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Holocene vegetation and climate change recorded in alpine bog sediments from the Borreguiles de la Virgen, Sierra Nevada, southern Spain

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ABSTRACT

High-resolution pollen and magnetic susceptibility (MS) analyses have been carried out on a sediment core taken from a high-elevation alpine bog area located in Sierra Nevada, southern Spain. The earliest part of the record, from 8200 to about 7000 cal yr BP, is characterized by the highest abundance of arboreal pollen and *Pediastrum*, indicating the warmest and wettest conditions in the area at that time. The pollen record shows a progressive aridification since 7000 cal yr BP that occurred in two steps, first shown by a decrease in *Pinus*, replaced by Poaceae from 7000 to 4600 cal yr BP and then by Cyperaceae, *Artemisia* and Amaranthaceae from 4600 to 1200 cal yr BP. *Pediastrum* also decreased progressively and totally disappeared at ca. 3000 yr ago. The progressive aridification is punctuated by periodically enhanced drought at ca. 6500, 5200 and 4000 cal yr BP that coincide in timing and duration with well-known dry events in the Mediterranean and other areas. Since 1200 cal yr BP, several changes are observed in the vegetation that probably indicate the high-impact of humans in the Sierra Nevada, with pasturing leading to nutrient enrichment and eutrophication of the bog, *Pinus* reforestation and *Olea* cultivation at lower elevations.

Introduction

The complex climatology of the Mediterranean basin, located at the transition between the temperate and humid climate to the north and the subtropical, arid climate to the south, presents challenges and opportunities for the paleoecologist interested in the long-term environmental history of the region. More specifically, the climate of this region is influenced presently, and probably has been in the past, by (1) atmospheric and oceanic linkages to the North Atlantic region (Harding et al., 2009), influenced by the North Atlantic Oscillation (NAO); (2) the seasonal expansion northward of the Hadley Cell circulation (Roberts et al., 2011) due to heating of the North African landscape; and (3) the indirect effects of the African and Asian monsoons as expressed in regions to the south and southeast (Lionello et al., 2006). The relative importance of each of these phenomena has undoubtedly varied through time (Tzedakis, 2007).

In the western Mediterranean, strong correlations have been observed between long-term Holocene paleoenvironmental data (i.e., lake levels, fire history, fluvial activity, Mediterranean surface temperature and salinity, marine sedimentation) with the main phases of the vegetation history from pollen and plant macrofossil sequences (Jalut et al., 2009 and references therein; Vanniere et al., 2011; Giraudi et al., 2011). These records show an early humid Holocene (11,000–7000 cal yr BP), a transition period (7000–5500 cal yr BP) and a late Holocene (5500 cal yr BP–present) characterized by a progressive aridification (Jalut et al., 2009). This sequence has been reproduced recently for a high elevation site—Laguna de Río Seco—in the Sierra Nevada of southern Spain (Anderson et al., 2011) that also records early Holocene (ca. 11,500–8500 cal yr BP) mesophyte maxima. However, in several lowland pollen sites from southern Spain, the late-early to middle Holocene (ca. 7500 to 5200 cal yr BP) may have been the humid maxima (Carrión et al., 2010 and references therein), and perhaps the highest lake levels (e.g. Reed et al., 2001). Therefore, discrepancies still exist about the timing and duration of the long-term climatic phases of the Holocene. Moreover, due to low temporal sample resolution, age uncertainties and/or sensitivity, there has been little consensus about the timing and causes of millennial- and centennial-scale fluctuations in continental vegetation records from this area. Climate and human impact are indistinctly mentioned as causes of these rapid oscillations in vegetation (see discussion in Jalut et al., 2009), yet efforts to disentangle these causes continue (e.g., Mercuri et al., 2011). Therefore, unresolved questions remain with respect to the timing, nature and mechanisms of abrupt millennial- and centennial-scale climate changes in the Western Mediterranean region.

High-elevation alpine lake and bog sediments have been shown to be sensitive to climate change, recording changes in subalpine treeline vegetation during the late glacial and early Holocene (Tinner and Theurillat, 2003; Tinner and Kaltenrieder, 2005; Jiménez-Moreno et al., 2008, 2011). In many regions, alpine environments present the

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additional advantage of being less disturbed by humans than low-elevation sites. Recently, a sedimentary record from an alpine lake in Sierra Nevada (Laguna de Río Seco; Anderson et al., 2011) provided an opportunity to examine the record of vegetation, climate and human disturbance from the highest mountain range in southern Iberia. In this paper, we extend our analysis of vegetation change within the Sierra Nevada by presenting an additional Holocene vegetation record from an alpine bog environment there—the Borreguiles de la Virgen. We use the combination of our new record with the Laguna de Río Seco (Anderson et al., 2011) record to document evidence for rapid fluctuations in treeline species in Sierra Nevada during the Holocene, and suggest the characteristics of climate teleconnections that modulate the regional vegetation signal. We also demonstrate the utility of comparing two sites from the range that differ in their aspects—south versus north—and how it might affect the record from each.

Study area

Sierra Nevada

The Sierra Nevada is the highest mountain range in southern Europe, stretching ca. 80 km in a west–east trending direction (Gómez Ortiz et al., 2005). Mountain valley glaciers probably originated from cirques on and near three high peaks—Mulhacén (3479 m), Veleta (3396 m) and Alcazaba (3366 m)—as documented by a number of glacial geomorphologic studies (i.e., Obermaier and Carandell, 1916; Dresch, 1937; Schulte, 2002). 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) that occur within the glacial limit, generally above ca. 2600 m. Borreguiles de la Virgen (this study) and Laguna de Río Seco (Anderson et al., 2011) form part of those high-elevation wetlands of glacial origin.

Regional climate

The climate of southern Spain, and the rest of the Mediterranean basin, is characterized by hot, dry summers, and mild, humid winters. Climate in the western Mediterranean is mostly controlled by factors expressed in the North Atlantic Oscillation (NAO), a major atmospheric circulation pattern of the North Atlantic realm, characterized by a seesaw between the Icelandic Low (cyclone) and the Azores High (anticyclone) (Li et al., 2006). The relative strength of the Low and High influence the latitudinal position of North Atlantic storm tracks (Lionello et al., 2006). In addition, the Mediterranean Sea is located in the north flank of the sub-tropical jet stream, which plays an important role in forming atmospheric teleconnections between the Mediterranean and regions far away (Li et al., 2006). In the summer months, developing high pressure over North Africa facilitates northward movement of the Hadley Cell circulation, expanding drying conditions (Roberts et al., 2011). The Mediterranean region is today only indirectly affected by events such as El Niño–Southern Oscillation (ENSO) and monsoons (Pozo-Vázquez et al., 2005; Li et al., 2006), with no specific spatial overlap between winter cyclonic and summer monsoonal precipitation (Roberts et al., 2011).

