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Postglacial history of alpine vegetation, fire, and climate from Laguna de Río Seco, Sierra Nevada, southern Spain

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A B S T R A C T

The Sierra Nevada of southern Spain is a landscape with a rich biological and cultural heritage. The range was extensively glaciated during the late Pleistocene. However, the postglacial paleoecologic history of the highest range in southern Europe is nearly completely unknown. Here we use sediments from a small lake above present treeline – Laguna de Río Seco at 3020 m elevation – in a paleoecological study documenting over 11,500 calendar years of vegetation, fire and climate change, addressing ecological and paleoclimatic issues unique to this area through comparison with regional paleoecological sequences. The early record is dominated by *Pinus* pollen, with *Betula*, deciduous *Quercus*, and grasses, with an understory of shrubs. It is unlikely that pine trees grew around the lake, and fire was relatively unimportant at this site during this period. Aquatic microfossils indicate that the wettest conditions and highest lake levels at Laguna de Río Seco occurred before 7800 cal yr BP. This is in contrast to lower elevation sites, where wettest conditions occurred after ca 7800. Greater differences in early Holocene seasonal insolation may have translated to greater snowpack and subsequently higher lake levels at higher elevations, but not necessarily at lower elevations, where higher evaporation rates prevailed. With declining seasonality after ca 8000 cal yr BP, but continuing summer precipitation, lake levels at the highest elevation site remained high, but lake levels at lower elevation sites increased as evaporation rates declined. Drier conditions commenced regionally after ca 5700 cal yr BP, shown at Laguna de Río Seco by declines in wetland pollen, and increases in high elevation steppe shrubs common today (*Juniperus*, *Artemisia*, and others). The disappearance or decline of mesophytes, such as *Betula* from ca 4000 cal yr BP is part of a regional depletion in Mediterranean Spain and elsewhere in Europe from the mid to late Holocene. On the other hand, *Castanea sativa* increased in Laguna de Río Seco record after ca 4000 cal yr BP, and especially in post-Roman times, probably due to arboriculture. Though not as important at high than at low elevations, fire occurrence was elevated, particularly after ca 3700 years ago, in response to regional human population expansion. The local and regional impact of humans increased substantially after ca 2700 years ago, with the loss of *Pinus* forest within the mountain range, increases in evidence of pasturing herbivores around the lake, and *Olea* cultivation at lower elevations. Though human impact was not as extensive at high elevation as at lower elevation sites in southern Iberia, this record confirms that even remote sites were not free of direct human influence during the Holocene.

1. Introduction

The Sierra Nevada – the largest mountain range in southern Spain and the highest range in Europe outside of the Alps – is an immense landscape with a rich biological and cultural heritage. Situated in the region of Andalucía, this area has been occupied and exploited by successive waves of human societies since at least Neolithic times, and perhaps even earlier (Carrión et al., 2007; Gil-Romera et al., 2010), including the Metallurgic Chalcolithic and Argaric (Bronze-Age) people, the Iberians (Iron-Age), Romans, Goths, Moors and Christians – each putting their own imprint on the landscape. Within a span of ca 40 km, the mountain range rises to nearly 3500 m elevation from sea level, creating a region of

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unsurpassed biodiversity in southern Europe. The Sierra Nevada is considered to be the most important center of biodiversity in the western Mediterranean region, with over 2100 different vascular plant taxa recorded, accounting for nearly 30% of the vascular flora of the entire Iberian Peninsula (Heywood, 1995; Blanca, 1996, 2002). It is not surprising, then, that given such immense landscape and biotic diversity, many human societies have chosen to settle there and exploit the Sierra Nevada area. In order to protect this region today, the highest elevations of the range were declared a part of a UNESCO Biosphere Reserve in 1986, a Natural Park in 1989, and a National Park in 1999 (Gómez Ortiz et al., 2005).

Yet, considering this diverse region, much of what we know about vegetation change within southern Iberia comes from sites at lower elevation (e.g., Carrión et al., 2007, 2010a,b; Gil-Romera et al., 2010), with little information from within the higher Sierra Nevada itself. One exception is the ca 1500-year-old record determined from several high elevation borreguiles (bogs) (Esteban, 1996). Longer, continuous records, extending back into the early to middle Weichselian come from cores of the Padul peat bog, 720 m asl and 20 km south of Granada (Menéndez Amor and Florschütz, 1962, 1964; Florschütz et al., 1971; Ortiz et al., 2004; Álvarez-Lao et al., 2009) or Alborán Sea sediments (Parra, 1994; Fletcher and Sanchez Goñi, 2008; Sánchez Goñi et al., 2008; Dormoy et al., 2009; Fletcher et al., 2010) to the south.

Here we report on the Holocene vegetation, fire and climate history determined from the sediment record of a small alpine lake, Laguna de Río Seco, in the Sierra Nevada. Analysis of the environmental history of Laguna de Río Seco in particular, and the Sierra Nevada in general, is important for several reasons. First, the site is one of the highest elevation records studied so far in southern Europe. The Laguna de Río Seco record preserves at least an 11,500 cal yr record of continuous environmental change, including not only the paleo-vegetation record, but also high-resolution fire history and lake level climate change records, for a region where few continuous Holocene lake records exist. This record provides an important comparison to those sites from lower elevation in the region, allowing a more comprehensive picture of vegetation change over a broader elevational gradient than exists presently. Second, Laguna de Río Seco, at ca 3020 m elevation, is near the upper elevation extent of late Holocene human landscape modification in southern Iberia. This is significant, since human disturbance in southern Iberia, as in most of the Mediterranean basin (Jalut et al., 2009), has been widespread, both spatially and temporally, and is better documented at lower elevations. At the same time, however, the Laguna de Río Seco record demonstrates that virtually nowhere in the region, even the highest elevations, has been immune to the results of human activities during the Holocene. For instance, although the lake is presently in the crioromediterranean (i.e., alpine) zone, our pollen studies document the likelihood of forest clearance near the lake, and the near certainty of pastoral activities around the lake, especially during the late Holocene.

We use pollen, charcoal and macrofossil stratigraphies to determine the Holocene vegetation, climate and fire history of the Sierra Nevada, answering the following questions:

- What changes in vegetation have occurred at high elevation, in an area presently above potential treeline?
- How has climate variability during the Holocene affected high elevation vegetation communities within this mountain range?
- What is the history of fire from a high elevation site, and how does that relate to Holocene vegetation and climate change?
- What is the record, if any, of human landscape occupation or modification, recorded in the proxy record as ecosystem disturbance, at the site?
- How does this record compare to nearby sites from lower elevation?

As landscapes have become increasingly fragmented and modified by human activities, and regions of "natural vegetation" have become smaller and more rare, the role of the paleoecologist has become essential in determining former vegetation patterns and disturbance regimes. Such research is critically important to human society, and natural and cultural landscapes, in the face of a rapidly changing climate. Models of future climate in the Mediterranean region suggest not only warmer summer temperatures (Gao and Giorgi, 2008) but increased drought variability [i.e., heat waves of greater intensity (Giorgi and Bi, 2005; Giannakopoulos et al., 2009)] and greater precipitation intensity (May, 2008) in the future, and indeed these trends may be accelerating (van Oldenborgh et al., 2009). Increased summer warmth (and drought) will have important effects on human activities and biotic communities, including water supply for domestic and agricultural production (Sumner et al., 2003; Arnell, 2004) natural disturbances such as fire (Dale et al., 2001), and perhaps forest die-off (Allen et al., 2010). Paleoecological research is also important to land managers as they determine strategies to restore natural vegetation to national preserves, to re-introduce natural processes such as fire, or simply to preserve remaining patches of rare vegetation types in the process of determining best management practices. Our goal is to understand this fragile alpine ecosystem that has been under substantial human pressure for centuries to millennia.

1.1. The Sierra Nevada

The Sierra Nevada is a west – east trending range within the larger Betic Range – a southwest – northeast mountain massif stretching ca 520 km from near the Strait of Gibraltar to La Nao Cape (Gómez Ortiz et al., 2005). The Sierra Nevada 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, but the exact chronology has yet to be determined (Schulte, 2002). Because of its location adjacent to the Mediterranean Sea, Gómez Ortiz et al. (2005) considered the thermal effect of the Mediterranean to predominate over the Atlantic. Consequently, late Pleistocene snowlines were higher in the Sierra Nevada than in other ranges in the Iberian Peninsula. Messerli (1965) determined average late Pleistocene snowlines to be 2300–2400 m on north-facing slopes, and 2400–2500 m on south-facing slopes. 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). It is the southernmost range to be glaciated during the Holocene in Europe (Schulte, 2002).

Both valley and cirque glaciers existed in the Sierra Nevada. However, subsequent melting of cirque glaciers allowed formation of numerous small lakes and wetlands, in an area of ca 100 km^2 above ca 2600 m, from the Pico del Caballo on the west to the Picón de Jérez on the east. The average elevation of the most important lakes is ca 2900 m (Castillo Martín, 2009).

1.2. Regional climate

The regional climate of southern Spain is Mediterranean, characterized by hot, dry summers, and mild, humid winters. Climate is governed largely by the relatively strengths of the Azores High (anticyclone) and the Icelandic Low (cyclone), which together influence the latitudinal position of North Atlantic storm tracks (Lionello et al., 2006; Fletcher et al., 2010), particularly as affected by the North Atlantic Oscillation (Li et al., 2006). Altitudinal contrasts contribute to a wide range of regional thermal conditions (Arévalo Barroso, 1992; Fletcher et al., 2010), with mean temperature of the warmest month (MTWA) between 20 and 25 °C, and mean temperature of the coldest month (MTCO) between 2 °C and 12 °C. Regional precipitation patterns are strongly influenced by the westerly Atlantic moisture sources and orographic precipitation. 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. Predominant wind directions are northwesterly during winter, with southerly and southwesterly winds occurring during summer associated with weakening of the westerlies.

