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# From pristine forests to high-altitude pastures: an ecological approach to prehistoric human impact on vegetation and landscapes in the western Italian Alps

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## Summary

**1.** This paper addresses the origin and development of the oldest prehistoric pasture in the timberline ecotone known so far in the Alps and its relation to anthropogenic pressure and natural climate change.
**2.** Palaeoecological and geochemical techniques were applied on the Crotte Basse mire stratigraphy (2365 m a.s.l, northwestern Italy) to describe changes in vegetation composition, forest biomass, land use and fertilization between c. 6400–1800 cal years BP.
**3.** Subalpine forests dominated by *Pinus cembra* occurred at very high-altitude up to c. 5600 cal years BP, when a sharp contraction of woody vegetation took place. This major vegetation shift is matched by increasing charcoal input and markers of pastoral/grazing activities (pollen, dung spores and forms of phosphorus) in the sediment sequence in this small basin.
**4.** Major phases of landscape change detected in our multiproxy record chronologically match intervals of cumulative probability density of $^{14}$C ages from nearby archaeological sites, suggesting that human activity was the factor leading to massive landscape change from the onset of the Copper Age (c. 5600 cal years BP). The change may have been reinforced by climate variability in the period 5700–5300 cal years BP.
**5.** Sensitivity of woody species to fires was statistically explored (Appendix S1, Supporting Information), revealing negative reactions of *P. cembra* and *Betula* to frequent fire episodes and positive reactions of *Alnus viridis* and *Juniperus*. Fire episodes do not affect *Larix* dynamics.
**6.** *Synthesis.* Mt. Fallère provides some of the oldest and consistent evidence so far available in the Alps for major anthropogenic pressure at the upper forest limit. As far back as 5600 cal years BP, high-elevation forest ecosystems were permanently disrupted and the alpine pastures were created. Palaeoecological data enable a clear distinction between a random and sporadic use of the alpine space, typical for Mesolithic and Neolithic societies, and an organized seasonal exploitation of natural resources, starting from the Copper Age onwards. The chronological comparison of independent climate proxies, palaeoecological information and pollen-based temperature reconstructions sheds light on the relationships between climate and humans since prehistoric times.

**Key-words:** $^{14}$C dating, archaeology, dung fungi, landscape ecology, nutrients, palaeoecology and land-use history, pastoralism, stratigraphy, subalpine forests

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## Introduction

Above the ecological limit for woody species, the alpine elevational belts support a wide variety of grasslands and pioneer communities (Ellenberg 1988). Their development is limited by climatic factors, i.e. persistence of snow cover, prolonged frost, short growing season, harsh temperatures and wind (Körner 2003). Grasslands occupy steep south-facing slopes, forming steppe-like communities. Flat surfaces host communities adapted to long snow cover, only partly herbaceous, similar to arctic tundra and thus sometimes called 'Alpine tundra'. Usually, 'Alpine tundra' grows over podzolized soils (Legros 1992) and is believed to originate from the removal of dwarf-shrub heaths or even from boreal-type forest (i.e. *Vaccinio-Piceetea*, Holtmeier 2003). Warmer, gentle slopes may support highly productive ecosystems including a widespread, *Nardus*-rich type, commonly related to anthropogenic forest clearance and pasture fertilization (Holzner & Numata 1982). Overall, distinguishing modern natural grasslands from human-shaped pastures is not straightforward. In this respect, palaeoecology can be of help, in that it allows the detection of the historical steps that formed modern high-elevation grasslands. Fossil plant remains (pollen, stomata, fruits and seeds, wood, charcoal) in soils and peat bogs provide evidence that timberline reached high altitudes in the early Holocene (Ali *et al.* 2005; Talon 2010). Seasonally stable husbandry and farming can be inferred based on palaeoecological indicators, such as nitrophilous macrophytes and fungi identifiable from their pollen and spores (Oeggl 1994; Wick 1996). Different lines of evidence (anthropogenic plant indicators, macrocharcoal peaks, nutrient concentrations in basins used for animal watering, and radiocarbon-dated archaeological structures) allow for a robust reconstruction of early human impact on high-elevation ecosystems. It has been shown that pollen indicators for ancient pastures increase as a result of animal grazing and respond to fertilization induced by increasing run-off (Festi, Putzer & Oeggl 2014). Palaeoecologists are urged to expand their environmental dataset (Seddon *et al.* 2014), including more palaeobotanical and geochemical proxies together with external proxies for climate change and a full consideration of the archaeological evidence. Climate change can be evaluated by comparing pollen-based climate reconstruction, glacier oscillations (Le Roy *et al.* 2015) and speleothem proxies (Luetscher *et al.* 2011). Most of these approaches form the basis of our research strategy.

Unequivocal evidence for a Neolithic pastoral system in the higher Alps is lacking and the origin of Alpine elevational pastures is still an open question – are they natural, climatic or anthropogenic, or the result of overlapping effects and feedbacks? What is the oldest evidence for heavily grazed, human-shaped subalpine pastures in the Alps? Are there events in human and climate history that triggered the transition from boreal forests and heaths to grass communities?

The recent discovery of prehistoric high-altitude human activities in the Western Alps (Pini *et al.* 2013; Fig. 1b) offers a new challenge to assess ecological facts, human and climate triggers and the origin of Alpine husbandry. Extensive archaeological surveys testify to human presence in the area since the Mesolithic (from c. 8500–8600 cal years BP) and provide robust evidence for human activities between the onset of the Copper Age (c. 5600 cal years BP) and the Roman period (c. 2100 cal years BP; see later on for cultural periodization). The development of alpine pastures here is particularly favoured by water availability, southern aspect morphology. Perhaps easy contacts with an early populated valley floor may have also played a major role. On the other hand, the surrounding mountains are harsh ecological environments, unfavourable for husbandry.

In this area, we developed a multiproxy high-resolution, stratigraphically ordered record in continuously deposited sediments in a medium-size pond showing temporal relationships between the observed events. Our research aims at (i) tracing back in time the origins of alpine pastures in this sector of the western Alps; (ii) understanding the role of regional ecological setting, humans and climate in triggering the changes depicted in the palaeoecological record; (iii) observing what happened to the natural landscape once it was impacted. The answer to this question is not obvious and should not be related to the initial triggering mechanism; (iv) evaluating the effects of nutrients on the vegetation in water bodies used for animal watering; (v) analysing the effects of fire disturbance at timberline before and at the onset of Alpine pastoralism; and (vi) pinpoint the most important clues in the ecological scenario to synthesize regional differences in historical landscape evolution of high-alpine areas in the latest Neolithic/Copper Age, i.e. the time when permanent pastoralism started.

### THE ECOLOGICAL SETTING OF THE ALPS BEFORE AND AT THE TIME OF THE FIRST HIGH-ALTITUDE PASTURES – FROM THE MESOLITHIC TO THE NEOLITHIC

Given the complexity of the historical background, additional information on Alpine climate and human prehistory during the early Holocene provides a setting for the present paper.

Patterns and rates of expansion of tree populations after the last deglaciation were driven mostly by natural factors (Tinner & Kaltenrieder 2005; Blarquez *et al.* 2010; Magri *et al.* 2015). The scattered Palaeolithic to Mesolithic populations and nomadic subsistence economies, based on hunting, gathering and raw material exploitation (Cusinato *et al.* 2003; Marzatico 2007), resulted in temporary ecosystem disturbances rather than the creation of anthropogenic landscapes (Oeggl & Wahlmüller 1994; Baroni 1997; Avigliano *et al.* 2000). No significant human effects on tree line or pasture plants have been recorded in the Mesolithic period in the Alps.

Farming communities first appeared in the Aosta Valley region and in an adjacent Swiss valley about 5 ka cal BC (Colombaroli *et al.* 2013). First signs of pastoral nomadism at low altitudes (*Alpwirtschaft*) appeared with the Late Neolithic, i.e. 4 ka cal BC (Della Casa 2003; Walsh 2005; Festi, Putzer & Oeggl 2014; Thöle *et al.* 2015). High-altitude seasonal camps (Curdy 2007) and sedDNA evidence of domestic