Geographical and altitudinal contrasts contribute to a wide range of regional climatic conditions. In the Sierra Nevada area, from the Mediterranean coast to the mountains, mean annual temperatures vary between 18°C (7 m a.s.l.; Almuñecar), 15.6°C (673 m; Granada) and 4.4°C (Sierra Nevada University Hostel; 2507 m; Oliva, 2006). A west–east precipitation gradient is also very significant and annual precipitation ranges from >1400 mm/yr in the western Betic highlands to <400 mm/yr in the semi-desert lowlands of the eastern basin (Arévalo Barroso, 1992; Fletcher et al., 2010). In Sierra Nevada (University Hostel; 2507 m elevation), the mean annual precipitation is about 700 mm (Oliva, 2006). Predominant wind directions are northwesterly during winter, with southerly and southwesterly winds occurring during summer associated with weakening of the westerlies.

Vegetation of the Sierra Nevada

Vegetation in the region is strongly influenced by thermal gradients, and by precipitation (Valle, 2003). At the highest elevations, above ca. 2800 m, climate is characterized by very cold winters, short growing season, high solar radiation and snowfall, strong winds and minimal soil development (Valle, 2003). Here, the crioromediterranean flora occurs as open grassland and plants with basal rosettes, such as *Festuca clementei*, *Hormatophylla purpurea*, *Erigeron frigidus*, *Saxifraga nevadensis*, *Viola crassiuscula*, and *Linaria glacialis* (Valle, 2003). Above ca. 1800 m elevation is the oromediterranean vegetation belt, composed mostly of xerophytic shrublands and pasturelands, with *Pinus sylvestris*, *P. nigra*, *Juniperus hemisphaerica*, *J. sabina*, *J. communis* subsp. *nana*, *Genista versicolor*, *Cytisus oromediterraneus*, *Hormatophylla spinosa*, *Prunus prostrata*, *Deschampsia iberica* and *Astragalus sempervirens* subsp. *nevadensis* (El Aallali et al., 1998; Valle, 2003). In the supramediterranean belt, between ca. 1400 m and 1800 m, deciduous oaks (*Quercus pyrenaica*, *Q. faginea*), and evergreen oaks (*Q. rotundifolia*) occur, with *Acer opalus* subsp. granatense, *Fraxinus angustifolia*, *Sorbus torminalis*, *Adenocarpus decorticans*, *Helleborus foetidus*, *Daphne gnidium*, *Clematis flammula*, *Cistus laurifolius*, *Berberis hispanicus*, *Festuca scariosa*, *Artemisia glutinosa*, and many others (El Aallali et al., 1998; Valle, 2003). Below this, in the mesoMediterranean zone (down to ca. 600–700 m; Valle, 2003), *Retama sphaerocarpa* becomes important (Valle, 2003), but also *Paeonia coriacea*, *Juniperus oxycedrus*, *Rubia peregrina*, *Asparagus acutifolius*, *D. gnidium*, *Ulex parviflorus*, *Genista umbellata*, *Cistus albidus*, *C. lauriflolius*, and many others (El Aallali et al., 1998). The evergreen oak (*Quercus rotundifolia*) is also established in this belt, especially on siliceous soils.

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, *P. sylvestris* and *P. nigra* grow in high-elevation zones on siliceous and limestone substrates respectively, *P. pinaster* prefers mid altitudes on dolomites, and *P. halepensis* the lowermost areas of the mesoMediterranean belt and below into the coastal lowlands. However the potential natural range of these trees is unknown, due to serious cutting pressures over the last millennia.

Borreguiles de la Virgen (BdlV)

Borreguiles de la Virgen (BdlV) is one of a series of small wetlands and bogs that have formed in small bedrock depressions within the range, all generally occurring above ca. 2500 m. This bog occurs in a north-facing cirque basin (37° 03′ 15″N, 3° 22′ 40″ W) at 2945 m in elevation in the uppermost part of the Río Dílar drainage valley (Fig. 1). The area of the bog is relatively limited—less than ca. 1 ha. The catchment area is about 25 ha. This basin formed by glacial erosion of the bedrock, which consists of low-grade metamorphic mica schists, part of the Veleta and Mulhacén Units of the Nevado–Filábride system (Martín Martín et al., 2010). The schist is polished and congelifracted; periglacial activity has most likely removed any morainal deposits that were laid down around this basin. The bog receives inflow from a small unnamed stream, with an inlet from a former rock glacier above (Gómez Ortiz et al., 2001), and with an outflow that drains water to lower elevation wetlands. The site is usually snow-free from June to October. As with most of these bogs, it

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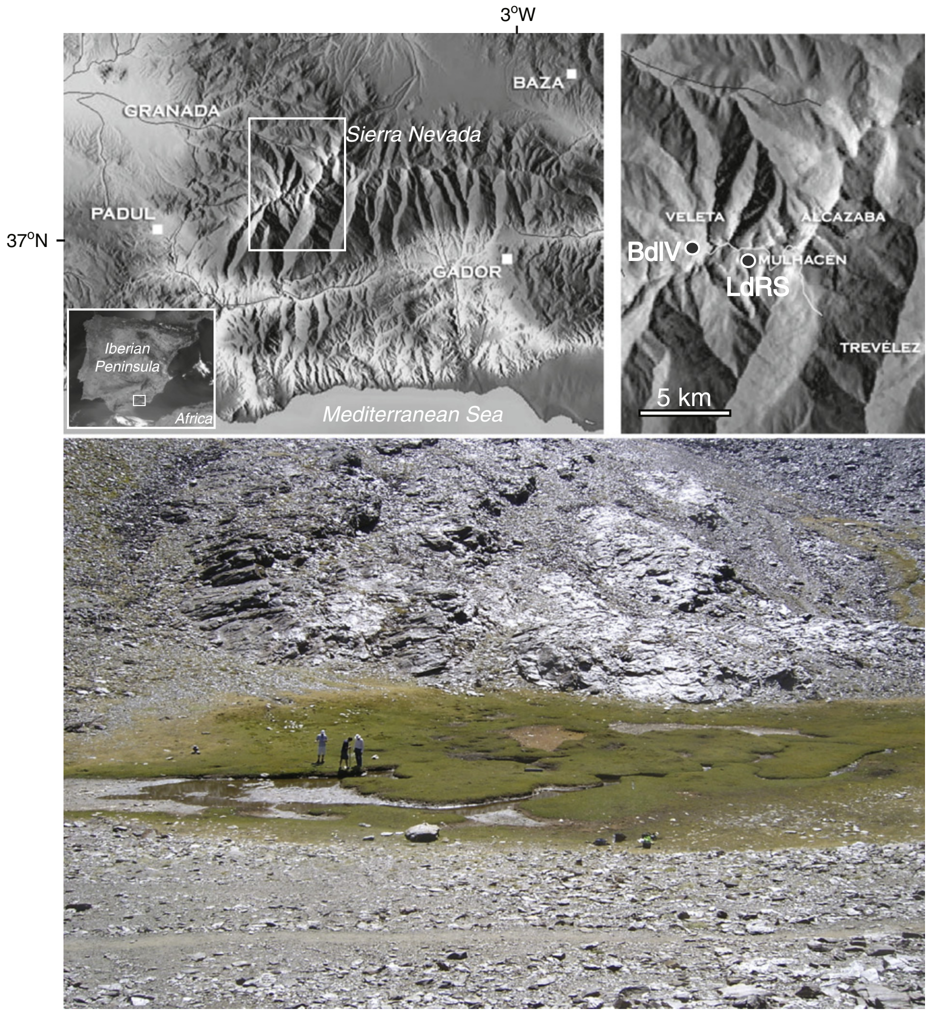

