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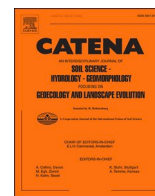
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Pedoanthracology sheds light the ancientness of the pastoral highlands of three mediterranean mountain: Sierra de Gredos (Spain), southeast Massif Central (France), and northern Apennines (Italy)

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ABSTRACT

The Mediterranean mountain zone is probably one of the parts of the world with the longest documented history of interactions between vegetation, climate, and human activities. The twofold objective of the present study was to examine and compare changes in three silvopastoral mountain areas, and to identify the natural and human processes that have shaped today's mountain landscapes. Although there were differences in vegetation and history between the three areas, there were also similarities in agropastoral practices, including livestock pressure and the use of fire. These similarities were supported by strong evidence based on soil charcoal and complemented by multiple other proxies (i.e., pollen analysis, archeology, historical documentation, and climatic data). The processes that led to the current physiognomy of the landscapes took place over the previous millennium, with a degree of synchrony over the past 500–800 years. The long co-evolution of humanity and landscape led us to reflect on the legacy of previous human practices and climatic changes, in terms of the composition of modern forests and the sensitivity of certain arboreal taxa (*Pinus gr. sylvestris*, *Abies alba* and *Taxus baccata*) that declined or disappeared during the late Holocene when the rates of vegetation change accelerated markedly. In summary, the comparative study of the history of the three highland landscapes attests to the interaction between long-term human impact (mainly pastoral societies, including livestock pressure and use of fire) and protracted climatic episodes that led to common changes in the study areas.

1. Introduction

Mountain areas occupy more than 40% of Europe (<https://www.euromontana.org/projet/a-new-cap/les-filieres-de-montagne/>; Gløersen et al., 2004), and are home to 20.3% of Europe's population, although this figure varies considerably across the countries of southwestern Europe (i.e., 38.5% for Spain, 32.6% for Italy, and 14.3% for France; Gløersen et al., 2004). A veritable hotspot of biodiversity, the Mediterranean area is particularly renowned for its rich history and diverse landscapes. Its climate and geographical position mean that it has been a strategic region for environmental resources since the Neolithic. Mont Lozère (Massif Central), Valle de las Pozas (Sierra de

Gredos), and Monte Cimone and Corno alle Scale (northern Apennines) have a convergent environmental, economic and social history resulting from an ancient silvopastoral system, the product of a thousand years of agropastoralism. Its present-day landscapes bear witness to the over-exploitation of resources by agropastoral and industrial societies and the latter's subsequent disappearance. Ancient structures, such as the ruins of pastoral huts, agricultural terraces and coal-mining platforms with or without retaining walls, as well as tortuous trees bearing the scars of past livestock farming (e.g., beech trees of Mont Lozère and Monte Cimone), are all markers of anthropization in the mountain landscape (Bal et al., 2010,2015; Ploquin et al., 2003; Rendu, 2003). We are at risk of losing these vestiges of ancient human practices, skills and knowledge if we do

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not value them and do not pass them on to future generations. However, variable amounts of research have been conducted on the history of these mountain landscapes. For example, in terms of heritage, conservation policies differ markedly between the mountain areas of the Mediterranean basin, owing to differences in management history and the environmental specificity of each area. Despite being exposed to the same problems of modern societies, they are still managed individually. A comparative study of their history could promote discussions among stakeholders at every level (country, mountain range, valley, or conservation area). After nearly 30 years of waiting, the *Sixth Assessment Report* of the Intergovernmental Panel on Climate Change finally contains a cross-chapter paper on mountains. This is a decisive move in both ecological and social terms toward more integrated decision-making about the mountains' future.

In the present study, we adapted the concept of *ancientness* that it is usually used for woodland systems (Bal et al., 2022; Cateau et al., 2015; Goldberg et al., 2007) to open mountain pastoral spaces. Cateau et al. (2015) defined *ancient woodland* as a woodland area that has been continuously wooded since a given date. We proposed to define the concept as follows, when applied to highlands: *area that has been continuously open since a given date*. This definition included the study of timberline and treeline dynamics and their relations with the highland landscape. Long-term human practices (mainly pastoral activities) have had a major impact on ecosystems through land-use at the Earth scale (Behre, 1988; Stephens et al., 2019; Ren et al., 2022) and, in particular, on Mediterranean ecosystems and landscape dynamics, and have led to the maintenance or opening of the highlands of southern Europe. Regarding the Mediterranean mountains, there is a considerable amount of local data, but inter-territorial comparisons are still a pending research topic. Thus, the objective was to identify the natural and human processes that led to the current pastoral landscape and determine when they emerged. As soil charcoal analysis provides local data on a lengthy timescale, we used pedoanthracology to assess the age of the open pastoral landscapes that are emblematic of southern European mountains. By studying three different mountain ranges, we were able to infer the role and importance of fire use since the beginning of agropastoralism in Europe. When considered alongside other proxies (e. g., pollen, climate change, dendrochronology, archeology, and historical sources), pedoanthracological records make it possible to reconstruct vegetation pattern dynamics across the Holocene.

We selected four sites in three different regions of southern Europe, in order to compare the evolution of their anthropo-sylvopastoral systems during the Holocene and identify the processes and their chronology that modeled the current open highland landscapes. Although each mountain area had different environmental features (i.e., climate, forest and grassland composition, co-evolution with human societies), all three had been impacted by the practices of pastoral societies, including livestock pressure and use of fire, and by lengthy climatic episodes affecting the whole of southern Europe.

This important interdisciplinary work led us to reflect on the legacy of past human practices and climatic changes in terms of modern woodland composition in the three mountain areas considered here. For example, three emblematic trees in the Mediterranean region (*Abies alba* Mill., *Taxus baccata* L., and *Pinus gr. sylvestris*) were found to exhibit patterns of rarefaction or disappearance during the late Holocene, when the rates of vegetation change accelerated markedly (Mottl et al., 2021). Overall, the multi-proxy approach applied in this study overcomes possible limitations due to each proxy being treated separately for the three study areas and allows for a reliable interpretation of the results. Botanical nomenclature was updated according to POWO (2022). In this study we aim to identify: How have past land use and fire events affected woodland composition and distribution? And, when has the current highland landscape been constructed?

2. Study sites

The study focused on three southern European mountain areas (Figs. 1 and 2): Massif Central (France), Sierra de Gredos (Spain), and northern Apennines (Italy).

2.1. Mont Lozère (Massif Central, France; Fig. 1D; Fig. 2A–E)

Mont Lozère, characterized by its high-altitude *Nardus stricta* grassland, is located at the heart of the Cévennes National Park (Central Massif, France) which is recognized as a Mediterranean agropastoral cultural landscape by UNESCO (<https://whc.unesco.org/en/list/1153/>). Mont Lozère is a granitic relief, 30 km long, ranging from 900 to 1700 m a.s.l. and oriented northwest–southeast. It has a Mediterranean mountain climate: humid, with annual precipitation values around 1500 mm and a mean annual temperature of around 6.5 °C. Between 400 and 900 m a.s.l., there is a forest system composed of *Quercus pubescens* Willd. and *Quercus petraea* (Matt.) Liebl. with occasional *Castanea sativa* Mill. Above 900 m a.s.l. and up to about 1480 m a.s.l. (the limit fluctuates between 1300 and 1480 m a.s.l.), at the current timberline, *Fagus sylvatica* L. is dominant (as it is in the rest of the Cévennes), with some occurrences of *Abies alba* Mill. Around the sampling area, the beech woodland is monospecific, with *Fagus sylvatica* trees characterized by thin, twisted trunks and no *Abies alba*. Above 1480 m a.s.l., the vegetation is dominated by grassland composed of *Nardus stricta* L., accompanied by *Vaccinium myrtillus* L., *Calluna vulgaris* (L.) Hull, and *Cytisus oromediterraneus* Rivas Mart. et al. There has been sporadic recolonization by early-successional species as *Pinus sylvestris* L., *Betula pendula* Roth., and *Juniperus communis* var. *saxatilis* Pall. The recolonization of the grassland by *Pinus sylvestris* and *P. uncinata* Ramond ex DC. resulted from the planting of a conifer forest, primarily on the southern slope, during the 19th and 20th centuries, thus decreasing pastoral pressure. The landscapes of this medium-altitude mountain were born out of the complementary exploitation of a variety of resources, in the form of agricultural production (Hélas, 1979), local and transhumant pastoralism forestry (Allée, 2003; Bal et al., 2015; Paradis-Grenouillet, 2012; Servera-Vives, 2014), mining and proto-metallurgy (Laurent, 2005; Ploquin et al., 2003, Ploquin et al., 2005), among others. The spatial distribution of natural resources (tiering, exposure), their accessibility, and their varied use in terms of timeframe (from seasonality to mutations over hundreds of years) have generated a very wide range of relationships between societies, local practices, and environments. The high-altitude grasslands of *Nardus stricta*, which are emblematic of Mont Lozère and protected from spontaneous recolonization by pine species, is an example of landscape transformation over the long term.

