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Once upon a time biomass burning in the western Alps: nesting effects of climate and local drivers on long-term subalpine fires

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Abstract

Background: The present article questions the relative importance of local- and large-scale processes on the long-term dynamics of fire in the subalpine belt in the western Alps. The study is based on soil charcoal dating and identification, several study sites in contrasting environmental conditions, and sampling of soil charcoal along the elevation gradient of each site. Based on local differences in biomass combustion, we hypothesize that local-scale or landscape-scale processes have driven the fire history, while combustion homogeneity supports the hypothesis of the importance of large-scale or macro-ecological processes, especially climate.

Results: Biomass burning during the Holocene resulted from the nesting effects of climate, land use, and altitude, but was little influenced by slope exposure (north *versus* south), soil (dryness, pH, depth), and vegetation. The mid-Holocene (6500–2700 cal BP) was an important period for climate-driven biomass burning in the subalpine ecosystems of the western Alps, while fires over the last 2500 years appear much more episodic, prompting us to speculate that human activity has played a vital role in their occurrence.

Conclusion: Our working hypothesis that the strength of local drivers should offset the effects of regional climate is not validated. The homogeneity of the fire regime between sites thus underscores that climate was the main driver during the Holocene of the western Alps. Long-term subalpine fires are controlled by climate at the millennial scale. Local conditions matter for little in determining variability at the century scale. The mid-Holocene was a chief period for climatic biomass burning in the subalpine zone, while fires during the late Holocene appear much more episodic, suggesting that social drivers has exercised key function on their control.

Keywords: Biomass burning, Subalpine forest, Climate, Landscape, Pedoanthracology, Radiocarbon dating, Pyrogenic carbon

1. Introduction

Events in recent years have dramatically shown that wildfires are essentially under the control of extreme heatwaves. The overall regulation of wildfires by climate is no doubted (e.g., Bond and Keeley, 2005; Flannigan et al., 2009; Moritz et al., 2012) and this issue should be a priority on the agenda of states and UNO stakeholders (IPCC, 2021). However, other drivers also act on wildfire regimes: soil granulometry, slope exposure, biomass quality and load, topography, altitude, and, of course, past or present land uses all play their part (Loehman et al., 2013). The relative function of climatic and non-climatic drivers can be difficult to unravel, while the local management of a fire regime needs fine distinctions in order to implement efficient management processes according to actual risks. Cold regions like boreal or temperate mountains present biomass with very similar elements in terms of climate (temperature, precipitation, seasonality, snow cover, etc.) and biota (functionally analogue woody species, structure of vegetation, etc.). However, they differ by their relief, which determines the fragmentation and the heterogeneity of landscape (slope degree and exposure, altitude, etc.). Altitude controls the moisture, the temperature (wetter and colder with increasing elevation) and the partial pressure of O₂ (pO₂) that is the biomass oxidizer during fire (10% change of pO₂ per 1,000 m in elevation). Further, the slope controls the water runoff and drainage, and the exposure regulates the solar radiation and the length of the growing season (Tian et al., 2001; Piedallu and Gégout, 2007) with potentially significant effects on the fire regime (Schumacher and Bugmann, 2006). In sum, as a first approximation, a number of evident similarities warrant some comparisons or assumptions between boreal and mountain systems, but the differences strongly encourage caution when considering management planning for wildfire and forest resources (Loehman et al., 2014; Moritz et al., 2014).

Here we test whether past climate controlled the fire regime in a temperate mountain region over the last 11 millennia, i.e. during the Holocene – a warmer and more humid time in mountains compared to Glacial and Lateglacial periods that were colder and drier. The principles of the study are based on the hierarchy theory (O'Neill, 1988; Allen, 2009), which states that if climate is the main driver, different sites that are close to each other should reveal a similar pattern of fire regime (Yocom Kent et al., 2017). If they do not show such similarities, local or landscape drivers must be considered, notably slope exposure, altitude, soil type, and vegetation. Of course, historic land use must also be taken into account as an important fire driver (Zumbrunen et al., 2009), but this has been difficult to prove in the past without resorting to speculation because accurate quantitative evidence of past land uses are often lacking, e.g., chronologies of people density, their *savoir faire*, and technologies. Vegetation is under the direct influence of mountain climate and soil types, through bedrocks that notably control the plant communities and their productivity. The vegetation is also largely shaped and controlled by traditional land uses that generally exclude woody plants and seek to sustain mountain grasslands that are not fire-prone or flammable. When traditional land

use in this context is abandoned, subalpine woody plants recover in decades (e.g., Didier, 2001; Tasser and Tappeiner, 2002; Motta and Lingua, 2005; Tasser et al., 2007; Lingua et al., 2008). For our purposes then, we here study three sites in close proximity, all located in the same valley of the western Alps. At each site, charcoal was extracted from several natural subalpine soils along the altitudinal gradient and further radiocarbon dated. The numerical analysis of ^{14}C age allows reconstructing of biomass burning as a surrogate of fire history (Payette and Gagnon, 1985; Carcaillet, 1998; Gavin et al., 2003), and enables us to determine homogeneities and differences by considering local drivers. Charcoal fragments were identified to reconstruct the past burned biomass, helping to test whether different woody communities were historically involved in these past fires. Here, two sites – both situated on south-facing slopes but contrasted by their soil – were selected: acidic and well supplied with water versus alkaline with poor water storage. The third site is intermediate in terms of soil, but has north-facing slopes. This last condition (a north-facing site) should result in less biomass burning (more stochastic), while a south-facing site on poor water storage soil should in theory promote a more homogeneous chronology of biomass burning at century-to-millennial scale, starting earlier during the Holocene, especially if vegetation was more fire-prone.

We hypothesize that due to the strength of mountain contrasts natural local drivers should offset the effects of regional climate. Alternatively, the homogeneity of the fire regime between sites would suggest that climate was the main historical driver. Confirmation of either hypotheses should result in different scenarios of land management, notably in planning the future of forest and woodlands facing global warming that will almost certainly be accompanied by more frequent and severe drought in the Alps (Gao and Giorgi, 2008; Im et al., 2010) – a *sine qua none* condition for dealing with future fire occurrences (Zumbrunen et al., 2009; Dupiré et al., 2019). The study is articulated on reused AMS ^{14}C dating already published (i.e., 34 by Carcaillet, 1998, 10 by Carcaillet, 2001) and on 49 unpublished datings, including 24 on a contrasted site. Finally, while this approach based on soil charcoal is opportune for exploring the biomass burning history of dry sites, it is unsuitable for classic sedimentary studies. A planning bias in land management, based on paleo-data from areas characterized by lakes and peatlands, would be to extrapolate these findings to unsuitable sites due to edaphic or climatic dryness that might therefore be subject to important fire regimes for millennia.

2. Material and Methods

2.1. Study sites

The three study sites are situated in the Maurienne valley that borders the Vanoise massif to the south, in western France. The three sites, namely St Michel, Aussois, and Lanslevillard, are situated at the same

latitude (ca 45.25°N) along a west–east transect of ca 40 km corresponding to a gradient of humidity linked to a complex rain-shadow process. St Michel is the most western site, 21 km from Aussois, the central site, and Lanslevillard is the easternmost of the three at 17 km from Aussois (geographic coordinates: Table 1).

St Michel is characterized by south-facing slopes and acidic soils on bedrock composed of thin glacial deposits (till) of admixed coalesced sandstones and shale rock fragments (Table 1). Aussois is also on south-facing slopes but has alkaline bedrocks mostly composed of thick glacial deposits (>150 cm): an admixture of dolomitic-origin, “cargneule”, and gypsum. Lanslevillard is on north-facing slopes but with alkaline bedrock resulting from a glacial admixture of marbles and calcareous shale fragments (Debelmas, 1989; Fudral et al., 1994). At St Michel and Lanslevillard, forest soils are acidic [$\text{pH}_{\text{H}_2\text{O}}$ 4.5–5.2] or neutral brunisol [$\text{pH}_{\text{H}_2\text{O}}$ 6.0–6.5], respectively, whereas at Aussois soils are calcimorph with $\text{pH}_{\text{H}_2\text{O}} > 7$ (Bartoli, 1967; Mourier et al., 2008). Slope degrees range between 20° and 30° (Table 1). St Michel and Lanslevillard show regular slopes, whereas Aussois presents more heterogeneous terrain.

Climate features vary among sites according to slope exposure and altitude of weather stations: ca 1,400 m above sea level (hereafter asl) at St Michel and Aussois, and 2,000 m asl at Lanslevillard, resulting in temperature values that are not totally comparable (Table 1). However, mean annual temperatures appear similar (ca 7°C at 1,400 m on south-facing slopes and ca 2.5°C at 2,000 m on north-facing). The mean monthly temperatures for the three winter months (T_{DJF}) are around 0°C at 1,400 m and –4°C at 2,000 m, and the temperatures of the growing season (T_{JJA}) are ca 14.5°C at 1,400 m and 10°C at 2,000 m. Snow covers the ground for 3–5 months per year at 2,000 m on southern slopes and 5–7 months on north-facing slopes (Table 1). Mean annual precipitation ranges between ca 900–950 mm at St Michel and Lanslevillard, and ca 700 at Aussois. Aussois is thus the driest site, with only ca 160 mm during the growing season, while both other sites receive 200–250 mm, i.e. +40% (Table 1).

To sum up, Aussois is the most stressed site for biological processes in terms of climate and soil, lowest precipitation, south-facing slopes (high solar radiation on soil increasing the effect of air temperature), alkaline and calcimorph deep morainic soil depleted in clay (and thus poor water storage). Lanslevillard is the coldest site with a shorter growing season, and St Michel is the site with the most acidic soil features.

2.2. Soil sampling and charcoal extraction

At St Michel, ten soil profiles were collected, eight at Aussois, and six at Lanslevillard. All sampling plots were selected in the subalpine belt (1,700–2,500 m asl) in Aussois and St Michel, whereas at Lanslevillard the sampling plots were selected between 1,600 and 2,300 m asl to take into account the slope exposure that triggers a lowering of about 200 m of vegetation belt limits between south- and north-facing slopes (less solar radiation, shorter growing season, colder air and soil temperatures, longer snow cover in spring).

