



Vegetation, fire, climate and human disturbance history in the southwestern Mediterranean area during the late Holocene

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ABSTRACT

Detailed pollen, charcoal, isotope and magnetic susceptibility data from an alpine lake sediment core from Sierra Nevada, southern Spain record changes in vegetation, fire history and lake sedimentation since ca. 4100 cal yr BP. The proxies studied record an arid period from ca. 3800 to 3100 cal yr BP characterized by more xerophytic vegetation and lower lake levels. A humid period is recorded between ca. 3100 and 1850 cal yr BP, which occurred in two steps: (1) an increase in evergreen *Quercus* between 3100 and 2500 cal yr BP, indicating milder conditions than previously and (2) an increase in deciduous *Quercus* and higher lake levels, between ca. 2500 and 1850 cal yr BP, indicating a further increase in humidity and reduction in seasonal contrast. Humid maxima occurred during the Roman Humid Period, previously identified in other studies in the Mediterranean region. Intensified fire activity at this time could be related to an increase in fuel load and/or in human disturbance. An arid period subsequently occurred between 1850 and 650 cal yr BP, though a decrease in *Quercus* and an increase in xerophytes. The alternation of persistent North Atlantic Oscillation modes probably played an important role in controlling these humid–arid cycles.

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Introduction

Recent evidence has suggested that future climates in the western Mediterranean, including all of the Iberian Peninsula, will be warmer and drier (Hertig and Jacobeit, 2008; López-Moreno et al., 2011) with declining precipitation frequency (May, 2008). Distinct changes in seasonal precipitation may be underway already (del Río et al., 2001; van Oldenborgh et al., 2009; de Luis et al., 2010). Given these present and future changes, our ability to understand the long-term relationships between climate, vegetation, fire occurrence and human impact for the region can be enhanced by paleoecological analyses from sediment cores from small lakes and wetlands in the area (Gil-Romera et al., 2010; Anderson et al., 2011). High-elevation alpine lake and bog sediments have been shown to be very sensitive to environmental changes through the analysis of a diverse suite of proxies (Tinner and Theurillat, 2003; Tinner and Kaltenrieder, 2005; Jiménez-Moreno et al., 2008, 2011).

The Sierra Nevada, the largest mountain range in southern Spain and one of the largest of southern Europe, is situated in an important climatic junction between the temperate and humid climate to the north and the subtropical, arid climate to the south (Jiménez-Moreno and Anderson, 2012). In this respect, Mediterranean forests have been proven to be

very sensitive to Northern Hemisphere climate variability (Tzedakis, 2007; Fletcher et al., 2010). As important, the range has been alternatively at the center and at the fringe of numerous human cultures and societies through time (Crow, 1985; Kennedy, 1996), each of which has left an imprint on the regional environment in their attempt to modify the landscape. Until recently, however, our understanding of the impact of natural climate change and human activities in the Sierra Nevada has been minimal, but has slowly increased in the last few years (Anderson et al., 2011; Jiménez-Moreno and Anderson, 2012).

We present here a multi-proxy sedimentary record from Laguna de la Mula (LdLM), which is the latest in a series of studies detailing aspects of the paleoecology of the Sierra Nevada (Anderson et al., 2011; Jiménez-Moreno and Anderson, 2012; Oliva and Gómez-Ortiz, 2012; García-Alix et al., 2012). Here we concentrate on the last ca. 4100 cal yr of vegetation, fire and climate history from LdLM, the lowest elevation and the westernmost lake studied in the range to date, with the two main goals: 1) determine the vegetation, fire and climate history during the late Holocene at this lower elevation site, comparing to other previous studies from the area, and 2) investigate human impact on the local vegetation.

Sierra Nevada

The Sierra Nevada is one of the highest mountain range in southern Europe, stretching ca. 80 km in a west–east trending direction, and

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includes the three highest peaks on the Iberian Peninsula: Mulhacén (3479 m), Veleta (3396 m) and Alcazaba (3366 m). Early investigators (i.e., Obermaier and Carandell, 1916; Dresch, 1937) recognized that the range was extensively glaciated during the late Pleistocene. Late Pleistocene snowlines were higher in the Sierra Nevada than in other ranges in the Iberian Peninsula (Gómez Ortiz et al., 2005). This is due to its southern location and influence of the Mediterranean Sea. Both valley and cirque glaciers existed during the past Pleistocene glaciations in Sierra Nevada. Glaciers of much more limited extent occurred during the Little Ice Age on the highest peaks (Gómez Ortiz, 1987; Gómez Ortiz et al., 2004; González Trueba et al., 2008), although none of these glaciations are well-dated at present. Subsequent postglacial melting of cirque glaciers allowed formation of the numerous small lakes and wetlands (Castillo Martín, 2009). They formed on the metamorphic bedrock (mostly schists) located at elevations generally above ca. 2600 m (Castillo Martín, 2009). Borreguiles de la Virgen (Jiménez-Moreno and Anderson, 2012; García-Alix et al., 2012), Laguna de Río Seco (Anderson et al., 2011) and Laguna de La Mula (this study) form part of those high-elevation wetlands of glacial origin.

Regional climate

The Mediterranean climate is characterized by its strong seasonal contrast. The summer is dry and hot, with the winter being humid and mild. More specifically, the climate of this region is strongly influenced by factors that control the North Atlantic Oscillation (NAO; Harding et al., 2009). Other important processes controlling climate in this area are the seasonal expansion northward of the Hadley Cell circulation (Roberts et al., 2011) due to heating of the North African landscape and the indirect effects of the African and Asian monsoons as expressed in regions to the south and southeast (Lionello et al., 2006). In addition, altitudinal contrasts contribute to a wide range of regional thermal conditions (Arévalo Barroso, 1992; Fletcher et al., 2010). In the Sierra Nevada Range, the mean annual temperature at ca. 2500 m is 4.5°C, and the mean temperature during the snow-free months is ca. 10 ± 6°C, but occasionally reaches ca. 21°C. Annual precipitation in southern Spain ranges from > 1400 mm/yr in the western Betic highlands to < 400 mm/yr in the semi-desert lowlands of the eastern basin. In Sierra Nevada (University Hostel; 2507 m elevation), the mean annual precipitation is about 700 mm/yr, seasonally concentrated between October and April, mostly as snow (Oliva, 2006). Predominant wind directions are northwesterly during winter, with southerly and southwesterly winds occurring during summer associated with weakening of the westerlies (Anderson et al., 2011; Jiménez-Moreno and Anderson, 2012).

Vegetation and treeline in the Sierra Nevada

Vegetation in the Sierra Nevada and throughout the region is strongly influenced by thermal and precipitation gradients (Valle, 2003; Table 1). It was recently reviewed in Anderson et al. (2011) and Jiménez-Moreno and Anderson (2012). The regional vegetation patterns not only result from climatic factors, but also from the impact of human landscape modification through the ages. Of great interest to ecologists and paleoecologists recently has been the determination of a natural treeline in the range. Plantations of *Pinus*, originating from efforts to combat erosion due to previous deforestation, originate from the mid-20th century (Valbuena-Carabaña et al., 2010), and encompass at least 15,000 ha in the Sierra Nevada (Arias Abellán, 1981). Overall, *Pinus sylvestris* and *Pinus nigra* grow in high-elevation zones up to ca. 2500 m on siliceous and limestone substrates respectively, *Pinus pinaster* prefers mid-altitudes on dolomites, and *Pinus halepensis* the lowermost areas of the mesomediterranean belt and below into the coastal lowlands. However the potential natural range of these

Table 1

Modern vegetation around the Lago de la Mula area, Sierra Nevada (El Aallali et al., 1998; Valle, 2003).

Vegetation belt	Elevation (m)	Most characteristic taxa
Crioromediterranean	> 2800	<i>Festuca clementei</i> , <i>Hormatophylla purpurea</i> , <i>Erigeron frigidus</i> , <i>Saxifraga nevadensis</i> , <i>Viola crassiuscula</i> , and <i>Linaria glacialis</i>
Oromediterranean	1900–2800	<i>Pinus sylvestris</i> , <i>P. nigra</i> , <i>Juniperus hemisphaerica</i> , <i>J. sabina</i> , <i>J. communis</i> subsp. <i>nana</i> , <i>Genista versicolor</i> , <i>Cytisus oromediterraneus</i> , <i>Hormatophylla spinosa</i> , <i>Prunus prostrata</i> , <i>Deschampsia iberica</i> and <i>Astragalus sempervirens</i> subsp. <i>nevadensis</i>
Supramediterranean	1400–1900	<i>Quercus pyrenaica</i> , <i>Q. faginea</i> , <i>Q. rotundifolia</i> , <i>Acer opalus</i> subsp. <i>granatense</i> , <i>Fraxinus angustifolia</i> , <i>Sorbus torminalis</i> , <i>Adenocarpus decorticans</i> , <i>Helleborus foetidus</i> , <i>Daphne gnidium</i> , <i>Clematis flammula</i> , <i>Cistus laurifolius</i> , <i>Berberis hispanicus</i> , <i>Festuca scariosa</i> and <i>Artemisia glutinosa</i>
Mesomediterranean	600–1400	<i>Quercus rotundifolia</i> , <i>Retama sphaerocarpa</i> , <i>Paeonia coriacea</i> , <i>Juniperus oxycedrus</i> , <i>Rubia peregrina</i> , <i>Asparagus acutifolius</i> , <i>D. gnidium</i> , <i>Ulex parviflorus</i> , <i>Genista umbellata</i> , <i>Cistus albidus</i> and <i>C. laurifolius</i>

trees is unknown, due to serious anthropogenic deforestation pressures over the last millennia.