2.2. Valle de las Pozas (Sierra de Gredos, Spain; Fig. 1A; Fig. 2B–F)

We focused on the northern slope of the central sector of the Gredos range (Central Massif of Gredos or High Gredos), which is a granitic horst containing the highest peaks of the range, including the Almanzor peak (2592 m a.s.l.). This sector enjoys a subcontinental Mediterranean climate, characterized by a long (3 months) summer drought (Font Tullot, 1983). Annual precipitation oscillates between 1000 and 2000 mm at the highest altitudes along the southern slopes, whereas it only reaches 500 mm in the northern lowlands. The mean annual temperature of the entire range is below 12 °C, and below 8 °C in the highlands above 1500 m a.s.l. (Font Tullot, 1983; Ninyerola et al., 2005). Evergreen *Quercus* (*Q. ilex* subsp. *rotundifolia* Lam. and *Q. suber* L.) and *Pinus pinea* L. woodlands are located between 400 and 1000 m a.s.l. Deciduous *Quercus* (*Q. pyrenaica* Willd.) and *Pinus pinaster* Aiton woodlands characterize the 900–1500 m a.s.l. vegetation belt. Scattered stands of *Q. pyrenaica* can be found up to 1700 m a.s.l. Above 1500 m a.s.l., Fabaceae shrub communities, mainly comprising *Cytisus oromediterraneus*, *Echinopartum barnadesii* (Graells) Rothm, *Genista cinerascens*

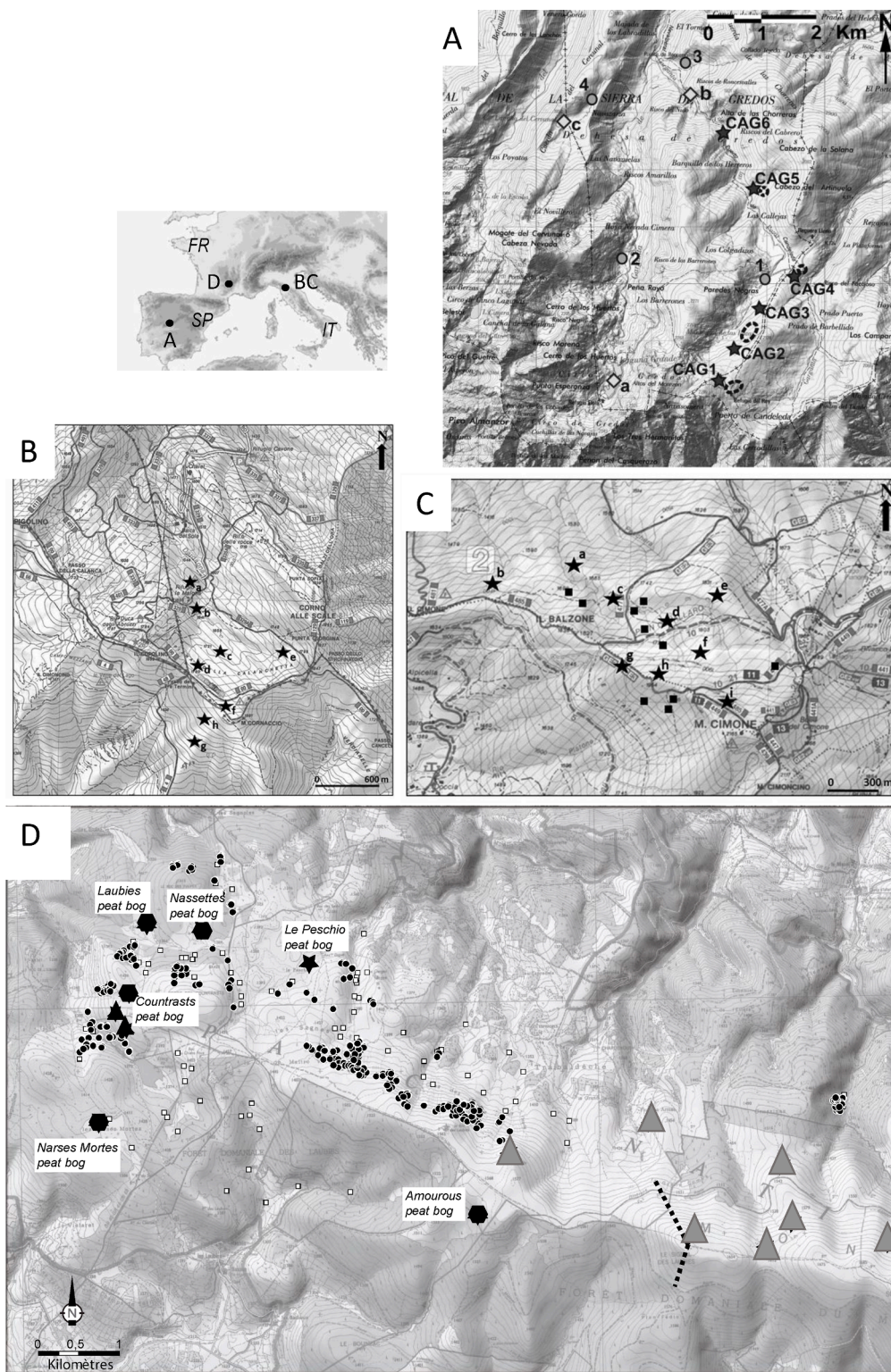


Fig. 1. The inset map shows the location of Spain (SP), France (FR) and Italy (IT) in Europe and the location of Mont Lozère in Central massif (D, France), Valle de la Pozas in Sierra de Gredos (A, Spain) and Monte Cimone and Corno alle Scale in the Northern Apennines (BC, Italy). Topographic maps with the location of relevant palaeocological sites: A Las Pozas del Vallès in Sierra de Gredos (this paper; García-Alvarez and others 2017); B and C respectively Corno alle Scale and Monte Cimones in Northern Apennines (this paper; Benatti and others 2018 and 2019) and D Mont Lozère in Central Massif (this paper; Bal and others 2015). For Gredos (A): **Round points:** macrofossil sites at Rubiales and others (2007) and Rubiales and Génova (2015); 1: Prado de Las Pozas; 2: Garganta de Gredos; 3: Roncesvalles; 4: Cuerda del Cervunal. **Star points:** pedoanthracological transect (García-Alvarez and others, 2017). **Dotted lines:** areas with pastoral structures observed during pedoanthracological sampling. For Apennines (B and C): Star points with letter “a” to “g” for B (Corno Alle Scale) and with letter “a” to “I” for C: pedoanthracological transect (Benatti, 2018; Benatti and others, 2018, 2019). For Mont Lozère (D): **Scattered line:** pedoanthracological transect. **Round points:** charcoal platforms (Paradis-Grenouillet, 2012). **Squared points:** slag sites (Ploquin and others, 2003; Baron, 2006). **Hexagonal shaped points:** peat bogs (Servera-Vives, 2014; Servera-Vives and others, 2014). **Black triangular shaped points:** pastoral structures dated. **Grey triangular shaped points:** pastoral structures geo-localised but not dated.

Lange, and *Cytisus scoparius* (L.) Link, dominate the landscape up to 2000 m a.s.l. This open landscape is dominated by a mosaic of scrub and grasslands. Occurrences of *Juniperus communis* var. *saxatilis* are juxtaposed with alpine pastures. Above 2000 m a.s.l., the landscape mainly consists of herbaceous assemblages with broom (*Cytisus oromediterraneus*). In contrast to Mont Lozère, there has not yet been any research in pastoral archeology, despite the presence of numerous archeological remains (huts and enclosures; Fig. 2B) testifying to a long history of

agropastoral practices in this mountain range (García-Álvarez et al., 2017).

2.3. Monte Cimone and Monte Corno alle Scale (northern Apennines, Italy; Fig. 1B-C; Fig. 2C-D-G-H)

Monte Cimone (2165 m a.s.l., Figs. 1C and 2C-G) and Monte Corno Alle Scale (1945 m a.s.l., Figs. 1B and 2D-H) are two of the highest peaks

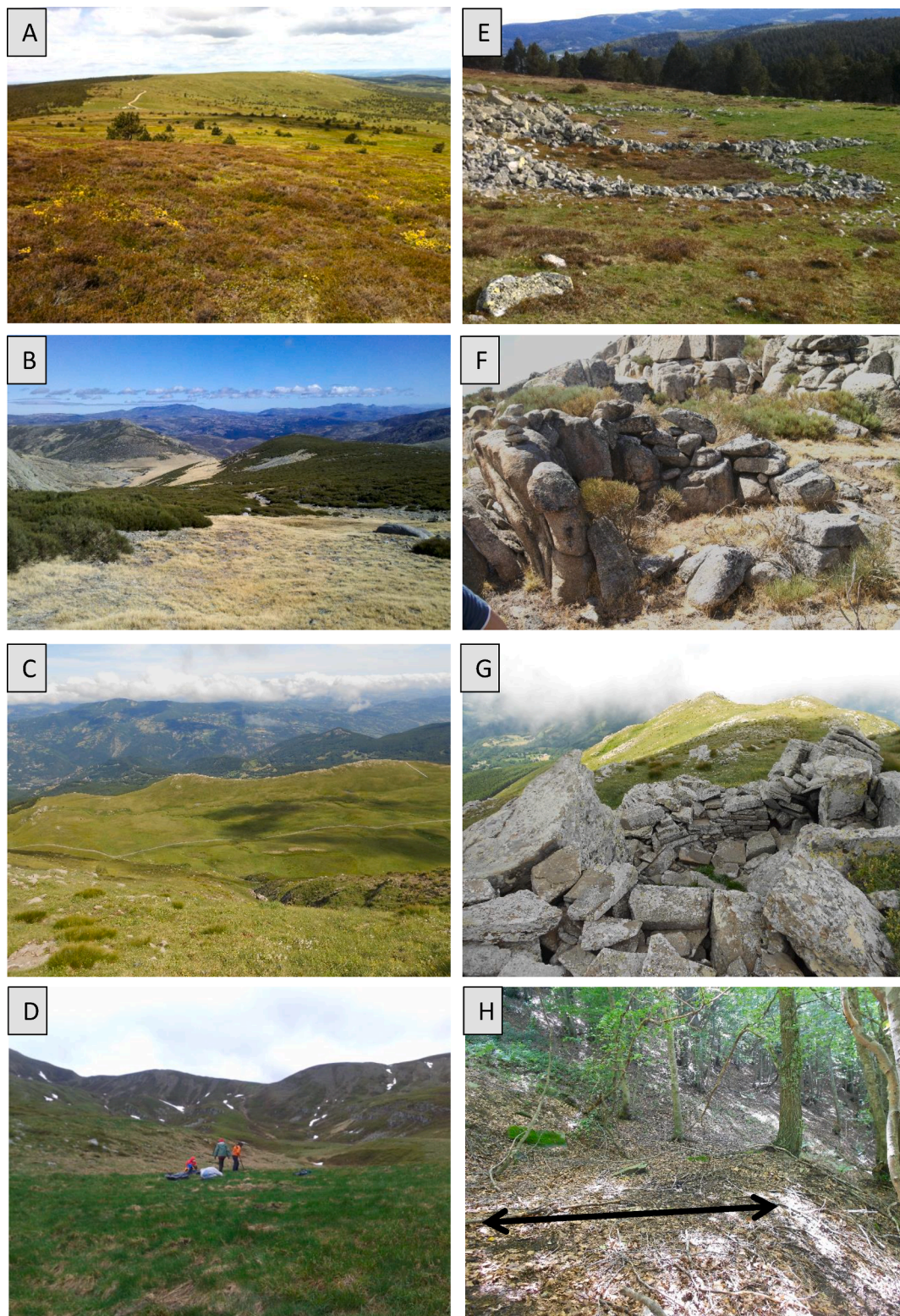


Fig. 2. The highlands in the Mont Lozère (A: the *Nardus stricta* grassland at 1670 m altitude), in the Valley de Las Pozas (B: the *matorral* broom community at 1900 m altitude), in the Monte Cimone (C: large plateau of shrub communities dominated by *Vaccinium myrtillus* located at around 2000 m altitude) and in the Corno Alle Scale (D: shrub communities dominated by *Vaccinium myrtillus*; pedoanthracological pit named CaS-e realized at 1775 m altitude), as examples of the current landscape after long history of livestock management. On these mountains, several ancient pastoral structures (in the Mont Lozère (E), in the Valley de Las Pozas (F) and in the Monte Cimone (G) and ancient charcoal platform in the Corno Alle Scale (H) testifying to the long history of use of the natural resources of these areas.

