The Holocene 20,1 (2010) pp. 35–44

Reconstruction of Holocene high-altitude vegetation cover in the French southern Alps: evidence from soil charcoal

Brigitte Talon*

(Aix-Marseille Université (Université Paul Cézanne), Institut Méditerranéen d'Ecologie et de Paléoécologie (IMEP UMR CNRS/IRD), Bâtiment Villemin, Europôle de l'Arbois – BP 80 F 13545 Aix-en-Provence cedex 04, France)

Received 13 February 2009; revised manuscript accepted 31 July 2009

A
HOLOCENE
RESEARCH
PAPER
THEMATIC SET

Abstract: The study presented here from the southern French Alps demonstrates the reliability of soil charcoal analysis for the study of Holocene past treeline positions. The occurrence of charcoal in mineral soils along transects from 1950 m up to 2920 m demonstrates the role of fire in the establishment of the present vegetation patterns. The abrupt decrease of charcoal concentration at about 2400–2600 m (which varies across the study sites) corresponds to the modern transition between subalpine forest and alpine tundra. Charcoal particles formed *in situ* provide high spatial-resolution data for the reconstruction of past forest and treeline changes. Soil charcoal analysis indicated that: (1) treeline was 300 m higher around 6800 cal. BP than today; and (2) the uppermost forest belt up to 2810 m was colonized by larch (*Larix decidua* Mill.) and arolla pine (*Pinus cembra* L.). This pine is present today but patchily distributed: it is absent from the three areas studied. Radiocarbon dates, ranging from *c*. 6800 cal. BP to the modern period, along with historical and archaeological data, suggest that the present pattern of the uppermost forest belt, and the patchy distribution of arolla pine in the studied area are the results of anthropogenic fire (mainly agropastoral activities). The question of global warming consequences on treelines in this part of the French Alps is discussed.

Key words: Soil charcoal analysis, treeline, Holocene, *Pinus cembra*, human impact, fire.

Introduction

This paper is the third in a Thematic Set on Pedoanthracology. The purpose of the set is to explore the potentialities of soil charcoal analysis. Here we present an application of pedoanthracology to treeline shift and composition reconstruction in the French southern Alps. The position of treeline in the Alps is strongly affected by climate. Therefore, past changes in treeline location have often been used to infer past climatic variations. The Holocene history of treeline dynamics in the Alps has been addressed by an increasing number of palaeoecological studies, mainly using pollen analysis (eg, de Beaulieu, 1977; Wegmüller, 1977; Burga, 1988; Ponel *et al.*, 1992; Amman and Wick, 1993; Tessier *et al.*, 1993; Oeggl and Wahlmüller, 1994; David, 1995, 1997; Haas *et al.*, 1998), sometimes supplemented by plant or insect macrofossil data (Tinner *et al.*, 1996; Birks and Birks, 2000; Tinner and Theurillat, 2003; Ali *et al.*, 2003; Carnelli *et al.*, 2004). Such research contributes to a detailed knowledge of postglacial altitudinal tree species spread, and an understanding of present vegetation distribution patterns. Although pollen records provide valuable information about past vegetation cover, pollen-based reconstructions of treeline altitudinal fluctuations are rarely precise because lowland vegetation covers wider areas than mountain-top vegetation, and its pollen is easily lifted by vertical air-mass movements and deposited at higher altitudes. Therefore, the spatial resolution of these analyses is not high enough for the reconstruction of past treeline positions. The present position of alpine treelines is also the result of ecological processes influenced by millennia of human land use, but palaeoecological studies reflect the integrated effects of climatic, biotic and anthropogenic impacts: the relative importance of climate and human activity on vegetation dynamics is therefore still speculative. In the French and Swiss Alps, treeline is proposed to have been situated 100–200 m higher than its potential position (Carcaillet *et al.*, 1998; Tinner and Theurillat, 2003; Heiri *et al.*, 2006). But as yet, it is unknown as to what this potential position is in the southern French Alps, because of a lack of both humid sites and palaeoecological studies with a high spatial resolution. Fire is supposed to have been the major disturbance of subalpine and uppermost forests ecosystems during the Holocene. Today, an outbreak of fire is expected as a consequence of climatic changes (Beniston, 2000). A better knowledge of past fire history of both

---

*Author for correspondence (e-mail: brigitte.talon@univ-cezanne.fr)

10.1177/0959683609348842

forest and tree limits is the key of a relevant sustainable management of these very sensitive and threatened ecosystems, in particular in the southern french Alps, still insufficiently studied and nevertheless very exposed to fire risks. The analysis of charred particles from sediment has often been employed in the reconstruction of past fire regimes (eg, Tolonen, 1986; Patterson *et al.*, 1987; Wein *et al.*, 1987; Clark *et al.*, 1989; Clark, 1990; Clark and Royall, 1996; Whitlock and Millspaugh, 1996; Haberle and Ledru, 2001). However, like pollen, this microscopic charcoal is easily transported by wind. Counting microscopic charcoal in pollen slides provides reconstructions of both local and regional fire events. Other methods estimate macroscopic charcoal (>200 μm) by sediment sieving. Macrocharcoal is unlikely to be transported far by wind. In this case, stand- to local-scale fire history can be reconstructed (Lynch *et al.,* 2004).

A more localized signal of past fire and burnt vegetation is offered by the study of macroscopic charcoal found in the soils. In contrast to pollen, charcoal is resistant to biological mineralization and preserved in all type of soils. Consequently, charcoal accumulates in the soil fire after fire. However, soil charcoal is not stratified because of physical disturbances and biological activities. Charcoal analysis is of limited use in vegetation reconstructions because of this lack in temporal resolution, but is very useful when reconstructing the past position of treeline and spatial distribution of woody species (Carcaillet and Thinon, 1996; Carcaillet, 1998; Talon *et al.,* 1998; Carcaillet and Brun, 2000; Carnelli *et al*., 2004; Carcaillet and Müller, 2005; Di Pasquale *et al*., 2008; Touflan *et al.,* 2010, this issue). Charcoal that is smaller than 10 mg (but > 1 mg) is easily dated by accelerator mass spectrometry (AMS). Dating charcoal from soils ranging along an altitudinal gradient allows the reconstruction of fire patterns in areas where peat or lakes are rare, such as at high altitude areas (above 2300 m/2400 m elevation) (Bortenschlager, 1993; Hopkins *et al*., 1993). The dating of such charcoal allows us to relate spatial variability of fire history to landscape structure. For instance, Gavin *et al.* (2003) have shown that natural fire does not occur with the same frequency on north- and south-facing slopes, and Carcaillet (1998) clearly demonstrates that alpine prehistoric human fires lightning was controlled, depending on landscape structure (exposition, slope, soil moisture, etc.).

Charcoal identification and dating offers great opportunities to decipher changes in vegetation composition and geographic extent in sensitive habitats (eg, Cherubini *et al.*, 1995; Carcaillet *et al.*, 1998; Talon *et al.*, 1998; Ali *et al.,* 2005; Schwartz *et al*., 2005; Touflan and Talon, 2009; Poschlod and Bauman, 2010, this issue; Henry *et al*., 2010, this issue).

In this paper we present a study of the reliability of macroscopic charcoal (Ø > 400 μm) identification for the reconstruction of vegetation composition and treeline uppermost elevation since the mid Holocene within the southern French Alps, at a local scale. We hypothesize that *Pinus cembra* patchy distribution and upper treeline elevation were strongly affected by anthopogenic influence as the result of differences in space and time of human activities (mainly clearcutting, burning and grazing) intensity since around 5000 cal. BP. This study is based on the charcoal analysis of 28 soil profiles and the AMS dating of 29 individual charcoal from three different areas ranging north–south through the southern part of the inner French Alps. First results of this study have already been partially published (Talon *et al*., 1998; Thinon and Talon., 1998; Ali *et al*., 2005). We present here the complete study with 19 supplementary and unpublished dates. The objectives are (1) to evaluate the maximum elevation reached by treeline in the past, (2) to compare between past and modern uppermost forest composition, (3) to explain the patchy distribution of arolla pine, and (4) to better understand the role of fire in the uppermost forest dynamics in the context of global change. A qualitative analysis has been used to describe vegetation in terms of species presence and species altitudinal range limit. The comparison between past and modern vegetation composition was based on the frequency of woody taxa. Treeline maximum elevation has been evaluated by means of a quantitative approach (soil charcoal concentration). Finally, the role of fire was deduced from AMS ^{14}C measurements from soil charcoal fragments.