Laguna de la Mula

Laguna de la Mula (LdlM; 37°3.583'N, 3°25.017'W; Fig. 1) is a small lake located at 2497 m elevation in a north-facing cirque depression that belongs to the Río Dílar drainage basin. The lake basin formed by glacial erosion of the bedrock, which consists of metamorphic mica schists of the Nevadofilábride system (Martín Martín et al., 2010). The lake has a diameter of about 45 m and a drainage basin of ca. 25 ha. The maximum depth of the lake when cored in July 2010 was 57 cm. The lake dries out completely by the end of the summer during years of low winter precipitation.

The lake presently occurs above treeline, within the oromediterranean vegetation belt. The aquatic plants *Polygonum aviculare* and *Cyperaceae* grow on the lakeshore. Algae, mostly *Spirogyra* and *Zygnema*, are also very abundant within the lake. Algal blooms occur by the end of the summer, before the lake dries. Vegetation around the lake consists of xerophytic shrublands and pasturelands dominated by *Genista versicolor*, *Poaceae* and *Cyperaceae*. Treeline in that area occurs lower in elevation, at ca. 2100 m, although centuries of forest clearance within the range, and subsequent reforestation makes it nearly impossible to determine the potential natural elevation of treeline (Anderson et al., 2011).

Materials and methods

Three sediment cores were taken in July 2010 from a small floating platform anchored to rocks on shore. Cores were taken in the deepest part of the basin using a Livingstone square-rod piston corer. LdlM 10-02 was the longest core with 32.5 cm and was used for this study (Fig. 2). The core was wrapped in plastic wrap and aluminum foil in the field, and transported back to the Laboratory of Paleoecology (LOP), Northern Arizona University, where it was stored, and sampled for various proxies.

Lithology of the LdlM 10-02 split core was described in the laboratory with respect to sediment characteristics and color. Magnetic susceptibility (MS), a measure of the tendency of sediment to carry a magnetic charge (Snowball and Sandgren, 2001), was measured with a Bartington MS2E meter in cgs units (cgsu). Measurements

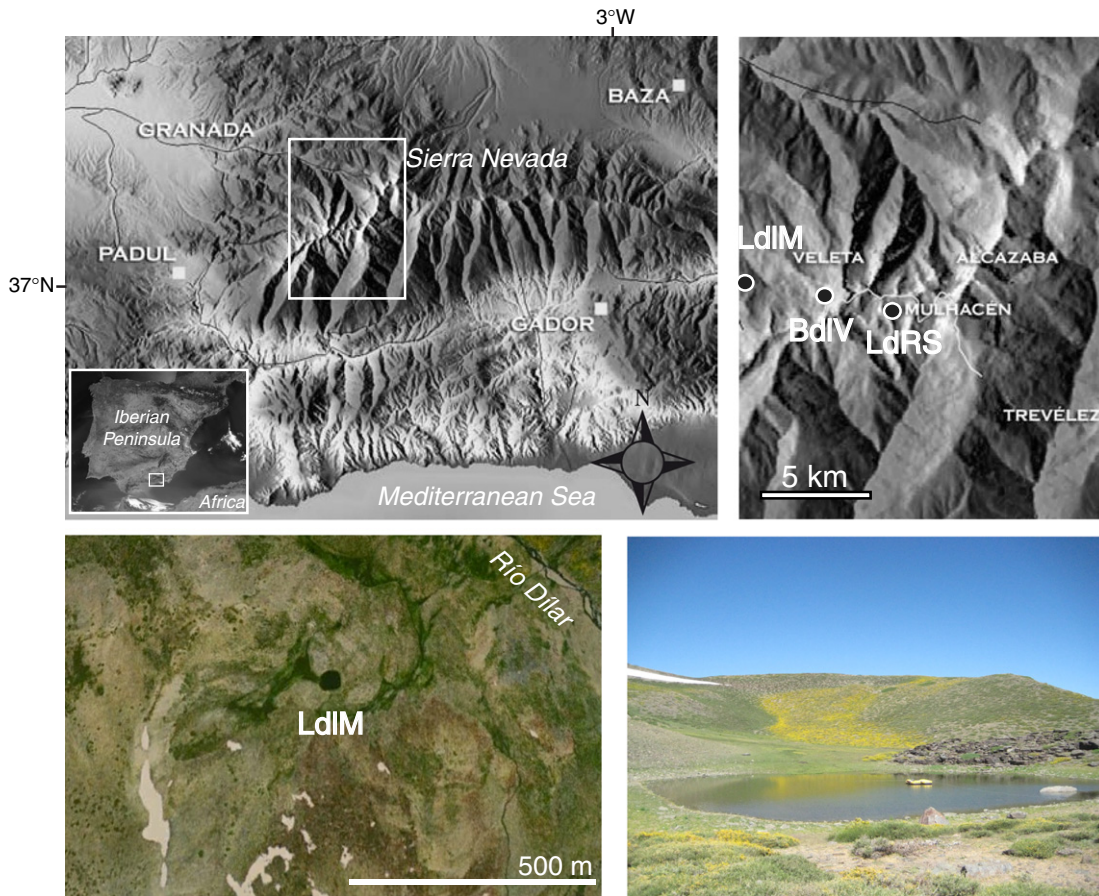


Figure 1. Above is the location of the Laguna de la Mula (LdIM), Laguna de Río Seco (LdRS) and Borreguiles de la Virgen (BdlV), Sierra Nevada, southern Spain. On the left is the location of the Sierra Nevada, with other major sites discussed in text (Baza, Gador and Padul). Below, on the left is the aerial photo of the LdIM. On the right is a photo of the LdIM, where the core was taken.

were taken directly from the core surface every 0.5 cm for the entire length of the LM 10-02 core (Fig. 2).

LdIM 10-02 core chronology was developed using seven calibrated AMS radiocarbon dates (Table 2; Fig. 2). Material for AMS dates

consisted of very organic bulk sediment samples. Samples for dating were initially dried and weighed before submission. Radiocarbon ages were calibrated to ‘calendar ages’ using IntCal09.14 (Reimer et al., 2004). We used the “clam” program to calculate the age–depth

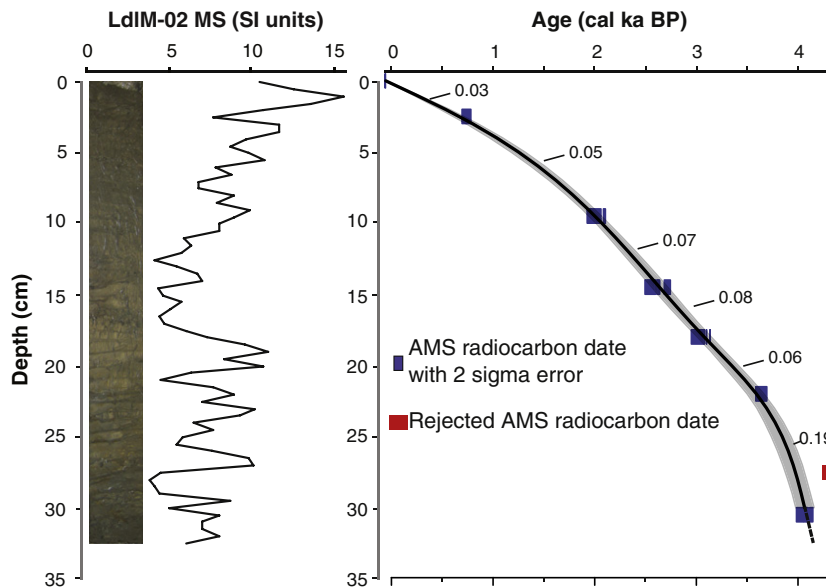


Figure 2. Core photo and magnetic susceptibility (MS) profile of the LdIM 10-02 core. On the right is the age–depth diagram for the LdIM record. The red square is a date that was not used in the age model. The sediment accumulation rates are shown.

relationship for the core (Blaauw, 2010; Fig. 2). The smooth spline option produced the best relationship for these dates.

