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ORIGINAL ARTICLE

Environmental dynamics of the western European Mediterranean landscape during the Pleistocene to Holocene transition

Sebastián Pérez-Díaz[1] · Mónica Ruiz-Alonso[2] · José Antonio López-Sáez[3] · Alfonso Alday[4] · Ana Cava-Almuzara[4]

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Abstract

A strategic aim of research into climate change in the distant past is to respond to the contemporary challenges of global warming at the present. Determining the processes of adaptation by ecosystems to these challenges, evaluating the effects of environmental change on human communities and finding which regions are more or less sensitive to climate change are among the key topics of environmental research today. Throughout the past millennia, some of the most abrupt environmental upheavals were the successive phases of the Late Pleistocene to Early Holocene transition, ranging from cold and dry to mild and damp climates. These phases differed in intensity and effects across all regions of the planet. In this paper, the long-term changes to both vegetation cover and human settlements within the upper Ebro river basin (northern Iberia, western Mediterranean) are shown by new palaeoenvironmental sequences from two archaeological sites dated between ca. 14,000 and 8,000 cal BP, which serve as proxy evidence for past vegetation cover. Summed radiocarbon probability distributions of other nearby archaeological sites were also used to study the dynamics of land occupation throughout the period. The main findings point to vegetation changes changing from the dominance of open landscapes with pines and deciduous woods during the late Pleistocene to the dominance of deciduous forest cover with few areas with open landscapes and far fewer pinewoods during the early Holocene.

Keywords Palaeoenvironment · Archaeological site · Rock shelter · Late Pleistocene · Early Holocene · Northern Iberian Peninsula

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✉ Sebastián Pérez-Díaz
sebastian.perezdiaz@unican.es

1 Departamento de Geografía, Urbanismo y Ordenación del Territorio, Canales y Puertos, Universidad de Cantabria. E.T.S. de Ingenieros de Caminos, Avenida de los Castros, 44, Santander 39005, Spain

2 Departamento de Botánica, Universidad de Granada, Campus Universitario de La Cartuja, Granada 18071, Spain

3 Instituto de Historia (IH), Centro de Ciencias Humanas y Sociales (CCHS), Consejo Superior de Investigaciones Científicas, C/ Albasanz 26-28, Madrid 28037, Spain

4 Departamento de Geografía, Prehistoria y Arqueología, Laboratorio de Evolución Humana, Universidad del País Vasco - Euskal Herriko Unibertsitatea (UPV-EHU), Unidad de Investigación Consolidada de la Junta de Castilla y León (UIC) 287, Universidad de Burgos, Burgos, Spain

Introduction

Global warming is a very topical issue, with clearly visible global impacts, including an increasing likelihood of extreme weather events, rising sea levels, receding glaciers and polar ice sheets, bleached coral reefs, changing patterns of wildlife migration and health, and increasingly virulent disease vectors and frequencies of localized epidemics, etc. (Wang and Chameides 2005; Ostberg et al. 2013; IPCC 2021; Santos et al. 2022).

Western Mediterranean Europe is one region where the effects of global warming appear to be intensifying. Vulnerable to climate fluctuations, it is already being affected, due to its geographical location and certain socioeconomic features. The especially serious consequences of climate change can reduce water resources and cause coastal degradation, the loss of biological diversity and natural ecosystems, and increase soil erosion processes associated with extreme climatic events such as flooding, forest fires and heat waves (Brochier and Ramieri 2001; Root et al. 2003; Almodóvar et al. 2012; Cramer et al. 2018). The response to these climate risks is still uncertain. However, a valuable theoretical approach is to look to the past and to analyse the palaeoecological records of sediments from both natural and archaeological deposits (Carrión and Leroy 2010; Mercury et al. 2013a; Mercury 2014). Such studies can further our understanding of likely environmental dynamics after cold or dry phases, depending on their severity and intensity, and can help us to evaluate whether the ecosystem has enough resilience to recover its original equilibrium over time or, after reaching a point of no return, changes beyond recognition (Carrión et al. 2010; González-Sampériz et al. 2010; Pérez-Díaz et al. 2015).

The ecosystems of the western Mediterranean have historically undergone both episodic disturbances such as from climatic fluctuations or natural wildfires, and long term ones such as soil degradation. Bearing in mind that both types of disturbance are responsible for the modern state of Mediterranean vegetation, analyses of their interactions from archaeology can deepen our understanding of past human and climatic ecosystem dynamics.

One of the most interesting areas of the western Mediterranean is the Iberian Peninsula, where the subtropical climatic system of northern Africa interacts with the mid-latitude North Atlantic system. Both systems influence the variability of the climate and have determined the unique environmental conditions of the landscape, biota, and development of human activity within this region (Martín-Puertas et al. 2010). These climatic interactions result in a great variety of biogeographical regions, endowing the region with one of the world's richest floras and biodiversities (Médail and Quézel 1997; Myers et al. 2000). The Iberian Peninsula therefore constitutes an exceptional "natural laboratory", due to its sensitivity to abrupt climatic changes, even of small magnitude, which have had far-reaching impacts, both on the use of natural resources and the history of vegetation, which have affected human economic activities and settlement models (Kohler et al. 2010). This sensitivity is a characteristic that results from geographical, environmental and historical processes that have determined the coexistence of taxa from very different origins. As a transitional zone between central European temperate forests and arid or semi-arid parts of North Africa, this region shares many taxa that are characteristic of both biomes (Tzedakis et al. 2002).

The Iberian Peninsula presents sharp geographical contrasts with its distinct mountain systems, high mesetas (plateaus) and broad river valleys. The sensitivity of each of these regions to climate changes is still an unresolved issue. There are numerous palaeoenvironmental studies on mountainous areas such as the Cantabrian mountains (Allen et al. 1996; López-Sáez et al. 2006; Moreno et al. 2011), the Pyrenees (González-Sampériz et al. 2006; Morellón et al. 2009; Pérez-Obiol et al. 2012; Galop et al. 2013), the mountains of the Spanish Central System (López-Sáez et al. 2010, 2020; Rubiales et al. 2010; Robles-López et al. 2020), inland continental areas (Vegas et al. 2010; Aranbarri et al. 2014; Morales-Molino et al. 2020), etc. However, there are still many regions that have been insufficiently studied, due to the absence or scarcity of natural deposits. In this study, the palaeoenvironmental characteristics of the upper Ebro river basin lowlands are approached through their archaeological records.

The palaeoenvironment, the outcome of interaction between humankind and nature, can be seen as a cultural construction that is considered within both an historical and an archaeological dimension. Its basic structure revolves around two scales, spatial and temporal, that delimit the pace and the nature of the process. From a historical perspective, if this type of dimensional approach is to function, then the relationship between humans and their environment must be studied with multidisciplinary research where the grounding of each discipline implies such dissimilar mind-sets that the presentation of common hypotheses and problems becomes especially challenging. Consequently, palaeoenvironmental studies represent an excellent opportunity for exploring human activities, their variability and their causes. On the contrary, features of the landscape that have not been sufficiently well described from other perspectives can be inferred or explained from the archaeological analysis of the ancient environment that reflect the decisions and strategies of prehistoric human groups for its uses. Given the complexity of cultural landscapes, it is generally recognized that a multidisciplinary, comprehensive approach will ensure that all issues may be addressed in depth (Lillios et al. 2016).

From among all the climatic fluctuations of the past, the climatic changes that defined the transition from the Late Pleistocene to the Early Holocene were some of the most abrupt events. In general terms, a reduction of the cold climate at the end of the last glacial cycle in Eurasia affected the whole of Europe, varying in intensity and duration across all regions. These climatic fluctuations caused human communities to rethink their models of organization and interaction with the environment. From an archaeological point of view, new attitudes, also rooted in internal social processes, inspired the creation of particular types of artefacts by which the various cultures are defined (techno-complexes) from between the end of the Palaeolithic (in the region of study, the Magdalenian) and the beginning of the Mesolithic (the Azilian and later the Sauveterrian), with their characteristic microlaminate stone tools. In order to understand these processes well, the relationship between climate change and cultural adaptations must be firmly situated at the centre of the debate, by understanding that humans can change the landscape and they also have to adapt themselves to general climatic conditions (Riera 1995; Sadori et al. 2013; Silva-Sánchez 2014). The progressive increase in temperatures and precipitation created environmental conditions with new opportunities such as an increase in biomass from plant growth, use of coastal areas, access to locations at higher altitudes, etc. In contrast to the traditional view, according to which human groups tried to adapt to new situations, a new scenario can be proposed. Paradoxically, some of the new decisions negatively affected the archaeological record, as climatic improvements led to the abandonment of cave dwellings, with a considerable decline in the prehistoric record given the poor preservation of open-air sites.

