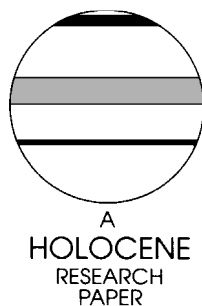


# Holocene vegetation dynamics, fire and grazing in the Sierra de Gádor, southern Spain

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**Abstract:** This paper examines the mid- to late-Holocene (c. 6850–1160 cal. yr BP) environmental history of Sierra de Gádor in southern Spain. The local vegetation dynamics are reconstructed through the palaeoecological record obtained from a lacustrine deposit situated at 1530 m. Various hypotheses are considered to explain the vegetation dynamics apparent in the palaeoecological evidence, including climatic change, fire occurrence and human activity. Although the vegetation in this region is sensitive to climatic change, threshold events driven by ecological factors are also apparent. Climatic events include a thermo-mesophytic optimum with abundance of deciduous trees and maximum lake water level found from c. 6850 to 5500 cal. yr BP. In contrast, changes in the frequency of major fire episodes appear to have shaped interspecific relationships and vegetation change, especially from c. 4200 cal. yr BP onwards. Biotic properties of the ecosystem such as the inertia of established tree populations, interconnected with competition adjustments, appear also to have played a role. Over the last two millennia, overgrazing, combined with natural and/or human-set fires, appears to have pushed mountain forests over a threshold leading to the spread of grassland, thorny scrub, junipers and nitrophilous communities.

**Key words:** Holocene, palaeoecology, pollen analysis, vegetation dynamics, climatic change, desertification, fire, anthropogenic disturbance, Spain, arid lands.

## Introduction

Most of the Quaternary palaeoenvironmental records available to date from the Mediterranean region are located in areas of relatively high precipitation/evaporation ratio with a large number of sites in the southernmost areas of Spain, Italy and Greece. This means that we remain very much in ignorance about the nature and timing of environmental changes in the most typical regions of Mediterranean climate. This gap in our knowledge is critical because it is precisely this unexplored part of the Mediterranean region that is largely vulnerable to climatic changes and specifically to aridity events and desertification.

Here we present a Holocene palynological sequence from Sierra de Gádor, a massif situated within one of the most arid territories of Europe, the Murciano-Almeriense phytoprovince of southeastern Spain (Mota *et al.*, 1997; Sánchez-Gómez *et al.*, 1998). This region extends over c. 13 000 km<sup>2</sup>, and represents a model area to address a variety of environmental issues because of its high plant-species diversity, its varied physiography with abundance of ecotonal territories, its great risk of desertification, and the antiquity of human pressure on the landscape. The few pollen analyses that have been carried out in this region have tended to concentrate on those sequences that were easily accessible, rather than on the more desirable ones. Those include adjacent marine sediments (Targarona, 1997); small peaty deposits in subcoastal mountains (Riera *et al.*, 1995); playa lakes (Burjachs *et al.*, 1997);

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valley-bottom fills in badland areas (Nogueras *et al.*, 2000); palaeolagoons and coastal marshes (Yll *et al.*, 1994; Pantaleón-Cano *et al.*, 2003); and prehistoric sites (Davis and Mariscal, 1994; Carrión *et al.*, 1995; 1999; Carrión, 2002a).

The aim of this paper is to reconstruct the local vegetation history of Sierra de Gádor and elaborate hypotheses about forcing mechanisms of vegetation change based on palaeoecological evidences of fire occurrence, human activity and climatic change. Specific subjects of controversy relate to: (i) whether this treeless mountain, today flanked by desert depressions, was forested at any time since the mid-Holocene, and, if so, which arboreal species were involved (Giménez, 2000; Grove and Rackham, 2001); (ii) whether the study-site catchment includes pollen/microfossil signal for the aridification trend discernible in lowland eastern Andalusia since *c.* 5500 cal. yr BP (Pantaleón-Cano *et al.*, 2003; Carrión, 2001a); (iii) whether fire events and other disturbances are critical factors in the tempo of vegetation change, and to which extent these influences are compatible with the determinism of the climatic system (Willis, 1994; Bennett and Willis, 1995; Carrión, 2001b); (iv) whether the palaeorecord of biotic changes, fire occurrence and anthropogenic disturbance can shed light on the characteristics of modern vegetation (Mota *et al.*, 1996); and (v) whether prehistoric patterns of human settlement are related with the Gádor environmental history, especially the Argaric collapse at *c.* 3600 cal. yr BP, often considered an anthropogenically induced catastrophe (Castro *et al.*, 1999).