Carbon stable isotopes and atomic C/N ratios were analyzed from 31 sediment samples taken at ~1-cm intervals throughout the Ldlm 10-02 core (Fig. 3). For comparison, six samples of algal crust from the lakeshore, one of living algae and sixteen plant samples from the catchment basin were analyzed in order to characterize the carbon isotopic composition of the present lake environment. Sediment and soil samples were decalcified with 1:1 HCl in order to eliminate the carbonate fraction. Carbon isotopes ($\delta^{13}\text{C}$), and the atomic C/N ratios were measured by means of an EA-IRMS elemental analyzer connected to a XL Thermo Finnigan mass spectrometer. Samples were measured in duplicate. Isotopic results are expressed in δ notation, using the standard V-PDB. The calculated precision, after correction for mass spectrometer daily drift, using standards systematically interspersed in analytical batches, was better than $\pm 0.1\%$ for $\delta^{13}\text{C}$.

Samples for pollen analysis (1 cm^3) were taken every 1 cm throughout the Ldlm 10-02 core (Figs. 4 and 5). Pollen extraction followed a modified Faegri and Iversen (1989) methodology. Counting was performed at $400\times$ magnification to a minimum pollen sum of 300 terrestrial pollen grains. Fossil pollen was identified using published keys and modern pollen reference collections. The raw counts were transformed to pollen percentages based on the pollen sum, not including *Polygonum*, as it is overrepresented in the studied samples. A summary of important pollen types (higher abundances than 1%) is plotted in Figure 4. Percentages of algae were calculated with respect to the total pollen sum and are shown in Figure 5 together with other aquatic plants. The pollen zonation was accomplished by cluster analysis of the pollen percentages of *Pinus*, *Olea*, *Quercus* total, *Artemisia*, *Amaranthaceae*, *Asteraceae*, *Lactucaceae*, *Caryophyllaceae*, *Plantago* and *Poaceae* using CONISS (Grimm, 1987).

Samples for charcoal analysis (1 cm^3) were taken every 0.5 cm throughout the core, with a total of 65 charcoal samples analyzed (Fig. 6). Charcoal analysis followed the protocol described in Whitlock and Anderson (2003). Processing included pretreatment with sodium hexametaphosphate to deflocculate clays. Each subsample was washed through a set of sieves that had mesh sizes of $125\ \mu\text{m}$ and $250\ \mu\text{m}$. Counting of charcoal particles was performed with a stereomicroscope at $10\text{--}70\times$ magnification. Charcoal counts for each sample were converted first to charcoal concentrations (CHAC; number of charcoal particles per cm^3), then to charcoal influx (CHAR; number of charcoal particles per cm^2 per yr) using CharAnalysis (Higuera et al., 2009; <http://charanalysis.googlepages.com/>). The analyses are based on the widely applied approaches that deconstruct a charcoal record into low- and high-frequency components.

Table 2

Age data for Ldlm 10-02 core, southern Spain.

Lab number ^a	Depth (cm)	Dating method	Age (^{14}C yr BP $\pm 1\sigma$)	Calibrated age (cal yr BP) 2σ ranges
	0	Present	AD 2010	–60
DirectAMS-1203-006	2.5	^{14}C	739 ± 19	695–781
DirectAMS-1203-007	9.5	^{14}C	1990 ± 24	1926–2105
DirectAMS-1203-008	14.5	^{14}C	2624 ± 28	2495–2744
DirectAMS-1203-009	18	^{14}C	3018 ± 20	3078–3136
DirectAMS-1203-010	22	^{14}C	3650 ± 20	3585–3693
DirectAMS-1203-011	27.5	^{14}C	4356 ± 22	4857–4971
UCIAMS81595	30.5	^{14}C	4042 ± 20	3985–4146

Note: In all samples the material dated was very organic bulk sediment. All ages were calibrated using IntCal09.14 (Reimer et al., 2004).

^a Sample number assigned at radiocarbon laboratory; DirectAMS# = Accium BioSciences, Seattle, Washington, UCIAMS# = University of California at Irvine W.M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory. In bold is the date that was considered too old and was not used in the age model.

Results

Chronology and sedimentary rates

Seven calibrated radiocarbon ages in Ldlm 10-02 were used to determine the sediment chronology. The age–depth model for the Ldlm record suggests that this record covers at least the last ca. 4100 cal yr (Table 2; Fig. 2). Radiometric dates show one seemingly excessive age of 4356 cal yr BP at 27.5 cm. We attribute this to mobilization and re-sedimentation of old organic material into the lake. That radiocarbon age was not used in the age-model construction. Sediment accumulation rates (SAR) were calculated between the radiocarbon dates. The highest SAR of 0.19 mm/yr occurred below ca. 22 cm [ca. 3600 cal yr BP]. Between ca. 18 cm [ca. 3000 cal yr BP] to the top of the core vary in a decreasing trend from ca 0.08 to 0.03 mm/yr.

Lithology and magnetic susceptibility

Relatively homogeneous clays characterize sediments from Ldlm 10-02 with subtle color changes between gray, brown and green. No mud crack zones or apparent discontinuities are observed in the sediment core. Gravels characterize the bottom of the core (last cm). From the core bottom at 32.5 cm to 17 cm (ca. 4100–2950 cal yr BP) the MS oscillate between 4.5 and 11 cgsu. The MS from ca. 16.5 to 1 cm (ca. 2800–2400 cal yr BP) increased from 4.4 to 15.6 cgsu. A decrease is observed at the very top of the core (last ca. 240 cal yr) to around 10.5 cgsu (Fig. 2).

Isotopes

Vegetation of the catchment basin primarily consists of members of the Poaceae and Cyperaceae. The mean measured $\delta^{13}\text{C}$ value of Poaceae and Cyperaceae is $-29.3 \pm 1.4\%$ and $-26.7 \pm 0.7\%$ respectively. By comparison, the carbon isotopic composition of the 16 plant samples (including Poaceae, Cyperaceae, *Artemisia*, *Asteraceae*, *Fabaceae*, *Lamiaceae*, *Plantago*, *Ranunculaceae* and an unidentified bryophyte) taken from near the lake ranges from -30.3% to -25.8% , with a mean value of $-27.0 \pm 1.4\%$. Values of $\delta^{13}\text{C}$ from algal crust range from -22.8% to -20.2% , with a mean value of $-21.7 \pm 0.8\%$, while the single algae sample has a $\delta^{13}\text{C}$ value of -21.8% .

Carbon isotopic values of the sediment core range from -23.7% to -21.5% , with a mean value of $-22.7 \pm 0.5\%$ (Fig. 3). The $\delta^{13}\text{C}$ values increase gradually from ~4000 to 2500 cal yr BP, recording the least negative values from ~3200 to 2500 cal yr BP. The most negative $\delta^{13}\text{C}$ values have been recorded during the last ~2000 yr, being extremely low from ~200 cal yr BP to present. Atomic C/N ratio ranges from 12 to 18, with a mean value of 15 ± 2 . Two intervals record the highest C/N ratio – one from ~3800 to 3200 cal yr BP, and other from ~2300 to 1850 cal yr BP.

Pollen and algae

Forty different pollen and three algal species have been identified in the Ldlm 10-02 core (Figs. 4 and 5), although some of the identified taxa occur in percentages lower than 1% and have not been plotted in Figure 4. This pollen record shows low percentages of forest species, mostly *Pinus*, *Quercus* and *Olea*, varying around 20%. Herbs and grasses such as *Artemisia*, *Lactucaceae*, other *Asteraceae*, *Amaranthaceae*, *Herniaria*, other *Caryophyllaceae*, *Plantago* and *Poaceae* dominate the pollen spectra. Aquatic plants are also abundant and are mostly represented by *P. aviculare* averaging ca. 28% of the total pollen sum. Aquatic algal spores are also very abundant and are made up of *Pediastrum*, *Zygnema* and *Spirogyra*.

We produced five pollen zones for the Ldlm 10-02 record (Fig. 4) using variations in pollen species as listed above and cluster analysis of the pollen data run through the program CONISS (Grimm, 1987).