Figure 1. Location of the Borreguiles de la Virgen (BdlV) and Laguna de Río Seco (LdRS), Sierra Nevada, southern Spain. On the left, location of the Sierra Nevada, with other major sites discussed in text (Baza, Gador and Padul). On the right, location of BdlV and LdRS near the three highest peaks in the range. Below, a photo of Borreguiles de la Virgen, where the core was taken.

presently occurs above a modern treeline, within the crioromediterranean vegetation belt.

Materials and methods

In July 2006 we collected a 169 cm-long sediment core (BdlV 06-01) using a Livingstone square-rod piston corer, in the visual depocenter of the bog-wetland area. 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 BdlV core (Fig. 2) was described from split core segments in the laboratory. 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 dimensionless cgs units (cgsu; Fig. 2). Measurements were taken directly from the core surface every 0.5 cm for the entire length of the BdlV 06-01 core.

The Borreguiles de la Virgen core chronology was developed from 9 calibrated AMS radiocarbon dates (Table 1; Fig. 2). Material for AMS dates consisted of terrestrial plant remains (Table 1). Samples for dating were initially dried and weighed before submission. Radiocarbon ages were calibrated to calendar ages using CALIB version 5.0.2 (Stuiver et al., 1998). Our chronology for most of the core consists of linear interpolation between adjacent ages, using the median value of the calibrated age of the date.

Samples for pollen analysis (1 cm^3) were taken every 1 cm throughout the core (Fig. 3), with a total of 122 pollen samples analyzed. Pollen extraction methods followed a modified Faegri and Iversen (1989) methodology. Counting was performed at 400× magnification to a minimum pollen sum of 300 terrestrial pollen grains. Fossil pollen was compared with their present-day relatives using published keys. The raw counts were transformed to pollen percentages based on the terrestrial sum, not including aquatics (i.e., Cyperaceae). The pollen zonation was accomplished objectively using CONISS (Grimm, 1987). Algae and thecamoebians were found together with the pollen grains in the pollen residue and were also counted. Their percentage was calculated with respect to the pollen sum (Fig. 4).

Results

Chronology and sedimentary rates

The age-depth model for the BdlV record suggests that this record covers at least the last ca. 8200 cal yr BP (Table 1; Fig. 2). Radiometric dates show two seemingly old ages of 6240 cal yr BP at 47.5 cm and 5722 cal yr BP at 54 cm. This is likely due to mobilization and re-sedimentation of old organic material into the bog. These

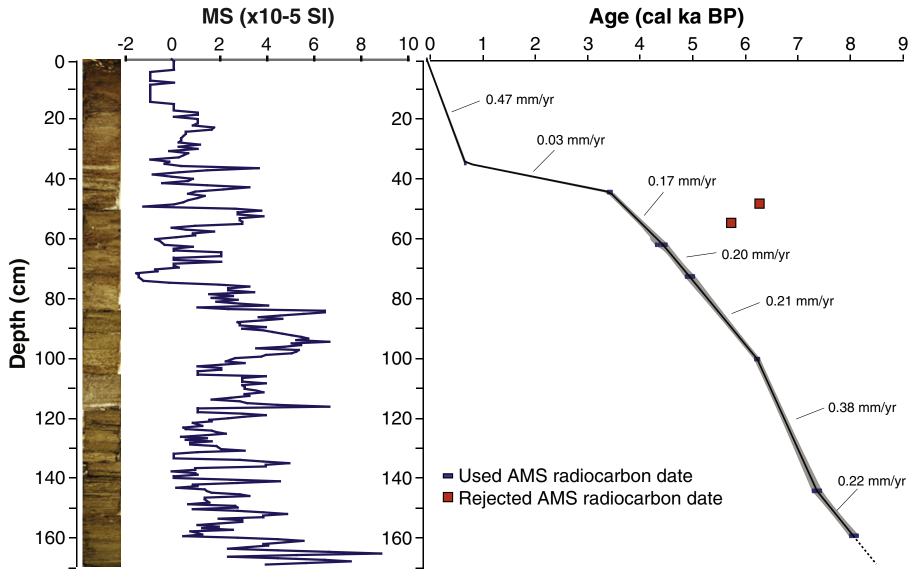

Figure 2. Core composite photo and magnetic susceptibility (MS) profile of the BdlV#06-01 core. On the right is the age-depth diagram for the BdlV record. The red squares are dates that were not used in the age model. The sediment accumulation rates are represented.

radiocarbon ages were not used in the age-model construction (Fig. 2), as a set of younger ages stratigraphically ordered were recorded downcore (Table 1). Sediment accumulation rates (SAR) were calculated based on linear interpolation between the radiocarbon dates. The SAR below ca. 45 cm is relatively constant, varying between ca 0.17 and 0.38 mm/yr. Between ca. 45 cm and ca. 35 cm, the SAR slows down to ca. 0.03 mm/yr, then increases to the core top at 0.47 mm/yr (Fig. 2).

