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Early anthropogenic change in western Mediterranean mountains (Sierra Nevada, SE Spain)

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ABSTRACT

Human impact on western Mediterranean mountains is gaining more attention, as they harbour a rich plant diversity threatened by global change. This paper presents an analysis of two pollen records from both sides of Sierra Nevada, the prime plant-diversity centre of the Mediterranean, spanning the last 5400 years. The analysis sought to answer the following key questions: When did natural systems transform to cultural landscapes? What was the intensity and extent of alterations driven by the diverse civilizations? A compilation of archaeological and palaeoclimatic data supported this analysis, as well as a multi-proxy palaeoecological study using pollen, non-pollen palynomorphs and microcharcoal, searching for the imprint that diverse societies left on these mountains. Results suggest that human influences started earlier than expected, with a strong impact on forest cover, oriented more towards crops on the southern face and towards livestock on the northern one, whereas mining and metallurgy were initial key drivers of population dynamics. Irrigation has supported farming since at least the Islamic period. More recent anthropogenic control and land-use management have allowed a further spread of the tree cover. Proper conservation strategies need long-term perspectives, including palaeoecological studies. The preservation of traditional human activities like grazing, high-elevation cropping or irrigation systems become essential to maintain current biodiversity.

1. Introduction

Mediterranean mountains are dynamic landscape systems, highly sensitive to climate change, which have hosted biotic refugia during glacial and interglacial stages (Vogiatzakis, 2012; Hughes and Woodward, 2016). The persistence until today of “biological relics” over geological times have turned these systems into key areas of genetic diversity (Taberlet and Cheddadi, 2002; Tzedakis et al., 2002; Carrión et al., 2003; Regato and Salman, 2008). A core priority is species and habitat conservation in the face of threats related to environmental change currently affecting the Mediterranean (Médail and Diadema, 2009).

Sierra Nevada (SN), a mountain range located in the south-western Mediterranean, has a special identity, harbouring a rich biodiversity of species among a unique orography (Blanca et al., 2019). A less explored feature of this mountain, however, is the complex framework of cultural landscapes shaped by humans over the last several millennia (McNeill, 2003; Gómez-Ortiz et al., 2013).

At millennial scale, climate has been one of the main agents shaping patterns of plant species distributions on SN. Numerous palaeoecological studies have highlighted the climate-induced plant dynamics (Fig. 1) on this mountain, most of them examining high-elevation deposits (*e.g.* Anderson et al., 2011; Jiménez-Moreno and Anderson, 2012; Ramos-Román et al., 2016). The low-elevation deposit of El Padul deserves mention as one of the longest Quaternary records (> 100 kyr) of Western Europe

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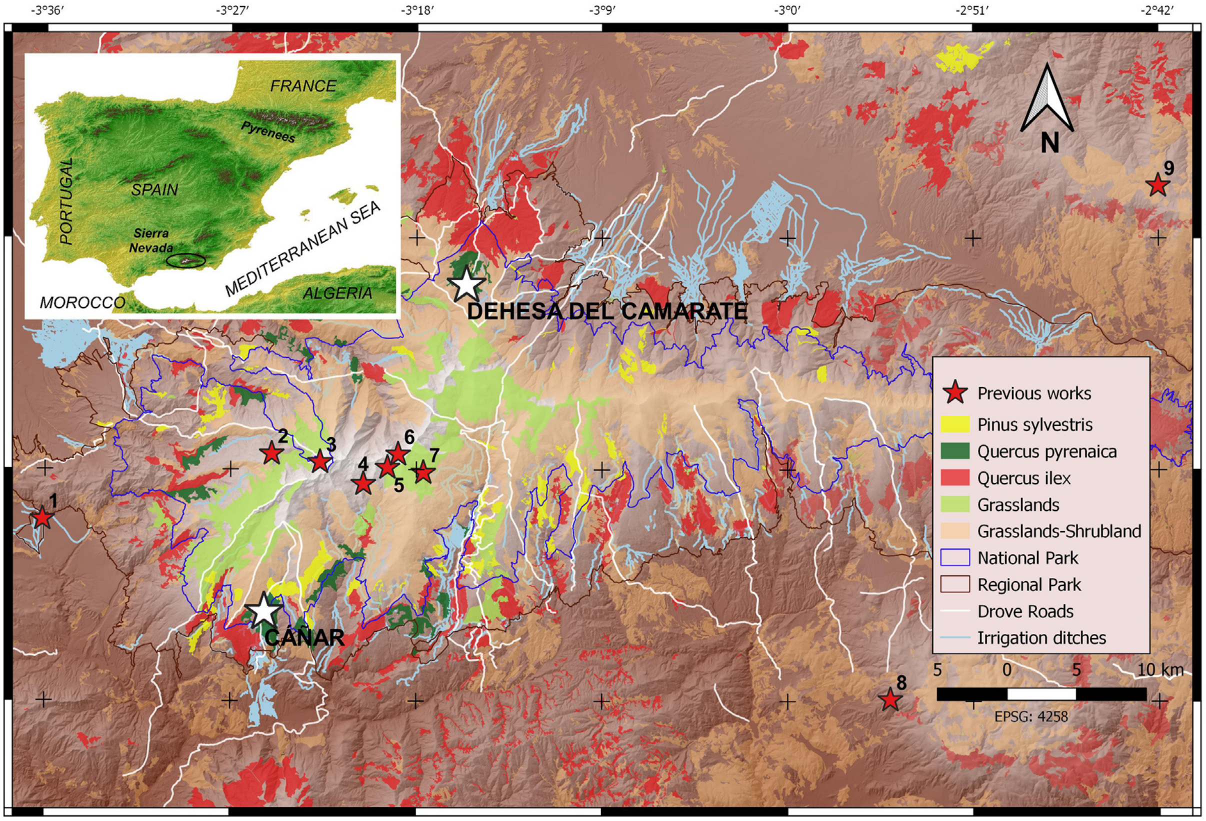

Fig. 1. Location of Dehesa del Camarate and Cáñar mires (white stars), showing the location of previous palynological works cited in the text (red stars): 1. Padul (Ramos-Román et al., 2018a, 2018b; Camuera et al., 2018, 2019); 2.Laguna de la Mula (Jiménez-Moreno et al., 2013); 3. Borreguiles de la Virgen (Jiménez Moreno and Anderson, 2012); 4. Laguna de Río Seco (Anderson et al., 2011); 5. Laguna de la Mosca (Manzano et al., 2019); 6. Borreguil de la Caldera (Ramos-Román et al., 2016); 7. Laguna Hondera (Mesa-Fernández et al., 2018); 8. Sierra de Gádor (Carrión et al., 2003); 9. Sierra de Baza (Carrión et al., 2007).

(*e.g.* Pons and Reille, 1988; Ramos-Román et al., 2018a, 2018b; Camuera et al., 2018, 2019). In addition to climate, human activity, at a millennial scale has moulded the diversity and abundance of plant taxa in the mesophilous and orophilous ecosystems of SN. This ecological diversity has provided a wide range of resources for human exploitation, giving rise to cultural landscapes since ancient times (Woodward, 2009; Mercuri and Sadori, 2014).

Early human influence as key driver shaping Mediterranean mountains has recently attracted growing interest (*e.g.* Smith and Zeder, 2013; Ruddiman, 2017; Roberts et al., 2019). Prehistoric human activities in Mediterranean high-mountain areas has been detected later than at low elevations, between 5500–4000 cal yr BP (López-Sáez et al., 2014; Pini et al., 2017; Cheddadi et al., 2019). At this time, humans also settled Sierra Nevada in mid- and low-elevation lands, more oriented to agriculture and grazing (Jiménez Olivencia et al., 2006), while mining was linked more to montane areas (Bertrand and Sánchez Viciana, 2008; Catalán et al., 2019).

Nevertheless, the scarcity of specific fossil records and palaeobotanical analysis conducted so far at proper elevations hinders the reconstruction of the transition from a natural landscape in SN, shaped by climate, towards a cultural one, despite the long human presence evidenced by the extensive archaeological surveys of the area (Fig. 2).

To improve the design of more realistic conservation measures in this area of high ecological value (Gillson, 2015; Catalán et al., 2019), this study addressed the following questions: (1) When did this tipping point take place in the landscape of SN, from natural toward a cultural one? (2) What was the intensity and extent of the alteration of the landscape by the diverse civilizations, regarding the successive cultural models or socioeconomic strategies?

In short, the present work sought to estimate the degree of ecological transformation in the orophilous-mesophilous landscapes of SN during the last millennia attributable to human activity (or to climate). Results thereby allowed evaluation of the imprint left by the distinct societies on this area.

To meet this aim, we conducted a multi-proxy palaeoecological study using pollen, non-pollen palynomorphs and microcharcoal. Two pollen sequences (northern and southern faces of SN) revealed the dynamics of vegetation patterns at an elevation that enabled detection of the signal of human settlements. Likewise, we compiled both archaeological and palaeoclimatic data to shed light on the feasible links between socioeconomic activities, climatic changes, and the depth of landscape transformation.