Study areas

The study took place in the inner southern French Alps in three distinct areas: Queyras, Ubaye and Tinée (Figure 1).

Queyras: Aigue-Agnelle Valley (44°44′ N–6°53′ E)

At St-Véran (2010 m a.s.l., 44°41′58N–6°51′55E), the weather station closest to the study area, indicates a mean annual temperature of about 5.8 ± 5.5°C, and mean monthly precipitation of 75 ± 16 mm. The climate is defined as an inner-alpine climate (low precipitation and high continental character) leaning towards a more Mediterranean climatic regime (Ozenda, 1985). This zone is one of the driest within the French Alps (Pache *et al*., 1996).

The woody vegetation (1700–2400 m) is composed mainly of woodlands dominated by *Pinus sylvestris* L., *P. uncinata* Mill. and *Larix decidua* Mill. Norway spruce (*Picea abies* Karst.) is less abundant as this is the southernmost limit of its range. The presence of *Abies alba* Mill. in the dry Guil valley could be explained by sufficient water supply of soil in north-facing slopes. The understorey is composed of *Rhododendron ferrugineum* L. and *Vaccinium uliginosum* L. on north-facing slopes, *Arctostaphylos uva-ursi* (L.) Spreng. and *Juniperus siberica* Burgsd. on south-facing slopes. The treeline is formed by larch (*Larix*) forest up to 2400 m on north-facing slopes. No arolla pine (*Pinus cembra* L.) can be observed today in this valley. South-facing slopes are covered with pastures and meadows from the valley floor (1900 m a.s.l.) up to the summit ridges (3000 m a.s.l.). The valley was an important line of communication for trade and industry as early as the Bronze Age and copper extraction was responsible for the destruction of much of the forest in the area (Barge *et al*., 1998).

Ubaye: Upper Ubaye Valley (44°36′ N–6°52′ E) and Parpaillon (44°29′N–6°38′E)

The upper Ubaye Valley is southeast of the Aigue Agnelle valley. The climate is similar, but a little drier (Ali *et al*., 2005). Woody vegetation patterns are more or less the same. South-facing slopes are covered up to 2100 m by montane pine (*P. uncinata*) and scots pine (*P. sylvestris*). From 2000 m to 3000 m a.s.l., the slopes are covered with meadows grazed by sheep; larch woodlands occupy north-facing slopes up to 2400 m a.s.l. Arolla pine is totally absent of the upper part of the valley. Stone engravings from the Bronze Age (Müller *et al*., 1991), along with iron slags discovered at 2000 m a.s.l. (in Talon, 1997a) are evidence of early human activity in this remote valley.

Massif du Parpaillon is located between Durance valley and Ubaye valley. The woody vegetation cover is mainly composed of larch and scots pines. South-facing slopes above 2000 m elevation are devoted to sheep grazing.

Tinée: Restefond – Sestrières (44°19′ N–6°48′ E)

The Tinée upper valley is the most meridional study site. The climate is more humid because of maritime climate influence. The montane belt is covered on south-facing slopes by scots pine and on north-facing slopes by silver fir (*Abies alba*). Larch is the dominant species between 1700 m and 2000 m (subalpine belt), with *Picea abies* Karst. on north-facing slopes. *Pinus cembra* is rare. Most of the landscape is devoted to pastoral activities, up to 2900 m elevation.

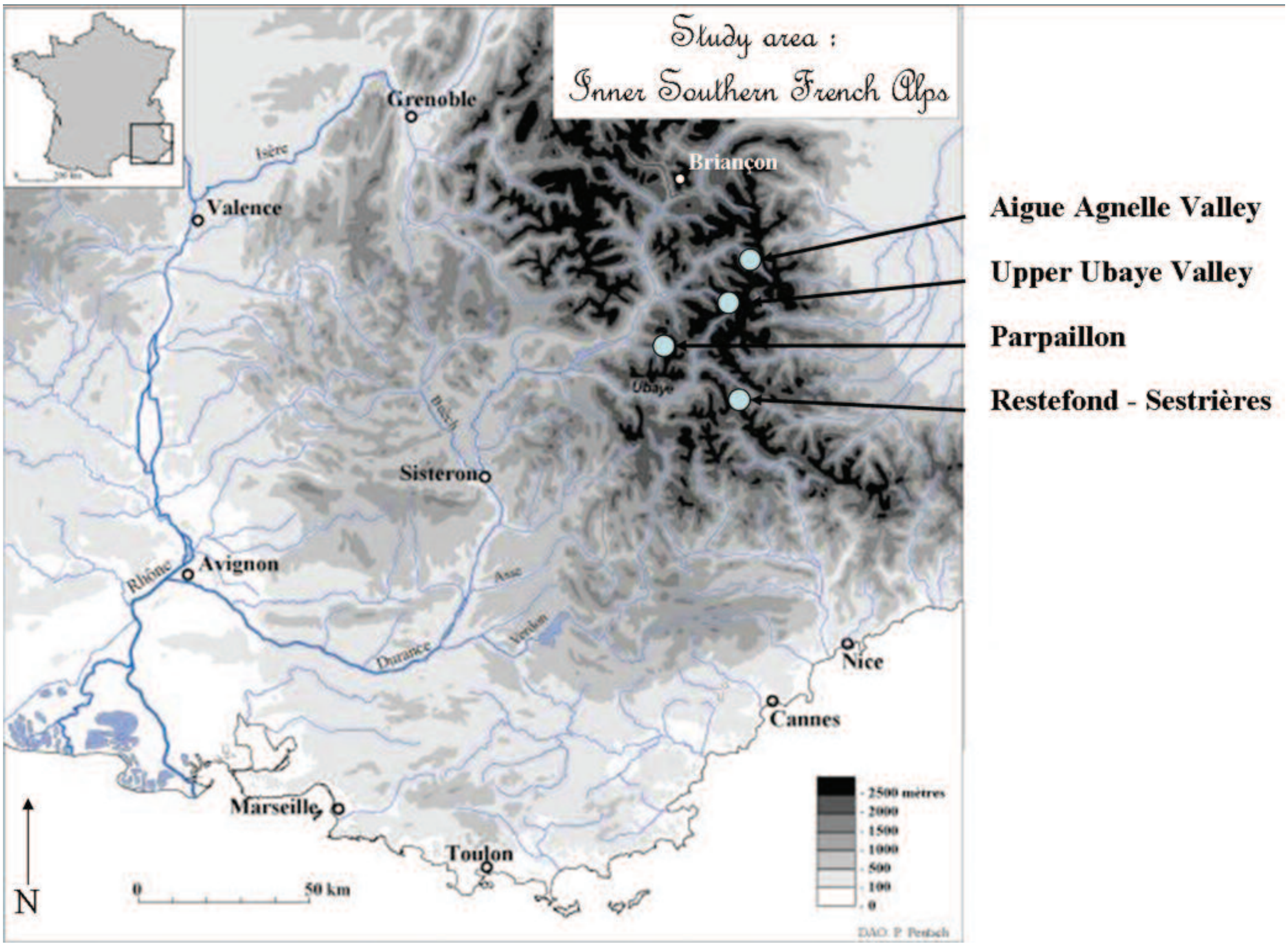

Figure 1 Location map of the study area

It is in this sector that we can observe the highest present treeline (*P. uncinata* between 2800 m and 2900 m)

Materials and methods

Sampling

In total, 28 soil profiles were sampled, mainly on south-facing slopes. Soils were sampled along altitudinal transects. Soil pit descriptions and codification are presented in Table 1.