The mean (\pm SE) sampling altitudes are $2,109 \pm 87$ m at St Michel, $2,051 \pm 80$ m at Aussois, and $1,970 \pm 79$ m at Lanslevillard.

Soils were collected according to the standardized pedoanthracological method (Carcaillet and Thinon, 1996; Carcaillet and Talon, 2001). Plots disturbed by human settlements were avoided, as well as soil located at the foot of steep or long slopes susceptible to concentrated charcoal transported by run-off (Talon et al. 2005), and eroded or hydromorphic soils poorly favorable to particulate sequestration. Soil profiles were sampled in trenches dug down to the bedrock whenever possible, or to the limits of plant roots on thick morainic deposits. Soil material was sampled by cutting soil blocks from the face of a vertical profile. Blocks were collected at different depths from the bottom to the surface to avoid particles falling from the upper horizons. Block limits were separated in several layers when the horizon thicknesses were greater than 20 cm or when the soil horizon limits were not visible. About 10 to 15 L of dry fine material were sampled per layers of ca 20 cm. Each complete dried profile weighed 30 to 100 kg depending on the soil texture, the organic content, and the horizon structures, and the depth of the profiles that determine the number of layers, from one to seven for 30 and 150 cm thick profiles, respectively.

A flotation procedure with an ascending water flow was used to extract charcoal from the soil matrix (Carcaillet and Thinon, 1996). Flotation with wet sieving (2, 0.8, 0.4 mm) followed by manual sorting under a binocular microscope, allowed the final separation of charcoal fragments from other soil particles. Only fragments larger than 0.4 mm in diameter were considered. Charcoal that is smaller than 0.4 mm may be transported over long distances, while the stand origin of charcoal larger than 0.4 mm is unequivocal (Clark et al., 1998; Ohlson and Tryterud, 2000; Lynch et al., 2004).

2.3. Dating and biomass burning chronology

In total, 93 AMS ^{14}C ages were obtained from soils at St Michel ($n = 43$), Aussois (26), and Lanslevillard (24). Thirty-four (34) out of these 93 AMS ^{14}C ages were already published, 18 at St Michel and 16 at Aussois (Carcaillet, 1998). Because in this preliminary study of 1988 (i) no dates covered the recent period from 2200 calendar years before the present (hereafter, cal BP) above 2,000 m asl at Aussois and above 1,700 m asl at St Michel, and (ii) none was obtained before 6500 cal BP, the strategy was to increase significantly the number of ^{14}C ages to fill in these gaps in the chronologies, or to strengthen the already reported pattern. The point was to question whether these chronological gaps resulted in a problem of low numbers or to see if they correspond to an actual lack of burning in some sites at certain altitudes. The additional site (Lanslevillard) allows us to test whether these reported chronologies per altitude class were strictly local or corresponded to a general pattern. In this region of the western Alps, no accurate sedimentary charcoal series are available below 2,000 m asl (Leys and Carcaillet, 2016), which prevents us formulating a response to this issue of fire patterns according to altitude. We assume that fire occurrences should be more

frequent at lower altitudes and on south-facing slopes compared to higher altitudes and north-facing slopes due to greater dryness (precipitation increases with elevation and south-facing slopes receive more solar radiation) (Schumacher and Bugmann, 2006), and posit their greater attractiveness to prehistoric humans who altered fire patterns in response to the drivers prevailing thousands of years ago, e.g., climate, vegetation, topography, soil, etc. (Leys and Carcaillet, 2016; Vanni re et al., 2016).

With a few exceptions (Table S1), each ^{14}C age was measured on one charcoal fragment. Prior to AMS dating, charcoal fragments were cleaned using an ultrasonic wave generator under a microscope ($\times 40$) to remove small roots, fungi hyphae, and particles that could potentially alter the dating result. Further, each fragment was processed with a solution of $\text{Na}_4\text{P}_2\text{O}_7$ or NaP_2O_4 to extract the organic compounds adsorbed in the charcoal porosity. The solution was changed daily up to the release end of organic compounds by the charcoal. Generally, five to seven days were needed to chemically clean the charcoal fragments (Carcaillet and Thinon, 1996).

The ^{14}C measurements were processed by several laboratories: the *NSF Arizona Facility Laboratory* (Arizona, USA), the *Centre de Datation par le Radiocarbone* (France), and the *LMC14* (a national facility lab, also in France). Dating codes were respectively labeled AA-xxxx, Lyon(OxA)-xxxx, and SacA-xxxx (Table S1).

The radiocarbon measurements were calibrated against dendrochronological years using the *CALIB* program version 8.2, based on the IntCal20 dataset, lab-error of 2 sigma (Stuiver et al., 2021), and reported with a probability range of 1.0. The probability distributions of ^{14}C ages were cumulated by site (e.g., Hajdas et al., 2007) and labeled local chronology. The probability distributions were obtained using the sum probability function of the *CALIB* program. Contrary to some assumptions (e.g., Payette et al., 2012; Couillard et al., 2019), such distribution cannot provide a chronology of fire events, but rather a chronology of burned biomass or soil charcoal stock. All fire dates cannot be captured by a limited number of ^{14}C date, or exceptionally, and a calibrated ^{14}C date can cover one or more fire date in areas where the mean fire interval is shorter than the range of calibration. Furthermore, fire frequency cannot be reconstructed based on soil charcoal because a ^{14}C date does not cover the fire date, or exceptionally: important lags between the ^{14}C date (radiocarbon age of wood) and the age of fire can exist, notably if the charcoal fragments used for dating came from the inner part of trunks for long-lived species such as those growing in subalpine forests (Carcaillet, 1998). To bypass this problem – which Gavin (2001) called the ‘inbuilt age’ – and in the absence of a fuel load/consumption model to fix it (Gavin, 2001), charcoal fragments corresponding to twigs were here selected for dating, when possible to reduce the range of the so-called inbuilt age. However, a maximum of cumulated calibration does not correspond to a fire event but to a stochastic period of burned biomass characterized by a concentration of ^{14}C dating and associated probability of calibration.

The statistical analyses of radiocarbon dating were based on their distribution revealed through violin-plots (*R package, ggplot2*). The violin-plot is more informative than the box-plots sometimes used to display dating distributions (e.g., Gavin et al., 2003), because a multimodal distribution is visual and illustrated by two bulges at least, whereas a unimodal distribution should present only one. The means of the site distributions were statistically compared based on Kruskal-Wallis test to detect a general difference among means, and to each other based on Wilcoxon-test to determine which site differ from the others. Calendar dates cannot be directly used because a date corresponds to a complex range of values, sometimes to several ranges associated with different probabilities within the full calibration range of the date considered (Telford et al., 2004). Consequently, the median of each probability distribution was extracted from CALIB and used as best single estimate representative of the dating (Telford et al., 2004) for analysis of ^{14}C age distributions based on violin-plots and the associated statistics. The median value divides the density function into two parts with equal probability, i.e. $p = 0.5$ (Michczyński, 2007). This process is not perfect but better than to use the mode corresponding to the maximum of probability distribution of a calibrated ^{14}C date (Michczyński, 2007).

2.4. Charcoal botanical identification and analysis

Extracted charcoal fragments were observed under an incident light microscope ($\times 200$, $\times 500$, $\times 1000$) to identify the woody taxa that burned. Identifications were realized with the help of specialist reference wood anatomy books (e.g., Jacquot, 1955; Jacquot et al., 1973; Schweingruber, 1990), and some specific studies on wood charcoal anatomy notably for *Larix* and *Picea*, for *Betula*, and for Empetraceae/Ericaceae. Because *Larix* and *Picea* can only be distinguished from each other in exceptional cases, they have been gathered under the taxon “*Larix-Picea* type” (Talon, 1997). *Betula* trees can be distinguished from *Betula* shrubs (Hellberg and Carcaillet, 2003). With regard to Ericaceae and Empetraceae, genera or species have been identified when possible based on the anatomy of the medulla: *Arctostaphylos*, *Empetrum*, *Erica*, *Rhododendron*, *Vaccinium myrtillus*, *V. vitis-idaea*, *V. uliginosum* (Talon, 2004). Further, *Pinus sylvestris* (a montane tree, growing up to 2,000 m) and *P. uncinata* (a true subalpine tree growing from 1,500 to 2,500 m asl) cannot be distinguished based on their wood anatomy, and are thus labeled *P. sylvestris/uncinata*. The assemblages of charcoal are considered to correspond mainly to dead woody debris, especially that lying on the ground, and to living twigs of trees and shrubs which can easily burn due to their small diameters or their low height in the vegetation (Bégin and Marguerie, 2002; Kasin et al., 2017). Charcoal was weighed and expressed in terms of charcoal mass (= anthracomass) relative to the dry soil mass ($\text{mg}_{\text{char}} \cdot \text{kg}_{\text{soil}}^{-1}$ or ppm; see Carcaillet and Talon, 2001). The charcoal mass was calculated per profile and per layer. The representation of past burned biomass based on anthracomass presents distortion potential due to the different consumption of species (Fréjaville et al., 2013a), burning conditions (Asgough et al., 2011), and the assumed resistance of charcoal to weathering processes in soil depending on soil type,

burning conditions, and plant anatomy (Preston and Schmidt, 2006). However, the representation of assemblages based on charcoal mass still remains an efficient way to figure out what the plant biomass had been at the time of the burning events.