1.3. Vegetation of the Sierra Nevada

As with other regions within the Mediterranean basin, vegetation composition is strongly influenced by thermal gradients, and by precipitation (Fletcher et al., 2010, and references therein). At the highest elevations, above ca 2900 m, characterized by very cold winters (coldest average maximum temperatures = −10 °C to −7 °C; Fletcher et al., 2010), short growing season, high solar radiation and snowfall, strong winds and minimal soil development (Valle, 2003), 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 1800–2000 m elevation is the oromediterranean vegetation belt, composed mostly of xerophytic shrublands and pasturelands, with *Pinus sylvestris*, *Pinus nigra*, *Juniperus hemisphaerica*, *Juniperus sabina*, *Juniperus 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). Numerous secondary species include *Thymus serpylloides*, *Arenaria pungens*, *Cerastium boissieri*, *Arenaria imbricata*, and others.

In the supramediterranean belt, between ca 1400–1500 m and 1900–2000 m, where maximum winter temperatures range −3–0 °C occurs, deciduous oak (*Quercus pyrenaica*, *Quercus faginea*), and evergreen oaks (*Quercus rotundifolia*) occurs, 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 800–1000 m; El Aallali et al., 1998), *Retama sphaerocarpa* becomes important (Valle, 2003), but also *Paeonia coriacea*, *Juniperus oxycedrus*, *Rubia peregrina*, *Asparagus acutifolius*, *D. gnidium*, *Ulex parviflorus*, *Genista umbellata*, *Cistus albidus*, *Cistus lauriflolius*, and many others (El Aallali et al., 1998). The evergreen oak (*Q. rotundifolia*) is also established in this belt, especially on siliceous soils.

Riparian vegetation is widespread along the abundant watercourses of Sierra Nevada, including gallery forests of *Salix atrocinerea* with *Salix alba*, *Salix pedicellata*, *Salix purpurea*, *Salix caprea*, and *A. glutinosa* in siliceous substrates, and *Salix eleagnos*, *Salix fragilis*, and *Salix triandra* on limestones and marls. Other habitual phreatophytes include *F. angustifolia*, *Populus nigra*, *A. opalus* subsp. *granatense*, *Sorbus aria*, *Prunus avium*, and *Rubus ulmifolius* (Blanca, 2002).

Plantations of *Pinus*, originating from efforts to combat erosion due to previous deforestation, originate from the mid-20th century, 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, *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 trees is unknown, due to serious anthropogenic deforestation pressures over the last millennia. Thus, the regional vegetation patterns not only result from climatic factors, but also from the impact of human landscape modification through the ages.

1.4. Laguna de Río Seco

One south-facing cirque basin contains Laguna de Río Seco, a small lake at ca 3020 m elevation. Laguna de Río Seco is located at 37°02.43′ N, 3°20.57′ W. The lake has a surface area of 0.42 ha, with a drainage basin of 9.9 ha (Morales-Baquero et al., 1999). Maximum depth of the lake when cored in 2006 was 1.7 m, but we have seen the lake when it was ca 3 m deep.

Though no weather station occurs near the lake, the Veleta station (ca 3070 m) is found ca 2 km west. Presently, temperature data is limited to a single year (2009), with January temperature averaging 3.5 °C and July temperature averaging 13.2 °C (F.J. Bonet García, pers. comm., 2010).

The lake presently occurs above treeline, within the crioromediterranean vegetation belt, although centuries of forest clearance within the range makes it nearly impossible to determine the potential natural elevation of treeline. At this elevation it is possible that the lake basin pollen stratigraphy provides an integrated record of both local and regional vegetation changes.

2. Material and methods

Using an inflatable raft, numerous transects across Laguna de Río Seco revealed a simple bathymetry with a maximum depth of 1.7 m (Fig. 1). Two sediment cores were taken on 7 September 2006 from a small floating platform anchored to rocks on shore. Core 06-01 was taken in the deepest part of the basin using a Livingstone corer; it measured 1.5 m long, ending in glacial clay. A second Core 06-02 was taken with a universal corer (Aquatic Research, Inc.) adjacent to Core 06-01; we retrieved 0.37 m of sediment.

In the laboratory, the sediments of both cores were described using Munsell color and other characteristics. Magnetic susceptibility (MS) was determined for Core 06-01 using a Bartington MS2E meter with readings taken every 5 mm throughout the length of the core. MS was not attempted for Core 06-02 as the sediments were contained in whirlpack bags. Nine samples in the lower core were analyzed for ^{14}C dating, with 11 samples from the upper 16 cm of core 06-02 analyzed for ^{210}Pb and ^{137}Cs dating. Radiocarbon ages were converted to calendar years before present (cal yr BP) using CALIB 5.2 (Stuiver et al., 1998).

Pollen analysis followed a modified Faegri and Iversen (1989) procedure, using 1-cm^3 of sediment. Processing included pretreatment with $(NaPO_3)_6$ to deflocculate clays and the addition of *Lycopodium* spores for calculation of pollen concentration. Sediments were suspended in $Na_4P_2O_7$ and sieved, then treated with HCl, HF, acetolysis solution. Samples were stained and suspended in silicone oil, and analyzed at 400–1,000× using a light microscope, with comparison to samples provided from the pollen collection at the University of Murcia, and the modern pollen reference collection at the Laboratory of Paleoecology (NAU). Pollen grains were identified at 400× magnification with a goal of 300 terrestrial pollen grains (average = 307; range 225–353 grains).

Pollen was identified to their lowest taxonomic level, mostly genus, sometimes family or other grouping. Rarely, pine (*Pinus*) grains were differentiated based on morphology of the leptoma (Moore et al., 1991); only a few diploxylon grains were encountered. However, *Pinus* was differentiated into small (<50–62.5 um), large (>62.5–75 um) and very large (>100 um) sizes. *Pinus* was differentiated from *Cedrus* (ca 85 um) by the latter types frilled

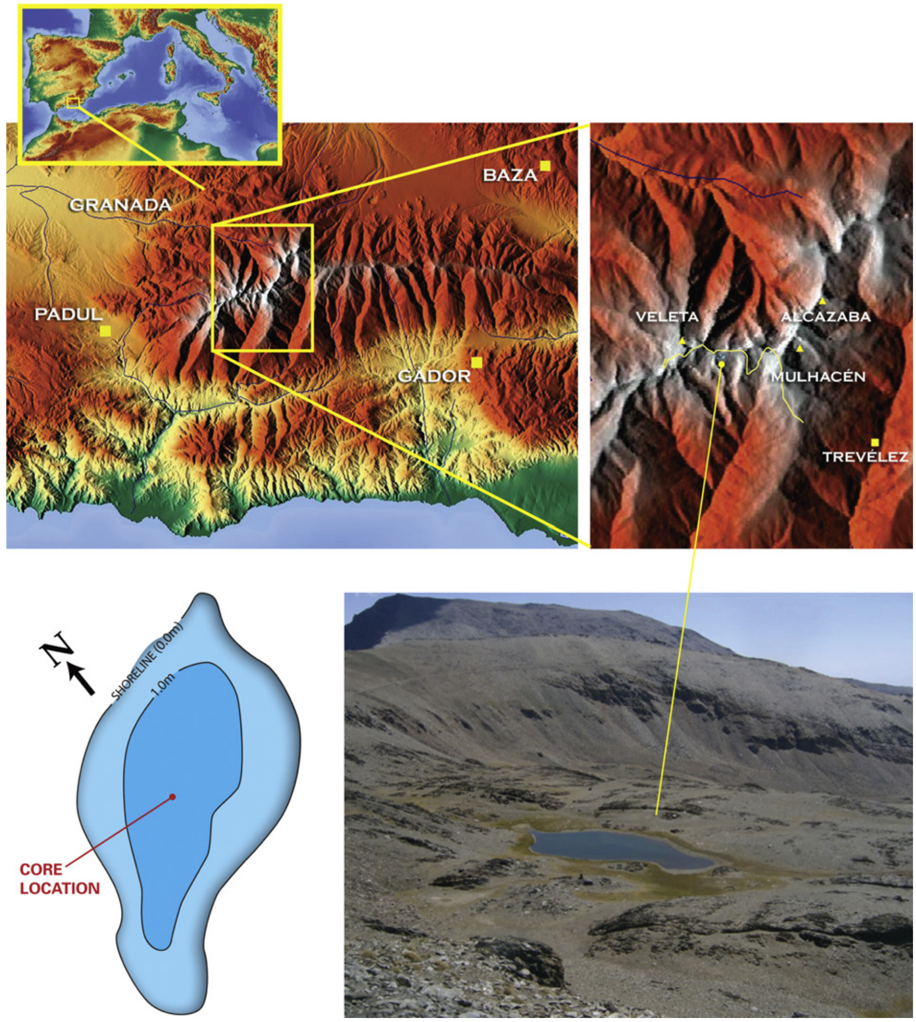

Fig. 1. Location of Laguna de Río Seco, Sierra Nevada, southern Spain. Upper left: Location of the Sierra Nevada in southern Spain, with other major sites near the lake discussed in text; upper right: Location of Laguna de Río Seco, near the three highest peaks in the range; lower right: photo of lake with landscape typical of the crioromediterranean zone in the range, note that the lake was at its low level phase when photographed in September, 2006; lower left: bathymetric map of the lake, with the coring location.

cappus. *Quercus* was differentiated into *Quercus* evergreen-type (locally *Q. rotundifolia*, but including *Quercus coccifera* from lower altitudes), *Quercus* deciduous-type (locally mostly *Q. pyrenaica* and *Q. faginea*) and other *Quercus*, based on surface and shape characteristics (Planchais, 1962; Sáenz de Rivas, 1973). Poaceae fell into three groups: small (<20 um, usually down to ca 15 um), large (>20 um), and *Zea mays*; while Chenopodiaceae occurred as small (<15–17.5 um) and large (>15–17.5 um) periporate grains. Asteraceae was differentiated into *Artemisia*, Cichorioideae, *Cirsium*, and Other Asteraceae, while Caryophyllaceae occurred as *Silene* large (>25 um) and *Silene* small (<25 um), *Herniaria*, *Stellaria*, *Illecebrum*-type, *Gypsophila*-type and other Caryophyllaceae. Fabaceae occurred as *Astragalus*, *Trifolium*, and other Fabaceae. All vesiculate-arbuscular (VA) mycorrhizal fungi (probably corresponding to Glomaceae chlamydospores) were lumped together. *Lycopodium* tracers, cryptogam spores, sedge, and other aquatic angiosperm types were tallied separately. The raw counts were transformed to pollen percentages based on the terrestrial sum. Pollen concentration is a measure of pollen density (grains per cc of sample sediment [gr/cc]).