2. Material and methods

2.1. Study area

The deposit of Dehesa del Camarate (DC: 37°10′11″N/3°15′50″W) is located at 1965 m above sea level (asl), on the northern slopes of SN, in Lugros (Granada), while the deposit of Cáñar (36°57′28″N/3°25′16″W) is situated at 1593 m asl on the southern side, in Cáñar (Granada; Fig. 1). Both records were the first studied in SN outside the surroundings of the highest summits of Veleta and Mulhacén (3398 and 3479 m asl, respectively).

They form part of the central core of this range, composed of micaschists and quartzites (Blanca López and Lo’pez Onieva, 2002). The climate varies from one point to another, with slightly higher annual rainfall in Cáñar (>700 mm) despite the elevation differences, as well as higher average temperatures (*ca.* 13 °C)

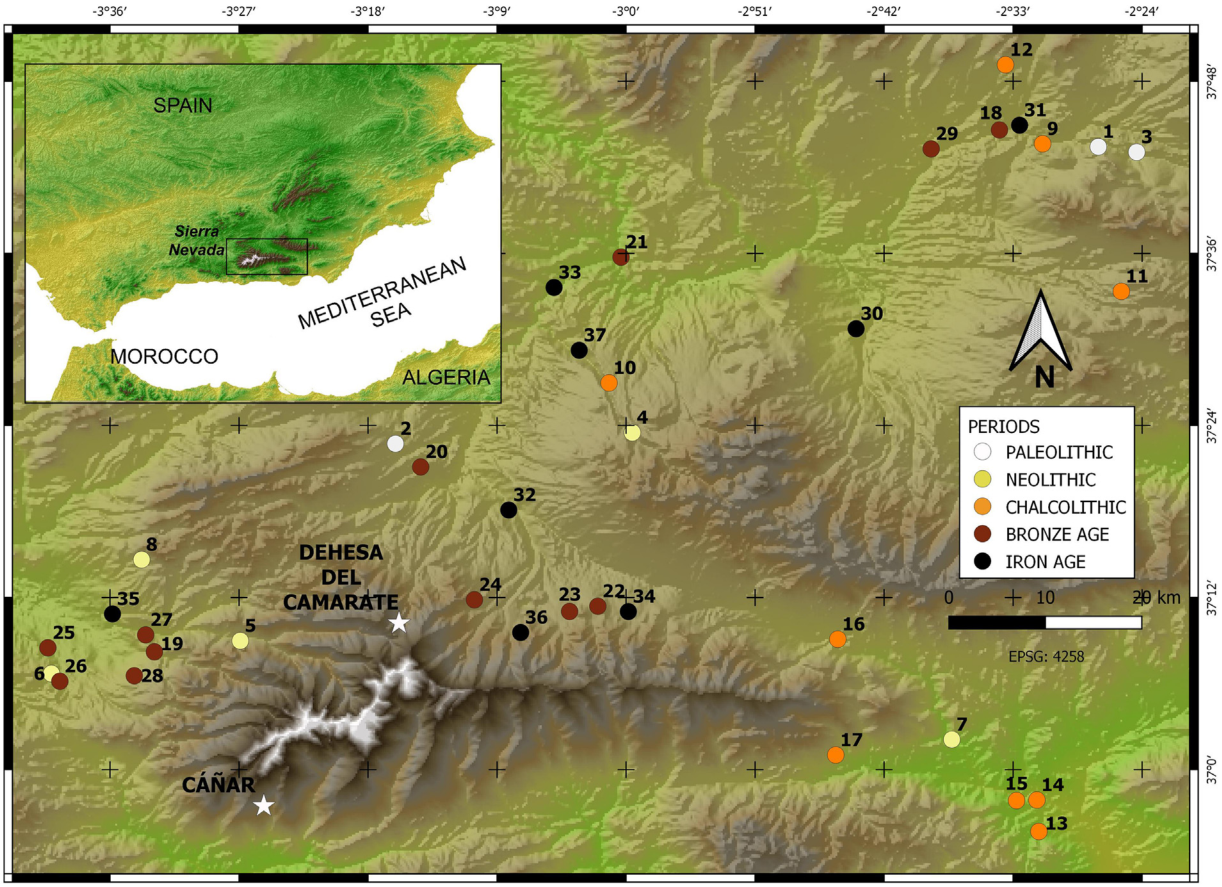

Fig. 2. Pre-Roman settlements in the surrounding study area. 1. Barranco León; 2. Cueva Horá; 3. Fuente Nueva; 4. Las Angosturas; 5. Cerro del Castillejo; 6. Cerro de San Cristóbal; 7. Peñón de la Reina; 8. Las Majolicas; 9. Cerro de la Virgen; 10. Dólmenes de Gorafe; 11. El Malagón; 12. Cueva Romero; 13. Necrópolis de Gádor; 14. Los Millares; 15. Loma de la Galera; 16. Peñón de las Juntas; 17. Cueva de Nieles; 18. Castellon Alto; 19. Cerro de la Encina; 20. Cuesta del Negro; 21. La Terrera del Reloj; 22. El Cardal; 23. Juan Canal; 24. Peñón de Arruta; 25. Cuesta de los Chinos; 26. La Quinta; 27. Barranco Tio Gabriel; 28. Cuevas de la Zubia; 29. Loma de la Balunca; 30. Cerro Cepero; 31. Tútugi; 32. Acci; 33. El Forruchu; 34. Cerro de la Calera; 35. Iliberri; 36. Campo de Marte; 37. Cueva de Montealegre.

than in DC (*ca.* 700 mm and 5 °C). The whole range lies within a Mediterranean semiarid high-mountain environment, with a marked contrast between the hot-dry season and the cold-wet one (Oliva et al., 2014). SN is considered the main plant-diversity centre of Mediterranean Region, with more than 100 endemic and 2000 vascular species (Blanca et al., 2019). The main species from the wet pastureland of DC are Poaceae (*Nardus stricta, Festuca iberica*), Cyperaceae (*Carex nigra*, *C. echinata*, *Cyperus longus*, *Eleocharis palustris*) and Juncaceae (*Juncus articulatus*, *J. effusus*). In the case of Cáñar, the pastureland is surrounded by an oak (*Quercus pyrenaica*) wood and composed mainly of Cyperaceae (*Carex camposii*, *Cyperus longus, Scirpus holoschoenus*), Juncaceae (*Juncus effusus*, *J. conglomeratus*), Poaceae (*Holcus lanatus*, *Anthoxanthum odoratum*, *Poa trivialis*), and Fabaceae (*Lotus uliginosus*, *Trifolium pratense*).

2.2. Land-use patterns of human settlement

Neolithic culture in south-eastern Iberia developed from the 8th millennium cal yr BP onwards (Fig. 2). During the 7th and 6th millennia cal yr BP, the recorded pollen indicators of human activity remained weak, linked with a low grazing pressure in the surroundings of SN (López-Sáez et al., 2011). The abundant available resources for farming and mining, as well as the strategic location of this area, encouraged further population growth (Cortés Sánchez et al., 2012).

Los Millares culture characterized the Chalcolithic Period (*ca.* 5100–4250 cal yr BP). Archaeological sites occupy south-eastern Iberia, usually in low-elevation areas. These settlements were firstly oriented towards mineral deposits, easily exploitable with primitive technologies, and then associated exclusively with farming (Lull et al., 2010; Zoido Naranjo and Jiménez Olivencia, 2015). Charcoal analyses for Los Millares site (Rodríguez Ariza and Esquivel, 1989) provide few signals of human impact on the mountain landscape. Conversely, widespread human impact becomes more apparent in most western Mediterranean sites both at low (Mercuri and Sadori, 2014) and high altitudes (Pini et al., 2017; Catalán et al., 2019), resulting in a significant reduction of the forest cover (Davis et al., 2015; Birks, 2019).

The Argaric culture represents the Bronze Age (*ca.* 4250–2850 cal yr BP) in the region, with a major surge in population (Lillios et al., 2016; Fyfe et al., 2019), which increased human pressure on all natural resources (Rodríguez Ariza, 1992), especially mining, leading to a large-scale deforestation (Murillo-Barroso et al., 2017). This qualitative leap is also recorded throughout the western Mediterranean, prompting many authors to mark this period as first in which human activity became the primary driver of vegetation change (Kaplan et al., 2009; Roberts et al., 2019). Despite the decline of this culture *ca.* 3500 cal yr BP (Schirrmacher et al., 2020), the forest cover did not appear to regenerate but rather underwent a further decline, firstly with the spread of Iron Age cultures *ca.* 2850 cal yr BP (Buxó, 2008; Gil-Romera et al., 2010). Once again, the link with mining appears strong in the northern and western parts of SN, while data remain scarce for southern slopes (Adroher Auroux et al., 2002; Martín Civantos, 2007). The few palaeobotanical studies available indicate that the

Table 1
Results of Radiocarbon (^{14}C) dating of core samples from Dehesa del Camarate, showing calibrated age ranges (2σ).