Charcoal assemblages were expressed as a percentage of the identified charcoal mass per taxon and per layer. At least, 200 fragments, taken randomly, were identified per soil layer, i.e. 100 from 0.4 to 0.8 mm, 100 from 0.8 to 2.0 mm, and all fragments > 2 mm that were generally infrequent. When charcoal fragments were not abundant ($n < 100$ per layer), mostly at altitude above 2,000 m, all fragments were identified. Unidentified charcoal fragments were not considered in this calculation but their contribution to the whole is reported in the Table S2. Unidentified charcoals were those fragments technically impossible to identify due to too few anatomical features for their definitive identifications, or glassy charcoal whose provenances still remain unknown despite experimentations (Théry-Parizot, 2002), e.g. in sample L4, L5 and L6 (Table S2). Taxa assemblages per layer were used for Correspondence Analysis (CA) to statistically distinguish the main organization of burned woody assemblages, and notably to test whether assemblages are distributed according to sites and to elevation. CA was computed using *FactoMineR* of the *R* package (Lê et al., 2008). For synthetic representation, charcoal concentrations per layers were averaged per taxon and per profile to calculate the composition gradient along the elevation. This averaging was possible because each charcoal layer is not stratified due to soil bioturbation (Carcaillet, 2001). The layers from a given profile were thus considered as replicates for that profile. For that purpose, infrequent taxa were clustered, as “broadleaved trees” for *Acer*, *Alnus* cf. *incana*, *Betula*, *Corylus*, *Fraxinus*, cf. *Populus*; “Ericaceae” for *Arctostaphylos*, *Erica*, *Rhododendron*, *Vaccinium*; “other shrub” for *Alnus* cf. *viridis*, *Berberis*, *Juniperus*, cf. *Ononis*, *Rhamnus*, *Rosa*, *Rosaceae Maloideae*, and cf. *Salix*; *Clematis alpina*, the only liana found, was included with “other shrubs” because it generally occurs in the shrub layer. The full list of taxa identified per profile and per layer is in the supplementary information (Table S2).

3. Results

3.1. Burning history

The three chronologies of burning present some differences of pattern at the century scale (Fig. 1), but all three sites show a common multimillennial motif. The main fact of note is that there are no ^{14}C ages on soil charcoal before ca 7580 cal BP [7730–7430 cal BP]. At Lanslevillard, the first occurred at ca 7140 cal BP [7270–6960 cal BP], while the first at Aussois occurred at ca 6390 cal BP [6530–6290 cal BP]. Most dates of soil charcoal coincide with a vague mid-Holocene period, with important evidence of biomass burning from 6500 to 2700 cal BP, although at Lanslevillard this period is much less pronounced. At St Michel and at Aussois, evidence of burning is well reported and continuous. The third period, from 2700 cal BP to the

present, is characterized by repetition of rather brief episodes of burning intermingled with episodes without burning. These brief episodes concern either two or three sites, notably at 2400–2100 cal BP (three sites) and 1700–1400 cal BP (three sites); from 1200 to the present the common pattern is less obvious, although biomass burned simultaneously at Lanslevillard and Aussois firstly between 1000 and 700 cal BP and secondly between 500 and 300 cal BP, and finally, the sites of St Michel and Aussois present a common burning phase during the last 300 years.

When observing the mid-Holocene, from 6500 to 2700 cal BP, it appears that soil charcoal dates occurred both at lower and higher altitudes at all sites (Fig. 1). From 4000 to 2000 cal BP, the number of dates decreases in the upper altitudes, earlier in St Michel, later in Lanslevillard. From 2000 cal BP, no dates on soil charcoal have been obtained above 1,900 m in Aussois, 1,950 m in St Michel, and 2,050 m in Lanslevillard. The occurrence of fire thus depends on both time and altitude.

3.2. Age of charcoal (pyrogenic carbon) stock

The means of the 3 distributions of ^{14}C ages display significant differences according to the Kruskal-Wallis test (KW-test): $p = 0.0019$ (Fig. 2), corresponding to significant differences between the mean of ^{14}C ages distribution of St Michel with from those of Aussois and Lanslevillard (Wilcoxon-test: St Michel vs Aussois $p = 0.0011$; St Michel vs Lanslevillard $p = 0.0099$) but not between sites of Aussois and Lanslevillard $p = 0.6834$). The violin-plot of St Michel illustrates this difference with those of Aussois and Lanslevillard. Further, it is rather regular, although a gentle bulge around 6000 cal BP reveals a first but minor phase of charcoal accumulation before the main bulge that is centred around 4200 cal BP. At Lanslevillard, the main bulge is around 2200 cal BP, but a minor one occurs around 5500 cal BP. Only Aussois shows a clear bimodal distribution with a first mode peaking around 4000 cal BP, and a second around 800 cal BP. These patterns pinpoint a certain independence in burning histories between sites. Both sites situated on south-facing slopes present differences of mean of ^{14}C datings (Wilcoxon-test: St Michel vs Aussois $p = 0.0011$), and both sites situated in very different environments (north- versus south-facing slopes, soil quality) present no differences in mean (Wilcoxon-test: Aussois vs Lanslevillard $p = 0.6834$).

3.3. Past burned biomass per site and per altitude

Correspondence analysis (CA) based on the percentage of taxa per layer shows that each site can be distinguished easily (Fig. 3a). Axis-1 captures 25.4% of the variance of the CA, and 17.1% by axis-2, accounting for a total of 42.5% on this first factorial map. The centroid of Lanslevillard assemblages is on the positive side of both axes, and at the opposite is situated the Aussois centroid (Fig. 3a). Axis-1 distinguishes well all Lanslevillard assemblages from the others, with assemblages above 2,000 m asl situated on the negative part of axis-2. Interestingly, all assemblages >2,000 m asl of the three sites are concentrated on the negative part of axis-2, except one from Aussois. St Michel assemblages from altitudes

below 2,000 m are intermediate and much more dispersed than those of Aussois and Lanslevillard for the same altitude class, indicating a greater heterogeneity and diversity of plant assemblages in the lower subalpine belt. Axis-1 opposes *Pinus cembra* and *Larix-Picea* type on the positive side and *Pinus sylvestris-uncinata* on the negative side. Axis-2 is characterized by *Abies* on the negative side (Fig. 3a). Although *Alnus incana* is correlated to the axis-1, and *V. cf. vitis-idaea* and *V. cf. uliginosum* to the axis-2 (Fig. 3a), they contribute little to the actual variance.

These statistical outputs of the CA are well illustrated in Fig. 3c, which depicts the structure of assemblages (in percentage of anthracomass) along the altitudinal gradient per site. The past subalpine vegetation at St Michel was broadly dominated by *Pinus cembra*, except below 1,800 m where *P. sylvestris/uncinata* dominated burned biomass. The other taxa are minor components of the burned vegetation, i.e., *Acer* (three taxa), *Alnus* (two taxa), *Abies*, *Larix-Picea* type, *Betula*, Ericaceae (five taxa), *Juniperus*, Rosaceae (*Prunus*, Malloideae, *Rosa*), *Corylus*, *Fraxinus*, cf. *Populus*, cf. *Salix*, *Sambucus* (Table S2). At Aussois, charcoal of *P. sylvestris/uncinata* is dominant from 1,700 to 2,100 m, whereas *Pinus cembra* abound above that altitude. The occurrence of Ericaceae is important, i.e., four taxa chiefly *Arctostaphylos* and *Erica*. Other taxa are *Abies*, *Larix-Picea* type, *Acer*, *Betula*, *Berberis*, *Juniperus*, cf. *Ononis*, *Prunus*, *Rhamnus*, cf. *Salix* (Table S2). At Lanslevillard, the lowest altitudes are characterized by both *Abies* and *Larix-Picea* type, whereas the upper altitudes are dominated by *P. cembra*. The minor component of the burned biomass is composed of *P. sylvestris-uncinata*, *Alnus*, *Betula*, *Clematis*, Ericaceae (six taxa), cf. *Salix*, *Sambucus* (Table S2). These three graphs clearly show that the burned biomass differs between sites in the lower subalpine belt but, in the upper subalpine belt, the compositions converge and are homogeneous (Fig. 3c).

Charcoal concentrations per soil profile (ppm) show a general decrease along the altitudinal gradient from 1,700 to 2,400 m (Fig. 3b), but there are some differences between sites. Considering all data until 2,660 m at St Michel and 2,500 m at Aussois, both sites present significant decreases following negative power function (St Michel $r = 0.82$, $p < 0.01$; Aussois $r = 0.81$, $p < 0.01$; no figure). At Lanslevillard, charcoal concentrations are rather homogeneous along the altitudinal gradient. Considering all data, the altitudes of 2,050–2,100 m asl appear as a threshold in the charcoal concentrations, which drop below 120 ppm between 2,100 and 2,500 m (higher subalpine belt). The mean concentrations of soil charcoal or pyrogenic carbon are not significantly different between sites (ANOVA, Tukey HSD post-hoc test; $F = 2.901$; $p = 0.077$; $DF = 2$): $p = 0.167$ for St Michel (mean \pm SE, 39 ± 17 ppm) versus Aussois (140 ± 60 ppm), $p = 0.107$ for St Michel versus Lanslevillard (163 ± 37 ppm), and $p = 0.923$ for Aussois versus Lanslevillard.

4. Discussion

The present study shows that biomass burning, a surrogate of fire regime reconstruction based on soil charcoal dating, presents both similarities and subtle differences among subalpine sites at millennial scale despite obvious contrasts in the local conditions of fire spread. Indeed, a site characterized by conditions of climatic, edaphic, and topographic dryness, with burned biomass dominated by fire-prone trees (i.e., Aussois), does not present significant differences of charcoal dating (Fig. 1) and of mean charcoal dates (Fig. 2) compared to a wetter and colder site with less flammable species (i.e., Lanslevillard; Fig. 2). Surprisingly, in contrast to one working hypothesis, these two sites did not reveal clear differences in burning periods (Figs. 1 and 2), while the burned biomass was significantly different (Fig. 3). The reconstruction of burned biomass was a crucial condition of the present study to test whether fuel composition might have contributed to similarities or differences of biomass burning between sites. Finally, Aussois was actually dominated – as it is at present – by fire-prone vegetation with some species possessing fire-resistance traits (notably the three pine species *P. sylvestris*, *P. uncinata*, and *P. cembra*), while burned biomass at Lanslevillard was characterized by less flammable species/community (*Larix*, *Picea*, *Abies*) with low fire-resistance traits (*Picea*, *Abies*) (Fréjaville et al., 2013b, 2018b; Bär and Mayer, 2020). The most significant differences concern: (i) the two sites exposed to the south (Aussois and St Michel), both in terms of burning chronology (Fig. 1) and mean age of charcoal stock (Fig. 2) and burned biomass (Fig. 3); and (ii) the fact that on north-facing slopes the burning chronology seems episodic (Lanslevillard), whereas chronologies were more continuous on south-facing slopes whatever the number of dating, i.e. 43 at St Michel whereas there are 26 at Aussois and 24 at Lanslevillard (Fig. 1). The following discussion develops over three sections, namely: (i) the nesting of processes highlighted by the present study; (ii) the evidence of land use during the late Holocene; and, finally, (iii) the question of the absence of charcoal dated during the early Holocene that cannot be the evidence of the absence of fire.