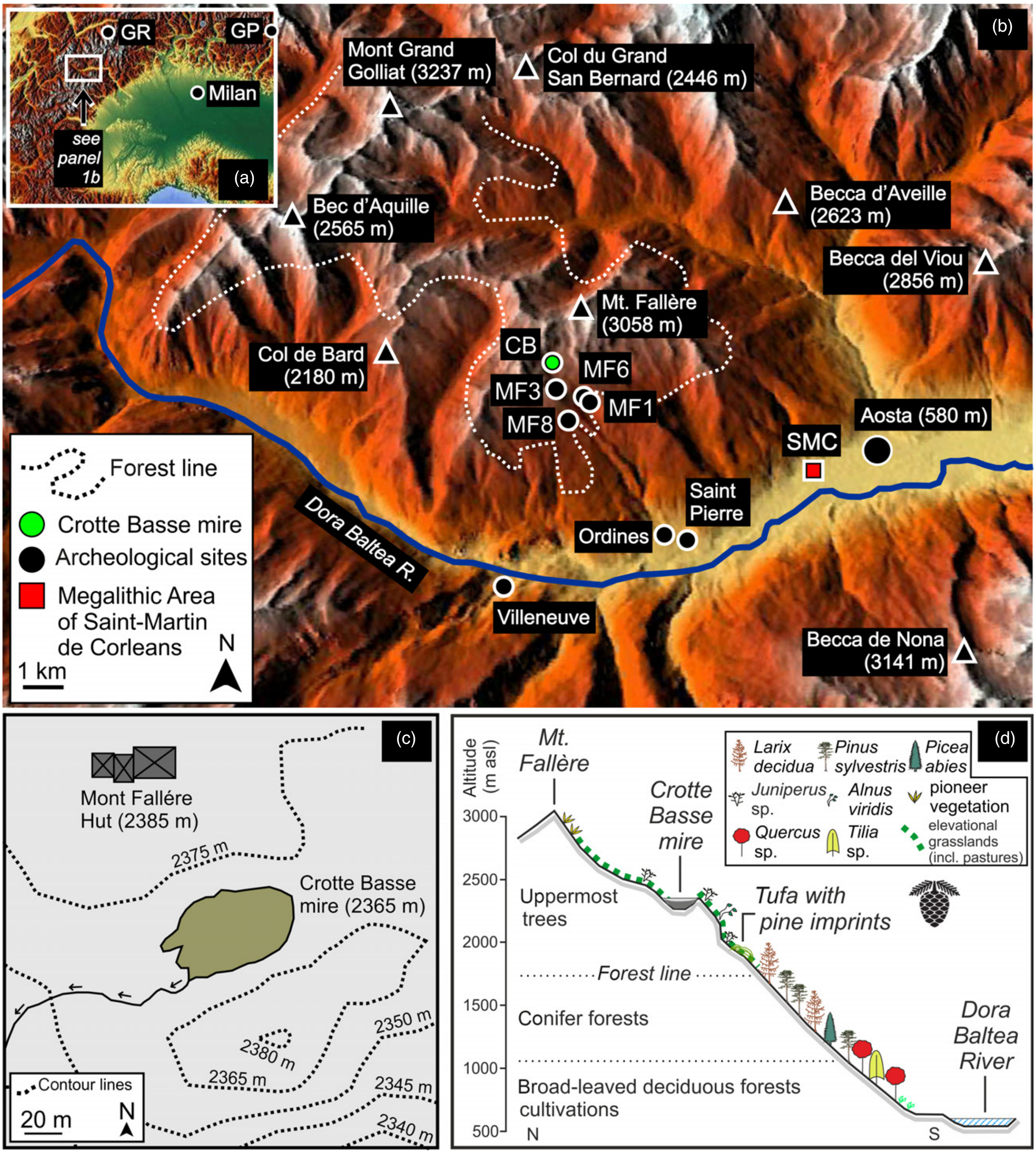


**Fig. 1.** (a) General overview of northern Italy and of the large alpine area. A square indicates the study area. GR: Gouillé Rion; GP: Gavia Pass. Source: http://www.maps-for-free.com/; (b) relief map of the study area, centred on the Mt. Fallère Massif. The dotted line indicates the present-day altitude of the forest line, depressed on the southern slope of Mt. Fallère. Acronym MF followed by numbers indicate local archaeological sites. Altitude (m a.s.l) of relevant sites discussed in the text as follows: Crotte Basse mire = 2365 m, site MF1 = 2241 m, site MF3 = 2292 m, site MF 6 = 2270 m, site MF8 = 2190 m, Megalithic Area of Saint Martin de Corléans = 583 m, Ordines = 730 m; (c) topographic sketch of the study area; (d) simplified altitudinal transect of the modern vegetation settled on Mt. Fallère. [Colour figure can be viewed at wileyonlinelibrary.com]

mammal (Giguet-Covex *et al.* 2014) envisage exploiting herb vegetation in the timberline ecotone during the Copper Age. However, husbandry strategy adopted by these early herders is not detectable from archaeological structures; was it nomadic or stable? which animals and stocking rates were involved?

## Materials and methods

### THE STUDY AREA

We focused on the westernmost sector of the Aosta Valley, Western Italian Alps. This area shows the typical alpine glacial landscape, with a wide valley floor bounded by steep slopes peaking with sharp, glaciated massifs (Mt. Bianco, 4810 m a.s.l). The subalpine-alpine belt is a landscape of cirques and uplands that were deglaciated early in the Lateglacial (Wirsig *et al.* 2016). Today, they host delightful pastures, lakes and mires.

The stratigraphic archive of the Crotte Basse mire (2365 m a.s.l) preserves a complete Holocene landscape history of the subalpine-alpine highlands of the Mt. Fallère southern flank, Aosta Valley (Fig. 1). The mire lies in a wide glacial cirque cut into a metamorphic bedrock of mica schists with garnets and sodium-amphiboles (Polino *et al.* in press). Pastures extend up to 2700 m altitude towards the ridges of Mt. Fallère (peak at 3065 m a.s.l). The mire has no superficial inlet, and its catchment is small, a 15 m belt around its edges. A small outlet flows from its western side (Fig. 1c). This is not the only basin which may have provided water for livestock in the past. However, in contrast to other mires nearby, an impermeable and deep water pool is constantly supplied via groundwater.

Together with the nearby Valais, the Aosta Valley is one of the oldest areas of intravalley permanent settlement of the Western Alps. It has witnessed a 7000 year-long history of human–landscape interaction. On Mt. Fallère highlands between 2100 and 2300 m prehistoric human presence consists of hearths, lithic industries in hyaline quartz, a green stone axe and charcoal-rich layers. Archaeological settlements of Middle–Late Neolithic and Copper Ages are located in the valley floor at lower altitudes.

## MODERN ECOSYSTEMS AND CLIMATE IN THE STUDY AREA

The elevational vegetation gradient is marked by the regional tree line, formed of Swiss stone pine (*Pinus cembra*) and larch. The uppermost individual of *Pinus sylvestris* (2 m high, upright) occurs at 2365 m on an exposed ledge, *Larix decidua* (2·5 m high) at 2360 m on rocks and *Betula alba* at 2307 m along the trail. Peat biomass accumulation takes place up to 2560 m a.s.l. Timberline may be hugely depressed down to even 1800 m, replaced by extensive *Nardus*-rich pastures and steppe-like grasslands. Above 1800 m pastures and alpine grasslands occur widely. Widespread communities include hay meadows (with *Avenula pubescens* and *A. pratensis*, *Gentiana lutea*, *Galium glaucum*), steppe-like communities (with *Pulsatilla halleri*, *Centaurea scabiosa*, *Galium verum*), dry heaths (with *Arctostaphylos uva-ursi*, *Juniperus communis* and *J. communis* ssp. *nana*, *Astragalus monspessulanus*, *Oxytropis campestris*) and subalpine *Nardus*-rich pastures grading upwards into tundra-like Alpine tussocks of *Carex curvula*.

A conifer belt with boreal affinity is usually preserved between the highest permanent villages (1400 m) and the local timberline. In the Alps as a whole, major differences in tree line composition are related to the variable role of Swiss stone pine as edificator of the timberline ecotone and of fir (*Abies alba*) as co-dominant in a potentially large forest belt (Ellenberg 1988). However, both these species are lacking in the modern vegetation of the study area. Nowadays *P. cembra* is almost absent in most part of the region, being present only in the Gressoney Valley and adjacent areas (San Grato and Arpy), c. 50 km east from Mt. Fallère. As for *A. alba*, its modern distribution in the region is highly fragmented. The modern closest stand is located 6 km north-east of the study site, covering an area of less than 6 ha. Larger stands (c. 80–120 ha) are located 8–10 km south of the study site.

Regional climate is alpine continental, with precipitation concentrated in the 3-month summer vegetative period. At the study site, mean temperature and precipitation for the reference period 1961–1990 modelled according to Brunetti *et al.* (2014) for the coldest month are $T_{jan}$ (January) −6·9 °C and 131 mm (1·3 °C and 40 mm, 68% confidence interval, respectively). For the warmest month $T_{jul}$ (July), they are 8·6 °C and 97 mm (0·9 °C and 18 mm, 68% confidence interval, respectively).

## PALAEOECOLOGY

Palaeoecological analyses were performed on sediments obtained with modified Russian corers down to 5·81 m. Pollen stratigraphy places the base of the core in the second part of the Bølling–Allerød interstadial (c. 13–12·8 ka cal BP). Here, we focus on the middle to late Holocene vegetation and environmental evolution.

Samples for pollen analysis (1–2 $cm^3$) underwent standard laboratory treatments for pollen extraction (including HF and acetolysis, no heavy liquids). A Leica DM LS2 light microscope at ×400, ×630 and ×1000 was used to identify pollen, fern and fungal spores, algal remains and other non-pollen palynomorphs (NPPs). Pollen identification relies on Punt *et al.* (1976–2009), Reille (1992–1998), Moore, Webb & Collinson (1991), Beug (2004) and the CNR reference collection. Microcharcoal particles were counted in pollen slides, distinguishing two size classes (10–50 μm and 50–250 μm length). *Lycopodium* tablets were added for pollen and microcharcoal concentration estimation (Stockmarr 1971). With the exception of the uppermost sample, at least 500 grains of upland plants were identified in each sample (min 526, max 684, total grains identified 25729). The calculation of pollen percentages was based on the sum of tree, shrub and upland herb pollen: aquatic and wetland species, spores, algae and NPPs are excluded from this sum. Tilia 2.0.2 (Grimm 2004) was used for % calculations and preparation of stratigraphical diagrams, then exported into CorelDraw for further modification (Figs 3 and 5).

## GEOCHEMISTRY

Loss-On-Ignition was performed on duplicates of pollen samples with an automated LECO® TGA 601 thermogravimetric analyser (LECO Corporation, Saint Joseph, MI, USA). Samples were weighed and then heated to constant weight at 105 °C, 550 °C and 980 °C, to measure water, total organic matter (TOM) + sulphides and the silicoclastic + oxides components, respectively. Total organic carbon (TOC) and carbonate fractions (+ sulphides and sulphates) were determined stoichometrically (Dean 1974).

Determinations of phosphorus concentrations (organic, inorganic and available) followed soil chemistry procedures (Colombo & Miano 2015). Total P was determined spectrophotometrically via blue phosphomolybdate complex. Organic P was calculated as difference between P obtained after sulphuric acid treatment with and without heating at 550 °C; inorganic P was calculated as the difference between total and organic P. Available P was extracted with sodium bicarbonate (Olsen method; Schoenau & O'Halloran 2008).

## DATINGS AND AGE–DEPTH MODEL

The Crotte Basse core chronology is provided by five AMS $^{14}C$ dates of terrestrial plant remains. Sediments were sieved, wood and charcoal of upland plants were picked out, cleaned with distilled water, dried and dated at the Ångström Laboratory in Uppsala and at the $^{14}C$ CHRONO Laboratory at Queen's Univ. Belfast. Dates were calibrated with Calib 7.0.2 (Table S1) based on the IntCal13 calibration curve (Reimer *et al.* 2013). Median probabilities of calibrated age intervals were linearly interpolated in Tilia 2.0.2 to create an age-depth model.

### ARCHAEOLOGY: SITES, DATES AND PERIODS

Survey and excavations were specifically designed to investigate and date human activities on Mt. Fallère highlands during the PhD project of one of the authors (L.R.). Standard archaeological protocols were applied, including the subdivision of the surface by means of 1 $m^2$, the horizontal removal of subsequent stratigraphic layers, and on-site sediment wet-sieving under a 1·5 mm mesh to recover artefacts for their field identification. Up to now, artefacts were discovered in nine sites. Weathered archaeological structures (pole pits, a hearth, charcoal accumulations) and few artefacts (a green stone axe and rock crystal fragments) preserved just below the present-day surface were found scattered between 2100 and 2300 m a.s.l (mostly at sites MF1, MF3, MF6 and MF8, Fig. 1b; Raiteri 2015). However, there are no diagnostic artefacts related to specific prehistoric human activities. Each archaeological layer was AMS-dated using charcoal fragments at CeDAD in Lecce. Twenty-six $^{14}C$ ages were calibrated and are here used to calculate intervals of cumulative probability function (CPF) (Table S1 and Fig. 2), obtained with the SUM function in the software Oxcal 4.2 (Bronk Ramsey 2009). CPF's are used as proxy to identify phases of human presence on the subalpine-alpine upland but not the magnitude of the events; the latter, indeed, is the challenge of the quantitative palaeoecological study.