Depth (cm)	Lab Code	Age ^{14}C	Age cal yrBP		Probability (%)
			Mín	Max	
35	Poz-64,946	780 ± 30 BP	670	738	95.0
63	Poz-62,302	1940 ± 30 BP	1822	1949	94.7
			1965	1965	0.2
83	Poz-64,947	3340 ± 30 BP	3480	3538	23.1
			3544	3640	70.3
			3671	3678	1.4
100	Poz-64,948	3750 ± 30 BP	3988	4047	20.8
			4067	4162	64.7
			4168	4179	1.9
			4199	4228	7.5
109	Poz-68,674	4525 ± 35 BP	5049	5194	61.5
			5212	5308	33.4

Table 2
Results of Radiocarbon (^{14}C) dating of core samples from Cáñar, showing calibrated age ranges (2σ).

Depth (cm)	Lab Code	Age ^{14}C	Age cal yrBP		Probability (%)
			Mín	Max	
16	Poz-92,960	260 ± 30 BP	151	171	12.2
			280	331	56.7
			357	431	29.7
32	Poz-92,961	745 ± 30 BP	662	726	100.0
48	Poz-92,962	1220 ± 30 BP	1063	1188	78.3
			1203	1258	21.7
62	Poz-64,990	2040 ± 30 BP	1903	1908	0.8
			1923	2068	91.8
			2079	2111	7.4

forest supplied essential wood for smelting and construction (Ruiz and Rodriguez Ariza, 2002).

The arrival of Roman culture (*ca.* 2150 cal yr BP) triggered an overall landscape transformation throughout the Mediterranean (Carrión et al., 2010; Roberts et al., 2019). In the study area, the Roman landscape heritage is linked to rural settlements. The palaeobotanical studies confirmed the widespread human transformation of landscape with settlements and open areas for pastures, together with the likely introduction of olive cultivation (Rodríguez-Ariza and Montes Moya, 2005).

Roman land-use patterns persisted for centuries (Salvador Ventura, 2012) until the Islamic Period beginning in the early AD 8th century, when a major landscape change occurred on SN, especially concerning irrigation and terracing, as well as the diversification of human activities (Salvador Oyonate, 2013; Martín Civantos, 2014). The transition from the medieval to the Modern Period is marked in the area by the repopulation impelled by the Christian Kingdom during AD 16th-17th centuries (Sayadi and Calatrava, 2001; Trillo San José, 2004). Population grew steadily in the following centuries, causing a further intensification in the use of natural resources, but also the establishment of different forest-protection measures (Mesa Garrido, 2016), which culminated in the declaration of the National Park of Sierra Nevada in AD 1999.

2.3. *Coring and chronology*

We extracted a core of 112 cm with a Russian peat corer in DC and divided into samples 2 cm thick for subsequent analyses. Five radiocarbon dating were performed at Poznan Radiocarbon Laboratory (Table 1). We used a similar method to draw a 64-cm core from the mire of Cáñar. Four radiocarbon datings were carried out at the same laboratory (Table 2). We calibrated ages BP (Stuiver et al., 2019) with confidence intervals calculated at 95 % (2σ). We then constructed age-depth models (Fig. 3) applying a smooth-spline solution with Clam 2.2 software (Blaauw, 2010).

2.4. *Pollen, non-pollen palynomorphs (NPPs) and microcharcoal analyses*

Sample treatment for pollen analysis followed the methodology of Faegri and Iversen (1989), using Thoulet solution for the densimetric separation of pollen and NPPs, and adding a *Lycopodium* tablet to each sample in order to estimate the pollen concentration. We used TILIA to process the data and graphics (Grimm, 2004).

We identified pollen and NPPs with the help of several keys and atlases (*e.g.* Reille, 1999; Van Geel, 2001) whereas nomenclature followed Miola (2012). We counted microcharcoals on the same pollen slides (Mooney and Tinner, 2011) and classified them into 2 categories (>100 and <100 μm) to indicate local or regional fires, respectively. A synthetic pollen diagram of each deposit was

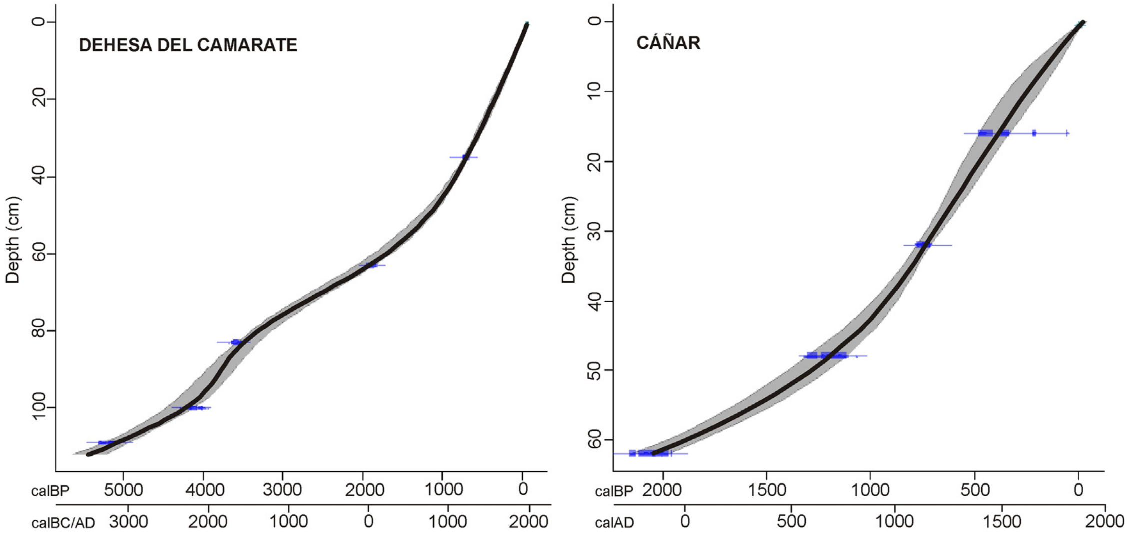

Fig. 3. Age-depth models for Dehesa del Camarate and Cáñar mires.

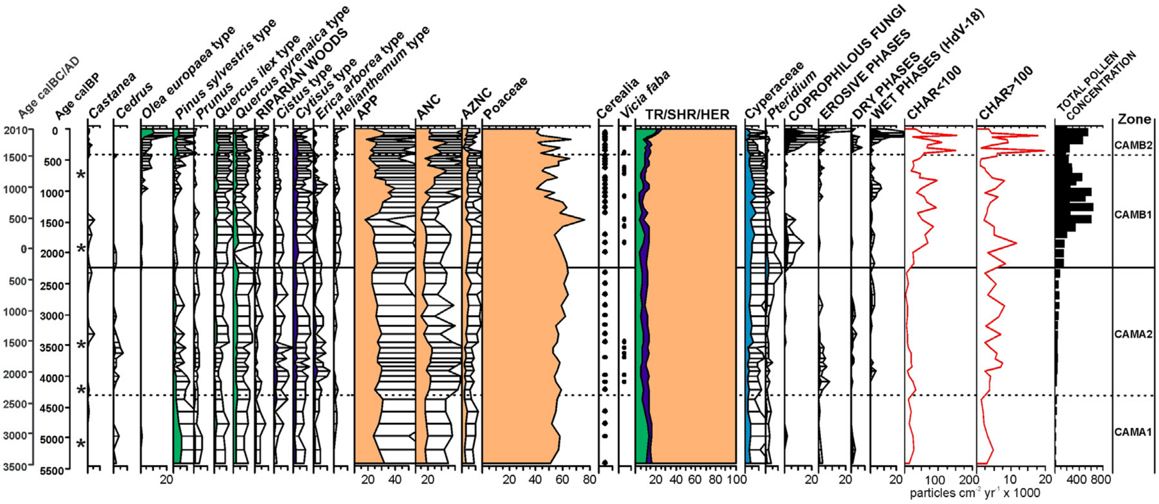

Fig. 4. Summary diagram of Dehesa del Camarate (DC), including selected pollen types, NPPs, CHAR and Total Pollen Concentration. APP: Anthropogenic Perennial Pastures; ANC: Anthropogenous Nitrophilous Communities; AZNC: Anthropozoogenous Nitrophilous Communities; TR: Trees (= Arboreal Pollen –AP-); SHR: Shrubs; HER: Herbs; Stars indicate Radiocarbon datings.