4.1. Nesting broad and local patterns of subalpine biomass burning history

At multi-millennial pattern can be discerned at the valley scale, suggesting a control of biomass burning by the regional climate (three main similar periods at the three sites, no clear differences in burning between the two most contrasting sites). However, local drivers can offset this common pattern, notably by promoting fire when other sites seem little or not all affected (i.e., around 7500–7000 at St Michel) or by suppressing fires (i.e., since 2000 years ago in St Michel) while other sites still remain active. This suggests nesting processes in the control of fire regimes in the subalpine forest ecosystem, involving large-scale and local drivers. Interestingly, the effect of north- versus south-facing slopes was highlighted at the millennial scale based on sedimentary lacustrine charcoal from the same region of the western Alps (Leys and Carcaillet, 2016), showing that fire frequency was more homogeneous between sites on north-facing slopes than on south-facing slopes where it was more stochastic, perhaps due to natural drivers but chiefly down to the effect of human activities. However, the main finding of the present study is that a drier site with

more fire-prone vegetation is not characterized by a longer or more continuous chronology of burning. However, the colder, wetter site depicts a more episodic chronology, suggesting that it has been less frequently subjected to fire, which is also an output of one model-based study set out by Schumacher and Bugmann (2006).

Many have underscored the importance of human activities as probable explanations of the alteration of fire regimes in alpine areas since 4000 or 4500 years ago (depending on the study, e.g., Leys and Carcaillet, 2016; Vanni re et al., 2016). The main period of biomass burning in the subalpine belt or high altitudes in the Alps, whatever the analytical methods used (sedimentary charcoal *versus* soil charcoal), is the mid-Holocene from ca 6000 to 2500 cal BP, although the exact timing of this ‘mid-Holocene’ period varies between studies due to the number of observations, the numerical methods implemented, and site locations (Leys and Carcaillet, 2016; Vanni re et al., 2016; present outputs). To avoid speaking about a ‘period’ with vague limits, it is preferable to evoke a humped-back pattern of biomass burning, peaking somewhere between 6000 and 2500 cal BP depending on local drivers, including human activities. As classically evoked with paleo-data, it is not easy to determine what, between frequency, severity, or extent, explains the changes in biomass burning history. Several studies mentioned the decrease in available biomass to explain the changes, while frequency was little involved as a driver but rather as a consequence of this change in forest biomass (Blarquez et al., 2012; Vanni re et al., 2016). One study in the same valley as the present study evidenced a sharp increase in fire frequency about 7500–7000, pre-dating and explaining the drop in biomass and the change in plant composition (Genries et al., 2009a). Similar results were obtained between 2500 and 1800 cal BP at other sites with final total woodland suppression after the rise in fire frequency, while from 7000 to 2500 cal BP the fire frequency and the vegetation were very steady and frequently moderate (Genries et al., 2009c), contrasting with the frequently reported humped-back mid-Holocene biomass burning in the western subalpine ecosystems (Leys and Carcaillet 2016). Further south (ca 50–80 km) in the driest and warmer area of the western Alps, similar chronologies of biomass burning, based on 29 and 54 datings of soil charcoal respectively (Talon, 2010; Saulnier et al., 2015), show long periods of burning starting around 7000 or 9000 cal BP, respectively, and lasting until ca 250 cal BP. Most of these charcoals came from north-, west-, or east-facing slopes. However, the best we can say is that the maximum of biomass burning occurred from 5000 to 500 cal BP (this will remain so, at least until a statistical analysis is conducted to accurately indicate the strength and the timing of these southern chronologies). An interesting fact of these southern studies is that most of the dated soil charcoal sampled in the higher subalpine belt (2,200–2,900 m asl) is concentrated during this 5000–500 cal BP period (Talon, 2010; Saulnier et al., 2015), contrary to the present study where the upper subalpine belt (2,100–2,500 m) burned earlier, between 6500 and 3000 cal BP, mostly on south-facing slopes (Fig. 1). This highlights regional/local differences. However, based on sedimentary charcoal, the fire frequency in the

subalpine belt in the southern Alps attained a maximum (humped-back) about 4000–3700 cal BP, during a long period that started 7000 cal BP and ended at ca 3000 cal BP (Carcaillet and Blarquez, 2017), matching with the present chronology (Fig. 1).

4.2. The obvious role of land use

A general fire motif of all these reported studies is that biomass burning generally starts to decrease sometime between 4000 and 2000 cal BP until today in the western Alps, depending on sites/valleys/massifs (e.g., Vanni re et al., 2016). In the northwestern Alps (Fig. 1), the evidence of fire in the upper subalpine became more and more rare after 3000 cal BP, probably foreshadowing the current subalpine grassland. Further, the brief episodes of biomass burning – common to two or three sites during the last 2500 years (Fig. 1) – could well be related to a phase of land use expansion using fire to clear forest understoreys or to create grasslands, although brief climatic episodes favorable to natural fire occurrence (i.e., warmer, drier periods) cannot be ruled out. The reporting of such motifs with the same dates in other areas of the western Alps would be needed to support a general climate interpretation. Similarly, the absence of quantitative archaeological data-base in the study area hinders any possibility of reaching firm conclusions as to the societal effect on the sequential motif of brief episodes in the last 2500 years.

At southern sites, this link between charcoal dates and altitude is less obvious because many dates cover the last 3000 years (Talon, 2010) or after 4500 cal BP (Saulnier et al., 2005), suggesting differences between sites/valleys/massifs. Associated to the altitudinal gradient is the charcoal concentration per soil profile that shows a general decrease along the altitudinal gradient in response to increasing stress, although this pattern varies a lot between sites (Fig. 3b). These distributions were expected (Carcaillet and Talon, 2001) and correspond to a common subalpine pattern (Carnelli et al., 2004; Talon, 2010) well explained by the primary productivity that decreases with the elevation, and the assumed low resilience rate of woodlands to disturbances near the treeline.

4.3. The early Holocene: No fire or bias due to residence time of soil charcoal?

On a first approach, the early Holocene seems characterized by the absence of biomass burning, but this needs careful and thorough interpretation, because the absence of evidence is not the evidence of absence. If we compare the chronology of St Michel with a charcoal sedimentary series available at the same location (Genries et al., 2009a), sampled from a pond 150 m from the present three plots situated at 1,960 m a.s.l. (i.e. M4, M7, M8; Table S1), the sediments demonstrate an abundance of charcoal from 9000 to 7000 cal BP, while soil reveals no charcoal during that period. After 7000 cal BP, the sedimentary charcoal concentrations decrease, while soil charcoal stock starts to amass (Fig. 1). Similar differences between charcoal stocks in sediments and in soil have been previously reported (e.g., Ohlson et al., 2013; Couillard et al., 2019). Such differences suggest that the residence time of macro-charcoal in soil might be

limited due to the fragmentation of charred particles under the effect of freeze–thaw, roots, and soil invertebrates (Carcaillet, 2001), or to the biochemical decay of charcoal which depends on their chemical stability (Preston and Schmidt, 2006; Ascough et al., 2011). Polyaromatic charcoals are the most stable and resistant to weathering or decay. Leaching or degradation of hydrophobic compounds of soil charcoal would decrease their residence time (Criscuoli et al., 2014). Polyaromatics are produced at higher temperatures (e.g., Novakov et al., 1997; Alexis et al., 2010), i.e., during very intense fires. Such intense fires – suitable for producing polyaromatics – do not seem to be a common feature in subalpine forests (Genries et al., 2009b); further, the extreme conditions needed to obtain intense fires are not so common (Dupiré et al., 2017; Fréjaville et al., 2018a) and then, simply, subalpine fires are rare at present.

Consequently, there are two alternative hypotheses: either the stock of charcoal >0.4 mm was too fragmented and weathered in the soil resulting in a rather brief residence time and thus its disappearance, or fire intensities changed during the Holocene around 7000 cal BP from low to highly intense. The change would have resulted in the disappearance of poorly aromatic charcoal of the early Holocene and the sequestration of highly polyaromatic charcoal stock produced by intense fires from 7000 cal BP to the present. This hypothesis still remains open and could be tested with FTIR spectra analyses on sedimentary charcoal (e.g., Maezumi et al., 2021).

5. Conclusion

Our working hypothesis that the strength of mountain natural and local drivers should offset the effects of regional climate is not validated. The homogeneity of the fire regime among sites thus underscores that climate was the main driver during the Holocene. Long-term subalpine fires are obviously controlled by climate at the millennial scale. Local conditions contribute little in determining variability the millennial to century scale. The mid-Holocene was an important period for climatic biomass burning in the subalpine zone of the western Alps, while fires since about 2500 years ago appear much more episodic, suggesting that human activities have exercised a key role on their control. Our study outcomes that the meticulous use of soil charcoal dating and identification can accurately reconstruct burning history at the landscape scale, as well as the age structure of the resistant carbon sequestered in soil. The establishment of a global database of soil charcoal dating is thus a needed future task to efficiently combine and complete sedimentary charcoal database, namely the Global Paleofire Database (Power et al., 2008).

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and material

All data generated or analyzed during this study are included in this published article and its supplementary information files.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

C.C. conceived and designed the study; C.C. realized all the samplings, and most of the charcoal identification; B.B. analyzed the radiocarbon dating, and F.C. contributed to statistical analyses; C.C. interpreted the results and wrote the manuscript, which was commented on and improved by B.B. and F.C.

