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Holocene environmental change in southern Spain deduced from the isotopic record of a high-elevation wetland in Sierra Nevada

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Abstract Small lakes and wetlands from high elevation within the Sierra Nevada Range (southern Spain) preserve a complete post-glacial Holocene record. Isotopic, TOC and C/N analyses, carried out on a sediment core, show various stages in the evolution of the Borreguiles de la Virgen, which today constitute a small bog at about 2,950 m above sea level. Glacial erosion generated a cirque depression, which became a small lake during the first phase of infilling (from 8,200 to 5,100 cal yr BP), as suggested by sedimentary evidence, including an atomic C/N ratio generally below 20, low TOC values and the highest δ^{13}C and δ^{15}N values of the record. These results imply significant algal productivity, which is confirmed by the microscopic algal remains. Drier conditions became established progressively in this area from 5,100 to 3,700 cal yr BP. Subsequently, the lake evolved into a bog as shown by geochemical evidence (C/N ratios above 20, high TOC content and low δ^{13}C values). Unstable conditions prevailed from 3,600 to 700 cal yr BP; an extremely low sedimentation rate and scarcity of data from this period do not allow us to make a coherent interpretation. Fluctuating conditions were recorded during the last ~700 cal yr BP, with wetter conditions prevailing during the first part of the interval (with C/N rate below 20) up to 350 years ago. In general, a gradual trend toward more arid conditions occurred since ~6,900 cal yr BP, with a further increase in aridity since ~5,100 cal yr BP. This evidence is consistent with other contemporaneous peri-Mediterranean records.

Keywords Holocene · Wetlands · Southern Spain · Isotopic geochemistry · Organic matter

Introduction

Many recent sedimentary studies using lake sediments of the Mediterranean region have focused on Holocene climate change (deMenocal et al. 2000; Bar-Matthews et al. 2000; Magny 2004; Zanchetta et al. 2007). One recurring conclusion of this research concerns the high sensibility of Mediterranean forests

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to Northern Hemisphere climate variability (Fletcher et al. 2010). Nevertheless, with the increasing number of studies, major new questions have arisen primarily related to the timing, impact and recognition of Holocene climate changes at different elevations within the region (Carrión et al. 2003, 2007; Gil-Romera et al. 2010). Recently, Anderson et al. (2011) suggested that seasonal differences in precipitation might be an important determinant, pointing to high altitude and coastal regions as areas most sensitive to climate variations. In this sense, high mountain lakes and peat bogs in formerly glaciated terrain have been shown to be ideal locations for recovering climate records and reconstructing the most recent climate changes in the Iberian Peninsula (Morellón et al. 2011; Moreno et al. 2011; Anderson et al. 2011). The location of the Sierra Nevada (~37°N)—the highest Iberian mountain range situated close to the Mediterranean Sea and between subtropical Africa (i.e., Sahara desert) and temperate Europe—means that its high-elevation wetland environments will likely be very sensitive to regional climate variation. However, despite these features, this area remains poorly studied and only a few recent investigations have revealed high-quality paleoclimate archives (Ortiz et al. 2004; Anderson et al. 2011; Jiménez-Moreno and Anderson 2012). In order to refine our knowledge of recent climate changes in southern Iberia we selected a sedimentary record for our isotopic evidence from a bog within the Sierra Nevada, where the history of paleovegetation change is known (Jiménez-Moreno and Anderson 2012). This allows us to compare an independent proxy of environmental change with a known record of vegetation change to provide a more comprehensive understanding of former environments of the mountain range.

The study area: the Borreguiles de la Virgen

Sierra Nevada is a W-E aligned mountain range located in southern Spain (Fig. 1). It contains the highest peaks in the Iberian Peninsula, three of which reach more than 3,300 m asl. Its current landscape is strongly conditioned by the geomorphologic action of glacial erosion during the Late Pleistocene (Schulte 2002) as one of the southernmost European glaciated areas during this period (Gómez Ortiz et al. 1996). The postglacial melting of these glaciers led to the creation of small lakes and wetlands. These small basins formed on the metamorphic bedrock (mostly schists) located at elevations higher than 2,600 m asl (Castillo Martín 2009).

In the Sierra Nevada Range, the mean annual temperature at ~2,500 m is 4.5 °C, and the mean temperature during the snow free months is ~10 ± 6 °C, but could occasionally reach ~21 °C. Annual precipitation is ~700 mm/year, seasonally concentrated between October and April, mostly as snow (Oliva et al. 2009). Due to the altitudinal gradient of Sierra Nevada (from ~900 to more than ~3,400 m), vegetation is strongly influenced by temperature and precipitation (Valle 2003), and different plant associations are characteristic of different elevations. Today, a largely

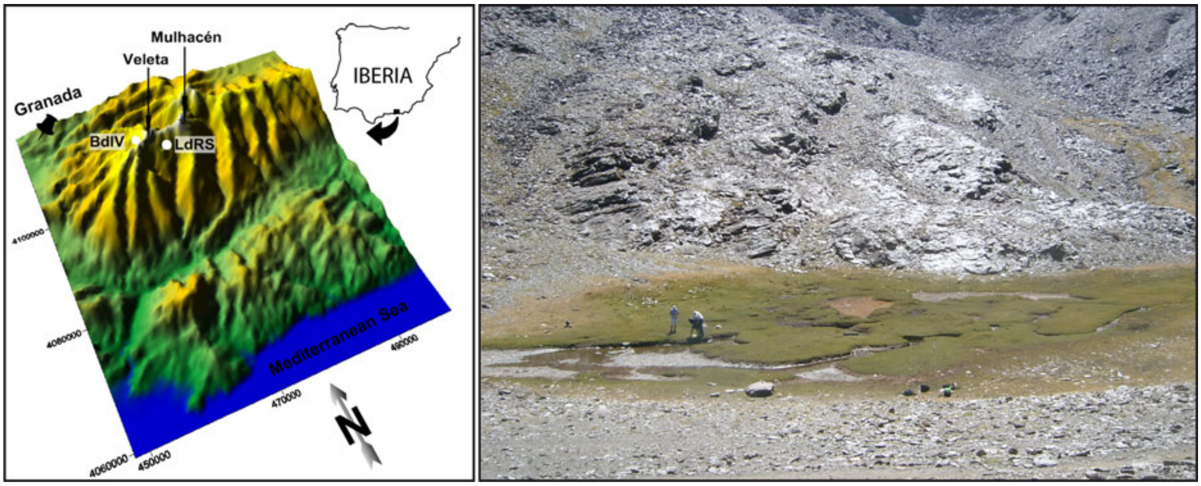

Fig. 1 Location of the Borreguiles de la Virgen (BdlV) and Laguna de Río Seco (LdRS) from Sierra Nevada (southern Spain). Right, photo of the sampling zone

artificial tree line occurs at ~2,550 m asl (Anderson et al. 2011).