The archaeological periods used in this paper follow the chronological boundaries established for western northern Italy (de Marinis & Pedrotti 1997; Mollo Mezzena 1997; de Marinis 2002; Pessina & Tinè 2008). The term Copper Age refers to the end member of the Neolithic sequence of the European context. In northern Italy, its onset has recently been lowered to c. 5600 cal years BP (Cocchi Genick 2013), while its end corresponds to c. 4200 cal years BP (beginning of the Bronze Age).

### STATISTICAL DATA TREATMENT

#### *Pollen zonation*

Constrained incremental sums-of-squares cluster analysis was performed with the program CONISS (Grimm 1987) to zone the pollen diagram. Edwards and Cavalli-Sforza's chord distance was used as dissimilarity coefficient. The analysis runs on taxa displaying values >2% in the considered interval. The dendrogram used to define the pollen zones is shown in Fig. 3.

#### *Ordination*

Ordination techniques were applied on the taxa selected for pollen zonation to detect major compositional changes. Given the short gradient length (<2 standard deviation units), principal component analysis (PCA) was preferred to detrended correspondence analysis and performed on the covariance matrix of log-transformed % data. Data standardization and ordination were carried out with the Vegan and Decorana packages (Oksanen *et al.* 2015) in R environment (R Core Team 2013). The graph displaying the scores on the first two PCA axes is presented in Fig. 4.

#### *Diversity estimations*

Rarefaction analysis (Birks & Line 1992) was used for estimations of palynological diversity based on a constant pollen sum ($n$ = 581). A pollen accumulation rate-based estimation of richness (van der Knaap 2009) is also provided, keeping in mind that this procedure may be affected by changes in sedimentation rates (Fig. 5).

#### *Correlograms*

Cross-correlation analysis was performed with the software SYSTAT 13 to detect positive/negative/leads and lags between woody species and charcoal series and between total P concentration in sediment and tree cover. Correlations between P forms, forest cover and selected geochemical parameters were further investigated by means of scatterplots, linear regression and Pearson correlation coefficients (Figs 6 and 7).

### QUANTITATIVE ESTIMATION OF PAST CLIMATE VARIABLES

Pollen-based reconstructions of January and July temperatures ($T_{jan}$ and $T_{jul}$) were obtained from the Crotte Basse spectra applying Locally Weighted Averaging technique with inverse deshrinking (Juggins & Birks 2012). The European Modern Pollen Database (Davis *et al.* 2013) was used as modern pollen-climate training set. The use of such a large dataset involves much noise in the data due to structural heterogeneity (Birks & Seppa 2004). In our case, the 30 closest modern analogues were identified by means of minimum square chord distance. Fossil and modern pollen data were used as percentages based on the terrestrial pollen sum. Prior to the calculation, fossil and modern data were harmonized, removing anthropogenic indicators and Gramineae. Model performance was assessed using leave-group-out cross-validation (10 groups). The root mean square error of prediction associated with the transfer function model provides a realistic estimate of prediction uncertainty (Fig. 7). The calculations were performed using the R package Rioja (Juggins 2014).

## Results

### RECORD LENGTH AND RESOLUTION

The palaeoecological record from the Crotte Basse mire (Figs 3 and 5) describes the history of subalpine landscapes over a time span of 4600 years, from c. 6400 to 1800 cal years BP. Average resolution of our reconstruction varies from c. one sample per 50–80 years in the Neolithic and most of the Bronze Age to one sample per 100–120 years between the Late Neolithic/Copper Age and the Early Bronze Age and from the Late Bronze Age to the Iron Age.

### VEGETATION AND LANDSCAPE DYNAMICS: FOSSIL POLLEN AND CHARCOAL ABUNDANCE, BIODIVERSITY INDICATORS AND GEOCHEMICAL MARKERS

Several phases are distinguished, based on pollen percentages of relevant species and charcoal data. Geochemical data add information for sediment characterization (composition and nutrient content).

#### *Phase 1, Middle Holocene – between 6400 and 5900 cal years BP*

Pollen spectra are dominated by conifers (*P. cembra* and, to a lesser extent, *Abies*, *P. sylvestris/mugo* and *Larix*). Pollen of woody plants accounts for more than 90–95% of the assemblages. Pine stomata occur in all sediment samples. Herb

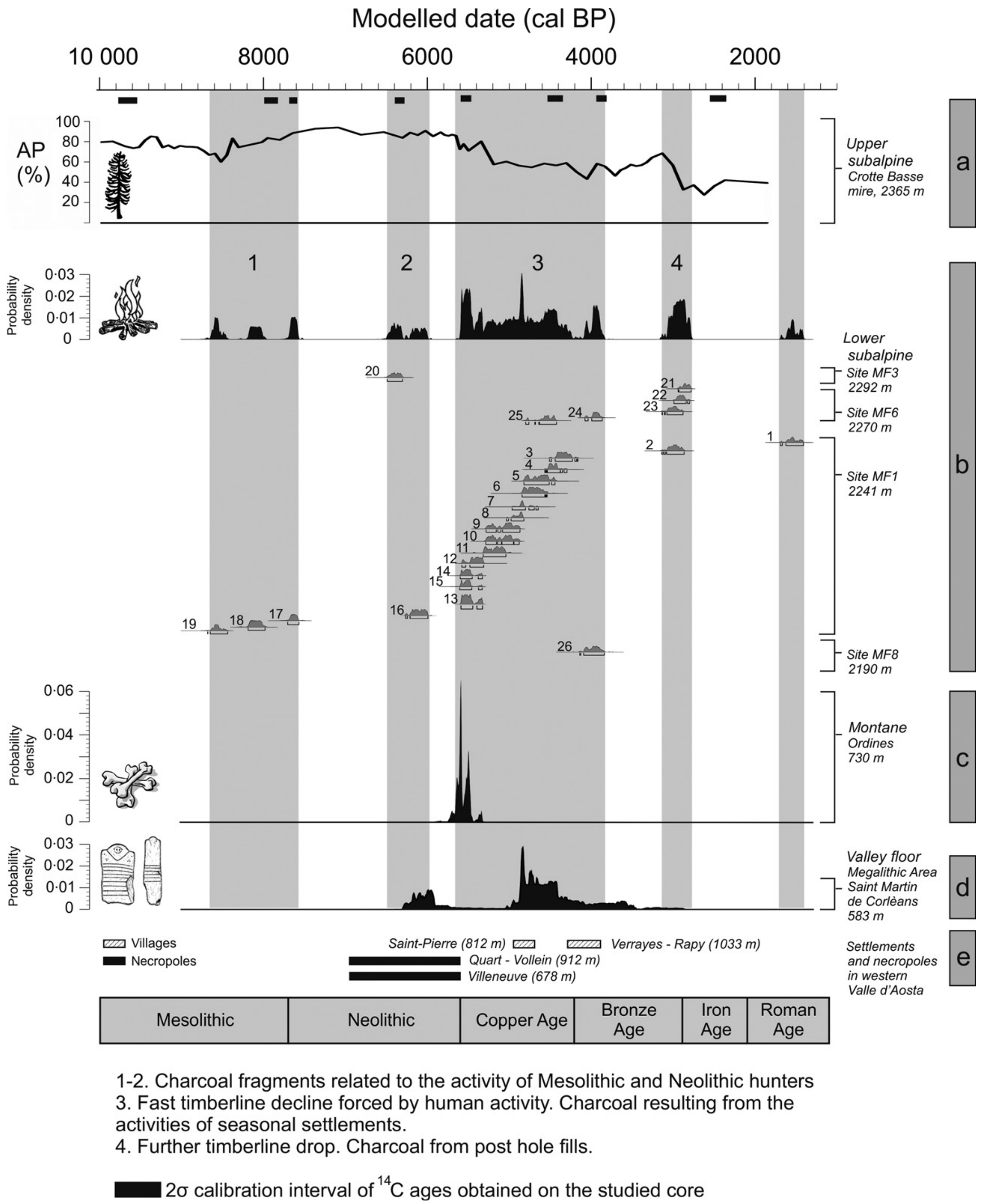


**Fig. 2.** Synoptic view of chronologies available from sites located on an altitudinal transect. (a) Arboreal Pollen (AP) record from the Holocene archive of the Crotte Basse mire (upper subalpine belt). (b) Calibration intervals for ages obtained at the archaeological excavations on Mont Fallére (MF sites; lower subalpine belt) and their cumulative probability density. (c) Cumulative probability density obtained from 3 $^{14}C$ ages from the site of Ordines, montane belt (sediments embedding charcoal and animal bones). (d) Cumulative probability density obtained from 127 $^{14}C$ ages from the Megalithic Area of Saint Martin de Corléans (valley floor, city of Aosta, unpublished data). Vertical grey bands highlight phases of human fires on Mont Fallére inferred from $^{14}C$ ages and their impact on the AP curve. (e) Chronology of valleyfloor and lower elevation settlements and necropoles in the westernmost sector of the Aosta Valley, based on archaeological and $^{14}C$ dating. Site altitudes are reported on the right side of the figure. $^{14}C$ Ages available from the Crotte Basse mire and MF sites are reported in Table S1.

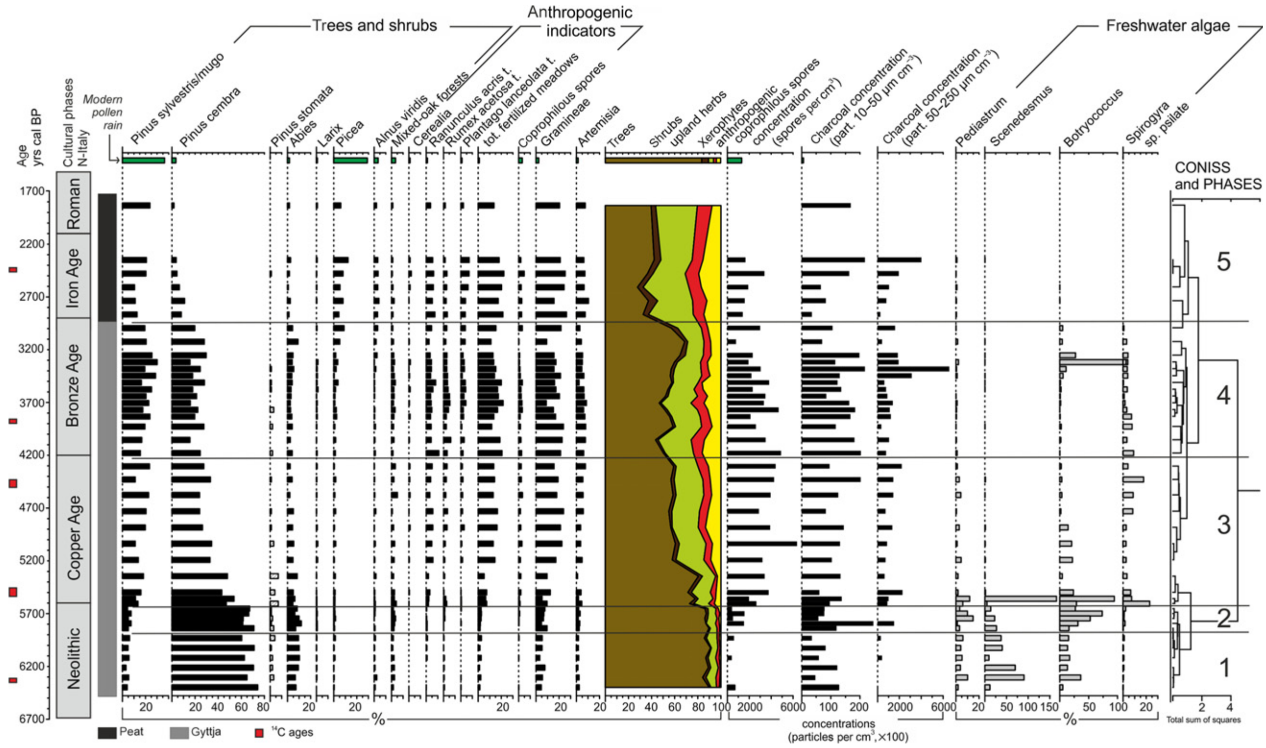

**Fig. 3.** Crotte Basse mire (2365 m a.s.l) - % record of selected taxa and concentrations data plotted vs. age. [Colour figure can be viewed at wileyonlinelibrary.com]