of the northern Apennines and are about 13 km apart. The geology of these mountains is typified by sandstone and clay outcrops (Bettelli et al., 1989). Mean annual temperatures are around 2 °C (data from Monte Cimone station), and mean annual precipitation ranges from around 690 mm (recorded at the top of Monte Cimone) to 2500 mm (recorded at a lower elevation) (Alessandrini et al., 2010; Tositti et al., 2014). The vegetation is composed of a *Fagus sylvatica* woodland, once highly coppiced and now left to natural wood regeneration, with some occurrence of *Abies alba*, *Acer pseudoplatanus* L., and *Laburnum alpinum* (Mill.) Bertcht. & J. Presl. (Tomaselli et al., 1996), from about 900 m a.s.l. to the timberline. Nowadays, only cultivated or naturalized *Abies alba* is found (Alessandrini et al., 2010), and it was not observed near our sampling points. The current timberline lies at 1700 m a.s.l. on Monte Cimone, and 1600 m a.s.l. on Corno alle Scale. Close to the timberline, shrub communities are dominated by Ericaceae (mainly *Vaccinium myrtillus*) or Fabaceae (e.g., *Cytisus scoparius* and *Genista tinctoria* L.). The meadow pastures are dominated by *Nardus stricta* and *Brachypodium pinnatum* (L.) P. Beauv. (Alessandrini et al., 2010). On these two mountains, several ancient pastoral structures (not yet dated) have been detected, and ancient charcoal kilns have been studied (Benatti et al., 2018), with input from historical and ethnographical sources (e.g., Albani, 1964; Rombaldi & Cenci, 2013), testifying to the long history of use of the natural resources of these areas.

3. Materials and methods

3.1. Sampling strategy

To reconstruct the history of highland pastoral landscapes, we dug several pedomorphological pits corresponding to an altitudinal transect between the forest boundaries and the top of the slopes considered in each European mountain area. The number of pits depends on several parameters, such as the geophysical characteristics of the mountain area (number of stone blocks, altitude, and degree of slope), the surface of the open pastoral space, the distance between the current timberline and the top of the slope, and the number of archaeological structures present in the studied area. Soil charcoal analysis, based on the taxonomic study of charcoals combined with radiocarbon dating, provided local data, specific to the hillside, on past changes in vegetation and fires. This method has already been applied to assess ancient fluctuations in treeline and timberline (e.g., Bal et al., 2015; Carcaillet & Thion, 1996; Talon, 2010; Touflan et al., 2010). The three surveyed transects corresponding to each mountain area were therefore located in prime areas with abundant signs of ancient human activities, including several pastoral structures identified during sampling. To avoid any charcoal contamination by former charcoal kilns, we conducted reconnaissance surveys beforehand, to confirm that there were no such kilns in the vicinity of the pedomorphological pits. The extraction of soil samples was carried out with special care, in order to reduce the ecological and visual impact. Each pit occupied an area of approximately 0.3 m². The sampling was carried out by stripping the soil in increments of 5–10 cm, starting from the surface and working down to the bedrock, imitating archaeological methodology (Bal and García-Álvarez, 2022; Benatti et al., 2019). About 5 kg of wet soil were collected from each sampling level. A pedological description was then carried out (Bal et al., 2015; Benatti et al., 2018,2019; García-Álvarez et al., 2017). Each pit was eventually backfilled and covered with the superficial herbaceous layer removed at the beginning of the sampling.

On Mont Lozère (Bal et al., 2015), four soil profiles (MONT1, MONT4, MONT6, and MONT10) were sampled within the *Nardus stricta* grassland and along an altitudinal transect between 1450 m and 1670 m a.s.l. (Figs. 1D and 2A). In Valle de las Pozas, six soil profiles (García-Álvarez et al., 2017) were sampled along the altitudinal transect from 1700 to 2200 m a.s.l. and within the scrubland open space, at intervals of approximately 100 m a.s.l. (Fig. 1A and 2B): CAG1, CAG2, CAG3, CAG4, CAG5, and CAG6. On Monte Cimone (Benatti et al., 2018,2019),

nine pits were excavated on the northwest slope following an altitudinal transect from 1650 to 2078 m a.s.l. (MtC-a, MtC-b, MtC-c, MtC-d, MtC-e, MtC-f, MtC-g, MtC-h, and MtC-i), from the beech woodland to the open landscape (Figs. 1B-C and 2C-D). A total of eight pits were dug on Corno alle Scale (Benatti et al., 2018,2019): six on the north side from 1602 to 1860 m a.s.l. (CaS-a, CaS-b, CaS-c, CaS-d, CaS-e (Fig. 2D), CaS-f), and two others on the south side at 1700 and 1750 m a.s.l. (CaS-g and CaS-h). All pits were located in the current open landscape (Figs. 1B and 2D).

3.2. Soil charcoal analysis

Soil samples were dried, to decrease the risk of charcoal fragmentation before sieving with water jet using a column of sieves (5.0, 2.0, 0.8 and 0.4 mm). The finest sieve size (0.4 mm) was chosen to allow the taxonomic identification of the charcoal fragments, and was greater than the size limit for fragments dispersed by wind transport and hot air currents generated by fires (Clark, 1988; Clark et al., 1998; Ohlson & Tryterud, 2000; Lynch et al., 2004). Charcoal fragments were hand-picked from the mineral organic fractions that remained in the sieves under a binocular microscope. All these fragments were then observed under an incident light microscope (50×, 100×, 200×, and 500×) to obtain their taxonomic identification. Several wood anatomy atlases were used (e.g., Inside Wood, 2017; Jacquot et al., 1973; Schweingruber, 1990).

3.3. Radiocarbon dates

Some of the charcoal fragments (14 for Mont Lozère, 23 for Valle de las Pozas, 16 for Monte Cimone, and 9 for Corno alle Scale) extracted from the pits were AMS ¹⁴C radiocarbon dated, either by the Center for Applied Isotope Studies (University of Georgia, USA), in the case of the Apennines and Mont Lozère, or by the 14CHRONO Centre of Queen's University (Belfast), in the case of Valle de las Pozas (Table 1). The fragments were selected according to i) the spatial distribution of the pits and depth horizons, to optimize the diversity of chronological insights, ii) currently absent tree taxa (e.g., *Prunus cf. avium* L. for Mont Lozère, *Pinus gr. sylvestris* for Valle de las Pozas), and iii) the chronologically most widespread taxa in the region (e.g., *Fagus sylvatica* for Mont Lozère and the Apennines), which allowed us to reduce bias in the record of fire events. The dates were calibrated using CALIB software (Stuiver & Reimer 1993) version 8.2, with the IntCal20 dataset (Reimer et al., 2020).

3.4. Data analysis

Results are summarized in three figures (Figs. 3A-B and 4), combining chronology and altitude for each study area. They summarize the evidence of pedomorphological data from the identified and dated charcoal fragments, combined with literature findings based on archeological, palynological, dendrochronological and archeo-anthracological data for the areas closest to the charcoal sampling locations. Historical sources and climatic data were also extracted from the scientific literature. Rich and complex relationships between agro-pastoral societies and the construction of the mountain landscape (forest dynamics, taxon distribution), past altitudinal fluctuations in vegetation types and the chronology of the open landscapes during the Holocene were identified from multiple sources.

4. Results and discussion

4.1. Ancientness of pastoral highlands in three Mediterranean mountain areas

4.1.1. Mont Lozère

On Mont Lozère, from the beginning of the Holocene (Boreal) to the first part of the Middle Holocene (Atlantic), at around 4100 cal. yr. BC

Table 1

AMS ¹⁴C dates from the pit soils (Mont: Mont Lozère; CAG: Gredos; Monte Cimone MtC and Corno Alle Scale CaS). Calibration in BP and in AD/BC at 2σ confidence interval, based on Calib8.2 data set. Stuiver M, Reimer P.J. 1993. Extended 14C database and revised CALIB 8.2 14C age calibration program. Radiocarbon 35:215–230.