The Borreguiles de la Virgen presently consist of a small bog with a surface less than ~1 ha, located in a north-facing cirque basin in the head of the Río Dílar at 2,945 m (37°03′ 15″N; 3°22′ 40″W; Fig. 1). The word 'Borreguil' is a local term for bog in the Sierra Nevada. The studied bog contains a sedimentary sequence that covers the last 8,200 cal yr BP (Jiménez-Moreno and Anderson 2012). At this altitude, vegetation is highly influenced by very cold winters and high snowpack, as well as high solar radiation, strong winds and minimal soil development. The snow free period is generally from June to October, so the growing season is short (Valle 2003).

Although most of the Borreguiles de la Virgen bog area is vegetated, there are presently a few small, shallow water pools (Morales-Baquero et al. 1999). The catchment basin is also small, ~0.25 km^2, and it mainly consists of bare metamorphic (schist) rock with steep slopes. Therefore, the isotopic information determined from organic matter (C, N) at this site is most likely influenced by local algal productivity, and to a lesser degree by external inputs of the very discontinuous distribution of vascular plants growing in the catchment basin (Meyers 1994). Especially in localities such as this, organic matter isotopic composition can provide a more local environmental signal than pollen, as pollen from this record includes both local as well as regional inputs (Jiménez-Moreno and Anderson 2012). However, the autochthonous and allochthonous contributions of these wetlands could have evolved through time, and the isotopic data of organic matter can help us to unravel this evolution, allowing us to estimate whether this area has acted as a wetland—or something else—during the Holocene. Therefore, the primary information determining the isotopic record in this case is the characteristic of the wetland instead of the entire watershed. This feature is very useful in identifying local and regional changes, allowing a more accurate interpretation of the geochemical data and pollen record. Nevertheless, the characteristics of the area are directly related to the larger environmental and hydrological conditions of the region.

Materials and methods

Carbon and nitrogen stable isotopes, total organic carbon (TOC), and atomic C/N ratios were analysed from a sediment core extracted from the center of the Borreguiles de la Virgen bog area (Fig. 1; Jiménez-Moreno and Anderson 2012). A total of 74 sediment samples were taken at ~1-cm intervals throughout the core. Samples were decalcified with 1:1 HCl in order to eliminate the carbonate fraction. Carbon and nitrogen isotopes (δ^{13}C and δ^{15}N), TOC percentages, and the atomic C/N ratios were measured by means of an EA-IRMS elemental analyser connected to a XL Thermo Finnigan mass spectrometer. Isotopic results are expressed in δ notation, using the standard V-PDB (carbon) and AIR (nitrogen). Samples were measured in duplicate. %TOC per g of sediment were calculated from %C yielded by the elemental analyser, and recalculated by the weight of the sample before and after decalcification. The atomic C/N ratio has been used in this paper.

The calculated precision, after correction for mass spectrometer daily drift, using standards systematically interspersed in analytical batches, was better than ±0.1 ‰ for δ^{15}N and δ^{13}C.

The age model for the studied core follows Jiménez-Moreno and Anderson (2012). It is based on 9 calibrated AMS radiocarbon dates that were calibrated using CALIB 5.0.2 (Stuiver et al. 1998). Sediment accumulation rates (SAR) for this study were calculated by Jiménez-Moreno and Anderson (2012). Because TOC concentrations depend on the SAR, and according to Meyers (2003) high SAR may dilute TOC concentrations, the sedimentation accumulation rates of organic carbon (SAR$_{oc}$) have been calculated by means of SAR data and TOC values. Nevertheless, the concentration of total organic matter in sediments is equivalent to about twice TOC values because typical organic matter contains approximately 50 % organic carbon (Meyers and Lallier-Vergès 1999; Meyers 2003). As the studied core comes from a wetland area, incorporating vegetation remains in situ, we also calculated the hypothetic SAR of total organic matter (SAR$_{om}$).

Results

Values of δ^{13}C and δ^{15}N range from −28.1 to −23.1 ‰ with a mean value of −26.4 ± 1.0 ‰ (V-PDB), and from −0.3 to 2.6 ‰, with a mean value of 1.4 ± 0.7 ‰ (AIR), respectively (Table 1). The highest values of δ^{13}C and δ^{15}N are concentrated, in

Table 1 Mean, standard deviation, maximum and minimum values of the geochemical data from the Borreguiles de la Virgen record

Age/zone	$\delta^{13}C$ ‰	$\delta^{15}N$ ‰	C/N	% TOC
8200–0 Total				
Max	−23.1	2.6	30	40
Min	−28.1	−0.3	13	3
Mean	−26.4	1.4	19	14
SD	1.0	0.7	4	8
8200–5100 Zone 1				
Max	−23.1	2.6	21	20
Min	−27.4	1.1	13	3
Mean	−25.9	1.8	18	10
SD	0.9	0.4	2	3
8200–6900 Subzone 1a				
Max	−23.1	2.6	18	16
Min	−27.4	1.1	13	6
Mean	−25.4	1.8	16	10
SD	1.1	0.4	1	2
6900–5100 Subzone 1b				
Max	−25.4	2.6	21	20
Min	−27.3	1.2	15	3
Mean	−26.3	1.9	19	10
SD	0.4	0.4	2	4
5100–3600 Zone 2				
Max	−26.8	1.3	30	40
Min	−28.1	0.1	22	12
Mean	−27.5	0.7	25	24
SD	0.4	0.4	3	11
3600–700 Zone 3				
Max	−26.8	1.2	21	13
Min	−27.5	0.9	16	6
Mean	−27.2	1.0	19	9
SD	0.4	0.2	2	3
700-Zone 4				
Max	−24.7	1.6	28	31
Min	−27.7	−0.3	16	12
Mean	−26.9	0.6	21	22
SD	0.5	0.6	3	6

general, in the oldest samples (from 8,200 to 5,100 cal yr BP), except $\delta^{13}C$ data, which also shows high values in the most recent 250 years. On the contrary, the lowest $\delta^{15}N$ values are recorded in the last 250 years (Table 1; Fig. 2).