In this paper, we present new palaeoenvironmental data recovered from pollen, spores, non-pollen palynomorphs (NPPs) and charcoal retrieved from the archaeological sites of Martinarri and Socuevas and contrast them with other available palaeoenvironmental data. Both sites are located in the upper Ebro river basin in northern Iberia, a region understood as an environmental crossroads. Even though it forms part of the Mediterranean biogeographical region, its mountainous nature and closeness to the Bay of Biscay make it a transitional area, with a flora that is characteristic of both Eurosiberian and Mediterranean regions (Rivas-Martínez 1987; Aseginolaza et al. 1996). This environmental interest can be transferred to the past. There have been many archaeological studies within the area, yet few palaeoenvironmental results from deposits that offer reliable chronologies, given the scarcity of suitable natural deposits.

Both the Martinarri and Socuevas sites were occupied from the end of the Late Pleistocene to the Early Holocene. Our main objectives are (1) to analyse the evolution of the vegetation and landscape during this period through pollen and wood charcoal data; (2) to determine the climatic characteristics and (3) to evaluate any possible consequences on human settlement patterns. To do so, we analysed pollen, spores, non-pollen palynomorphs, wood charcoal and regional human occupation from ca. 14,000–8,000 cal BP.

Study area and archaeological background

Martinarri and Socuevas, the two archaeological sites presented in this paper, are located in northern Iberia (Fig. 1). Although within the Mediterranean biogeographical region, their proximity to the Bay of Biscay and the characteristics of the relief, generally on an east-west alignment, forming a mountain range running along the coastline, give the climate characteristics of both Atlantic and Mediterranean environments. Local lowland vegetation cover consists of oak woods with *Quercus robur* L. (pedunculate oak), *Q. pyrenaica* Willd. (Pyrenean oak) and small woods of *Q. faginea* Lam. (Portuguese oak), together with areas of *Q. ilex* L. (holm oak) and *Pinus sylvestris* L. (Scots pine) (Aseginolaza et al. 1996).

The Martinarri archaeological site (UTM 30T, 538840, 4723191, 780 m a.s.l., near the village of Obécuri, Burgos province) was discovered in 2007. Its south-facing rock shelter is almost 3 m to the roof and around 15 m long and 3–4 m in breadth (Fig. 1). Located in an area of rolling hills where streams and rivulets are interspersed, the environment and soils around Martinarri are today covered with dense deciduous forests with *Quercus pyrenaica* Willd. (Pyrenean oak), *Betula* sp. (birch), *Ilex aquifolium* (holly), *Acer* sp. (maple), *Fagus sylvatica* (beech) and impenetrable thickets of shrubs. The deposits in the rock shelter consisted of the surface level (A), a weak layer of humus and sands with some modern materials (Alday et al. 2012) that ruled it out for palaeoenvironmental study, and four archaeological levels (Table 1; Fig. 2) which have been dated from the end of the Upper Palaeolithic to the final Mesolithic, from ca. 13,500 to 8,000 cal BP (Table 2).

The Socuevas archaeological site (UTM 30T, 507652.45, 4739855.84, 540 m, near the town of Pobes, Álava province) is a rock shelter that must have originally covered around 80 m^2, before most of its overhead ceiling collapsed (Fig. 1). F. Muga discovered its location in the middle of the Bayas river basin when observing archaeological material on the surface. In 1982, A. Baldeón (1984) completed a first archaeological assessment. Later on, A. Alday and A. Cava-Almuzara conducted field work between 2009 and 2012 that defined the archaeological site (Alday and Cava-Almuzara 2010, 2011, 2012, 2013). From an environmental point of view, its position is important, with easy access to the river Bayas and the surrounding lowlands of its valley and also to mountainous areas with different degrees of insolation on the valley slopes which determine the vegetation there. A diverse combination of animal and plant resources may be expected in its vicinity, in any period of non-extreme climatic. Today the valley plains are extensively cultivated without encroaching upon the sprawling woody vegetation along the river bank and the valley slopes. There are, therefore, notable differences between the local environments of Martinarri and of Socuevas. Archaeological excavations have identified eight archaeological levels in the two archaeological profiles G6/He and D10, but preservation has only been good enough in six of them (levels II-VII) for archaeobotanical analysis (Table 1; Fig. 2). Radiocarbon dates indicates prehistoric occupation of the site, with date ranges from the end of the Upper Palaeolithic to the late Mesolithic, from ca. 14,000 to 8,300 cal BP (Table 2).

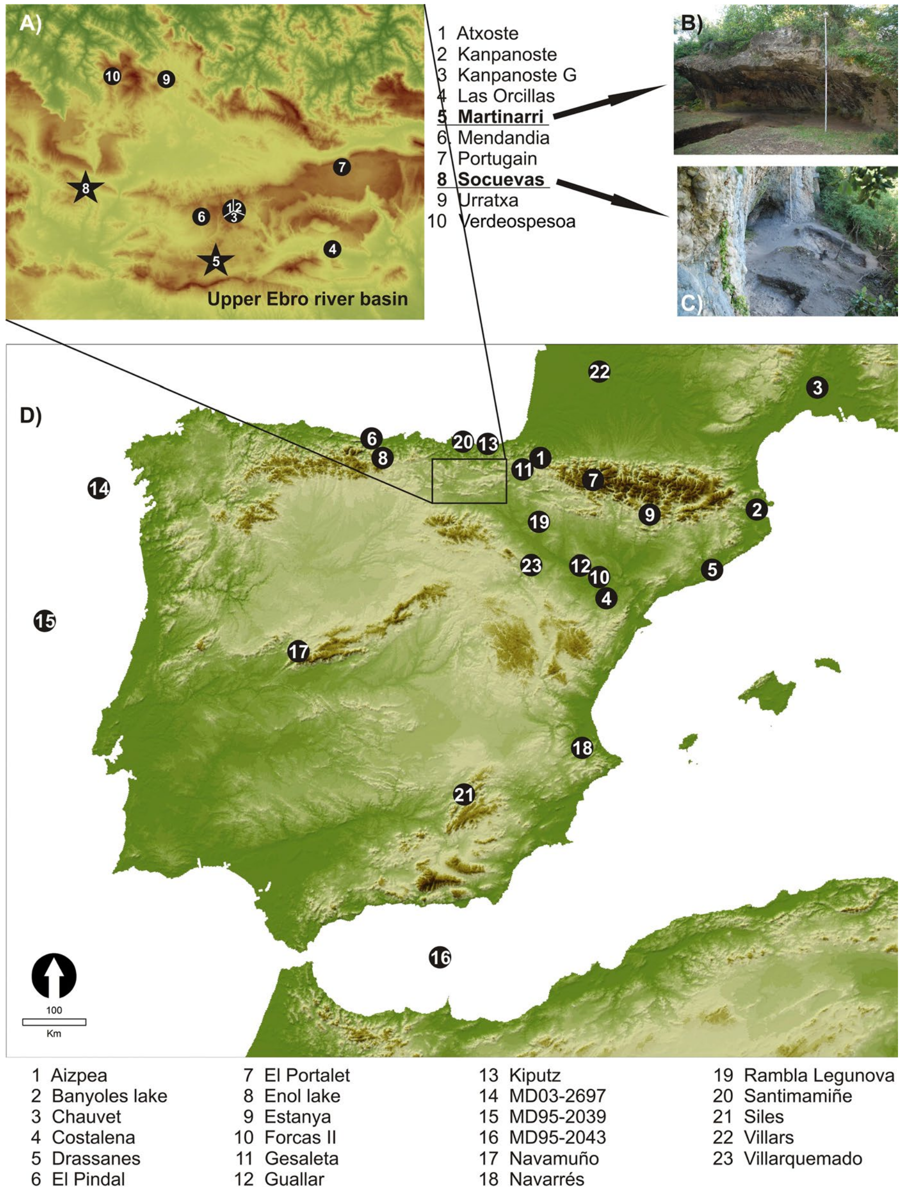

Fig. 1 Location of the sites mentioned in the text. **A**, Sites located in the upper Ebro river basin; **B**, Martinarri archaeological site; **C**, Socuevas archaeological site; **D**, other sites discussed in the text

Materials and methods

Pollen analysis

In all, 18 palynological samples were analysed, nine from the east and another nine from the south stratigraphic profiles at Martinarri (Fig. 2). Samples from the upper levels were discarded before analysis, given the likelihood of recent human activity having affected this level. From Socuevas, 15 samples were used for the pollen analysis from Sector 2 profiles G6/H6 and D10 (Table 2). Samples from the upper part of level V (profile G6/H6) were discarded, following confirmation of recent human activity (Fig. 2).

