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

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ABSTRACT

Aim In this study, charcoal-based data for Pinus cembra L. (arolla pine) were gathered from soil and travertine sequences in order to reconstruct its historical biogeography at the landscape level in the inner western Alps during the Holocene.

Location The study sites are located between 1700 and 2990 m a.s.l., in the southern (Queyras Massif and Ubaye Valley) and the northern (Maurienne Valley) parts of the inner French Alps.

Methods Charcoal fragments were extracted from sediments by water sieving, using meshes of 5, 2, 0.8 and 0.4 mm. The charcoal mass of P. cembra was determined in each charcoal assemblage. Accelerator mass spectrometry and conventional ¹⁴C measurements were used to date the fragments.

Results Supported by 40 ¹⁴C datings, the fragments show that, over 2000 m a.s.l., P. cembra accounts for around 40% (mean value) of identified fragments. Data reveal that arolla pine once extended between 260 and 375 m above the present-day local tree lines. It was established in the southern and the northern French Alps from at least c. 9000 and 6000 cal yr BP, respectively.

Main conclusions While present-day populations of P. cembra are very fragmented in the inner French Alps, charcoal records indicate large past occurrences of this tree since the early Holocene. Human disturbance since the Neolithic seems to be the main reason for the regression of the arolla pine woodlands. On the south-facing slopes of the study sites, currently deforested, this species extended up to 2800 m a.s.l. In the northern areas, charcoal records of the P. cembra expansion are consistent with the regional pollen archives, but in the southern massifs charcoal records indicate its presence c. 2600 years earlier than other palaeobotanical studies suggest. This discrepancy highlights the necessity to crosscheck data using several different proxies in order to assess the validity of conclusions regarding tree development in space and time.

Keywords Biogeography, charcoal, fire, French Alps, Holocene, Pinus cembra, soil, travertine.

INTRODUCTION

Pinus cembra L. (arolla pine) is today distributed in mountainous regions from the Carpathian Mountains and Transylvania to the French Alps (Polunin & Walters, 1986). Arolla pine is a key species at high altitudes, and its regeneration depends on the European nutcracker, Nucifraga caryocatactes L. (Mattes, 1994; Camaret et al., 1998). This bird, which exploits diverse vegetation ‘pockets’ for feeding and removes seeds, assists in seed dispersal, especially in rocky open patches.
that are sparsely covered with dwarf woody shrubs in wind-exposed sites (Crocq, 1990). Consequently, the regeneration success of the arolla pine is spatially limited in comparison with that of other sympatric competitive coniferous species, such as Pinus uncinata Mill. (mountain pine), Larix decidua Mill. (larch) and Picea abies (L.) Karst. (spruce), that have wind-dispersed seeds. The present-day distribution of Pinus cembra is highly fragmented in the inner French Alps, where it forms homogeneous or mixed woodlands in association with L. decidua, P. uncinata and P. abies. The French forest inventory administration (Inventaire Forestier National) observed that P. cembra forests currently cover 1513 ha, whereas L. decidua and P. uncinata cover 90,140 and 16,650 ha, respectively (http://www.ifn.fr/), highlighting the scarcity of arolla woodlands. P. cembra essentially grows on the north-facing slopes of valleys, while the south-facing slopes are generally deforested, with large pasture areas devoted to agropastoral uses (Contini & Lavarello, 1982). However, with the collapse of human activities in mountain regions since c. AD 1950, the abandoned lands above 2000 m a.s.l. have been progressively colonized by larch and spruce stands with scattered arolla individuals (Didier, 2001; Motta & Nola, 2001).