Atomic C/N ratio ranges from 13 to 30, with a mean value of 19 ± 4 (Table 1). The lowest values are recorded from 8,200 to 5,100 cal yr BP, being extremely low from 8,200 to 6,900 cal yr BP. The highest values are recorded between 5,100 and 3,600 cal yr BP and during the last decades (Table 1; Fig. 2).

TOC values range from 3 to 40 %, with a mean value of 14 ± 8 % (Table 1). Highest TOC values are recorded from 5,100 to 3,600 cal yr BP, and in the last 700 cal yr BP. The lowest values are found from 8,200 to 5,100 cal yr BP, and from 3,600 to 1,400 cal yr BP (Table 1; Fig. 2).

Jiménez-Moreno and Anderson (2012) noted that the SAR was stable in almost 75 % of the core (below ~45 cm), varying between 0.17 and 0.38 mm year^{-1} (Fig. 2). In the uppermost 45 cm, two different and anomalous SARs occur: 0.47 mm year^{-1} from 0 to 35 cm (from −57 to 675 cal yr BP), and 0.03 mm/year from 35 to 45 cm (from 700 to 3,600 cal yr BP). These anomalous intervals affect the SAR$_{oc}$ and, consequently the SAR$_{om}$ (Fig. 2). There are three periods with high SAR$_{oc}$ and SAR$_{om}$: (1) 6,900 to 6,300 cal yr BP, with minima ~6,600 cal yr BP; (2) 5,100 to 3,600 cal yr BP; and (3) during the last ~700 cal yr BP (Fig. 2). During the time interval from 5,100 to 3,600 cal yr BP, SAR values correspond mostly to the accumulation of organic material. The interval during the last ~700 cal yr BP corresponds to anomalously high SAR; these rates are due to the absence (or scarceness) of compaction in the uppermost centimetres of this organic-rich peat sediment, mainly composed of vegetal remains. Therefore, we suspect this mainly records the accretion rate of the in situ vegetation growth during this interval. There is no a clear justification for the abnormally low SAR from 3,600 to 700 cal yr BP, and a potential explanation is discussed in the next section.

The isotopic, TOC and C/N record permits the division of the core into four zones, corroborated by Euclidean cluster analysis (Fig. 2). Values from each zone (maximum, minimum, mean, standard deviation, median, first and third quartile) are summarized in Fig. 3 and Table 1.

Zone 1, from 8,200 to 5,100 cal yr BP

In this zone, the highest $\delta^{13}C$ and $\delta^{15}N$ are recorded, with mean values of −25.9 ± 0.9 ‰ (V-PDB) and 1.8 ± 0.4 ‰ (AIR), respectively. C/N values are, in general, below 20, with a mean value of 18 ± 2. Relatively low TOC values are recorded, with a mean

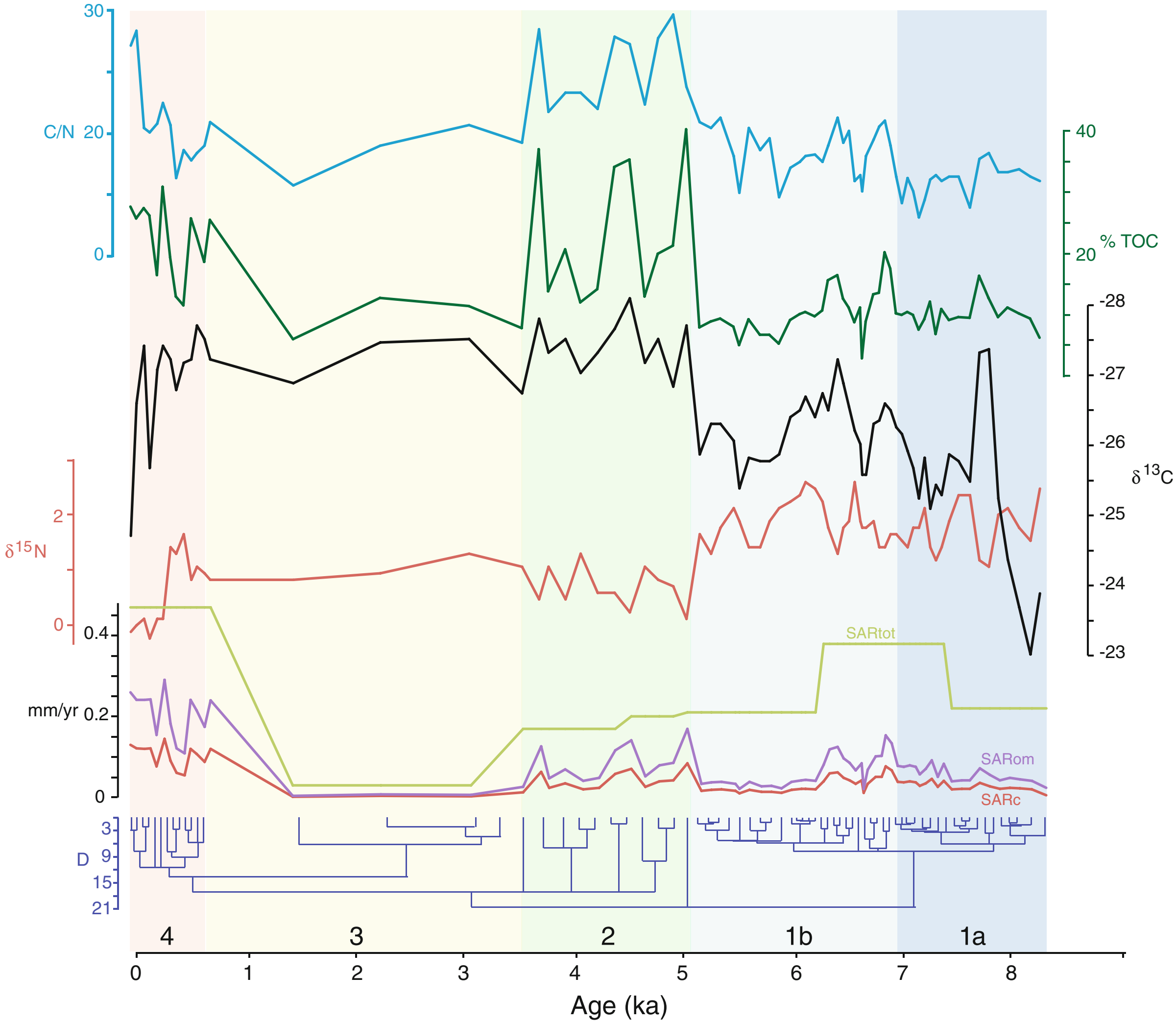

Fig. 2 Comparison of cluster diagram, δ^{13}C, δ^{15}N, atomic C/N ratio, %TOC values, total sediment accumulation rates (SAR), organic carbon sediment accumulation rates (SAR$_{oc}$), and deduced organic matter sediment accumulation rates (SAR$_{om}$) from the Borreguiles de la Virgen core. Note that the scale of δ^{13}C values is reversed. *1 (a and b)* lacustrine environment, *2* bog environment, *3* low SAR period, *4* fluctuating environment

value of 10 ± 3 %. We divide this zone into two subzones. Subzone 1a, ranging from 8,200 to 6,900 cal yr BP, records the highest δ^{13}C and the lowest C/N rates. Subzone 1b, ranging from 6,900 to 5,100 cal yr BP, records lower values overall of δ^{13}C and higher C/N ratio than during Subzone 1a.