## Physical setting

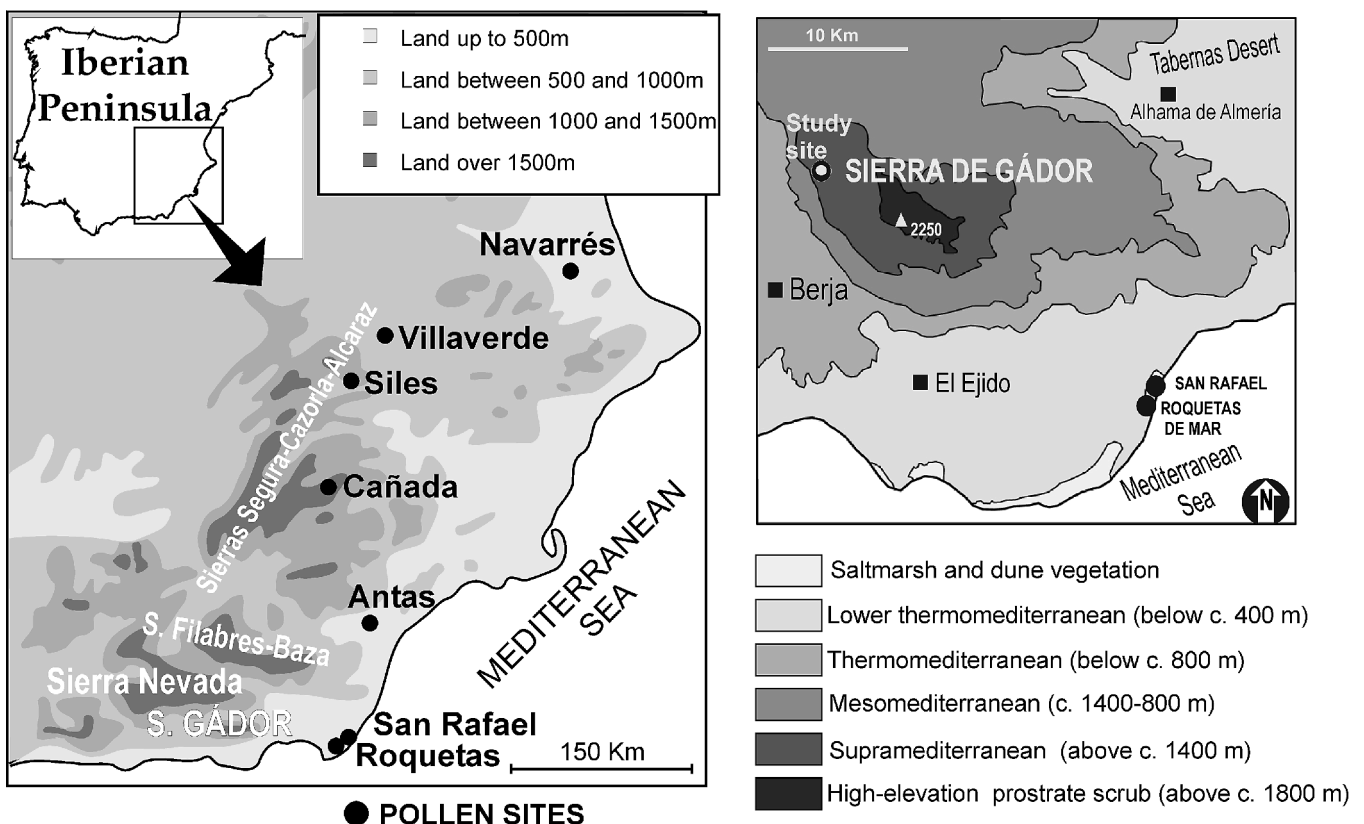
The study site ( $2^{\circ} 55'W$ ,  $36^{\circ} 54'N$ , 1530 m a.s.l.) is a small lacustrine deposit (*c.*  $400 \times 350$  m), 11 km northeast of the village of Berja, in the western flanks of the highest Sierra de Gádor (2250 m a.s.l.), Almería province, southeastern Spain (Figure 1). Sierra de Gádor is basically a calcareous mountain formed by

Triassic limestones and dolomites, lying south of Sierra Nevada (3482 m) and Sierra de Baza-Filabres (2271 m), west of the Tabernas desert depression, and *c.* 5–30 km north of the Mediterranean Sea (Figure 1). The study basin, which still inundates periodically, has served historically as a pool for domestic stock and adjacent cultivars; it is more rarely cultivated for cereals. The basin has no incoming streams and is fed by direct precipitation and surface runoff from the catchment. The depositional context is a massive bed of organic calcareous clays overlying calcreted conglomerates. The uppermost 20 cm represent a disturbed agricultural horizon (Figure 2).

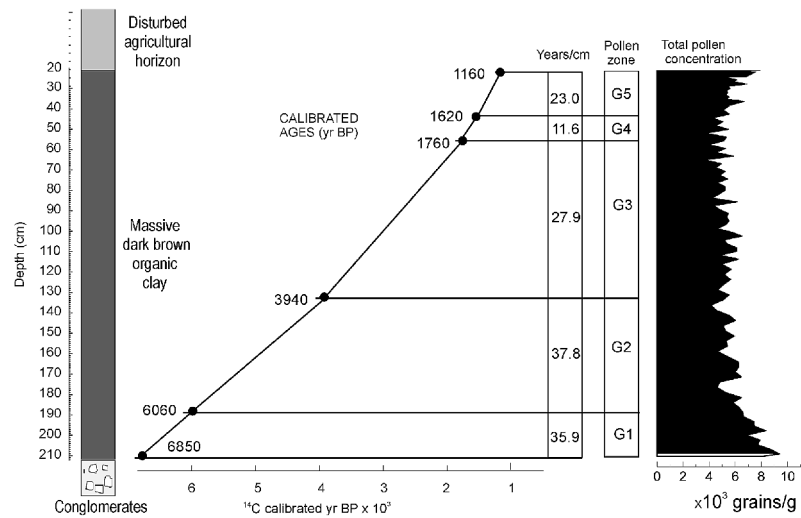
The study site lies in the supramediterranean bioclimatic belt, close to the mesomediterranean belt (Figure 1). Local mean annual temperature and precipitation at this altitude average 11–12°C and 450–500 mm, respectively. Precipitation is, however, distributed unevenly across Sierra de Gádor due to elevational gradients and localized rain-shadow effects. Precipitation increases with altitude, often exceeding 670 mm above 1800 m, but dropping below 200 mm along the southern and eastern slopes.