To date, the biogeography of P. cembra has been investigated principally using pollen analyses. Pinus cembra has been present in the central Alps since at least 13,000 cal yr BP (Burga, 1988; Heiri et al., 2003). Pollen-based studies suggest that it progressively diffused from central to western areas (Burga, 1988), establishing at c. 9500 cal yr BP in the northern French Alps (Wegmüller, 1977; David, 1995) and at c. 6400 cal yr BP in the southern massifs (de Beaulieu, 1977; Coutéaux, 1982, 1984; Fauquette & Talon, 1995; Nakagawa et al., 2000). However, it has been shown in alpine-tundra zones that pollen analyses alone cannot provide precise reconstructions of plant occurrence and biogeography (Payette & Gagnon, 1985; Ritchie, 1995; Kullman, 1996, 2001, 2002; Carcaillet et al., 1998; Odgaard, 2001): pollen records must be coupled with studies of plant macrofossils in order to decipher past high-elevation vegetation composition and structure (Jackson et al., 1997; Birks & Birks, 2000; Ali et al., 2003; Birks, 2003). This is partly because of differences between species in the altitudinal variability of pollen production, and partly because the wind-dispersal of pollen can give misleading indications about species distribution, especially for Pinus, Betula and Alnus species (Birks & Birks, 2000; Odgaard, 2001; Kullman, 2002).

Moreover, woodland from high elevations can grow in the alpine tundra as dispersed and isolated trees or as tree islands (Holtmeier & Broll, 1992), with inevitable reductions in pollen production (Moe, 1998) and developing vegetative reproduction processes (Tranquillini, 1979; Arquillière, 1986).

In the present study, we report data gathered from the analysis of charcoal fragments preserved in travertine and natural soil located in southern (Aigue Agnelle, Guil and upper Ubaye valleys) and northern (upper Maurienne Valley) parts of the inner French Alps. Travertine sequences are natural calcareous deposits resulting from both physicochemical and biological processes related to the bicarbonate saturation of water (Magnin et al., 1991; Geurts & Watts, 1997; Guendon et al., 2003). Mountain travertines frequently enclose charcoal remains in detrital layers (Ali et al., 2002, 2004, 2005).

According to studies of charcoal transportation during and after fires, fragments > 0.4 mm are not mass-transported by air by more than a few metres from the sources of ignition (Clark et al., 1998; Blackford, 2000; Ohlson & Tryterud, 2000; Lynch et al., 2004), and thus represent reliable palaeobotanical proxies to reconstruct past vegetation composition and structure with high spatial resolution. The present data, based on charcoal > 0.4 mm and supported by radiocarbon datings, allow the altitudinal and geographical distribution of P. cembra in the inner French Alps during the Holocene to be reconstructed.

**STUDY AREAS**

The valleys of Aigue Agnelle (44°44’ N, 6°53’ E) and Guil (44°44’ N, 6°58’ E) are located 5 km apart in the Queyras area (Fig. 1), along the French/Italian border. The present-day climate in the area has montane mediterranean-continental characteristics, with a precipitation minimum in summer (July: 50 mm) and a maximum in late spring (June: 100 mm). The climatic data were obtained from the weather station of Saint-Véran (2125 m a.s.l.) in a neighbouring valley. Mean monthly
precipitation amounts to 75 ± 16 mm, while the mean annual temperature is 5.8 ± 5.5 °C. Mean temperatures for the coldest (February) and warmest (July) months are −3.0 and +13.0 °C, respectively. The woody vegetation is composed of woodlands spreading between 1700 and 2400 m a.s.l., and is dominated by *L. decidua*, *P. cembra* and *P. uncinata*. The understorey is dominated by *Rhododendron ferrugineum* L., *Vaccinium uliginosum* L. (mostly on north-facing slopes), *Arctostaphylos uva-ursi* (L.) Spreng. (on south-facing slopes) and *Juniperus communis* L. The tree line on the north-facing slopes is formed by a mosaic of *L. decidua* woodlands, spreading up to 2400 m a.s.l. On the south-facing slopes, traditional land use has been devoted mainly to livestock grazing (mostly sheep), resulting in large areas of meadows and heathland slopes, where trees are absent above 2000 m. The upper Ubay Valley (44°36’ N, 6°52’ E) is located in the south-east of the Queyras region (Fig. 1). The climate is similar but a little drier than that of the Queyras area. The vegetation is more or less the same, but *P. cembra* is present sporadically.