Zone 2, from 5,100 to 3,600 cal yr BP

In this zone, the lowest δ^{13}C data of the core (ranging from −28.1 to −26.8 ‰; mean value, −27.5 ± 0.4 ‰ vs. V-PDB) are registered. δ^{15}N values are lower than in zone 1, with a mean value of 0.7 ± 0.4 ‰ (AIR). This section records the highest percentage of TOC, higher than 12 %, with a mean value of 24 ± 11 %, and the atomic C/N ratio is always above 22, with a mean value of 25 ± 3.

Zone 3, from 3,600 to 700 cal yr BP

In this zone TOC and C/N values drop (mean values about 9 ± 3 % and 19 ± 2, respectively) with respect of the previous zone. Although δ^{13}C and δ^{15}N values are slightly similar to those of zone 2 (mean values of

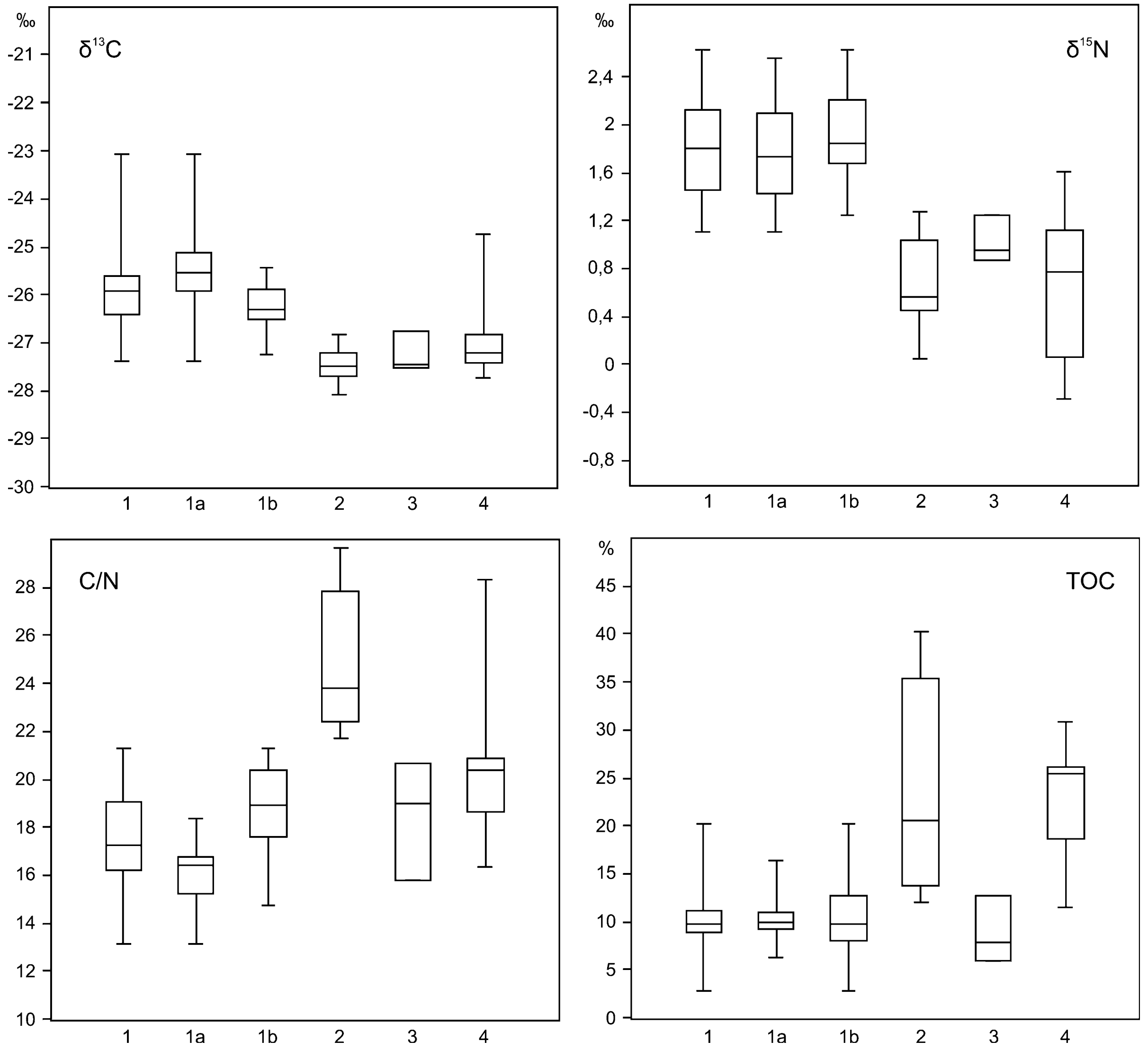

Fig. 3 Boxplot diagram showing the δ^{13}C, δ^{15}N, atomic C/N ratio and TOC records from the Borreguiles de la Virgen core. The median, first quartile (*lower limit of the box*), third quartile (*upper limit of the box*), and whole range of data are shown. *1 (a and b)* lacustrine environment (8,200–5,100 cal yr BP), *2* bog environment (5,100–3,600 cal yr BP), *3* low SAR period (3,600–700 cal yr BP), *4* fluctuating environment (~ 700 cal yr BP—present)

−27.2 ± 0.4 ‰ vs. V-PDB and 1.0 ± 0.2 ‰ vs. AIR), δ^{13}C values are slightly higher than before. The boundaries of this zone are imprecisely dated due to very low SAR recorded in this section.