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References

- Alexis, M.A., Rumpel, C., Knicker, H., Leifeld, J., Rasse, D., Péchot, N., Bardoux, G., Mariotti, A., 2010. Thermal alteration of organic matter during a shrubland fire: a field study. *Org. Geochem.* 41, 690–697.
- Allen, T.F.H., 2009. Hierarchy theory in ecology, in: Jorgensen, S.E. (Ed.) *Ecosystem ecology – a derivative of encyclopedia of ecology*. Elsevier, Amsterdam.

- Ascough, P.L., Bird, M.I., Francis, S.M., Thornton, B., Midwood, A.J., Scott, A.C., Apperley, D.C., 2011. Variability in oxidative degradation of charcoal: influence of production conditions and environmental exposure. *Geochim. Cosmochim. Acta* 75, 2361–2378.
- Bär, A., Mayr, S., 2020. Bark insulation: ten central alpine tree species compared. *For. Ecol. Manag.* 474, 118361. <https://doi.org/10.1016/j.foreco.2020.118361>
- Bartoli, C., 1966. Etudes écologiques sur les associations végétales forestières de la Haute Maurienne. *Ann. For. Sci.* 23, 432–751.
- Bégin, Y., Marguerie, D., 2002. Characterization of tree macroremains production in a recently burned conifer forest in northern Québec, Canada. *Plant Ecol.* 159, 143–152.
- Blarquez, O., Carcaillet, C., Elzein, T.M., Roiron, P., 2012. Needle accumulation rate model-based reconstruction of palaeo-tree biomass in the western subalpine Alps. *Holocene* 22, 579–587. <https://doi.org/10.1177/0959683611427333>.
- Bond, W.J., Keeley, J.E., 2005. Fire as a global “herbivore”: the ecology and evolution of flammable ecosystems. *Trends Ecol. Evol.* 20, 387–394. <https://doi.org/10.1016/j.tree.2005.04.025>.
- Carcaillet, C., 1998. A spatially precise study of fires, climate and human impact within the Maurienne valley, North French Alps. *J. Ecol.* 86, 384–396. <https://doi.org/10.1046/j.1365-2745.1998.00267.x>.
- Carcaillet, C. 2001. Soil particles reworking evidences by AMS ¹⁴C dating of charcoal. *Comptes Rendus Acad. Sci. Paris, Ser. II-A.* 332, 21–28. [https://doi.org/10.1016/S1251-8050\(00\)01485-3](https://doi.org/10.1016/S1251-8050(00)01485-3).
- Carcaillet, C., Blarquez, O., 2017. Fire ecology of a tree glacial refugium on a nunatak with a view on Alpine glaciers. *New Phytol.* 216, 1281–1290. <https://doi.org/10.1111/nph.14721>.
- Carcaillet, C., Talon, B., 2001. Soil carbon sequestration by Holocene fires inferred from soil charcoal in the dry French Alps. *Arct. Antarct. Alp. Res.* 33, 282–288. <https://doi.org/10.1080/15230430.2001.12003432>.
- Carcaillet, C., Thion, M., 1996. Pedoanthracological contribution to the evolution of the upper treeline in the Maurienne Valley (North French Alps): Methodology and preliminary data. *Rev. Palaeobot. Palynol.* 91, 399–416. [https://doi.org/10.1016/0034-6667\(95\)00060-7](https://doi.org/10.1016/0034-6667(95)00060-7).
- Carnelli, A.L., Theurillat, J.P., Thion, M., Vadi, G., Talon, B., 2004. Past uppermost tree limit in the central European Alps (Switzerland) based on soil and soil charcoal. *Holocene* 14, 393–405.
- Clark, J.S., Lynch, J., Stocks, B., Goldammer, J., 1998. Relationships between charcoal particles in air and sediments in west-central Siberia. *Holocene* 8, 19–29.
- Couillard, P.L., Tremblay, J., Lavoie, M., Payette, S., 2019. Comparative methods for reconstructing fire histories at the stand scale using charcoal records in peat and mineral soils. *For. Ecol. Manag.* 433, 376–385. <https://doi.org/10.1016/j.foreco.2018.11.015>.
- Criscuoli, I., Alberti, G., Baronti, S., Favilli, F., Martinez, C., Calzolari, C., Pusceddu, E., Rumpel, C., Viola, R., Miglietta, F., 2014. Carbon sequestration and fertility after centennial time scale incorporation of charcoal into soil. *PLoS ONE*, e91114. <https://doi.org/10.1371/journal.pone.0091114>.
- Debelmas, J., 1989. Geologic Map 775, Carte Géologique de la France, feuille de Modane, 1:50 000. Edition du BRGM, Orléans, France.
- Didier, L., 2001. Invasion patterns of European larch and Swiss stone pine in subalpine pastures in the French Alps. *For. Ecol. Manag.* 145, 67–77.
- Dupire, S., Curt, T., Bigot, S., 2017. Spatio-temporal trends in fire weather in the French Alps. *Sci. Total Environ.* 595, 801–817. <https://doi.org/10.1016/j.scitotenv.2017.04.027>.
- Dupiré, S., Curt, T., Bigot, S., Fréjaville, T., 2019. Vulnerability of forest ecosystems to fire in the French Alps. *Eur. J. For. Res.* 138, 813–830. [10.1007/s10342-019-01206-1](https://doi.org/10.1007/s10342-019-01206-1).

- Flannigan, M.D., Krawchuk, M.A., de Groot, W.J., Wotton, B.M., Gowman, L.M., 2009. Implications of changing climate for global wildland fire. *Int. J. Wildland Fire* 18, 483e507, <https://doi.org/10.1071/WF08187>.
- Fréjaville, T., Carcaillet, C., Curt, T., 2013a. Calibration of charcoal production from trees biomass for soil charcoal analyses in subalpine ecosystems. *Quat. Intern.* 289, 16-23. <https://doi.org/10.1016/j.quaint.2012.02.043>.
- Fréjaville, T., Curt, T., Carcaillet, C., 2013b. Bark flammability as a fire-response trait for subalpine trees. *Front Plant Sci.* 4, 466. <https://doi.org/10.3389/fpls.2013.00466>.
- Fréjaville, T., Curt, T., Carcaillet, C., 2018a. Higher potential fire intensity at the dry margins of European mountain trees. *J. Biogeogr.* 45, 2003-2015. <https://doi.org/10.1111/jbi.13386>.
- Fréjaville, T., Vilà-Cabrera, A., Curt, T., Carcaillet, C., 2018b. Aridity and competition drive fire resistance trait covariation in mountain trees. *Ecosphere* 9, e02493. <https://doi.org/10.1002/ecs2.2493>.
- Fudral, S., Deville, E., Nicoud, G., Pognante, U., Guillot, P.L., Jaillard, E., 1994. Geologic map 776, Carte Géologique de la France, feuille de Lanslebourg-Mont-d'Ambin, 1:50 000. Edition du BRGM, Orléans.
- Gao, X., Giorgi, F., 2008. Increased aridity in the Mediterranean region under greenhouse gas forcing estimated from high resolution simulations with a regional climate model. *Glob. Planet. Change* 62, 195–209. <https://doi.org/10.1016/j.gloplacha.2008.02.002>.
- Gavin, D.G., 2001. Estimation of inbuilt age in radiocarbon ages of soil charcoal for fire history studies. *Radiocarbon* 43, 27–44.
- Gavin, D.G., Brubaker, L.B., Lertzman, K.P., 2003. Holocene fire history of a coastal temperate rain forest based on soil charcoal radiocarbon dates. *Ecology* 84, 186–201.
- Genries, A., Mercier, L., Lavoie, M., Muller, S.D., Radakovitch, O., Carcaillet, C., 2009a. The effect of fire frequency on local cembra pine populations. *Ecology* 90, 476-486. <https://doi.org/10.1890/07-1740.1>.
- Genries, A., Morin, X., Chauchard, S., Carcaillet, C., 2009b. The function of surface fires in the dynamics and structure of a formerly grazed old subalpine forest. *J. Ecol.* 97, 728-741, <https://doi.org/10.1111/j.1365-2745.2009.01518.x>.
- Genries, A., Muller, S.D., Mercier, L., Bircker, L., Carcaillet, C., 2009c. Fires control spatial variability of subalpine vegetation dynamics during the Holocene in the Maurienne valley (French Alps). *Ecoscience* 16, 13-22. <https://doi.org/10.2980/16-1-3180>.
- Hajdas, I., Schlumpf, N., Minikus-Stary, N., Hagedorn, F., Eckmeier, E., Schoch, W., Burga, C., Bonani, G., Schmidt, M.W.I., Cherubini, P., 2007. Radiocarbon ages of soil charcoals from the southern Alps, Ticino, Switzerland. *Nucl. Instrum. Methods Phys. Res. B* 259, 398–402.
- Hellberg, E., Carcaillet, C., 2003. Wood anatomy of West-European *Betula*: quantitative descriptions and applications for routine identification in paleoecological studies. *Ecoscience* 10, 370-379. <https://doi.org/10.1080/11956860.2003.11682786>.
- Im, E.S., Coppola, E., Giorgi, F., Bi, X., 2010. Local effects of climate change over the Alpine region: A study with a high resolution regional climate model with a surrogate climate change scenario. *Geophys. Res. Lett.* 37, L0570.
- IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.
- Jacquot, C., 1955. Atlas d'anatomie des bois de conifères. Centre technique du bois, Paris.
- Jacquot, C., Trenard, Y., Dirol, D., 1973. Atlas d'anatomie des bois des Angiospermes (Essences feuillues). Centre technique du bois, Paris.