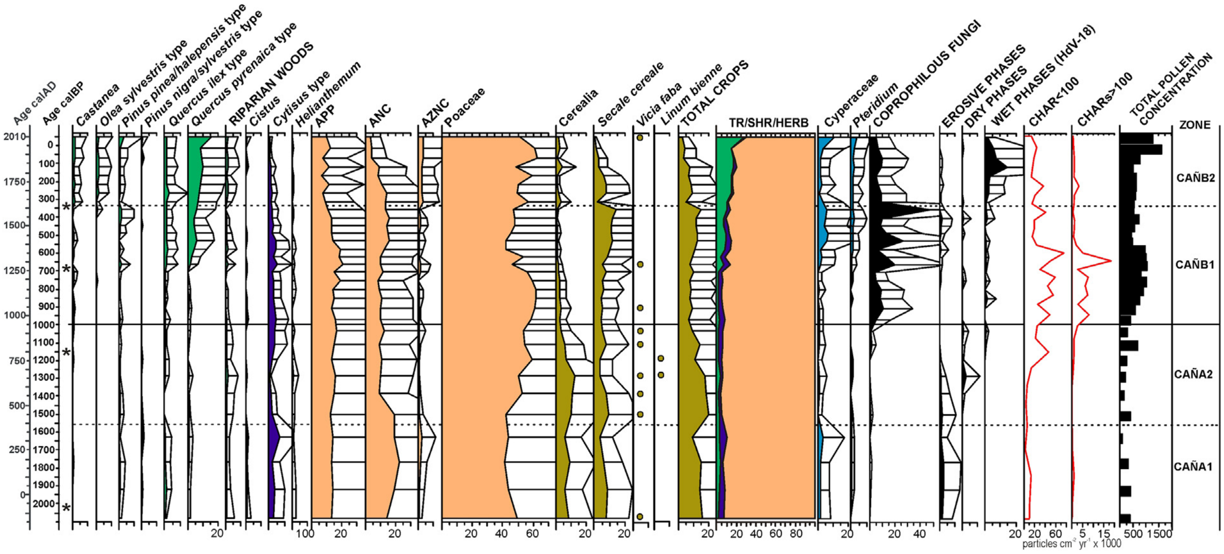

Fig. 5. Summary diagram of Cáñar, including selected pollen types, NPPs, CHAR and Total Pollen Concentration. APP: Anthropogenic Perennial Pastures; ANC: Anthropogenous Nitrophilous Communities; AZNC: Anthropozoogenous Nitrophilous Communities; TR: Trees (= Arboreal Pollen –AP-); SHR: Shrubs; HER: Herbs; Stars indicate Radiocarbon datings.

included (Figs. 4 and 5), where a number of pollen types and NPPs were merged according to their ecological affinities (Table 3), as well as charts showing the Total Pollen Concentration and the Charcoal Accumulation Rates (CHAR). This latter chart was determined by dividing the concentration of microcharcoals by the sedimentation rate of each sample obtained from the age-depth model.

3. Results

The sequence of DC starts *ca.* 5410 cal yr BP, while the one of Cáñar begins *ca.* 2080 cal yr BP. Both of them were divided into four distinct subzones (Tables 4 and 5; Figs. 4 and 5). Likewise, main results are summarized and compared with other proxies and studies in Fig. 6.

4. Discussion

*4.1. The last remaining ancient forests during the Chalcolithic (*ca. *5410–4300 cal yr BP)*

The deepest part of DC (CAMA1) core corresponds to the transition from Middle to Late Holocene (Walker et al., 2012), a period climatically defined by an aridification process throughout the western Mediterranean (Jalut et al., 2009; Pérez-Obiol et al., 2011). This aridity trend (Fig. 6) has also been detected in SN and nearby ranges (*e.g.* Anderson et al., 2011; Oliva et al., 2014), starting *ca.* 5700 cal yr BP, and could be behind the origin of this deposit (García-Alix et al., 2012).

This pollen diagram (Fig. 4) shows a remarkably low percentage (*ca.* 13 %) of arboreal pollen (AP) in this subzone (Table 4) compared

Table 3
Groups of pollen and non-pollen palynomorphs according to their ecological affinities.

Group	Pollen and NPPs
Riparian woods	*Alnus, Betula, Corylus, Fraxinus, Juglans, Prunus, Salix, Ulmus*
Crops	Cerealia, *Secale cereale, Vicia faba, Linum*
Anthropogenic Perennial Pastures (APP)	*Allium*, Apiaceae, *Artemisia*, Brassicaceae, *Campanula*, Caryophyllaceae, Fabaceae, Liliaceae, *Ranunculus*, Rosaceae, Scrophulariaceae, *Viola*
Anthropogenic Nitrophilous Communities (ANC)	*Anthemis, Aster*, Boraginaceae, Cardueae, *Centaurea cyanus, C. nigra*, Cichorioideae, *Erodium, Galium, Geranium, Malva sylvestris*
Anthropozoogenic Nitrophilous Communities (AZNC)	Chenopodiaceae, *Plantago* spp., *Rumex* spp., *Urtica dioica*
Coprophilous fungi	*Gelasinospora* sp. (HdV 1), *Gelasinospora* cf. *retispora* (HdV 2), *Chaetomium* sp. (HdV 7A), *Sordaria*-type (HdV 55), *Cercophora* sp. (HdV 112), *Sporormiella* sp. (HdV 113), *Coniochaeta* cf. *ligniaria* (HdV 172), *Podospora*-type (HdV 368)
Erosive phases	*Glomus, Pseudoschizaea circula, Entorrhiza* (HdV 527)
Dry conditions	*Pleospora* sp. (HdV 3B), HdV 16C, HdV 63C
Wet conditions	HdV 18

Table 4
Description of pollen zones from Dehesa del Camarate (DC). AP: Arboreal Pollen = TR in Figs. 4 and 5; APP: Anthropogenic Perennial Pastures; ANC: Anthropogenous Nitrophilous Communities; AZNC: Anthropozoogenous Nitrophilous Communities; CHAR: Charcoal Accumulation Rates.

SUBZONE Depth (cm)/ Age (cal BP)	Trees/Shrubs	Herbs	NPPs	Pollen Concentration/CHAR
CAMA1112–101 cm*ca.* 5410–4300 cal yr BP/ 3460–2350 cal yr BC	AP (TR in Figs. 4 and 5): 7–12,8%*Pinus sylvestris (5,9–1,7%), Quercus pyrenaica* (1–2%), *Q. ilex* (1–2%)Riparian woods (>1%)Sporadic occurrences of *Abies* and *Cedrus Cytisus* (1–2%), *Cistus* (0–2%), *Erica arborea* and *Helianthemum* (<1%)	Poaceae (51–58%)APP (13,5–21,8%)ANC (7,2–9,4%) AZNC (2,4–4%)Sporadic CerealiaCyperaceae (4–1,3%)	Coprophilous fungi only *ca.* 5000 cal yr BPLow levels of Erosive and Dry phases indicators	Lowest Pollen concentrationLow levels of CHAR, higher of bigger ones
CAMA2101–67 cm*ca.* 4300–2250 cal yr BP/ 2350–300 cal yr BC	AP: 5–8,4%*Pinus sylvestris* (2,4–0,2%), *Quercus pyrenaica* (1–4%), *Q. ilex* (1–2%) Continuous curve of *Cedrus* from 3800 to 3300 cal yr BP < 1%Riparian woods (∼1%)*Cytisus* (1–2,6%), *Cistus* (0,5–3%), *Erica* (0–2,4%)	Poaceae (53–64%)APP (20,5–13,1%)ANC (12,7–7,8%) AZNC (2–6,8%)Continuous curve of Cerealia (<1%), *Vicia faba* appears sporadicallyCyperaceae (2,4–3,6%)	Coprophilous fungi nearly absentIncrease of Erosive phases indicatorsAlternative low levels of Dry and Wet phases indicators	Slight increase of Pollen concentrationLow levels of CHAR < 100 andmedium ones of CHAR > 100 µm
CAMB167–23 cm*ca.* 2250–410 cal yr BP/ 300 cal yr BC-1540 cal yr AD	AP: 4–9,5%*Pinus sylvestris* (0–2%), *Quercus pyrenaica* (3,9–2%), *Q. ilex* (2–3%) Continuous curve of *Castanea* ∼1400 cal yr BP and *Olea* from ∼1050 cal yr BPSporadic occurrences of *Cedrus*Riparian woods (∼1%)*Cytisus* (1–3,6%), *Cistus* (0,2–1,5%), *Erica* (0–2%), *Helianthemum* (1%)	Poaceae (62,7–54%)APP (16,7–12,3%)ANC (6,3–14,1%) AZNC (4,1–5,2%)Almost continuous curve ofCerealia (<1%), *Vicia faba* appears sporadicallyMaxima of Cyperaceae (8,3%)	Coprophilous fungi increase initiallySignificant increases of Wet and Erosive phases indicators ∼1135–860 cal yr BPDry phases indicators nearly absent	Initial increase and final decrease of Total Pollen ConcentrationHigher values of CHAR
CAMB223–0 cm*ca.* 410 cal yr BP/1540 cal yr AD-present	AP: 9,7–21,1%*Olea* (1–10,4%), *Pinus sylvestris* (2–4,1%), *Quercus pyrenaica* (2–3%), *Q. ilex* (2–4%)Riparian woods (1–2%)*Cytisus* (3,2–2,7%), *Cistus* (<1%), *Erica* (<1%), *Helianthemum* (0,6–1,5%)	Poaceae (43,2–42,8%)APP (15,1–13,4%)ANC (20–12%) AZNC (6,2–4,3%)Cerealia (<1%), sporadic *Vicia faba*Cyperaceae (0,2–3,7%)	Maxima of Coprophilous fungi and Erosive phases indicatorsHigh levels of Wet phases indicators and lower of Dry phases indicators	Final drop of Pollen ConcentrationMaxima of CHAR

to previous high-mountain fossil records from SN (Fig. 1), where it is represented mainly by *Pinus* and consistently over 20 %. Furthermore, all of them are located at significantly higher elevations (*ca.* 2500–3000 m asl), further from both the timberline and human signal during that period. This anomaly might be attributed to higher aridity in DC, as rainfall decreases eastwards in SN and temperatures also fall along the northern slopes (Olivares et al., 2011), both limiting forest development (Oliva et al., 2014). Nevertheless, the forest decline detected in DC could be rather ascribed to human impact, which probably started earlier on this mountain side, as shown by the presence of significant levels of Anthropogenous Nitrophilous Communities (ANC) and minor ones of Anthropozoogenous Nitrophilous Communities (AZNC) and microcharcoals, as well as the sporadic appearances of coprophilous fungi and pollen of Cerealia. It would have given rise to an open landscape where scrubland and mostly grasslands became a predominant part, after the depletion of the last remaining ancient pine forests. This latter demise occurred at *ca.* 5200 cal yr BP in Laguna de Río Seco (Anderson et al., 2011) and somewhat later (*ca.* 4300–4000 cal yr BP) in the other records. This delayed response could be related to the cited higher location of these deposits.