Zone 4, the most recent ~700 cal yr BP

Fluctuating values are observed in this zone. In general, high TOC is recorded, with an average of 22 ± 6 %, with the exception of two samples around 400 cal yr BP, when TOC values dropped. C/N has an average value of 21 ± 3, but in the most recent samples it peaks at 27–28. An increasing trend is observed in the δ^{13}C record during this zone. Its mean value is −26.9 ± 0.5 and reaches −24.7 ‰ (V-PDB) in the most recent sample. During the first part of the zone, δ^{15}N values remain around 1 ‰ (AIR), even if occasionally they are slightly more positive; however, in the last 250 years, δ^{15}N values dropped to ~0 ‰ (AIR), with some values being slightly negative.

Discussion

The results obtained from the Borreguiles de la Virgen core allow us to interpret the evolution of the different sources of organic matter for the last 8,200 cal yr BP in this bog. Freshwater algae are enriched in nitrogen and impoverished in carbon content respect to vascular plants, so low atomic C/N ratios in organic sediments indicate the predominance of algae ($C/N < 10$), while high ratios ($C/N > 20$) note the predominance of external vascular plant tissue (cellulose-rich and protein-poor). Intermediate values (C/N rates between 10 and 20) signify the influence of both (Meyers 1994; Meyers and Teranes 2001). Therefore, TOC content is usually higher in land-derived organic matter than in algae remains (Meyers and Horie 1993). Furthermore, in this paper we use the $\delta^{15}N$ and $\delta^{13}C$ record to identify sources of organic matter, and productivity levels (Meyers and Horie 1993; Meyers 1994; Herczeg et al. 2001; Talbot 2001). High $\delta^{15}N$ and $\delta^{13}C$ values might suggest higher primary productivity (Brenner et al. 1999; Talbot and Laerdal 2000; Teranes and Bernasconi 2000): algae use Dissolved Inorganic Carbon (DIC) and Dissolved Inorganic Nitrogen (DIN) from water masses, preferentially incorporating the lighter isotopes. With increasing productivity, this discrimination leads to an increase in the heavier isotope of the water DIC, and DIN pools. Consequently, the algae that use those are enriched in both heavier isotopes (O'Leary 1988; Hodell and Schelske 1998; Wolfe et al. 2001). When the organic matter content in lacustrine sediments mainly come from the external input of vascular plants, increase in $\delta^{13}C$ values can be read in terms of water use efficiency during dry conditions (Farquhar et al. 1982).

The carbon isotopic record from organic matter of Borreguiles de la Virgen, ranging from −28.1 to −23.1 ‰, agrees with the isotopic composition of C3 plants (O'Leary 1981, 1988; Meyers 1994). However, samples that record the highest values probably include contributions from phytoplankton (Galimov 1985), which is supported by the atomic C/N ratio. Due to the small size of the catchment basin, around 0.25 km^2, and its minimally vegetated area, parallel variations of C/N and $\delta^{13}C$ usually mark fluctuations in the source of organic matter (external inputs or local algal productivity). Organic matter occurring in the Borreguiles de la Virgen core can either originate from land plants or a mix of land plants and lacustrine algae. These data, combined with those from TOC and $\delta^{15}N$, and together with the palynological and algal record (Jiménez-Moreno and Anderson 2012), allow us to describe the paleoenvironmental evolution of an alpine wetland from a small lacustrine system to a bog system. Based upon our analyses, we identify four primary stages of the paleoenvironmental evolution of the Borreguiles de la Virgen alpine wetland.

Lacustrine environment (from 8,200 to 5,100 cal yr BP)

The onset of the Borreguiles de la Virgen record is composed of a fine heterometric sand layer of ~3 cm, which dates to 8,200 cal yr BP, and appears very similar to glacial debris (i.e., moraine sediments). This layer is a remarkable feature that could be important in confirming the potential impact of the 8,200 cal yr BP event in the Mediterranean region (Zanchetta et al. 2007), as well as the poorly known Holocene glacier record in Sierra Nevada (Schulte 2002). Three different Holocene glacier advances have been recognized (Gómez Ortiz et al. 1996) and moraines associated with the 8.2 ky cal BP apparently reached 2,993 m asl in the Guarnón Valley (north face of the Sierra Nevada). The lack of older deposit and/or erosive features recognized in the Borreguiles de la Virgen indicates that intense cold conditions were reached, either because of (1) lingering snow at this site, preventing the development of the high mountain vegetation that sustain the sedimentary record and/or (2) perhaps erosion of previously deposited sediments. We consider this as evidence that the 8.2 cal ka BP cold event has a clear impact at least at high elevation in the Mediterranean area.

This period between 8,200 and 5,100 cal yr BP, corresponding to zone 1, is characterized by relatively low atomic C/N ratio, low TOC, high $\delta^{13}C$, and high $\delta^{15}N$ (Fig. 2). All these data, together with the maximum Holocene presence of the alga, *Pediastrum* (Jiménez-Moreno and Anderson 2012; Fig. 4) allow us to interpret the occurrence of a small lake in this basin at this time. Although there is a contribution of both algae and vascular plants to the record of sedimentary organic matter, deduced by C/N rates, it seems that algal production had more influence during this period, as suggested by the low TOC content and high nitrogen and carbon isotopic values.