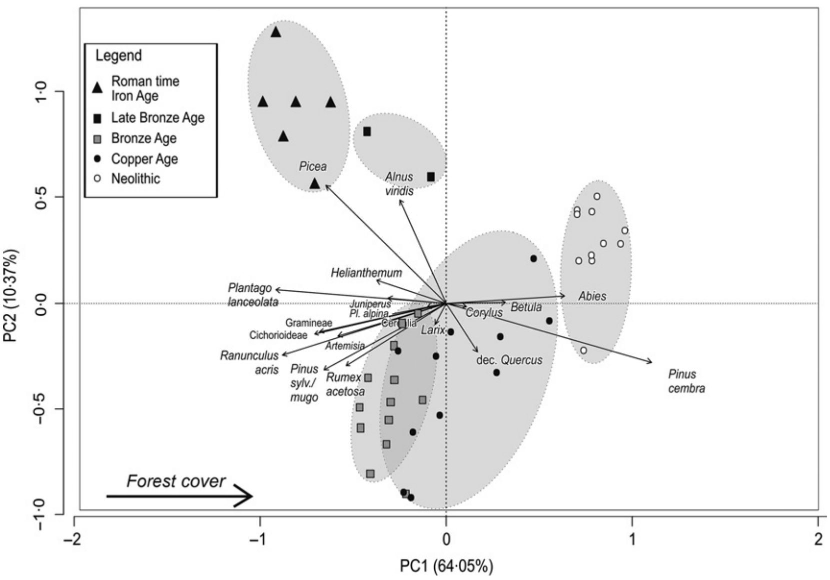

**Fig. 4.** Principal component analysis scatterplot of species identified in the palaeoecological record of the Crotte Basse mire and relevant for the description of vegetation history at local and regional scale. The first two axes account for nearly 75% of the total variance.

communities are represented by xerophytic elements (*Artemisia*, Crassulaceae, *Plantago alpina* type). Algal communities are represented by planktonic colonies of *Pediastrum*, *Scenedesmus* and *Botryococcus*: sporadic individuals of *Spirogyra* occur. Biodiversity estimates were the lowest of the whole sequence (between 30 and 40 taxa per sample). Dung spores were sporadic.

Small charcoal particles account for most of the charcoal in the sediments, the frequency of larger particles being negligible. Total P concentrations remain below 800 mg kg$^{-1}$ of sediment: ratios between P forms are stable. Total organic matter content of sediments is between 30% and 40%, which is fairly high for limnic, organic-rich (gyttja-type) deposits.

### *Phase 2, Middle Holocene – between 5900 and 5600 cal years* BP

Conifer pollen is still dominant. At c. 5800 cal years BP micro- and macro-charcoal concentrations peaked, being up to three times higher than in the lowermost core section, indicating enhanced input of both smaller (10–50 μm length) and larger (50–250 μm) charcoal particles. Minor and temporary

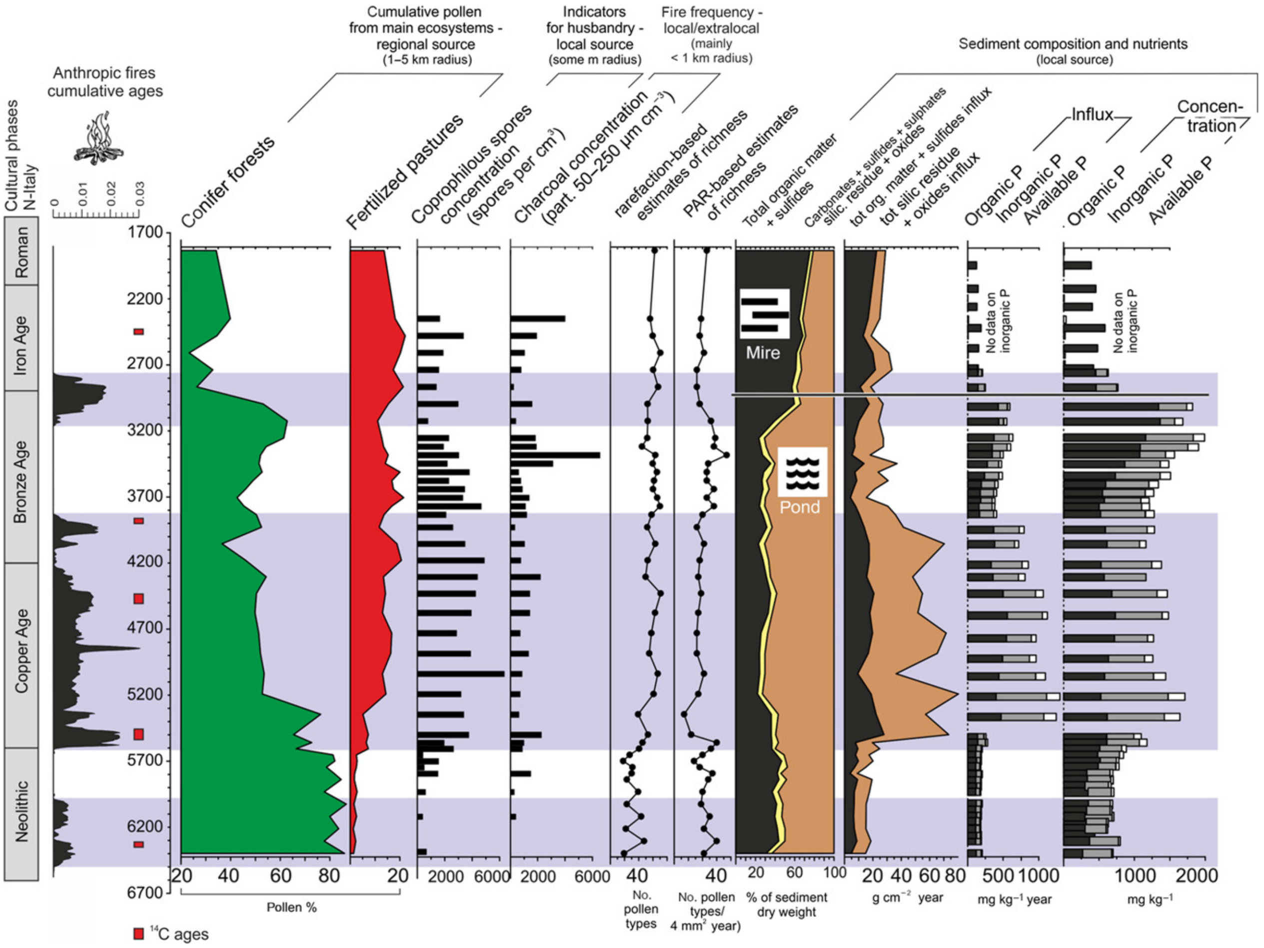


**Fig. 5.** Vegetation types (forest vs. pastures), indicators of human activities and of the sedimentary environment and phases of human presence on Mt. Fallère. The occurrence of charcoal particles in periods where no human presence is so far testified on Mt. Fallére may be interpreted as secondary charcoal ('older' charcoal preserved on surfaces and mobilized by subsequent rains and alluvial events). Grey belts show a visual correlation between ages of anthropic fires on Mont Fallére and all the plotted indicators. [Colour figure can be viewed at wileyonlinelibrary.com]

decreases in *P. cembra* % and stomata frequency parallel the charcoal peak. Planktonic algal colonies are abundant, accompanied by *Spirogyra*.

Charcoal concentrations increased again from c. 5700 cal years BP, peaking at c. 5550 cal years BP. This sequence of fire events over more than a century is marked by the steady decrease of *P. cembra* %, the expansion of herbaceous pollen and enhanced input of dung spores (Sordariaceae and *Sporormiella*) into sediments, which continued further during the succeeding phase 3.

Biodiversity estimations and loss-on-ignition (LOI) data are similar to those obtained for phase 1.

### *Phase 3, Middle Holocene – between 5600 and 4200 cal years BP*

There is a steady decrease of arboreal pollen (from 70% to 50%), mostly related to the loss of *P. cembra* pollen, reduced to mean values of 30% in a few centuries. Several herb species (*Ranunculus acris* type, *Rumex acetosa* type, *Plantago lanceolata* type, *Trifolium repens* type, *Phyteuma*, *Lotus*, *Euphorbia*, *Gentiana pneumonanthe* type, *Polygonum viviparum* type, *Geranium molle* type, and *Asphodelus albus*) show increased frequencies adding up to nearly the 20% of the whole pollen spectra. Cereal pollen is detected in almost all the analysed samples. A turnover is visible in the composition of algal communities, with a steady decrease of *Pediastrum* and *Scenedesmus* colonies.

Biodiversity estimations point to increasing species richness (up to 50–55 taxa per sample, numbers according to the rarefaction-based method). Concentration of dung spores increased from 5600 cal years BP, followed one century later by increasing phosphorus concentration, displaying a first major peak at 5350 cal years BP. During phases 3–4, P concentrations are as much as double those recorded in the lowermost core section. LOI data indicate decreasing contents of TOM and increasing detrital components (silicoclastic and oxides).