Lithology and magnetic susceptibility

Sediments from BdlV 06-01 are relatively inorganic in the lower portion of the core, progressively becoming more organic towards the top (Fig. 2). However, high-variability is observed in the BdlV sedimentary record. MS variation generally coincides with lithologic change throughout the core, with lighter and relatively organically-depleted clays corresponding to higher MS values (Fig. 2). The core bottoms at 169 cm with relatively light brown sandy clay resting on the mica schist bedrock. The highest MS are then recorded near the core bottom, with values close to 9 cgsu. Between 160 and 117 cm (ca. 8100–6700 cal yr BP) sediments become more organic, and are characterized by the alternation of lighter and darker brown clays with MS values around 2 cgsu. More massive and lighter brown clays occurred from 117 to 75 cm (ca. 6700–5000 cal yr BP) with somewhat higher MS values (Fig. 2). Three organically depleted intervals are observed, centered at 117, 94 and 85 cm depth. However, organic sedimentation increases between 75 and 18 cm (ca. 5000–300 cal yr BP) where brown peaty clays predominate. MS values around 0.5 cgsu are recorded but high-variability is observed, reaching even negative MS values in peat levels centered at ca. 72, 60, 50, 39 and 33 cm. From 18 cm to the core top (last ca. 300 yr) a very organic peat occurs with negative MS around −1 cgsu.

Pollen analysis

We used variations in six pollen types—*Pinus* total, *Olea*, *Artemisia*, Amaranthaceae, Lactucaceae and Poaceae—to objectively zone the pollen data using the program CONISS (Grimm, 1987), producing five pollen zones for the Borreguiles de la Virgen record (Figs. 3 and 4).

Zone BdlV-1 [ca. 8200 to 6800 cal yr BP (163–124 cm depth)]. BdlV-1—the early Holocene—is characterized by the highest abundance of *Pinus*, with values reaching up to 30% (Fig. 3). Poaceae (20–40%), Lactucaceae (to 20%), Cyperaceae (generally 10–15%) and Apiaceae (3–4%) are also important in the assemblage. The aquatic alga *Pediastrum* is most abundant, and the dung fungus *Sporormiella* is also abundant, in this zone (Fig. 4).

Table 1
Age data for Borreguiles de la Virgen, Spain.

Lab number[a]	Core	Depth (cm)	Material dated	Dating method	Age (^{14}C yr BP ± 1σ)	Calibrated age (cal BP) 2σ ranges	Median
	Br. V-1	0		Present	AD2007	−57	−57
UCIAMS-51248	Br. V-1	34.5	Vegetal remains	^{14}C	730 ± 15	665–686	675
UCIAMS-69120	Br. V-1	44.2	Vegetal remains	^{14}C	3220 ± 20	3387–3470	3428
UCIAMS-67124	Br. V-1	47.5	Vegetal remains	^{14}C	5435 ± 25	6201–6291	6240
UCIAMS-67125	Br. V-1	53.96	Vegetal remains	^{14}C	5000 ± 20	5657–5791	5722
UCIAMS-67126	Br. V-1	61.8	Vegetal remains	^{14}C	3960 ± 20	4303–4439	4430
UCIAMS-51249	Br. V-1	72.4	Vegetal remains	^{14}C	4395 ± 15	4872–4980	4941
UCIAMS-51250	Br. V-1	100	Vegetal remains	^{14}C	5410 ± 15	6195–6279	6241
Beta-22171	Br. V-1	144	Vegetal remains	^{14}C	6470 ± 40	7291–7440	7375
UCIAMS-51251	Br. V-1	159	Vegetal remains	^{14}C	7245 ± 20	8002–8074	8052

Note: All ages were calibrated using CALIB 5.0.2 (Stuiver and Reimer, 1993).
[a] Sample number assigned at radiocarbon laboratory; Beta# = Beta Analytic, Inc., UCIAMS# = University of California at Irvine W.M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory.

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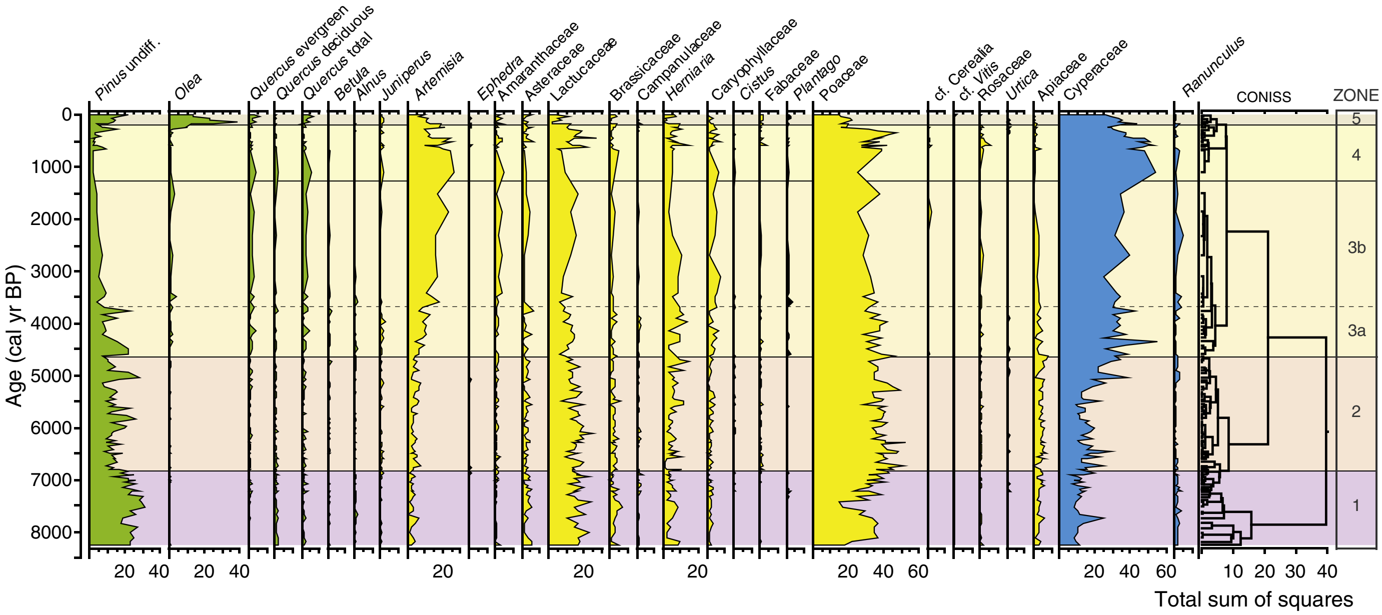

Figure 3. Pollen diagram of the BdlV record showing percentages of selected taxa. The aquatics were excluded from the total pollen sum. The zonation was made using cluster analysis provided by CONISS (Grimm, 1987).