In the upper Maurienne Valley, two neighbouring sites, separated by 10 km, were studied in the localities of Saint-Michel-de-Maurienne (45°15’ N, 6°30’ E) and Aussois (45°15’ N, 6°45’ E) (Fig. 1). The upper Maurienne Valley is one of the driest of the Alps. The following climate data were recorded at 1360 m a.s.l. in Saint-Michel and at 1490 m in Aussois. The mean monthly precipitation amounts to 79 ± 14 mm at Saint-Michel-de-Maurienne and 59 ± 10 mm at Aussois. The mean annual temperatures are 7.0 and 6.2 °C, respectively; the mean temperatures for the coldest month at Aussois. The mean annual temperatures are 7.0 and 6.2 °C.

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### MATERIAL AND METHODS

#### Sampling

In total, 37 soil profiles were sampled in the upper Maurienne (23), the upper Ubay (7) and the Aigue Agnelle (7) valleys, mostly on the south-facing slopes. Soil profiles were dug in trenches down to the bedrock whenever possible. About 10–15 L of dry material was sampled per soil layer of c. 20 cm depth. Charcoal fragments were extracted from the soil matrix using deflocculation and flotation processes with an ascending water current to separate mineral particles from charcoal, followed by water-sieving through meshes of 5, 2, 0.8 and 0.4 mm (Carcailliet & Thinon, 1996).

Charcoal fragments from 10 travertine sequences were sampled in the Aigue Agnelle (6) and Guil (4) valleys. The quantity of sediment sampled depended on the abundance of charcoal per detrital level. In levels containing charcoal horizons, 10 L of sediment were extracted, and in levels enclosing dispersed fragments, 30 L were extracted. The charcoal fragments were recovered in the laboratory by water-sieving the sediment samples through 5 and 2 mm meshes.

#### Charcoal identification and analysis

Charcoal fragments were manually broken and their anatomical characteristics were observed in transversal, tangential and radial sections, under a reflected-light microscope (x100, x200, x500 and x1000). Identifications were made by comparing subfossil fragments with reference collections of charred modern wood species and wood anatomy atlases (e.g. Jacquiot, 1955; Schweingruber, 1990). In each charcoal assemblage, the charcoal mass of *P. cembra* was expressed as a percentage. This approach allowed the importance of this species to be determined relative to the other burned taxa.

#### Dating

Accelerator mass spectrometry (AMS) measurements were used to date charcoal fragments from soil profiles. This technique was necessary because of the low mass of charcoal collected in soils (usually < 10 mg/assemblage), and because soil stratification was not demonstrated (Carcaillet, 2001a,b). Most of the datings were carried out on single fragments of *P. cembra*. The abundance of charcoal sampled in travertine sequences and the stratification of the deposits generally allowed conventional 14C dating to be carried out on the individual charcoal assemblages containing *P. cembra* fragments (Ali et al., 2005). All 14C dates were calibrated using the calibration data set INTCAL98 (Stuiver et al., 1998) and the CALIB REV 4.4.2 program (copyright 1986–2004 Stuiver & Reimer). For 14C dates that have already been published, references are provided (Table 1). Eighteen new datings are presented for the first time in this paper.

#### RESULTS

Figure 2 displays the charcoal masses of *P. cembra* (%) found within the various charcoal assemblages (169 in total), with increasing altitude. *Pinus cembra* accounts for between 0% and 100% of the identified fragments, indicating a possible patchy distribution of woodlands in space and time between 1700 and 2775 m a.s.l. Mean values of 38% (Fig. 2a) and 42% (Fig. 2b) were obtained for the southern (Queyras region and upper Ubay Valley) and the northern (Maurienne Valley) areas, respectively. The other fragments belonged to taxa such as *Abies alba* Mill. (silver fir) *Pinus sectio sylvestris*, *L. decidua*, *P. abies*, *Acer opalus* Mill. (opalus maple), *Acer pseudoplatanus* L. (sycamore), *Alnus cf. incana* (L.) Moench. (grey alder), and
Betula sp. (birch) (Carcaillet, 1996; Talon, 1997; Ali et al., 2005). Most of these taxa were found only at elevations lower than 2000 m a.s.l.