### *Phase 4, Late Holocene – between 4200 and 2900 cal years BP*

Pollen spectra show the abundance of herbaceous taxa, accompanied by woody taxa adding up to average 50–55%

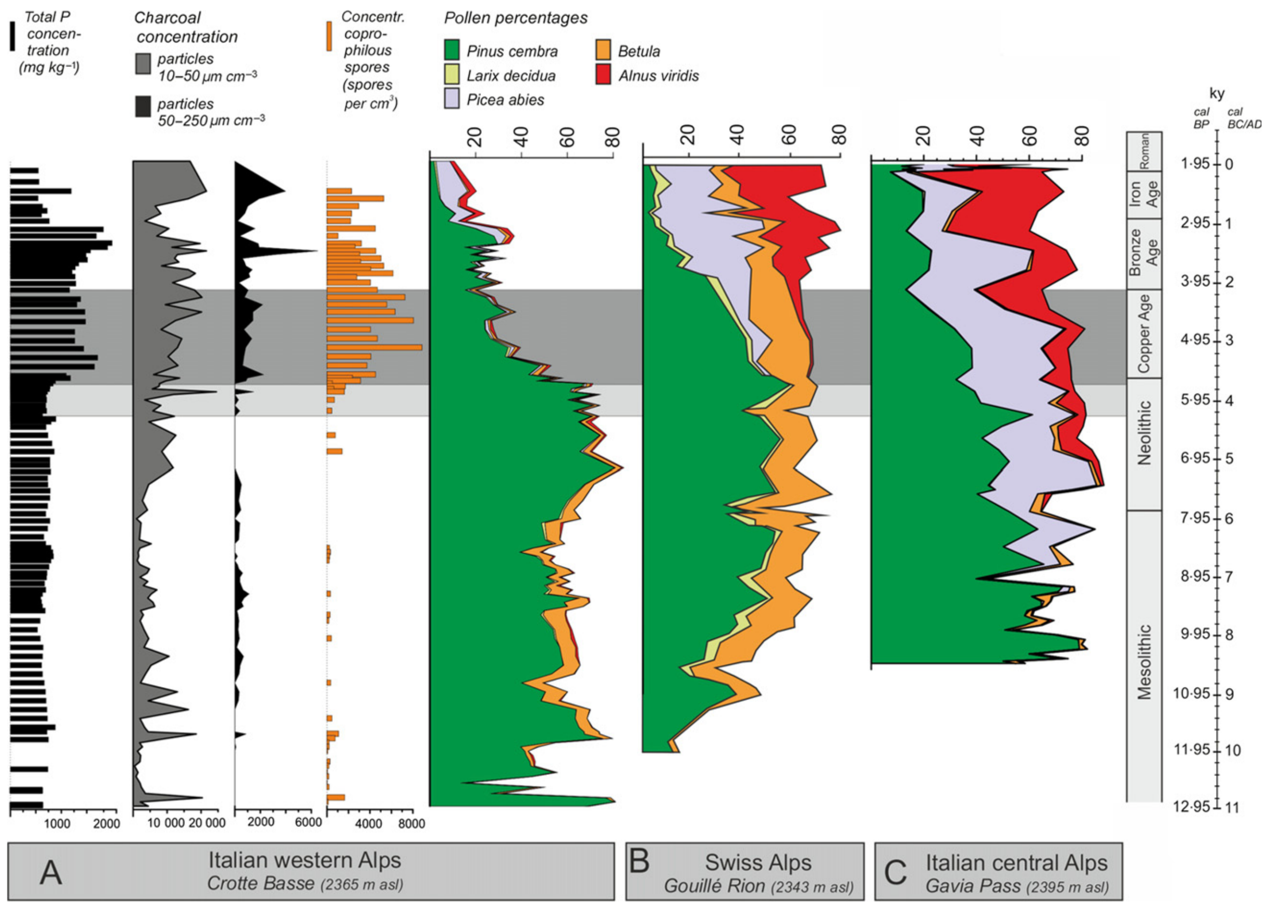


**Fig. 6.** Early decline of subalpine pristine forests in the western and central Alps. Simplified pollen records from the Crotte Basse mire and Gouillè Rion show remarkably similar trend in *Pinus cembra* extirpation. At Crotte Basse, this decrease is matched by increased charcoal abundance, total P and dung spores concentrations in sediments. References for cited sites: Crotte Basse (2365 m a.s.l; Pini *et al.* this paper and unpublished data); Gouillè Rion (2343 m a.s.l; Tinner, Ammann & Germann 1996); Gavia Pass (2395 m a.s.l; Aceti, unpublished data). [Colour figure can be viewed at wileyonlinelibrary.com]

of the pollen sum. Dung spores in sediment are still abundant. Rare planktonic algal colonies of *Pediastrum* are found, with rare *Scenedesmus*. A peak in *Botryococcus* frequencies is recorded between 3200 and 3300 cal years BP. *Spirogyra* is continuously detected (0·4–9·1% based on the pollen sum).

Charcoal concentrations peak at 3300–3400 cal years BP. Increasing concentration of organic P is also detected from c. 3400 cal years BP (second half of the Bronze Age). Biodiversity estimates were high (between 45 and 55 taxa per sample). A TOC increase, detected by LOI, occurs at the gyttja to peat transition, c. 3000 cal years BP (196 cm depth), revealed by very high % of TOM (70–80% of dry sediment weight).

At 3100 cal years BP % values of *Picea* pollen start increasing.

### *Phase 5, Late Holocene, from 2900 cal years BP*

Time resolution for the Iron Age and the beginning of the Roman time is rather low but still allows the detection of the main steps in vegetation history.

A further fall of woody taxa % values marks this phase (from mean 60% in phase 4 to 35–40%). *Pinus cembra* and *Abies* reach minimum values, compatible with their local extirpation. This loss is partially balanced by increasing *Picea* and *Alnus viridis*. Pollen of upland herbs is abundant (up to 20% of the pollen sums, mostly composed of grasses), as well as xerophytes and anthropogenic indicators. Algal colonies (both planktonic and benthonic) disappeared. Charcoal concentrations are still high, dung spores decrease. Biodiversity estimates were stable at around 50 taxa per sample. Concentrations of P forms decreased sharply. Total organic matter in sediment is high, as expected in peat deposits.

## ORDINATION

PCA scatterplot identifies the relationships between species and ecological gradients (Fig. 4). Sample scores distribution, shown with geometric symbols, strongly follows the chronological position of the samples. Clouds of Neolithic, Late Bronze and Iron–Roman Age samples are clearly separated whereas Copper and Bronze Age samples are closer together. PCA axis 1 (64% variance) is related to forest cover; it

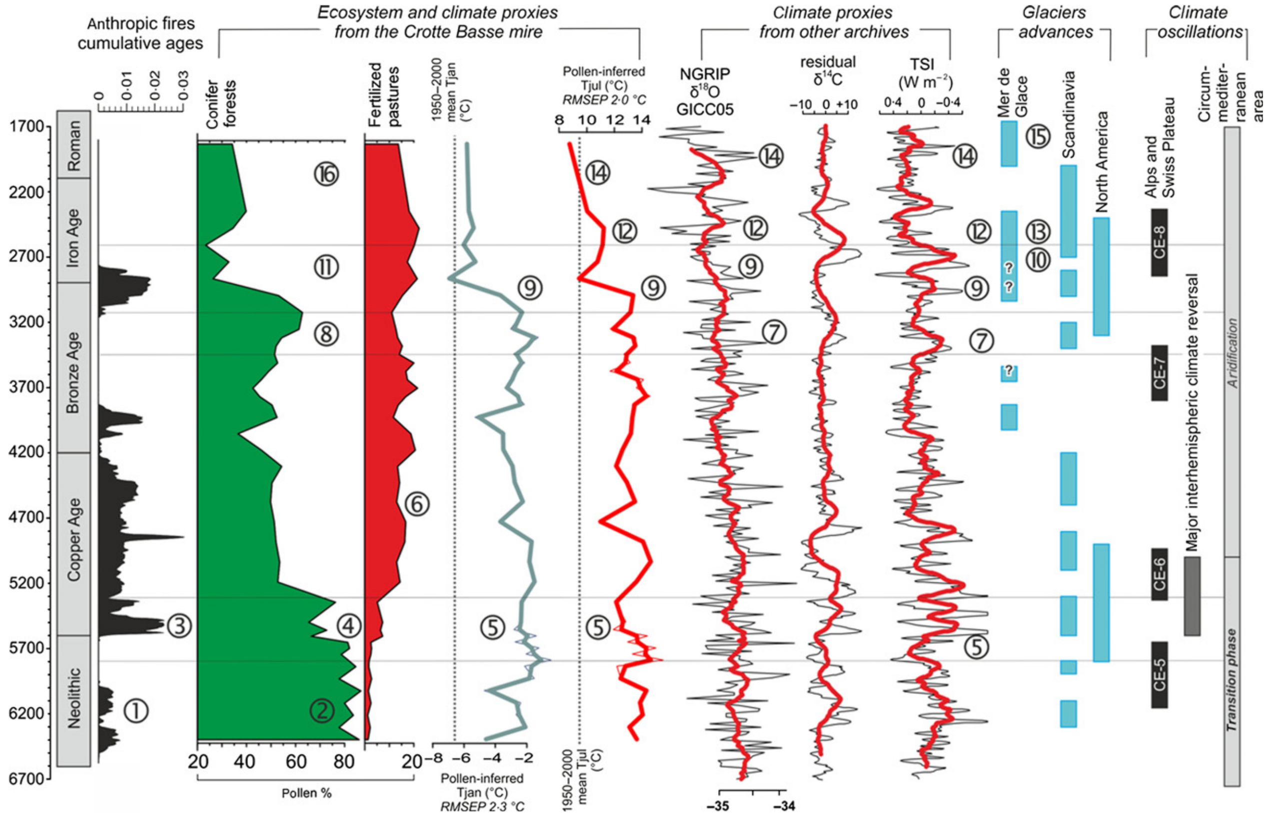


**Fig. 7.** Main ecosystems and climate proxies on Mt. Fallere between 1700 and 6700 cal years BP compared with independent records from ice cores (NGRIP $\delta^{18}O$, GICC05 chronology; Vinther *et al.* 2006), atmosphere (residual $\delta^{14}C$, Reimer *et al.* 2013; total solar irradiance (TSI), Steinhilber, Beer & Frölich 2009), glaciers (Denton & Karlén 1973; Nesje 2009; Le Roy *et al.* 2015) and other terrestrial archives (Haas *et al.* 1998; Magny & Haas 2004; Jalut *et al.* 2009). Key to numbers: (1) sporadic humans at high altitude for hunting and gathering activities; (2) very high tree line altitude favoured by climate conditions; (3) increasing human pressure; (4) demise of forests and pastures development; (5) reconstructed $T_{jan}$, $T_{jul}$ and TSI decrease; (6) intensification of agro-pastoral activities; (7) TSI and $\delta^{18}O$ decrease; (8) beginning of the expansion of local Picea populations; (9) reconstructed $T_{jan}$, $T_{jul}$, $\delta^{18}O$, residual $\delta^{14}C$ and TSI decrease; (10) Alpine glaciers advance; (11) tree line lowering and pastures development; (12) reconstructed $T_{jul}$ and $\delta^{18}O$ increase; (13) Alpine glaciers declined; (14) reconstructed $T_{jul}$, $\delta^{18}O$ and TSI decrease; (15) Alpine glaciers expand; (16) further forest decline. [Colour figure can be viewed at wileyonlinelibrary.com]

describes the transition from pristine *P. cembra*-dominated subalpine forests (phases 1–2 of the pollen record, Fig. 3) to a landscape with reduced tree cover, rich in herbs (phases 3–5). A minor component of the variance is explained by PCA axis 2 (10%) and can be related to successional stages ending up with the local expansion of alder scrublands and spruce stands.