Zone BdlV-2 [ca. 6800 to 4600 cal yr BP (124–66 cm depth)]. Zone 2 is characterized by a significant decrease in *Pinus* (declining to values around 15%) and, on the other hand, an increase in Poaceae (around 40%). *Artemisia* begins a slight increase during this zone. Cyperaceae and Apiaceae increase slightly as well (reaching values up to 20% and 5%, respectively). *Pediastrum* decreases considerably, and *Sporormiella* disappears in the early part of the zone (Fig. 4).

Zone BdlV-3 [ca. 4600 to 1200 cal yr BP (66–36 cm depth)]. *Pinus* continues to decline in Bdlv-3a, averaging around 7% of the sum by BdlV-3b. Evergreen *Quercus* increases during BdlV-3, along with minor amounts of *Olea*, as does several shrubs such as *Artemisia*, Amaranthaceae, Caryophyllaceae, and Cyperaceae. In general, this occurs in two steps (throughout zones BdlV-3a and 3b). Cereal (Cerealia) pollen is first encountered in Bdlv-3b. *Pediastrum* is still present but in very small amounts. *Sporormiella* is only found in BdlV-3a.

Zone BdlV-4 [ca. 1200 to 200 cal yr BP (36–11 cm depth)]. Pollen spectra of BdlV-4 show the lowest *Pinus* percentages (down to 2%). However, the highest percentages in *Artemisia* (25%), Amaranthaceae (5%) and Cyperaceae (55%) are observed during this zone, and evergreen *Quercus* remains relatively abundant. Other pollen types, such as Caryophyllaceae, remain with high percentage. *Pediastrum* no longer occurs in the record. At the end of this zone, *Pinus* increases progressively up to 15%, and *Sporormiella* also increases.

Zone BdlV-5 [ca. 200 cal yr BP to AD 2006 (11–0 cm depth)]. *Pinus* continues to increase, and in the last sample analyzed it reaches

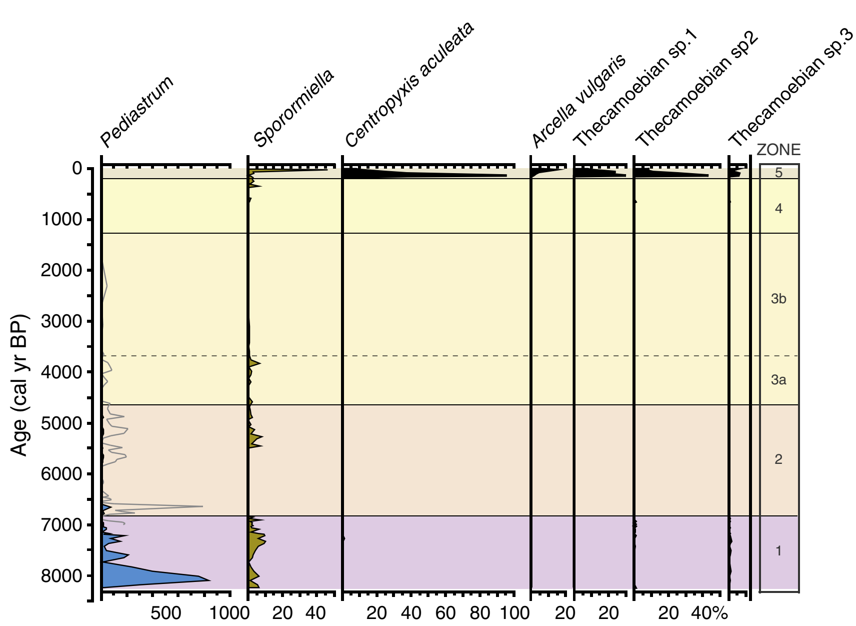

Figure 4. Main algae, spore and thecamoebian diagram of the BdlV record showing percentages of selected taxa. Percentages were calculated with respect to the terrestrial pollen sum. Zones shown are the same as defined by the pollen data (see Fig. 3).

percentages of 22% of the pollen sum. However, *Olea* pollen, which has been found sporadically through the record, increases to maximum Holocene percentages (up to 38%). The herbivore dung fungus, *Sporormiella*, is most abundant at this time, as are several species of thecamoebians.

Discussion

The record from Laguna de Río Seco (LdRS; Anderson et al., 2011) has provided an opportunity to examine the postglacial history of vegetation, climate and human disturbance from one of the highest alpine lakes in the Sierra Nevada. Though the LdRS and BdlV sites are located at similarly high elevations within the range—3020 m and 2950 m, respectively—and are ca. 4 km distant from each other, they have very different aspects. While LdRS has a south-facing aspect, BdlV sits in a cirque that faces northwest. We use this new record to compare sedimentary sequences between a bog (BdlV) and a lake (LdRS), with other regional sedimentary records, to further characterize the paleoclimatic and paleoenvironmental history of this important region.

Deglaciation of high elevation Sierra Nevada

The general outline of the glacial history of the Sierra Nevada began nearly 100 yr ago (Obermaier and Carandell, 1916). Subsequent researchers (e.g., Dresch, 1937; Schulte, 2002; others) further refined the chronology by more detailed field mapping. Although Anderson et al. (2011) documented deglaciation in the Laguna de Río Seco cirque by at least 11,000 cal yr BP, bottom dates from other cirques have yet to be obtained, and the specific deglacial history of the range remains largely unknown.

Despite the lack of a specific chronology, mapping by Messerli (1965), Gómez Ortiz et al. (2005) and others determined average late Pleistocene snowlines for the Sierra Nevada to be higher than other ranges in Europe, and ca. 2300–2400 m on north-facing slopes, and 2400–2500 m on south-facing slopes. This was undoubtedly due to generally higher insolation on south-facing slopes versus north-facing ones. This may have influenced the relative ages of the BdlV versus LdRS records. Since the age of bottom sediments of BdlV are nearly 2800 yr younger (ca. 8200 cal yr BP) than those for LdRS (ca. 11,000 cal yr BP) we suggest that ice lingered longer in the north-facing BdlV cirque basin, with melting delayed compared to the south-facing LdRS cirque. Alternatively, it is possible that a short-lived glacial advance, perhaps related to the well-documented cold, dry (Reed et al., 2001; Gasse, 2002) 8.2 ka event, formed on the north face of the Sierra Nevada at that time, eroding previously deposited sediments in the BdlV cirque. So far, however, no early Holocene moraine deposits have been identified from this drainage.