All samples were chemically treated with HCl, KOH and HF, as described in Moore et al. (1991), and underwent density separation using Thoulet solution (Goeury and de Beaulieu 1979). Pollen grains were identified with the help of various keys and pollen atlases, such as Fægri and Iversen (1989), Moore et al. (1991) and Reille (1992), and the reference collection of the Archaeobiology Laboratory of CSIC (Madrid, Spain). Non-pollen palynomorphs (NPPs) were identified according to van Geel (1978, 2001), van Geel and Aptroot (2006) and van Geel et al. (1980, 1989, 2003). Pollen counts of up to 300 grains of total land pollen per sample were identified and counted (Figs. 3 and 4). *Aster* type, Cichorioideae and Cardueae were excluded from the sums because they are insect pollinated (Carrión 1992). The pollen diagrams were plotted using TGview (Figs. 3 and 4; Grimm 2004).

Table 1 Main characteristics of the archaeological levels of Martinarri and Socuevas on which archaeobotanical studies have been carried out, based on Alday et al. (2012)d nchez-López et al. (2018)

Site/level	Thickness (cm)	Sediment description	Archaeological remains
Martinarri			
B-100	15	Very compact sandy texture, with roots and almost without any stones	15 small holes were identified, perhaps serving as postholes for a shelter structure. At this level, 500 lithic (stone) fragments mixed in Mesolithic soil layers were identified
B1-101	23	Light brown sandy sediment with clast, block and quartz	5,000 lithic fragments, showing the abundance of hunting equipment, scrapers and some matrices demonstrating the stoneworking carried out on site, and 6,000 faunal remains from a Mesolithic settlement
C-102	20	Light brown sediments	5,200 lithic remains, many retouched to serve as armour, scrapers, burins, notches, denticulates and perforators, while other remains are linked to carving operations and faunal remains (ca. 3,370) corresponding with the Laminar Mesolithic
D-103	20	Granular matrix sediments of gravels and sandstones, with yellowish, greyish and reddish colour depending on the area and less compact than the one above	4,000 lithic fragments (hunting equipment is the most abundant among the retouched objects) and 3,000 faunal remains have been identified corresponding to the Upper Magdalenian technocomplex of artefact types. Presence of a worked stone mortar or mill for processing vegetable products
Socuevas			
II	20	Light coloured sediment, with abundant clasts within its lower part	2,000 fragmented faunal remains have been collected from that level and a hearth and Mesolithic tools have been found
III	10–30	Brown sediment	One hearth and post holes, along with approximately 2,500 faunal remains have been found and stone tools of the Sauveterrian technocomplex
IV	5–10	Brown sediment	400 faunal remains have been recovered and Sauveterrian technocomplex stone tools
V	65–70	Brown and black coloured sediment and hearths and limestone blocks	6,900 faunal remains have been recovered. Among the more than 400 objects of retouched flint, we may highlight 150 blades and back tips, 50 scrapers, many denticulated, and 8 burins
VI	30	Blocks	1,500 bone remains have been recovered, added to 200 retouched pieces; evidence of mastery of hunting weapons followed by burins and scrapers
VII		Sandy brown sediment	100 remains of fauna. Among the 100 retouched objects, the burins, denticulates and backs amounted to 50% of the finds

Charcoal analysis

At both archaeological sites a double sampling strategy was used systematically. On the one hand, sediment was sampled and sieved by the flotation method, using 1 mm mesh on the inside of the flotation machine and 0.25 mm on the outside. The charcoal fragments were then screened for individualization in a stack of 4, 2, 1, 0.5 and 0.25 mm sieves (Zapata-Peña and Peña-Chocarro 2013). On the other hand, during the excavation process pieces of charcoal were recovered in situ and recorded by their archaeological levels.

At Martinarri, a total of 97 samples of botanical material were recovered from four levels and a total of 495 charcoal fragments were identified from 56 L of sediment. At Socuevas, a total of 17 samples were collected from three levels, giving a total of 229 charcoal fragments from 93 L of sediment (Table 2). All of the remains were preserved as a result of having been carbonized.

Wood charcoal remains larger than 2 mm were studied with a Leica DM 4000 M reflection microscope at 50–500×, studying the radial, transverse and longitudinal sections. Comparisons were drawn with a collection of modern wood samples and with atlases on wood anatomy (Schweingruber 1978, 1990; Hather 2000; Vernet et al. 2001). The charcoal diagram is plotted against age using TGview (Fig. 5; Grimm 2004).

Radiocarbon dates and chronologies of the archaeological sites

Radiocarbon dates from Martinarri and Socuevas were calibrated using CALIB v. 8.2 with the IntCal20 curve (Reimer et al. 2020) (Table 2). We used the summed probability distribution (SPD) curves of radiocarbon dates with a standard deviation less than or equal to 100 years, in order to infer demographic patterns of settlement (Table 3). This method is to date the most widely accepted tool for proxy records of prehistoric occupation (Gamble et al. 2005; Shennan and Edinborough 2007; Buchanan et al. 2008; Williams 2012; Crema et al. 2016). Oxcal v. 4.2) was used for this, and calibrated to the 2 sigma range (95.4% probability) with the

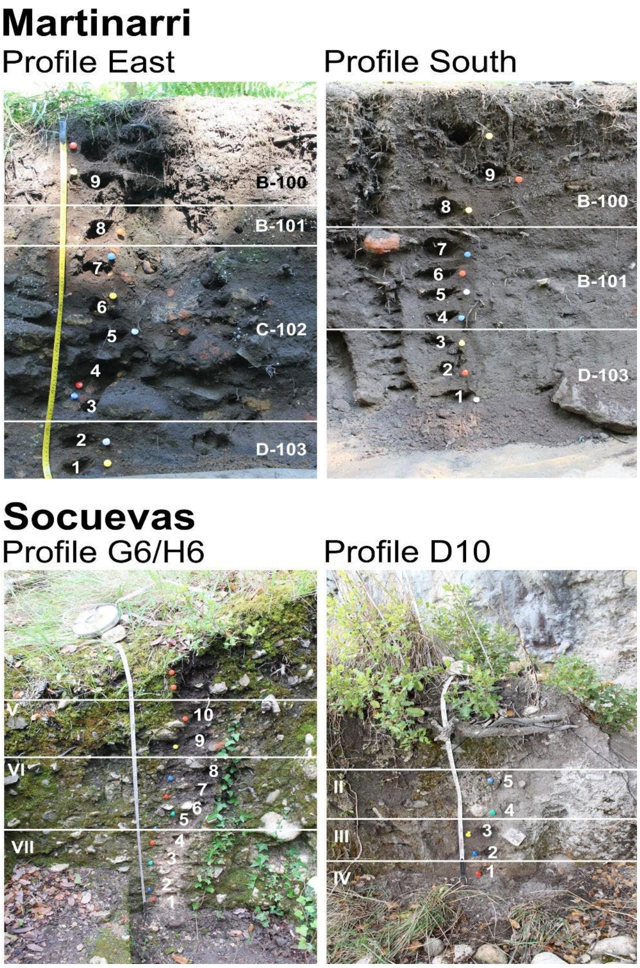

Fig. 2 Matinarri and Socuevas archaeological sites, stratigraphic profiles. Roman numerals, archaeological levels; Arabic numerals, pollen sampling points

IntCal20 calibration curve (Reimer et al. 2020). The software uses Bayesian statistics to model the dates.

Results and discussion

The Late Pleistocene to Early Holocene transition covers some of the most abrupt environmental changes of the past 14,000 years. The end of the last ice age and the beginning of the Holocene marked the end of the Upper Palaeolithic cultures and the beginning of new ways of life adapted to the milder climatic conditions and a significantly different landscape composition. Through the archaeobotanical data from pollen, spores, non-pollen palynomorphs and wood charcoal from samples covering the period from 14,000 to 8,000 cal BP, we are able to determine landscape evolution, climatic characteristics and its influence on human settlement patterns in the upper Ebro river basin.