Sampling was performed according to Carcaillet and Thinon (1996). Samples (*c.* 10–12 litres of decompacted soil/10 to 15 kg of dry soil) were taken from the base to the upper part of the pit, following pedological horizons, or every 15 cm when horizons were not distinct. Collecting this large amount of soil is necessary in order to guarantee adequate quantities of charcoal for identification and dating.

Charcoal extraction and identification

Samples were air-dried and weighed before sieving in order to calculate the quantity of charcoal per kilogram of soil (charcoal concentrations). The dry material was then carefully wet-sieved through four sieves of 5 mm, 2 mm, 800 µm and 400 µm (400 µm corresponds to the minimum size for handling and anatomical identification). Charcoal was extracted from the mineral fraction (sand) by floatation in a column with an ascending water current (further details in Carcaillet and Thinon, 1996), and from the organic fraction (roots and other plant remains) by hand-picking material under a low power binocular microscope. Identifications of charcoal fragments were based on wood anatomical criteria employing the charred wood reference collection from the Mediterranean Institute of Ecology and Palaeoecology (IMEP, Marseilles, France), along with atlases of wood anatomy (Jacquiot, 1955; Greguss, 1959; Jacquiot *et al.*, 1973; Schweingruber, 1990). An episcopic microscope equipped with interference contrast was used for charcoal identification under magnifications of 200×, 500× and 1000×. Wood anatomy of *Larix* and *Picea* has been previously studied (Talon, 1997b) in order to distinguish between the two anatomically similar taxa. As a precaution, the term '*Larix/Picea*' was applied when fragments were too small or too damaged to identify. Scots pine (*P. sylvestris*) and montane pine (*P. uncinata*) are impossible to distinguish from one another (Schweingruber, 1990), and were therefore placed under the same designation *P. sylvestris/uncinata*.

Charcoal quantification and dating

Charcoal concentration was expressed as a soil charcoal concentration (mg of charcoal/kg of dry soil: ppm) which include only particles ≥ 0.4 mm. This quantity (named also SA = specific anthracomass) was calculated for the whole profile (GSA, general specific anthracomass) or for a single taxon within a profile (SAT).

A total of 29 single identified charcoal fragments (possessing > 0.8 mg of mass) extracted from different pits and levels from the four areas studied were radiocarbon dated using Accelerator Mass Spectrometry (AMS) at the NSF Laboratory of Tucson (Arizona, USA) and at the Poznan Radiocarbon Laboratory (Poland). The ^{14}C dates were calibrated as AD/BC and BP using CALIB 5.0 software (Stuiver *et al.*, 2006). Prior to dating charcoal was cleaned under a

Table 1 Physical characteristics of the soil pits

Site name	Pit name	Elevation (m a.s.l.)	Aspect	Present-day vegetation
Queyras : Aigue Agnelle Valley 44°42′ N – 6°58′ E	Quey 6	2919	SO	Scraped alpine meadow
	Quey 5	2870	SO	Alpine meadow
	Quey 1	2775	NO	Alpine meadow
	Quey 2	2670	S	Alpine meadow
	Quey 3	2665	N	Scraped alpine meadow
	Quey 4	2635	S	Alpine meadow
	Quey 7	2400	SO	Subalpine meadow
	Quey 8	2200	O	Subalpine meadow
	Quey 9	1950	N	Larch woodland
Ubaye : Upper Ubaye Valley 44°36′ N – 6°52′ E	Uba 1	2850	S	Scraped alpine meadow
	Uba 3	2650	E	Alpine meadow
	Uba 4	2430	O	Alpine meadow
	Uba 2	2330	S	Alpine meadow
	Uba 5	2210	O	Subalpine meadow
	Uba 6	2050	NO	Larch forest ecotone
Ubaye : Parpaillon 44°29′ N – 6°38′ E	Par 1	2670	ESE	Scraped alpine meadow
Tinée : Restefond 44°19′ N – 6°48′ E	Rest 1	2810	SE	Scraped alpine meadow
	Rest 2	2685	ESE	Alpine meadow
	Cair 1	2650	NO	Alpine meadow
	Cair 2	2650	NO	Alpine meadow
	Cair 3	2650	NO	Alpine meadow
	Rest 3	2500	NO	Alpine meadow
	Rest 4	2300	S	Subalpine meadow
	Rest 5	2100	SO	Larch and Scott pine forest ecotone
Tinée : Sestrières 44°19′ N – 6°49′ E	Ses 1	2440	S	Alpine meadow
	Ses 2	2270	N	Subalpine meadow
	Ses 3	2070	NO	Arolla pine and larch forest ecotone

Table 2 ^{14}C AMS dates

Profile	Altitude (m a.s.l.)	Taxa	Age BP	Cal. BP	Cal. BC/AD	Reference
Quey 9	1950	*Larix*	1175±45	972–1182	AD 695–981	AA31361 (unpublished data, 1999)
Quey 9	1950	*Pinus cembra*	5990±60	6674–6969	5040–4729 BC	Ali *et al.* (2005)
Quey 8	2200	*Larix*	3870±55	4146–4425	2471–2144 BC	AA31362 (unpublished data, 1999)
Quey 8	2200	*Betula*	3990±60	4246–4620	2551–2201 BC	AA18002 (unpublished data, 1995)
Quey 8	2200	*Pinus cembra*	5990±60	6674–6969	5040–4729 BC	Ali *et al.* (2005)
Quey 7	2400	*Larix/Picea*	3050±50	3140–3376	1428–1129 BC	AA31363 (unpublished data, 1999)
Quey 7	2400	*Pinus cembra*	3310±50	3442–3643	1731–1449 BC	Ali *et al.* (2005)
Quey 2	2670	*Pinus cembra*	1475±70	1288–1522	AD 430–690	Talon *et al.* (1998)
Quey 2	2670	*Pinus cembra*	1535±45	1339–1528	AD 428–636	Talon *et al.* (1998)
Uba5	2400	*Pinus cembra*	3130±80	3142–3511	1597–1132 BC	Ali *et al.* (2005)
Uba5	2210	*Pinus cembra*	3175±60	3261–3490	1599–1316 BC	Ali *et al.* (2005)
Uba4	2430	*Pinus cembra*	2465±60	2359–2715	795–399 BC	Ali *et al.* (2005)
Uba4	2430	*Pinus cembra*	5805±60	6465–6742	4801–4498 BC	Ali *et al.* (2005)
Uba2	2330	*Pinus cembra*	255±65	255–491	AD 1478–1954	AA18775 (unpublished data, 1996)
Uba2	2330	*Ononis* sp.	935±70	722–963	AD 985–1259	AA18774 (unpublished data, 1996)
Uba2	2330	*Larix*	1520±70	1299–1541	AD 410–660	AA18773 (unpublished data, 1996)
Uba2	2330	*Larix/Picea*	1750±70	1522–1829	AD 123–434	AA18772 (unpublished data, 1996)
Uba2	2330	no identifiable	3750±80	3900–4300	2452–1923 BC	AA18771 (unpublished data, 1996)
Par1	2670	*Larix/Picea*	3510±45	3685–3899	2090–1686 BC	Talon *et al.* (1998)
Rest5	2100	*Larix/Picea*	1725±30	1557–1707	AD 240–400	Poz-13888 (unpublished data, 2005)
Rest 5	2100	*Rhododendron*	145±30	59–153	AD 1660–1950	Poz-13886 (unpublished data, 2005)
Rest 5	2100	*Larix/Picea*	325±30	306–470	AD 1470–1650	Poz-13889 (unpublished data, 2005)
Rest 5	2100	*Pinus cembra*	620±30	551–658	AD 1290–1400	Poz-13887 (unpublished data, 2005)
Rest 5	2100	*Larix/Picea*	1340±30	1234–1306	AD 640–720	Poz-13885 (unpublished data, 2005)
Rest 4	2300	*Ericaceae*	3975±35	4385–4527	2580–2430 BC	Poz-13883 (unpublished data, 2005)
Rest 4	2300	pith	4250±35	4808–4868	2920–2850 BC	Poz-13882 (unpublished data, 2005)
Cair 2	2650	no identifiable	2925±30	2968–3164	1220–1010 BC	Poz-13891 (unpublished data, 2005)
Cair 2	2650	pith	4390±40	4853–5054	3110–2900 BC	Poz-13892 (unpublished data, 2005)
Cair 3	2650	*Pinus cembra*	3280±50	3399–3630	1690–1440 BC	Poz-13893 (unpublished data, 2005)

dissecting microscope to remove small roots and mineral particles (clay). Each fragment was then treated over 24 h in a solution of $Na_4P_2O_7$ for organic compound extraction. Uncalibrated and calibrated BC/AD and BP (2 σ) radiocarbon ages are presented in Table 2.