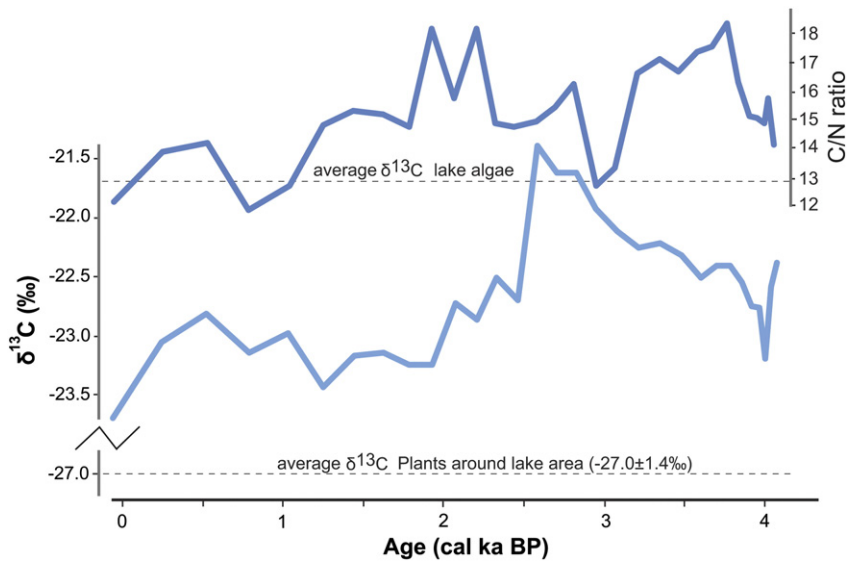


Figure 3. Isotope data from the Ldlm record. Dashed lines represent the average $\delta^{13}\text{C}$ values of plants around the lake area and lake algae.

These data provide a general framework for discussion of vegetation change during the late Holocene around the Sierra Nevada, southern Spain.

Zone LM-1 (ca. 4100 to 3800 cal yr BP [32.5–25.0 cm depth]) is characterized by the highest abundance of *Pinus* (around 20%) and relatively high percentages of *Quercus* (around 5%). Most herbs, such as *Artemisia* (ca. 10%), Lactucaceae (ca. 15%), other Asteraceae (ca. 5%), Amaranthaceae (ca. 2%) and other Caryophyllaceae (<5%), show relatively low percentages. Aquatic and wetland pollen and spores also show relatively low abundances in this zone, with *P. aviculare* occurring at around 20% and the algae *Pediastrum*, *Zygnema* and *Spirogyra* showing minimum values (Fig. 5).

Zone LM-2 (ca. 3800 to 3100 cal yr BP [25.0–18.5 cm depth]) shows a significant decrease in forest species (*Pinus* [reaching 5%] and *Quercus* [recording a minima of less than 1%]). Maxima in *Artemisia* (ca. 24%) and *Plantago* (ca. 15%) and an increase in Caryophyllaceae (to ca. 10%) are observed through this zone. Aquatic and wetland pollen and spores generally increase at this time (Fig. 5).

Zone LM-3 (ca. 3100 to 1850 cal yr BP [18.5–9.0 cm depth]) is mostly characterized by the highest percentage in *Quercus*. Evergreen

Quercus peaks first, in LM-3a (ca. 3100–2500 cal yr BP) followed by deciduous *Quercus* somewhat later in LM-3b (ca. 2500–1850 cal yr BP; Fig. 7). Total *Quercus* peaks total at ca. 10% in LM-3b at ca. 2200 cal yr BP. *Olea* also shows an increase in LM-3b to ca. 10%. With respect to the herbs, *Artemisia* shows minimum values in this zone of ca. 10%. Aquatics show a significant increase and *P. aviculare*, Ranunculaceae, *Zygnema* and *Spirogyra* show maximum values during LM-3b at ca. 2200 cal yr BP (Fig. 5).

Zone LM-4 (ca. 1850 to 650 cal yr BP [9.0–2.5 cm depth]) witnesses a decrease in arboreal species: *Quercus* (to ca. 2%), *Pinus* (reaching ca. 5%) and *Olea* (to ca. 1%). Relatively high values are observed in *Artemisia* (ca. 15%), Lactucaceae (around 25%) and other Asteraceae (with a maximum value of ca. 13%). Aquatics generally show lower values with respect to the previous zone.

Zone LM-5 (ca. 650 cal yr BP to Present [2.5–0.0 cm depth]) shows increases in tree species, particularly in *Olea* (reaching ca. 15%) but also slightly in *Pinus* and *Quercus*. With respect to the herbs, *Artemisia*, Lactucaceae, other Caryophyllaceae and *Plantago* decrease through this zone. The aquatics Ranunculaceae, *Pediastrum* and *Zygnema* also decrease in this zone.

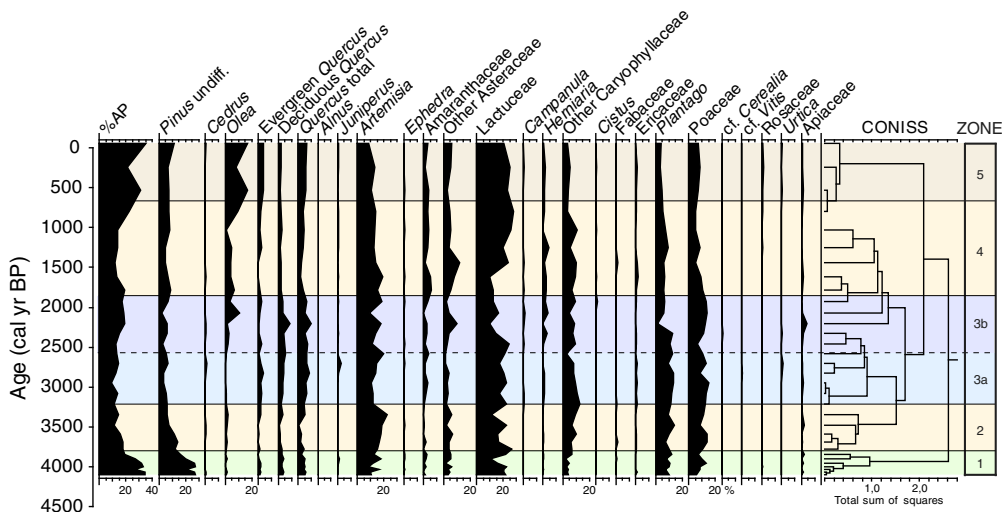


Figure 4. Pollen diagram of the Ldlm record showing percentages of selected taxa. *Polygonum aviculare* was excluded from the total pollen sum due to its overrepresentation. The zonation, on the right, was made using cluster analysis provided by CONISS (Grimm, 1987).

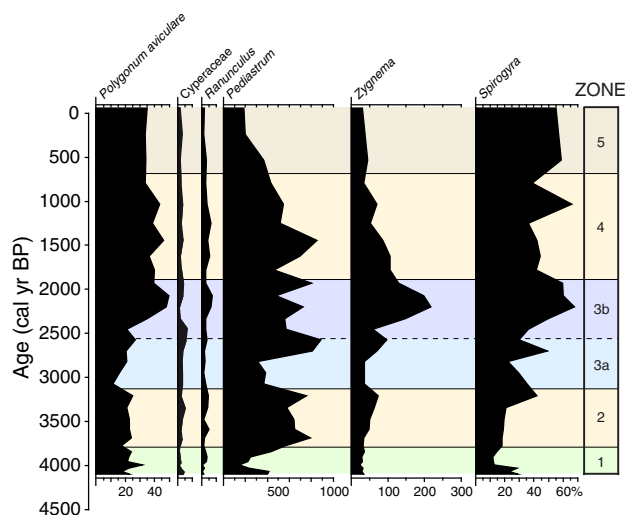


Figure 5. Percentages of wetland plants and aquatics (pollen and algae) of the LdlM record. The zonation, on the right, is the same as in Fig. 4 and deduced by the pollen.

Charcoal analysis

Charcoal analysis (Fig. 6) shows low charcoal concentrations up to ca. 17 particles/cm³ (to ca. 0.1 particles/cm² yr) between ca. 4200 to 2500 cal yr BP (ca. 32.5–12.5 cm depth). However, a significant increase in charcoal concentration is observed from ca. 2500 to 1850 cal yr BP (12.5–9.0 cm depth). The concentration of charcoal particles shows three maxima, with the highest concentration of ca.

43 particles/cm³ (0.3 particles/cm² yr). A decreasing trend in the charcoal particle concentration is observed from ca. 1850 cal yr BP to Present (9.0–0.0 cm depth), from ca. 20 to 0 particles/cm³ (from ca. 0.1 to 0 particles/cm² yr).