Late glacial interstadial palaeoenvironment in the upper Ebro river basin

The oldest occupations within our study area correspond to levels VII, VI, V and IV in Socuevas (dated ca. 14,042–12,838 cal BP) and level D-103 in Martinarri (dated ca. 13,797–13,561 cal BP), which relate to the Magdalenian and Sauveterrian techno-complex of artefacts from this period. At this time, both sites showed very high arboreal pollen values (ca. 78–93%), the most highly represented taxon being *Pinus sylvestris*, with values of 42–59% and 47–55% at Socuevas and at Martinarri, respectively (Figs. 3 and

Table 2 Radiocarbon dates from Martinarri and Socuevas. Radiocarbon dates were calibrated using CALIB 8.2 software with the IntCal20 curve (Reimer et al., 2020). Ch. = charcoal samples. P. = pollen samples

Site/level	Lab.code	Material	Age BP	Age cal BP	Technocomplex	Ch.	P.
Martinarri							
B-100					Mesolithic	X	X
B1-101	Beta-410010	Bone	7,350 ± 30	8,285–8,029	Mesolithic	X	X
C-102	GrA-46014	Bone	8,455 ± 45	9,537–9,328	Mesolithic	X	X
	Beta-410009	Bone	9,870 ± 40	11,393–11,204	Mesolithic		
D-103	GrA-45940	Bone	11,890 ± 50	13,999–13,598	Magdalenian	X	X
Socuevas							
I						X	X
II	GrA-46015	Bone	7,590 ± 45	8,517–8,222	Mesolithic	X	X
III	Beta-282213	Bone	9,260 ± 50	10,571–10,264	Sauveterrian	X	X
	Beta-282214	Bone	10,550 ± 50	12,697–12,475			
IV	Beta-282215	Bone	11,130 ± 50	13,158–12,910	Sauveterrian		X
	Beta-312042	Bone	11,470 ± 50	13,460–13,200			
V	Beta-282216	Bone	11,530 ± 50	13,491–13,308	Magdalenian		X
	Beta-312041	Bone	11,540 ± 50	13,495–13,311			
	Beta-312040	Bone	12,040 ± 50	14,041–13,800			
VI					Magdalenian		X
VII					Magdalenian		X

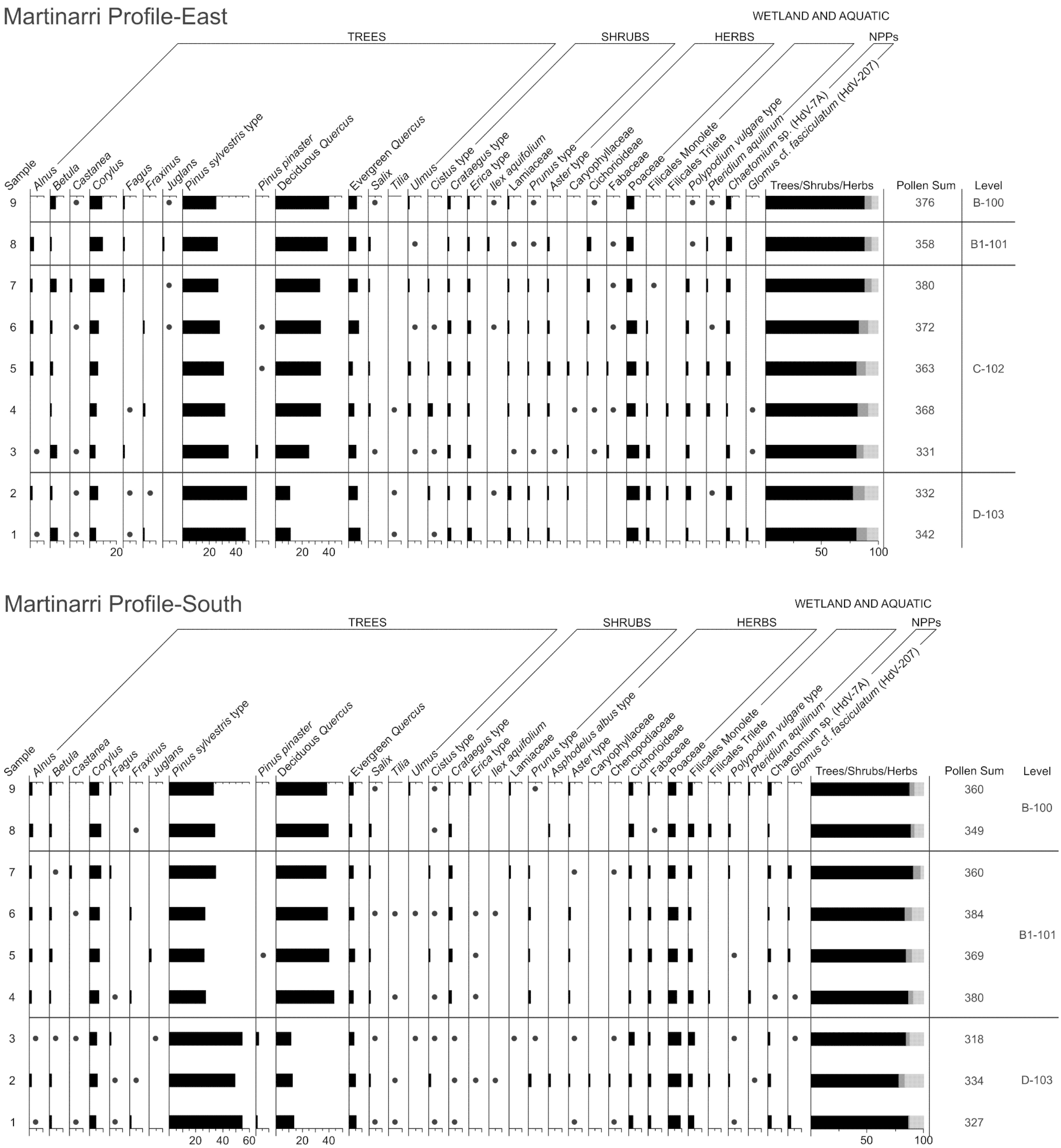

Fig. 3 Palynological diagram of Martinarri showing percentages of pollen, spores, non-pollen palynomorphs, wetland and aquatic taxa

4). The real ecological representation of those pines might however have been less important than the percentages might suggest, as it is known that most pines, due to their high pollen production and good dispersal ability, have a larger pollen dispersal area than some other trees (Poska and Pidek 2010). To address this question, some modern pollen rain studies have been done in some well-developed forests, mainly of *Pinus sylvestris*. According to the results, we can infer the presence of large pine forests only when the *Pinus* values reach ca. 60% of the pollen sum (López-Sáez et al. 2013). Without excluding the possibility of the pine pollen being regional rather than local in origin, as the percentages were close to 60%, the presence of local pines may be assumed, although very probably within dominant mature

Fig. 4 Palynological diagram of Socuevas showing percentages of pollen, spores, non-pollen palynomorphs, wetland and aquatic taxa

forests. The results of the macro-remains study also supported this assumption, showing that pine wood was used at Martinarri, but not at all regularly (<4% charcoal, Fig. 5). At the nearby site of Atxoste (Fig. 1), the charcoal analysis at the Magdalenian levels, dated ca. 14,500–13,300 cal BP (Alday 2006a; Alday et al. 2012), confirmed the predominance of *Pinus* sp. (66%) among the wood fragments that had been collected (Ruiz-Alonso 2014). In view of the data from Martinarri, Socuevas and Atxoste, the presence of pine forests in the study area was likely during the Late Pleistocene, although they have no modern phytosociological equivalent in northern Spain (Rivas-Martínez 1987).