- Kasin, I., Ellingsen, V.M., Aspun, J., Ohlson, M., 2017. Spatial and temporal dynamics of the soil charcoal pool in relation to fire history in a boreal forest landscape. *Can. J. For. Res.* 47, 28-35.
- Lê, S., Josse, J., Husson, F., 2008. FactoMineR: An R Package for Multivariate Analysis. *J. Stat. Software* 25, 1-18.
- Leys, B., Carcaillet, C., 2016. Subalpine fires: the roles of vegetation, climate and, ultimately, land uses. *Clim. Change* 135, 683–697 <https://doi.org/10.1007/s10584-016-1594-4>.
- Lingua, E., Cherubini, P., Motta, R., Nola, P., 2008. Spatial structure along an altitudinal gradient in the Italian central Alps suggests competition and facilitation among coniferous species. *J. Veg. Sci.* 19, 425–436.
- Loehman, R.A., Reinhardt, E., Riley, K.L., 2014. Wildland fire emissions, carbon and climate: Seeing the forest and the trees – Across-scale assessment of wildfire and carbon dynamics in fire-prone, forested ecosystems. *For. Ecol. Manage.* 317, 9-19.
- Lynch, J.A., Clark, J.S., Stocks, B.J., 2004. Charcoal production, dispersal, and deposition from the Fort Providence experimental fire: Interpreting fire regimes from charcoal records in boreal forests. *Can. J. For. Res.* 34, 1642–1656.
- Maezumi, S.Y., Gosling, W.D., Kirschner, J., Chevalier, M., Cornelissen, H.L., Jeinecke, T., McMichael, C.N.H., 2021. A modern analogue matching approach to characterize fire temperatures and plant species from charcoal. *Palaeogeogr. Palaeoclim. Palaeoecol.* 578, 110580. <http://doi.org/10.1016/j.palaeo.2021.110580>
- Michczyński, A., 2007. Is it possible to find a good point estimate of a calibrated radiocarbon date? *Radiocarbon* 49, 393-401. <http://doi.org/10.1017/S0033822200042326>.
- Moritz, M.A., Batllori, E., Bradstock, R.A., Gill, M., Handmer, J., Hessburg, P.F., Leonard, J., McCaffrey, S., Odion, D.C., Schoennagel, T., Syphard, D.A., 2014. Learning to coexist with wildfire. *Nature* 515, 58–66. <http://dx.doi.org/10.1038/nature13946>.
- Moritz, M.A., Parisien, M.A., Batllori, E., Krawchuk, MA, Van Dorn, J, Ganz, DJ, Hayhoe, K, 2012. Climate change and disruptions to global fire activity. *Ecosphere* 3, 49. <http://dx.doi.org/10.1890/ES11-00345.1>.
- Motta, R., Lingua, E., 2005. Human impact on size, age, and spatial structure in a mixed European larch and Swiss stone pine forest in the Western Italian Alps. *Can. J. For. Res.* 35:1809–1820.
- Mourier, B., Poulénard, J., Chauvel, C., Faivre, P., Carcaillet, C., 2008. Distinguishing subalpine soil types using extractible Al and Fe fractions and REE geochemistry. *Geoderma* 145, 107-120. <https://doi.org/10.1016/j.geoderma.2008.03.001>
- Novakov, T., Cachier, H., Clark, J.S., Gaudichet, A., Macko, S., Masclat, P., 1997. Characterization of particulate products of biomass combustion, in: Clark, J.S., Cachier, H., Goldammer, J.G., Stocks, B. (eds), *Sediment Records of Biomass Burning and Global Change*, pp. 117–143. Springer Verlag, Berlin. https://doi.org/10.1007/978-3-642-59171-6_6
- Ohlson, M., Kasin, I., Nordtug Wist, A., Bjune, A.E., 2013. Size and spatial structure of the soil and lacustrine charcoal pool across a boreal forest watershed. *Quat. Res.* 80, 417-424.
- Ohlson, M., Tryterud, E., 2000. Interpretation of the charcoal record in forest soils: Forest fires and their production and deposition of macroscopic charcoal. *Holocene* 10, 519–525.
- O’Neill, R.V., 1988. Hierarchy theory and global change, in: Rosswall, T., Woodmansee, R.G., Risser, P.G. (eds) *Scales and global change*, pp 29–45. Wiley, New York.
- Payette, S., Delwaide, A., Schaffhauser, A., Magnan, G., 2012. Calculating long-term fire frequency at the stand scale from charcoal data. *Ecosphere* 3, 59. <https://doi.org/10.1890/ES12-00026.1>

- Payette, S., Gagnon, R., 1985. Late Holocene deforestation and tree regeneration in the forest-tundra of Quebec. *Nature* 202, 469-461.
- Power, M.J., Marlon, J., Ortiz, N., Bartlein, P.J., Harrison, S.P., Mayle, F.E., Ballouche, A., Bradshaw, R.H.W., Carcaillet, C., Cordova, C., Mooney, S., Moreno, P.I., Prentice, I.C., Thonicke, K., Tinner, W., Whitlock, C., Zhang, Y., Zhao, Y., Ali, A.A., Anderson, R.S., Beer, R., Behling, H., Briles, C., Brown, K.J., Brunelle, A., Bush, M., Camill, P., Chu, G.Q., Clark, J., Colombaroli, D., Connor, S., Daniau, A.-L., Daniels, M., Dodson, J., Doughty, E., Edwards, M.E., Finsinger, W., Foster, D., Frechette, J., Gaillard, M.-J., Gavin, D.G., Gobet, E., Haberle, S., Hallett, D.J., Higuera, P., Hope, G., Horn, S., Inoue, J., Kaltenrieder, P., Kennedy, L., Kong, Z.C., Larsen, C., Long, C.J., Lynch, J., Lynch, E.A., McGlone, M., Meeks, S., Mensing, S., Meyer, G., Minckley, T., Mohr, J., Nelson, D.M., New, J., Newnham, R., Noti, R., Oswald, W., Pierce, J., Richard, P.J.H., Rowe, C., Sanchez Goñi, M.F., Shuman, B.N., Takahara, H., Toney, J., Turney, C., Urrego-Sanchez, D.H., Umbanhowar, C., Vandergoes, M., Vanniere, B., Vescovi, E., Walsh, M., Wang, X., Williams, N., Wilmshurst, J., Zhang, J.H., 2008. Changes in fire regimes since the Last Glacial Maximum: an assessment based on a global synthesis and analysis of charcoal data. *Clim. Dyn.* 30, 887-907. <https://doi.org/10.1007/s00382-007-0334-x>.
- Preston, C.M., Schmidt, M.W.I., 2006. Black (pyrogenic) carbon: a synthesis of current knowledge and uncertainties with special consideration of boreal regions. *Biogeosciences* 3, 397–420.
- Saulnier, M., Talon, B., Edouard, J.L., 2015. New pedoanthracological data for the long-term history of forest species at mid-high altitudes in the Queyras Valley (Inner Alps). *Quat. Int.* 366, 15–24.
- Schumacher, S., Bugmann, H. 2006. The relative importance of climatic effects, wildfires and management for future forest landscape dynamics in the Swiss Alps. *Glob. Change Biol.* 12, 1435e1450. <https://doi.org/10.1111/j.1365-2486.2006.01188.x>.
- Schweingruber, F.H., 1990. Anatomie europäischer Hölzer. Paul Haupt, Bern.
- Stuiver, M., Reimer, P.J., Reimer, R.W., 2021. CALIB 8.2 [WWW program]. <http://calib.org>.
- Talon, B., 1997. Etude anatomique et comparative de charbons de bois de *Larix decidua* Mill. et de *Picea abies* (L.) Karst. *C. R. Acad. Sci. Paris Life Science* 320, 581-588.
- Talon, B., 2004. Wood anatomical criteria for identification of European Boreo-Alpine Ericaceae. International symposium of wood sciences, IAWA-IAWS, 24-29 October 2004, Montpellier, France.
- Talon, B., 2010. Reconstruction of Holocene high altitude vegetation cover in the French Southern Alps: evidence from soil charcoal. *Holocene* 20, 34-44.
- Talon, B., Payette, S., Filion, L., Delwaide, A., 2005. Reconstruction of the long-term fire history of an old-growth deciduous forest in southern Québec, Canada, from charred wood in mineral soils. *Quat. Res.* 64, 36–43.
- Tasser, E., Tappeiner, U., 2002. Impact of land use changes on mountain vegetation. *App. Veg. Sci.* 5, 173–184.
- Tasser, E., Walde, J., Tappeiner, U., Teutsch, A., Noggler, W., 2007. Land use changes and natural reforestation in the Eastern Central Alps. *Agr. Ecosyst. Environ.* 118, 115–129
- Telford, R.J., Heegaard, E., Birks, H.J.B., 2004. The intercept is a poor estimate of a calibrated radiocarbon age. *Holocene* 14, 296-298.
- Théry-Parisot, I., 2002. Fuel management (bone and wood) during the Lower Aurignacian in the Pataud Rock Shelter (Lower Palaeolithic, Les Eyzies de Tayrac, Dordogne, France). Contribution of experimentation. *J. Archaeol. Sci.* 29, 1415-1421.
- Tian, Y.Q., Davies-Colley, R.J., Gong, P., Thorrold, B.W., 2001. Estimating solar radiation on slopes of arbitrary aspect. *Agr. For. Meteorol.* 109, 67-74.

- Yocom Kent, L.L., Fulé, P.Z, Brown, P.M., Cerano-Paredes, J., Cornejo-Oviedo, E., Cortés Montano, C., Drury, S.A., Falk, D.A., Meunier, J., Poulos, H.M., Skinner, C.N., Stephens, S.L., Villanueva-Díaz, J., 2017. Climate drives fire synchrony but local factors control fire regime change in northern Mexico. *Ecosphere* 8, e01709. <https://doi.org/10.1002/ecs2.1709>.
- Zumbrunnen, T., Bugmann, H., Conedera, M., Bürgi, M., 2009. Linking forest fire regimes and climate – a historical analysis in a dry inner Alpine valley. *Ecosystems* 12, 73–86. <https://doi.org/10.1007/s10021-008-9207-3> .