Results and discussion

Maximal elevation reached by treeline

Charcoal is widespread in all soil profiles, from 1900 m a.s.l. up to 2919 m a.s.l., at almost all depths. But concentrations vary greatly from one pit to another. GSA are between 0.1 ppm (Quey6) and 9233 ppm (Quey8) (Table 3). *Pinus cembra* and *Larix/Picea* are the most abundant taxa. Charcoal concentrations of the 28 profiles (GSA) are presented in Figure 2, with a logarithmic scale.

We can observe that soil charcoal concentration decreases with increasing elevation in the same way across the three areas studied. The decline occurs between 2400 m and 2635 m elevation in Aigue Agnelle and Upper Ubaye valleys, but around 2700 m in Restefond-Sestrières, the most meridional site of the study. Thus, the elevation of 2400 m in Queyras and Ubaye (2670 m in Tinée) corresponds to a threshold above which charcoal concentration suddenly decreases (Figure 2). We interpreted this decrease as the ecotone between dense forest and uppermost treeline, ie, the maximal elevation reached by timberline (not the upper treeline) during the Holocene. Therefore it is probable that the uppermost Holocene treeline in Queyras and Ubaye was situated *c.* 350 m higher than today, at *c.* 2780 m elevation, as suggest by the secondary decline in charcoal concentration that occurred between 2775 m and 2850 m elevation (Figure 3). In Tinée, the uppermost treeline is thought to have been higher. It is worthwhile to note that *P. uncinata* and *P. cembra* saplings reached an elevation of 2800 m in this area (Talon, personal observations, 1996). Some palaeoecological studies, coupling pollen and plant macrofossil analysis (eg, Tinner and Theurillat, 2003; Carnelli *et al.,* 2004) suggested lower positions (*c.* 100–150 m higher than today, that is to say 2500–2550 m a.s.l.). High spatial resolution of soil charcoal analysis then leads us to pose an important question: are alpine soil charcoal (found above 2500–2550 m elevation) of local origin? It is well established that charcoal is frequently transported down slope by overland flow and snowmelt (Clark, 1988; Thinon, 1992; Meyer *et al.*, 1992). This process may contribute to the reduction of soil charcoal concentrations in high elevation soils, and conversely augment it in lower elevations. On the other hand, amounts of small charcoal found above the present-day treeline may have been transported by wind from mountain and subalpine belts forests. The minimum size of charcoal collected from samples is 400 μm. Clark (1988) suggests that charcoal particles between 50 and 10 000 μm in length probably never enter suspension in the convective column above a fire, but a process similar to saltation may transport them. This latter kind of transport is limited by micro relief, preventing long-distance displacement, particularly for fragments larger than 400 μm (Clark, 1988; Clark *et al*., 1998; Blackford, 2000; Ohlson and Tryterud, 2000; Lynch *et al*., 2004) which are the fragments identified.

Moreover, the frequency and bulk of indeterminable overglazed charred particles in the samples are worth noting, particularly above 2400 m. Charcoal is thought to overglaze when the wood is still green when it burns (Thinon, 1992). In most cases, these unidentifiable fragments of cylindrical shape are derived from shrub twigs. They are more resistant to fragmentation, and are thus well-represented in soils. Moreover, the density of an overglazed charcoal fragment is higher than well-carbonized wood (*c.* 0.4–0.6 g/cm^3) and thus more comparable with mineral particle densities (2.65 g/cm^3). According to Clark (1988), these overglazed particles ≥ 400 μm could not have been transported by wind. Finally, if upslope charcoal motion occurred on an extensive scale, then the decrease in charcoal mass (Figure 2) would have been more gradual with elevation. Considering the minimum size of collected charcoal and the occurrence of heavy overglazed charcoal fragments up to 2775 m elevation (Quey1, data not shown), it can be assumed that charcoal found in mineral soils between 2500 m and 2775 m elevation is *in situ,* and has not been transported from lower forest zones. Thus, the present-day upper forest belt on south-facing slopes was covered up to *c.* 2700 m with a mosaic of shrubs and trees.

Past uppermost forest and treeline/tundra ecotone composition

Charcoal identification provides new data on the composition of the past uppermost forest belt. The most frequent identified taxa are *Larix/Picea* (100% of pits) and *Pinus cembra* (82%). (Table 3). Other important taxa are Ericaceae (57%) and *Juniperus* (50%). Less frequent identified trees or schrubs are *Salix*, *Vaccinium*, Rosaceae, *Pinus sylvestris/uncinata*, *Betula*, *Arctostaphylos*, *Ononis* sp., *Rhododendron* and *Pinus* sp.

Larix/Picea, attributed to *Larix*, has been identified in all soil profiles. It was a very common and widely distributed tree in the southern inner French Alps. According to the radiocarbon dates (Table 2), this tree is not recorded in soil charcoal before 4425–4146 cal. BP in the Aigue Agnelle valley (Quey8), 3685–3899 cal. BP in Ubaye (Par1) and 1234–1306 cal. BP in the Tinée area (Rest 5). This species was still present at 2200 m a.s.l. *c.* 2400 years ago (Quey8), and at 2670 m elevation (Par1) *c.* 2000 years ago. Note that its postglacial arrival is dated by pollen-based analysis back to 8000 cal. BP in the southernmost Alps (eg, Ortu *et al*., 2005).

The soil charcoal records give no evidence for the prevalence of larch over arolla pine, as attested in some recent palaeoecological studies (Muller *et al.*, 2006). On the contrary, charcoal of *P. cembra* is clearly dominant in soils of Restefond and Sestrières (Figure 2).

P. cembra were recovered in all but five of the pits (Ses2, Quey6, Quey5, Quey3 and Uba1), which indicate a formerly widespread distribution between 1950 m and 2770 m elevation. Results from the Restefond and Sestrières sites show that it was more frequent, and grew at higher elevation than in the other valleys (Table 3).

Between 1950 m and 2400 m elevation forest diversity was higher than today. During the middle of the Holocene (6674–6969 cal. BP, Quey8 and Quey9), arolla pine played a major role in the vegetation cover of the subalpine belt, along with larch and scattered birches. It is important to note that charcoal of this species is very fragile and not well preserved in soil. The occurrence frequency of Ericaceae and *Juniperus* support the presence of a landscape mosaic.

Between 2400 m and 2770 m elevation charcoal data suggest an open landscape with ericaceous shrubs and scattered stands of arolla pine and larch. The charcoal composition is the same as that in the lower elevation pits, but lower concentrations and higher frequencies of ericaceous charcoal support the interpretation of a parkland transition between forest and meadow-heathland mosaic vegetation. In the Restefond site, this open land reached 2600 m during late Neolithic (3399–3630 cal. BP, Cair3). The diversity of the understorey is also higher than in others sites with the occurrence of *Arctostaphylos*, *Rhododendron* and *Ononis*. Thus, charcoal data indicate that treeline (larch and arolla pine) reached 2650 m elevation in the Ubaye Valley (Uba3), 2685 m in Tinée and 2775 m in the Aigue-Agnelle Valley (Quey1).

Above 2775 m elevation, charcoal analysis reveals the occurrence of arolla pine and larch (Rest1), larch, shrubs (Ericaceae and Rosaceae), and willow (Quey5, Quey6, Uba1).