Plant communities of Sierra de Gádor are characterized by a majority of Mediterranean contingent species (65%), including Iberian, Murcian-Almerian, Ibero-North African and Ibero-Iranian endemics. Trees are extremely rare, and most potential arboreal species, such as *Quercus rotundifolia* and *Q. faginea*, display shrubby habit, or occur as isolated trees in gullies (Mota *et al.*, 1996; 1997; Giménez, 2000).

High-elevation areas of the supramediterranean belt, above 1400 m, are dominated by scrub of *Berberis hispanica* and *Juniperus oxycedrus*, with *Crataegus monogyna*, *Quercus rotundifolia*, *Lonicera arborea*, *Prunus ramburii*, several species of *Rosa* and a basal layer of hardleaved grasses. Prostrate thorns such as *Vella spinosa*, *Hormatophylla spinosa*, *Ononis aragonensis*, *Erinacea anthyllis*, *Echinospartum boissieri*, *Dianthus pungens*, *Rhamnus saxatilis* and *Prunus prostrata* become the



**Figure 1** Location of Gádor and other pollen sites in southeastern Spain. Vegetation belts follow Mota (1990). Gádor Lake lies within the supramediterranean belt, in close proximity to the mesomediterranean belt.



**Figure 2** Sediment depth and litho- and pollen stratigraphy to radiocarbon age relationships from the Gádor section. Lines connecting each plotted point are interpolated sediment-accumulation rates.

dominant vegetation in the wind-exposed areas above 1800–1900 m (Mota *et al.*, 1993). The mesomediterranean areas, extending from *c.* 800 to 1400 m, are characterized by *Genista cinerea*, *Ulex parviflorus*, *Asparagus acutifolius*, *Phlomis purpurea* and *Lavandula lanata*, with patches of *Quercus coccifera*, *Q. rotundifolia* and *Juniperus oxycedrus*. The thermomediterranean belt, 200–800 m, is characterized by rich communities of *Pistacia lentiscus*, *Chamaerops humilis*, *Salsola webbii*, *Quercus coccifera*, *Bupleurum gibraltarium*, *Rhamnus alaternus*, *R. oleoides*, *Asparagus albus*, *Ephedra fragilis*, *Olea europaea*, *Genista umbellata* and *Cistus albidus*, among others. Sclerophyllous brushwoods characterized by Ibero-north African species (*Maytenus europaeus*, *Ziziphus lotus*, *Periploca angustifolia*, *Calicotome intermedia*, *Withania frutescens*, *Launaea arborescens*, *Osyris lanceolata*) are abundant along the southern and eastern slopes below 400 m. The very sparse stands of pines (*Pinus nigra*, *P. pinaster*, *P. sylvestris*, *P. halepensis*) are considered as derived from historical afforestations (Giménez, 2000). Saline depressions and intermittent watercourses, very common throughout the region, are colonized by *Artemisia*, *Nerium oleander*, *Chenopodiaceae*, *Tamarix*, *Limonium* and *Poaceae* species.