At that time, human populations expanded as a result of advances in agriculture and farming (Martín Socas et al., 1999; Carrasco Rus et al., 2016). From Neolithic to Calcolithic human

Table 5

Description of pollen zones from Cáñar. AP: Arboreal Pollen = TR in Figs. 4 and 5; APP: Anthropogenic Perennial Pastures; ANC: Anthropogenous Nitrophilous Communities; AZNC: Anthropozoogenous Nitrophilous Communities; CHAR: Charcoal Accumulation Rates.

SUBZONE Depth (cm)/ Age (cal BP)	Trees/Shrubs	Herbs	NPPs	Pollen Concentration/ CHAR
CAÑA162–56 cm*ca.* 2000–1560 cal yr BP/ 50 cal yr BC-390 cal yr AD	AP (TR in Figs. 4 and 5): 2–3,3% *Pinus pinea/halepensis, Quercus pyrenaica* and *Q. ilex* below 1% respectively; Riparian woods (~1%)*Cytisus* (3–6,6%), *Cistus*, *Erica* and *Helianthemum* (<1%) respectively	Poaceae (41,7–49,3%)APP (13,1–14,4%)ANC (14,1–22,1%) AZNC (0,4–2,3%)Cerealia (8–5%), *Secale* (8–4%) Cyperaceae (1,7–3,5%)	Coprophilous fungi, Dry and Wet phases indicators almost absentMedium levels of Erosive phases indicators	Medium Pollen concentrationLow levels of CHAR
CAÑA256–44 cm*ca.* 1560–1000 cal yr BP/ 390–950 cal yr AD	AP: 1,8–3,8%*Pinus pinea/ halepensis, Quercus pyrenaica* and *Q. ilex* below 1% respectively; Riparian woods (~1%)*Cytisus* (1,9–3,4%), *Cistus*, *Erica* and *Helianthemum* (<1%) respectively	Poaceae (42,2–59,3%)APP (12,5–16,7%)ANC (19,3–12,9%) AZNC (<1%)Cerealia(10–3%), *Secale* (9–6%)Cyperaceae (~1%)	Final slight increase of Coprophilous fungiErosive phases indicators decrease, while Dry phases indicators prevail over Wet phases ones	Increase of Pollen concentrationMaximum of CHAR < 100 and low ones of CHAR > 100 μm
CAÑB144–16 cm*ca.* 1000–335 cal yr BP/ 950–1590 cal yr AD	AP: 2,6–10,2%*Quercus pyrenaica* (0,5–6,1%), *Q. ilex* (0,7–1,8%), *Pinus pinea/ halepensis* (0,5–2%), *Olea europaea* (<1%)Riparian woods almost disappear*Cytisus* (4,2–2%), *Cistus*, *Erica* and *Helianthemum* (<1%) respectively	Poaceae (58,8–47%)APP (15,5–11,1%)ANC (10,4–13,3%) AZNC (>1%)Cerealia (2,2–0,5%), *Secale* (4,6–14%)Cyperaceae (0,7–5,6%)	Coprophilous fungi final maximumDry, Wet and Erosive phases indicators keep their levels	Increase of Pollen ConcentrationMaxima of CHAR
CAÑB216–0 cm*ca.* 335 cal yr BP/1590 cal yr AD-present	AP: 10,8–28,1%*Quercus pyrenaica* (6,4–15,9%), *Pinus pinea/halepensis* (0,4–3,1%), *Olea europaea* (0,4–2,3%), *Castanea*, *Q. ilex* and Riparian Woods (>1%) respectively *Cytisus* (1,3–0,7%), *Cistus* (<1%)	Poaceae (57,4–51%)APP (9,4–9,9%)ANC (13,4–3,5%) AZNC (2,8–3,3%)Cerealia (<2%), *Secale* (<1%)Cyperaceae (0,2–3,7%)	High levels of Coprophilous fungiHigh levels of Wet phases indicators and lower of Dry and Erosive phases indicators	Final maximum of Pollen ConcentrationMinor but significant levels of CHAR

traces (Fig. 2) spread not only to coastal zones but also to montane areas of Southern Iberia (Rodríguez-Ariza, 2000; Nocete, 2006).

The Chalcolithic (*ca.* 5300–4250 cal yr BP), represented mainly by the Los Millares copper culture (Lull et al., 2010; García Sanjuán and Murillo-Barroso, 2013), registered a further rise after *ca.* 4800 cal yr BP (Schirrmacher et al., 2020), which matched the retreat of pine forests as well as the parallel minor signs of human activities near the study area.

Beyond the dynamics of major forest taxa, the pollen diagram records the sporadic presence of some noteworthy types, such as *Betula* or *Cedrus*. Although these underwent different dynamics throughout the Holocene, their appearance in the pollen diagram remained under 1%. The DC pollen diagram shows that the *Betula* populations were no larger than the current ones for the last 5000 years.

Cedrus presence in several pollen diagrams of south-eastern Spain has long been attributed to the Saharian winds (Magri, 2012), mainly in arid periods (see details on Alba-Sánchez et al., 2018). However, its appearance in the present study and other works for the SN (Anderson et al., 2011; Jiménez-Moreno et al., 2013; Manzano et al., 2019) does not correspond (Fig. 6) to the periods with the highest incidence of African winds (Jiménez-Espejo et al., 2014), a finding that supports the persistence of small, isolated pockets of *Cedrus* in SN during the Holocene, which would have gone extinct as a result of human impact (Postigo-Mijarra et al., 2010). Nevertheless, further studies are needed to clarify this controversy.

*4.2. Forest demise and increasing human pressure during Bronze and Iron ages (*ca. *4300–2250 cal yr BP)*

Conditions in the study area remained arid and even became drier as well as cooler (Anderson et al., 2011; Zielhofer et al., 2019; Schirrmacher et al., 2020) at least until 3100 cal yr BP (Jiménez-Moreno et al., 2013; Ramos-Román et al., 2016). Later, a wet period beginning *ca.* 2600 cal yr BP occurred in SN and nearby areas (Martin-Puertas et al., 2010; Nieto-Moreno et al., 2011; Ramos-Román et al., 2018b).

For this initial phase of subzone CAMA2, the pollen diagram (Figs. 4 and 6) shows minimum percentages of AP (Table 4). *Pinus* maintains its steady decline, while, among herbs, ANC significantly advances, whereas *Vicia faba* joins Cerealia for the first time. Indicators of both Erosive and Wet phases also become notable. The former is made up mainly of *Glomus* (HdV 207), which has been also related to the decline of conifer forests (Montoya et al., 2018). The appearance of the latter, HdV 18, in a marked arid phase has been linked to the advent of rudimentary irrigation (Abel Schaad and López-Sáez, 2013). These clear traces of human presence near the study area are also revealed by a higher incidence of local fires, denoted by the increasing levels of larger particles of microcharcoal, which reach a maximum *ca.* 3800 cal yr BP.