### POLLEN-INFERRED QUANTITATIVE TEMPERATURE ESTIMATIONS

$T_{jan}$ and $T_{jul}$ pollen-inferred temperatures (Fig. 7) display frequent oscillations along the sequence. Up to 3800 cal years BP, the amplitude of temperature oscillations remains within 3–4 °C for both reconstructions. Increasing amplitude is visible from the Middle Bronze Age onwards, with a major shift centred at the Bronze–Iron Age transition. This is the time of a phase of climate deterioration promoting glacier advances recorded by several glacier systems in the Alps (Aletsch Glacier, Holzhauser, Magny & Zumbühl 2005; Mer de Glace, Le Roy *et al.* 2015). A comparison with other climate proxies for the period 6400–1800 cal years BP will be discussed below.

## Discussion

### VEGETATION ECOLOGY BETWEEN THE PRE-ANTHROPOGENIC MIDDLE HOLOCENE AND ROMAN TIME

#### *The Middle Holocene subalpine belt of conifer forests*

High pollen % and occurrence of needles and stomata in the Crotte Basse record point to local *P. cembra* forests in the mid Holocene, from c. 8800 to 5600–5700 cal years BP. The timberline must have been higher than 2360 m a.s.l. The role of *A. alba* in the timberline ecotone is uncertain. Although fir may be competitive in cool oceanic climates and may grow at timberline temperatures (Crawford 1989; Tinner *et al.* 2013), there are no modern analogues in the Alps. In the analysed sequence, *Abies* pollen % values are often above the threshold limit indicating local presence (4%, van der Knaap *et al.* 2005), but stomata were found in one sample only. High proportions of *Abies* pollen may not coincide with stomata abundance, due to needle-preservation issues (Wick *et al.* 2003) and to their limited airborne dispersal. *Abies* has long-lived, dense evergreen needles which are often found burnt, taken up by convective fire columns; otherwise, *Abies* needles may accumulate after floatation through melting water runoff and rivers, unlikely in closed lakes and anoxic peatlands. Besides, Euroasiatic firs do not grow on lake-fringing peat belts (Walter & Breckle 1986; Ellenberg 1988). The study site was just a gap within a closed pine forest, thus an upward, massive pollen transport by local winds is improbable. Two taphonomic hypotheses may explain these non-analogue fossil pollen data at the pond altitude – either the occurrence of fir stands around the pond, or the presence of a large fir belt immediately below the pine belt. Judging from the effects of local fires, which reduced pine but had only moderate effect on fir pollen proportions, we favour the second option. Evidence for middle Holocene subalpine fir forest around 2300 m altitude is not unprecedented in the Western Alps (Badino 2016).

A minor influx of *P. sylvestris/mugo* pollen can be referred to pine woodlands in the mountain belts, above the broad-leaved limit. *Pinus sylvestris* cones, needles and wood imprints preserved in calcareous tufa at 1950 m a.s.l on the same Massif have been dated to 9100–5800 cal BP (Pini *et al.* 2011).

The occurrence of *P. alpina* type and Crassulaceae pollen tracks forest gaps with xeric communities. Today, such communities occur in a 50 m-radius around the site on rocky ridges with dry and poorly developed soils.

The forest structure inferred so far shows a remarkable multi-millennial stability, without charcoal peaks, from c. 8200 to 5700–5600 cal years BP. In this period, no sign of human impact is detected, despite evidence of Neolithic hunting activities that is apparent at sites MF1 and MF3, 200–600 m distance from the pond, and dated 6400–6000 cal years BP (Fig. 2). It is generally accepted that Mesolithic to Neolithic hunter/gatherers produced only temporary ecosystem disturbance in subalpine forest by fire intensification, rather than creating anthropogenic landscapes (Oeggl & Wahlmüller 1994; Baroni 1997; Cusinato *et al.* 2003).

### *Late Neolithic disturbance before the development of permanent pastures*

A single charcoal peak at c. 5800 cal years BP suggests the occurrence of fires near the lake, c. 200 years before major effects of deforestation (see next section). Although biomass was plentiful, charcoal flux to sediments was limited and had no effect on the pond nutrient cycling, as shown by low and stable concentrations of P forms. Freshwater algae display some minor reactions, with *Pediastrum* and *Botryococcus* blooms. Dung spores occur regularly from c. 5800 cal years BP. They might testify to first activities of gathering herds for watering by Neolithic shepherds coming down from the natural alpine pastures. However, there are no archaeological structures $^{14}$C-dated to be coeval (Fig. 2). Overall, the evidence consists of sporadic coprophilous fungi and of a moderate amount of charcoal, with no sign of deforestation or pond eutrophication. This may suggest nomadic activities at higher altitude, leaving no permanent trace on the subalpine forest.

On the other hand, subsequent fire peaks, around 5600–5500 cal years BP, show clear correlation with major and permanent landscape changes. These events occurred at the beginning of a prolonged and stable phase of local human presence, documented mostly at site MF1 (Fig. 2). What did human groups do up there? Pollen and geochemical data provide hints to answer this question.

### *Development of permanent pastures – plant indicators*

The first stage of upper subalpine conifer forest demise is correlated with Late Neolithic fires (Fig. 5) and occurred in less than 50 years, as shown by *P. cembra* decline centred at c. 5650 cal years BP (Fig. 3). A sudden landscape opening around the pond is mirrored by the spread of nutrient-rich pastures. Qualitative pollen indicators of nitrophilous herb communities (some listed in Behre 1981) are *R. acris* type, *R. acetosa* type, *P. lanceolata* type, *T. repens* type, *Phyteuma*, *Lotus*, *Euphorbia*, *G. pneumonanthe* type, *P. viviparum* type and *G. molle* type. These are presented in the 'fertilized pastures' curve in Fig. 5. Some of these species are seen as apophytes, i.e. tall herbs native to the montane to subalpine belts, with primary habitat in nutrient-rich litter understorey of wet subalpine forests (*Betulo-Adenostyletea* Br.-Bl. et Tx. 43) (Ellenberg 1988). Several of these taxa already occurred in the pre-anthropogenic conifer phase and increased as the forests cleared. In pastures, plant species richness correlates with nutrient availability (Pausas & Austin 2001). Given known relationships between plant cover and pollen production for plants of grazed and mown areas (Hjelle 1998) and the availability of modern pollen spectra from the Crotte Basse site, quantitative palynological criteria can be used to assess the occurrence of pastures around the lake. Increasing abundances of *P. lanceolata*, *R. acetosa* type and *R. acris* type pollen are recorded from 5600 cal years BP. From this moment on, their % values are compatible with the presence of those plants, typical of grazed areas, within a few metres from the site. For example, *R. acetosa* type pollen is often above 6%, pointing to plant occurrence within less than 10 m. *Plantago lanceolata* pollen, sporadically recorded before 5600 cal years BP, displays values between 2% and 7%, much higher than the 0·6% in the modern pollen rain of the (grazed) area, where *P. lanceolata* grows 50 m away from the coring site.

In our record, the expansion of pasture indicators coincides with an interval of systematic use of fire for c. two centuries, between 5650 and 5500 cal years BP, matched by increasing concentrations of dung spores and P forms and increased sedimentation rate (Figs 5 and 6). We interpret this evidence as the result of dung deposition, increased runoff and consequent nutrient enrichment of the lake water due to livestock watering, trailing and grazing.

### *Coprophilous spores as grazing indicators and the problem of species composition of pastoral herds*

Laboratory studies on herbivore dung focussed on relating fungal spores to specific domesticated or wild animals (Richardson 1972; Ellis & Ellis 1998).

Dung spores are usually referred to as proxies for local megaherbivore presence (Baker, Bhagwat & Willis 2013; Gill *et al.* 2013) and for pastoral and farming activity (Cugny, Mazier & Galop 2010; Gauthier *et al.* 2010). Gill *et al.* (2013) checked on the dispersal distance of *Sporormiella* spores, inferring a relevant source radius on the order of c. 25 m, with spores washed in from the catchment where they grow on dung after defecation. *Sporormiella* is strictly coprohilous and referred to as a very local indicator of grazing.

In the Crotte Basse record, dung spores are represented by *Sporormiella*, Sordariaceae and a single *Podospora* spore. In the pre-farming Lateglacial, Sordariaceae peaks are clearly correlated to charcoal peaks. In the same samples, *Sporormiella* is almost missing, thus these peaks of coprophilous fungi may be related to decomposition of burnt wood, rather than to megaherbivore grazing. On the other hand, scattered finds of *Sporormiella* in the pre-farming Holocene (Fig. 6) can be related to visits of wild animals (ibex, chamois, hares), suggesting that this subalpine areas could provide natural pastures and water resources in a forested landscape. Increasing values of dung spores are recorded from 6400 cal years BP onwards, indicating a deliberate use of the pond for occasional livestock watering and related input of faeces. Independent proxies from our stratigraphic record (P forms) point to enhanced nutrient supply from the Late Neolithic/early Copper Age, related to discharge and mineralization of faecal products. This situation persisted for several millennia, amounting to strong evidence of the use of the pond in an area naturally poor of water.

No modern analogues are available to estimate the prehistoric stocking rate at our study site based on the concentration of dung spores. The hypothesis that high-elevation areas on Mt. Fallère supported cattle herds as early as the onset of the Copper Age will be explored below.

### Increasing nutrient content and algal turnover

The lake sediments registered a first major increase in phosphorus content at c. 5350 cal years BP, contemporaneous with a phase of enhanced runoff, leading to a significant change in the freshwater algal community (Fig. 3). In a few decades, *Pediastrum* and *Scenedesmus* colonies almost disappeared and *Botryococcus* drastically decreased, suggesting enhanced eutrophication of the aquatic ecosystem. Phosphorus has often been identified as the primary limiting nutrient causing eutrophication in water bodies (Daniel, Sharpley & Lemunyon 1998). Enrichment of water quality via siltation (Cournane, McDowell & Condron 2010) and reduced water transparency were not tolerated by these algae. On the other hand, algae such as *Spirogyra* seem to have been favoured under these new conditions.

### After pasture development. Long-term dynamics of anthropogenic pressure on terrestrial and aquatic environments

Radiocarbon chronology of the archaeological sites on Mt. Fallère indicates a major phase of human presence between 5600 and 4300 cal years BP (Fig. 2). Palaeoecological data from lake sediments identify this period as the time of strongest landscape modification. As previously discussed, pollen and geochemical data indicate alpine farming. Stable pastures were maintained by coupling intentional fires and grazing for more than three millennia, i.e. until Roman times. The history of this long-term disturbance deserves a short focus.