In addition to pines, other local forests were growing in this region during the Magdalenian period (Fig. 6). According to the data, they must have been mainly composed of deciduous taxa. Deciduous *Quercus*, with values between

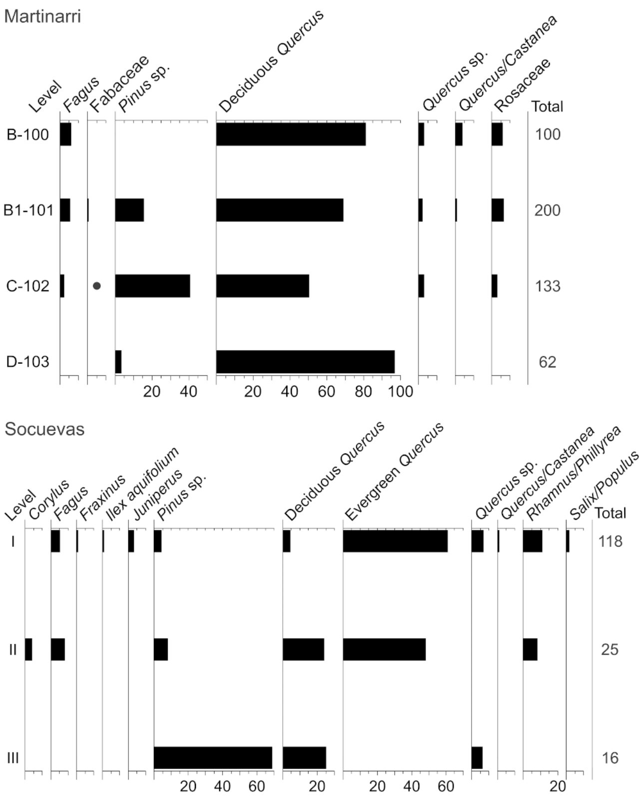

Fig. 5 Charcoal diagrams of Martinarri and Socuevas

11 and 14% and between 13 and 27% at Martinarri (Fig. 3) and at Socuevas (Fig. 4), respectively, is the most abundant in the pollen record, reflecting open woods. Oak was also confirmed at Martinarri where *Quercus* represented over 95% of the charcoal fragments that were recovered, underlining its general use as fuel (Fig. 5). Other deciduous taxa which are also represented in the pollen diagram such as *Corylus* and *Betula*, are absent from the charcoal records of both Martinarri and Socuevas, but present, albeit at low frequencies, at Atxoste (Ruiz-Alonso 2014).

Fagus (beech) is another deciduous tree recorded in the sequences from Socuevas and Martinarri, with a very interesting palaeoenvironmental record in the Iberian Peninsula. Its presence in both macro and micro-remains from the Late Pleistocene has been frequently observed, confirming that this region acted as a glacial refuge in times of cold (Ruiz-Alonso et al. 2019). In this context, the findings from Martinarri and Socuevas at ca. 14,050–13,200 cal BP are consistent. Its pollen values reached maxima of 2 and 3% there, respectively, which although insufficient to suggest the local presence of large forests, is significant evidence of sufficiently damp climatic conditions for it to have grown at both sites, also confirmed by the soil micromorphological analysis (Pérez-Fernández et al. 2020). No macro-remains of *Fagus* have yet been found. Subsequently, the notable growth of beech throughout the mountains of northern Iberia during the Late Holocene formed some of the most widespread forests in that region today (Ramil-Rego et al. 2000; Muñoz-Sobrino et al. 2009; Uzquiano et al. 2015; Pérez-Obiol et al. 2016; Ruiz-Alonso et al. 2019).

The presence of *Castanea sativa* Mill. (sweet chestnut) in the Mediterranean basin is still a subject of debate, as some authors consider that its intensive cultivation since the Greco-Roman period explains its presence in this region (Scarascia-Mugnozza et al. 2000). However, recent archaeobotanical finds in northern Iberia point to an earlier presence (Pérez-Díaz and López-Sáez 2021), as in this case, where *Castanea* pollen grains have been identified from both Mattinarri and Socuevas at ca. 14,042–12,838 cal BP. In these samples, values were low (1%), yet indicative of a local presence (Krebs et al. 2004; López-Sáez et al. 2017).

Juglans (walnut) is usually considered to have been introduced into western Mediterranean Europe during the Late Holocene (Beug 1975), but research over the past few decades has provided sufficient data to demonstrate its indigenous presence in the Iberian Peninsula (Sánchez-Goñi 1988; Carrión and Sánchez 1992; Silva-Oliveira 2012; Mercury et al. 2013b; Pérez-Díaz et al. 2016). In this case, pollen from *Juglans* was identified from the Late Pleistocene levels at both Martinarri and Socuevas with values < 1%, confirming its indigenous character in this area.

Taking into account the taphonomic considerations of the pollen percentages of pines and of deciduous woodland taxa (less than 35%), the presence of open areas during the LGI in the upper Ebro river basin is noteworthy. Shrubs, such as *Prunus, Erica*, Lamiaceae and *Cistus*, which mainly grow in deciduous forests, were detected although infrequently. Poaceae reaches maximum values of 10% (Fig. 6), while all other herbs show very low frequencies. Wetland and aquatic taxa never reach high values (< 5%), but show rising trends in the as yet undated Magdalenian levels VII and VI at Socuevas (Fig. 6), together with Filicales monolete, F. trilete, *Pteridium aquilinum* and *Polypodium vulgare* which grow in moister environments. Only three non-pollen palynomorphs (NPPs) were detected, *Chaetomium* sp. (HdV-7 A) at both sites, its ascospores indicative of fire, probably of human origin during the occupation of both sites (López-Sáez et al. 1998, 2000). *Glomus* cf. *fasciculatum*, an indicator of erosive processes, was also detected (Figs. 3 and 4), with the highest values in Socuevas, sample 9 (12%). In the same sample, the single occurrence of HdV-18 was found, suggesting damp conditions (van Geel et al. 1989), which are confirmed from the isotopic analysis of *Cervus elaphus* (red deer) bone collagen from the deposit of animal remains in the Kiputz IX cave (Mutriku, Gipuzkoa), suggesting wetter and warmer conditions (Castaños et al. 2014).

Table 3 Sites with radiocarbon dates equal to or less than 100 years, between 14,000–8,000 cal BP in the Ebro river basin. Radiocarbon dates calibrated using OxCal v. 4.2 with the IntCal20 curve (Reimer et al. 2020). UFM, Upper Final Magdalenian; MG, Mesolithic (Geometric facies); ML, Mesolithic (Laminar facies); MD, Mesolithic (notches and denticulates facies); N, Neolithic; SAUV, Sauveterrian

Site	Complex	Level	Lab.code	Age BP	Age cal BP	References
Aizpea	I	MG	GrN-16221	7,150 ± 70	8,184–7,740	Barandiarán and Cava-Almuzara 2001
Atxoste	IIIb2	MG	GrA-13468	7,550 ± 50	8,519–8,182	Alday 2014
	IV	MG	GrA-13469	7,570 ± 50	8,538–8,191	Alday 2014
	VI	MD	GrA-15700	8,510 ± 80	9,887–9,141	Alday and Cava-Almuzara 2006
	VI	MD	GrA-15699	8,760 ± 50	10,150–9,543	Alday and Cava-Almuzara 2006
	D	MD	GrA-13473	8,840 ± 50	10,192–9,560	Alday and Cava-Almuzara 2006
	E	ML	GrA-35141	9,450 ± 50	11,080–10,497	Alday 2002
	VIb2	ML	GrA-35142	9,510 ± 50	11,152–10,574	Alday 2002
	VI	MD	GrA-15858	9,550 ± 60	11,185–10,581	Alday and Cava-Almuzara 2006
	VIIc	UFM	GrA-23107	11,690 ± 80	13,791–13,318	Barandiarán et al. 2006
	VIIb	UFM	GrA-22865	11,720 ± 70	13,794–13,352	Barandiarán et al. 2006
	H	UFM	GrA-19870	11,730 ± 80	13,987–13,319	Barandiarán et al. 2006
	VIIc	UFM	GrA-22866	11,760 ± 70	13,993–13,405	Barandiarán et al. 2006
	VIIc	UFM	GrA-22900	11,800 ± 60	13,995–13,465	Barandiarán et al. 2006
	F	UFM	GrA-26666	11,910 ± 60	14,039–13,519	Barandiarán et al. 2006
	F2	UFM	GrA-19554	12,070 ± 60	14,157–13,765	Barandiarán et al. 2006
	G	UFM	GrA-19502	12,200 ± 90	14,858–13,791	Barandiarán et al. 2006
Costalena	c3	MG	MAMS-29828	7,265 ± 45	8,195–7,939	Domingo-Martínez et al. 2018
Forcas II	IV	MG	Beta-290932	7,235 ± 40	8,179–7,939	Utrilla et al. 2014
	IIIb2	MG	Beta-250944	7,340 ± 40	8,326–8,016	Utrilla et al. 2014
Kanpanoste	Lanhi	MD	GrN-22442	7,225 ± 100	8,368–7,742	Cava-Almuzara 2004
Kanpanoste Goikoa	IIIinf	MD	GrN-20215	7,165 ± 80	8,287–7,699	Alday 1998
	IIIinf	MD	GrN-20215	7,620 ± 80	8,640–8,180	Alday 1998
Las Orcillas	I	ML	Beta-252434	8,610 ± 50	9,888–9,469	Fernández-Eraso et al. 2010
Martinarri	B1-101	ML	Beta-410010	7,350 ± 30	8,323–8,021	Alday et al. 2012
	C-102	ML	GrA-46014	8,455 ± 45	9,544–9,297	Alday et al. 2012
	C-102	ML	Beta-410009	9,870 ± 40	11,605–11,185	Alday et al. 2012
	D-103	UFM	GrA-45940	11,890 ± 50	14,025–13,517	Alday et al. 2012
Mendandia	III-sup.	NA	GrN-22742	7,180 ± 45	8,174–7,860	Alday 2006b
	III-sup.	NA	GrN-19658	7,210 ± 80	8,325–7,789	Alday 2006b
	III-sup.	NA	Ua-34366	7,265 ± 70	8,336–7,870	Alday 2006b
	IIIinf	MG	GrN-22743	7,620 ± 50	8,591–8,214	Alday 2006b
	IV	MD	GrN-22745	7,780 ± 40	8,721–8,412	Alday 2006b
	IV	MD	GrN-22744	7,810 ± 50	8,980–8,414	Alday 2006b
	V	ML	GrA-6874	8,500 ± 60	9,677–9,294	Alday 2006b
Portugain	II	ML	GrN-14097	10,370 ± 90	12,683–11,749	Barandiarán and Cava-Almuzara 2008
Rambla Legunova	2	MG	GrA-64001	7,225 ± 40	8,179–7,935	Montes-Ramirez et al. 2015
	2	MG	GrA-61768	7,260 ± 45	8,193–7,939	Montes-Ramirez et al. 2015
Socuevas	II	MG	GrA-46015	7,590 ± 45	8,543–8,204	Sánchez-López et al. 2018
	III	SAUV	Beta-282213	9,260 ± 50	10,655–10,241	Sánchez-López et al. 2018
	III	SAUV	Beta-282214	10,550 ± 50	12,730–12,190	Sánchez-López et al. 2018
	IV	SAUV	Beta-282215	11,130 ± 50	13,173–12,840	Sánchez-López et al. 2018
	IV	SAUV	Beta-312042	11,470 ± 50	13,491–13,175	Sánchez-López et al. 2018
	V	UFM	Beta-282216	11,530 ± 50	13,580–13,238	Sánchez-López et al. 2018
	V	UFM	Beta-312040	11,540 ± 50	13,584–13,240	Sánchez-López et al. 2018
	V	UFM	Beta-312040	12,040 ± 50	14,081–13,773	Sánchez-López et al. 2018
Urratxa III	II	ML	Ua-11433	10,240 ± 100	12,613–11,324	Muñoz and Berganza 1997