For macrocharcoal analysis we used sediment subsamples of 1 cc taken at 0.5 cm intervals from both cores. Samples were soaked in sodium hexametaphosphate, then washed and sieved into 125 μm and 250 μm components. Each size component was transferred to a Petri dish marked with a 1 cm grid and counted using a dissecting microscope at approximately 25–50× magnification. Raw charcoal counts were converted to charcoal influx after calculation of charcoal concentrations. Charcoal was generally not abundant in this record, and so we did not use standard analysis programs, such as CharAnalysis (Higuera et al., 2009) for this record.

3. Results

3.1. Sediment stratigraphy and chronology

The stratigraphy of the upper portion of long Core 06-01 was nearly identical to that of short Core 06-02, and matching was accomplished by visual inspection, providing a composite stratigraphy. The composite Laguna de Río Seco record consists of 150 cm of banded peaty (primarily bryophyte) clays and silty clays above ca 133 cm. The section ca 73–89 cm is a transition to greater clay content below. A thin, but distinctive, brown bryophyte layer occurs at 122.5–123 cm. Below 133 cm to the core bottom is bluish-gray (2.5Y 4/1) glacial clay (Fig. 2).

Eleven determinations of ^{210}Pb and ^{137}Cs in 06-02, and nine calibrated radiocarbon ages in 06-01 (Table 1) were used to

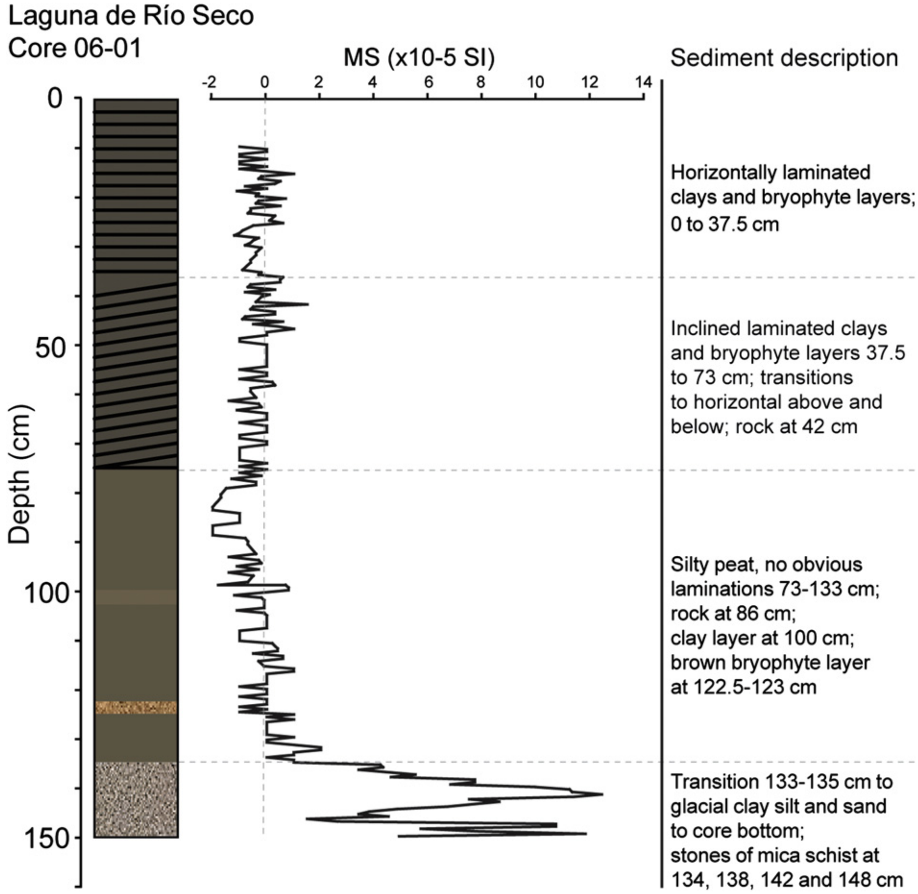

Fig. 2. Sediment stratigraphy and description of Laguna de Río Seco core 06-01, with magnetic susceptibility measurements.

determine the sediment chronology (Fig. 3). ^{210}Pb is suitable for dating the most recent 150 years, since its half-life is 22.26 $\pm$ 0.22 years (Appleby, 2001). ^{137}Cs has a half-life of ca 30 years, and was produced in great abundance during nuclear atmospheric testing beginning in 1945 (Olsson, 1986; Beck and Bennett, 2002). The Laguna de Río Seco ^{137}Cs profile shows a distinct maximum at 5 cm, with low concentrations below. This indicates the AD 1963 horizon (Beck and Bennett, 2002), indicating an accumulation rate of about 0.9 mm/y. The ^{210}Pb is roughly concordant. Our ^{210}Pb model suggests an accumulation rate of 1.3 $\pm$ 0.3 mm/y, close to that of the ^{137}Cs rate.

All nine ^{14}C ages were in stratigraphic order (Fig. 3). We used the program R to calculate an age model and varied the values of k from 1 to 9, choosing a model with $k = 8.5$, which provided the best fit to the data. All k value models projected the top 5 cm too far into the future. So we provided a linear model for the top 5 cm of the record, projecting to the present (i.e., AD 2006, when the core was taken) from the AD 1963 horizon (Fig. 3). As expected, the highest

Table 1
Radiometric ages from Laguna de Río Seco cores 06-01 and 06-02.

Laboratory Code	Core	Depth (cm)	^{14}C age (yr BP)	SD ($\pm$)	Calibrated Age (cal yr BP)[a] or yr AD
	06-02	5.0	^{137}Cs		1963 AD
	06-02	15.0	^{210}Pb		1891 AD
UCIAMS 51255	06-01	20.0	1520	15	1398
UCIAMS 63003	06-01	26.5–27.0	2255	20	2234
UCIAMS 51256	06-01	40.0	3060	15	3295
UCIAMS 63004	06-01	46.0	3525	20	3786
UCIAMS 51257	06-01	60.0	4010	15	4480
UCIAMS 51258	06-01	80.0	5450	30	6246
UCIAMS 63005	06-01	83.0–83.5	5505	20	6298
UCIAMS 63006	06-01	109.5	6550	20	7453
UCIAMS 32495	06-01	123.0–124.0	8570	60	9540

[a] Median calibrated age year before present.

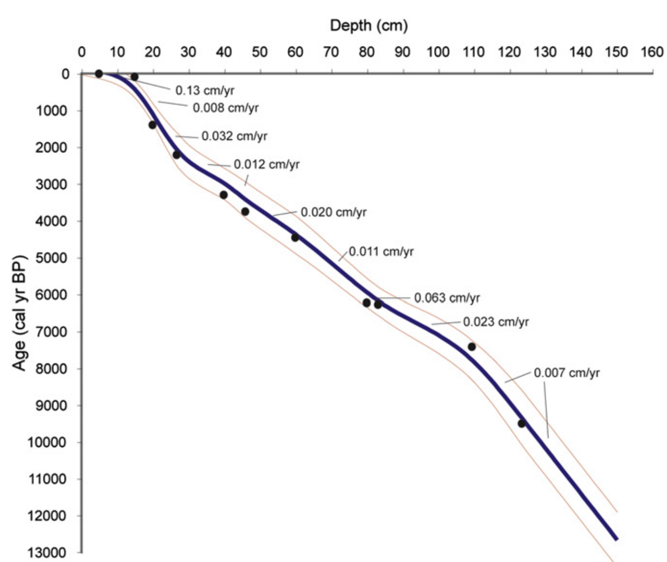

Fig. 3. Sediment accumulation rate curve for Laguna de Río Seco core 06-01. See text for description of curve construction.

sediment accumulation rate (SAR) of 0.13 cm/yr occurred above ca 15 cm. SAR varied below 15 cm from 0.007 to 0.063 cm/yr (Fig. 3), but with an overall SAR for the entire core of 0.013 cm/yr. We used this rate to project to the core bottom at 150 cm depth, where sufficient ^{14}C-dateable materials were not found, providing a calculated bottom age of ca 11,580 cal yr BP.

3.2. Magnetic susceptibility

MS values show little variability throughout most of the profile (Fig. 2), and in fact, many samples had negative values. We suspect that this is due to the nature of the Holocene sediment, relatively rich in organic matter, which is diamagnetic, and can produce negative values of magnetic susceptibility when the magnetic field interacts with the orbital motion of electrons (Dearing, 1999). However, sediments deposited prior to ca 10,500 cal yr BP (ca 133 cm depth), in the glacial clays, show MS values up to 8X the Holocene average.

3.3. Pollen and charcoal

Pollen was well-preserved, but did not occur in sediments below 137 cm. Pollen assemblages were zoned using CONISS (Grimm, 1987), and the following pollen types: *Olea*, *Pinus*, *Pinus* "small", *Quercus* evergreen-type, *Betula*, *Populus*, *Artemisia*, Poaceae, and *Silene*-type.

3.3.1. Zone 1 (core bottom to ca 10,500 cal yr BP)

This zone consists of just three pollen samples. Sediments in this zone are glacial clays, with small amounts of *Pinus* and *Quercus* evergreen-type pollen (Fig. 4). The pollen assemblage is distinguished by the highest percentages of *Artemisia*, Chenopodiaceae, and *Ephedra* pollen (Fig. 5), relatively small amounts of Poaceae, *Juniperus*, *Salix*, *Herniaria*, and *Silene*-type pollen (Fig. 6), and the highest percentages of the pelagic *Botryococcus* colonies in the record (Fig. 7). Neither plant macrofossils nor charcoal were recovered from these sediments (Fig. 8).

3.3.2. Zone 2 (ca 10,500–ca 5700 cal yr BP)

Zone 2 encompasses the early to middle Holocene; the subzone 2a–2b boundary is at ca 7800 cal yr BP, essentially separating the early from the middle Holocene. Zone 2 is characterized by increasing, then maximum percentages of *Pinus*, including both the "large" and "small" types (Fig. 4). *Betula* and deciduous *Quercus* are most abundant in this zone, but evergreen *Quercus* also occurs. *Cedrus* increases in the later part of the zone. *Artemisia*, *Juniperus* and Chenopodiaceae are at their Holocene minimums, as is *Silene*-type, but Poaceae is at a maximum, and other alpine herbs, such as members of the Cichorioideae, *Oxyria*, *Plantago*, *Campanula*, *Papaver*, *Herniaria* and Brassicaceae are important. *Alnus* and *Salix* are consistently found here. Prior to ca 7800 cal yr BP (subzone 2a) *Betula* and deciduous *Quercus* percentages are higher, but subsequently in 2a, *Pinus* and *Juniperus* increase. Charcoal is found in nearly all samples, but in low numbers, except between 91 and 95 cm (Fig. 8).