Sample id	Date BP	Date Cal BP	14C age Cal AD/BC	Charcoal species	Pit and altitude	Latitude/Longitude
UGAMS11151	900 ± 25	911–741	CE 1117–1210	<i>Fagus sylvatica</i>	Mont10 1450 m	44°26'32.39"N/3°41'07.07"E
UGAMS11753	1140 ± 25	1146–971	AD 857–980	<i>Fagus sylvatica</i>	Mont6 1550 m	44°26'15.41"N/3°41'32.96"E
UGAMS11354	1670 ± 25	1620–1528	AD 326–426	<i>Fagus sylvatica</i>	Mont4 1670 m	44°25'48.83"N/3°43'10.11"E
UGAMS9237	2180 ± 25	2308–2121	360–171 BCE	<i>Prunus cf avium</i>	Mont4 1670 m	44°25'48.83"N/3°43'10.11"E
UGAMS11152	2170 ± 25	2308–2112	359–275 BCE	<i>Fagus sylvatica</i>	Mont10 1450 m	44°26'32.39"N/3°41'07.07"E
UGAMS14226	2490 ± 25	2723–2485	770–518 BCE	<i>Betula</i>	Mont1 1580 m	44°25'42.25"N/3°41'46.26"E
UGAMS14228	2730 ± 25	2870–2768	920–819 BCE	<i>Fagus sylvatica</i>	Mont1 1580 m	44°25'42.25"N/3°41'46.26"E
UGAMS9239	3790 ± 30	4257–4084	2308–2135 BCE	<i>Prunus cf avium</i>	Mont4 1670 m	44°25'48.83"N/3°43'10.11"E
UGAMS9240	3820 ± 30	4354–4093	2349–2194 BCE	<i>Prunus cf avium</i>	Mont4 1670 m	44°25'48.83"N/3°43'10.11"E
UGAMS11353	4010 ± 25	4525–4422	2575–2474 BCE	<i>Fagus sylvatica</i>	Mont4 1670 m	44°25'48.83"N/3°43'10.11"E
UGAMS11755	4030 ± 25	4569–4424	2587–2475 BCE	<i>Fagus sylvatica</i>	Mont6 1550 m	44°26'15.41"N/3°41'32.96"E
UGAMS11754	4850 ± 25	5645–5487	3695–3633 BCE	<i>Fagus sylvatica</i>	Mont6 1550 m	44°26'15.41"N/3°41'32.96"E
UGAMS9238	4870 ± 30	5655–5583	3706–3635 BCE	<i>Prunus cf avium</i>	Mont4 1670 m	44°25'48.83"N/3°43'10.11"E
UGAMS14227	5320 ± 25	6185–6001	4235–4051 BCE	<i>Prunus cf avium</i>	Mont1 1580 m	44°25'42.25"N/3°41'46.26"E
UBA-24463	1102 ± 29	1064–952	AD 886–998	<i>Leguminosae</i>	CAG3 2000 m	40°15'54.29"N/5°14'40.69"O
UBA-26096	1196 ± 24	1181–1059	AD 769–891	<i>Leguminosae</i>	CAG1 2200 m	40°15'00.78"N/5°15'19.89"O
UBA-26104	1893 ± 28	1895–1770	AD 55–180	<i>Leguminosae</i>	CAG4 1900 m	40°16'10.45"N/5°14'24.73"O
UBA-26098	2086 ± 37	2148–1969	199–20 BC	<i>Leguminosae</i>	CAG2 2100 m	40°15'32.18"N/5°15'00.89"O
UBA-24464	2121 ± 32	2156–1998	207–49 BC	<i>Leguminosae</i>	CAG4 1900 m	40°16'10.45"N/5°14'24.73"O
UBA-26105	2200 ± 33	2317–2131	368–182 BCE	<i>Leguminosae</i>	CAG4 1900 m	40°16'10.45"N/5°14'24.73"O
UBA-26107	3052 ± 35	3357–3170	1408–1221 BCE	deciduous <i>Quercus</i>	CAG5 1800 m	40°17'29.56"N/5°15'07.94"O
UBA-27833	3213 ± 43	3514–3362	1565–1413 BCE	<i>Pinus gr. sylvestris</i>	CAG6 1700 m	40°17'58.77"N/5°15'39.70"O
UBA-24467	3474 ± 53	3876–3610	1927–1661 BCE	<i>Leguminosae</i>	CAG5 1800 m	40°17'29.56"N/5°15'07.94"O
UBA-26097	4419 ± 30	5062–4870	3113–2921 BCE	<i>Leguminosae</i>	CAG1 2200 m	40°15'00.78"N/5°15'19.89"O
UBA-26102	4458 ± 35	5289–4963	3340–3014 BCE	<i>Betula sp</i>	CAG3 2000 m	40°15'54.29"N/5°14'40.69"O
UBA-26101	4932 ± 42	5739–5593	3790–3644 BCE	<i>Maloideae</i>	CAG3 2000 m	40°15'54.29"N/5°14'40.69"O
UBA-27834	5388 ± 30	6284–6175	4335–4226 BCE	<i>Pinus gr. sylvestris</i>	CAG6 1700 m	40°17'58.77"N/5°15'39.70"O
UBA-26103	5537 ± 38	6401–6285	4452–4336 BCE	<i>Populus sp</i>	CAG3 1900 m	40°16'10.45"N/5°14'24.73"O
UBA-26099	5862 ± 51	6793–6531	4844–4582 BCE	<i>Betula sp</i>	CAG2 2100 m	40°15'32.18"N/5°15'00.89"O
UBA-26100	6217 ± 37	7208–7007	5259–5058 BCE	<i>Leguminosae</i>	CAG2 2100 m	40°15'32.18"N/5°15'00.89"O
UBA-26106	6800 ± 41	7690–7580	5741–5631 BCE	<i>Prunus sp</i>	CAG5 1800 m	40°17'29.56"N/5°15'07.94"O
UBA-27836	6840 ± 36	7744–7596	5795–5647 BCE	<i>Pinus gr. sylvestris</i>	CAG6 1700 m	40°17'58.77"N/5°15'39.70"O
UBA-24462	7675 ± 45	8548–8393	6599–6444 BCE	<i>Leguminosae</i>	CAG1 2200 m	40°15'00.78"N/5°15'19.89"O
UBA-24465	8013 ± 47	9018–8715	7069–6766 BCE	<i>Betula sp</i>	CAG4 1900 m	40°16'10.45"N/5°14'24.73"O
UBA-24466	8667 ± 59	9794–9530	7845–7581 BCE	<i>Maloideae</i>	CAG4 1900 m	40°16'10.45"N/5°14'24.73"O
UBA-27835	8757 ± 46	9912–9558	7963–7609 BCE	deciduous <i>Quercus</i>	CAG6 1700 m	40°17'58.77"N/5°15'39.70"O
UBA-27837	8914 ± 40	10188–9911	8239–7962 BCE	deciduous <i>Quercus</i>	CAG6 1700 m	40°17'58.77"N/5°15'39.70"O
	10 ± 25	/	/	<i>Ericaceae</i>	CaS-b 1648 m	44°7'13.95"N/10°49'0.29"E
	560 ± 20	561–530	CE 1389–1420	<i>Ericaceae</i>	MtC-c 1746 m	44°12'8.92"N/10°41'17.73"E
	730 ± 30	709–653	CE 1241–1297	<i>Fagus sylvatica</i>	CaS-e 1775 m	44°7'3.24"N/10°49'33.84"E
	760 ± 20	709–670	CE 1241–1280	<i>Abies alba</i>	MtC-b 1684 m	44°12'10.47"N/10°40'56.71"E
	770 ± 25	729–672	CE 1221–1278	<i>Fagus sylvatica</i>	CaS-h 1750 m	44°6'41.01"N/10°49'0.20"E
	810 ± 25	768–681	CE 1182–1269	<i>Ericaceae</i>	CaS-a 1602 m	44°7'24.37"N/10°48'52.25"E
	940 ± 20	887–796	CE 1063–1154	<i>Abies alba</i>	MtC-c 1746 m	44°12'8.92"N/10°41'17.73"E
	960 ± 20	873–797	CE 1077–1153	<i>Ericaceae</i>	MtC-I 2078 m	44°11'42.70"N/10°41'48.82"E
	990 ± 20	956–903	AD 994–1047	<i>Ericaceae</i>	MtC-f 1850 m	44°11'55.04"N/10°41'44.51"E
	1310 ± 20	1290–1233	AD 660–710	<i>Taxus baccata</i>	MtC-c 1746 m	44°12'8.92"N/10°41'17.73"E
	1520 ± 20	1418–1350	AD 532–600	<i>Abies alba</i>	MtC-a 1650 m	44°12'12.39"N/10°41'5.38"E
	1540 ± 20	1522–1452	AD 428–498	<i>Abies alba</i>	MtC-a 1650 m	44°12'12.39"N/10°41'5.38"E
	1690 ± 20	1624–1545	AD 326–405	<i>Ericaceae</i>	MtC-c 1746 m	44°12'8.92"N/10°41'17.73"E
	1750 ± 20	1714–1604	AD 236–346	<i>Ericaceae</i>	MtC-e 1810 m	44°12'8.85"N/10°41'50.37"E
	1860 ± 20	1865–1729	AD 85–221	<i>Fabaceae</i>	MtC-d 1778 m	44°12'2.64"N/10°41'34.45"E
	1970 ± 20	1952–1876	AD 74–3 BC	<i>Laburnum sp.</i>	MtC-b 1684 m	44°12'10.47"N/10°40'56.71"E
	2150 ± 25	2164–2048	215–99 BC	<i>Fagus sylvatica</i>	MtC-c 1746 m	44°12'8.92"N/10°41'17.73"E
	2160 ± 20	2181–2107	232–158 BCE	<i>Ericaceae</i>	MtC-h 1946 m	44°11'47.92"N/10°41'29.51"E
	2170 ± 20	2305–2233	356–284 BCE	<i>Ericaceae</i>	MtC-g 1870 m	44°11'52.46"N/10°41'20.40"E
	2240 ± 30	2272–2154	323–205 BCE	<i>Fagus sylvatica</i>	CaS-d 1740 m	44°6'57.00"N/10°49'5.33"E
	2240 ± 30	2272–2154	323–205 BCE	<i>Fagus sylvatica</i>	CaS-d 1740 m	44°6'57.00"N/10°49'5.33"E
	2260 ± 30	2260–2158	311–209 BCE	<i>Fabaceae</i>	CaS-d 1740 m	44°6'57.00"N/10°49'5.33"E
	2900 ± 25	3080–2957	1131–1008 BCE	<i>Fraxinus sp.</i>	CaS-g 1700 m	44°6'39.47"N/10°48'57.35"E
	7870 ± 25	8728–8592	6779–6643	<i>Fraxinus sp.</i>	MtC-a 1650 m	44°12'12.39"N/10°41'5.38"E
	8770 ± 30	9906–9658	7957–7709 BCE	<i>Ericaceae</i>	CaS-f 1860 m	44°6'45.66"N/10°49'9.54"E

(Fig. 3A), the landscape was composed of oak woodland accompanied by deciduous taxa (*Ulmus*, *Tilia*, *Fraxinus*, *Corylus avellana* L.). Occurrences of *Abies alba* were found up to about 1550 m altitude (Servera-Vives, 2014). Higher up, the landscape probably consisted of a marquetry of wooded and open spaces. Two fragments of *Prunus cf.*

avium charcoal from pits located at 1550 m and 1670 m a.s.l. and dated to 4850 ± 25 BP (3695–3633 cal. yr. BC) and 4870 ± 30 BP (3706–3635 cal. yr. BC) confirmed the local presence of a mosaic landscape (Bal et al., 2015). *Fagus sylvatica* appeared around 4100 cal. yr. BC. At the scale of the oriental Massif Central, Cubizolle et al. (2016)