Early Holocene warm and humid period

The oldest part of the BdlV record, from 8200 to about 7000 cal yr BP (pollen zone BdlV-1), is characterized by the highest abundance of arboreal pollen (mostly *Pinus*) and *Pediastrum*, suggesting the warmest and wettest conditions for the Holocene in this area. Considering the arboreal pollen, these results are very similar to the pollen data from LdRS (Anderson et al., 2011; Fig. 5), where, in addition to *Pinus*, highest Holocene percentages of other mesic forest species (i.e., *Betula*) also occur. Today in the Sierra Nevada and nearby ranges (Sierra de Baza, Sierra de Segura), subalpine treeline is formed by *Pinus* stands (*P. sylvestris*, *P. nigra*; Carrión et al., 2001). Therefore, here and elsewhere (Anderson et al., 2011) we interpret the early Holocene peak in *Pinus* as representing the highest elevation of treeline recorded in the Sierra Nevada, although we are presently unable to determine the precise elevation of subalpine treeline. In locations where *P. sylvestris* trees are present, *Pinus* percentages are nearly

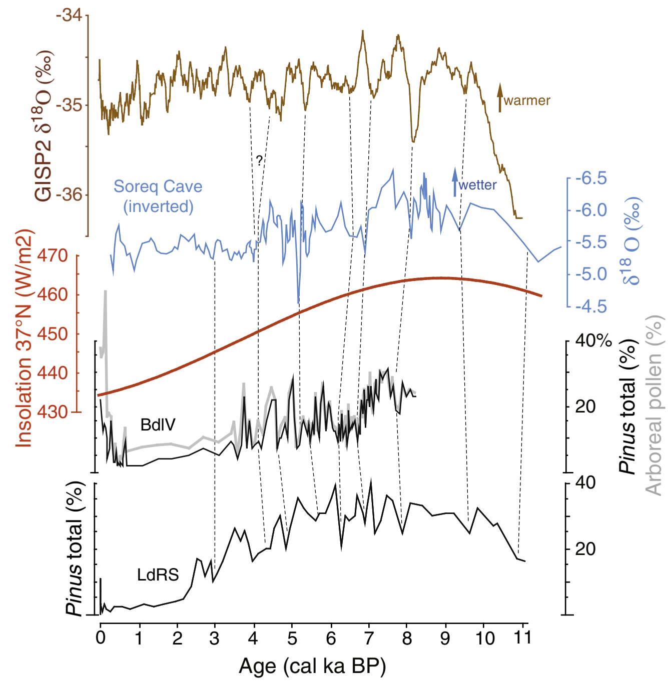

Figure 5. Comparison the total percentage of *Pinus* from the Sierra Nevada records (BdlV and LdRS) with the July insolation at 37°N (Laskar et al., 2004), the Soreq Cave isotopic record and the 300-yr running mean of the isotopic record from Greenland (GISP2; Grootes et al., 1993). Dashed lines are tentative correlations between the different records.

always 50–60% of the pollen sum (Andrade et al., 1994). As *Pinus* never reached percentages higher than 30–40% in this area (Fig. 5), they probably never grew around these alpine environments (Anderson et al., 2011), and treeline must have been below 2950 m elevation. Because treeline is sensitive to temperature and thus growing season length (Valle et al., 1989), our alpine pollen records from Sierra Nevada point to the highest temperatures during the early Holocene (until ca. 7000 cal yr BP). The relatively lower occurrence of *Pinus* and mesophytic trees such as *Betula* or deciduous *Quercus* in the BdlV record, when compared with the LdRS record (Anderson et al., 2011), is explained by edaphic differences between the sites. BdlV and LdRS are located in the north and south side of the Sierra Nevada, respectively. Therefore, treeline and forest species are likely to have occurred at lower elevation on the north side (around BdlV) with respect to the south side (LdRS) during the early Holocene, as they do today (Schmidt, 1956), with pollen percentages varying accordingly. Similarly, but considering the aquatic pollen and spore record, the abundance in *Pediastrum* (in BdlV), *Botryococcus* and other aquatics (i.e., *Botrychium*, *Potamogeton* in LdRS; Anderson et al., 2011) confirms that this was the wettest period in the record.

These generally warm and humid conditions were punctuated in the alpine pollen records from the Sierra Nevada by at least one short-term climatic variations. For example, a dry period can be observed in the BdlV and LdRS records centered at ca. 7800 cal yr BP (Fig. 5), shown as a decline in *Pinus* but an increase in Poaceae. This dry event was interpreted in Anderson et al. (2011) as the beginning of long-term aridification in the Sierra Nevada, but the BdlV data suggest that this short-term fluctuation existed during the more humid early Holocene here until about 7000 cal yr BP.

Support for these interpretations of a generally warm and humid early Holocene phase (11,000–7000 cal yr BP) in the Mediterranean region comes from many sources, as summarized by Jalut et al. (2009) and modeled by Brayshaw et al. (2011). Within the region, our pollen data agree with those from the lowland Padul (Pons and

Reille, 1988), Elx and Salines (Burjachs et al., 1997) sites, and marine core MD95-2043 (Fletcher and Sanchez Goñi, 2008), which all document greatest forest development at this time.

Outside of Iberia, Magny (2004) recorded the highest lake levels around 7500 cal yr BP from the French and Swiss Alps. Greater effective precipitation is also observed in speleothem records from Italy (Zanchetta et al., 2007) and the Eastern Mediterranean (Soreq cave; Bar-Matthews et al., 2000; Fig. 5) and from lake deposits in the Sahara desert (African Humid Period; deMenocal et al., 2000; Gasse, 2002). This increased precipitation in the Mediterranean area generated enhanced continental freshwater runoff that increased the nutrient supply into the Mediterranean Sea (Martínez-Ruiz et al., 2003), resulting in deposition of organic-rich sapropels in the eastern Mediterranean. Low eolian input into the Mediterranean and subtropical western Africa during this period confirms the generally humid conditions at that time, when the Sahara was nearly completely vegetated and supported numerous perennial lakes (deMenocal et al., 2000; Jimenez-Espejo et al., 2008).