Zone 2 has the highest richness and percentages of many aquatic and wetland plants. For instance, Cyperaceae is most abundant in this zone, but also *Potamogeton* and the algae *Botryococcus*. Pollen of *Typha* is present, but ferns of different species (especially *Botrychium*; Fig. 7) are also abundant. This includes macrofossils as well, with seeds or fruits of *Juncus* or *Alnus*, as well as exoskeletons of the aquatic mite, *Hydrozetes*, are predominantly found here (Fig. 8). Aquatic and wetland species are more prominent prior to ca 7800 cal yr BP (subzone 2a) than after (subzone 2b).

3.3.3. Zone 3 (ca 5700–ca 2800 cal yr BP)

Pollen of many woody species continued to be important until ca 3900 cal yr BP (subzone 3a–3b boundary), declining substantially thereafter. This was particularly true for *Pinus* (including both the "large" and "small" types), *Betula* and *Cedrus*. On the other hand, both deciduous and evergreen *Quercus* remained relatively unchanged, and *Castanea* and *Populus* actually increased (Fig. 4). For shrub types, *Juniperus*, *Alnus* and *Salix* percentages increased in this zone, as did both *Artemisia* and Chenopodiaceae, especially for the latter two after ca 3900 cal yr BP (Fig. 5; subzone 3b). Several herbs

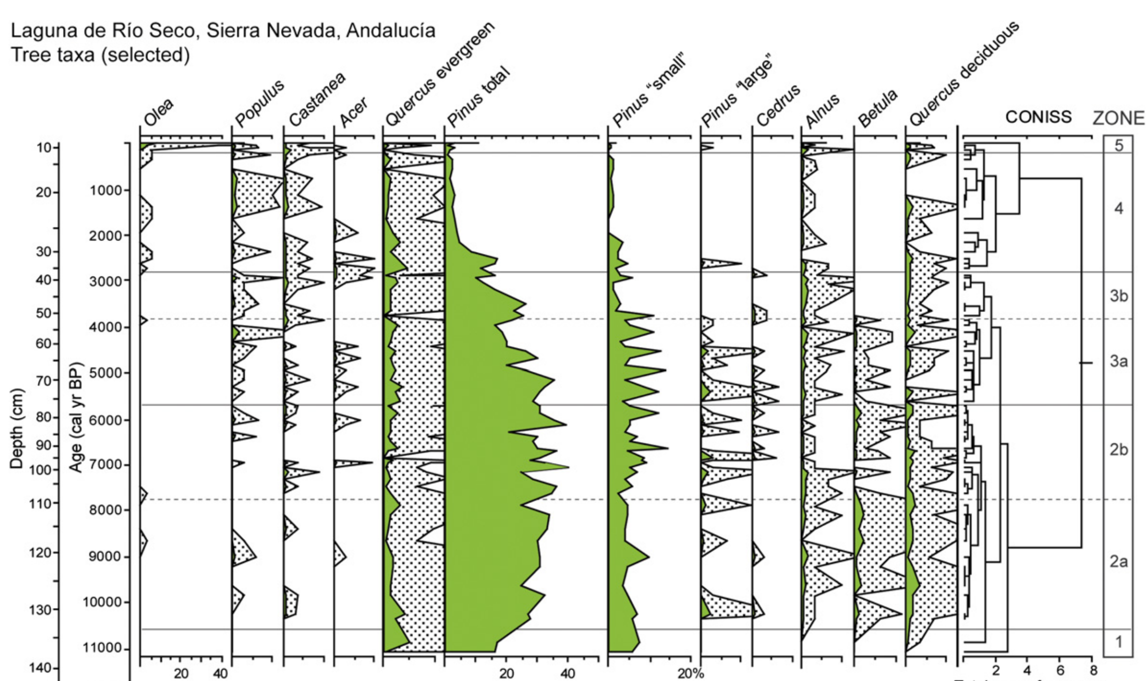

Fig. 4. Pollen percentages (*X*-axis) of major tree pollen taxa from Laguna de Río Seco core 06-01, along with the CONISS analysis of pollen zones. Silhouette is 10X actual pollen percentage.

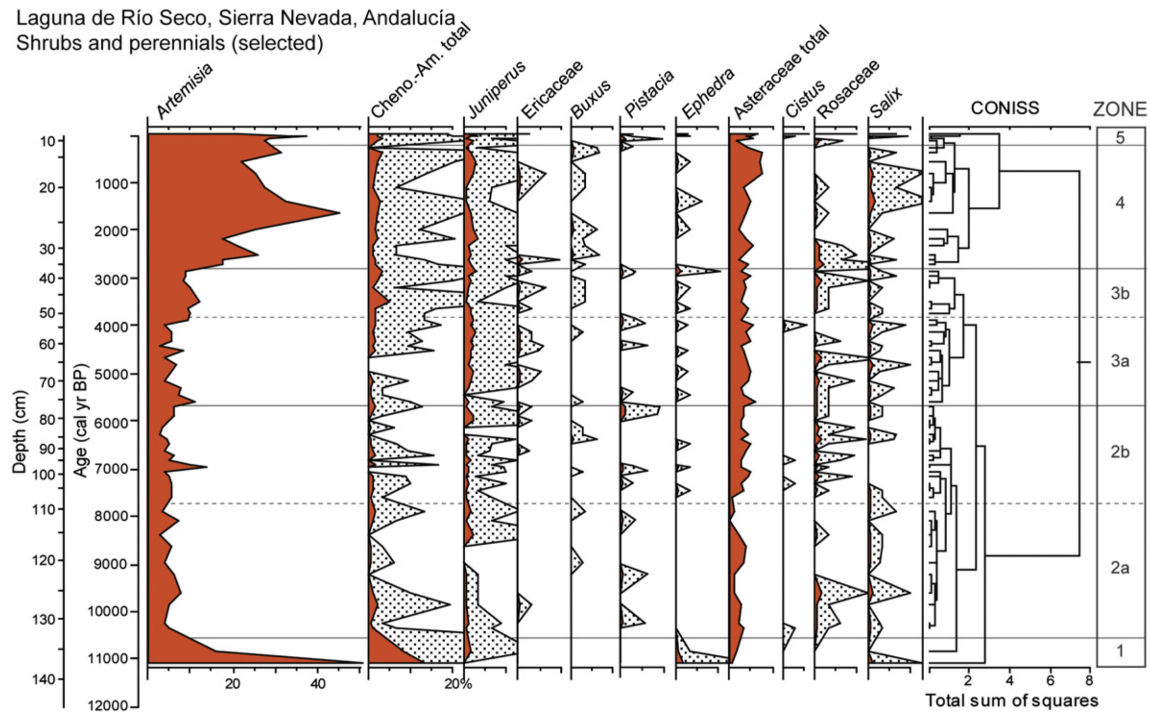

Fig. 5. Pollen percentages of major shrub and perennial pollen taxa from Laguna de Río Seco core 06-01, along with the pollen zone analysis. Silhouette is 10X actual pollen percentage.

become more prominent, especially after ca 5000 cal yr BP, including *Silene*-type, Caryophyllaceae, *Erodium*, *Rumex*, and members of the Brassicaceae, but Poaceae declined somewhat (Fig. 6). Most aquatic and wetland pollen and spores, most notably Cyperaceae, do not maintain their prominence in the local flora after ca 5700 cal yr BP (Fig. 7). Of great interest is the more consistent occurrence of the dung fungus, *Sporormiella*, as well as charcoal particles (Figs. 7 and 8) after ca 3900 cal yr BP (subzone 3b).

3.3.4. Zone 4 (ca 2800–ca 100 cal yr BP)

Distinguishing characteristics of this zone include the lowest percentages (mostly <5%) of *Pinus*, but the major expansion of *Artemisia* (Figs. 4 and 5). *Juniperus*, Chenopodiaceae, and Asteraceae remain important, as does a large variety of herb pollen, including *Silene*, *Rumex*, *Plantago*, *Herniaria*, Cichorioideae and Poaceae (Fig. 6). The disappearance of *Betula*, *Cistus* and nearly total absence of *Pistacia* are also remarkable. Aquatic types are further reduced, but

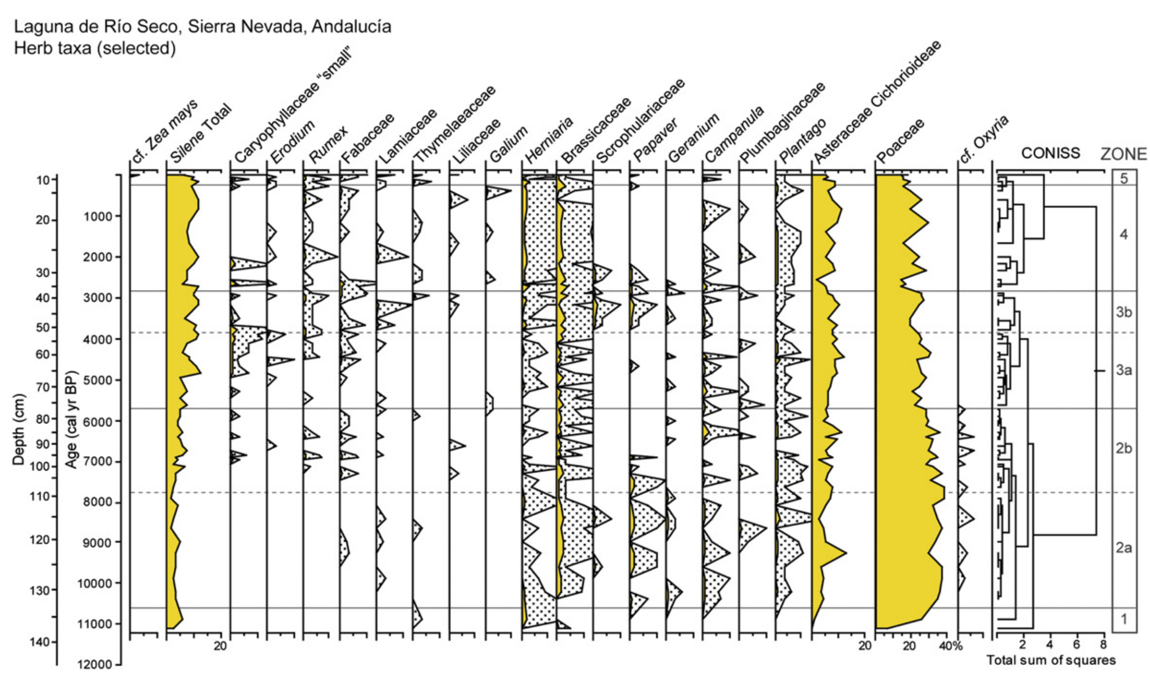

Fig. 6. Pollen percentages of predominant herb pollen taxa from Laguna de Río Seco core 06-01. Silhouette is 10X actual pollen percentage.