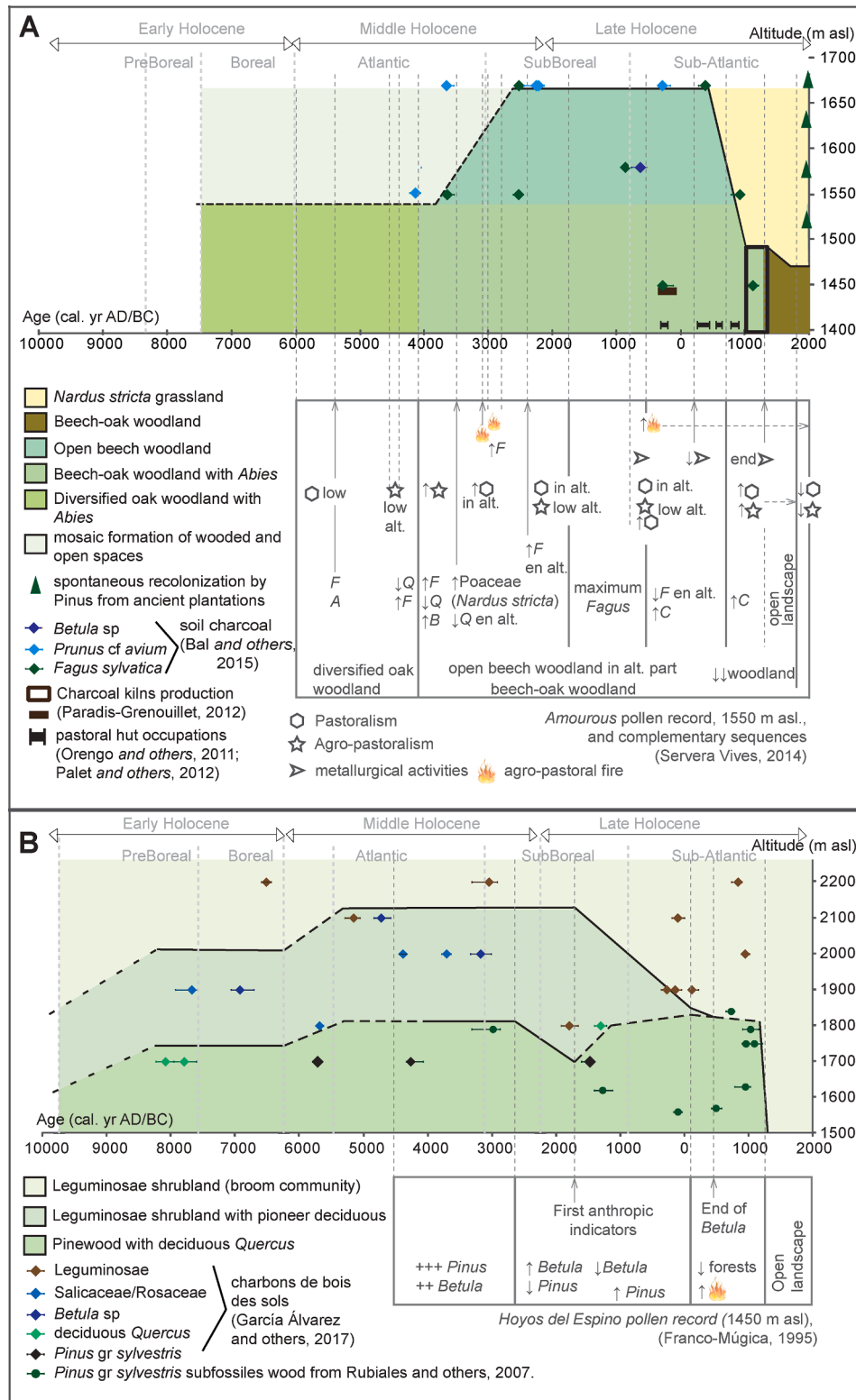


Fig. 3. Models of altitudinal distributions of plant formations: **(A)** at Mont Lozère since 7000 years ago from Orengo and others (2011), Palet and others (2012), Paradis-Grenouillet, 2012, Servera-Vives (2014), Servera-Vives and others (2014), Bal and others (2015); **(B)** at valley de Las Pozas (Sierra de Gredos) during Holocene (figure modified from Garcia-Alvarez and others 2017). The Holocene division follows the proposal of Walker and others (2012).

point out that the soil moisture revealed in the previous phase seems to be disappearing. Oak-beech woodland replaced the oak woodland system, and beech woodland then gradually established itself up to the top (around 1700 m), occupying the upper spaces around 2500 cal. yr. BC and up to about 400 cal. yr. AD. Based on their studies realized in Massif

Central, van der Knaap et al. (2022) postulate that the expansion of the beech in large parts of Europe during the late-Holocene is related to a human instigated process rather than a natural process. Furthermore, it seems that *Fagus sylvatica* is less sensitive to grazing impacts and therefore replaces other deciduous trees that are more sensitive to

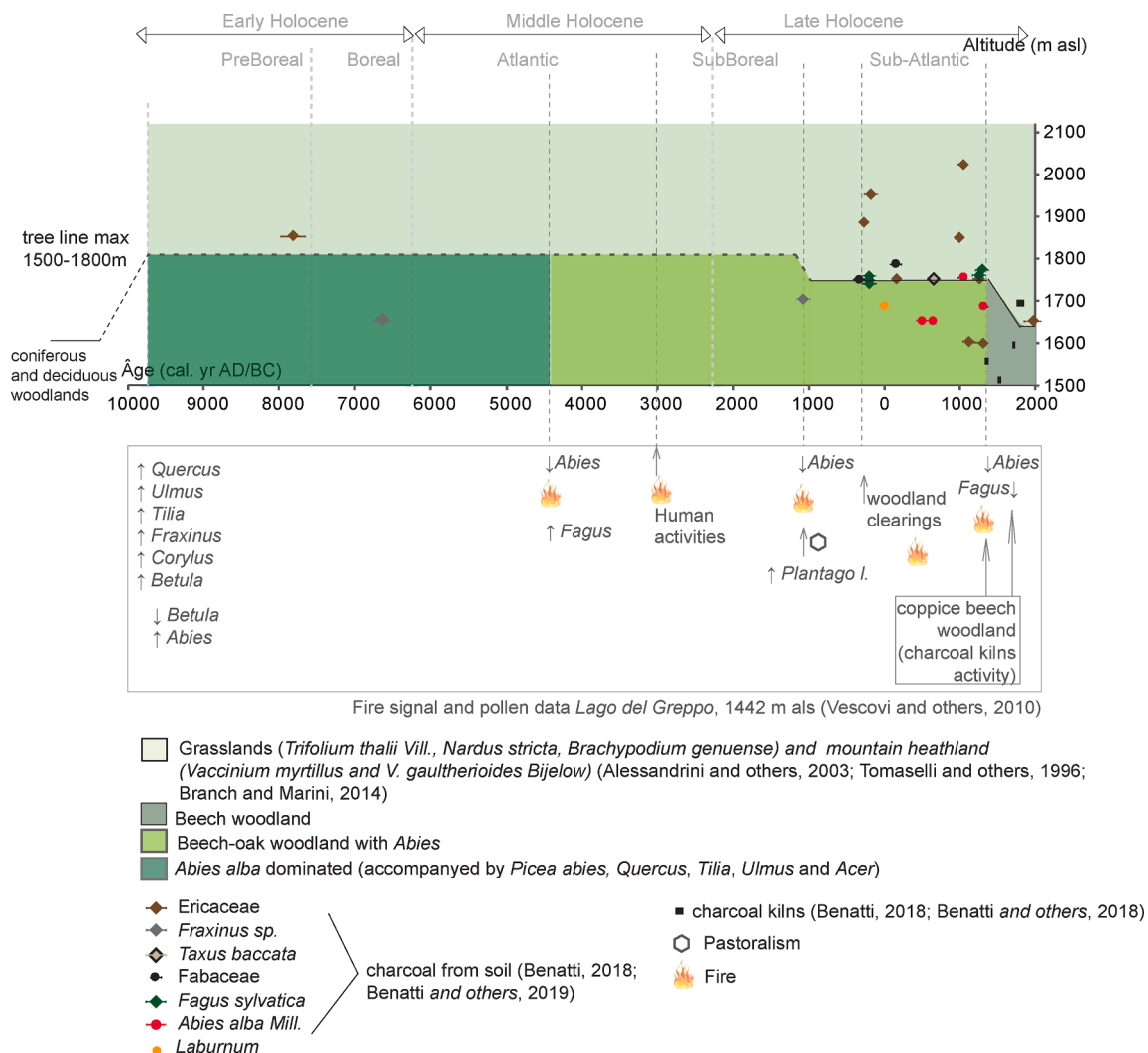


Fig. 4. Models of altitudinal distributions of plant formations at the Northern Apennines: Monte Cimone and Corno Alle Scale (Italy) during Holocene from Benatti and others (2018, 2019), Vescovi and others (2010), Alessandrini and others (2003), Tomaselli and others (1996), Brand and Marini (2014). The Holocene division follows the proposal of Walker and others (2012).

herbivore impact. Pollen and pediaanthracological data (Bal et al., 2015; Servera-Vives, 2014) supported the hypothesis of an open beech woodland formation, as it was associated with heliophilous taxa indicating different stages of succession, such as *Betula* sp. (2490 ± 25 BP, 770–518 cal. yr. BC), *Salix*, *Corylus avellana*, and *Prunus cf. avium* (at 1670 m a.s.l. 2180 ± 25 BP, 360–171 cal. yr. BC). Ericaceae remnants were linked to agropastoral practices using fire as a slash-and-burn technique (Iversen, 1956) as the initial phase in his landnam model at both high and low altitudes. Forest clearings that appeared between the Middle Neolithic (4230 cal. yr. BC) and High Middle Ages (c. 1200 cal. yr. AD) were related to pastoral activities (Bal et al., 2015; Servera-Vives, 2014) that do not appear to have depleted the woodland system. This is in agreement with the hypothesis developed by van der Knaap et al. (2022) for the Mont du Forez in the Massif Central. During the Final Bronze Age, reduced pastoral pressure and the European climatic deterioration (van Geel et al., 1996, 1999) allowed the open beech woodland to continue occupying the higher part of Mont Lozère (Bal et al., 2015). Soil charcoal analyses indicated the presence of open beech woodland associated with *Prunus cf. avium* and *Betula* sp. (Bal et al., 2015) up to the Roman period. Intensive attacks on the beech woodland between the Second Iron Age and the Roman period were confirmed for the Massif Central. Pastoral pressure on Mont Lozère was supported by archaeological data, as evidenced by radiocarbon dates from huts