Species indicating fertilized pastures and meadows close to the sedimentary archive are recorded throughout the Bronze Age, displaying a second major phase of expansion between c. 3950–3400 cal years BP, matched by abundance of dung spores and increasing P concentrations. Later on, however, between 3400 and 3000 cal years BP, Arboreal Pollen values increased (Fig. 3), suggesting enhanced forest regeneration at regional scale in the Middle to Late Bronze Age. A local fire is detected by charcoal abundance at c. 3400–3300 cal years BP, followed by a further increase in organic P concentration, reaching the maximum values in the whole sequence (around 1000 mg $kg^{-1}$ of sediment). Charcoal particles were possibly acting as a nutrient source, initiating the *Botryococcus* bloom recorded shortly after. Regardless to the 3400–3300 cal years BP fire episode, the long-term regional trend of Arboreal Pollen increase persists, peaking at 3300–3000 cal years BP. This phase also shows a temporary abandonment of local pastures by the time of the so-called 'Late Bronze Age crisis'. Collapse of several human societies marked the end of the Bronze Age in the plains of Northern Italy (Terramare Culture, Cremaschi, Pizzi & Valsecchi 2006), Eastern Mediterranean, Levant and Anatolia (Knapp & Manning 2016). However, the cultural evidence in the high Alps is not fully understood yet.

### Restyling Alpine farming at the onset of the Iron Age

At about 3000 cal years BP, the local sedimentary environment developed from a shallow pond into a mire due to *in situ* overgrowth, shown by a gyttja-to-peat transition in the sediment and by the steady increase of TOM in the LOI record (Fig. 5). Local aquatic habitats supporting algal life disappeared. In the meantime, sharp changes occurred in the surrounding landscape.

At 3000–2900 cal years BP, a sharp fall in Arboreal Pollen marks a major forest reduction leading to forest cover values lower than today (Fig. 3). Renewed increases in charcoal, coprophilous spores and fertilized pastures taxa are mirrored by independent evidence of coeval anthropogenic fires on the highlands (3000–2850 cal years BP). Phosphorus and detrital inorganic detritus, however, remain low. Nutrients and minerogenic material could no longer reach the site due to the development of the encircling mire which prevented inflow from the catchment. Overall, the onset of Iron Age is the time of the second main step of increasing human impact in the Mt. Fallère highlands. The spread of early Iron Age cultures is known to have deeply affected the inner alpine valleys (Curdy 2007). A concurrent trigger by climate change (cold oscillation between 2900 and 2600 cal years BP: Holzhauser, Magny & Zumbühl 2005; Le Roy *et al.* 2015) is difficult to disentangle from our data as it is obscured by human impact.

## HISTORY OF PHOSPHORUS SUPPLY, RELATION TO SEDIMENT COMPOSITION AND EXTERNAL INPUTS

LOI data from the Crotte Basse sediments depict runoff changes and evidence of sedimentary transitions. Enhanced minerogenic detrital input since deforestation at c. 5700 cal years BP, and an increase of TOM from gyttja to peat at c. 3000 cal years BP imply increase and decrease in nutrient supply by runoff processes, respectively (Figs 3 and 5). Therefore, information on nutrients and their cycling can be obtained by comparing LOI with P forms data.

Total phosphorus concentration (hereafter [$P_{tot}$]) increased at c. 5600 cal years BP. Cross-correlograms (Fig. S1) show a negative correlation of [$P_{tot}$] with the total pollen percentage of trees ($r = -0{\cdot}443$) and a positive correlation with anthropogenic taxa ($r = 0{\cdot}524$) We can further 'decompose' the signal of [$P_{tot}$] in its components (organic, inorganic, available).

[$P_{inorg}$] increased at the transition from a pristine to a cultural landscape. Influxes of $P_{inorg}$ and minerogenic detrital sediment component are highly correlated ($r = 0{\cdot}946$; Fig. S1), suggesting a common process behind both variables. Erosional processes and enhanced superficial runoff enhanced supply from the small catchment around the pond (see Fig. 1c). Phosphatic rocks as possible sources of inorganic P do not occur in the study area, but [$P_{inorg}$] may also derive from animal dung. Experiments on amounts and relative solubilities of P in manure revealed that 63–92% of [P] is referred to [$P_{inorg}$] (Sharpley & Moyer 2000). Major peaks of [$P_{inorg}$] are recorded between c. 5350–5100 cal years BP. Between 5100 and 3100 cal years BP, [$P_{inorg}$] were more or less stable, suggesting a strong runoff input of $P_{inorg}$ maintained by the contribution from manure and persistent stocking rate at the site. [$P_{inorg}$] decreased markedly after about 2900 cal years BP, once that runoff accumulation was hampered by the development of a peat mire (Fig. 5).

$P_{org}$ in soils is usually released by microbial mineralization of humus and fresh organic matter. Indeed, in our record the curve of [$P_{org}$] resembles that of TOM, with higher values of $P_{org}$ (up to 1370 mg $kg^{-1}$ of sediment) at the transition from gyttja to peat. The Pearson correlation coefficient ($r = 0{\cdot}273$) indicates the positive relationship between these two variables throughout the three millennia examined here (Fig. S1). Although a significant amount of $P_{org}$ occurs in animal manure as well (He & Dou 2010), our [$P_{org}$] signal is primarily derived from TOM, therefore obscuring the manure contribution and therefore not allowing the stocking rate to be estimated from these data.

Available P ($P_{av}$), obtained by dissolution of inorganic phosphorus forms, is essential for plant growth and influences soil fertility. In agriculture, a soil is considered fertile when [$P_{av}$] ≥15–30 mg $kg^{-1}$ (Hall 2008). Our record testifies to high [$P_{av}$] up to the Roman Age, with values ranging from c. 20–257 mg $kg^{-1}$ of sediment, providing highly favourable conditions for forage and biomass production to support cattle grazing.

[$P_{tot}$] drastically decreased around 2900 cal years BP, when peat accumulation started at the site. We assume that the main source of $P_{org}$ and $P_{inorg}$ was animal dung and that the degradation products were easily transported to the lake by streams and run-off. When the sedimentary environment turned from a pond into a mire, the possibility of horizontal transport decreased thus leading to a strong reduction of [P] in sediments.

To our knowledge, only one phosphorus record associated with pollen data and documenting early human impacts, is available (Selig, Leipe & Dörfler 2007). We agree that (i) changes in sediment composition (organic matter and mineral content) are mainly related to different land use and changes in the catchments, (ii) highest P accumulation reflects former periods of human settlement activities in the catchment.

## ECOLOGICAL AND CULTURAL SCENARIO IN NW ALPS AT THE TIME OF THE EARLIEST PERMANENT PASTURES

We have discussed the palaeoecological evidence for the formation of permanent pastures during the Late Neolithic/Copper Age transition in the uplands of the Aosta Valley. We now examine the regional ecological and cultural backgrounds, in order to pinpoint the most important anthropogenic and climate drivers of pastures development, as well as the role of regional landscape differences in shaping high mountain areas. First, we consider the ecological scenario in the timberline ecotone of the western Alps before permanent pastoralism became established.

### *Before pastures. From the Mesolithic hunters to Middle Holocene maximum timberline elevations*

During the early Holocene, timberline dynamics were mostly influenced by climate (Burga & Perret 1998; Wick *et al.* 2003; Nicolussi *et al.* 2005; Tinner 2007). Warming at the Holocene onset led to a fast timberline rise in the Alps, eventually reaching as high as 2400–2700 m a.s.l (see Fig. 6). In the western Alps, dense *P. cembra* forests developed at the timberline, while rapidly expanding *Picea abies* populations colonized the eastern and central Alps. The highest timberline position was reached by conifer forests at about 6000 cal years BP following a millennia-long uphill expansion of trees.

The timing and regional development of high-altitude human populations are usually attributed to Mesolithic cultures using alpine areas to hunt game. The Italian central Alps provide an interesting example of such practices, with almost 200 sites discovered between 1900 and 2300 m a.s.l in the Dolomites (Cusinato *et al.* 2003). Mesolithic human presence is testified by lithic industries linked to charcoal layers. A vast literature deals with fire use in Mesolithic times and its control by humans (Bennett, Simonson & Peglar 1990; Moore 2000 and references therein). Mesolithic people exploited natural alpine resources following a pattern of vertical nomadism (Broglio 1992; Cusinato *et al.* 2003), a seasonal migration from winter sedentary camps in the lowlands and temporary summer camps above the timberline.

Fires related to the activity of Mesolithic people above 2100 m on Mt. Fallère are inferred both from the charcoal record of the Crotte Basse mire (Fig. 6), and from the radiocarbon ages of archaeological structures (Fig. 2). The Arboreal Pollen curve (Fig. 2) does not show significant reduction of tree cover, and there is no increase of pasture indicators. As inferred elsewhere in the central and eastern Alps, Mesolithic activities resulted in temporary ecosystem disturbance by forest fire intensification, rather than the creation of cultural landscapes (Oeggl & Wahlmüller 1994; Baroni 1997; Peresani & Ravazzi 2009).

Doubts have been cast on the existence of Mesolithic groups at the time of the evolution of the first Neolithic communities. If hunter/gatherers and first farmers ever met, this happened during a very limited time span (the *chronological vacuum* of Pessina & Tiné 2008). Consistently, the phase of Mesolithic fires in the timberline ecotone ended around 8–7·5 ka cal BP, well before the earliest onset of farming in the early populated Alpine valleys between 7 and 6 ka cal BP (Colombaroli *et al.* 2013; Pini *et al.* 2016). A temporary timberline depression has been related to the 8·2 ka cal BP climate oscillation (Schwörer *et al.* 2014), but maximum timberline altitudes were reached after that (Tinner 2007), still without signs of human impact. Overall, no human interference is recorded in the high-elevation ecological scenario at the onset of farming activities in the lowlands.

### *Neolithic activities in NW Alps – cultural clues to the first high-elevation pastures*

The Neolithic Revolution reached the NW Alpine region – Valais and Aosta Valley – about 7 ka cal BP (Pessina & Tiné 2008), establishing a farming economy and promoting demographic growth (Gignoux, Henn & Mountain 2011). Rare permanent settlements penetrated a few Alpine valleys (see Fig. 1). The number of seasonal mountain camps was apparently very low, as hill and valley floor settlements were favoured (Curdy 2007; Martini 2008). Actually, high mountain passes across the Alps were used, as shown by human artefacts at unusual altitudes (Grosjean *et al.* 2007) and ceramic and lithic trades between north and south sides of the Alps (Barfield *et al.* 2003). The Aosta Valley and Valais valley floors were already settled at the time of pasture development on Mt. Fallère. During the 3rd millennium BC, the Megalithic Area of Saint Martin de Còrleans developed, c. 8 km downstream of Mt. Fallère (Fig. 1b), consisting of a sacred and ritual area extending for almost 10 000 m$^2$ within the modern town of Aosta (Mezzena 1997). Burnt cow skulls, interpreted as foundation rites, were laid at the base of some post-holes. Recent researches date the alignment of wooden posts to 2980–2520 cal years BC (4930–4470 cal years BP, Fig. 2), coinciding with the major phase of pasture development on Mt. Fallère. The presence of a large ritual area demonstrates a certain demographic pressure on the lowland. The need for more food for human consumption, coupled with the paucity of productive pastures on the dry valley floor and, indeed, the existence of accessible mountain and subalpine areas rich in water and forage, may have increased the interest for transhumance practices and thus initiating small-scale transhumant pastoralism in the large highland plot of Mt. Fallère. The regional differences in the landscape of the high mountains surrounding the Aosta valley floor are believed to have strongly influenced early attempts to establish alpine pastures. Indeed, uplands with difficult access near the town of Aosta, which were also palaeoecologically investigated, did not show any evidence of pre-protohistoric human impact until at least Roman times (Rutor glacier forelands; Badino 2016).