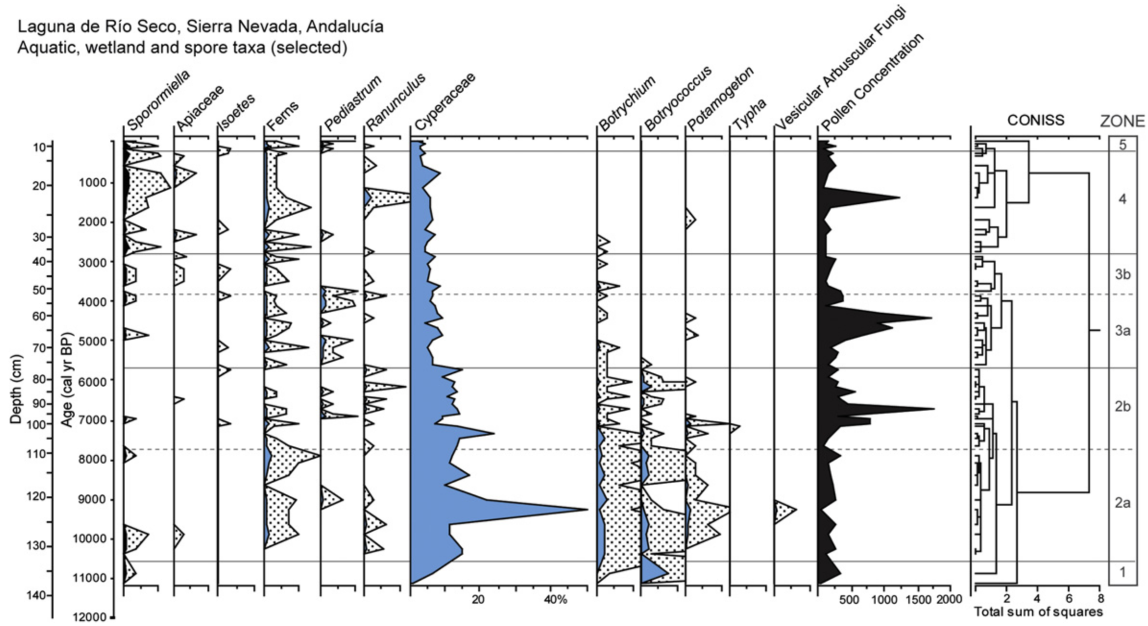

Fig. 7. Percentages of dominant aquatic and wetland pollen, and spore taxa from Laguna de Río Seco core 06-01. Silhouette is 10X actual pollen or spore percentage.

wetland plants are either relatively unchanged (i.e., Cyperaceae), or remain important (i.e., ferns, *Ranunculus*). Some of the herbs above probably also grew in the wetland around the Laguna. The herbivore dung fungus, *Sporormiella*, is most abundant at this time, and macroscopic charcoal is also most abundant in zone 4 (Figs. 7 and 8).

3.3.5. Zone 5 (ca 100 cal yr BP to AD 2006)

Many of the trends established in zone 4 persist into Zone 5, but with important differences. For example, a suite of woody species becomes important here. Most important among these are *Olea* and “large” *Pinus*, but also *Castanea*, *Acer*, *Morus*, and *Pistacia* (Fig. 4). A single grain of *Z. mays* is found. Plant macrofossils are nearly absent, and the concentration of charcoal particles also declines significantly (Fig. 8).

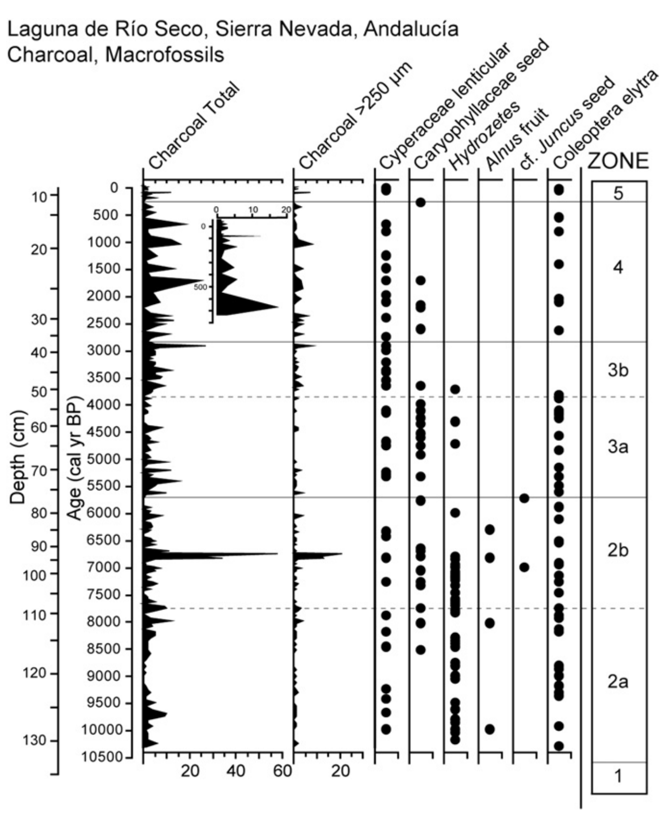

Fig. 8. Charcoal and macrofossil stratigraphy from Laguna de Río Seco core 06-01.

4. Discussion

The vegetation history of southern Spain has been explored in a number of papers, dealing almost exclusively with low to mid-elevation sites in the supra and mesomediterranean vegetation belts (to ca 1900 m) and below (see summary in Gil-Romera et al., 2010; Carrión et al., 2010a). The record from Laguna de Río Seco in the Sierra Nevada, over 1000 m higher than other sites from the region, provides an opportunity to examine the record of vegetation, climate and human disturbance from the highest mountain range in southern Iberia.

4.1. Vegetation change at high elevation in the Sierra Nevada

Most north-facing valleys in the Sierra Nevada, such as the Guarnon Valley, had long valley glaciers as much as 5.4 km long (Schulte, 2002) during the late Pleistocene. However, the glaciers on the south-facing slopes, where Laguna de Río Seco is located, were considerably smaller, and probably mostly confined to cirques (Gómez Ortiz, no date). Until our study, no bottom dates have been determined from these cirque basins, and the chronology of late Pleistocene deglaciation in the Sierra Nevada has remained unclear (Schulte, 2002). The fact that the lowest 17 cm of the Laguna de Río Seco core consists of glacial clays suggests that our record captures the transition from glacial to interglacial environments, and that organic sediment was being deposited there by ca 11,000 cal yr BP. This may represent the local expression of the late Younger Dryas, or the early Preboreal periods; our chronology is inadequate to be more specific. Although not hydrologically connected, this is broadly consistent with ages of the last major late Pleistocene outwash terraces of rivers east of the Sierra Nevada (Schulte, 2002; and others).

During this transition period at Laguna de Río Seco, the pollen is dominated by *Artemisia*, Chenopodiaceae, and *Ephedra*, with small amounts of *Quercus* evergreen-type and *Pinus*. Though sequences of this age are rare in southern Spain, this assemblage must represent a widespread, relatively cool, dry steppe vegetation in the lowlands and mountain slopes, as it is nearly identical to zone P3l (Younger Dryas) of the Padul Basin (785 m asl; Pons and Reille, 1988), a large basin draining the western Sierra Nevada from the east, and from Carihuela Cave (1020 m asl; Fernández et al., 2007) to the north. A similar pollen assemblage also occurs in the Alborán Sea cores, which integrate the western Mediterranean record from multiple terrestrial basins (Dormoy et al., 2009; Fletcher et al., 2010). Pons and Reille (1988) considered elevated steppe with small amounts of mesic elements (e.g., *Pinus*, *Juniperus*, deciduous *Quercus*), to suggest that the main characteristic of the Younger Dryas climate was dry conditions, not necessarily cold. But pollen indices calculated from the Alborán Sea pollen assemblages suggest dry and cool conditions, while reconstructed sea surface temperatures suggest 3–7 °C cooling over early Holocene maximums (Cacho et al., 1999). The highest percentage of *Botryococcus* colonies in the Laguna de Río Seco record at this time suggests either relatively high lake levels or perhaps a flush of nutrients during deglaciation.

The early to middle Holocene (ca 10,500–ca 5700 cal yr BP) at Laguna de Río Seco is characterized by declines in steppe elements (*Artemisia*, *Juniperus* and Chenopodiaceae), but major increases in *Pinus* (perhaps two distinct species; see below), and more mesic tree and shrub species, such as *Betula*, deciduous *Quercus* and *Alnus* are most abundant in this zone. The occurrence of the more mesic upland tree and shrub species argues for generally wetter conditions at this time than before. The alpine herb flora became important during this time (e.g., Poaceae, Lactuceae, *Plantago*, *Campanula*, *Papaver*, *Herniaria* and Brassicaceae). This may have been the period of greatest Holocene development of alpine flora at high elevations in the Sierra Nevada. Aquatic and wetland plants are most abundant during this period, and especially prior to ca 7800 cal yr BP. The occurrence of pollen and macrofossils, as well as spores (significantly the pelagic chlorophyte *Botryococcus* and the hygrophytic fern *Botrychium*), of individuals within these groups argues for either more permanent water or higher lake levels at Laguna de Río Seco than at any time prior or subsequent to this here.