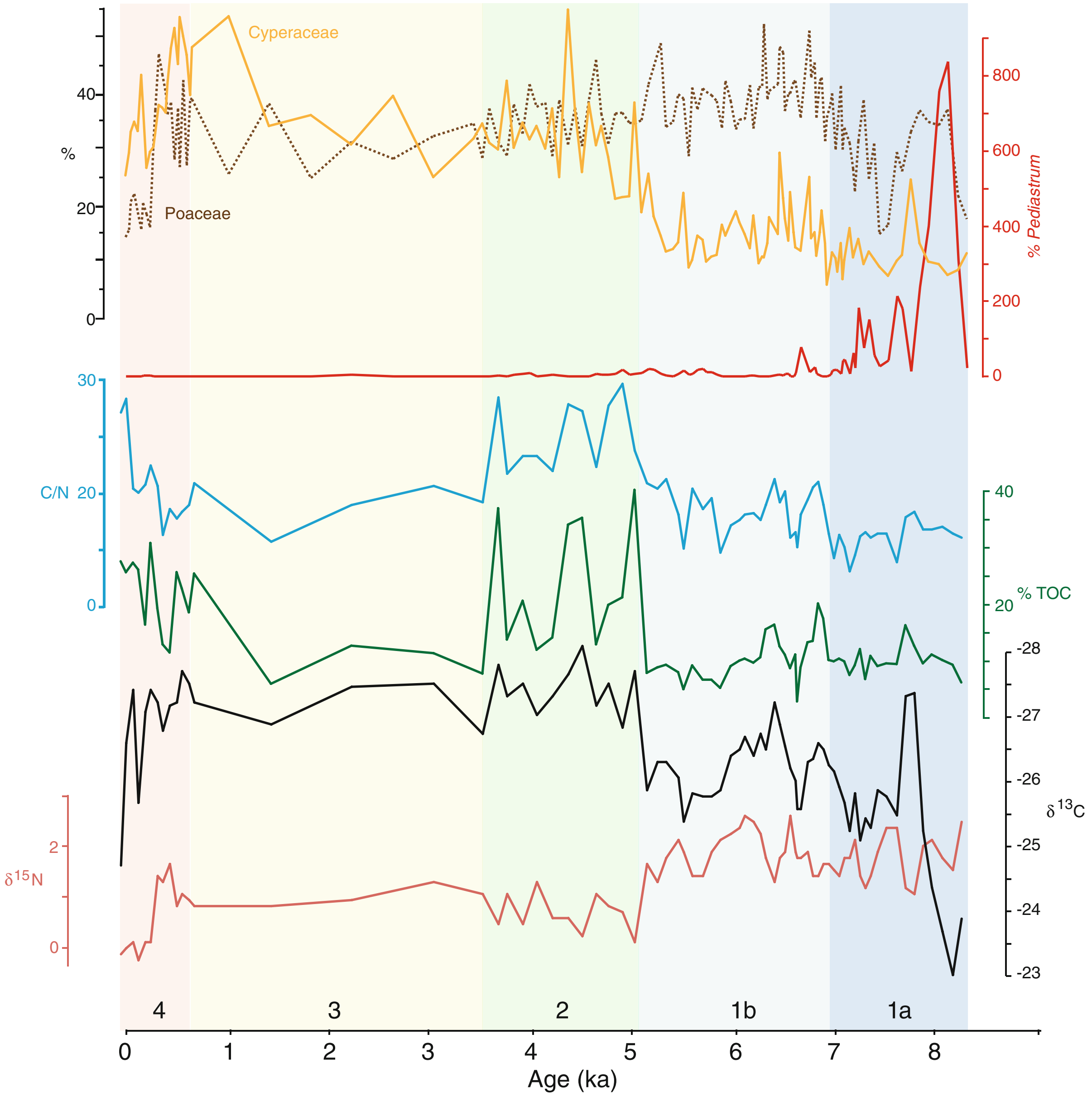

Fig. 4 Comparison of δ^{13}C, δ^{15}N, atomic C/N ratio, %TOC values, *Pediastrum*, Poaceae and Cyperaceae abundances (Jiménez-Moreno and Anderson 2012) from the Borreguiles de la Virgen core. Note that the scale of δ^{13}C values is reversed. *1 (a and b)* lacustrine environment, *2* bog environment, *3* low SAR period, *4* fluctuating environment

Somewhat different environmental conditions are interpreted for the two subzones (Figs. 2, 4). The oldest stage 1a (8,200–6,900 cal yr BP) records the lowest C/N and highest δ^{13}C values (Fig. 4), and highest *Pediastrum* (algae) concentration in this core (Jiménez-Moreno and Anderson 2012). We interpret this period as being more humid, and with the lake being more productive and with higher water levels than during the younger stage 1b (6,900–5,100 cal yr BP). These three proxies show a coupled tendency—high δ^{13}C values and low C/N ratio usually occur with abundant *Pediastrum* content (Fig. 4), whereas lower *Pediastrum* percentages usually occur with low δ^{13}C and higher C/N ratio—all suggesting a very important algal contribution to the organic matter record at that time. TOC values and δ^{15}N values also support this interpretation (Fig 2, 4). *Pediastrum* is mainly found in lakes with high productivity rates, related to inputs from rich organic soils (Lézine et al. 2005; Sarmaja-Korjonen et al. 2006). Anderson et al. (2011) and Jiménez-Moreno and Anderson (2012) suggested that the warmest and wettest conditions occurred between 8,200 and 7,000 cal yr BP in the Sierra Nevada area, being deduced from two pollen records that show the highest percentages of tree species (mostly *Pinus* but also *Betula* and *Quercus*) at that time. Therefore, the environmental conditions in the area were optimal for more frequent algal blooms. Sedimentation in this small lake was then dominated by primary production, however the external inputs of land plants from the catchment basin also occurred, for example at ~7,800 cal yr BP, when the abundance of *Pediastrum* dropped sharply (Jiménez-Moreno and Anderson 2012), the TOC values and the C/N rate increased, and the δ^{13}C values dropped to −27.4 ‰ (Figs. 2,4).

Although in general, climatic conditions remained humid, a drier trend is observed after ~7,800 cal yr BP, agreeing with the nearby Laguna de Río Seco record (Anderson et al. 2011). An increased contribution from vascular plants within the catchment basin is observed in the core record at ~7,800 and from 7,500 to 7,300 cal yr BP (increase in C/N rate and decrease in δ^{13}C values). The relative aridification can also be recognized in coastal environments in southern Iberia where a decline in arboreal species and increase in xerophytes is recognized (Carrión et al. 2001, Fletcher et al. 2007) in opposition to mid-elevation forest where expansion occurred (Carrión et al. 2009). This complicated pattern occurs along the entire western Mediterranean basin where coeval wet and dry conditions can be recognized during this period (Dormoy et al. 2009; Zhornyak et al. 2011). This lack of coherence between different records has been related to greater differences in seasonal insolation between early and middle Holocene (Wanner et al. 2008), translated into different humidity conditions at sites from higher or lower elevations (Anderson et al. 2011).

Our climatic inferences suggesting higher precipitation than today in the early Holocene agree with other sites in the Mediterranean basin, including Lago di Pergusa (Sicily; Sadori and Narcisi 2001) and Lago de Vico (Central Italy; Magri and Parra 2002). In addition, this relatively wet period, punctuated by dry episodes, appears to be synchronous between the western Mediterranean and the Indian and African moonsonal regions (Jalut et al. 2009). Aeolian inputs, reconstructed by geochemical proxies (Zr/Th and La/Lu), indicate the first arrival of Saharan dust to Sierra Nevada also during this period in agreement with marine cores from the western Mediterranean (Rodrigo Gámiz et al. 2010).