(318–207 cal. yr. BC; Palet & Orengo 2012), geochemical analyses from two nearby peat bogs (Narses Mortes & Countrast; documenting the beginning of intensive mining during the Second Iron Age, ca. 220 cal. yr. BC; Servera-Vives et al., 2014; Baron et al., 2005, 2006), and the presence of an opencast argentiferous lead mine dating from the second century BC (Cauuet, 2012). This was in line with the discovery of a Gallic charcoal platform located at 1450 m, which confirmed the presence of *Fagus sylvatica* and *Prunus cf. avium* (Paradis-Grenouillet, 2012). At the end of the Roman period, the summit of the mountain underwent a major erosion phase linked to an extension of agropastoral practices on Mont Lozère (Servera-Vives et al., 2014) and throughout the Massif Central (Allée, 2003). Thus, from 400 cal. yr. AD onwards, the beech woodland located at the top of this mountain was more strongly impacted by human activity (Servera-Vives et al., 2014; Pulido, 2006). Surveys of pastoral huts (Palet et al., 2011) attest to occupation between 250 and 900 cal. yr. AD. This is supported by several phases of increasing coprophilous fungi such as *Sordaria*, *Sporormiella* and *Cercophora*, suggesting that Countrasts bog (Fig. 1D) began to be frequented by grazing livestock during this time window (Servera-Vives et al., 2014). The decline in the beech forest was accompanied by the expansion of *Nardus stricta* grassland in the mountain stage and the regression of the oak-beech forest up to 1500 m altitude. Geolocation of ancient charcoal platforms up to 1500 m a.s.l. confirmed this ancient limit of the

beech wood between the 11th and 14th centuries (Paradis-Grenouillet, 2012). At around 1300 cal. yr. AD, *Abies* disappeared (Servera-Vives et al., 2014). In more recent periods, the beech wood continued its retreat until it reached the current limit of 1480 m altitude. Scots pine is currently gaining a great deal of ground through spontaneous recolonization from old plantations dating back to the late 19th century. Juniper is also participating in the recolonization of *Nardus stricta* grasslands. Our most recent data (Bal et al., 2015; Servera-Vives, 2014) show that in the history of these agropastoral landscapes (going back at least 7000 years), the *Nardus stricta* grassland has not always occupied the summit of Mont Lozère. The process began 1600 years ago (around 400 cal. yr. AD), and the current highland landscape has existed for approximately 1000 years.

4.1.2. Valle de las Pozas

Compilation of the soil charcoal data (García-Álvarez et al., 2017), subfossil wood results (Rubiales et al., 2007; Rubiales & Génova, 2015), and pollen data (Franco-Múgica, 1995) in Fig. 3B shows that between the beginning of the Holocene (end of Preboreal) and the Middle/Late Holocene transition (beginning of Subboreal), three plant assemblages dominated the landscape of Valle de las Pozas. Up to around 1700 and 1800 m altitude, there was an open pine woodland (at 1700 m a.s.l.: *Pinus gr. sylvestris* dated to 5795–5647 cal. yr. BC, 4335–4226 cal. yr. BC, and 1565–1413 cal. yr. BC; at 1570 m a.s.l.: subfossil pine wood dated to 3000 cal. yr. BC) accompanied by deciduous oak (purportedly *Quercus pyrenaica*) (at 1700 m a.s.l.: dated to 8239–7962 cal. yr. BC and 7963–7609 cal. yr. BC). The open stage of the woodland was suggested by the presence of heliophilous taxa: *Betula* sp., Salicaceae/Rosaceae (at 1800 m a.s.l.: *Prunus* sp. dated to 5741–5631 cal. yr. BC) and shrubs identified within the soil charcoal, probably close to its altitudinal limit. Above, it gave way to a leguminous moorland with the presence of pioneer deciduous trees (e.g., *Betula* sp. at 1900 m a.s.l. dated to 7069–6766 cal. yr. BC; at 2100 m a.s.l. dated to 4844–4582 cal. yr. BC; at 2000 m a.s.l. dated to 3340–3014 cal. yr. BC), *Populus* sp. (at 1900 m a.s.l.: dated to 4452–4336 cal. yr. BC) and Maloideae (at 1900 m a.s.l.: dated to 7845–7581 cal. yr. BC; at 2000 m a.s.l.: dated to 3790–3644 cal. yr. BC) up to around 2000 m a.s.l. at the beginning of the Holocene and 2100 m a.s.l. during the middle Holocene (García-Álvarez et al., 2017). The presence of these pioneer taxa may have been relatively substantial at 1900–2000 m a.s.l., as evidenced by the 15 subfossil woods of *Betula* sp. found by Rubiales et al. (2007). These associations point to the ancient existence of a transitional area between the pine woodland (maximum elevation ca. 1800 m) and the exclusive broom community (above 2100 m) in Valle de las Pozas during the Early and Middle Holocene, a scenario that has no parallel in the area today. During this period, *Betula* sp. predominated in pollen data, reaching a maximum of 80% ca. 3670 cal. yr. BP (around 2100 BCE) (Franco-Múgica, 1995). Birch woodland in Sierra de Gredos started a long and gradual decline at around 1700 cal. yr. BC, finally disappearing ca. 400 cal. yr. AD (Franco Múgica, 1995). During this time, the *matorral* (local name for broom community) took on greater spatial importance, as confirmed by the radiocarbon dates of six charcoal fragments of Fabaceae (García-Álvarez et al., 2017) located between 1900 and 2200 m a.s.l. (368–182 cal. yr. BC, 207–49 cal. yr. BC, 199–20 cal. yr. BC, 55–180 cal. yr. AD, 769–891 cal. yr. AD, 886–998 cal. yr. AD). Soil charcoal data, together with 33 woods and 9 cones of *Pinus gr. Sylvestris* found at 1750–1840 m a.s.l. within a 10-km radius of the study area (Rubiales et al., 2007; Rubiales & Génova, 2015), suggest a pine woodland limit that oscillated around 1800 m a.s.l. The scrub had been in contact with the pine forest for about 800 years that is, since the disappearance of the birch and Scots pine from Valle de las Pozas, estimated to have taken place in the 13th century (Rubiales et al., 2015). Since 1700 cal. yr. AD, the farming nature of these areas is easily identified in pollen diagram by the increase of nitrophilous and other anthropogenic taxa, as well as coprophilous NPP indicators (*Sordaria*, *Cercophora* and *Sporormiella*) that suggest nearby pastures (López-Merino et al., 2009). Scots pine has not been able to

naturally recolonize the valley since then. Scrub became the dominant vegetation formation, with the exception of 20th-century Scots pine plantations between 1450 and 1500 m a.s.l. in nearby valleys such as Barbellido. Thus, the current open landscape of the summit (or high plateau) of Valle de las Pozas has been present for 800 years.

4.1.3. Northern Apennines (Monte Cimone and Corno alle Scale)

From the onset of the Holocene to the first part of the Middle Holocene (Fig. 4), *Abies alba* woodland accompanied with *Picea abies* (L.) H. Karst, *Quercus* sp., *Tilia* sp., *Fraxinus* sp. and *Acer* sp. dominated the landscape up to 1800 m (Vescovi et al., 2010a). This is supported by a fragment of ash dated to 8728–8592 cal. BP (MtC-a) at 1650 m a.s.l., that is, 150 m higher than today (Benatti et al., 2019; Pignatti et al., 2017, 2019). Today, above the beech woodland there is grassland composed of *Trifolium thalii* Vill., *Nardus stricta*, and *Brachypodium genuense*, and mountain heathland composed of *Vaccinium myrtillus* and *V. uliginosum* subsp. *uliginosum* (Alessandrini et al., 2003; Tomaselli et al., 1996).

A charcoal fragment of Ericaceae (7957–7709 cal. yr. BC) from Corno alle Scale at 1860 m a.s.l., and the lack of tree charcoals in that sampling pit, suggest that during the Early Holocene, the ridge was already open and without forest cover.

Pollen data from the northern Apennines (Branch & Marini, 2014; Vescovi et al., 2010a, 2010b; Watson, 1996) demonstrate that in the Middle Holocene, *Abies alba* decreased and *Fagus* increased around 4500 cal. yr. BC. The fir-dominated woodland was replaced by a beech-oak woodland accompanied by fir. Archeological surveys have detected several open spaces that are thought to have been cleared by pastoral societies (Cardarelli & Malnati 2006; Cevasco, 2012; Stagno, 2016).