Carrión et al. (2010a) pointed out that the first part of the Holocene is a period of environmental variability in southern Spain, but overall constituted the “mesophytic maximum, the xerophytic minimum, and the period of lowest fire activity, and of relatively high lake levels” (see also Carrión et al., 2001a; Carrión, 2002).Pollen based indices from the Alborán Sea core – the integrative regional perspective – suggest sustained trends toward wetter conditions during the early Holocene as well (Dormoy et al., 2009). But whereas the early Holocene (i.e., prior to ca 7800 cal yr BP) appears to be the wettest period at Laguna de Río Seco, the late-early to middle Holocene (ca 7500–5000 cal yr BP) may have been the mesophytic maximum at other lowland sites (Carrión et al., 2010a), and perhaps the highest lake levels (e.g., Reed et al., 2001) at lower elevations.

What can account for this difference in timing? We suggest that at least three possibilities exist – (1) climate differences over the elevational gradient; (2) differences in the extent of human activities; or (3) geomorphic changes in the lake basin. Throughout the Holocene, southern Spain has occurred at an important transition between an Atlantic European climate to the north and the monsoonal climate of Africa to the south (Reed et al., 2001). Greater differences in insolation between winter and summer in the early Holocene 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. Support for this comes from Dormoy et al. (2009), who modeled generally low winter temperatures and high winter precipitation from the Alborán Sea data, and from Davis et al. (2003) from a suite of pollen samples across Europe and North Africa. However, 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.

We can probably exclude the effect of forest clearance increasing runoff as an explanation (e.g., Vassiljev, 1997) as the record from low elevations was widespread, not local (Harrison and Digerfeldt, 1993) and serious anthropogenic landscape influences did not begin until after ca 6000 cal yr BP (Carrión et al., 2010a). However geomorphic changes within the Laguna de Río Seco lake basin could account for these differences as well if the original deeper lake slowly filled and shallowed in the early Holocene. The physical stratigraphy of the lake sediments does not support this potential explanation, since peaty sediments prevail throughout (Fig. 2) and the sediment accumulation rate is not significantly greater in the early Holocene than later (Fig. 3).

After ca 5700 cal yr BP at Laguna de Río Seco declines in mesic deciduous *Quercus* and *Betula* (Fig. 4), coupled with long-term increases in evergreen *Quercus*, suggest the beginning of aridification of the flora of southern Spain, documented at virtually all of the lowland sites of the region (Carrión et al., 2010a; Gil-Romera et al., 2010). The disappearance of *Betula* from ca 4000 cal yr BP onwards is especially interesting. Birch, like other mesophytes such as hazelnut (*Corylus*), has experienced population extinction and regional depletion in Mediterranean Spain from the mid to late Holocene, a phenomenon exacerbated in historical times (Carrillo et al., 2010). However, relictual populations of *Betula celtiberica* can be still found in the Betic Mountains, including the Sierra Nevada. An inverse pattern is observed with *Castanea sativa*, which increases in Laguna de Río Seco after ca 4000 cal yr BP, and especially in post-Roman times, probably due to arboriculture, although competitive factors and plagues may also have played a role in these tree dynamics (Carrillo et al., 2010). Indeed, the decline of *Betula* in Sierra Nevada may have favored, and/or be somewhat linked to expansions in *Populus*, *Castanea*, *Acer*, *Salix*, Ericaceae, and *Buxus*.

Trends in the tree pollen flora, especially for *Quercus*, are not as striking at Laguna de Río Seco as at lowland sites, where *Quercus* woodlands were important (Carrión et al., 2010a). More importantly for high elevations near Laguna de Río Seco are long-term increases in high altitude steppe vegetation, such as *Artemisia*, *Juniperus*, *Ephedra*, and somewhat later, Chenopodiaceae, at the expense of an alpine herbaceous vegetation important in the early Holocene (see above). The fact that aridification was not confined to low elevations, but also occurred at higher elevations directly within the lake's watershed, is shown by the marked changes in the aquatic environment of the lake, with significant declines in wetland herbs and floating-leaved aquatics (Fig. 7). These changes also occur in context with a long-term decline in *Pinus*, which may have been due not only to climate but anthropogenic changes. Each of these trends accelerated after ca 3900 cal yr BP, including an increase in charcoal from burning, and but at a faster rate after 2800 cal yr BP.

At the lower elevation sites, aridification was well underway by ca 5000 cal yr BP (Carrión et al., 2010a). For instance, at Sierra de Baza, a *Pinus* forest with deciduous *Quercus* and other mesophytes in the early to middle Holocene gave way increasingly to scrub vegetation, becoming more prominent after ca 3800 cal yr BP (Carrión et al., 2007). This included an increase in microcharcoal at precisely the same time as the increase in macrocharcoal at Laguna de Río Seco (Fig. 8). A new phase of final forest decline and spread of thorny matorral commenced by ca 2600 cal yr BP, marking the establishment of the modern vegetation in the Sierra de Baza of grazed areas dominated by spiny shrubs, juniper with pine, and grasslands, most certainly driven by the expanding human influence on the landscape by pasturing, forest clearance, mining, and finally agriculture (Carrión et al., 2007, 2010a).

At the even lower Sierra de Gádor site, mesic conditions may have persisted a little longer into the late Holocene, but aridification witnessed by the expansion of steppe elements, such as *Artemisia* and members of the Asteraceae and Chenopodiaceae, began as early as ca 5000 cal yr BP (Carrión et al., 2003). The vegetation became increasingly xeric after ca 3940 cal yr BP, shown by continued expansion of steppe elements but also by evergreen oaks. Higher fire incidence and variations in pine and evergreen oak after ca 3940 reflect not only increasingly arid conditions, but also an expanded human influence (Argaric culture) on the landscape (Carrión et al., 2003, 2010a). With local variations, similar patterns of increasing aridity in southern Spain are also documented from sites at Villaverde (Carrión et al., 2001a) and San Rafael (Pantaleón-Cano et al., 2003), which also show the replacement of mesophytic by more xeric vegetation by ca 3800 cal yr BP, then spread of grasslands and thorny matorral after ca 2500 cal yr BP (Carrión et al., 2010a).

4.2. The question of Pinus forest or woodland around Laguna de Río Seco

The inability to reliably differentiate pollen of southern Iberian *Pinus* species hampers our biogeographic interpretations. Nevertheless, the past occurrence of *Pinus* forest in southern Spain during the Holocene has been much debated (e.g., Carrión et al., 2010a; Rubiales et al., 2010), as has its future (Benito et al., 2008). During the Late Pleistocene, abundant *Pinus* pollen has been recovered from predominantly coastal sites and sites along lowland river valleys (see discussion in Carrión et al., 2008). Remains of both *P. nigra* and *P. pinaster* were recently recovered from an MIS 3–4-age site in Doñana Natural Park near Huelva (Postigo-Mijarra et al., 2010), while *P. nigra* remains were also identified from Nerja Cave, near Málaga, dating between ca 28,800 and 20,800 cal yr BP (24,000–17,500 yr BP) (Badal, 1998). *Pinus* dominates the pollen record in the Padul bog (720 m asl) during the late Pleistocene, to between ca 16,000 and 14,000 cal yr BP (recalculated from Pons and Reille, 1988; Florschütz et al., 1971), and prior to ca 15,000–13,000 cal yr BP (Fletcher and Sanchez Goñi, 2008; Dormoy et al., 2009) in the Alborán Sea sediment record and Carihuela Cave pollen record (Fernández et al., 2007).

During the early Holocene mesophytic maximum, *Pinus* cf. *nigra* forest replaced grassland at the 1320 m asl Siles site in the Segura mountains to the north of the Sierra Nevada (Carrión, 2002). *Pinus* was part of a mixed *Quercus* – *P. nigra* forest with broadleaved trees at the 1530 m asl Sierra de Gádor site (Carrión et al., 2003) until ca 6060 cal yr BP. Similarly, *Pinus* may have dominated in a woodland including deciduous *Quercus* and other broadleaved trees prior to ca 6300 cal yr BP at the 1900 m asl Sierra de Baza site (Carrión et al., 2007). Subsequently, *Pinus* declined through the middle Holocene but scattered *Pinus* trees may have persisted in the Sierra de Baza until ca 2500 cal yr BP. At the Sierra de Gádor site *Quercus* – *P. nigra* forest was replaced by a primarily deciduous *Quercus* forest, but between 3940 and 1780 cal yr BP alternating increases in *Pinus* and *Quercus* evergreen-type suggest controls other than climate on the landscape. At Siles, the pine forests are initially replaced by deciduous *Quercus* forests, then a more xeric Mediterranean vegetation, between ca 7400 and 5300 cal yr BP, with a general return to *P. nigra*/*P. pinaster* and *Quercus* forest thereafter (Carrión, 2002).

Unfortunately, *Pinus* pollen is probably widely overrepresented in Iberian records. In locations where *P. sylvestris* trees are present, *Pinus* percentages are nearly always 50–60% of the sum, but where the trees are locally absent, *Pinus* pollen can still be 10–40% of the sum (Andrade et al., 1994). *Pinus* pollen dominates the early to middle Holocene at Laguna de Río Seco (Fig. 4), declining between ca 4000 and 2500 cal yr BP. But it generally averages ca 30%, never exceeding 35%, of the pollen sum. This suggests that the lake probably was above the elevation of the *Pinus* forest prior to its ultimate decline in the Sierra Nevada. Three lines of evidence support this conclusion. First, natural treelines are unclear in the Sierra Nevada, but an upper treeline of *P. nigra* occurs today at 1600–2100 m in the Segura Mountains to the north (Carrión, 2002), while remnant naturally established individuals of *P. sylvestris* occur to ca 2100 m in both the Sierra de Baza and the Sierra Nevada (Castro et al., 1999). Plantations of *P. sylvestris* occur as high as 2550 m elevation (pers. observation, 2010), but all populations occur well below the present elevation of Laguna de Río Seco (3020 m). It is difficult to imagine such a climatic shift during the Holocene. Second, although negative evidence is never preferred, this interpretation is reinforced by the lack of recovery of both wood and abundant charcoal in Laguna de Río Seco sediments during this time (Fig. 8). And third, a model of the mid-Holocene (ca 6000 cal yr BP) distribution of *P. sylvestris* in Iberia suggests only minimal occurrence of the tree above 2000–2600 m then (Benito et al., 2008).