Chronological changes in the proportion of charcoal fragments in the detrital layers of the travertine sequences show that *P. cembra* woodlands have declined through time in the Queyras area (Fig. 3). Before 7000 cal yr BP, this species accounts for between 80% and 100% of the charcoal mass recovered above 2000 m a.s.l. in this region, suggesting that it was probably a dominant tree at the beginning of the Holocene. From 4000 cal yr BP, however, its abundance appears to have decreased, until, by around 1700 cal yr BP, it accounts for only 7% of the charcoal (Fig. 3).

All radiocarbon dates measured for wood charcoal fragments of *P. cembra* are shown in Table 1. The results reveal that *P. cembra* was present in the French inner Alps during the Holocene between 1700 and 2775 m a.s.l. In the southern region, the dates reveal that the establishment of *P. cembra* had occurred by 9090–9330 cal yr BP at the latest (Fig. 4a). Despite the number of datings performed (*n* = 23), we did not obtain any data for the period between 6000 yr BP and 5000 cal yr BP.

In the Maurienne Valley, arolla pine was established on the south-facing slopes by at least 5740–5960 cal yr BP. Most of the

<table>
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<th>Aspect</th>
<th>Dating</th>
<th>Ages BP</th>
<th>Cal. BP (2σ)*</th>
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*Datings are rounded to the nearest 10 years.*
dates are concentrated during the mid-Holocene, suggesting that *P. cembra* woodlands burned principally between c. 6000 and 3000 years ago (Fig. 4b).

In the southern region, *P. cembra* charcoal fragments were found up to 2775 m a.s.l., but radiocarbon dates were obtained only up to 2670 m a.s.l. (Fig. 4a). The charcoal concentration in the soils decreases drastically with elevation (Carcaillet & Talon, 2001). Consequently, between 2670 and 2775 m a.s.l., charcoal fragments collected could not be dated because of their small size and weight (< 1.0 mg). Nevertheless, the results clearly indicate that *P. cembra* extended to elevations similar to that of the present-day upper tree line (2400 m a.s.l.) during the major part of the Holocene, but also up to 375 m higher during an uncertain period (Fig. 4a). In the Maurienne Valley, dates were obtained from materials recovered up to 2510 m a.s.l. (Fig. 4b). Between 2510 m a.s.l. and 2660 m a.s.l., charcoal fragments collected could not be dated for the same reason as in the southern region. The results indicate that *P. cembra* expanded up to 260 m above the present-day tree line, at least between 4200–3400 cal yr BP (Fig. 4b).

DISCUSSION

*Pinus cembra* was a common tree during the Holocene in the subalpine and alpine belts of the inner French Alps (Fig. 2). Its history is associated with the occurrence of fire, owing to the fact that charcoals result from burned vegetation. In the southern French Alps, the earliest pollen grains of *P. cembra* found so far have been recovered from sediments of the Siguret lake (Durance Valley; 1066 m a.s.l.), dating to the Alleröd and Late Dryas chronozones (de Beaulieu, 1977). However, concerning the Holocene, synthesis of available pollen studies shows that *P. cembra* forests are not attested in the regional vegetation during the early Holocene. Arolla pine expansion did not occur before c. 6400 cal yr BP (Coûteaux, 1982, 1984; Fauquette & Talon, 1995; Nakagawa *et al.*, 2000). This comparison thus reveals a discrepancy, since some of the charcoal fragments of *P. cembra* dated in Queyras travertine are 2600 years older than the earliest pollen records. It is surprising that *P. cembra*, which was seemingly present during the Alleröd in the study areas, should be so minor a component of the vegetation until 6400 yr BP as to be invisible in the pollen records. Pollen grains of *P. cembra* associated with *L. decidua* and *Betula* have been found in the central Alps continuously since c. 13,000 cal yr BP (Burga, 1988; Heiri *et al.*, 2003). Its expansion in the Queyras area at least c. 9000 cal yr BP, i.e. 4000 years after its first establishment in the central Alps, is conceivable according to the westward colonization routes proposed by Burga (1988). Moreover, the record of pollen grains of *P. cembra* in sediments of the Durance Valley, dating to Alleröd and Late Dryas chronozones (de Beaulieu, 1977), suggests possible refuge areas from which this species