Table 3 Charcoal concentration (in ppm) per profile and for the two most abundant tree species *(P. cembra and Larix/Picea)*

	Occurrence frequency: altitude (m a.s.l.)	GSA (ppm)	Larix/Picea 1 SAT (ppm)	Pinus cembra 0.82 SAT (ppm)	Ericaceae 0.57	Juniperus 0.5	Salix 0.17	Vaccinium 0.17	Rosaceae 0.17	Pinus sylv./ uncinata 0.14	Betula 0.08	Arctostaphylos 0.08	cf. Ononis 0.08	Rhododendron 0.05	Pinus sp. 0.05
Aigue Agnelle															
Quey 6	2919	0.1	0.04	0.00											
Quey 5	2870	0.9	0.02	0.00	×		×		×						
Quey 1	2775	1.2	0.15	0.05											
Quey 2	2670	1.3	0.02	0.64		×		×							
Quey 3	2665	0.1	0.04	0.00											
Quey 4	2635	0.7	0.02	0.05		×									
Quey 7	2400	443	3.29	77.13	×	×		×	×						
Quey 8	2200	9233	207.80	216.00	×	×	×	×	×		×				
Quey 9	1950	122	5.57	13.50	×	×			×	×					×
Upper Ubaye															
Uba 1	2850	0.3	0.03	0.00	×										
Uba3	2650	0.5	0.08	0.03						×					
Uba4	2430	38	0.09	6.15	×										
Uba2	2330	292	0.72	0.24	×	×		×				×	×		
Uba5	2210	756	4.37	45.76	×							×			×
Uba6	2050	3986	264.80	74.75	×	×			×	×					
Parpaillon															
Par1	2670	×	×	×											
Restefond															
Rest 1	2810	0.5	0.02	0.01											
Rest 2	2685	3.7	0.05	0.02		×	×								
Cair 1	2650	3	0.40	0.70	×	×									
Cair 2	2650	4	0.08	0.69	×	×	×				×	×	×		
Cair 3	2650	2.5	0.20	0.98	×	×								×	
Rest 3	2500	0.55	0.06	0.15	×						×				
Rest 4	2300	3.7	0.67	0.17	×										
Rest 5	2100	365.5	101.70	0.34	×	×			×				×	×	
Sestrières															
Ses 1	2440	7.8	0.23	0.34						×					
Ses 2	2270	7	1.10	0.00		×		×							
Ses 3	2070	77	5.85	5.48	×	×	×	×							

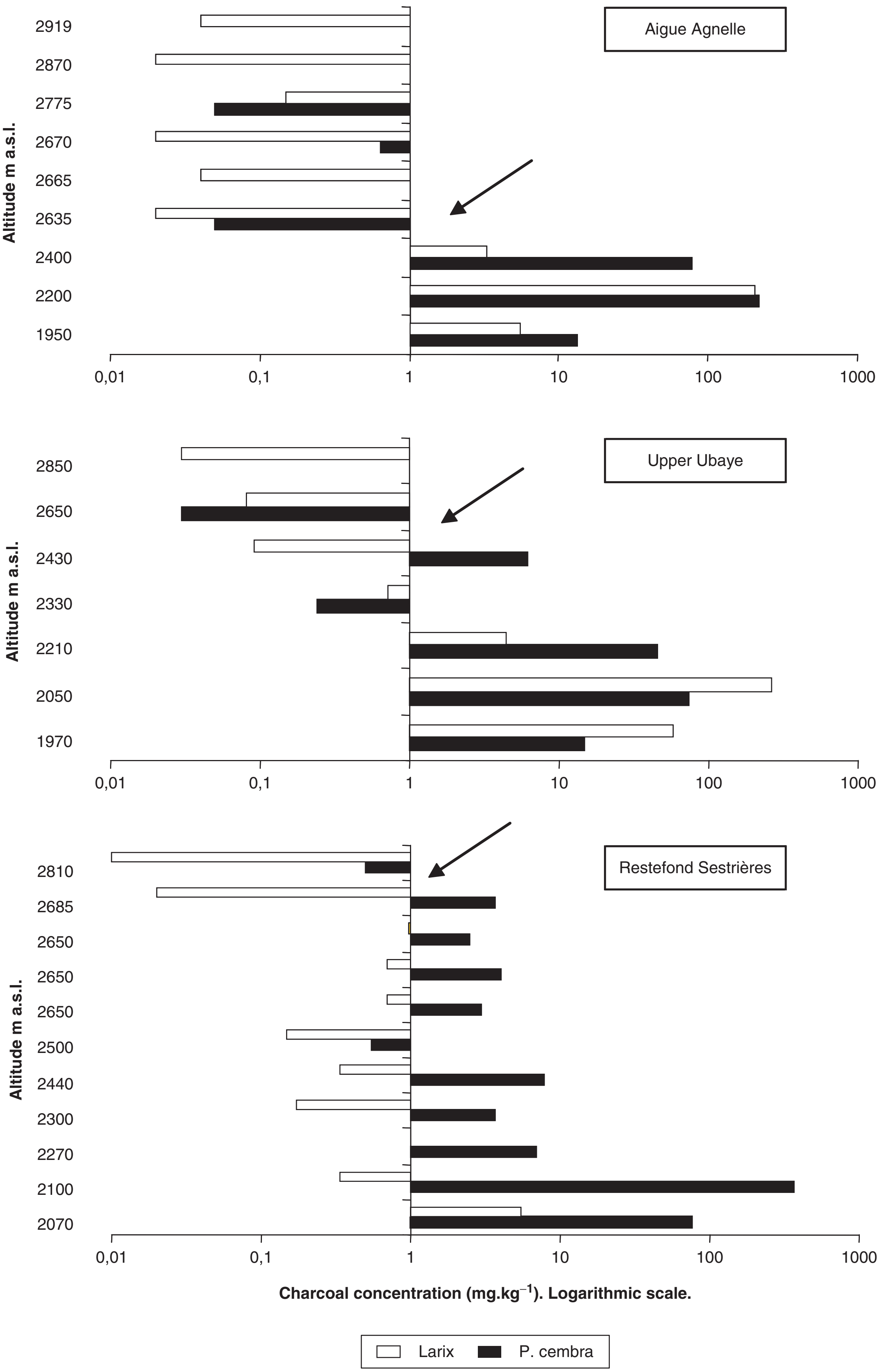

Figure 2 Decreasing charcoal concentration with increasing elevation in each areas studied. Histograms correspond to the concentration of charcoal of *P. cembra* and *Larix* only, per profile. Data are expressed in mg/kg on a logarithmic scale. Pits are in elevation range. Arrows indicate sudden decrease in charcoal concentrations

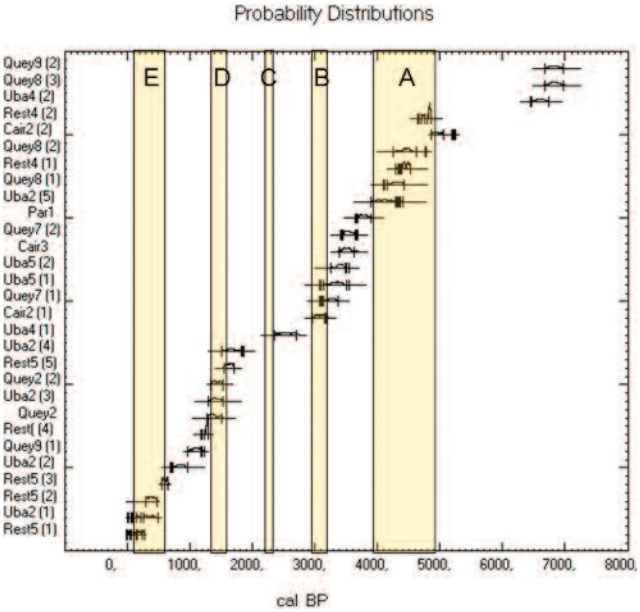

Figure 3 Temporal distribution of the 29 dated charcoal and principal phases of climatic deterioration. Three periods of fire can be distinguished (1) 7500–6500 cal. BP; (2) 5500–2500 cal. BP and 2000 cal. BP–modern period. Climatic deteriorations: (A) Piora2; (B) climatic deterioration at *c*. 3500 BP; (C) Göschenen 1; (D) minor cold event at *c*. 1500 BP; (E) 'Little Ice Age' (more details in text)