Discussion

Detailed palynological studies on continuous lacustrine sequences have shown that the high sensitivity of many records can track changes of vegetation related to rapid millennial-scale climate variability (Jiménez-Moreno et al., 2007; Jiménez-Moreno et al., 2010; Jiménez-Moreno et al., 2011). In the Mediterranean area, one pollen type in particular (i.e., *Quercus*) has been extensively used to track changes from relatively humid (increases) to arid (contraction) periods, during the late Pleistocene and Holocene (Fletcher et al., 2007; Fletcher and Sanchez Goñi, 2008; Fletcher et al., 2010). In this study we use *Quercus* abundances, together with other pollen/algae taxa, as a proxy for changes in precipitation.

The atomic C/N ratio has been used as a proxy of the organic matter source in lacustrine sediments (Meyers, 1994; Meyers and Teranes, 2001). Fresh organic matter from lake algae (protein-rich and cellulose-poor) usually has values <10, while values for vascular land plants (protein-poor and cellulose-rich) often exceed 20. Intermediate values indicate a mixed source (algal and vascular plants) (Meyers, 1994; Meyers and Teranes, 2001). C3 vascular plants and lacustrine algae have a similar isotopic carbon signature under normal conditions (Meyers, 1994; Meyers and Teranes, 2001). However, during concrete environmental conditions, isotopic values can differ. For example, a $\delta^{13}\text{C}$ increase in vascular plants, can be read in terms of water use efficiency during dry conditions (Farquhar et al., 1982).

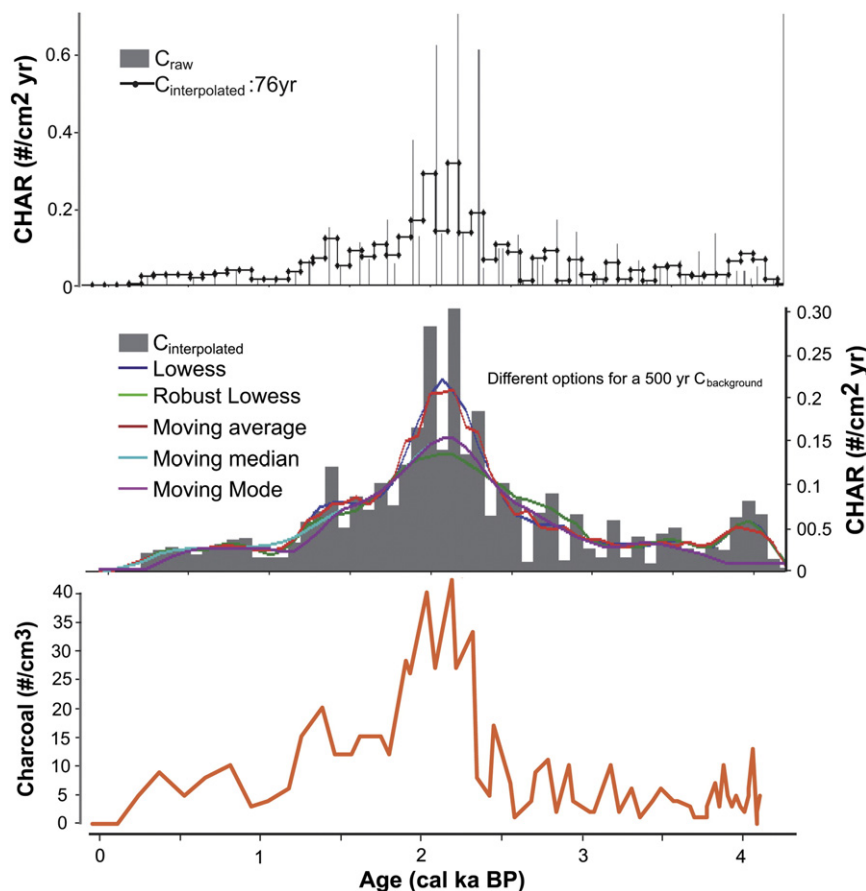


Figure 6. Charcoal record from the LdlM. From bottom to top: Charcoal concentrations (no. charcoal particles/cm³). Charcoal accumulation rates (CHAR; no. charcoal particles/cm² yr¹) where background is smoothed using a locally weighted regression with a time window of 500 yr. Charcoal accumulation rates (CHAR; no. charcoal particles/cm² yr¹ re-sampled at 76-yr constant time interval). CharAnalysis (Higuera et al., 2009) was used to calculate the CHAR and plot the data.

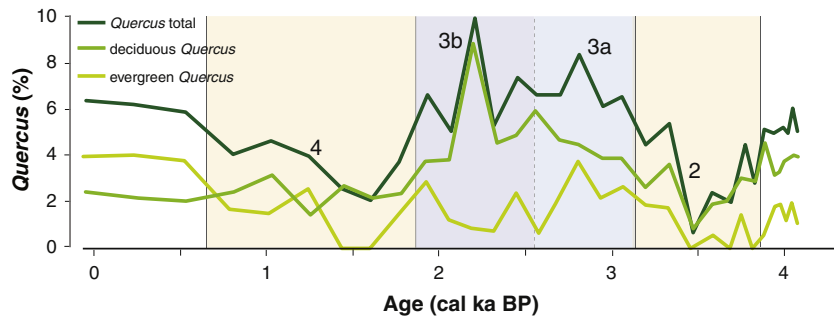


Figure 7. Percentages of total, evergreen and deciduous *Quercus* from the LdlM record. Pollen zones (see previous figures) are also represented.

Algae preferentially incorporate the lighter isotopes from the water's dissolved inorganic carbon (DIC) pool; therefore, a productivity bloom enriches the carbon isotopic composition of the water, leading to the same isotopic enrichment in the algae from water mass (O'Leary, 1988; Hodell and Schelske, 1998; Wolfe et al., 2001; among others). In this study we used the atomic C/N ratio and $\delta^{13}\text{C}$ values measured throughout the LdlM sediment core to decipher the evolution of the source of the organic matter and the environment around this lake area.

Charcoal analysis is based on the accumulation of charcoal particles in sediments during and following a fire event. Stratigraphic levels with abundant charcoal (so-called charcoal peaks in the core) are inferred to result from past fire activity (Whitlock and Anderson, 2003). Macroscopic charcoal particles ($> 100 \mu\text{m}$) express occurrence of nearby fires, because particles of this size do not travel far from their source (Whitlock and Anderson, 2003). The charcoal analysis on the sediments from the LdlM core provides an opportunity to examine how fire regimes were affected by periods of major climate change and vegetation reorganization in the past. Charcoal was generally not abundant in this record.

Magnetic susceptibility (MS), a measure of the tendency of sediment to carry a magnetic charge (Snowball and Sandgren, 2001), is in alpine lakes mostly related to the relative abundance of detritics (thus magnetic minerals) and organic matter in the sediments. Organic matter is a diamagnetic material (Dearing, 1999), thus magnetic susceptibility is relatively lower when it is abundant.

The multi-proxy analysis of the LdlM in the Sierra Nevada provides an opportunity to examine the record of vegetation, fire history, climate and human disturbance from the highest mountain range in southern Iberia. Here we compare our record with other local, regional and more distant records to further characterize the paleoclimatic and paleoenvironmental history of this important region.

Late Holocene climate and paleoenvironments deduced from LdlM

Paleoclimate records from the western Mediterranean area show that the late Holocene was relatively drier than earlier in the Holocene (Carrión, 2002; Fletcher and Sanchez Goñi, 2008; Jalut et al., 2009; Carrión et al., 2010; Pérez-Obiol et al., 2011). An aridification trend, starting in the middle Holocene until present, has been observed in many studies, including the record from Laguna de Río Seco and Borreguiles de la Virgen in the Sierra Nevada (Anderson et al., 2011; Jiménez-Moreno and Anderson, 2012; García-Alix et al., 2012). The LdlM record also shows generally arid climate conditions during the late Holocene. This is deduced by the low percentage of tree pollen taxa in the pollen spectra (generally lower than 20%), indicating a very open environment at lower elevations, and the abundant herb taxa including arid adapted species such as *Artemisia*, *Lactucaceae*, other *Asteraceae*, *Amaranthaceae* and *Ephedra*.

The carbon isotopic record (ranging from -21.5% to -23.7%) and the atomic C/N ratio (from 12 to 18) during the last 4100 cal yr

BP from LdlM indicate a mixed source of organic matter (terrestrial vascular plant and algae) in the lake. The data fall within the range between the isotopic composition of the present vegetation around the lake ($-27.0 \pm 1.4\%$) and lake algae ($-21.7 \pm 0.8\%$) (Fig. 3). The carbon isotopic composition suggests that the allochthonous organic matter comes from C3 vascular plants of the catchment basin (O'Leary, 1981, 1988; Meyers, 1994). This agrees with previous studies that show no isotopic evidence of C4 plants during the Holocene in the Sierra Nevada or in the surrounding area (Ortiz et al., 2004; García-Alix et al., 2012). However, the carbon isotopic values are relatively high, suggesting an important contribution of algae to the sediment, which agrees with the algal record and atomic C/N ratio (Fig. 5).