The second part (1b) of the main lacustrine period (from 6,900 to 5,100 cal yr BP) represents the progressive transition from a small lake to a bog, fully recorded in the successive zone 2. The nearly coupled relationship between C/N rate and δ^{13}C values is also observed during this period (Figs. 2, 4). However, some differences from stage 1a exist. *Pediastrum* percentages (Jiménez-Moreno and Anderson 2012) were much lower than in stage 1a, and they were only coupled to the C/N and δ^{13}C variations during beginning of the stage 1b (Fig. 4). At the beginning of stage 1b, C/N values are twice above 20 (~6,800 and ~6,400 cal yr BP), in the range of typical vascular plants, and coinciding with high abundance of Poaceae and Cyperaceae in the pollen record (Jiménez-Moreno and Anderson 2012; Fig. 4). These plants dominate the typical vegetation that surrounds small alpine lakes, or grows in wetlands in the Sierra Nevada today (Anderson et al. 2011; Jiménez-Moreno and Anderson 2012). At those times, *Pediastrum* abundance dropped dramatically and TOC values reached the highest values of zone 1 (Fig. 4). We suggest that these two phases of lowered water levels (6,800 and 6,400 cal yr BP) also witnessed graminoid encroachment locally into the basin. These two events record sporadic bog development, arrested from 6,700 to 6,600 cal yr BP by a period of increased water level [increase in *Pediastrum*, δ^{13}C values, and decrease in C/N (15–16; Fig. 4)].

Between 5,800 and 5,600 cal yr BP, δ^{13}C increased up to −25.8 ‰, the C/N ratio stabilized at 18–20, and TOC values were low, but slowly increasing (Fig. 2). Pollen evidence showed a drop in the abundance of Cyperaceae, but with stable Poaceae levels (Fig. 4). Organic sedimentation was probably dominated by vascular plants with some algal influence on the sedimentation, which increased occasionally around ~5,500 cal yr BP. Besides the minor influence of algal productivity, the slight increase in

δ^{13}C may be due to drier conditions, which can increase the δ^{13}C values of plants because of the plant water-use efficiency effect (Farquhar et al. 1982). This feature may be linked to a slow lake level drop that led to an increase in riparian/wetland vegetation on the shore. Later, by ~5,500 cal yr BP, the lake-level may have increased slightly (lower C/N and higher δ^{13}C). Finally, this period ends with a sharp increase in C/N (above 20) and Cyperaceae, and a decrease in δ^{13}C values (Fig. 4), which ends the transition from a lacustrine to a full bog environment.

Bog environment (5,100–3,600 cal yr BP)

During this period *Pediastrum* is rarely recorded (Jiménez-Moreno and Anderson 2012), and the contribution of phytoplankton to the total organic matter of the sediment was probably negligible, as suggested by the C/N values (>21) that point to a vascular plant input (Figs. 2,4). Calculated organic matter $\mathrm{SAR}_{\mathrm{om}}$ is very high, up to 75 % of the total SAR. TOC values increased significantly during this period (Fig. 2). These values are surprisingly high, given the reduced catchment basin, and the scarce soil development. Jiménez-Moreno and Anderson (2012) and Anderson et al. (2011) proposed an increase in aridity during this period in the Sierra Nevada, as part of a general aridification trend since ~5,000 cal yr BP for all of southern Spain (Carrión et al. 2003, 2010). Because of these factors we do not postulate a large influx of terrestrial matter from the catchment basin in order to generate this TOC and Organic SAR values (Fig. 2). Rather this points to an environmental change towards bog conditions, where in situ growth of vascular plants, mostly Cyperaceae and Poaceae, predominated (Fig. 4). Apparently both groups colonized these wetlands when lake levels dropped due to the increase in aridity. This is also supported by δ^{13}C values, which decreased during this period, with values around −27 ‰ or lower, recording the lowest values of the record (Fig. 2, 4).

This hydrologic evolution contrasts with that from Laguna de Río Seco located in the south face of the Sierra Nevada, where a lake existed through the entire Holocene. However, pollen, algal spores and geochemical proxies also indicate an increase in aridity at that time (Anderson et al. 2011).

Low SAR period (3,600–700 cal yr BP)

The few data available from this time interval (only 4 samples in ~2,600 years) preclude us from detailed interpretations. The main characteristic of this period is the abnormally low SAR values (total and from organic matter; Fig. 2). C/N ratios are mostly less than 20, and TOC values are very low. δ^{13}C data show values around −27 ‰, and δ^{15}N around 1 ‰ (Figs. 2, 4). δ^{13}C values are slightly higher than during the previous period and from 4,500 to 700 cal yr BP show a general trend to less negative values (Fig. 2, 4). *Pediastrum* is almost absent in this interval, and the C/N and δ^{13}C proxies do not reach the extreme values recorded in the oldest part of the core (from 8,200 to 5,100 cal yr BP; Fig. 4). However, the coincidence of slightly declining C/N ratio with weak increases in δ^{13}C values could suggest minor algal contribution to the organic sediments around 3,500 and 1,400 cal yr BP. From the pollen record, *Artemisia* increased, and this was presented as strong evidence for deepening aridity (Anderson et al. 2011; Jiménez-Moreno and Anderson 2012).

There is no single clear explanation for the abnormally low SAR recorded during this period (Fig. 2). According to Anderson et al. (2011) and Jiménez-Moreno and Anderson (2012), climate conditions were dry at that time in the high-elevation environments of Sierra Nevada. We suggest several explanations for the unusually slow SAR during this period:

1. The low SAR might reflect one or more unconformities in the record, due to drying of the deposit. In this case, the organic matter could have been altered, which would have triggered subsequent changes in the C/N ratio (lower C/N ratio) and in the δ^{15}N (with both lower and higher values; Fogel and Tuross 1999). As a very robust parameter, δ^{13}C values of bulk organic matter would remain invariable (Ficken et al. 1998; Fogel and Tuross 1999). This hypothesis is consistent with Jiménez-Moreno and Anderson (2012), suggesting decomposition or low bog productivity relating to increased aridification.
2. Physical erosion could also account for the low apparent SAR. Periodic water supply from melting or precipitation could develop rivulets across the sampling zone that could erode part of the deposits.

3. If the low SAR does not imply diagenetically altered isotopic values, these values would be consistent with a wetland with moderate water level, some algal proliferation and scarce external organic matter inputs due to the general dry conditions. However, it is very unlikely that a true lake would have developed.

With the present data, we do not have enough information to favour one explanation over another. However, the higher values of δ^{13}C strongly suggests an intensifying trend towards aridity, as described locally by Anderson et al. (2011) and Jiménez-Moreno and Anderson (2012), and regionally by Carrión et al. (2003; 2010) and (Fletcher and Zielhofer in press).