## Methods

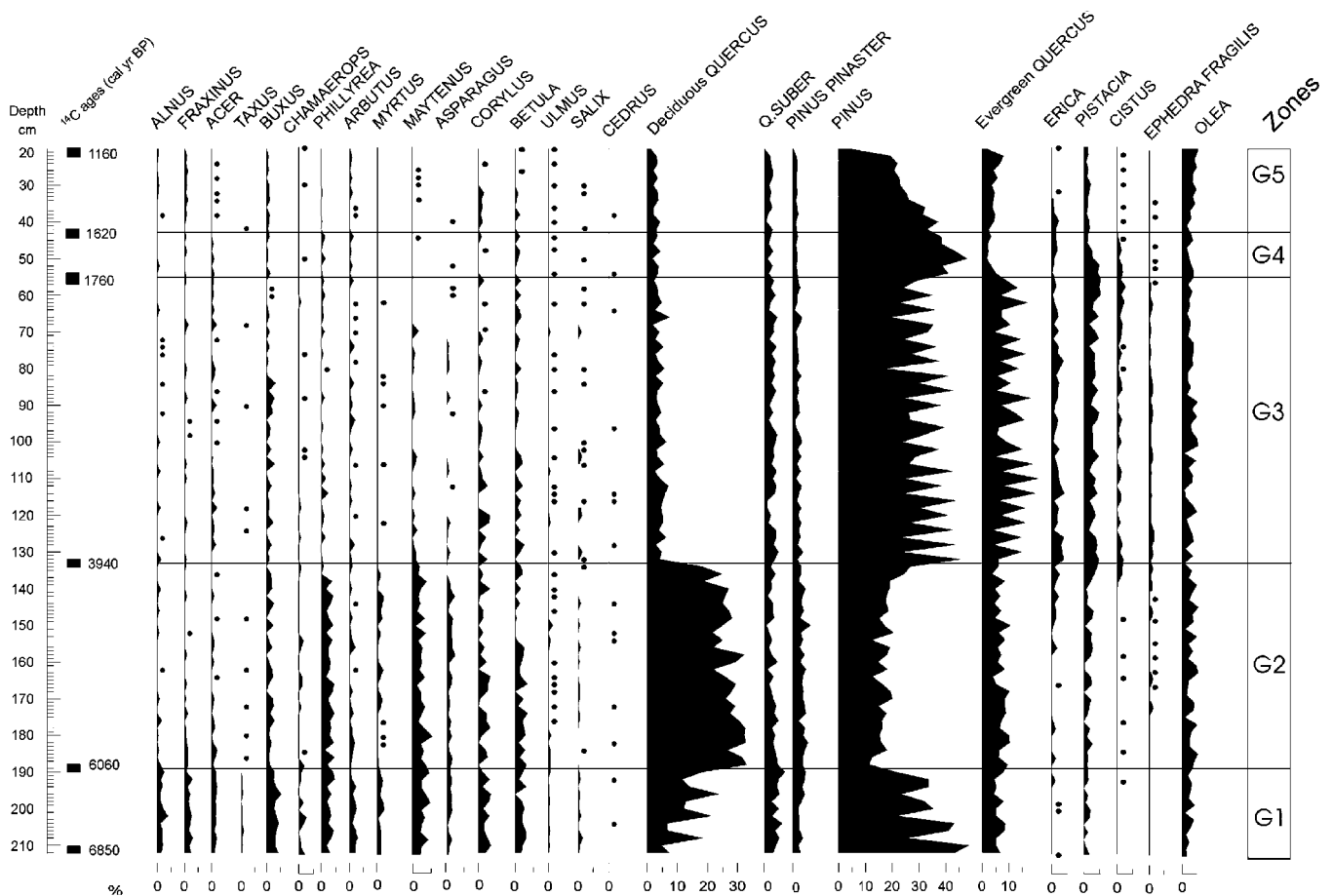
A sediment core was collected from a central point in the dry depression during late summer using a 6 cm diameter piston sampler. Coring was stopped at 212 cm due to the hardness of the sediments (Figure 2). The core was extruded in the field, wrapped in clingfilm, and placed in labelled sections of PVC guttering cut lengthways. Given the predominantly minerogenic character of the sediment, subsamples (*c.* 2 cm thick) were taken contiguously in order to obtain sufficient sediment for pollen, microfossil analysis and radiocarbon dating analyses. No microfossil remains were found throughout the sediment core, which, together with the total absence of peaty layers, suggest that organic matter decomposition and mineralization must have been important throughout the sequence.

Extraction of palynomorphs follows the standard procedure described in Moore *et al.* (1991). Mineral separation with heavy liquid density 2.0 was used for all the samples. Exotic *Lycopodium* tablets of a known concentration were added to calculate pollen concentrations. After chemical and physical treatment, a minimum of 250 pollen grains (excluding non-pollen microfossils) were identified under a light microscope using the reference collection of the Laboratory of Palynology at the

University of Murcia. Most identification criteria for regional pollen types have been given in previous papers (Carrión and van Geel, 1999; Carrión *et al.*, 2000), but several local taxa deserve detail. *Chamaerops*, being the only natural palm species in this area (where it is abundant nowadays), was distinguished from *Phoenix* by its larger and less isodiametric pollen. *Asparagus* pollen is relatively small when contrasted against the commonest size pattern for the Liliaceae, and is characteristically elliptical in polar view. *Lycium* pollen was separated from other Solanaceae types based on its characteristically small apocolpium and striate apertural membrane. *Withania* pollen shows a peculiar foveolate pattern, striate markings being seldom visible across the mesocolpium. *Ziziphus* was discriminated from *Rhamnus* on the basis of its less clearly marked reticulum and less pronounced differences in lumina width towards the centre of the mesocolpium. *Calicotome* pollen is clearly different from *Genista*-type, displaying thicker reticulum muri, rectangular shape in equatorial view and more flattened mesocolpium.

Pollen diagrams (Figures 3–6) were constructed using the computer program PSIMPOLL (Bennett, 2000). Hydroseral pollen (*Apium*, *Typha*, *Cyperaceae*), algal (*Zygnemataceae*), bryophytic (*Riccia*) and fungal spores (*Sordariaceae*) and other non-pollen palynomorphs (*Pseudoschizaea*) were excluded from the pollen sum. The delimitation of Gádor (G) pollen assemblage zone boundaries was obtained from an optimal division of the sequence using the information content criterion (Bennett, 2000). G-zones were based on the values of types that exceeded 2% in any sample, excluding non-pollen palynomorphs and pollen from aquatic and littoral vegetation. A synthetic diagram including selected pollen and microfossil curves, and microscopic charcoal abundance, is shown in Figure 5. In this diagram, ‘thermophytes’ include *Chamaerops*, *Phillyrea*, *Myrtus*, *Maytenus*, *Pistacia*, *Cistus*, *Ephedra fragilis*, *Ziziphus*, *Withania*, *Periploca*, *Osyris* and *Calicotome*. ‘Other mesophytes’ include *Alnus*, *Fraxinus*, *Acer*, *Corylus*, *Betula*, *Ulmus* and *Salix*. ‘Xerophytes’ include *Ephedra fragilis*, *Artemisia*, *Chenopodiaceae*, *Lamiaceae*, *Asphodelus*, *Lygeum*, *Thymelaea*, *Tamarix*, *Euphorbia*, *Aizoaceae*, *Ziziphus* and *Periploca*.