Charcoal particles, ranging from 0 to ca. 40 particles/cm³, are generally rare on the LdlM sediments. A small number of charcoal particles also characterize the record from Laguna de Río Seco, at higher elevation in the Sierra Nevada. This is probably due to a distant source of charcoal particles from fires at lower elevations in this mountain range. Natural fires today are extremely rare above treeline in the Sierra Nevada and were probably very rare in the past. We can infer, from the rare charcoal and low percentage of arboreal pollen (lower than 20%), that treeline was lower than 2500 m (the elevation of the LdlM) during the late Holocene (details in Jiménez-Moreno and Anderson, 2012).

Even though the pollen records show generally arid conditions during the late Holocene in the Sierra Nevada (Anderson et al., 2011; Jiménez-Moreno and Anderson, 2012; this study), abundances of *Quercus* and other tree species co-vary with several proxies studied in this sedimentary record (i.e., charcoal, algae, isotopes; Fig. 8), reinforcing the paleoclimatic interpretation. Below we interpret the main features distinguished in the LdlM record and compare it with other records.

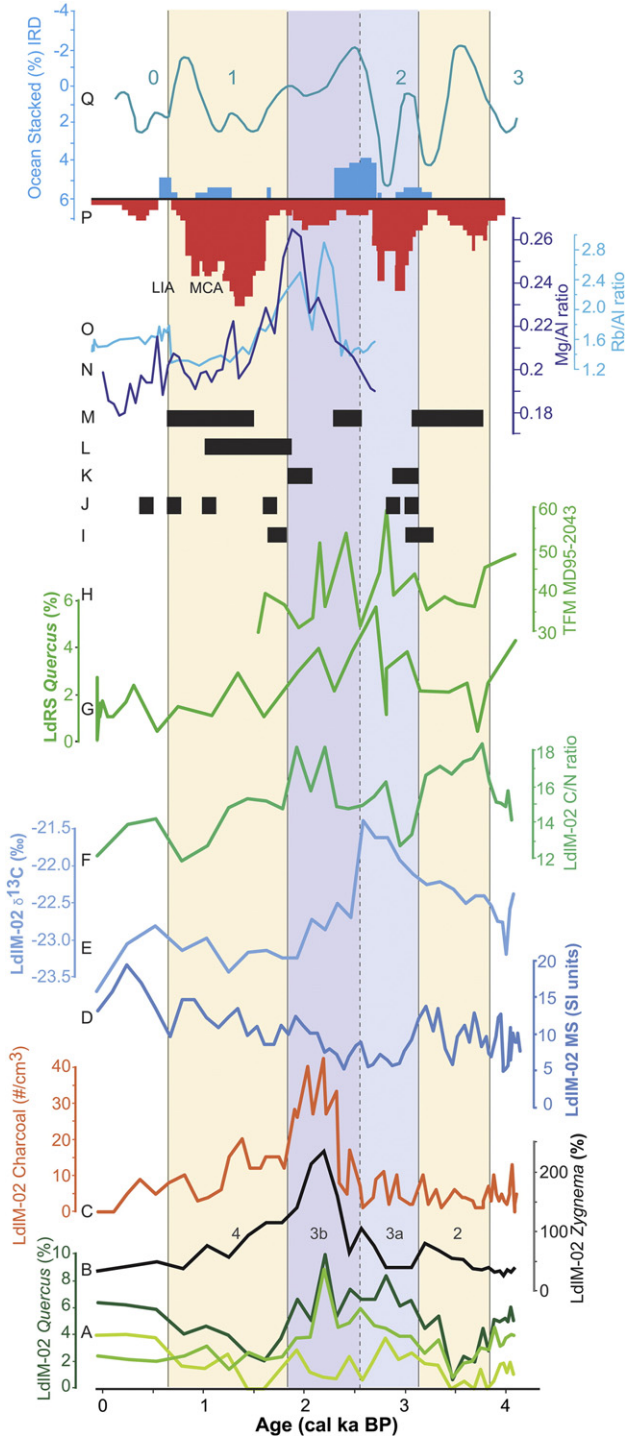
Arid period between ca. 3800 to ca. 3100 cal yr BP

This period coincides with pollen zone LM-2 and is characterized by the lowest percentages of *Quercus* pollen, showing a minimum at ca. 3500 cal yr BP. This, together with the maxima in the abundance of arid adapted *Artemisia*, indicates deepened aridity in this area (Figs. 4, 7 and 8). Percentages of *Zygnema* and *Spirogyra* and concentration of charcoal particles are also relatively low (Figs. 5, 8).

Carbon isotopic composition and atomic C/N ratio changed gradually through this interval. During most of this period (ca. 3800 to ca. 3200 cal yr BP), $\delta^{13}\text{C}$ values ranged from -22.6% to -22.3% , and atomic C/N ratio oscillated between ~ 16.5 and ~ 18 . These data point to a main source of organic matter from vascular plants in the catchment basin, and the heavy carbon isotopic values trending to slight dry conditions, related with water use efficiency (Farquhar et al., 1982). However, dry conditions and relatively low lake levels could have also occasionally created more eutrophic lake conditions from an increased algal influence. The C/N record decreased substantially (to ~ 13.5) at the end of this period (ca. 3200 to ca. 3100 cal yr BP),

suggesting an increase in algal contribution to the sediment, which is interpreted as a transition to the following humid period (Figs. 3, 8).

Arid climate conditions at that time have been observed in many other pollen records from the southwestern Mediterranean region, corroborating the LdlM record. The Laguna de Río Seco record shows relatively low percentages of *Quercus* pollen (Anderson et al., 2011). A very similar pattern is observed in the Alboran Sea (MD95-2043 and ODP 976) sites with a decrease in pollen of temperate and Mediterranean tree forest species (including *Quercus*; Fletcher and Sanchez Goñi, 2008; Combourieu Nebout et al., 2009; Fig. 8). An increase in xerophytic pollen taxa from core CM-5, Guadiana Valley, Portugal also indicates strong aridity at around that time (Fletcher et al., 2007).



This arid period is in concordance with low lake levels in southern Spain (Lake Zoñar; Martín-Puertas et al., 2008) and central Europe (Magny, 2004) (Fig. 8). Cold and arid conditions are inferred during this period in the western Mediterranean Sea (M3; Frigola et al., 2007) and strong winds in the Sahara (Zr/Al ratio; Martín-Puertas et al., 2010). However, the sea-surface temperatures (SST) deduced from the western Mediterranean area do not show a very clear pattern for this time (Cacho et al., 2002).

A persistent positive NAO index has been interpreted to be the cause of this cold and arid period in the western Mediterranean (Fletcher et al., in press). At that time, the North Atlantic region would have then been characterized by different conditions, a humid period, with an opposite pattern very similar to Present (Lionello et al., 2006). This is consistent with a loess mean grain-size record from Iceland that shows strong winds and related above-average precipitations (Jackson et al., 2005; Fletcher et al., in press).

Humid period from ca. 3100 to 1850 cal yr BP

This period (pollen zone LM-3) is characterized by the increase in *Quercus*, indicating an increase in temperature and precipitation, reaching maxima at ca. 2200 cal yr BP. We interpret the initial portion (pollen zone LM-3a [ca. 3100 to ca. 2500 cal yr BP]) as being slightly less humid than the later portion (pollen zone LM-3b [ca. 2500 cal yr BP to ca. 1850 cal yr BP]).

During the initial period an increase in *Quercus* – particularly in evergreen *Quercus* – occurs, probably indicating an increase in temperature and precipitation after the previous arid event. During the subsequent period evergreen *Quercus* decreases but deciduous *Quercus* becomes more abundant, reaching a maximum coinciding with the Roman Humid Period (Martín-Puertas et al., 2010; Fig. 7). This pattern is very similar to changes in evergreen/deciduous *Quercus* during the early to mid-Holocene in the Mediterranean area (Fletcher et al., 2007; Tzedakis, 2007; Carrión et al., 2010) and has been ascribed to an increase in humidity and the reduction in seasonality (cooler summers and warmer winters; Tzedakis, 2007). Paralleling the increase and maxima in deciduous *Quercus* and thus precipitation is *Zygnema* (Fig. 8), suggesting meso- to eutrophic stagnant shallow water under milder climate and longer snow free periods (Carrión, 2002).