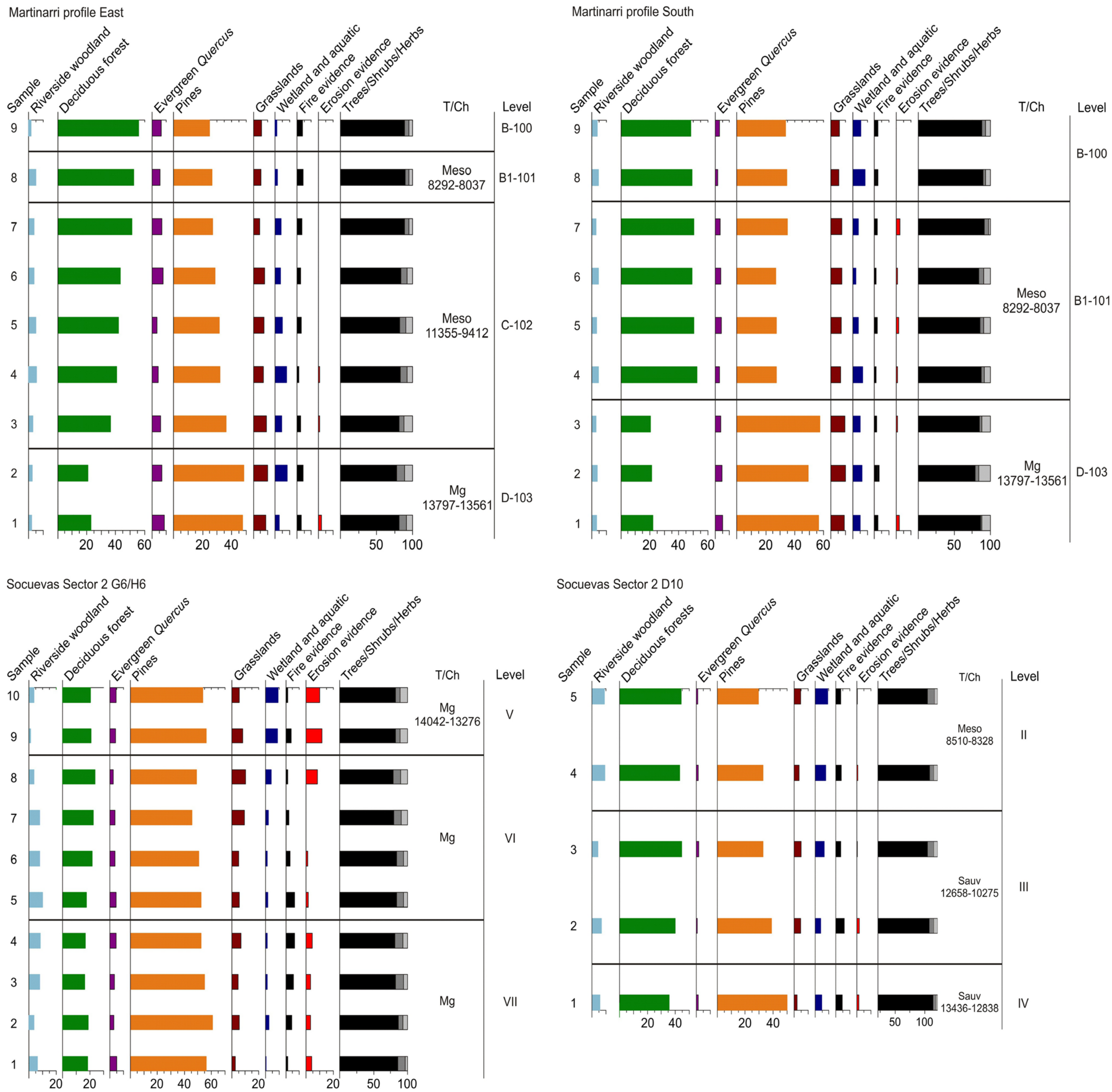

Fig. 6 Synthetic palynological diagrams of Martinarri and Socuevas. Riverside woodland (*Alnus*, *Fraxinus*, *Salix*, *Ulmus*); Pines (*Pinus sylvestris* type, *Pinus pinaster*); Deciduous forest (*Betula, Castanea, Corylus*, *Fagus*, *Juglans*, Deciduous *Quercus, Tilia*); Evergreen *Quercus*; Grasslands (Poaceae); Wetland and aquatic (Filicales Monolete, Filicales Trilete, *Polypodium vulgare*-type, *Pteridium aquilinum*); Fire evidence (*Chaetomium* sp.); Erosion evidence (*Glomus* cf. *fasciculatum*)

In the same region, but located in a mountainous area at 1,115 m (Fig. 1), pollen analysis results from the Verdeospesoa mire show a vegetation generally very similar to those interpreted for both Martinarri and Socuevas during the LGI, with open deciduous woodland and increasing aquatic and wetland taxa. In contrast to the lowlands, there was a decreasing trend in the xerophytic taxa *Juniperus*, *Artemisia*, Chenopodiaceae, *Centaurea* and Cichorioideae (Pérez-Díaz and López-Sáez 2021) indicating dry conditions at Verdeospesoa. This presence of xerophytic taxa at high altitudes could be explained by the higher sensitivity of mountain vegetation to climate oscillations, which are not so easily detected in the lowlands.