The total number of microcharcoal particles higher than 10  $\mu\text{m}$  and 50  $\mu\text{m}$  (two categories) were counted on the slides prepared for pollen analysis and their concentrations calculated with reference to the *Lycopodium* counts (Figure 5). The number of charcoal particles can be taken as an indication of regional fire occurrence (MacDonald *et al.*, 1991), although it is clear that particles larger than 50  $\mu\text{m}$  must reflect relatively more local burning processes. Because of the many problems inherent to the taphonomy



**Figure 3** Pollen diagram of Gádor for trees and shrubs. Gádor (G) pollen assemblage zone boundaries determined according the information content criterion (Bennett, 2000) for pollen taxa displaying percentages above 2% in Figures 3 and 4. Points indicate pollen frequencies below 2%. Ages in calibrated radiocarbon years BP (CALIB 4.3, Stuiver *et al.*, 1998).

of charcoal in these depositional environments, we cannot provide further detail on the geographic extent of fire events in the Gádor sequence.

## Chronology

The Gádor environmental record spans from *c.* 6850 to 1160 cal. yr BP. The chronology was established on the basis of six radiocarbon dates. Samples consisted of bulk organic sediment, dated by the AMS method where necessary because of low carbon content in the organic extracts (Table 1). Dates were calibrated using CALIB 4.3 (Stuiver *et al.*, 1998). Calibrated ages BP were taken as the midpoint of the 95.4% (2 sigma) probability interval. The probability that the dates are affected by hardwater error cannot be excluded, but the internal consistency of the series provides no evidence that this has in fact occurred (Figure 2). An age-depth model based on interpolated ages between adjacent pairs of dates was obtained (Figure 2). Sediment-accumulation rates are such that 1 cm represents, on average, 35.9 years for zone G1, 37.8 years for zone G2, 27.9 years for zone G3, 11.6 years for zone G4 and 23.0 years for zone G5.

## Pollen stratigraphy and vegetation history

The pollen sequence can allow insights into the vegetation history of the supra and mesomediterranean areas of Sierra de Gádor from *c.* 6850 cal. yr BP to *c.* 1160 cal. yr BP (Figures 3–6). As in topographically similar mountain sites of Spain, the pollen catchment

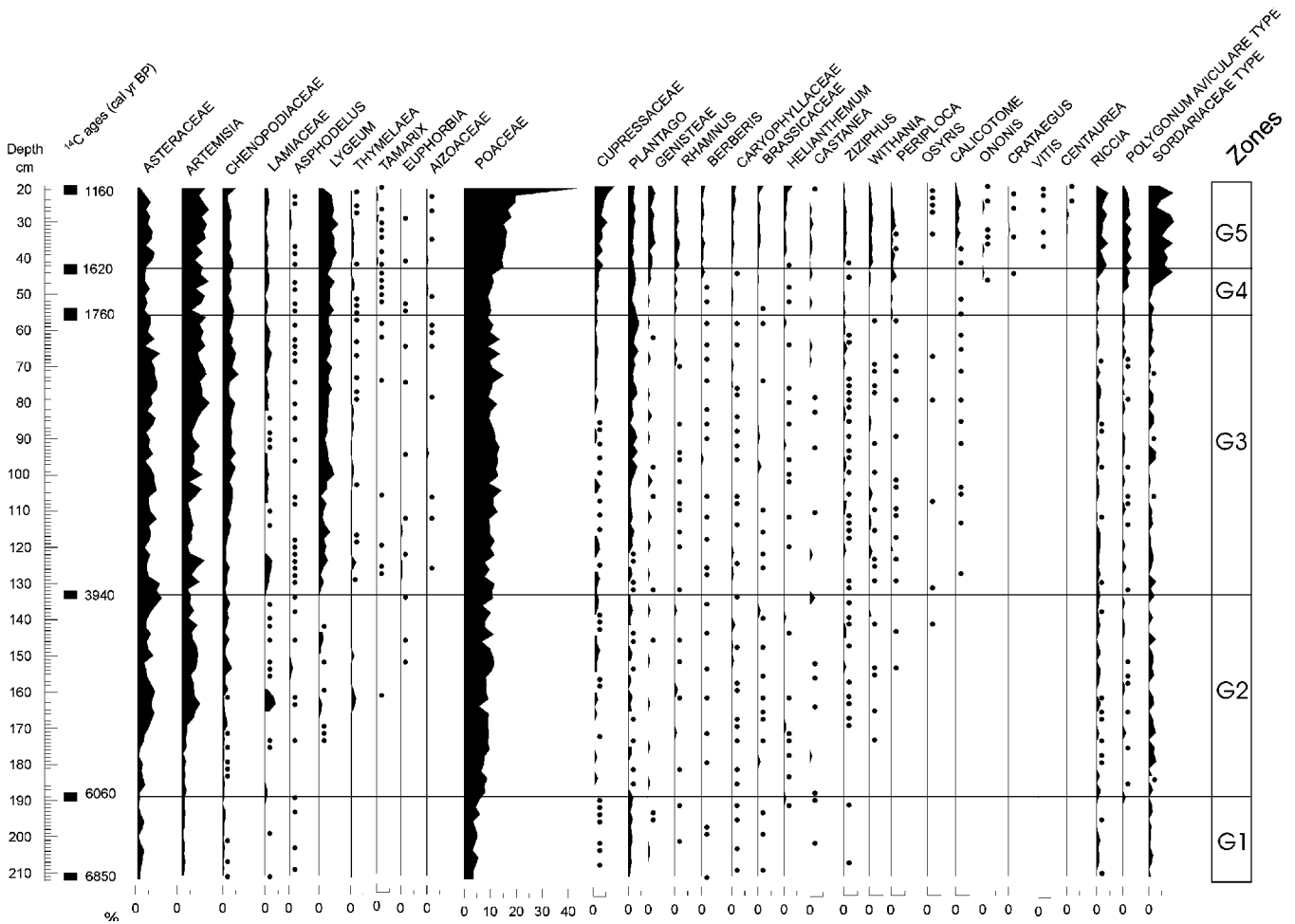
is very likely to include a lower-altitude, thermomediterranean signal caused by ascending airflow along slopes (Vázquez and Peinado, 1993).