4.3. The record of high altitude human impact near Laguna de Río Seco

Unlike the substantial record of human impact well documented from lower elevation sites (e.g., Carrión et al., 2007; Gil-Romera et al., 2010) human impact on the high elevation Laguna de Río Seco site has been considerably less. Here we examine the sedimentary evidence of pasturing, exotic cultivars and of fire from Laguna de Río Seco to suggest the potential level of human disturbance at high elevations in the Sierra Nevada during the Holocene.

4.3.1. Evidence of late Holocene grazing around Laguna de Río Seco

Sporormiella (Sporormiaceae, Pleosporales, Ascomycetes) is a genus of coprophilous fungi requiring herbivore digestion to complete its life cycle. It produces spores in the dung, primarily of mammals (Gill et al., 2009). Spores of *Sporormiella* have been recovered from many lake sediments, the spores presumably originating from animals that used the lakes as a water source (Raper and Bush, 2009). Several studies have correlated the occurrence and decline of late Pleistocene megafauna and *Sporormiella* (Robinson et al., 2005; Davis and Shafer, 2006; Gill et al., 2009), and with human settlement in the archaeological record (Burney et al., 2003; Cugny et al., 2010; Gauthier et al., 2010; Feeser and O'Connell, 2010). In North America increases in *Sporormiella* during the historic period are associated with introduction of livestock grazing on the landscape (Davis and Shafer, 2006; Anderson et al., 2010).

Although spores of *Sporormiella* occur at Laguna de Río Seco prior to ca 4000 years ago (Fig. 7), they are consistent and most abundant during zones 4 and 5, after ca 2700 cal yr BP, and probably indicate intensified grazing in the higher elevations of the Sierra Nevada at this time. This increase roughly coincides with higher percentages of *Rumex* pollen, associated elsewhere with pasturing (Anderson et al., 2010; Gauthier et al., 2010; many others). Modern studies by Gauthier et al. (2010) suggest that this combination of palynomorphs is more common in sheep dung, than horse dung. Of course, we cannot rule out the possibility of an increase in native herbivores, such as the Iberian wild goat or ibex (*Capra pyrenaica*). However, the coincidence of other factors suggesting increased human exploitation of the range at this time (i.e., increase in charcoal from fires, increased *Castanea* and *Olea*, loss of *Pinus*) is highly suggestive of an increase in summer seasonal pasturing activities for domesticated herbivores. This seasonal use of highland landscapes for livestock pasturing is consistent with documented historical regional patterns of transhumance (Naranjo and López Ontiveros, 2000).

4.3.2. Exotic cultivar record from Laguna de Río Seco sediments

To the northeast and east of the Sierra Nevada, and at lower elevation, are the Sierra de Baza (Carrión et al., 2007) and Sierra de Gádor (1530 m; Carrión et al., 2003) sites, two sites comparable in time range and resolution to Laguna de Río Seco. Both ranges have a long history of human occupation, probably not entirely continuous (Carrión et al., 2007). Unlike other parts of southern and southeastern Iberia, neither site contains direct evidence of human activities during the Mesolithic, but during the Neolithic (between ca 7400 and 5700 cal yr BP) definitive evidence of human activities is found in numerous cave sites, especially in Baza (Carrión et al., 2007). In general, the paleobotanical evidence suggests that human impact upon the lowland landscapes may have been relatively intense since ca 5200–5000 cal yr BP. This includes evidence of grazing/pastoralism beginning perhaps 7000 cal yr BP, and an increase in fire in both records after ca 4200 cal yr BP.

It is during the late Holocene, however, that the record of human activities, quite apparent by ca 4000 years ago, intensifies, including an increase in at least two plants characteristic of pastures, *Rumex crispus* and *Plantago*, between 2500 and 2600, and the first spore records of *Tilletia* and *Puccinia*, which are often regarded as indicators of more widespread agriculture (Carrión and van Geel, 1999; Carrión et al., 2001a). Along with an opening of the landscape, suggested by increases in Poaceae and declines in *Pinus*, and conversion of local vegetation to thorny matorral, came increases in the cultivars olive (*Olea*) and grape (*Vitis*). At the same time, the concentration of microcharcoal particles reached maximum values, and soil erosion substantially increased, with sediment accumulation rates rising nearly 20-fold, and with higher deposition rates of the vesicular-arbuscular mychorrizal fungi *Glomus*, again at Baza (Carrión et al., 2007).

The high elevation of Laguna de Río Seco makes it extremely unlikely that agriculture was successfully conducted near the lake. Instead, it is more likely that the lake watershed was the site of pastoral activities, especially during the late Holocene, as documented above. Even so, the pollen and charcoal record clearly reflect the general land use patterns of agriculture and human activities so common at lower elevations of the Sierra Nevada and surrounding valleys.

Today, Andalucía is the largest olive (*Olea europaea* L.) oil-producing region in the world (Gálan et al., 2008), with areas of active cultivation extending over the southern half of the Iberian Peninsula. However, the region where wild *Olea* trees grow today is limited to a thin coastal belt in present day Spain and southern Portugal, extending inland along the Guadalquivir River lowlands in southern Spain (Carrión-Marco et al., 2010). Using wood charcoal occurrences, these authors mapped the paleo-distribution of *Olea*. During MIS 3 and 2, *Olea* probably grew in thermophilous refugia in coastal Mediterranean regions, while its distribution may have been reduced during the LGM. Expansion occurred during the early Holocene (ca 11,500–8800 cal. BP) elevations of the thermomediterranean bioclimatic belt. During the early to middle Holocene (ca 8800–5600 cal yr BP), the species became very abundant or dominant in the thermomediterranean zone, and may have grown in favorable sites even higher than this, although this is not obvious from either the Baza (Carrión et al., 2007) or Gádor (Carrión et al., 2003) pollen records.

In the Laguna de Río Seco record, pollen of *Olea* is not consistently recovered until ca 2700 cal yr BP, and even then in very small amounts (Fig. 4). This is several hundred years earlier than the first occupation of the Iberian Peninsula by the Romans, who encouraged cultivation of *Olea*, beginning in the late centuries BC (Bull, 1936; Rodríguez-Ariza and Moya, 2005). Most recently, however, during the last 100 years of the record, *Olea* increased to over 20% of the sum. This corresponds to the great increase in olive oil production in southern Spain beginning in the 1920s (Bull, 1936), leading to the present situation in which Spain produces 33% of the world's olive oil, with Andalucía (Jaén, Granada, Córdoba) accounting for 80% of total Spanish output (Gálan et al., 2005). Since the vast majority of land presently in *O. europaea* cultivation is under 700 m asl (Gálan et al., 2008), the occurrence of such high concentrations of *Olea* pollen at the 3020 m asl Laguna de Río Seco site clearly constitutes pollen displaced short distances by updrafts to higher elevation sites.

At least two other pollen types recovered from 20th century sediments as probable extralocal pollen include *Z. mays* and *Pinus*. A single grain attributable to *Zea* by size and pore shape was recovered at 5 cm depth (Fig. 6). *Z. mays* is commonly grown today in the vega adjoining Granada (pers. observations); *Zea* pollen is rarely moved far from its source (Raynor et al., 1972; Lane et al., 2010), and its occurrence in our sediments is suggestive also of short distance updraft into the mountains. On the other hand, *Pinus* "large" pollen shows an increase in the 20th century as well, after being absent in the record in the previous ca 2500 years (Fig. 4). Its abrupt occurrence probably results from plantations of *P. sylvestris* trees within 10 km of Laguna de Río Seco, but no higher than ca 2550 m elevation (pers. observations). Significant plantings of *P. sylvestris* trees commenced in the mid-20th century in the Sierra Nevada, to combat erosion (Arias Abellán, 1981).

4.4. Fire history record at Laguna de Río Seco

A recent compilation compared published Holocene fire histories in southeastern Spain for five inland sites (Baza, Cañada de la Cruz, Gádor, Siles, Villaverde, Navarrés), from 1900 to 225 m asl (Gil-Romera et al., 2010) near and east of Laguna de Río Seco. Individual charcoal influx records were normalized (NCHAR) by comparison to the 3000 cal yr BP values for each of the sites. Though considerable local variability exists between the six sites, the data show either high or stable charcoal anomalies during the early Holocene, trending toward lower (with exceptions) anomalies during the middle Holocene. Greater anomalies (greater charcoal) occurred generally after ca 3000–4000 cal yr BP. Comparison to the pollen records for each of the sites allowed a discussion of the relationship between fire activity, climate change and potential anthropological influence during the Holocene.

The relatively cooler temperatures and greater seasonality of the early Holocene generally favored the continuation of pine forests across much of the region (Gil-Romera et al., 2010). However, decreasing seasonality allowed a trend towards warmer and wetter climate, perhaps with a reduction in summer drought, between ca 8500 and 5500 cal yr BP. At many lowland sites, broadleaved trees – including deciduous *Quercus*, *Betula* and *Corylus* – partially replaced conifers at most sites (Carrión, 2002; Carrión et al., 2003, 2007), being a distinctive feature in a regional pollen record from Alborán Sea marine cores as well (e.g., Fletcher and Sanchez Goñi, 2008). Deciduous *Quercus* and other mesophytes reached their maximum expansion between 7500 and 6000 cal yr BP, when low, or even lowest fire activity occurred (Gil-Romera et al., 2010). In general, increasing aridity during the mid to late Holocene (Tinner et al., 2009; Carrión et al., 2010a) – after ca 6000 but especially after ca 4000 cal yr BP (Vanniere et al., 2008), enhanced development of modern Mediterranean and xerophytic vegetation. From ca 3000 cal yr BP onward