Figure captions

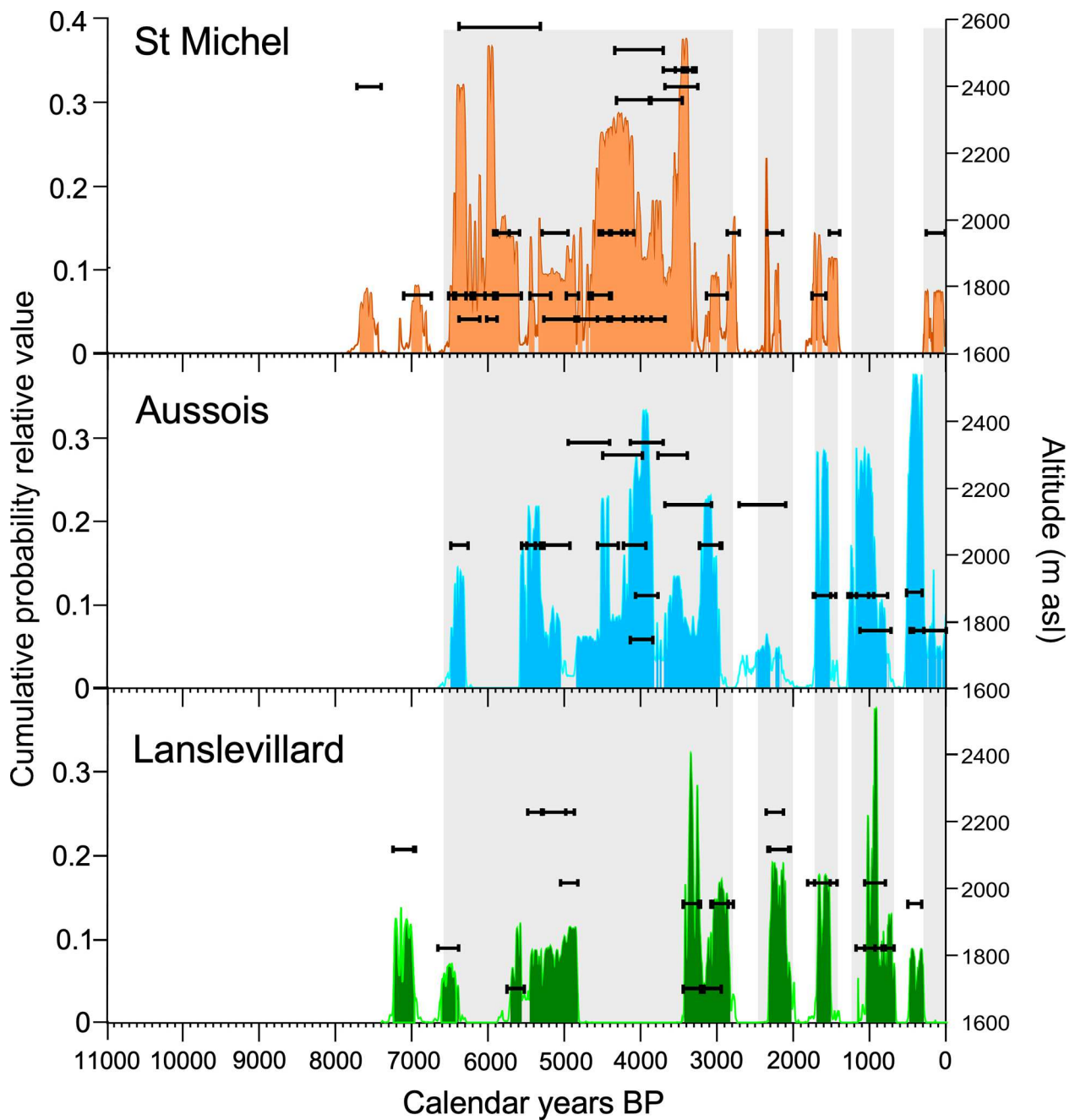


Figure 1. Biomass burning chronology during the Holocene, expressed in probability density function of calendar ^{14}C dating ((left-end y-axis)): 43 dates at St Michel, 26 at Aussois, and 24 at Lanslevillard. '0 cal yr BP' corresponds to 1950 CE by convention. The ranges of the individual ^{14}C ages are shown by horizontal bars and plotted against the sampling altitude (right-end y-axis).

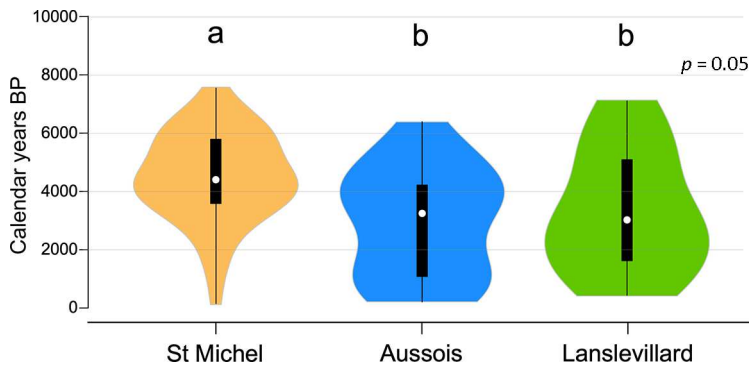


Figure 2. Violin-plots represent the distribution of ^{14}C ages per site illustrating the periods of biomass burning and charcoal sequestration in soil. The white dots represent the median and the black rectangles are the interquartile range, and the envelope is a kernel density estimation of the distribution. The different letters indicate significant differences in the mean at $p = 0.05$ (Wilcoxon-test).