### Mid-Holocene pine forests (6850–6060 cal. yr BP)

During the zone G1 (*c.* 6850–6060 cal. yr BP) *Pinus* dominates the pollen spectra, showing three short-lived phases of decline at *c.* 6750, 6550 and 6350 cal. yr BP, which are coetaneous with deciduous *Quercus* peaks. Based on the current ecology of Iberian species, *Pinus nigra* and *Quercus faginea* are, respectively, the most likely pine and oak pollen-producing species at these altitudes in the calcareous Betics (Carrión *et al.*, 2001b), although some contribution of *P. halepensis* from lower-altitude areas and *Q. pyrenaica* from siliceous outcrops is also possible. The zone G1 is also characterized by maximum abundance and diversity of deciduous trees (*Alnus*, *Fraxinus*, *Acer*, *Corylus*, *Betula*, *Ulmus*, *Salix*), and other mesothermophilous taxa (evergreen *Quercus*, *Taxus*, *Chamaerops*, *Phillyrea*, *Arbutus*, *Myrtus*, *Maytenus*, *Asparagus*, *Olea*, *Pistacia*). The thermic element is slightly more abundant during the period from *c.* 6850 to 5200 cal. yr BP, which represents the thermo-mesophytic optimum (Figure 5). This is further supported by the relatively high amounts of *Apium* and *Typha* pollen, and Zygnemataceae spores, suggesting the existence of a semi-permanent body of shallow water during the zone G1 (Figure 5).

### Deciduous oak forests and the onset of xerophyte spread (*c.* 6060–3940 cal. yr BP)

During the zone G2 (*c.* 6060–3940 cal. yr BP), pine forests are replaced by deciduous *Quercus* with components of broadleaved trees such as *Betula*, *Corylus*, *Ulmus* and *Salix*, which remain



**Figure 4** Pollen diagram of Gádor for Poaceae, Cupressaceae, xerophytes, thorny scrub and anthropogenic indicators. G-zone boundaries according to the information content criterion (Bennett, 2000) for pollen taxa displaying percentages above 2% in Figures 3 and 4. Points indicate pollen frequencies below 2%. Ages in calibrated radiocarbon years BP (CALIB 4.3, Stuiver *et al.*, 1998).

predominant until *c.* 4800–4500 cal. yr BP. This zone is also characterized by declines of *Alnus*, *Fraxinus* and *Arbutus*, rises of *Artemisia* and Chenopodiaceae, relative abundance of *Maytenus*, *Phillyrea*, *Buxus*, *Myrtus*, *Asparagus*, *Pistacia* and *Chamaerops*, and the first occurrences of *Withania*, *Lygeum* (*c.* 5600 cal. yr BP), *Ephedra fragilis*, *Thymelaea*, *Tamarix*, *Euphorbia*, *Periploca* and *Osyris*.

#### Pines versus evergreen oaks (*c.* 3940–1760 cal. yr BP)

The zone G3 (*c.* 3940–1760 cal. yr BP) is characterized by rapid alternation of *Pinus* and evergreen *Quercus* at the expense of deciduous *Quercus*, which declines abruptly. Up to 17 peaks of *Pinus* and evergreen *Quercus* are recorded, delaying each other *c.* 50 years on average (Figure 3). The context is xeric, as suggested by raised curves of *Lygeum*, Chenopodiaceae, *Artemisia*, Lamiaceae and *Ephedra fragilis*, higher recurrence of *Asphodelus*, *Thymelaea*, *Tamarix*, *Euphorbia*, *Ziziphus*, *Osyris* and *Withania*, and the first contributions of Aizoaceae and *Calicotome* pollen. While xerophytes progressively increase, the mesophytic element continues its decreasing tendency started in the former zone at *c.* 6000 cal. yr BP (Figure 5). A rise in the *Plantago* curve is also visible, especially after *c.* 3000 cal. yr BP. Additional characteristics of this zone include increases of *Erica*, *Pistacia* and *Cistus*, and episodic occurrences of *Acer*, *Corylus* and *Betula*. Other woods such as *Buxus*, *Phyllirea*, *Maytenus* and *Myrtus* experience conspicuous declines after *c.* 4100–3900 cal. yr BP, with the last taxon disappearing at *c.* 2000 cal. yr BP.