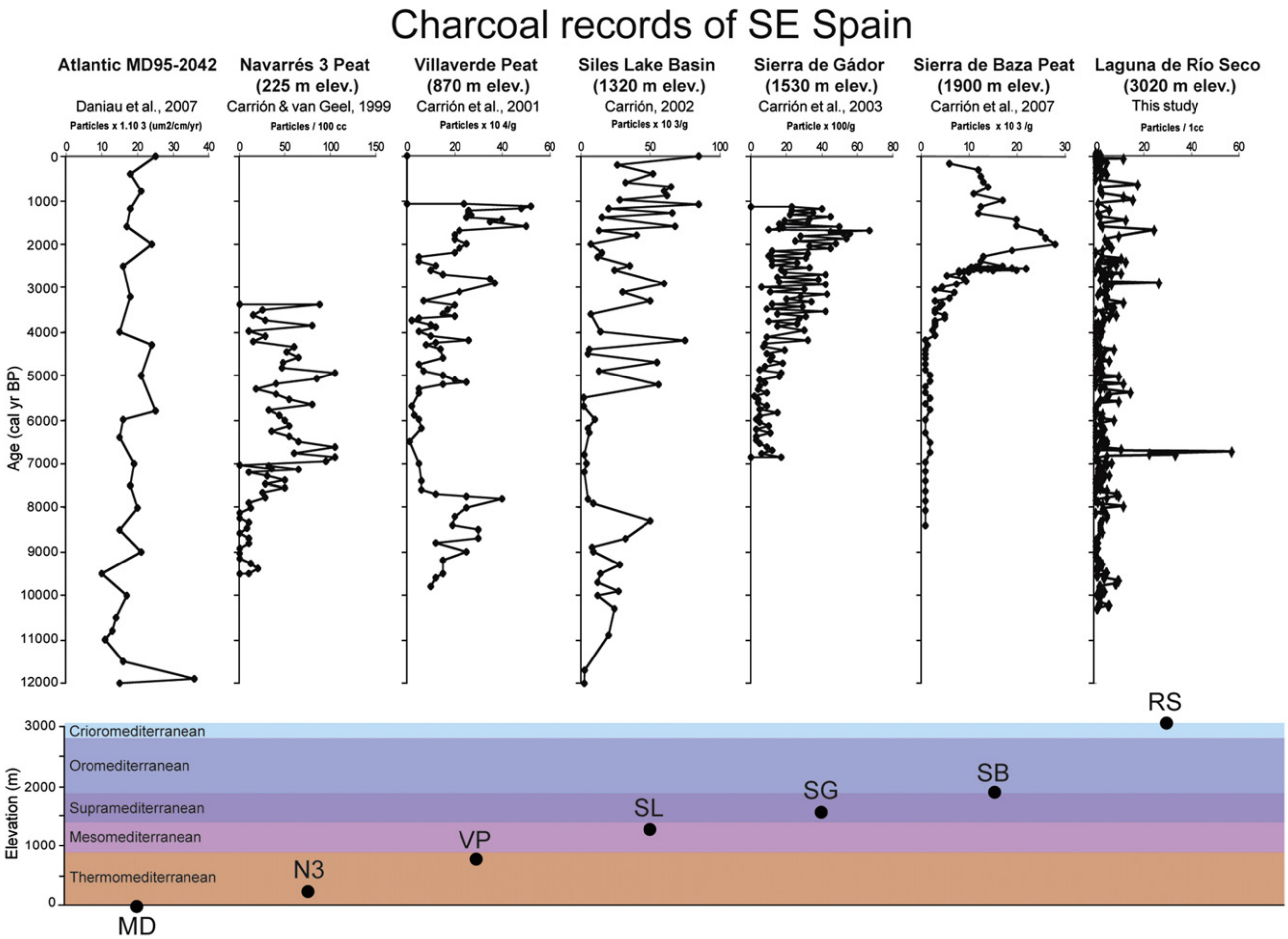

Fig. 9. Comparison of charcoal (fire) record from Laguna de Río Seco with those from other sites in southern Iberia. At diagram bottom is the location of each site within the climatic vegetation belts characteristic of southern Iberia.

a combination of vegetation instability, and increasingly arid climate, combined with increasing pressure from human population expansion and consequent activities, led to elevated fire occurrence throughout much of southeastern Spain. Thus, climate may have been more important in determining vegetation composition and fire occurrence in the early to middle Holocene, while the consequences of human modification of the landscape were perhaps more important than climate during the later Holocene.

The Laguna de Río Seco site adds the perspective from the highest elevation of the region, where natural fires today are extremely rare, with no recorded fires in the crioromediterranean zone since at least 1988 (F. J. Bonet García, pers. comm., 2010). Though the total amount of charcoal recovered from the Laguna de Río Seco site is considerably less than from lowland sites (Fig. 9), the pattern is very similar to that from the Sierra de Baza site (Carrión et al., 2007; Gil-Romera et al., 2010). For Laguna de Río Seco, small amounts of charcoal are found in all samples prior to ca 3700 cal yr BP (zone 3a-3b boundary). (One exception occurs at ca 6500–6800 cal yr BP, where the highest influx of charcoal in the entire record occurs). However, after ca 3700, until ca 100 years ago, the charcoal influx is consistently higher than before. In the Sierra de Baza, Carrión et al. (2007) indicated the increase in charcoal after ca 4100 cal yr BP was due to a combination of increasing aridity with more widespread flammable vegetation, and increased deforestation by humans due to accelerated mining and grazing activities. This climate–human activity explanation is particularly appropriate for places like Baza, which has a well documented archaeological record of settlement, and exploitation by mining and pasturing. This explanation may also be appropriate for higher elevations of the Sierra Nevada, but is complicated by two factors. First, little is known about the settlement of the highest elevations of the range. As mentioned above, we believe that most, if not all, of the human activity in the highest elevations consisted of pasturing/grazing during the short summer season. Second, based on the modern vegetation of the crioromediterranean zone of the Sierra Nevada, it is unlikely that there was enough vegetation coverage to carry fire for any distance during the late Holocene (see photo Figs. 1 and 8). In this case, the charcoal record possibly reflects more of an extralocal fire record. Certainly less charcoal was recovered in sediments deposited during the 20th century than in the previous 3700 years (Fig. 8). Our analysis included particles >125 μm, more likely to be produced locally (Whitlock and Anderson, 2003). However, Whitlock and Millspaugh (1996) documented particles >125 μm at sites <7 km from known fires, suggesting larger charcoal particles can travel significant distances. We believe that the very small amounts of charcoal particles in this size range, combined with lack of a significant woody component in the local vegetation, suggests an extralocal source of charcoal probably from fires at lower elevations in the range.

5. Conclusions

The vegetation and climate history of the western Mediterranean has increasingly come into focus in the past several decades as our understanding of role of human societies in environmental modification though time has become clearer. This record is particularly complicated due to its long history of human settlement combined with its particularly sensitive position relative to climate, specifically the variable and changing influence of high latitude North Atlantic and lower latitude monsoon precipitation (Dormoy et al., 2009). Future climate changes toward drier and more arid conditions are expected in southern Iberia (Gao and Giorgi, 2008), and, as Cheddadi et al. (2001) have suggested, significant impact on all terrestrial systems are anticipated. It is within this context that paleoecological records from sensitive sites with minimal human impact through time become important in our understanding of Holocene vegetation and environmental change. It might be nearly impossible to find sites in the Mediterranean region that are free of direct human influence during the Holocene (Carrión et al., 2009), but the high elevation Laguna de Río Seco site in the Sierra Nevada is unique in recording only modest local impact but also the main features of lowland landscape modification and climate change in southern Spain.

Comparison of vegetation change and climate reconstruction from both high elevation (Laguna de Río Seco) and lower elevation sites (primarily Baza, Gádor) show that, for the most part, the main features of Holocene vegetation change are roughly similar and synchronous among these sites. These include the early Holocene expansion of *Pinus* forest, which, though it probably existed around the Sierra de Baza (1900 m) and Sierra de Gádor (1300 m) sediment core sites, certainly did not grow as high as the 3020 m elevation Laguna de Río Seco site. Pine pollen percentages at Laguna de Río Seco never exceed the minimums suggestive of local occurrence of *Pinus* trees (Arias Abellán, 1981). Instead at Laguna de Río Seco, modest *Pinus* pollen percentages were associated with a low pollen producing alpine flora. However, the timing of maximum precipitation (reflected in lake levels at Laguna de Río Seco) may have differed from high elevation to low, with greatest moisture prior to ca 7800 cal yr BP at the higher site, and more after this at the lower sites. In general, aridification of the landscape is evident at all elevations during the mid-Holocene, after ca 5700 cal yr BP, with a long-term decline in mesic forest elements, such as *Pinus*, evergreen *Quercus*, and *Betula*, and a long-term increase in steppe elements, such as *Artemisia*, *Juniperus*, *Ephedra* and Chenopodiaceae. Increasingly xeric conditions occur by ca 3900 cal yr BP, after which time occurs the maximum deposition of charcoal at both Laguna de Río Seco and Sierra de Baza (Fig. 9), concurrent with development of the modern vegetation at these locations.

In comparison to the lower elevation sites in this region, relatively little evidence of human impact on the local high elevation environment is found in the Laguna de Río Seco record – with the probable exception of grazing. With the late Holocene development of steppe near the lake – or perhaps as a result of that development – occurrence of the dung fungus *Sporormiella* increases, along with increases in plants typical of grazed pasture (e.g., *Rumex*, *Plantago*). Pollen evidence suggests that this may have occurred as early as 5000 years ago, but probably intensified by ca 2800 years ago. Direct evidence of agriculture in the Laguna de Río Seco record is limited primarily to the last 100 years, with suggestions that increases in *Olea* and the occurrence of *Z. mays* pollen represent drifters from lower elevation orchards and fields. Unlike the record from lower elevation sites, activities such as mining and agriculture left little record at this high elevation site, where soils and elevational constraints were not appropriate for these activities. However, the Laguna de Río Seco record is clear in recording the late Holocene decline, and latest Holocene virtual disappearance, of *Pinus* forest and woodland, due to cutting and aridification of the lowlands. The mid-20th century increase in *Pinus* from government plantations of *P. sylvestris* is evident, however (Valbuena-Carabaña et al., 2010). So the pollen record from Laguna de Río Seco appears to clearly record a combination of vegetation assemblages at different elevations through time, while also providing information on the local environment directly around Laguna de Río Seco.

The occurrence of fire is clearly recorded in the sediments as charcoal, found in nearly all levels of the core. Yet the generally low influx of charcoal suggests that fires may have been a consistent but not widespread ecosystem process around Laguna de Río Seco during the Holocene. The fact that maximum charcoal concentrations occur after ca 3900 to near modern times – coeval with evidence of forest clearance and landscape modification at all elevations, suggests that it represents a regional expression of burning, very similar to that from the nearby Sierra de Baza. The virtual lack of charcoal in the 20th century sediments reflects a recent significant shift away from the use of fire in the regional environment.

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