![Figure 2](image-url)
could have begun its colonization of the southern French Alps after the deglaciation. It is possible that scattered P. cembra individuals migrated quite early in the southern French Alps or have survived since late-glacial times, but their numbers were not sufficient to enable detection in regional pollen records. A similar situation has been proposed to explain the palynological silence in the early Holocene of P. abies in the Scandinavian mountains, where pollen grains of spruce are very rare (Segerström & von Stedingk, 2003), while trunks have been dated from this time in the same area (Kullman, 1996). It is also important to note that it is difficult to distinguish the pollen grains of P. cembra from those of other pines (de Beaulieu, 1977; Couëtoux, 1984; Nakagawa et al., 2000). We may assume that P. cembra has been underestimated in the pollen records and that it was probably locally important at the beginning of the Holocene in the southern French Alps.

In the Maurienne Valley, arolla pine has been present in the vegetation since at least c. 6000 cal yr BP, while the pollen studies indicate that it has been established in the regional vegetation since at least c. 9500 cal yr BP (Wegmüller, 1977; David, 1995). At this stage of research, no fire events have been recorded before 6000 cal yr BP in the northern French Alps (Carcailllet, 1998). Consequently, the apparent chronological discrepancy between the pollen and charcoal records concerning the establishment of P. cembra in the Maurienne Valley could be a result of the lack of detected fire events.

Altitudinal and spatial variations of Pinus cembra: climatic or human forcing?

Today, in the inner French Alps, P. cembra is present in fragmented populations, mostly on the north-facing slopes of valleys and massifs (Contini & Lavarello, 1982; Rameau et al., 1993; Chas, 1994). In some valleys, such as the Aigue Agnelle and the upper Ubaye and in the Saint-Michel-de-Maurienne locality, P. cembra is absent. Our results reveal that this tree was a common tree at high elevations in all investigated sites during the mid-Holocene. Indeed, the soil and travertine charcoal show that it grew at higher elevations than it does today. The elevational decline of this species was c. 375 m in the Queyras area and upper Ubaye Valley, and 260 m in the upper Maurienne Valley. According to the radiocarbon datings
(Table 1) and the regional development of *P. cembra* inferred from pollen analyses (de Beaulieu, 1977; Wegmüller, 1977; David, 1995; Nakagawa et al., 2000), this altitudinal drop may have occurred between 4000 yr BP and 2000 cal yr BP.

It is important to note that in the French Alps no pollen investigations have been carried out on sites located above 2400 m. Moreover, studies have revealed unfavourable conditions such that the temperature and soil characteristics are limiting factors close to the tree line, and such conditions could cause significant reductions in the pollen production of local trees (Moe, 1998; Hicks, 2001). Consequently, there may be little or no trace of trees growing between 2400 and 2800 m a.s.l. in the pollen records. Carnelli et al. (2004) have published similar findings from studies in the central Swiss Alps, also based on charcoal from soils, indicating that during the Holocene *P. cembra* colonized very high altitudes, up to 300 m above the present local tree line. In reference to our previous studies (Carcaillet et al., 1998; Talon et al., 1998; Carcaillet & Brun, 2000; Ali et al., 2005) and new results presented in this present paper, we suggest that *P. cembra* may have formed a forested belt between 1700 and 2400 m a.s.l. in the inner French Alps, along with other woody species, for example *P. uncinata*, *L. decidua*, *B. pendula* and *B. pubescens*. Isolated trees might have occurred at altitudes of up to almost 2800 m a.s.l.

