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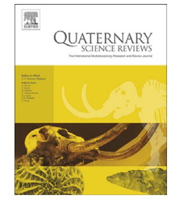

Centennial-scale vegetation and North Atlantic Oscillation changes during the Late Holocene in the southern Iberia

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A B S T R A C T

High-reso CE to lution pollen analysis, charcoal, non-pollen palynomorphs and magnetic susceptibility have been analyzed in the sediment record of a peat bog in Sierra Nevada in southern Iberia. The study of these proxies provided the reconstruction of vegetation, climate, fire and human activity of the last ~4500 cal yr BP. A progressive trend towards aridification during the late Holocene is observed in this record. This trend is interrupted by millennial- and centennial-scale variability of relatively more humid and arid periods. Arid conditions are recorded between ~4000 and 3100 cal yr BP, being characterized by a decline in arboreal pollen and with a spike in magnetic susceptibility. This is followed by a relatively humid period from ~3100 to 1600 cal yr BP, coinciding partially with the Iberian-Roman Humid Period, and is indicated by the increase of *Pinus* and the decrease in xerophytic taxa. The last 1500 cal yr BP are characterized by several centennial-scale climatic oscillations. Generally arid conditions from ~450 to 1300 CE, depicted by a decrease in *Pinus* and an increase in *Artemisia*, comprise the Dark Ages and the Medieval Climate Anomaly. Since ~ 1300 to 1850 CE pronounced oscillations occur between relatively humid and arid conditions. Four periods depicted by relatively higher *Pinus* coinciding with the beginning and end of the Little Ice Age are interrupted by three arid events characterized by an increase in *Artemisia*. These alternating arid and humid shifts could be explained by centennial-scale changes in the North Atlantic Oscillation and solar activity.

1. Introduction

Recent studies have demonstrated a response of terrestrial vegetation, atmosphere and ocean environments to changes in solar radiation (Jiménez-Moreno et al., 2008, 2013a; Fletcher et al., 2012). Occurring at the boundary between temperate, subtropical and tropical climate regimes the Mediterranean region is a key area in our attempt to understand the interactions between these environments (Alpert et al., 2006). Numerous global paleoclimate proxy records for the Holocene show that weak changes in solar activity triggered climatic variability not only at millennial-scales (e.g.; Bond et al., 1997), but also at centennial- and decadal-scales (e.g. Bond et al., 2001; Bard and Frank, 2006). In addition, one of the main mechanisms influencing present climate in the Mediterranean region is the North Atlantic Oscillation (NAO) and many studies have attempted to relate atmospheric dynamics of the NAO with environmental change in this area (e.g. Lionello and Sanna, 2005). In the last years a variety of multiproxy records have been used for the reconstruction of past NAO conditions (e.g. D'Arrigo et al., 1993; Trouet et al., 2009; Olsen et al., 2012; Baker et al., 2015). These show that positive NAO conditions triggered a decrease in precipitation in the western Mediterranean area, while wetter conditions occurred during negative NAO phases.

Holocene sediment records from lakes, peat bogs and marine environments from the western Mediterranean have been very informative in relating records of vegetation, fire activity and human impact to climate change. Several high-resolution multiproxy lake records from northern and central Iberia have documented

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centennial-scale paleoclimate evolution for the last millennia (e.g. Martín-Puertas et al., 2008; Morellón et al., 2011; Currás et al., 2012; Moreno et al., 2012; Corella et al., 2013). Most of the Holocene paleoclimate reconstructions in the southern Iberian Peninsula come from lake and peat deposits at low and montane altitudes, as well as from marine cores (Carrión, 2002; Carrión et al., 2001a,b, 2003, 2007, 2010; Martín-Puertas et al., 2008, 2010; Nieto-Moreno et al., 2011; Moreno et al., 2012; Jiménez-Moreno et al., 2015). Studies at higher elevations are scarcer and mostly come from lake and peat bog sedimentary deposits from the Sierra Nevada range (Anderson et al., 2011; Jiménez-Moreno and Anderson, 2012; García-Alix et al., 2012, 2013; Jiménez-Moreno et al., 2013b). These studies have provided a strong record of Holocene vegetation, fire, human impact and climate evolution at millennial- and centennial-scales. Currently this region lacks high-resolution records of change that can capture decadal-scale variations such as the NAO.

Within the region, Sierra Nevada has been a key location for paleoecological studies, due to its high elevation records for southern Europe and its sensitive alpine wetland environments (Anderson et al., 2011). Previous records from the range showed that humans influenced these alpine environments during the late Holocene, especially in the last millennium, with increases in pasturing, cultivars and *Pinus* reforestation. However, human impact in these alpine environments is minimal compared to other sites at lower elevations in the area (Anderson et al., 2011; Jiménez-Moreno and Anderson, 2012; Jiménez-Moreno et al., 2013b). Although numerous studies have suggested that the Mediterranean vegetation evolution during the Holocene was largely due to human impact (Reille and Pons, 1992; Pons and Quézel, 1998), Jalut et al. (2009) considered climate change to be a more important determining factor. Others have suggested that we are still far from understanding the correlation between vegetation, fire, climate and human activity, because of the importance of ecological factors in shaping the timing of vegetation responses to disturbances (Carrión et al., 2007).