Fluctuating environment (~700 cal yr BP—present)

A general trend towards increasing δ^{13}C values occurs during this period (Figs. 2,4). However, between 700 and 350 cal yr BP, C/N values are lower than 20. Taken together with a slight increase in the δ^{13}C and δ^{15}N values (Figs. 2,4), this indicates a periodic algal contribution to the sediment, perhaps signaling temporary increases in the water level on the wetland. It must be noted, however, that there is no direct evidence of important algal blooms, as shown by the lack of *Pediastrum* in the palynological record (Jiménez-Moreno and Anderson 2012; Fig. 4).

Poaceae and Cyperaceae are very abundant during the beginning of this period (Jiménez-Moreno and Anderson 2012; 700/600 to 350 cal yr BP; Fig. 4), which may be coeval with the Little Ice Age (LIA; 600–200 cal yr BP). The cold LIA was characterized in the Iberian Peninsula, at least in the beginning, by a humid period (Martín-Puertas et al. 2010; Morellón et al. 2011; Valero-Garcés and Moreno 2011). Based on our dates, the humid phase of the LIA may have persisted longer at Borreguiles de la Virgen than at low altitude Iberian record (up to 350 cal yr BP). We suggest that this may be due to lesser evapotranspiration rates at these high elevations, compared to lower elevation sites. Alternatively, our age model may not be as accurate for this stage of the record.

During last ~350 years of the record there is an increase in the C/N ratio, TOC and δ^{13}C that is consistent with full bog development and in situ growth of vascular plants (C/N $>$ 20; Figs. 2,4). Therefore, the increase trend in δ^{13}C could be interpreted as an aridification trend, which led to better water use efficiency in plants (Farquhar et al. 1982). This increase in aridification is in agreement with an increase in Saharan dust input (Mulitza et al. 2010), also identified in lacustrine systems in southern Iberia (Martín-Puertas et al. 2010) and Iberian margin marine records (Jimenez-Espejo et al. 2008). The $\mathrm{SAR_{om}}$, might represent half of the total SAR (Fig. 2), also indicating an important supply to the TOC of vascular plants.

Summary: Borreguiles de la Virgen in context with the southern Iberia paleoclimatic record

Our isotopic record from Borreguiles de la Virgen presents an opportunity to expand our knowledge of environmental history of the Sierra Nevada, complementing the pollen data of Jiménez-Moreno and Anderson (2012). We suggest that the isotopic record is highly influenced by the features of the catchment basin, which has a small area with steep slopes and sparse soil development on mica-schist bedrock. Thus, the main organic external inputs to the wetland system are limited to a very small area with plant development in the bog. In general, during the 8,200-yr record from Borreguiles de la Virgen, deposition occurred during wet periods, whereas arid periods represented changes in the sedimentation/erosion equilibrium.

Lake sedimentation occurred in the Borreguiles de la Virgen site between 8,200 and 5,100 cal yr BP, occupying most of the surface of the present Borreguiles de la Virgen basin. The main development of the lake system was recorded from 8,200 to 6,900 cal yr BP. A progressive reduction of the lake and development of a bog occurred between 6,900 and 5,100 cal yr BP. Anderson et al. (2011) and Jiménez-Moreno and Anderson (2012) pointed out that pollen records from the Sierra Nevada show a regional replacement of *Pinus* (below alpine treeline) by Poaceae (from 7,000 to 4,600 cal yr BP), and by Cyperaceae and *Artemisia* (from 4,600 to 1,200 cal yr BP). However, Cyperaceae, a family composed of typical wetland species, increased early in this transition (~5,000 cal yr BP). The previous sharp increases in Cyperaceae at ~6,800 and ~6,400 cal yr BP, during the phase of lacustrine drying, could indicate occasional bog development. From 5,100 to 3,600 cal yr BP our record shows full bog development, which is consistent with increased representation of Cyperaceae (Jiménez-Moreno and Anderson 2012).

Therefore, isotopic and palynological records from Borreguiles de la Virgen show a gradual trend towards drier conditions from 8,200 to 3,600 cal yr BP. This agrees with Early-Middle Holocene climatic patterns in the Mediterranean area. The maximum lacustrine development during the Early Holocene climate optimum related with overall warm and humid climate conditions (Street and Grove 1979; deMenocal et al. 2000; Bar-Matthews et al. 2000; Carrión 2002). The transition from a lake to a bog environment, documented at Borreguiles de la Virgen between 7,000 and 5,500 cal yr BP, agrees with a transitional climate phase from previously humid to more arid conditions in the Mediterranean area, as observed by many authors (Debret et al. 2009; Jalut et al. 2009; Anderson et al. 2011; Jiménez-Moreno and Anderson 2012). According to Magny et al. (2002), a decrease in southern Mediterranean lake levels began by 6,500 cal yr BP, at the time of punctuated development of bog conditions in the Borreguiles de la Virgen record. Finally, there is a general trend toward more arid conditions since ~5,500 cal yr BP in the Mediterranean region (Jalut et al. 2009). Because of slow SAR, isotopic data from the Borreguiles de la Virgen record between 3,900 and 700 cal yr BP could be biased, so the interpretation for this period is less certain. However, pollen records from the Sierra Nevada, which record a more regional signal, and the δ^{13}C data from Borreguiles de la Virgen, indicate that an increasing trend towards arid conditions occurred at that time (Anderson et al. 2011; Jiménez-Moreno and Anderson 2012).

Relatively wet conditions were recorded in the Borreguiles de la Virgen isotopic record from 700 to 350 cal yr BP. This could be caused by relatively humid climate conditions during the first part of the LIA in southern Spain (Martín-Puertas et al. 2010), which would have led to an increase in the water availability in the basin. However a true lake did not develop, and during the last 350 years the geochemical evidence points to the continuation of bog conditions. In the most recent centuries, our data suggest somewhat drier conditions, which in the future might imply the gradual replacement of bog by meadows.

These different phases described in the Borreguiles de la Virgen record agree with the different stages of evolution of a typical 'Borreguil' from the Sierra Nevada: from a small lake to a bog, according to Castillo Martín (2009). In view of our record and the climatic evolution of the Sierra Nevada Mountain Range, we propose the combined influence of climatic and sedimentary factors for the evolution of wetlands in this area. The optimum climatic conditions for the Early Holocene, after the phase of melting glaciers, favoured the erosion and accumulation of sediments in the small depression generated by ice erosion during the last glacial. The progressive infill of this depression, together with drier conditions during the middle Holocene, could have favoured the development of a bog. However, it seems that in the Borreguiles de la Virgen record, climatic change (i.e., aridity), is the main factor that caused the evolution from a lacustrine system to a bog at ~5,100 cal yr BP, instead of the single effect of lacustrine filling.

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