Soil charcoal data (Benatti et al., 2019) confirm this ancient woodland composition during the Late Holocene, characterized by *Fagus sylvatica* (323–205 cal. yr. BC, 215–99 cal. yr. BC, 1221–1278 cal. yr. AD, and 1241–1297 cal. yr. AD) dominance, with the presence of *Fraxinus* sp. (1131–1008 cal. yr. BC) and *Abies alba* (428–498 cal. yr. AD, 532–600 cal. yr. AD, 1063–1154 cal. yr. AD, 1241–1280 cal. yr. AD), the latter only identified on Monte Cimone. *A. alba* is currently known only as cultivated and naturalized by plantations (Alessandrini et al. 2010), and it was not detected near our sampling points. From the end of the Iron Age to the Late Middle Ages, the timberlines on both Monte Cimone and Corno alle Scale decreased and oscillated around 1750 m a.s.l. The presence of *Laburnum* sp. (dated to 3 cal. yr. BC–74 cal. yr. AD, Roman period) on Monte Cimone, and Ericaceae (dated to 1182–1269 cal. yr. AD, Late Middle Ages) on Corno alle Scale close to the timberline confirms the clearance episodes. The latter can be linked to pastoral activities, with the use of fire to create open spaces, during both the Roman period (Geri, 1992; Giordani, 2006) and the Middle Ages (a key period for large-scale European deforestation through agropastoral activities; Bal et al., 2015), with evidence of the importance of sheep breeding in the highest belts of the Apennines (Cremaschi and Dall'Aglio, 1988). This open woodland system seems to have been favorable to *Taxus baccata*, which has been identified close to the timberline (1746 m) and dated to 660–717 cal. yr. AD (Benatti et al., 2019). Linares (2013) suggested that open-canopy stands have a higher relative proportion of healthy *Taxus baccata* trees than denser stands, as there is less competition from crowding tree species (Dhar et al., 2007; Iszkulo et al., 2005; Ruprecht et al., 2010). Today, the yew is a relict species with a fragmented distribution. In the province of Modena, there are only two spots of natural populations (15 km from our study areas), which are protected by parks (Alessandrini et al. 2010). In Europe, yew populations have quantitatively decreased over the past 6000–4000 years for many reasons, including grazing, woodland practices, and competition (Dhar et al., 2007; Linares 2013; Piovesan et al., 2009; Ruprecht et al., 2010; Thomas & Polwart, 2003; Tittensor, 1980).

From the Late Middle Ages to the current period, the timberline receded by 46 m on Monte Cimone and by 150 m on Corno alle Scale, to below the ancient timberlines (Benatti et al., 2019). Beyond 1600 m a.s.l. on Corno alle Scale, and beyond 1740 m a.s.l. on Monte Cimone,

shrubs (*Ericaceae* 10 ± 25 Contemporary Age; Benatti et al., 2019) became prevalent in soil charcoal data, suggesting that these areas were used as pasture over a relatively long period. On Monte Cimone and Corno alle Scale, just below the current timberline, between 1500 and 1700 m a.s.l., 71 ancient charcoal platforms were discovered (Benatti et al., 2018), 48 of which were analyzed (charcoal identification and radiocarbon dated). Results reinforced the dominance of a beech woodland system from 1616 to 1948 cal. yr. AD. One date confirmed the functioning of a charcoal platform on Corno alle Scale around 1390–1477 cal. yr. AD. In our study areas, the presence of charcoal platforms just below the current timberline suggest that this ecotone did not recede between the 15th and 20th centuries.

4.2. *Abies alba*, *Taxus baccata* and *Pinus gr. sylvestris*, three rare or relict tree taxa in the three study areas: Update on their distribution during the Holocene

Natural and human-induced fires have played an important role on Mediterranean mountains, possibly shaping the present landscape, owing to the disappearance of less fire-tolerant taxa such as *Pinus gr. sylvestris* (García-Álvarez et al., 2017), *Abies alba* (Bal et al., 2015, Benatti et al., 2019), and *Taxus baccata* (Benatti et al., 2019). There is variable documentation of the paleo-distribution of these three taxa: *Abies alba* and *Pinus gr. sylvestris* are very well documented on the European scale by pollen data in databases such as the European Pollen Database (Aix-Marseille University, Pytheas Institute, and IMBE) and on the pyrenean scale by the Paleopyr Lerigoleur et al., 2015 Database (GEODE Laboratory, Toulouse University). By contrast, none of the Neotoma databases, including the European Pollen Database, provide any information about the paleo-presence of *Taxus baccata* in the Pyrenees, and data are incomplete for the northern Apennines. Our study confirmed that high spatial resolution paleo-data make it possible to identify the presence of a specific taxon, and in particular its altitudinal dynamics—an essential parameter in mountainous areas. Pedaanthracology allows for just such spatial resolution (detailed above, Fig. 5). The study of past ecology and the dynamics of taxa at high resolution is

essential if we are to explore new ways in which Mediterranean woodland could respond to global warming, which is currently accelerating its demise. For example, Tinner et al. (2013) showed how paleoecological data can potentially improve future forest dynamics in response to global change. Anthropogenic disturbance (in the form of fire or grazing) may well have a critical impact on *Abies alba*, even though it is theoretically able to survive with precipitation of about 800 mm per year.

4.2.1. *Pinus sylvestris*

Pinus sylvestris is widespread throughout Eurasia, and its westernmost natural continental distribution limit lies on the northern slopes of the Central Iberian System (Sierra de Gredos). However, it has only a meager presence there, represented solely by the pine forests of Valle de Iruelas, Navalacruz-Navarredondilla, Hoyocasero and Navarredonda de Gredos-Hoyos del Espino, all of which are located in the eastern part of the range, between 1230 and 1500 m. There are a number of sites at high altitudes (e.g., Dorado-Valiño et al., 2001; Franco Múgica et al., 1997; López-Merino et al., 2009) that show a sharp and synchronous change, with spreading grasslands and declining forests (mainly *Pinus gr. sylvestris*) since the Bronze Age, but trees may experience recovery, and fire is not massively found in the micro- and macrocharcoal records. Taken together, data from pedoanthracology (García-Álvarez et al., 2017) and analyses of 33 woods and 9 cones of *Pinus gr. sylvestris* found at 1750–1840 m a.s.l. within a 10-km radius of the study area (Rubiales et al., 2007; Rubiales & Genova, 2015) confirm the presence of a *Pinus gr. sylvestris* woodland limit at around 1700–1800 m a.s.l. in Valle de las Pozas, where pine is absent from the current landscape. The EUFGIS information system for forest genetic resources listed Scots pine as a conserved forest genetic resource not far from the collection site, in Hoyos del Espino at 1513 m.

Thus, the scarcity of *Pinus sylvestris* in the highlands of northern Gredos (Fig. 3B and 5) is related to a long tradition of pastoralism in this mountainous area (asylvatic) that is still maintained today and plays an important role in these landscapes. A turning point came with the repopulation of the Gredos range from 1100 cal. yr. AD onwards

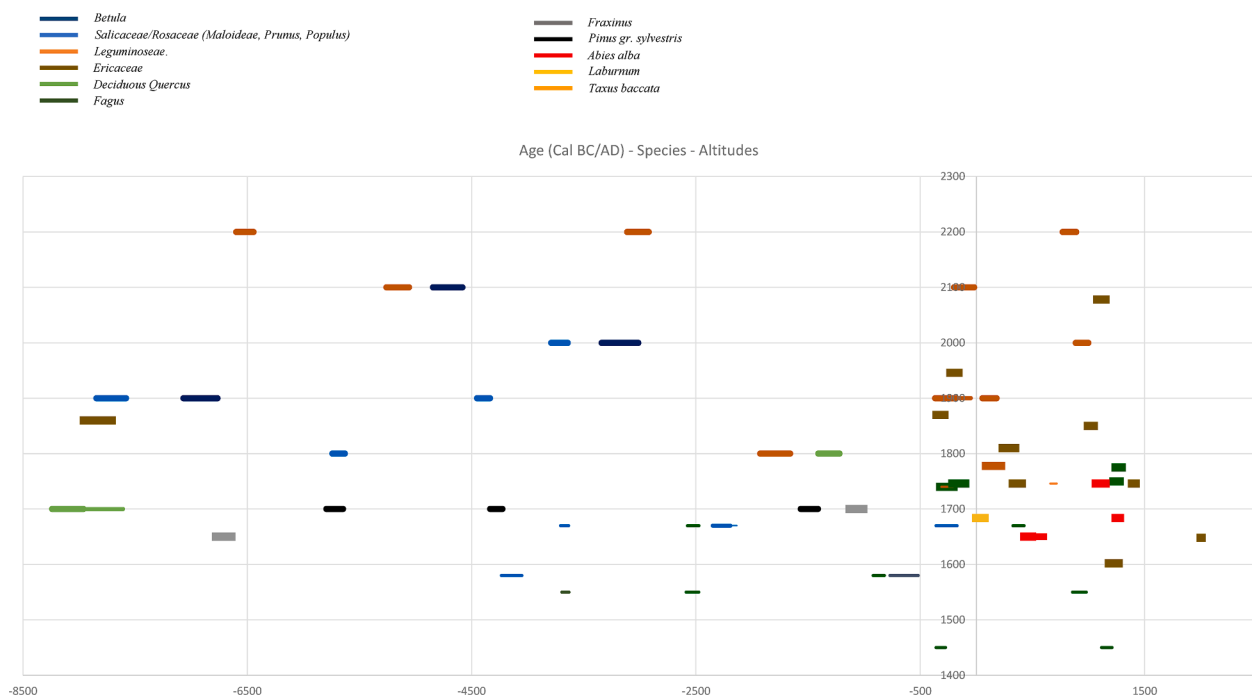


Fig. 5. Palaeo-altitudinal distributions of identified taxa at the scale of the 3 sites (Gredos, Lozère and Apennines) during Holocene. Age (Cal BC/AD – species – altitudes (m asl)). Each color correspond to an identified species and the line form correspond to the geographical site (thick line with round tips: Valle de Las Pozas; thin line with round tips: Mont Lozère; thick line with square tips: Apennines (Corno Alle Scale and Monte Cimone)).

(Monsalvo, 2003), bringing a clear increase in agropastoral activities and the rural economy. Abundant historical information from this period onwards reinforces this idea. A powerful organization (Honrado Concejo de la Mesta) that protected livestock owners and their animals was incorporated in the Crown of Castile during the 13th century. So-called *transhumance* involved sheep that were generally owned in Gredos and further north (where they had their summer pastures), migrating to and from winter pastures as far away as southern Extremadura. The relation between rapid deforestation and the development of large wool markets in Europe is found in other mountain regions of southern Europe, such as the Pyrenees. Taken together, sources such as written documents, geomorphological studies and paleoecological information (e.g., García-Ruiz et al., 2020) show that struggles for control over summer grasslands were related to a rapid decline in woodland and a steep increase in sedimentation rates following deforestation, suggesting intense erosion. For example, rapid deforestation of the Pyrenean subalpine belt from the Middle Ages onwards caused a sudden increase in geomorphic processes leading to hill slope instability. Historical soil erosion, gully, rilling, and shallow landslides have regularly been described (e.g., García-Ruiz et al., 2010; Montserrat, 1992), and landslides are mainly detected on deforested, grassland-covered hill slopes, not in adjacent forested areas. This makes deforestation the major contributing factor for soil erosion, through changes in soil hydrology, reducing root cohesion and consequently soil strength in critical conditions coinciding with snowmelt and large rainstorms (Beguería, 2006). Fire has long been used to form and maintain high altitude meadows to avoid shrub recolonization. A decrease in pastoral pressure and changes in the types and methods of herd exploitation has driven scrubland expansion and dynamics. Today, conserving the few remaining natural arboreal remnants (mainly of *Pinus sylvestris*, *P. nigra*) is a priority for central and regional government, in this mountain marked by a dry summer period and strong thermal oscillation, in a global context of global warming. Plans for managing the heritage landscape and trees (here *Pinus sylvestris*) and making the most of these assets are key in local and societal terms in Sierra de Gredos, particularly its northern part, an area with a low population whose main economic activity is cattle breeding, with very little tourism.

