L	2020 [95]
108.0–109.0	Poz-14261	3610 ± 35	TOC	4068 [117]
117.0–118.0	Poz-15218	5320 ± 40	TOC	6110 [155]
151.0–152.0	Poz-15219	6880 ± 40	Poaceae L	7719 [99]
164.0–165.0	Poz-14262	11 730 ± 60	*Drepanocladus* sp.	13 585 [149]

TOC: total organic carbon from bulk sediment; L: leaf; N: needle; S: seed; Sc: catkin scale.