#### Last spread of pine (*c.* 1760–1620 cal. yr BP)

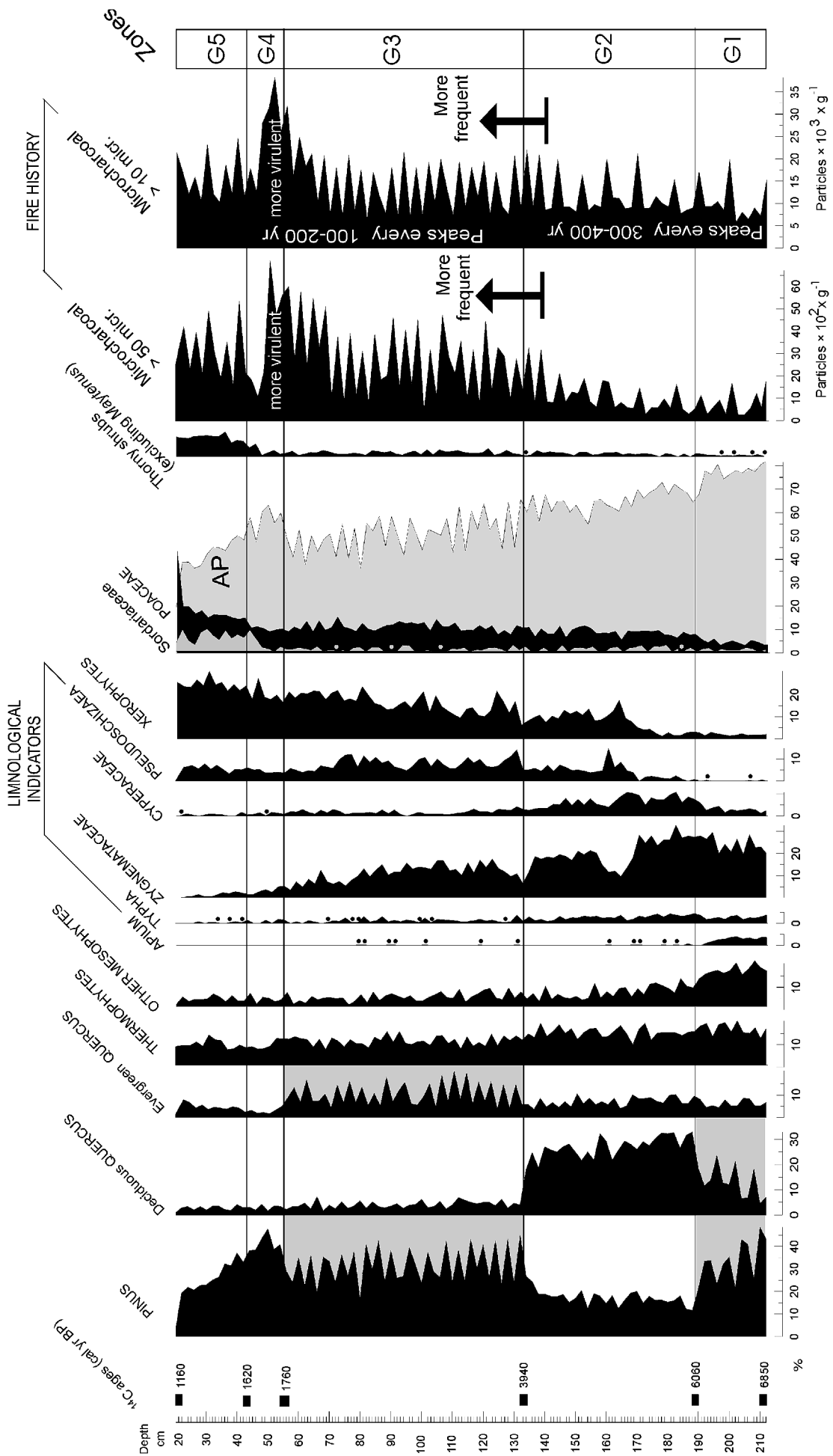
Shortly during the zone G4 (*c.* 1760–1620 cal. yr BP), the *Pinus* curve rises up to a last peak at *c.* 1700 cal. yr BP coinciding with the evergreen *Quercus* sequence minimum (Figure 3). Shortly after this event, *Pinus* starts decreasing, coetaneously with increases of evergreen *Quercus*, Cupressaceae and Poaceae. Thorny scrub of Genisteteae, *Rhamnus*, *Berberis* and *Periploca* show pollen curves after *c.* 1650 cal. yr BP (Figure 4).

#### Recent forest decline (*c.* 1620–1160 cal. yr BP)

Progressively during G5 (*c.* 1620–1160 cal. yr BP), *Pinus* decreases, while Poaceae, Cupressaceae and *Lygeum* become more frequent, showing maxima of about 40%, 7% and 3%, respectively (Figure 4). The Poaceae peak at *c.* 1600 cal. yr BP is preceded by rising curves of Sordariaceae, *Polygonum aviculare*, *Riccia* and Genisteteae (Figures 4 and 5). This zone shows continuous incidence of *Rhamnus*, *Berberis*, *Ononis*, *Ziziphus*, *Periploca*, *Calicotome*, Caryophyllaceae, *Helianthemum* and Brassicaceae, and the first pollen records of *Vitis* at *c.* 1680 cal. yr BP and *Centaurea* at *c.* 1300 cal. yr BP.