The early Holocene thermal maximum can be explained by orbital-scale boreal summer insolation maxima (Fig. 5). This contributed to climate warming, the highest subalpine treeline in the Sierra Nevada and full forest development at this time. The humidity maximum is more difficult to explain and some authors invoked enhanced summer precipitation (a Mediterranean summer monsoon; see discussion in Tzedakis, 2007). Typically, however, the summer insolation maxima in the early part of an interglacial is associated with extensive summer aridity in the Mediterranean vegetation (Tzedakis, 2007). Therefore, it seems more likely that enhanced fall/winter precipitation occurred in this area during the early Holocene (Tzedakis, 2007; Fletcher and Sanchez Goñi, 2008). Recent climate models show that summer insolation maxima would favor stronger land/sea temperature contrasts over the Mediterranean Sea in the fall as the land cools faster than the sea, and this would generate enhanced winter precipitation (Tuenter et al., 2003; Meijer and Tuenter, 2007).

Mid- and late Holocene cooling and aridification in the Mediterranean

The pollen record from BdlV shows a decrease in *Pinus* that is replaced first by Poaceae (pollen zone BdlV-2) from 7000 to 4600 cal yr BP and then by Cyperaceae and *Artemisia* (pollen zone BdlV-3) from 4600 to 1200 cal yr BP (Fig. 3). *Pediastrum* also decreased progressively and totally disappeared at around 3800 cal yr BP. The decrease in *Pinus* could be interpreted as a movement of treeline species towards lower elevations due to climate cooling. However, aridification seems to play the main role transforming the vegetation in this area, as observed at the nearby LdRS record (Anderson et al., 2011) and many other sites (Carrión, 2002; Carrión et al., 2010; Pérez-Obiol et al., 2011). Basinwide, the first stage of aridification commenced by ca. 7000 cal yr BP, as suggested by speleothem data (Bar-Matthews et al., 2000; Zanchetta et al., 2007), and by the end of the S1 sapropel deposition in the eastern Mediterranean (Emeis et al., 2000). Jalut et al. (2009) observed that 7000 cal yr BP marks the beginning of a vegetation transition until 5500 cal yr BP, characterized by increasing aridity in the Mediterranean vegetation with respect to the preceding more humid period. Magny et al. (2002) also documented a decrease in river activity in Western Europe as well as lake-level lowering in the northern Mediterranean area, suggesting a general evolution from wetter to drier climatic conditions at that time. A rapid development of human settlement in the southern Sahara region is observed at 6800 cal yr BP, announcing the abandonment of the northern Sahara settlements (Vernet and Faure, 2000). The Neolithic–Chalcolithic transition occurred during this period (around 6000 cal yr BP; Carrión et al., 2007; Mercuri et al., 2011) in the western Mediterranean area, a cultural changes perhaps precipitated by environmental stress (Mercuri et al., 2011; Roberts et al., 2011).

Regionally at lower elevation, a change from deciduous to Mediterranean xerophytic forest taxa is also observed at Padul and Lake Siles at that time (Pons and Reille, 1988; Carrión, 2002). However, the late-early to middle-Holocene (ca. 7500 to 5200 cal yr BP) may have been the mesophytic maximum at many other lowland sites (see Carrión, 2002; Carrión et al., 2010 for a synthesis). Lake-level investigations in southwestern Spain (Reed et al., 2001) support the idea of a general trend to climatic aridification over the second half of the Holocene but the Laguna de Medina record also shows a wet mid-Holocene stage at 7200–5500 cal yr BP. The difference in timing between the alpine and the lower elevation records were suggested by Anderson et al. (2011) as greater differences in insolation between winter and summer in the early Holocene that may have translated to greater snowpack and subsequently higher lake levels at higher elevations, but not necessarily at lower elevations, where higher summer temperatures continued to provide greater evaporation rates. With declining seasonality after ca. 8000 cal yr BP, but continued expansion of the ITCZ and influence of African monsoonal flow (Cheddadi et al., 1997; Jolly et al., 1998; Broström et al., 1998; Magny et al., 2002; others), lake levels at the highest elevation sites could remain high, but lake levels at lower elevation sites would increase as evaporation rates declined.

Even though slight differences exist in the timing of the Holocene mesophytic maxima, most of the pollen records from this area show enhanced aridification in the late Holocene, starting at around 5000 cal yr BP (see syntheses in Carrión, 2002; Carrión et al., 2010; Fletcher et al., 2007; Jalut et al., 2009). The alpine records from Sierra Nevada also show an increase in the aridification process at that time with increasing presence of xerophytic plants such as *Artemisia* or Amaranthaceae (Anderson et al., 2011; Fig. 3). At BdlV, the SAR is very low between ca. 3400 and 700 cal yr BP, suggesting either enhanced decomposition or lowered bog productivity, either resulting from more arid conditions. Other evidence of enhanced aridity comes from simulation studies (Renssen et al., 2003) and a marine record off northwestern Africa (deMenocal et al., 2000) that shows an significant increase in eolian dust at around 5500 cal yr BP, which was interpreted as the abrupt end of the African Humid Period.

Long-term vegetation changes shown here (semi-desert expansion and Mediterranean forest decline) parallel declining summer insolation (Fig. 5), undoubtedly a critical factor for the mesophytic forest decline, by impacting the length of the growing season. Insolation changes affected sea surface temperatures contributing to a cooling trend from the Holocene maxima in the early Holocene until today (Cacho et al., 2002). Precipitation was also affected by this decrease in summer insolation in that it may have promoted regional atmospheric aridity through several mechanisms, including reduced intensity of the global hydrological cycle, reduced global temperatures resulting from increased albedo, and intensification of wind systems leading to enhanced sea-surface cooling and evaporative stress on plant life (Fletcher and Sanchez Goñi, 2008).