Our results reveal that *P. cembra* was a common tree at high elevations across all of the sites investigated, while this species is absent today in all of the areas studied. The present-day fragmented distribution of *P. cembra* in the inner French Alps has been explained by the ecological requirements of this taxon (north-facing slopes, rocky patches) (Contini and Lavarelo, 1982) and as a result of anthropogenic activities and poor forest regeneration (Bono and Barbero, 1971). Arolla pine distribution is closely related to its seed dispersal mechanism: the European nutcracker (*Nucifraga caryocatactes*) caches seeds as winter stock in well-exposed shallow soils, in areas having little snow cover, or free of snow relatively early and in forests at the base of trees (Hättenschwiler and Körner, 1995). This corvid assists seed dispersal, especially in wind exposed sites (Crocq, 1990; Camaret *et al*., 1998). Pollen analysis places postglacial establishment of *P. cembra* in the southern French Alps at *c*. 6400 cal. yr BP (de Beaulieu, 1977; Fauquette and Talon, 1995; Nakagawa *et al*., 2000). Extensive spreads of this taxon in the subalpine zone occurred between 4000 cal. yr BP and 2000 cal. yr BP (Ali *et al.*, 2005). Radiocarbon datings obtained from arolla pine charcoal range between 5040–4729 BC (Neolithic) and AD 1478–1954 (Modern period) (Table 2).The disappearance of this pine from the valleys studied has thus been progressive. The complete eradication of arolla pine occurred recently, after the Middle Ages (AD 1478–1954). Therefore, the current discontinuous distribution of this species is probably the result of past deforestation rather than ecological requirements.

Timbers are largely absent from the most of the study area, but saplings can be observed everywhere under larch woodland and at the upperforest/alpine toundra ecotone.

Role of fires

The history of high elevation environments is closely linked with the occurrence of fire, owing to the fact that charcoal is produced from burnt vegetation. All radiocarbon dates available for this study are shown in Table 2. Although it would have been preferable to date more charcoal, notably charcoal from high elevations soils, the quality of material and the small amount of C available were insufficient for proper AMS datings. These data revealed that woody species, especially *Larix/Picea* and *Pinus cembra* were present in the inner southern French Alps between 1950 m and 2670 m a.s.l. from the middle Holocene (6674–6969 cal. BP) to the modern period.

Three periods of fires can be distinguished (Figure 3): (1) *c*. 7500–6500 cal. BP, (2) *c*. 5500–2500 cal. BP and the more recent one (3) *c*. 2000 cal. BP–modern period. Of course, more dates could detect more periods. Gaps between fire periods have therefore to be interpreted cautiously. The oldest dates correspond to the early Neolithic climatically warm period (before 6500 cal. BP). First part of the second period (5000–2500 BP) coincides with the climatic deterioration of Piora2 (late Neolithic, *c*. 5000–4000 BP); middle part can be clustered with the Bronze age (*c*. 4000–3000 BP), including the climatical deterioration at *c*. 3500 BP (Magny, 1995); and the end coincides with the recurrence of cold and dry climatic conditions (Provansal, 1995) of the Iron Age (*c*. 3000–2300 BP) including the Göschenen 1 climatic deterioration (Magny, 1995). The third and last period ranges from *c*. 2000 BP to modern period, including a minor cold event at *c*. AD 700 (1500 BP) (Magny, 1995), the 'Medieval Warm Period' (Esper *et al*., 2002) and the 'Little Ice Age'. We can observe that lightning occurred at any time, whatever the climate and the archaeological chronozone. It thus can be assumed that fires could have been favoured during warm and dry periods but that most of them are not climatically determined.

Radiocarbon dates ranging from *c*. 7000 cal. BP to 1800 cal. BP (Table 2) coincide with the early and extensive human impact recorded in pollen diagrams, along with archaeological and historical evidence for cultivation and fuel clearings (Clark *et al.*, 1989; Tinner *et al*., 1998, 2003; Walsh and Richer, 2006; Walsh *et al*., 2007). Fire was particularly frequent during the late Neolithic (*c*. 5000–3000 BP) according to recent studies (Ali *et al*., 2005; Heiri *et al*., 2006) and from Antiquity to modern period, linked to increasing cultivation and pastoralism practices. This strongly argued in favour of human impact as the main cause of the lowering of the treeline and the local extinction of *Pinus cembra* in the study area. There is little doubt that the major cause of fires during this time period is of anthropogenic origin (Touflan *et al*., 2010, this issue).

Conclusion

Charcoal from mineral soils may be used as a reliable indicator for altitudinal forest shifts during the Holocene, as well as evidence for the former occurrence of woody taxa at given sites. All pits distributed between 1950 m and 2919 m elevation provided charcoal fragments suggesting that the uppermost forest of the three areas studied has been burnt at least once during the Holocene, regardless of elevation and exposure. The altitudinal gradient of charcoal amounts and the *in situ* origin of charcoal assemblages helped define the maximum elevation reached by forest and tree limits during the Holocene. The middle Holocene treeline upper limit was at most 300 m higher than today's tree limit. The taxonomical composition of these ecotones was determined by charcoal identifications. It reveals that the ligneous biodiversity was higher before *c*. 7000 BP. In addition, the present discontinuous occurrence of *P. cembra* was caused by fire and deforestation. It was the most important conifer in the southern French Alps forests until *c*. 6800 cal. BP, occupying, along with larch, the whole upper forest belt from 2400 m to 2810 m elevation. Trees were established above the present-day treeline at elevations up to 2700 m during the optimal climatic periods (Atlantic period 8000–5000 BP.). They did not survive the consequences of changes induced by repeated fire events on microclimatic conditions and slope stability. Natural fires, and/or human-induced processes (it remains impossible to attest the true origin of fire) were responsible for a considerable lowering of the upper treeline and loss of biodiversity. However, these conclusions are based on one proxy only. In addition to soil charcoal analysis, further palaeoecological methods (soil morphology and micromorphology, phytoliths) archaeological investigations and model-based reconstruction of Holocene treeline should be conducted with respect to changing vegetation and palaeoclimatic reconstruction in order to better define former treeline position and composition. It would be then possible to better understand the factors driving past vegetation changes and attempt to assess future vegetation dynamics in a changing climate: recolonisation by arolla pine will take time in valleys from which it totally disappeared.

Acknowledgements

This research was supported by a multidisciplinary research program from the French Ministry of Environment (DRAEI 93019). The author thanks J.P. Bouchot, A. Nicault and H. Barakat for helpful assistance in field and laboratory, K. Walsh for aiding in the English version and two anonymous referees for their considerable help in improving the final version of this paper.

References

Ali, A.A., Carcaillet, C., Guendon, J.-L., Quinif, Y., Roiron, P. and **Terral, J.-F.** 2003: The early Holocene treeline in the southern inner French Alps: new evidence from plant imprints within travertine. *Global Ecology and Biogeography*,12, 411–19.

Ali, A.A., Carcaillet, C., Talon, B., Roiron, P. and **Terral, J.-F.** 2005: *Pinus cembra* L. (arolla pine), 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, 1659–69.

Amman, B. and **Wick, L.** 1993: Analysis of fossil stomata of conifers as indicators of the alpine tree line fluctuations during the Holocene. In Frenzel, B., editor, 'Oscillations of the Alpine and polar tree limits in the Holocene'. *Paläoklimaforschung* 9, 175–85.

Barge, H., Ancel, B., Rostran, P. and **Guendon, J.L.** 1998: La mine des Clausis à St-Véran (Hautes-Alpes): exploitation et aire de réduction du minerai de cuivre d'époque préhistorique. In Mordant, C., Pernot, M. and Rychner, V., editors, *L'atelier du bronzier en Europe du XXe au VIIe siècle avant notre ère*. CTHS Publishers, 71–81.