In the absence of continuous high-resolution pollen records in the study area, we have to consider other continental palaeoenvironmental sequences for evidence of environmental conditions during this period. According to general nomenclature and chronology established from the proposals of the INTIMATE group (Rasmussen et al. 2014), the Late Glacial Interstadial (ca. 14,700–12,900 cal BP) had a damp temperate climate (Greenland Interstadial 1, GI-1), after the cold and dry Oldest Dryas (ca. 17,500–14,700 cal BP) and the subsequent Younger Dryas (ca. 12,900–11,700 cal BP), also characterized by low temperature and precipitation leading up to the start of the Holocene. The GI-1 is subdivided into different stages, not all of them visible in all records, from the warmer Bølling

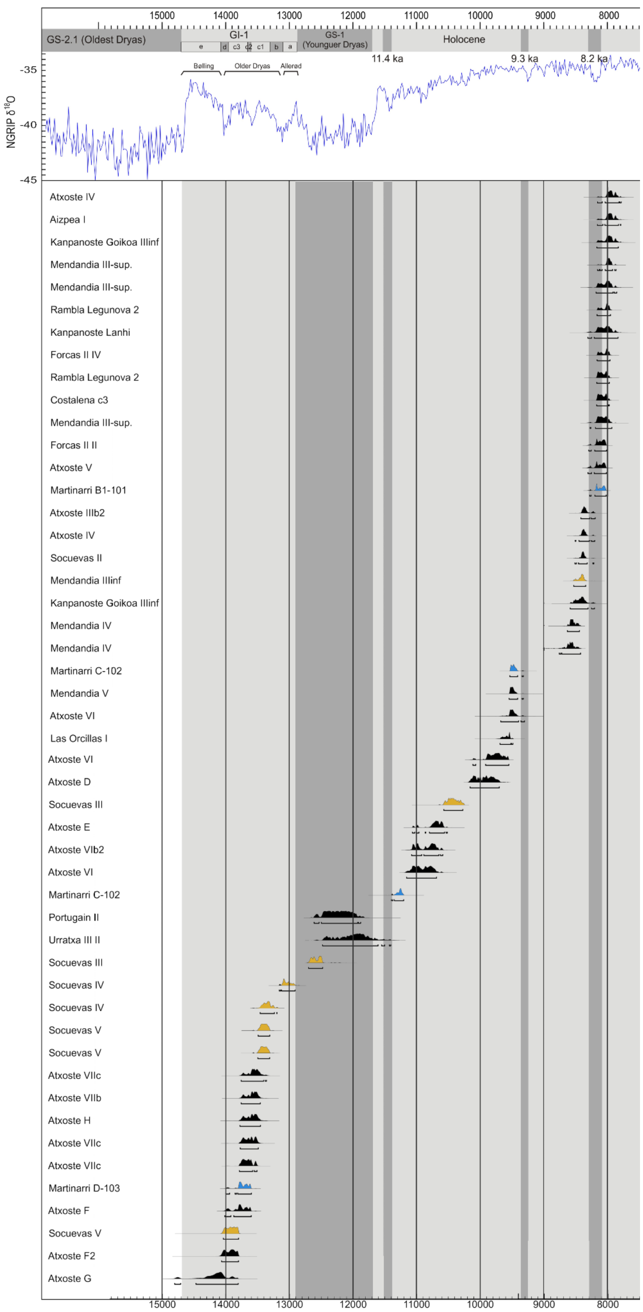

Fig. 7 Phases of the Late Glacial and Early Holocene with the regional summed probability distribution of radiocarbon dates equal to or less than 100 years from the various sites. Orange curves, Socuevas site; blue curves, Martinarri

(GI-1e, 16,700–14,075 cal BP) and Allerød (GI-1a, 13,100–12,900 cal BP) oscillations and the succession of cold-dry to warm-wet episodes such as GI-1d (14,075–13,950 cal BP), GI-1c (13,950–13,300 cal BP, including sub-stages c1, c2, c3 and GI-1b (13,300–13,100 cal BP).

The first periods of occupation at Martinarri and Socuevas (ca. 14,050–12,800 cal BP) were during the sub-stages GI-1d, GI-1c (including the Older Dryas) when, according to the NGRIP record, the climate was generally mild and damp (Rasmussen et al. 2014). For the upper Ebro river basin we can confirm these features because we have, as mentioned, detected the dominance of taxa such as deciduous *Quercus*, *Corylus*, *Betula*, *Castanea*, *Fagus*, *Juglans*, *Tilia* and riverside taxa such as *Alnus*, *Fraxinus*, *Salix* and *Ulmus*, together with some presence of pines and the absence of xerophytic taxa such as *Juniperus*, *Artemisia*, Chenopodiaceae, *Centaurea* and Cichorioideae, which are present only in mountainous areas, confirming that there were warm climatic conditions in the lowlands (Fig. 6).

This environment suggests a region with a favourable climate for human occupation. An analysis of occupation of sites located in the upper Ebro river basin, with 14 radiocarbon dates of archaeological levels with a standard deviation equal to or less than 100 years (Fig. 7; Table 3), provides clear evidence of the occupation of at least three archaeological sites, Socuevas, Martinarri and Atxoste, during the sub-stages mentioned above. The temperate climate at that time might also have favoured the presence of herds of ungulates, mostly *Cervus elaphus* (red deer), *Rupicapra rupicapra* (chamois) and *Capreolus capreolus* (roe deer), widely documented in the other archaeological records from this period (Yravedra and Gómez 2010; Arias et al. 2011; Marín-Arroyo 2013). These settlements were located at strategic places, such as narrow mountain passes, or at the entrance or at the end of a valley and near varied biotopes providing access to a large range of animal and plant resources (Alday et al. 2020).

At a regional scale, the rising temperature and precipitation during the Late Glacial Interstadial in the lowlands of the upper Ebro river basin is clearly defined in most sequences through different proxies, but with some differences that are related to altitude and continentality. In other regions, at this time some speleothems (mineral deposits) started to grow in southwestern Europe (Fig. 1), such as the stalagmites in the caves at Chauvet, Villars (Genty et al. 2006) and El Pindal (Moreno et al. 2010a). The records of small vertebrates from the Santimamiñe cave (near the town of, Kortezubi), show a clear increase in tree cover during the LGI (Rofes et al. 2014). In the same way, a palaeoclimatic reconstruction of conditions around Lago Enol (Moreno et al. 2010b) show clearly warmer climates than before, reflecting a supra-regional trend. In the Pyrenean region (Fig. 1), this phase is represented by the deglaciation period documented for El Portalet (González-Sampériz et al. 2006), at the lakes Banyoles (Pérez-Obiol and Juliá 1994) and Estanya (Morellón et al. 2009). Some marine sequences in the Iberian Atlantic margin (MD03-2697 and MD95-2039) showed an increase in sea surface temperatures (SST), an increasing trend in deciduous *Quercus* and decreasing values of steppe taxa (Roucoux et al. 2001; Naughton et al. 2016). The increase in SST in the MD95-2043 Alboran sea record coincides with this trend (Fletcher and Sánchez-Goñi 2008).

In other regions, such as inner Iberia, the continental Villarquemado sequence shows different patterns during the Late Glacial Interstadial, with an abundance of pines (ca. 40%), xerophytes and low percentages of mesophytes representing neither wet nor dry conditions, probably because of the resilience of the continental ecosystems to increased moisture availability during the LGI, although vegetation changes may be partly masked by the low sample resolution in this record (Aranbarri et al. 2014). In the mountains of the Aragon region, the climatic improvement of the Bølling-Allerød (ca. 14,600–12,900 cal BP) was interrupted by the start of the Younger Dryas (Aranbarri et al. 2014; González-Sampériz et al. 2017). The early Holocene was cold and dry there, and *Juniperus, Pinus* and some mesophyllous taxa dominated the landscape up to ca. 10,500 cal BP. From that time onwards, the increase in precipitation and temperature was progressive, which favoured the expansion of mesophyllous deciduous forests during the Boreal. In the west of the basin, data from archaeological sequences between the end of the LGI and the beginning of the Holocene reveal a rapid spread of woodland, with some local peculiarities dependent on the altitudinal levels. In general, *Quercus* and *Corylus* were most abundant, although pine forests were important in some areas such as those around Zatoya.

In central Spain, a high resolution study from the Navamuño peat bog clearly showed the Bølling oscillation ca. 14,700–14,000 cal BP, with increasing tree cover, a continuous curve of deciduous *Quercus* and riparian woods, the Older Dryas ca. 14,000–13,400 cal BP, with low tree cover and dominance of a steppe-like landscape, and the Allerød (ca. 13,400–12,600 cal BP) with a rise of riverside woodlands and deciduous *Quercus*, decreases in taxa representing cold and dry conditions in a deposit located at the high altitude of 1,505 m on Spanish Central System (López-Sáez et al. 2020).