The long-term trend towards aridity was punctuated in the Sierra Nevada alpine pollen records by even drier short-term events. Dry periods can be observed in the BdlV and LdRS records centered at ca. 6500, 5200 and 4000 cal yr BP with very similar reductions of up to 20% in *Pinus* in both records (Fig. 5). These events coincide in time and duration, within radiocarbon dating error, with dry periods observed in paleoclimatic records from the Mediterranean and other areas. For example, a drier period centered at ca. 6500 cal yr BP in our Sierra Nevada records is well-recognized in speleothem records from the Mediterranean (Soreq Cave and CC26 records; Bar-Matthews et al., 2000; Zanchetta et al., 2007; Fig. 5), low lake levels in central Europe (Magny, 2004) and at Laguna de Medina, Spain (Reed et al., 2001), a dry/cold event observed in the Mediterranean Sea (M6; Frigola et al., 2007) and cold surface temperatures in Greenland (Fig. 5; Grootes et al., 1993). The ca. 5200 and 4000 cal yr BP dry events coincide with increases in xerophytic pollen in southern Iberia (Carrión et al., 2001, 2010; Carrión, 2002; Pantaleón-Cano et al., 2003; Fletcher et al., 2007;), other western Mediterranean forest depletions (Jalut et al., 2009), desiccation events in Lake Siles (Carrión, 2002), low lake levels in North Africa (Lamb and van der Kaars, 1995), decreases in precipitation in northern Italy and the eastern Mediterranean (Bar-Matthews et al., 2000; Drysdale et al., 2006; Fig. 5) and cold/dry events in the Mediterranean Sea (M5 and M4; Frigola et al., 2007) and Greenland (Grootes et al., 1993; Fig. 5). The ca. 4000 cal yr BP dry event has received a lot of attention lately and seems to be recorded globally (Thompson et al., 2002; Booth et al., 2005; Arz et al., 2006; Magny et al., 2009). These arid phases coincide with major breaks in the eastern Mediterranean archeological record, namely, Early Bronze Age/Middle Bronze Age (at ca. 5200 cal yr BP), and Late Bronze Age/Iron Age (at ca. 4000 cal yr BP) (Thompson et al., 2002; Arz et al., 2006; Roberts et al., 2011). Locally, the collapse of the Argaric culture (at ca. 3600 cal yr BP; Carrión et al., 2010) could be related to this severe drought, as other many factors observed by Carrión et al. (2007, 2010).

The fact that the alpine Sierra Nevada pollen records show millennial-scale climatic events that are recognized globally (i.e., Greenland) supports the hypothesis of a highly efficient climatic coupling between the North Atlantic and the western Mediterranean region during the Holocene. Positive NAO years are associated with Iberian dryness and cold temperatures in Greenland, and more persistent and stronger winter storms crossing the Atlantic Ocean (Hurrell, 1995; Frigola et al., 2007). Therefore, the dry events recognized in the alpine pollen records from Sierra Nevada could be associated with periods of persistent positive NAO index, which would strengthen northwesterly airflow over the northwestern Mediterranean Basin (Muñoz-Díaz and Rodrigo, 2003; Frigola et al., 2007).

Human impact on vegetation, grazing and cultivation

Pollen records from Sierra Nevada and other Mediterranean sites demonstrate that aridification continued progressively until the present (Magny et al., 2002; Carrión et al., 2010). However, in the last millennia human impact on the vegetation increased substantially, and changes are more difficult to interpret (Carrión et al., 2010). For instance, increases in charcoal at ca. 3900 cal yr BP at LdRS (Anderson et al., 2011) and the nearby Sierra de Baza (Carrión et al., 2007) indicate increase in fire activity that could be increased aridity but also enhanced human influence on the landscape from pasturing, forest clearance, mining, and finally agriculture (Carrión et al., 2007, 2010; Anderson et al., 2011). Thus, the regional vegetation patterns in the last millennia undoubtedly result from a complex of climatic and human factors.

In the early part of the pollen record from BdlV, *Sporormiella* occurs sporadically, but increased substantially in the last 500 yr (specially in pollen zone BdlV-5; Fig. 4). This increase is also observed in the nearby LdRS record after ca. 2700 cal yr BP and became very abundant in the last millennium (Anderson et al., 2011). *Sporormiella* is a genus of coprophilous fungi requiring herbivore digestion to complete its life cycle. It produces spores in the dung, primarily of mammals (Ahmed and Cain, 1972; Gill et al., 2009). Their abundance probably indicates intensified grazing in the higher elevations of the Sierra Nevada at this time associated with introduction of livestock on the landscape (Anderson et al., 2011).

The increase in *Sporormiella* in the last centuries in BdlV roughly coincides with important increases in *Olea* and *Pinus*, associated with cultivations of olive (*Olea*) and reforestation with *P. sylvestris* trees at lower elevations (Anderson et al., 2011). Significant plantings of *P. sylvestris* trees commenced in the mid-20th century in the Sierra Nevada, to combat erosion (Arias Abellán, 1981). The presence of Cerealia (cereal) pollen, most likely planted at lower elevations, seems to be consistent in the pollen record from BdlV since the last 2000 cal yr BP. *Vitis* (grapevine) is only present in the BdlV record in the last sample (present) (Fig. 3). These results are very similar to the pollen data from LdRS and other lower elevation sites in this area (i.e., Carrión et al., 2007; Anderson et al., 2011). However, the collective data from BdlV (this study) and LdRS (Anderson et al., 2011) data show that human impact on the high elevation Sierra Nevada sites has been considerably less than at lower elevations.

The high abundance of thecamoebians in the last 150 yr in the BdlV record (Fig. 4) could also confirm nutrient enrichment of the wetland environment due to the introduction of livestock in this area. Thecamoebians are freshwater amoeboid protozoans, characterized by an agglutinated test held together by organic cement, that occur in a variety of wetland habitats including moss, soil, peat and standing water from tropical to polar environments (Boudreau et al., 2005). *Centropyxis aculeata*, the most abundant species in the core top samples, has been reported as an opportunistic genus, adaptable to severe conditions such as very eutrophic environments (Asioli et al., 1996; Scott et al., 2001; Escobar et al., 2008).

Conclusions

Alpine pollen records from Sierra Nevada (southern Spain) show the warmest and wettest conditions during the early Holocene, related to Holocene summer insolation maxima. The pollen evidence is consistent with long-term aridification of the environment since ca. 7000 cal yr BP until today, probably related to the decrease in insolation during the middle and late Holocene, and the ending of the African Humid Period. This long-term aridification trend was modulated by millennial-scale variability evident in our pollen records by dry events at ca. 6500, 5200 and 4000 cal yr BP. These dry events coincide in timing and duration with droughts in the Mediterranean and other distant areas, and cold events from Greenland, suggesting climate teleconnections between the Mediterranean and the North Atlantic. Further, we suggest that these dry events in the BdlV record could be associated with a more persistent NAO index, strengthening the northwesterlies over the northwestern Mediterranean. Climate is not the only driver of environmental change in the Sierra Nevada. A human impact on the vegetation is also observed in Sierra Nevada, notably in the last millennium, with a strong increase in the pollen record of grazing, cultivars and *Pinus* reforestation, in keeping with our results at other sites within the range (Anderson et al., 2011).

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