### *Copper Age cattle husbandry at high altitude? Merging cultural and palaeoecological evidence*

The discovery of a large archaeological area with thick charcoal layers and huge amounts of animal bones in the foothills of Mt. Fallère (site of Ordines, Fig. 1b; Mezzena 2006 and unpublished data) provides robust arguments for Copper Age slaughtering at middle altitudes. Three radiocarbon ages (4860–4805 $^{14}$C years BP, c. 5600–5500 cal years BP; RAVA Archaeological Survey, see Fig. 2 for their cumulative probability density curve) proved this site to be coeval with the early Crotte Basse pasture. This connection provides two significant clues (i) most probably animals were not slaughtered at high altitude, but instead led down valley at the end of the summer/beginning of fall season when they were in peak conditions and could provide most meat for human consumption (e.g. Barker 1985); (ii) cattle slaughtered at Ordines support that herds were maintained on summer pastures on Mt. Fallère as early as the onset of the Copper Age, in agreement with our evidence of high P concentrations recorded in pond sediments there inferred as a result of cattle watering.

Zootechnical requirements of alpine livestock species further evidence. Goats and sheep require small amounts of water and, due to their small body size, are well adapted to steep substrates with poorly developed herb cover. These conditions prevail in the mediterranean mountains where this form of prehistoric pastoralism is documented (Chang & Tourtellotte 1993). Cattle require greater water availability and plant biomass for forage production (Prins & van Langevelde 2008; Meehan, Stokka & Mostrom 2015) conditions met in the cool climate areas with summer rain of the higher Alps. Upland areas on Mt. Fallère provided the primary habitats of herbs still abundant in modern alpine pastures. The demise of alpine conifer forests testified at the Crotte Basse site started at c. 5600 cal years BP and quickly enlarged the areas available for those herbs. Fertilization was enhanced by domesticated animals, favouring a further expansion of pastures species.

We argue that the Crotte Basse area provided abundant plant biomass and water availability on fairly flat substrates, enough to keep herds of cows at high altitudes in summer during the early Copper Age (5700–5600 cal years BP). This hypothesis is supported by sedDNA evidence of domestic mammals in northern French Alps (Giguet-Covex *et al.* 2014) revealing the presence of *Bos* sp. as early as c. 5000 cal years BP.

### *Climate history in the second part of the Holocene from selected proxies*

Between 6100 and 5700 cal years BP, Western and Central Alps experienced forest decline, increasingly evident from 5700 to 5600 cal years BP onwards (Fig. 6). The site studied in this paper testifies that prehistoric human interference directly shaped a single high-altitude landscape plot in a more suitable form for the new-borne subsistence economy. But what about climate? To what extent, natural climate variability favours prehistoric human activities? Can the role of climate and humans in the ecological history of our study area be disentangled?

Up to 5700–5600 cal years BP, the Crotte Basse site was below the timberline, the altitude of which was controlled by climate gradients. Occasional human presence did not influence the forest limit; human impact on vegetation composition was limited to the pond access for animal watering, documented in the latest Neolithic (6400–5700 cal years BP). Reconstructed pollen-inferred $T_{jan}$ and $T_{jul}$ suggest a slight cooling between 5800 and 5600 cal years BP, roughly coeval with evidence from the Swiss Plateau and the Alps (cold event CE-5, c. 6200 and 5700 cal years BP; Haas *et al.* 1998). Between 5600 and 5300 cal years BP, total solar irradiance (TSI) repeatedly oscillated around its minimum Holocene values (Steinhilber, Beer & Frölich 2009), mirroring the residual $\delta^{14}C$ curve (Reimer *et al.* 2013). Available data point to glacier advances both in Scandinavia and North America and the beginning of a major phase of interhemispheric climate reversal lasting until 5000 cal years BP (Magny & Haas 2004).

Palaeocological and archaeological data from Mt. Fallère suggest that prehistoric populations possibly took advantage of a progressive climate deterioration, which may have driven a natural lowering of the timberline. However, the effects of anthropogenic pressure on local high-altitude areas were much greater than might be expected from climate changes and resulted in permanent vegetation changes. The mummified 'Alpine Iceman', found at 3280 m a.s.l (Baroni & Orombelli 1996), testifies to a phase of rapid climate cooling and increased persistent snow cover on previously deglaciated areas between c. 5300–5050 cal years BP (age of the burial). The idea that the body belonged to a prehistoric farmer (Spindler 2005) was questioned and further hypotheses on his social status were suggested (Oeggl 2009).

The effects of climate variability in a context where there is no evidence of human impact between 10 to 4 ka cal BP are shown in the pollen record from Passo Gavia (Fig. 6: Aceti, unpublished data). Here, the lowering of the timberline started between 9 and 8 ka cal BP and intensified in the mid Holocene, leading to the expansion of meadows containing no species with a clear anthropogenic affinity.

Between 5300 and 3400 cal years BP, reconstructed $T_{jan}$ and $T_{jul}$ mirror the trends of the $\delta^{18}O$ NGRIP record (Fig. 7). Residual $\delta^{14}C$ values are stable for most part of that period. total solar irradiance displays mostly minor fluctuations, pointing to limited variations in solar activity. During this period, humans exploited subalpine forests on Mt. Fallère and agropastoral activities intensified. In this time span, there is at least a record of lowering of the timberline and pastures development attributed to anthropogenic impact (c. 5355 cal years BP: Gouillè Rion, 2343 m a.s.l, Tinner, Ammann & Germann 1996). However, in this core section, the dating effort and the spectrum of palaeoecological indicators are too limited for more accurate evaluations.

Around 3400 cal years BP, a renewed phase of climate deterioration is suggested by decreasing values of $\delta^{18}O$ NGRIP record, coupled with slightly decreasing values of TSI and residual $\delta^{14}C$. Increasing afforestation on Mt. Fallère is related to the local expansion of spruce (*Picea*) populations. The expansion of green alder and juniper scrublands, starting at 3200 cal years BP (Late Bronze Age) may be related to the positive effects of fires but also to increased precipitation and snow cover (Wick & Tinner 1997).

Around 3000 cal years BP, evidence of glacier advance in the Alps comes from the Mer de Glace Glacier (Le Roy *et al.* 2015), coupled with $\delta^{18}O$ and residual $\delta^{14}C$ values. Decreasing $T_{jan}$ and $T_{jul}$ are reconstructed from our pollen data at the same time as a two centuries-long phase of human occupation at high altitude on Mt. Fallère.

From 2500 to 2400 cal years BP, reconstructed $T_{jul}$ declined, mirroring a further reduction of forest cover.

## Conclusions

Our research allows general and site-specific conclusions to be drawn:

**1**. Mesolithic activities had limited impacts on ecosystem on high-altitude areas in the Western Alps and did not lay the foundation of anthropogenic landscapes.

**2**. Around 5600 cal years BP, shortly after the first evidence of timberline exploitation, humans abruptly opened a large highland plot uphill of early settlements located in the valley floor, leading to the creation of the so far known oldest elevational pasture in the Alps. Interestingly, the area still hosts large montane to subalpine grazed areas, indicating continuity over several millennia.

**3**. No human interference is shown by palaeoecological indicators before this process started. The shaping of landscapes and vegetation at high altitudes was strongly related to the presence or absence of settlements in the valley floor and to the vocation of highlands to pastoralism. In the case study, installation of pastures coincided with the Copper Age onset, marked by a phase of anthropic pressure in the valley floor and of slaughtering activity at middle altitudes. The phenomenon is diachronous in different parts of the Alps (from the Late Neolithic/Copper Age to the late Middle Ages).

**4**. Forests opened around the site at c. 5700–5600 cal years BP, and nutrient-rich pastures increased. Dung accumulation, largely from grazing animals, enhanced runoff and nutrient supply to the lake water soon became relevant processes for the fate of the site.

**5**. Stable pastures were maintained for more than three millennia, i.e. until Roman times, by coupling intentional fires and grazing. P records suggest persistently significant stocking rate. Elevational grasslands and pioneer communities have been deeply re-shaped by long-term human pressure, increasing their original biodiversity after altitudinal range expansion of native herbs.

**6**. Regional climate regimes (summer rain season) rather than abrupt changes may have favoured the prehistoric development of alpine pastures. At favourable high-elevation sites, late Neolithic human groups took advantage of climatic timberline lowering. This lowering has also been documented under pristine conditions. However, the effects of anthropogenic pressure were disproportionately large if compared with the underlying climatic trigger and resulted in permanent changes to the natural landscapes.

**7**. This research underlines the need for extensive $^{14}C$ dating of archaeological structures and for expanded datasets of past ecological settings, including environmental proxies and precise identification of plant indicators. Better chronological control is required to enable precise correlation between palaeoecological and archaeological records during prehistoric times.

## Authors' contributions

R.P. and C.R. acquired the fundings, conceived the ideas and wrote the paper; R.P. coordinated the research, sampled and performed palaeoecological and LOI analysis; L.R. and A.G. coordinated the archaeological excavation and provided the cultural framework; L.C. obtained the quantitative estimations of past temperature based on pollen data; R.C. is responsible for pedochemical analyses on phosphorus forms. All authors contributed critically to the drafts and gave final approval for publication.

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## Data accessibility

Data available from the Dryad Digital Repository https://doi.org/10.5061/dryad.3jm3s (Pini *et al.* 2017).

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## Supporting Information

Details of electronic Supporting Information are provided below.

**Fig. S1.** Cross-correlation plots and scatterplots showing positive or negative relationships between selected palynological (total % of trees and anthropogenic taxa) and geochemical indexes (total P concentration in sediments, influx of organic and organic P, influx of silicoclastic residue and total organic matter).

**Fig. S2.** Cross-correlation plots between selected local and extralocal tree species and charcoal concentrations (microscopic charcoal = particles length 10–50 μm; macroscopic charcoal = particles length 50–250 μm).

**Table S1.** AMS $^{14}$C ages for the Crotte Basse mire and the archaeological sites on Mt. Fallère. Numbers in column 1 refer to Fig. 2. Provenance = relationships with the archaeological context.

**Appendix S1.** Woody species sensitivity to fire.