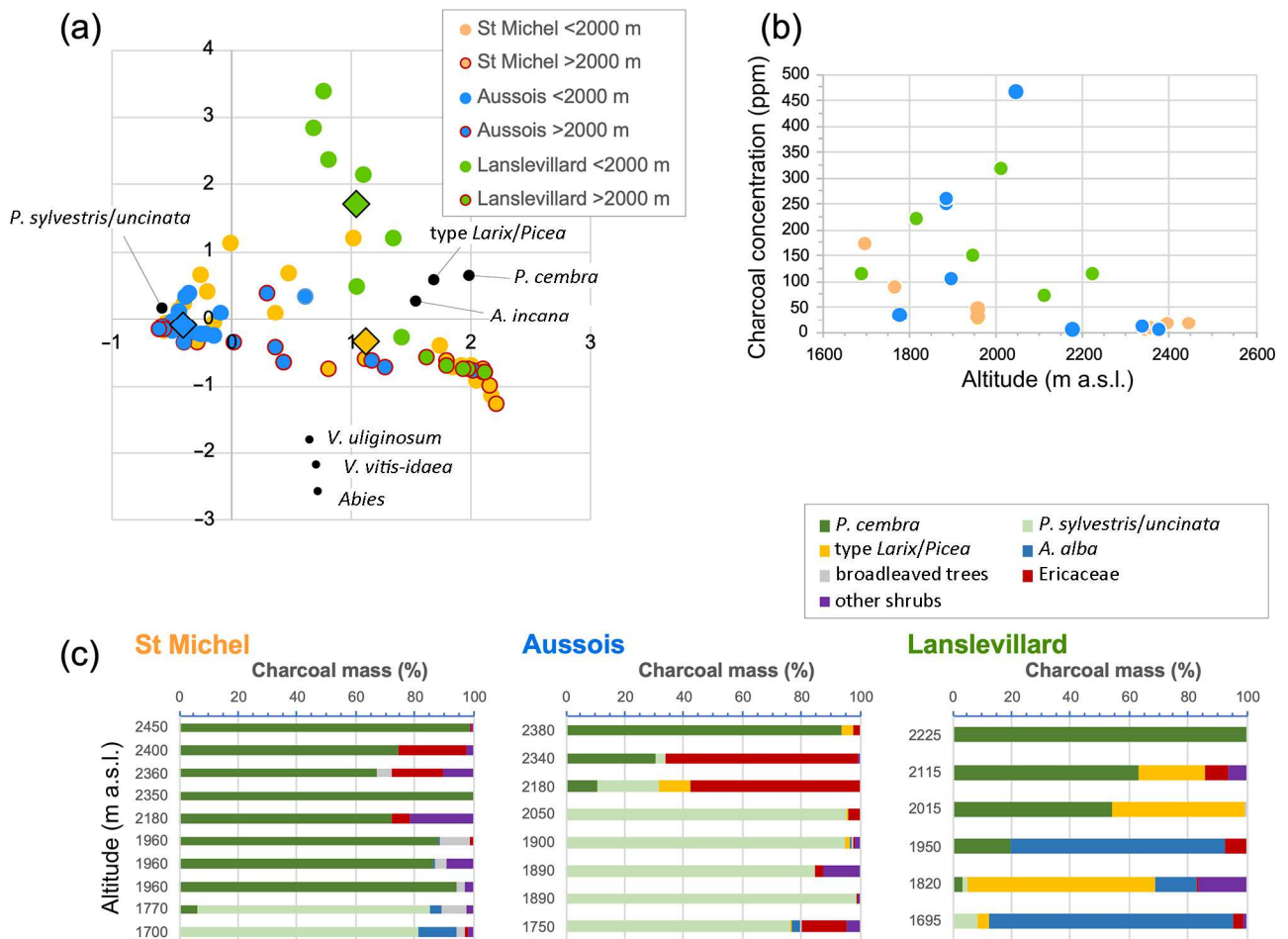


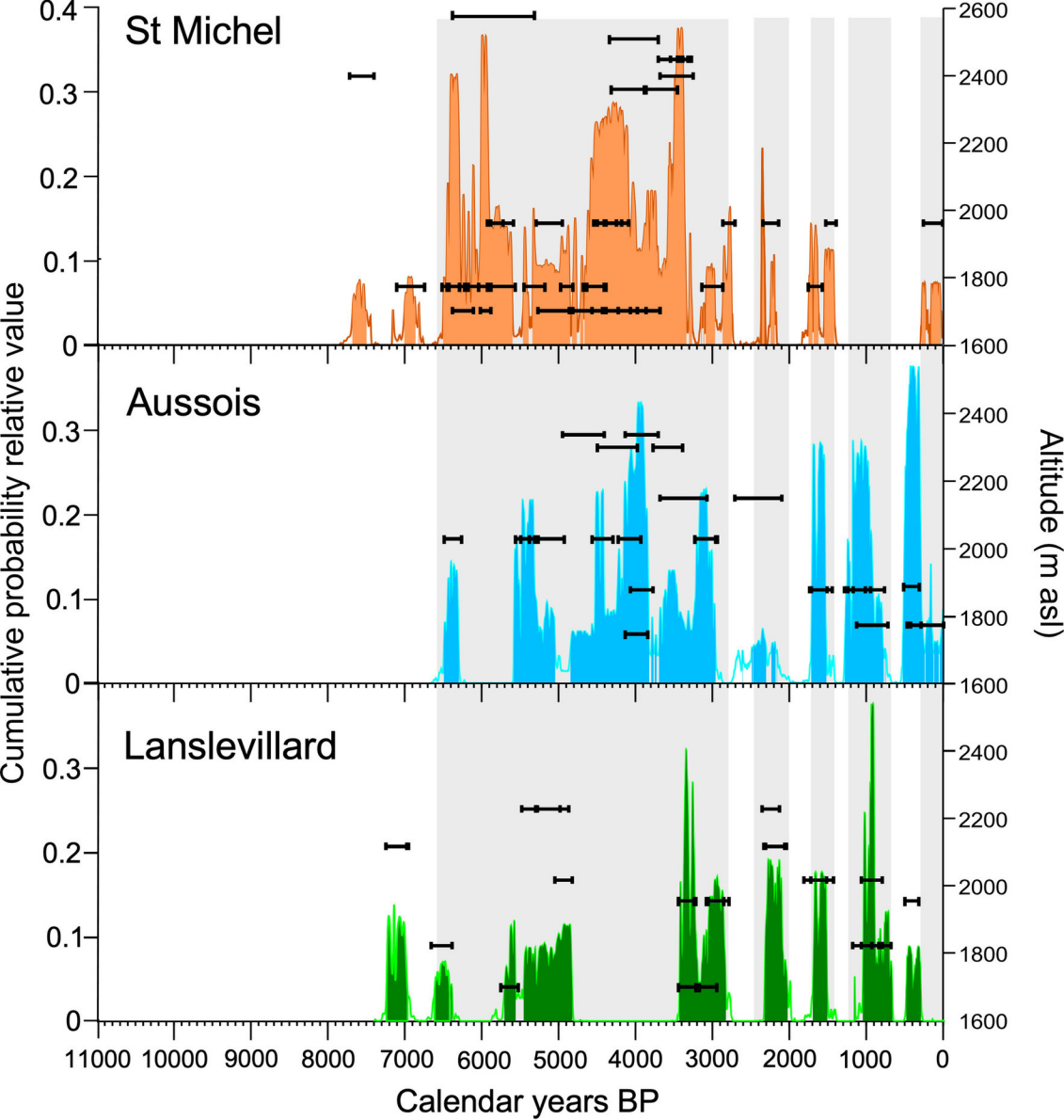
Figure 3. Synthesis of burned biomass at the three sites. **(a)** Biplot of axes 1 and 2 of a correspondence analysis based on identified charcoal assemblages per soil layer; dots correspond to layers, and large diamonds correspond to the centroid of dots per site; dots with a red border are layers from plots >2,000 m asl. **(b)** Total charcoal concentration per profile ($\text{mg}_{\text{char}} \cdot \text{kg}_{\text{soil}}^{-1}$ or ppm) plotted against altitude. **(c)** Diagram

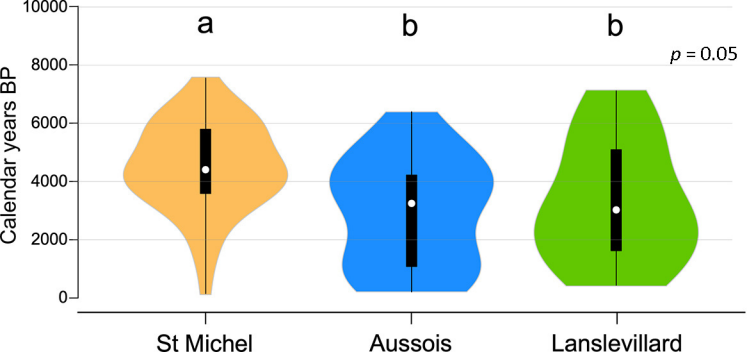
of charcoal abundances plotted against altitude (percentage of soil charcoal mass per species averaged per profile); this representation depicts the structure of assemblages of burned biomass along the altitudinal gradient and per site. Common color chart in **(a)** and **(b)**, such as yellow dots for St Michel, blue for Aussois, and green for Lanslevillard.

Table 1. Main landscape features of sampling sites and number of radiocarbon datings per site.

Site name	Saint-Michel	Aussois	Lanslebourg
Sampling altitude range	1,700–2,450 m asl	1,750–2,380 m asl	1,965–2,255 m asl
Longitude (°)	45.24°N	45.24°N	45.28°N
Latitude (°)	6.48°E	6.75°E	6.95°E
Slope exposure	south	south	north
Slope degree	20°–30°	20°–30°	20°–30°
Bedrock	Westphalian black (coal) sandstones and shales, glacial till	Triassic dolomite, cargneule and gypsum, glacial till	Cretaceous marbles and calcareous shales, glacial till
Soil	Acidic brown soil pH 4.0–5.0	Neutral brown soil pH 5.5–6.5	Alkaline calcimorph pH >7.0
Climate (mean \pm sd)			
Alt. weather station	1,360 m asl	1,490 m asl	2,000 m asl
Period	[1967–1999]	[1950–1999]	[1970–1999]
T_{Ann} (°C)	7.1 \pm 0.6	7.2 \pm 0.6	2.5 \pm 1.0
T_{JJA} (°C)	14.4 \pm 0.9	14.5 \pm 0.7	10.1 \pm 1.5
T_{DJF} (°C)	0.4 \pm 1.5	0.7 \pm 1.2	–4.2 \pm 1.8
P_{Ann} (mm·year ⁻¹)	947 \pm 184	712 \pm 149	925 \pm 233
P_{JJA} (mm)	204 \pm 59	156 \pm 49	247 \pm 96
Present-day vegetation	subalpine grasslands	subalpine grasslands intermixed with mixed conifer forest (<i>Pinus cembra</i> , <i>Pinus uncinata</i> , <i>Picea abies</i> , <i>Pinus sylvestris</i>)	subalpine grasslands (upper altitudes) or mixed conifer forest (<i>Pinus cembra</i> , <i>Pinus uncinata</i> , <i>Picea abies</i> , <i>Larix decidua</i> , <i>Abies alba</i>)
Number of ¹⁴ C ages	43	26	24

T_{Ann} : mean annual temperature; T_{JJA} : mean monthly temperature of June, July and August (summer); T_{DJF} : mean monthly temperature of December, January and February (winter); P_{Ann} : mean annual precipitation; P_{JJA} : mean summer precipitation.





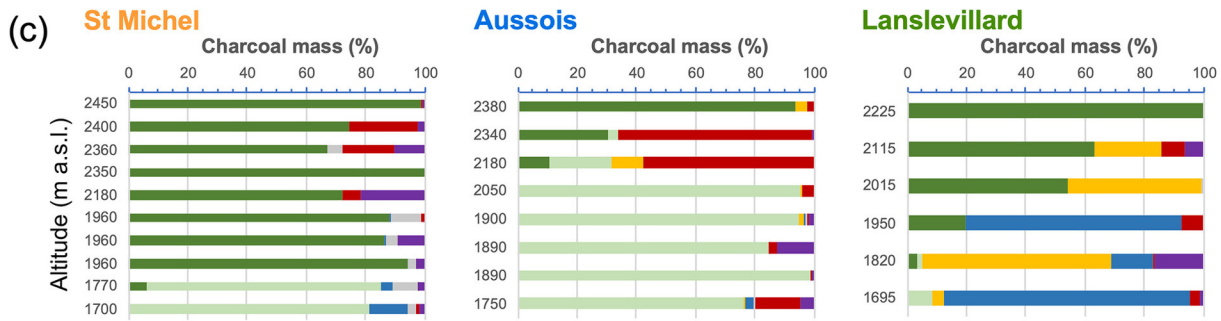
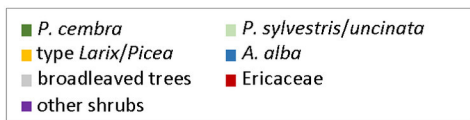
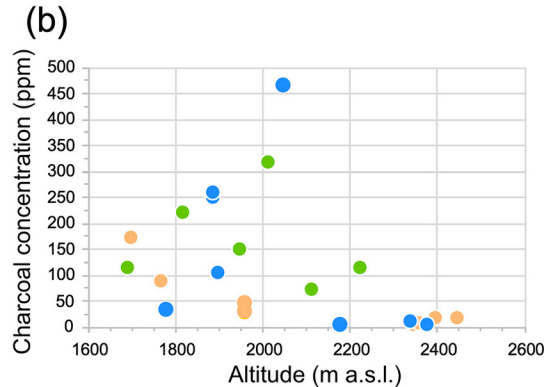
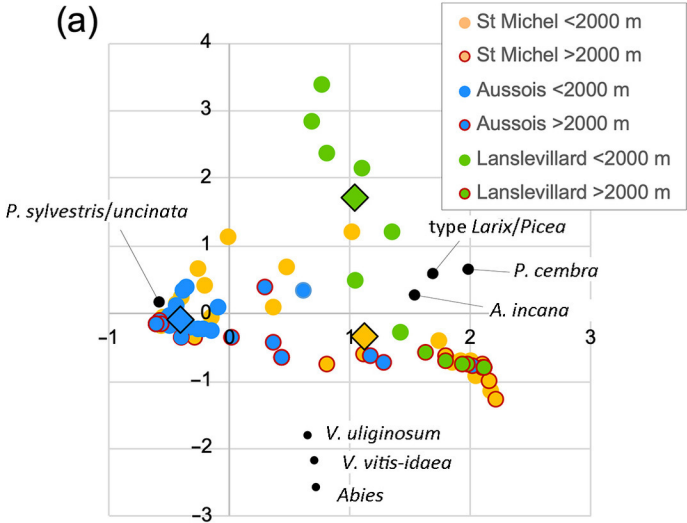


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