The carbon isotopic composition tends to be heavier from ca. 4000 to ca. 2500 cal yr BP. This trend intensifies from ca. 3100 to ca. 2500 cal yr BP (LM-3a). This fact, together with the C/N ratio can be read as a change in the contribution of algae and vascular plant to the bulk organic matter. During LM-3a time there is an important contribution of algae (high $\delta^{13}\text{C}$ and occasional low C/N rate), which could be interpreted as originating from algal blooms. From ca. 2500 to ca. 1850 cal yr BP (LM-3b) there is an increase in vascular plant

Figure 8. Comparison of different proxies studied from LdlM for the last ca. 4 ka (A–F) with other paleoclimate records from the Sierra Nevada (G) and other areas (H–S). (A) *Quercus* percentages from LdlM, Sierra Nevada (see Fig. 7 for more details). (B) Percentages of the alga *Zygnema* from LdlM record. (C) Charcoal from the LdlM record. (D) Magnetic susceptibility (MS) record from LdlM. (E) $\delta^{13}\text{C}$ record from LdlM (‰). (F) C/N ratios from the LdlM record. (G) *Quercus* percentages from the Laguna de Río Seco (LdlRS), Sierra Nevada (Anderson et al., 2011). (H) Percentages in temperate and Mediterranean tree forest species (TFM) from marine core MD95-2043, Alboran Sea (Fletcher and Sanchez Goñi, 2008). (I) Xerophytic pollen taxa from core CM-5, Guadiana Valley, Portugal (Fletcher et al., 2007). (J) Laguna de Medina, Cádiz, desiccation events (Reed et al., 2001). (K) Lake Siles desiccation phases (Carrión, 2002). (L) Sea-surface cold temperature event (AC1) from the Alboran Sea (Cacho et al., 2002). (M) Cold and dry events deduced from a pollen record from ODP 976 core, Alboran Sea (Combourieu Nebout et al., 2009). (N) Mg/Al ratio from site ODP 976, Alboran Sea (Martín-Puertas et al., 2010). (O) Rb/Al ratio from Zoñar Lake, Córdoba (Martín-Puertas et al., 2010). (P) Lake-level reconstruction for central Europe (Magny, 2004). Low and high lake levels are represented in red and blue respectively. (Q) Ocean stacked ice-rafting debris (IRD) from the North Atlantic (Bond et al., 2001). Numbers 0, 1, 2 and 3 indicate cold events. Pollen zones (2, 3 and 4; this study) are also shown. MCA and LIA are abbreviations for Medieval Climate Anomaly and Little Ice Age respectively.

contribution (increases in C/N rate and lower $\delta^{13}\text{C}$) (Fig. 3). Although the isotopic record suggests an important algae contribution during LM-3a time palynological data suggests that the maximum contribution from most algae species was from ca. 2500 to ca. 1850 cal yr BP (LM-3b time; Fig. 5). This trend can be explained as a moderate increase in temperature and humidity during LM-3a, which had two effects on the organic matter deposition. First, isotopic evidence suggests deposition of algal remains as the major component of bulk organic matter in the sediments. Yet, the wetter conditions during LM-3b time also encouraged greater development of terrestrial vegetation (Fig. 4). Increased runoff transported more terrestrial organic matter into the lake (higher C/N and lower $\delta^{13}\text{C}$). This runoff would have also triggered an increase in the nutrient supply, producing enhanced algal development. However, the algal contribution to the bulk organic matter would have somehow been little with respect to the higher input of organic matter from external vascular plants. Minimum values of magnetic susceptibility during this time are consistent with these observations.

The humid conditions during LM-3 time include the well-documented Roman Humid Period (Martín-Puertas et al., 2010) and are recognized in many other pollen records (Fig. 8), such as the Laguna de Río Seco in the Sierra Nevada (Anderson et al., 2011); two records from the Alboran Sea (MD95-2043 and ODP 976; Fletcher and Sanchez Goñi, 2008; Combourieu Nebout et al., 2009); Lake Siles (Sierra de Cazorla; Carrión, 2002); Laguna de Medina (Cádiz; Reed et al., 2001); and in the Guadiana Valley (Algarve; Fletcher et al., 2007). It also is recognized as higher lake levels from southern Spain and central Europe (Magny et al., 2004; Martín-Puertas et al., 2010), and is confirmed by other precipitation proxies (Mg/Al and Rb/Al ratios from site ODP 976, Alboran Sea and Zoñar Lake, southern Spain; Martín-Puertas et al., 2010) that show maximum rainfall during this period (Martín-Puertas et al., 2010; Fig. 8). Additionally, it is generally characterized by warm climate in the North Atlantic area (Bond et al., 2001) and in the Alboran Sea (Cacho et al., 2002; Fig. 8). Humid conditions in the SW Mediterranean could be explained by a persistent negative NAO index, as suggested by Fletcher et al. (in press; and references therein).

It is interesting to note that the Ldlm is also characterized by a short arid event at ca. 2500 cal yr BP that subdivides zones 3a and 3b within this generally humid period. This is deduced by the decrease in *Quercus* and increase in xerophytes at that time (Fig. 4). This short event also occurs in pollen records from ODP 976 and MD95-2043 cores, Alboran Sea (Fletcher and Sanchez Goñi, 2008; Combourieu Nebout et al., 2009) as a reduction in forest species (including *Quercus*).

Arid period between ca. 1850 to ca. 650 cal yr BP

This period, pollen zone LM-4, including the Dark Ages from ca. 1450 to ca. 1050 cal yr BP and the Medieval Climate Anomaly (MCA; from ca. 1050 to ca. 700 cal yr BP; Moreno et al., 2012) is characterized by the decrease in the percentage of *Quercus* pollen and algae (i.e., *Zygnema*; Fig. 8) and an increase in xerophytes such as Asteraceae (including *Artemisia*, Lactucaceae and other Asteraceae). This can be interpreted as a decrease in precipitation and an increase in aridity in this area. A similar pattern in the vegetation is observed in the Laguna de Río Seco record (Anderson et al., 2011), in the Alboran Sea (MD95-2043 and ODP 976 cores; Fletcher and Sanchez Goñi, 2008; Combourieu Nebout et al., 2009) and in the Guadiana Valley, Portugal (Fletcher et al., 2007). The Laguna de Medina, Cádiz, record documents desiccation events at that time (Reed et al., 2001) and the Mg/Al and Rb/Al ratios from the Alboran Sea and Lake Zoñar

show a significant decline in precipitation (Martín-Puertas et al., 2010). Lake levels are also low at this time in southwestern and central Europe (Magny et al., 2004; Martín-Puertas et al., 2010). This arid event dates slightly earlier in the Siles Lake, in the Sierra de Cazorla, compared to our record (Carrión, 2002; Fig. 8).

C/N ratios around 15 and the $\delta^{13}\text{C}$ values of ca. -23‰ point to a mixed source of organic carbon in the sediment, but with a predominance of external vascular plant contribution for the first part of this period (from ca. 1850 to 1250 cal yr BP). However, a decline in C/N ratio occurs at ca. 1000 cal yr BP, agreeing with a slight increase in $\delta^{13}\text{C}$ values. These changes could be due to a modest increase in *Zygnema* and a large increase in *Spirogyra* (algae). This is entirely consistent with a period eutrophication caused by the nutrient concentration in lowered lake levels during the dry and warm conditions during the MCA in the Mediterranean Iberia (Moreno et al., 2012).

Cold conditions in the North Atlantic and Alboran Sea are generally inferred for most of this period (Bond et al., 2001; Cacho et al., 2002; Fig. 8), with a warming only by the end of this period, during the MCA (Moreno et al., 2012). Even though temperatures seem to change through time, a persistent positive mode of the NAO most likely dominated this period (including the MCA; Trouet et al., 2009; Moreno et al., 2012; Fletcher et al., in press) leading to overall arid conditions for this area. The opposite, more humid, conditions are observed for northern Europe (including NW Iberia; Jackson et al., 2005; Moreno et al., 2012).