The pine forest demise in DC coincides with this date. This depletion also appears to be more or less coetaneous in the other records of SN (Fig. 1), but not always so strong (Anderson et al., 2011; Jiménez-Moreno and Anderson, 2012; Mesa-Fernández et al., 2018). In addition to the aforementioned harsh climatic conditions, human activities would have reduced the tree cover to its minimum. A peak of fire incidence has also been reported between *ca.* 4200 and 3700 cal yr BP in most of the records studied in the area (Carrión et al., 2007; Gil-Romera et al., 2010; Manzano et al., 2019). The concurrent record of other indicators cited in DC suggests a human origin to these fires. In fact, this period coincides with the broadest expansion of the Argaric culture (*ca.* 4200–3500 cal yr BP) in south-eastern Iberia during the Early Bronze Age, entailing a surge in population and an intensification of metallurgy

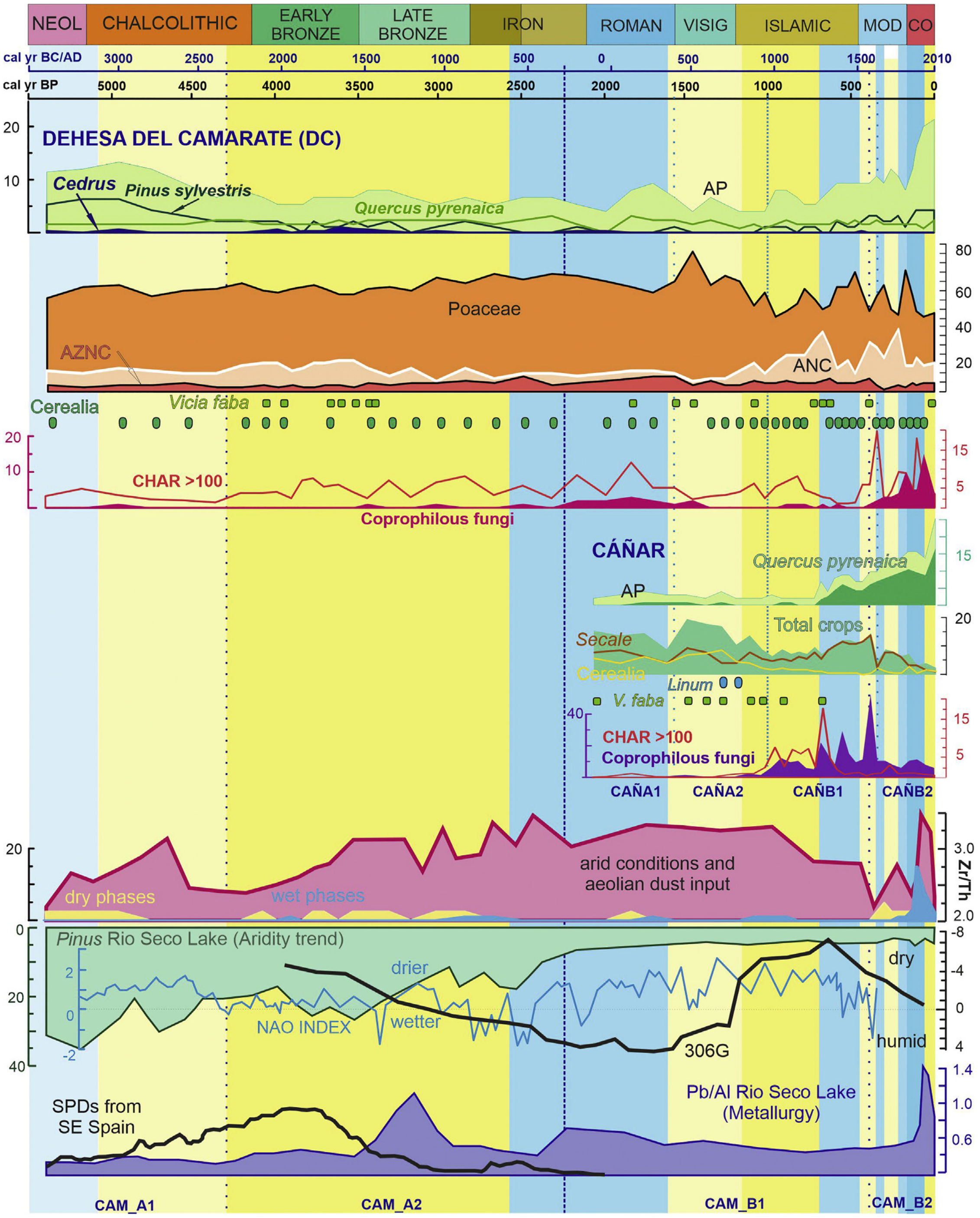

Fig. 6. Main environmental changes in Sierra Nevada during the last 5300 years based on the analysis of Dehesa del Camarate (DC) and Cáñar mires. (Aeolian dust input from Jiménez-Espejo et al., 2014; Aridity trend of Río Seco Lake from Anderson et al., 2011; Dry *versus* humid climate conditions of the west Balearic-Algerian Basin 306 G core from Nieto-Moreno et al., 2011; NAO Index from Olsen et al., 2012; Palaeodemographic proxy (SPDs) for SE Spain from Fyfe et al., 2019; Pb/Al of Río Seco Lake from García-Alix et al., 2013). Humid (blue) and Dry (yellow) phases have been set based on Martin-Puertas et al., 2010; Nieto-Moreno 2011; 2013; and García-Alix et al., 2017. MOD: Modern Period; CO: Contemporary Period.

(García-Alix et al., 2013; Fyfe et al., 2019; Schirrmacher et al., 2020). The cultivation of legumes, such as *Vicia faba*, as well as small-scale irrigation (Lull et al., 2013) could point to the presence of this culture in this high-mountain environment.

Likewise, the collapse of this culture at *ca.* 3500 cal yr BP could be reflected in the pollen record (Figs. 4 and 6; Table 4) by the decrease of ANC, the disappearance of *Vicia faba*, Erosive and Wet Phases indicators against the sporadic occurrence of coprophilous fungi and the slight increase of AZNC. These cues appear to indicate a land-use change during the Late Bronze Age, oriented more towards livestock (Lull et al., 2013). After the disintegration of the Argaric culture, a major population drop has been recorded in south-eastern Iberia (Schirrmacher et al., 2020), which could have favoured the recovery of forests, particularly at high altitudes. The persistent aridity, high rate of landscape degradation and the impact of grazing would have prevented the growth of woody vegetation (Fyfe et al., 2019).

In any case, mining formed a major part of human activities at this time in this region (Carrión et al., 2003), as shown by the numerous sites located close to the study area (Fig. 2), most of them in use since the Bronze and even the Copper Age (Adroher Auroux et al., 2017). They became more robust with the onset of Iron Age (*i.e.* Iberian Period), *ca.* 2850 cal yr BP, when the population again increased, especially from 2550 cal yr BP onwards (Buxó, 2008).

The Iberian Period is considered a time of major human impact on south-eastern Spain (Gil-Romera et al., 2010; Anderson et al., 2011), where a high incidence of human-induced fires has also been documented (Carrión et al., 2007). Moreover, a wet period occurred in this region (Fig. 6), beginning *ca.* 2700 cal yr BP (Martin-Puertas et al., 2010; Jiménez-Moreno et al., 2013; Ramos-Román et al., 2018b), which appeared to favour a forest recovery. Increasing wetness was confirmed in the pollen diagram (Fig. 4; Table 4) by the almost continuous presence of HdV 18. However, no significant land-use change is detected in the record of DC, where the landscape appears to have remained almost unaltered during this period, compared to the previous one. A slight intensification of grazing activities, favoured by fires, presumably impoverished the grasslands, as indicated by the overlap of the increase of AZNC and Poaceae, the lowering of APP as well as the permanent levels of coprophilous fungi and microcharcoal particles.

4.3. *Crops* vs. *Livestock on each slope of SN (*ca. *2250–410 cal yr BP)*

4.3.1. *Roman period (*ca. *2150–1530 cal yr BP)*

The arrival of Romans (*ca.* 2150 cal yr BP) to the south-eastern Iberian Peninsula resulted in an overall landscape change (Carrión et al., 2010). The rise of temperatures, together with increasing rainfall (Martin-Puertas et al., 2010; Nieto-Moreno et al., 2011) helped the intensification of human pressure, particularly related to agriculture (McCormick et al., 2012). Nonetheless, mining activities were likely the first attraction for Romans in this area (González Román, 2001; García-Alix et al., 2013). Later, during the High Empire (*ca.*1950–1750 cal yr BP), the general population underwent a further surge strongly associated with agriculture, which gave rise to a large number of *villae* as well as smaller and more scattered farms (Salvador Oyonate, 2012). Finally, the population levels fell during the Low Empire (*ca.* 1750–1530 cal yr BP), when agrarian lands became consolidated into fewer hands and the populace moved to higher elevations (González Martín, 2014).

The core of DC (Fig. 4 and 6; Table 4) initially registered a minimum of AP, perhaps related to the simultaneous rise in metallurgy (Bertrand and Sánchez Viciana, 2008). Thereafter, a slight recovery of oak forests matches the reported wettest period around *ca.* 1700 cal yr BP (Martin-Puertas et al., 2010; Nieto-Moreno et al., 2011), despite greater human pressure, also observed in nearby deposits (Carrión et al., 2003, 2007; Anderson et al., 2011). Fires prevented further forest recovery, firstly affecting heathlands and later also forests, as landowners sought to provide grazing for the increasing livestock density, this being reflected by the growing levels of coprophilous fungi, although pastoralism has not been particularly related to Romans (Gómez-Pantoja, 2016). The DC record also indicates an increasing trend in AZNC, pointing to a parallel increase in grazing pressure, possibly related to the spread of different kinds of farms in the nearby area (Salvador Oyonate, 2012). Moreover, the synchronous high levels of microcharcoals coincide with maxima in most of the records of SN (Jiménez-Moreno et al., 2013), which show no imprint of grazing activities, whereas they are located at higher elevations. By contrast, livestock pressure clearly increased in Sierra de Gádor during this period (Carrión et al., 2003).