The early Holocene in the upper Ebro river basin

After the Greenland Stadial I (Younger Dryas) during which no occupations were detected at either site, some Mesolithic microlaminate tools from the Early Holocene technocomplexes (artefact typologies) were detected, which could be ascribed both to Azilian and Sauveterrian types, dated between 11,355 and 8,000 cal BP and 10,569-8,300 cal BP at Martinarri and at Socuevas, respectively. In this last case, Level III is chronologically dated between two radiocarbon dates, 10,550 ± 50 BP (ca. 12,658–12,402 cal BP) and 9,260 ± 50 BP (10,569–10,275 cal BP), although the results of analysing some stone tools suggested that the first date was too old, while the youngest was more characteristic of this level. This assumption is consistent with the landscape inferred from the pollen record, as will be explained below.

For these Early Holocene levels, we observed some significant changes in the landscape in relation with previous situation. Noteworthy rises of deciduous taxa (Fig. 6), such as deciduous *Quercus* reaching maximum values of 40% and *Corylus* (10%) characterized levels C-102 (ca. 11,355-9,400 cal BP), B1-101 (ca. 8,292-8,037 cal BP), and B-100 at Martinarri and Levels III (ca. 10,569–10,275 cal BP), and II at Socuevas (ca. 8,510-8,328 cal BP). *Betula* was present as a continuous but irregular curve, with maximum values of 5%. The rest of the deciduous trees showed a scattered presence (*Castanea*, *Fagus*, *Juglans*). The riverside taxa *Alnus*, *Fraxinus*, *Salix*, *Tilia* and *Ulmus* showed very similar trends to previous patterns. Likewise, *Pinus sylvestris* type (pines) showed a clear downward trend, with minimum values of 25%. Grasslands also showed some decreasing trends.

A new more wooded landscape emerged with these characteristics where deciduous forests covered most of the landscape in a clear well-studied trend also seen in other western Mediterranean sequences, but until now hardly explored in this region. Other records such as the pollen diagram from the Mendandia archaeological site (Alday 2006b) show the extent of forest growth at that time (maximum ca. 50%), in which deciduous trees were dominant on a local scale. Specifically, there was a mixed forest, in which *Corylus* (hazel) was more important than deciduous *Quercus* (oak), *Betula* (birch), *Tilia* (lime), *Taxus* (yew) and *Salix* (willow). Pine is present in the diagram, though at low percentages (ca. 7%, Iriarte 2006). This question is very interesting, because the charcoal record shows the extensive use of pine, although clearly very poorly represented in the vicinity. A large number of wood charcoal remains have been identified with distorted, vitrified anatomies, which are related to the carbonization of pinewood when green, freshly cut and undried (Zapata-Peña and Peña-Chocarro 2006). Its use in this way may suggest its use as fuel for smoking food (Alday and Cava-Almuzara 2006; Alday 2007), in a clear example of the selection of specific use of plants for particular purposes. In the same way, this frequent use of pine although it was apparently scarce, rather than the widespread deciduous oak was also reflected in the Early Holocene levels at Atxoste (Ruiz-Alonso 2014). In any case, the regional dominance of deciduous trees was confirmed through the pollen analyses of Kananoste and Kanpanoste Goikoa (Iriarte 1998; Zapata-Peña 1998, 2002; Sánchez-Goñi 2004).

At a regional scale, this increase in moisture and temperature was detected in other high-resolution proxies, such as that from the Gesaleta mire (Fig. 1) where deciduous forests were dominant from ca. 11,400 cal BP, with pines decreasing (Ruiz-Alonso et al. 2019), and at Lago Enol, with a high lake level from ca. 11,600-8,700 cal BP and an increase in the percentages of carbonates, organic matter and mesophytes (Moreno et al. 2011). A very similar trend was detected at Verdeospesoa where an increase in organic content was detected from ca. 11,000 to 8,700 cal BP (Pérez-Díaz and López-Sáez 2021) and in the small mammal record from Santimamiñe (Rofes et al. 2014), reflecting increasing temperatures and development of woodland in the Early Holocene. From Navamuño mire, from ca. 11,500 cal BP, a noteworthy increase in *Betula*, *Quercus pyrenaica*-type and *Alnus* was detected (López-Sáez et al. 2020).

Despite this evidence of a general increase in temperatures and rainfall, which caused a great spreading of deciduous forests in northern Iberia, some climatic events have been detected that represent a contrast to this general trend. According to INTIMATE group proposals (Rasmussen et al. 2014), during the Early Holocene three major climatic events took place, the 11.4 ka cal BP event (ca. 11,520–11,400 cal BP), the 9.3 ka cal BP event (ca. 9,350-9,240 cal BP) and the 8.2 ka cal BP event (ca. 8,300-8,140 cal BP). Radiocarbon dates from the archaeological sites in the upper Ebro river basin show no clear occupation during the 11.4 and the 9.3 ka cal BP events (Fig. 7; Table 3; Alday et al. 2018; Alday and Soto-Sebastián 2018), but the scarcity of archaeological data and the absence of high resolution palaeoenvironmental analysis covering this period has so far prevented any understanding of whether these events had any detectable impact on the landscape (Alday et al. 2018). One such example could be the 8.2 ka cal BP event, an especially cold period that occurred at a global scale ca. 8,300-8,140 cal BP (Bond et al. 1997; Barber et al. 1999; Tinner and Lotter 2001; Dean et al. 2002; Alley and Ágústsdóttir 2005; López-Sáez et al. 2008; Rasmussen et al. 2014).

In numerous pollen sequences, both natural and archaeological, and from different Iberian regions, the decreases (sometimes abrupt and other times slight) in the values of tree pollen and the emergence of cold indicators are clearly the main characteristics of the 8.2 ka event, as at Lago Enol (Moreno et al. 2011), Drassanes (Riera 1995), Gual-lar (Davis and Stevenson 2007), Navarrés (Carrión and van Geel 1999), Siles (Carrión 2002) (Fig. 7) etc., but the situation appears to differ in the upper Ebro basin. In this case, the pollen diagram from level B1-101 at Martinarri showed a large arboreal pollen value (89%), representing deciduous forests, with some pines and riverside trees. We detected no decrease in the tree pollen values compared with the preceding period, nor any appearance of plants representing colder and drier environments (Fig. 6). Furthermore, the vegetational landscape shows a marked continuity, with no apparent alterations between the levels before the 8.2 ka cal BP event (level C-102) and the subsequent one (level B-100). As this is a globally detected climate event, its effects on the upper Ebro river basin are more than likely. However, at the moment, there is no evidence of its consequences on ecosystems, perhaps because of the insufficient number of sites and samples.

Changes to climates and landscapes are often linked to human cultural responses. For the phases and area under analysis here, we can suggest some possible scenarios. The climatic warming allowed human occupation of the interior and high areas that took place at the end of the Pleistocene, and the upper Ebro is a good example of this dynamic (Barandiarán et al. 2006). The landscape change allowed increased productivity of plant and animal biomass which occurred throughout the early Holocene, and it placed a certain restriction on the mobility of human communities. The tendency was to substitute lengthier distances of travel at the end of the Pleistocene for shorter ones. The spread of lowland vegetation to higher land during the (Alday et al. 2020) led to a process of semi-permanent occupation, based on territories rather than particular sites, which implied a tendency to move towards a certain cultural and social identity. Finally, the human cultural responses could link the 8.2 ka cal BP event with the beginnings, of the geometric Mesolithic culture at a European scale, a matter that calls for more research.

Conclusions

The new palaeoenvironmental sequences from Martinarri and Socuevas have contributed to the knowledge of landscape development throughout the Late Pleistocene and Early Holocene in the lowlands of the upper Ebro river basin, northern Iberia. The results have clearly shown the presence of open areas, deciduous woodlands and pinewoods during the Late Glacial Interstadial, a warmer phase than the Oldest Dryas. After a phase with no records, corresponding with the Younger Dryas and requiring further research, the Early Holocene is characterised by widespread growth of deciduous woods, evidence of increasingly warm and moist conditions. No evidence of cold events has yet been detected, but high-resolution studies of natural deposits could change that assumption.

Human occupation throughout the period 14,050–8,000 cal BP has been clearly shown in this region throughout the LGI and the Early Holocene, but not during the

11.4 and the 9.3 ka cal BP cold events. In the records from both Martinarri and Socuevas, only one radiocarbon date is clearly within the 8.2 ka cal BP event, though the effects of these environmental crises during the Early Holocene on this region may be debated in greater depth. Further research on this topic with extensive sampling and dating would be essential to assess the incidence of these abrupt climatic events on both the landscape and human settlement patterns.

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