In this paper we present a multi-proxy high-resolution study from Borreguil de la Caldera (BdlC), a peat bog that records the last ~4500 cal yr BP of vegetation, fire, human impact, and climate history from the Sierra Nevada in southern Spain. The main focus of this study is to elucidate the relationship between vegetation and fire activity with solar cyclicity and atmospheric dynamics. High-resolution studies such as the one here from Borreguil de la Caldera, with ca. 30-yr resolution for the last 1500 yr BP and ca. 120-yr resolution between approximately 4450 to 1600 cal yr BP, allow us to detect changes in the NAO through time and its impact on the environment. In addition, we also comment on the record of human impact in the Sierra Nevada during the late Holocene.

1.1. Sierra Nevada: climate and vegetation

Sierra Nevada is a W-E aligned mountain range located in southern Spain. The range is one of the southernmost European areas to be glaciated during the Late Pleistocene (Schulte, 2002). The postglacial melting of cirque glaciers allowed the formation of lakes and wetlands. These formed on the metamorphic bedrock located at elevations between 2600 and 3100 m asl. Some of these lakes have filled sediments and have transitioned to small peat bogs (Castillo Martín, 2009). Bedrock is Permotriassic and Palaeozoic metamorphic rocks mostly characterized by micashists (Martín Martín et al., 2010).

In the Sierra Nevada Range, the mean annual temperature at 2500 m asl 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/yr, seasonally concentrated between October and April, mostly as snow (Oliva et al., 2009). Situated between a temperate humid climate to the north and at subtropical, arid climate to the south, its location proximal to the last-glacial coastal shelves and its high-altitude make this area a particular vegetation hotspot in southern Europe (Carrión et al., 2008;González-Sampériz et al., 2010; Anderson et al., 2011; Jiménez-Moreno and Anderson, 2012; Jiménez-Moreno et al., 2013b). Sierra Nevada is one of the most important centers of plant diversity in the western Mediterranean region. With more than 2100 vascular taxa (species and subspecies) catalogued, it accounts for nearly 30% of the entire vascular flora of the Iberian Peninsula (Blanca, 1996; Blanca et al., 2002). Due to the altitudinal gradient of Sierra Nevada (from 900 to more than 3400 m) this mountain range is strongly influenced by thermal and precipitation gradients allowing well-characterized vegetation belts (Valle, 2003). The crioromediterranean vegetation belt characterized principally by *Festuca clementei*, *Hormatophylla purpurea*, *Erigeron frigidus*, *Saxifraga nevadensis*, *Viola crassiuscula*, and *Linaria glacialis* is the highest in the area and occurs above ~2800 m. The oromediterranean belt, between ~1900 and 2800 m, bears *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* as the most representative species. The supramediterranean belt, from approximately 1400 to 1900 m of elevation principally includes *Quercus pyrenaica*, *Quercus faginea*, *Quercus rotundifolia*, *Acer opalus* subsp. *granatense*, *Fraxinus angustifolia*, *Sorbus torminalis*, *Adenocarpus decorticans*, *Helleborus foetidus*, *Daphne gnidium*, *Clematis flammula*, *Cistus laurifolius*, *Berberis hispanicus*, *Festuca scariosa* and *Artemisia glutinosa*. The mesomediterranean between ~600 and 1400 m of elevation are characterized by *Quercus rotundifolia*, *Retama sphaerocarpa*, *Paeonia coriacea*, *Juniperus oxycedrus*, *Rubia peregrina*, *Asparagus acutifolius*, *D. gnidium*, *Ulex parviflorus*, *Genista umbellata*, *Cistus albidus* and *Cistus lauriflolius* (El Aallali et al., 1998; Valle, 2003). The human impact over this area affected the vegetation distribution especially during the last millennium. The most important examples of human disturbance in the area are the *Olea* increase for cultivation at relatively low elevations and *Pinus* reforestation (Anderson et al., 2011; Jiménez-Moreno and Anderson, 2012; Jiménez-Moreno et al., 2013b).

1.2. Borreguil de la Caldera (BdlC)

This bog presently occurs above treeline, in the crioromediterranean vegetation belt (Valle, 2003). In Sierra Nevada small bogs such as this one are locally known as “Borreguiles”, which are installed on cirque basin environments with constant moisture characterized by tundra-like vegetation with Cyperaceae as the most representative species. Other secondary species are represented by *Nardus stricta*, *Festuca iberica*, *Leontodon microcephalus*, *Luzula hispanica*, *Ranunculus demissus, Sagina saginoides* subsp. *nevadensis, Campanula herminii, Saxifraga stellaris* subsp. *alpigena*, *Veronica turbicola*, *Sedum anglicum* subsp. *melanantherum*, *Festuca rivularis* and some species of briophytes. Around this peat bog other plant species occur, such as *Armeria splendes*, *Agrostis nevadensis*, *Ranunculus acetosellifolius*, *Plantago nivalis* and *Lepidium stylatum* (Molero Mesa et al., 1992). BdlC formed part of those high-elevation wetland areas; it is a small peat bog located at 37° 03′ 02″ N and 3° 19′ 24″ W in the south face of Sierra Nevada at ~2992 m elevation (Fig. 1). It is situated right below Laguna de la Caldera, another cirque-lake basin located in the upper drainage part of the Mulhacen River. The peat bog area is 0.17 ha. The surface of the drainage basin is 62 ha and includes the Mulhacen (3479 m asl), the highest peak of the Iberian Peninsula. The area is snow-free