On the other hand, crops appear to have diminished, since Cerealia became scarcer, albeit *Vicia faba* appears in the record again. The almost continuous curves of *Castanea* and *Olea* should also be noted, as characteristic cultivated tree species of this period (Rodríguez-Ariza and Montes Moya, 2005), despite the fact that both of them appeared sporadically much earlier in the profile.

The pollen diagram of Cáñar (Figs. 5 and 6; Table 5) started shortly after the arrival of the Romans (*ca.* 2080 cal yr BP) and shows an open landscape, widely dominated by grasslands, with a significant area occupied by cereal crops. The remarkable low levels of AP indicate intense deforestation in former times, likely related to mining or agriculture (Martín Civantos, 2014). The curves for both Cerealia and *Secale cereale* (rye) indicate their local cultivation (López Sáez and López Merino, 2005). *Vicia faba* is also recorded in the first sample. The low levels of coprophilous fungi and AZNC reflect the minor amount of livestock grazing on this southern slope as well as the limited associated fires, pointed by microcharcoals. Indicators of Erosive phases could be linked to agricultural activities, focused mainly on herbaceous crops, as pointed by the absence of *Castanea* or *Olea* pollen during this period.

Therefore, over the Roman period, a distinct land use was taking shape on each side of SN. While crops grew on the southern slopes, even at rather high altitudes, livestock grazing appeared to be better adapted to northern slopes, where cooler temperatures would have hindered a major expansion of agriculture. At the end of this period, a slight decrease is revealed both by crops and by coprophilous fungi, presumably linked to the aforementioned Low Empire crisis, also recorded in DC.

4.3.2. *Middle ages (*ca. *AD 420–1492)*

After the fall of the Roman Empire (*ca.* CE 420), a period of political instability began in south-eastern Iberia, marked by the Visigothic Period *ca.* CE 589 (Salvador Ventura, 2012). Meanwhile, dryness progressively increased from about 350 CE until peaking around CE 650, accompanied by cooler temperatures, typifying Dark Ages (Nieto-Moreno et al., 2011). In DC, Poaceae reaches a maximum in the profile (Figs. 4 and 6), apparently in relation to the abandonment of livestock grazing and cereal cultivation, but it appears to be more closely related to human than to climate-induced changes, as cereal crops recover and even surpass their levels in the following samples. This trend is more pronounced in Cáñar, where Cerealia reaches its highest percentages, with notable levels of *Secale cereale* and, for the first time, the sporadic occurrence of *Vicia faba*, while coprophilous fungi, indicating livestock grazing, remain almost absent.

In the early 8th century (AD 711), the Islamic Period begins in Iberia, lasting until the end of 15th century (AD 1492). The beginning coincides roughly with the onset of a new phase of aridity, the so-called Medieval Climate Anomaly (MCA), from AD 800–1300 (Nieto-Moreno et al., 2011), more intense between AD 1000 and 1300 (Nieto-Moreno et al., 2013), and also warmer than the previous one (Moreno et al., 2012).

Overall, al-Andalus communities were based on a multi-productive system. Although agriculture was the main land use, both metallurgy and livestock were well represented in the area, the former mostly near north-western slopes (Martínez Ruiz, 1999; Martín Civantos, 2001, 2014; Liarte Alcaine, 2010). Farms were not large, particularly in mountain areas, but grew a large number of crops, through the installation of new irrigation systems as well as the communal use of more distant lands (Trillo San José, 2004). Both the deposit of DC and Cáñar (Fig. 1) are currently located next to an irrigation channel (MEMOLA Project, 2014). All of these infrastructures are believed to have been built towards the first half of 10th century (Trillo San José, 2004).

During the initial period of Islamic Period, until *ca.* CE 950, few changes appear in the pollen diagram of Cáñar (Figs. 5 and 6), revealing the transition towards new ways of land management. After this short event, a shift begins with the first appearance of *Linum*, the decline in Cerealia as well as the increase in *Secale cereale* and, to a lesser extent, of *Vicia faba*. In addition, coprophilous fungi reached significant levels, coinciding with the return of HdV 18. This NPP, indicating wet phases in the most arid segment of the MCA (Nieto-Moreno et al., 2013), could be related to the first traces of irrigation in this area.

The initial stages of the following subzone, CAÑB1, until *ca.* CE 1250, follow the same trend, beginning with a major increase of coprophilous fungi and the virtual demise of Cerealia, while *Secale cereale* remains the main crop. This severe human pressure is accompanied by a stronger incidence of fires, reflected in the remarkable proliferation of microcharcoals, presumably to reduce the extent of shrubland and increase the grassland areas. This earlier part of the subzone spans the establishment of the Caliphate in the 10th century, and the start of the “al-Andalus agricultural revolution” during the 11th century (Hernández Bermejo and García Sánchez, 2000). Irrigation systems were developed and new crops were grown. In this sense, dry farming was virtually abandoned, these lands being transformed to pastureland, mostly in mountain areas (Trillo San José, 2004). The profile of Cáñar clearly shows this dynamic (Fig. 5). Cereal was previously grown without irrigation, as in the Roman agricultural system (Beltrán Lloris and Willi, 2011) in wet areas, but at this time the crop disappears from the pollen diagram, parallel to the spread of coprophilous fungi, pointing to the exploitation of those lands by livestock grazing. *Secale cereale*, better adapted to poor soils and the lower temperatures of high-altitude areas (Hernández Bermejo and García Sánchez, 2008), would eventually be irrigated in spring, as described for this area even in recent times (Guzmán Álvarez, 2010; Martín Civantos, 2014).

Moreover, in the following phase, coinciding with the Nasrid Kingdom (*ca.* AD 1250–1500), dry farming lands were virtually abandoned, allowing the marked expansion of *Quercus pyrenaica* (Figs. 5 and 6), and irrigation networks would have been expanded to water pasturelands also, as indicated by the increase in Poaceae and, especially, Cyperaceae, with the parallel occurrence of high peaks of coprophilous fungi. In addition, new fields were ploughed for the cultivation of rye, as reflected by the concurrent maxima of *Secale cereale* and Erosive phases indicators. Herds, mainly of goats, would stay only seasonally in these high-altitude areas, as indicated also by the low percentages of AZNC, within a short-distance transhumance system (Martínez Ruiz, 1999; Trillo San José, 2004). It should also be noted that a new climatic phase, the Little Ice Age (LIA) began *ca.* AD 1300 (Nieto-Moreno et al., 2013), shifting to a colder and slightly wetter climate, which could have further improved the cultivation of rye against other grains.

Similarly, the pollen diagram of DC (Fig. 4) reveals the likely broadening of irrigation *ca.* AD 850, with the occurrence of HdV 18 shortly after the onset of MCA (Nieto-Moreno et al., 2013), parallel to peaks for indicators of Erosive phases. The retreat of Poaceae and the concurrent increase in APP, mainly due to Apiaceae, could be attributed to an enrichment in palatable species among grasslands through irrigation, as reported by other records in the Iberian Central System (Abel-Schaad and López-Sáez, 2013). However, the absence of concurrent grazing indicators could point to the cultivation of any crop belonging to this family, currently fallen in disuse, such as *Smirnium olusatrum* or *Foeniculum vulgare* (Hernández Bermejo and García Sánchez, 2000). Later, during the Nasrid Kingdom (*ca.* AD 1250-1500), grazing pressure increased slightly, as shown by the levels of coprophilous fungi, the seasonal nature of the grazing being indicated by the limited percentages of AZNC. On the other hand, *Olea* undergoes a notable advance, especially during the last two centuries of this period. By contrast, *Castanea* is the main tree crop on the southern slopes in Cáñar, both trees attesting to agricultural intensification during Islamic Period, even in mountain areas (Trillo San José, 2004).

4.4. The final landscape shaping of SN (ca. AD 1500-present)

4.4.1. Modern Period (ca. AD 1500-1800) AD 1500-1800)

Wet and dry phases alternated within the colder climate corresponding to LIA in this area (Nieto-Moreno et al., 2013).

The pollen diagrams (Figs. 4–6) suggest an earlier change in northern slopes, *ca.* AD 1540, than in the southern ones, where prior conditions remained until *ca.* AD 1600. These dates could be considered the beginning of the repopulation on each side of the mountain by new settlers coming from northern areas (Trillo San José, 2004). This overall change initially involved a severe depopulation (Bañuelos Arroyo, 2008), the slow reconstruction of villages and irrigation systems (Romero Funes, 2016), as well as a greater amount of livestock raising and rainfed farming within a cereal-fallow-pasture system (Sayadi and Calatrava, 2001).

The DC core shows a slight early advance of AP (Figs. 4 and 6), led by *Pinus sylvestris* and *Quercus ilex*, perhaps favoured by colder temperatures in addition an easing of human pressure. *Castanea*, absent since Roman times, recovers its continuous curve, while *Olea* maintains previous levels and Cerealia slightly diminishes, almost disappearing. Conversely, livestock grazing appears to intensify, as indicated by the rising levels of coprophilous fungi, aided by the use of fire on shrublands, with maximum values for microcharcoals. The drop in both HdV 18 and Cyperaceae, as well as the rising levels of Dry phases indicators, could be related to the abandonment of the prior irrigation system.