4.2.2. *Abies alba*

Like yew, *Abies alba* has a much less widespread distribution today (EUFORGEN database, European Forest Genetic Resources Program) than in the past. An important element of the European forest landscape, silver fir has been an indispensable resource for societies in the past, depending on the era: cleared, used for carpentry and shipbuilding or as supplementary fodder (Ducci et al., 1998). Fir is very sensitive to fire and grazing (Bernetti, 1995; Morales-Molino et al., 2021; San-Miguel-Ayanz et al., 2016; Tinner et al., 2013). All these uses explain its slow decline. It appears to have been more resistant to warm and dry conditions in the past than it is today (Morales-Molino et al., 2021). Major programs such as EUFORGEN-EUFGIS take *Abies alba* into account in their projects for the conservation and sustainable use of forest genetic resources in Europe. The EUFGIS information system lists the locations where the forest genetic resource is conserved. In the northern Apennines, the fir's forest genetic reserve is in *Abetone* (*bee fir* in Italian), which lies within a forest massif of 584 ha distributed between 1190 m and 1530 m of altitude. Less than 10 km away, on Monte Cimone, *Abies alba* is absent from the current plant assemblage, but pedoanthracological data (Benatti et al., 2019) has revealed low occurrences at the end of the Roman–early medieval period and at the end of the Middle Ages at 1746 m, that is, at the ancient limit of the forest, higher than its current one (Figs. 3 and 4). It has also been identified on Monte Cusna (northern Apennines, 25 km from our study areas), at the same elevation and during the Late Holocene (Compostella et al., 2013). According to Morales-Molino et al. (2021), *Abies alba* continued to decline as human activities and fire occurrences increased, finally disappearing in the

northern Apennines around 1000 and 500 cal. yr. BP. *Abies alba* is currently known only as cultivated and naturalized by plantations (Alessandrini et al. 2010), and was not detected near our sampling points. In the mid-19th century, the beech climate zone underwent reforestation with conifers, with the aim of safeguarding the soil in areas degraded by erosion. Reforestation was carried out with native species of the study area such as *Abies alba* and *Picea abies*, as well as other species like *Pinus nigra*, *P. mugo* Turra, and *Larix decidua* Mill. (Alessandrini et al., 2003; Tomaselli et al., 1996). The reforestation period coincided with the apogee of sheep and goat livestock farming in our study areas (Benatti et al., 2019). According to Watson (1996) and Vescovi et al. (2010a), *Abies alba* plays a markedly subordinate role today. On Mont Lozère, the beech woodland located near the study area is a monospecific forest with *Fagus sylvatica* trees with narrow twisted trunks and few occurrences of *A. alba*. According to Beaulieu and Pons (1979), Reille (1990), Guilliot (2001), Pulido (2006) and Servera-Vives et al. (2014), *Abies* began to decline around 450 cal. yr. AD, disappearing around 1300 cal. yr. AD. During the Early Middle Ages, woodland deforestation was linked to the development of agropastoral activities, which have also been reported in other mountain areas of the Massif Central, such as Cantal, Aubrac, and Margeride (Beaulieu and Pons, 1979; Faure, 2012; Reille, 1988; Servelle & Galop, 2006; Surmely et al., 2009). In the western part of Mont Lozère, in Countrasts, changes in land use occurred as the result of a local decline in mining and metallurgy (Servera-Vives et al., 2014). Historical studies indicate that transhumant flocks crossing Mont Lozère (Margeride *draille* in western part, and Gévaudan *draille* in eastern and central parts) from the littoral plain of Languedoc intensified from the 11th century onwards (Pulido, 2006). It has also been suggested that long-distance livestock movements took place before the 10th century (Durand, 2003).

4.2.3. *Taxus baccata*

The yew (*Taxus baccata*), a fragile species that is not very competitive when other conifers encroach, has been reduced to the state of vestige in several zones of Europe. Its distribution has increased as a result of isolated plantations such as ornamental trees, but natural patches are relatively rare, so this species is now protected (EUFORGEN-EUFGIS). Paradoxically, few data are available on its paleo-distribution. The Neotoma databases, including the European Pollen Database, do not provide any information about the paleo-presence of *Taxus baccata* in the Pyrenees, and are incomplete for the northern Apennines. In 2014, J.-L. De Beaulieu initiated a project to produce maps on a European scale from paleo-distribution data of common yew, based on the European Pollen Database and available archeological data (wood charcoal, macro-remains). Unfortunately, the review paper on *Taxus baccata* is still not available, nor are the paleo-distribution maps. On a larger scale, that of the Pyrenees, yew is present in the forest between Sorède and Les Albères, and isolated individuals are scattered on limestone soil from the Ariège Pyrenees to the Atlantic Pyrenees. In the Spanish Pyrenees, *Taxus baccata* is rarely dominant, but it is very frequent (https://coleccion.es/rjb.csic.es/#card.php?id_name=124986/) as an accompanying species of beech and fir forests (because of its shade tolerance). On the Spanish Pyrenean side, it is found in the form of a stand in the Irati forest. Archeo-anthracological data indicate its presence in the Atlantic Pyrenees on the Aneu mountain pasture (Bal, unpublished) between 1400 and 2000 m during the Late Bronze Age, mixed with pectin fir and juniper accompanying beech, the dominant taxon of the assemblages. Several fossil spots for common yew have been recorded in Haut-Videssos (Freychinède Forest, Bernadouze) and Haut-Couserans (Aulus-les-Bains, Port de Saleix), on a transect ranging from 1400 to 1600 m (Py et al., 2020). This species also has a very fragmented distribution in the northern Apennines. In the province of Modena, it is found solely as a remnant in two natural stands (Alessandrini et al., 2010) located 15 km from Monte Cimone, where *Taxus baccata* is now absent from the forest. Benatti (2018) demonstrated its presence in Late Roman/early medieval times at the ancient timberline at 1746 m

altitude (i.e., 150 m higher than its current distribution). There are few data on the paleo-distribution of yew in northern Italy, with no record of it in pollen diagrams for the most recent phases of the area in question (Watson, 1996; Vescovi et al., 2010a, 2010b). Yew has only been reported for the Subboreal (Copper Age and Bronze Age), in a pollen study carried out during the geoarchaeological excavation of the Mesolithic site of Monte Bagioletto, located 25 km from Monte Cimone (Cremaschi et al., 1984). Thus, the few Holocene studies conducted so far show that this species has a long history, and had a much larger geographical area in the past than it does now. The strong agro-sylvopastoral pressure exerted on the mountainous massifs since the Neolithic period partly explains the steep decline and even disappearance of this particular taxon, which sometimes inspired fear in societies of the past, on account of its toxicity, and sometimes constituted an asset on account of its usefulness as fodder or the quality of its wood.

5. Concluding remarks: What does the comparison of Mediterranean mountains tell us?

Our comparison of the several natural and human processes that shaped the highlands of these pastoral Mediterranean mountains revealed several interesting facts.

First, fire episodes occurred much earlier (10,000 cal. yr BP), and with greater frequency, in Valle de la Pozas at the beginning of the Holocene (Fig. 4), where the woodland landscape was composed of *Pinus* gr. *Sylvestris*, accompanied by deciduous *Quercus* and *Maloideae*, than in the northern Apennines and on Mont Lozère. There was high fire activity in the southwestern Mediterranean region during the Early Holocene (Bal et al., 2011; Carrión et al., 2003, 2012; Tinner et al., 2013; Vannièr et al., 2011). In addition, fire event ancientness in these three mountain areas followed a geographical gradient from west to east (Figs. 1 and 5).

Second, data highlight the importance of slow changes to the landscape brought about by several human practices (agropastoralism, charcoal production, mining, etc.) and it is heavily supported by the findings of Rendu (2003), Bal (2006), Bal et al. (2010), Palet et al. (2013) and, more recently, García-Álvarez et al. (2017), Benatti et al. (2018, 2019) and Garcia-Ruiz et al. (2020) in their comparative study of deforestation in the subalpine belt of the central Spanish Pyrenees and transhumance.

Third, concerning the altitudinal structure of the vegetation landscape, changes in vegetation have shifted differently in the northern Apennines than in the other western Mediterranean mountain areas presented in this manuscript. The vegetation in the Apennines seem to have been characterized by a more stable plant landscape throughout the Late Holocene that contrasts strongly with the large displacements (from 250 to 400 m) identified on Mont Lozère, and more particularly in Valle de las Pozas and other European mountain areas (García-Ruiz et al., 2020), including the Alps (Ali et al., 2005; Badino et al., 2018; Carnelli et al., 2004; Talon et al., 1998; Talon, 2010) and the Pyrenees (Bal et al., 2011; Cunill et al., 2012).

Fourth and last, the establishment of the current beech or beech-oak woodland, following the decline of *Abies*, in the northern Apennines (Branch, 2013; Morales-Molino et al., 2021; Vescovi et al., 2010a,) and on Mont Lozère appears to have taken place relatively recently (i.e., 500–600 years ago). This is in line with the hypothesis defended by González Sampéris et al. (2019) who emphasizes that the establishment of the pastoral cultural landscape of the highlands did not occur in the Central Pyrenees (NE Iberia) until 700 years ago (1300 cal. yr. AD).

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Author Contributions

M.-C. B. conceived and designed the study; S. G.-A., A. B. and M.-C. B. produced the paleoecological data, supervised by M.-C. B., A.-M. M., G. B. and J.-M. R.; M.-C. B. led the writing of the manuscript, with contributions of the rest of co-authors; all authors approved the final version of the manuscript.

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