It is known that climatic variations can induce significant changes in the upper altitudinal limits of tree species (LaMarche & Mooney, 1972; LaMarche, 1973; Carrara et al., 1991; Kullman, 1995; Wick & Tinner, 1997; Seppä & Birks, 2001). In the Alps, the Holocene has been characterized by small climatic shifts with oscillations of both precipitation and temperature (Haas et al., 1998; Magny et al., 2003). These climatic changes could have induced variations in the altitudinal development of *P. cembra*. However, there is insufficient evidence to conclude that these climatic modifications are responsible for the substantial altitudinal decline of the upper tree line and fragmentation of *P. cembra* woodlands, and sometimes for its local extinctions. Since the mid-Holocene, mankind has become a major ecological factor, profoundly disturbing alpine ecosystems (see, for instance, Burga, 1976; Vorren et al., 1993; Carcaillet, 1998; Talon et al., 1998; Carcaillet & Brun, 2000; Gobet et al., 2003; Ali et al., 2005). It is very difficult to demonstrate directly that human activities were the main causes of the altitudinal changes of the tree limit and the geographical distribution of *P. cembra*. Nevertheless, the strong differences in woody vegetation between the south- and north-facing slopes within valleys support the hypothesis that local anthropogenic processes have been responsible for changes in the structure of the local vegetation. The diversity of trajectories and the historical pattern of the local extinctions imply a human hand in the causation of *P. cembra* population decline. For instance, the abrupt disappearance of *P. cembra* trunks and pollen in the sediments of Cristol Lake (2200 m a.s.l.) at

![Figure 4](image-url)
human settlements could be as ancient as the early Neolithic, excavations in the Maurienne Valley have shown that local Holocene in this area (Carcaillet, 1998). Recent archaeological processes may have controlled fire ignition during the Aussois localities, located 10 km apart, imply that local patterns of fire between Saint-Michel-de-Maurienne and Neolithic populations for agropastoral activities. In the upper sites (Queyras area, present paper), supports this hypothesis.

massifs from the Bronze Age onwards (Barge, 1995, 1998; Ancel, 1997; Leveau & Martinez, 2002). Nevertheless, it is possible that human communities might have occupied the southern French Alps episodically during the early Neolithic for transhumance purposes (Breeching & Riols, 1999; Fedele, 2002). The impact of human practices, with recurrent use of fire, appears to have caused the fragmentation of P. cembra populations and the simultaneous expansion of L. decidua, P. abies and P. sylvestris woodlands. These changes in vegetation may reflect the poor capacity of P. cembra populations to regenerate and expand after fire events and on the resulting bare soils. The other sympatric species are better adapted to recurrent perturbations. However, the intensification of woodland opening without reduction of anthropogenic activities appears to have caused the total regression of woody plants and the establishment of large grassland areas such as those on the south-facing slope of the Aigue Agnelle Valley. Thus, anthropogenic disturbance could have been the main factor affecting the biogeography of P. cembra in the inner French Alps since the mid-Holocene. Our results indicate that P. cembra was well established in the past on the south-facing slopes of valleys, and that its present-day scarcity is a consequence of changes in the fire regime and human practices.

**CONCLUSIONS**

During the early and the mid-Holocene in the French inner Alps, P. cembra was more widely distributed than it is today. This species colonized high elevations of up to almost 2800 m a.s.l. In the northern and southern parts, P. cembra shows altitudinal drops of 260 and 375 m, respectively. Arolla pine was abundant on the south-facing slopes of valleys, which are today dominated by grasslands. Human practices since the Neolithic seem to have played a significant role in the biogeography of P. cembra, particularly in respect of its local extinction. However, we cannot rule out the influence of climate on the upper tree-line decrease. Finally, we want to stress the need for further investigations using combined methods such as analyses of charcoal, macro-remains, pollen and travertine imprints, in order to date precisely and understand the nature of the Holocene dynamics of the upper tree line, and the historical biogeography of woody plants in the area.

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