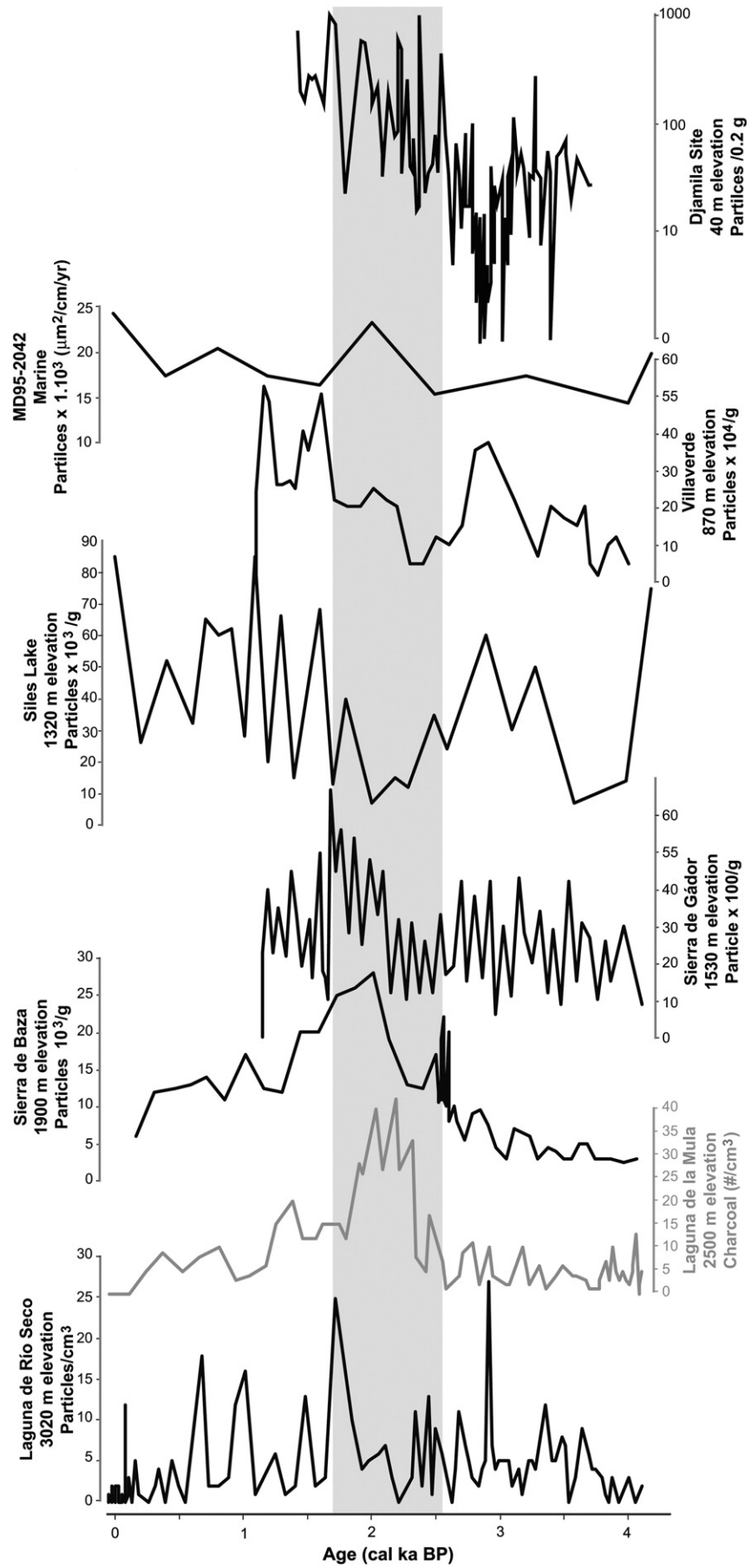
Fire history during the late Holocene in SW Mediterranean area

A comparison of sedimentary charcoal records – a proxy for fire activity – from southern Spain, the Alboran Sea and northern Morocco suggests that regional as well as local fire signals can be determined (Fig. 9). A maximum in charcoal concentrations occurs in the Ldlm record from ca. 2500 to ca. 1850 cal yr BP, coinciding with the most humid period detected in the area (pollen zone LM-3b; Figs. 6 and 8). Considerably lower charcoal concentrations are found prior and subsequent to this period (Fig. 9). Most of the charcoal records from the western Mediterranean show maxima in charcoal particle concentration around that time as well. For example, an increasing trend in fire frequency is observed at Laguna de Río Seco, in Sierra Nevada between ca. 3000 and 2000 cal yr BP (Anderson et al., 2011) and the Sierra de Baza charcoal record shows striking similarities to the Ldlm record with charcoal maxima at ca. 2000 cal yr BP (Carrión et al., 2007). Maxima in charcoal around that time are also observed in the Sierra de Gádor (Carrión et al., 2003), Alboran Sea (Combourieu Nebout et al., 2009) and Djamilia, northern Morocco (Linstädter and Zielhofer, 2010) records. However the records from Sierra de Cazorla (Siles Lake and Villaverde), about 100 km north of Sierra Nevada, seem to show the opposite trend with low charcoal particle concentration. We suspect that this may be due to differences in the fire regime characteristics – altitude, slope aspect orientation, precipitation, and vegetation – as observed by Linstädter and Zielhofer (2010). The concurrence of a regional increase in fire activity humid conditions between 3000 and 2000 cal yr BP may be related to increased fuel loads on the landscape, as noted at the Djamilia site (Linstädter and Zielhofer, 2010), as many Mediterranean fire regimes today are conditioned by fuel load variations (Daniau et al., 2007; Linstädter and Zielhofer, 2010).

Human impact in the Sierra Nevada

Of course, many fires originate naturally due to specific weather conditions or long-term climate trends, and natural fire regimes are

Figure 9. Comparison of charcoal (fire) records from Laguna de la Mula with those from other sites in southern Iberia and northern Africa. Plots are organized from higher to lower elevation (from bottom to top). From bottom to top: Laguna de Río Seco, Sierra Nevada (Anderson et al., 2011); Laguna de la Mula (Ldlm; this study); Sierra de Baza (Carrión et al., 2007); Sierra de Gádor (Carrión et al., 2003); Siles Lake, Sierra de Cazorla (Carrión, 2002); Villaverde, Sierra de Cazorla (Carrión et al., 2001); MD95-2042 (Daniau et al., 2007); Djamilia site, N Morocco (Linstädter and Zielhofer, 2010).



often determined by these and additional factors including vegetation type, landscape characteristics, changing climate and others. Fires can also originate by anthropogenic factors, with enhanced human influence on the landscape from pasturing, forest clearance, mining, and finally agriculture (Carrión et al., 2007, 2010; Anderson et al., 2011). In the previous section we discussed the role of climate and vegetation in determining fire activity in arid environments such as Sierra Nevada. We interpret the LdlM record in terms of climate and vegetation change leading to enhanced fuel loads. However, we cannot rule out an increase in pressure from human population expansion and activities (Anderson et al., 2011) and both climatic and anthropogenic factors together probably led to elevated fire occurrence throughout much of southeastern Spain at times in the past.

In fact, the period of maximum fire activity as registered in sedimentary charcoal from Laguna de la Mula (ca. 2500–ca. 1850 cal yr BP) coincides with peaks of lead deposition from early mining activities observed in other southern Spain records. This includes the period of the Iberian culture (2300–2100 cal yr BP) at Zoñar Lake (Martín-Puertas et al., 2010) and during the Roman Empire period (ca. 2050–1750 cal yr BP as defined by Renberg et al., 2001) for both Zoñar Lake and from core ODP-976 in the Alboran Sea. Human activities could have altered the natural dynamic of charcoal production during the extraction of metal ores and in smelting. Huge fuel loads (wood or charcoal) were needed during the early stage of metallurgy for these activities (Constantinou, 1982, 1992; Stöllner, 2003) and evidence of the relationship between metal extraction, deforestation and charcoal production has been recognized, for prehistoric times, in southern Iberia (Nocete et al., 2005; Moreno Onorato et al., 2010) as well as in other Mediterranean areas, such as Cyprus (Weisgerber, 1982).

Additional evidence of increasing human activity at lower elevation in the Sierra Nevada in the last 2000 cal yr come from well-documented increases in *Olea* (olive tree) pollen in the LdlM, the Laguna de Río Seco (Anderson et al., 2011) and Borreguiles de la Virgen (Jiménez-Moreno et al., 2012) records. This coincides with the occupation of the Iberian Peninsula by the Romans, who encouraged cultivation of *Olea* (Bull, 1936; Rodríguez-Ariza and Moya, 2005).

Conclusions

A multiproxy analysis of a sediment core from Laguna de la Mula, an alpine lake in the Sierra Nevada, allowed us to reconstruct the vegetation, climate, fire history and aspects of human disturbance for the past ca. 4100 cal yr in the Sierra Nevada. Through comparing this study with other records from Sierra Nevada and more distant areas we obtained the following main conclusions:

- 1) Climate in this area between ca. 3800 and 3100 cal yr BP was arid.
- 2) Relatively milder conditions characterized the period between ca. 3100 and 2500 cal yr BP.
- 3) Wettest conditions were reached between 2500 and 1850 cal yr BP, during the Roman Humid Period.
- 4) Arid conditions were reached again between ca. 1850 and 650 cal yr BP.
- 5) Fire activity in this area is maxima during the wettest period, which could indicate that fire is mostly controlled by fuel load. Also, it could indicate more human disturbance, as indicated by increasing mining and cultivation at that time.
- 6) These arid events in the southwestern Mediterranean could be associated with persistent positive NAO index and related decreases in winter precipitation.

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