Beniston, M. 2000: *Environmental change in mountains and uplands.* Key Issues in Environmental Change. Arnold.

Birks, H.H. and **Birks, H.J.B.** 2000: Future uses of pollen analysis must include plant macrofossils. *Journal of Biogeography* 27, 31–35.

Blackford, J.J. 2000: Charcoal fragments in surface samples following a fire and the implications for interpretation of subfossil charcoal data. *Palaeogeography, Palaeoclimatology, Palaeoecology* 164, 33–42.

Bono, G. and **Barbero, M.** 1971: À propos des cembraies des Alpes cottiennes italiennes, maritimes et ligures. *Allionia* 17, 97–120.

Bortenschlager, S. 1993: Das höchst gelegene Moor der Ostalpen 'Moor am Rofenberg' 2760 m. *Dissertationes Botanicae* 196, 329–34.

Burga, C.A. 1988: Swiss vegetation history during the last 18000 years. *New Phytologist* 110, 581–602.

Camaret, S., Guérin, B. and **Leclerc, D.** 1998: Mise en évidence de l'impact du casse-noix moucheté (*Nucifraga caryocatactes* L.) sur la distribution spatiale de la régénération du pin cembro (*Pinus cembra* L.). *Bulletin de la Société Zoologique Française* 123, 383–92.

Carcaillet, C. 1998: A spatially precise study of fires, climate and human impact within the Maurienne Valley, North French Alps. *Journal of Ecology* 86, 384–96.

Carcaillet, C. and **Brun, J.-J.** 2000: Changes in landscape structure in the northwestern Alps over the last 7000 years: lessons from soil charcoal. *Journal of Vegetation Science* 11, 705–14.

Carcaillet, C. and **Müller, S.D.** 2005: Holocene tree-limit and distribution of *Abies alba* in the inner French Alps: anthropogenic or climatic changes? *Boreas* 34, 468–76.

Carcaillet, C. and **Thinon, M.** 1996: Pedoanthracological contribution to the evolution of the upper treeline in the Maurienne Valley (North French Alps): methodology and preliminary data. *Review of Palaeobotany and Palaeoecology* 91, 399–416.

Carcaillet, C., Talon, B. and **Barbero, M.** 1998: *Pinus cembra* et incendies pendant l'Holocène, 300 m au-dessus de la limite actuelle des arbres dans le Massif de la Vanoise (Alpes du nord-ouest). *Ecologie* 29, 277–82.

Carnelli, A.L, Theurillat, J.-P., Thinon, M., Vadi, G. and **Talon, B.** 2004: Past uppermost tree limit in the central European Alps (Switzerland) based on soil and soil charcoal. *The Holocene* 14, 393–405.

Cherubini, P., Berli, S. and **Schoch, W.** 1995: Analisi antracologiche per la ricostruzione della storia della vegetazione e negli incendi boschivi negli ultimi 7000 anni nelle Centovalli (Ticino, Svizzera*).* *Bolletino della Societa Ticinese di Scienze Naturali* 83, 113–20.

Clark, J.S. 1988: Particle motion and the theory of charcoal analysis: source area, transport, deposition and sampling. *Quaternary Research* 30, 67–80.

—— 1990: Fire and climate change during the last 750 years in northwestern Minnesota. *Ecological Monographs* 60, 135–59.

Clark, J.S. and **Royall, P.D.** 1996: Local and regional sediment charcoal evidence for fire regimes in presettlement north-eastern North America. *Journal of Ecology* 84, 365–82.

Clark, J.S., Merk, J. and **Müller, H.** 1989: Post-glacial fire, vegetation, and human history on the northern alpine forelands, south-western Germany. *Journal of Ecology* 77, 897–925.

Clark, J.S., Lynch, J., Stocks, B.J. and **Goldammer, J.G.** 1998: Relationship between charcoal particles in air and sediments in west-central Siberia. *The Holocene* 8, 19–30.

Contini, L. and **Lavarelo, Y.** 1982: *Le pin cembro. Répartition, écologie, sylviculture et production*. INRA.

Crocq, C. 1990: *Le Casse-noix moucheté*. Lechevalier-Chabaud.

David, F. 1995: Vegetation dynamics in the Northern French Alps. *Historical Biology* 9, 269–95.

—— 1997: Holocene tree limit history in the northern French Alps: stomata and pollen evidence. *Review of Palaeobotany and Palynology* 97, 227–37.

De Beaulieu, J.-L. 1977: Contribution pollenanalytique à l'histoire tardiglaciaire et holocène de la végétation des Alpes méridionales françaises. PhD Thesis, University Aix-Marseille 3.

Di Pasquale, G., Marziano, M., Impagliazzo, S., Lubritto, C., De Natale A. and **Bader, M.Y.** 2008: The Holocene treeline in the northern Andes (Ecuador): first evidence from soil charcoal. *Palaeogeography, Palaeoclimatology, Palaeoecology* 259, 17–34.

Esper, J., Cook, E.R. and **Schweingruber, F.H.** 2002: Low-frequency signals in long tree-ring chronologies for reconstructing past temperature variability. *Science* 295, 2250–53.

Fauquette, S. and **Talon, B.** 1995: Histoire de la végétation forestière d'un site du Briançonnais: le Lac de Cristol (Hautes-Alpes, France). *Comptes Rendus de l'Académie des Sciences Paris (IIa)* 321, 255–62.

Gavin, D.G., Brubaker, L.B. and **Lertzman, K.P.** 2003: Holocene fire history of a coastal temperate rain forest based on soil charcoal radiocarbon dates. *Ecology*, 84, 186–201.

Greguss, P. 1959: *Holzanatomie der europaïschen Laubhölzer und Straücher*. Akadémiai Kiado.

Haas, J.N., Richoz, I., Tinner, W. and **Wick, L.** 1998: Synchronous Holocene climatic oscillations recorded on the Swiss Plateau and at timberline in the Alps. *The Holocene* 8, 301–309.

Haberle, S.G. and **Ledru, M.P.** 2001: Correlations among charcoal records of fires from the past 16,000 years in Indonesia, Papua New Guinea, and Central and South America. *Quaternary Research* 55, 97–104.

Hättenschwiler, S. and **Körner, C.** 1995: Response to recent climate warming of *Pinus sylvestris* and *Pinus cembra* within their montane transition zone in Swiss Alps. *Journal of Vegetation Science* 6, 357–68.

Heiri, C., Bugmann, H., Tinner, W., Heiri, O. and **Lischke, H.** 2006: A model-based reconstruction of Holocene treeline dynamics in the Central Swiss Alps. *Journal of Ecology* 94, 206–16.

Henry, F., Talon, B. and **Dutoit, T.** 2010: The age and history of the French Mediterranean steppe revisited by soil wood charcoal analysis. *The Holocene* 20, (this issue).

Hopkins, M.S., Ash, J., Graham, A.W., Head, G.J. and **Hewett, R.K.** 1993: Charcoal evidence of the spatial extent of the Eucaluptus woodland expansions and rainforest contractions in North Queensland during the late Pleistocene. *Journal of Biogeography* 20, 357–72.

Jacquiot, C. 1955: *Atlas d'anatomie des bois de Conifères*. Centre technique du bois.

Jacquiot, C., Trénard, Y. and **Dirol, D.** 1973: *Atlas d'anatomie des bois des Angiospermes (essences feuillues)*. Centre Technique du bois.

Lynch, J.A., Clark, J.S. and **Stocks, B.J.** 2004: Charcoal production, dispersal, and deposition from the Fort Province experimental fire: interpreting fire regimes from charcoal records in boreal forests. *Canadian Journal of Forest Research* 34, 1642–56.

Magny, M. 1995: *Une histoire du climat*. Errance.

Meyer, G.A., Wells, S.G., Balling, R.C., Jr and **Jull, A.J.T.** 1992: Response of alluvial systems to fire and climate change in Yellowstone National Park. *Nature* 357, 147–50.