A similar trend was noted in Cáñar (Figs. 5 and 6), although a few decades later. The pattern of higher percentages for Cerealia and lower ones for *Secale cereale* marks the beginning of such a change. AP also increases, but on this south side led by *Quercus pyrenaica* and *Q. ilex*, as well as the tree crops *Castanea* and *Olea*. Likewise, irrigation appears initially to disappear. Rainfed cereal farming alternated with pastures for livestock, which would be more stable, as indicated by the increase in AZNC.

By AD 1650 and soon afterwards, cultivated areas doubled through the ploughing of new lands, and livestock herds substantially increased (Sayadi and Calatrava, 2001; Bañuelos Arroyo, 2008).

At this time, microcharcoals reach their maxima in DC (Figs. 4 and 6; Table 4) coinciding with high levels of coprophilous fungi and increasing percentages of ANC and AZNC. In addition, Cerealia and *Olea* maintain their levels, whereas *Quercus ilex* and *Q. pyrenaica* diminish, likely related to their use as charcoal and firewood. These trends imply a panorama of overexploitation of natural resources, well described in the chronicles of this period (Mesa Garrido, 2016).

By contrast, the diagram from Cáñar (Figs. 5 and 6) appears to point to less human pressure, as might be inferred from the increase of AP (Table 5), not only by cultivated trees such as *Castanea*, *Olea* or *Juglans*, but also, and especially, by *Quercus pyrenaica*. In the mid 18th century the first management measures were implemented for forests in Spain, in order to increase the timber production for shipbuilding (Martínez González, 2014). Most oak forests from Cáñar and other nearby areas were included in a catalogue of these guarded forests (Mesa Garrido, 2016). On the other hand, both Cerealia and mostly *Secale cereale* increased but far from previous percentages. Conversely, coprophilous fungi fall but still display significant levels, presumably revealing more stable livestock rearing, as shown by the concurrent rising levels of AZNC, within a likely integrated cycle associated with crops (Sayadi and Calatrava, 2001). Both the low levels of microcharcoals and ANC, as well as the retreat of shrubland with the advance of grasslands would support this scenario. Likewise, the significant rise of HdV 18 levels as well as the slighter one of Cyperaceae and riparian woods, could point to the restart of the prior irrigation channel.

4.4.2. Contemporary Period (ca. AD 1800-present) AD 1800-present)

The overall impact on vegetation during this period on the one hand is negative, as a result of the opening of new mines, large-scale ploughing, and increasing livestock herds. On the other hand, it is positive for the establishment of a set of regulations intended to protect extant forests and restore degraded areas (Sayadi and Calatrava, 2001; Valbuena-Carabaña et al., 2010; Mesa Garrido, 2016). This new time period also overlaps with the so-called Industrial Period, during a period characterized by increasing moisture in this region, which lasted until the 2nd half of the 20th century. Then, rainfall followed a negative trend until the present (Nieto-Moreno et al., 2013).

A significant increase in AP begins the pollen diagram of DC (Figs. 4 and 6; Table 4), mainly due to *Olea*, but also to *Pinus sylvestris*, likely favoured by increasing wetness and by the implementation of Reforestation Plans in this area from AD 1940 onwards (Mesa Garrido, 2016). Other tree taxa, such as *Quercus* or riparian woodlands expanded only slightly in the last sample, as a consequence of the later establishment of protective measures during the 20th century, resulting in the establishment of the Sierra Nevada National Park. Previously, the successive Disentailment Laws in the mid-19th century triggered further pressure on vegetation (Valbuena-Carabaña et al., 2010), specially indicated by the high levels of microcharcoals and coprophilous fungi. The rising values of HdV 18, Cyperaceae, together with the enrichment of grasslands indicated by APP, may reflect a broader irrigation system for pastures, which would have allowed a longer presence of herds in the area, as suggested by the increase in AZNC.

The diagram from Cáñar (Figs. 5 and 6; Table 5) reveals a shift towards a more livestock-oriented land use at the expense of crop cultivation, reflected in the decreasing percentages of herbaceous crops, especially *Secale cereale*, the spread of grasslands and the concurrent advance of coprophilous fungi. The irrigation of these pasturelands, indicated by the maxima of HdV 18, would have likewise extended the stay of flocks, within the traditional short-distance transhumance system (Rubio de Lucas et al., 1995). Tree crops such as *Olea* and particularly *Castanea* also became more prevalent in the area during this period. Among the other tree taxa, *Quercus pyrenaica* maintained its percentages throughout most of 19th and 20th centuries, probably because of the exemption of their forests in Cáñar from the ones included in the Disentailment Laws and their subsequent accreditation as Public Mounts. They were likely used by the local settlers for firewood, leaves or acorns but maybe not for grazing (Mesa Garrido, 2016). The strikingly low levels of microcharcoals in the pollen diagram support this idea. In any case, *Q. pyrenaica* is considered resilient to human impact (Valbuena-Carabaña and Gil, 2013) and even benefits by it (Salomón et al., 2017). This was one of the first areas where reforestation works started (Mesa Garrido, 2016), in the beginning of 20th century. *Pinus pinea/halepensis* and *P. sylvestris* display a significant increase in the top sample, likely related to these tasks, but also to the lowering of human pressure and the new management measures after the Declaration of SN as National Park.

4.5. Implications for conservation

The conservation of cultural landscapes, such as SN (Jiménez-Olivencia et al., 2006; Gómez-Ortiz et al., 2013) requires integration of a long-term perspective for current and future management strategies (Gillson, 2015; Whitlock et al., 2018). Land-use history becomes an essential information in the Mediterranean, where human activities developed since at least the Middle Holocene (Davis, 2015), with a distinct dynamics in mountain areas (Zamora Rodríguez et al., 2015; Catalán et al., 2019). In this sense, our work provides some valuable issues which should be taken in consideration:

- Forest cover was quite thinner in the final stages of the mid-Holocene (*ca.*5400 cal yr BP) than currently on the northern slopes of SN, with a minor extent of pinewoods, which show a high vulnerability against human activities. Environmental change appears to have been induced by human influence rather than by climate since then. The collapse of ancient forests could be set at *ca.* 4000 cal yr BP.
- Current forest cover in SN has expanded quite recently. Oak forests of *Quercus pyrenaica* only spread since *ca.* AD 1250 on the southern slopes, first helped by the abandonment of dry-farming lands and the multiple resources they provided, and later by the increasing protection measures. Both *Castanea* and *Olea*, despite their early origin, gain relevance during the last three centuries. Current pine woodlands were mainly planted in 20th century.
- Grasslands have been the predominant part of vegetation during, at least, 5000 years, together with other herbaceous species. They have been fostered and kept by humans for agriculture, mostly for pastures. Irrigation systems enhanced their maintenance, especially since *ca.* AD 1000, during Islamic Period and later on, becoming the basis of the traditional multiproductive system.

Therefore, the high biodiversity of SN has been also preserved and promoted by humans over the last millennia, beyond the influence of progressive climate changes. Current and future warming is not the sole thread to biodiversity that environmental managers should cope, but also land abandonment related to depopulation, which only could be controlled with the preservation of traditional human activities like grazing, high-elevation cropping or irrigation systems. In this sense, the implementation of good practices for maintaining these long-established activities becomes essential.

5. Concluding remarks

In conclusion, the analysis of two pollen records from both sides of SN in the western Mediterranean mountains provides answers to the two main research questions posed in this paper.

First, the main tipping point when natural systems transformed to cultural landscapes occurred during the Chalcolithic (*ca.* 5400 cal yr BP). This transformation was defined by very low percentages of AP (half of current forest cover), and concurrent traces of human activities. So far, human impact in SN had been established more than 1000 years later, during the Bronze Age.

Second, a further intensification of human activities occurred during the Argaric culture (*ca.* 3800 cal yr BP) and reached its maximum degree with the onset of Iron Age, when climate became more humid. Mineral resources, but not solely, apparently acted as main drivers of population growth, causing a severe decline of ancient forests.

Later, Romans triggered an increase of livestock pressure to northern slopes, whereas crops grew on the southern ones, but with a lesser extent as described at low elevations.

A significant land-use change occurred during Islamic Period, with the installation of an irrigation network within a multi-productive system, against the warm and dry conditions of the M*ca.*

Climate hampered an eventual forest recovery due to the arid mid-to-late Holocene conditions. Later, despite favourable climatic conditions during certain periods, only land-use changes have allowed the spread of the tree cover, in the form of orchards (*Castanea* and *Olea*), afforestation (*Pinus*) or the development of secondary forests (*Quercus pyrenaica*). Ultimately, the implementation of environmental protection measures has promoted the spread of the most extensive forest cover.

SN mountain vegetation has been strongly changing over a long temporal scale. Long-term studies involving climate-human-vegetation interactions are required for current ecosystem restoration and sustainable forest management, as well as for a better understanding of SN forest resilience and the tipping points which occurred in the past. The preservation of traditional human activities becomes crucial to ensure orophilous-mesophilous biodiversity in the face of oncoming threats.

Declaration of Competing Interest

None.

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