Müller, A., Jorda, M. and **Gassend, J.-M.** 1991: Les gravures préhistoriques de la vallée de l'Ubaye (environ du lac Longet) et les modalités du peuplement de la zone inter-alpine. In *Gravures préhistoriques alpines*. International symposium, Mont-Bégo, Tende, France, 5–11 July 1991. Laboratoire de Préhistoire du Muséum d'Histoire Naturelle, 155–62.

Muller, S.D., Nakagawa, T., de Beaulieu, J.-L., Court-Picon, M., Fauquette, S. and **Genries, A.** 2006: Paléostructures de végétation à la limite supérieure des forêts, dans les Alpes françaises internes. *Comptes Rendus Biologies* 329, 502–11.

Nakagawa, T.,Edouard, J.-L. and **de Beaulieu, J.-L.** 2000: A scanning electron microscopy (SEM) study of sediments from Lake Cristol, southern French Alps, with special reference to the identification of *Pinus cembra* and other Alpine *Pinus* species based on SEM pollen morphology. *Review of Palaeobotany and Palynology* 108, 1–15.

Oeggl, K. and **Wahlmüller, N.** 1994: A mesolithic seasonal dwelling site in the high-alpine region of the eastern Alps. In Davis, O.K., editor, *Aspects of archaeological palynology: methodology and applications*. American Association of Stratigraphic Palynologists, Contributions Series 29, 147–60.

Ohlson, M. and **Tryterud, E.** 2000: Interpretation of the charcoal record in forest soils: forest fires and their production and deposition of macroscopic charcoal. *The Holocene* 10, 519–25.

Ortu, H., David, F. and **Caramiello, R.** 2005: Effet des paramètres locaux sur le developpement de la végétation dans le vallon de St-Anna di Vinadio (Alpes Maritimes, Italie). *Ecoscience* 12, 122–35.

Ozenda, P. 1985: *La végétation de la chaîne alpine dans l'espace montagnard européen*. Masson.

Pache, G., Michalet, R. and **Aime, S.** 1996: A seasonal application of the GAMS (1932) method, modified Michalet (1991): the example of the distribution of some important forest species in the Alps. *Dissertationes Botanicae* 258, 31–54.

Patterson, W.A., Edwards, K.J. and **Maguire, D.J.** 1987: Microscopic charcoal as a fossil indicator of fire. *Quaternary Science Reviews* 6, 3–23.

Ponel, Ph., de Beaulieu, J.-L. and **Tobolski, K.** 1992: Holocene palaeoenvironnements at the timberline in the Taillefer Massif, French Alps: a study of pollen, plant macrofossils and fossils insects. *The Holocene* 2, 117–30.

Poschlod, P. and **Baumann, A.** 2010: The historical dynamics of calcareous grasslands in the Central and Southern Franconian Jurassic mountains: a comparative pedoanthracological and pollen analytical study. *The Holocene* 20, this issue.

Provansal, M. 1995: The role of climate in landscape morphogenesis since the Bronze Age in Provence, southeastern France. *The Holocene* 5, 348–53.

Schwartz, D., Thinon, M., Goepp, S., Schmitt, C., Casner, J., Rosique, T., Wuscher, P., Alexandre, A., Dambrine, E., Martin, C. and **Guillet, B.** 2005: Premières datations directes de défrichements protohistoriques sur les chaumes secondaires des Vosges (Rossberg, Haut-Rhin). Approche pédoanthracologique. *Comptes Rendus Géosciences* 337, 1250–56.

Schweingruber, F.H. 1990: *Anatomie europäischer Hölzer. Anatomy of European woods*. Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf. Verlag Paul Haupt.

Stuiver, M., Reimer, P.J. and **Reimer, R.W.** 2006: CALIB 5.0. URL. http://radiocarbon.pa.qub.ac.uk/calib/calib.html.

Talon, B. 1997a: Evolution des zones supra-forestières des Alpes sud-occidentales au cours de l'Holocène. Analyse pédoanthracologique. PhD Thesis, Aix-Marseille 3 University.

—— 1997b: Etude anatomique et comparative de charbons de bois de *Larix decidua* Mill. et de *Picea abies* (L.) Karst. *Comptes Rendus de l'Académie des Sciences de Paris (Life Science*) 320, 581–88.

Talon, B., Carcaillet, C. and **Thinon, M.** 1998: Études pédoanthracologiques des variations de la limite supérieure des arbres au cours de l'Holocène dans les Alpes françaises. *Géographie physique et Quaternaire* 52, 193–206.

Tessier, L., de Beaulieu, J.-L., Coûteaux, M., Edouard, J.-L., Ponel, P., Rolando, C., Thomas, A., Thinon, M. and **Tobolski, K.** 1993: Holocene palaeoenvironment at the timberline in the Alps (Taillefer Massif, French Alps): a multidisciplinary approach. *Boreas* 22, 244–54.

Thinon, M. 1992: L'analyse pédoanthracologique. Aspects méthodologiques et applications. PhD Thesis, Aix-Marseille 3 University.

Thinon, M. and **Talon, B.** 1998: Ampleur de l'anthropisation des étages supérieurs dans les Alpes du sud: données pédoanthracologiques. *Ecologie* 29, 323–28.

Tinner, W. and **Theurillat, J.-P.** 2003: Uppermost limit, extension and fluctuations of the timberline and treeline ecocline in the Swiss Central Alps during the past 11.500 years. *Arctic, Antarctic, and Alpine Research* 35: 158–69.

Tinner, W., Ammann B. and **Germann, P.** 1996: Treeline fluctuations recorded for 12,500 years by soil profiles, pollen and plant-macrofossils in the Central Swiss Alps. *Arctic and Alpine Research* 28, 131–47.

Tinner, W., Conedara, M., Ammann B., Gäggeler, H.W., Gedye, S., Jones, R. and **Sägesser, B.** 1998: Pollen and charcoal in lake sediments compared with historically documented forest fires in southern Switzerland since AD 1920. *The Holocene* 8, 31–42.

Tinner, W., Lotter, A.F., Ammann, B., Conedera, M., Hubschmid, P., van Leeuwen, J.F.N. and **Wehrli, M.** 2003: Climatic change and contemporaneous land-use phases north and south of the Alps 2300 BC to 800 AD. *Quaternary Science Reviews* 22, 1447–60.

Tolonen, K. 1986: Charred particles analysis. In Berglund, B.E., editor, *Handbook of palaeoecology and palaeohydrology*. John Wiley and Sons, 485–96.

Touflan, P. and **Talon, B.** 2009: Spatial reliability of soil charcoal analysis: the case of subalpine forest soils. *Ecoscience* 16, 23–27.

Touflan, P., Talon, B. and **Walsh, K.** 2010: Soil charcoal analysis: a reliable tool for spatially precise studies of past forest dynamics: a case study in the French Southern Alps. *The Holocene* 20, (this issue).

Walsh, K. and **Richer, S.** 2006: Attitudes to altitude: changing meanings and perceptions within a 'marginal' Alpine landscape – the integration of palaeoecological and archeological data in a high-altitude landscape in the French Alps. *World Archeology* 38, 436–54.

Walsh, K., Mocci, F. and **Palet-Martinez, J.M.** 2007: Nine thousand years of human/landscape dynamics in a high altitude zone in the southern French Alps (Parc National des Ecrins, Hautes-Alpes, 05). *Preistoria Alpina* 42, 9–22.

Wegmüller, S. 1977: *Pollenanalytische Untersuchungen zur spät- und postglazialen Vegetationsgeschichte der französischen Alpen (Dauphiné)*. Verlag Paul Haupt.

Wein, R.W., Burzynski, M.P., Sreenivasa, B.A. and **Tolonen, K.** 1987: Bog profile evidence of fire and vegetation dynamics since 3000 years B.P. in the Acadian Forest. *Canadian Journal of Botany* 65, 1180–86.

Whitlock, C. and **Millspaugh, S.H.** 1996: Testing the assumptions of fire-history studies: an examination of modern charcoal accumulation in Yellowstone National Park, U.S.A. *The Holocene* 6, 7–15.