#### Controls of vegetation change

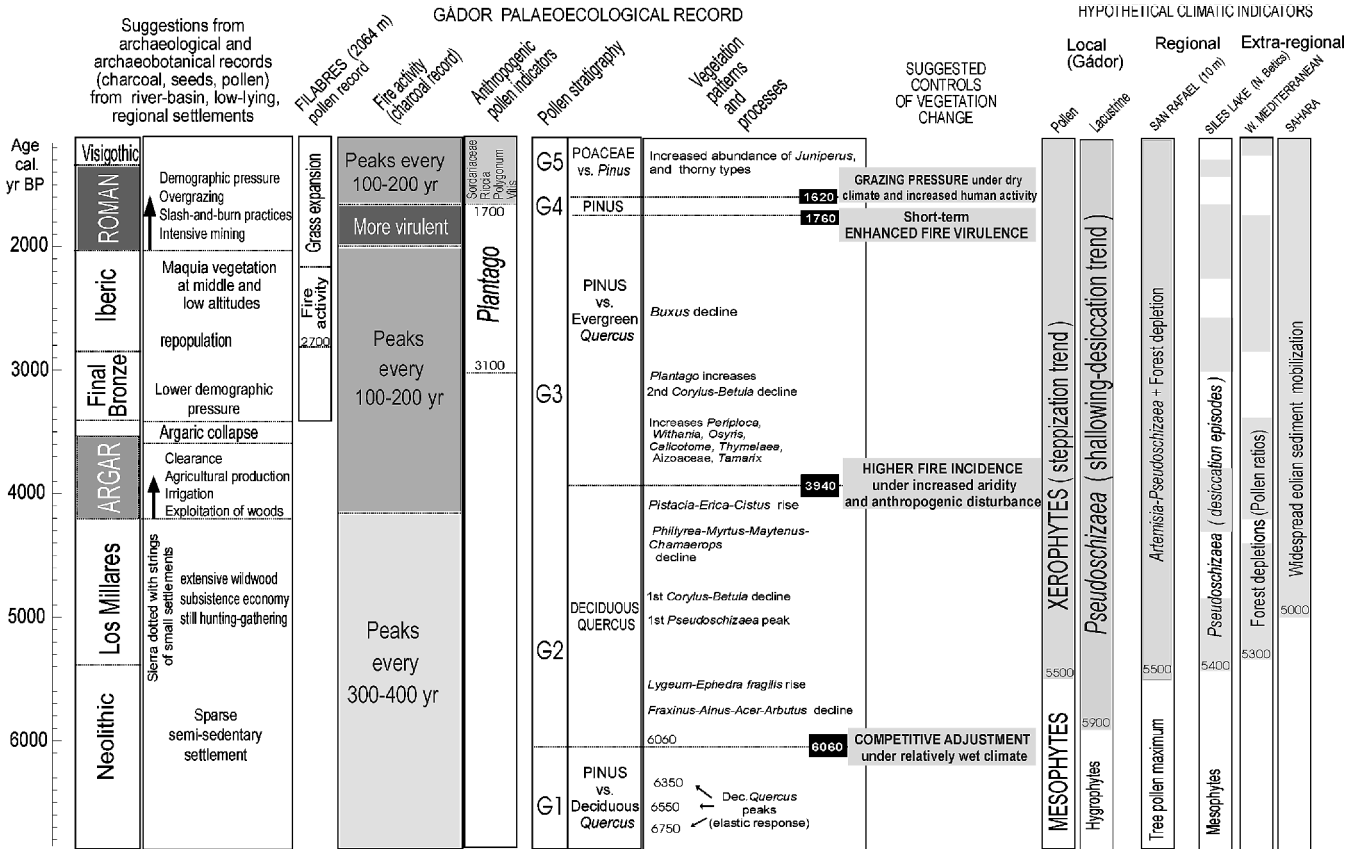
The pollen record of vegetation can be compared with the microfossil record of lacustrine hydrological variation, micro-charcoal indication of fire activity, and palynological record of anthropogenic disturbance to raise a picture of influences for the



**Figure 5** Synthetic pollen diagram and microcharcoal variation in the Gádor sequence. G-zones according to Figures 3 and 4. Points indicate pollen frequencies below 2%. Ages in calibrated radiocarbon years BP (CALIB 4.3, Stuiver *et al.*, 1998).

**Table 1** Radiocarbon age determinations on bulk sediment (organic clay) from the Gádor sequence. Calibrations were carried out following Stuiver *et al.* (1998) (CALIB 4.3). The calibrated age BP was taken as the midpoint of the 95.4% (2 sigma) probability interval

Lab. ref	Depth (cm)	Conventional age ( <sup>14</sup> C yr BP)	Calibrated age range	Calibrated age years BP	Analysis
GrA-17553	20–22	1240 ± 40	1263–1063	1160	AMS
GrA-17556	42–44	1705 ± 40	1705–1532	1620	AMS
GrA-17554	54–57	1825 ± 40	1834–1691	1760	AMS
GrA-17557	132–134	3645 ± 45	3989–3891	3940	AMS
Beta-155407	188–190	5290 ± 70	6202–5921	6060	conventional
Beta-155408	210–212	6020 ± 80	6949–6748	6850	conventional



**Figure 6** Processes and controls of vegetational developments in the Gádor sequence, and correlation with regional and extra-regional environmental records, and with patterns of human settlement. Climatic influences are shaped by competitive interactions, changes in fire regime and grazing pressure.

Gádor environmental sequence (Figure 6). While climate exerted long-term control of the species pool in Gádor, the response of vegetation to climate exhibits important timelags, which suggests the contingency of ecological factors.

**Invasion of pine forests by deciduous oaks**

The invasion of pine forests by deciduous oaks at c. 6060 cal. yr BP is difficult to explain from this pollen record alone. Such a change in the vegetation could be interpreted as an immediate response to increased water availability (Burjachs *et al.*, 1997; Carrión, 2001b). However, pollen of mesophilous species diminishes after the G1–G2 boundary, while Cyperaceae increases with respect to *Apium*, suggesting lowered water levels under enhanced summer drought. In addition, the rises of *Pseudoschizaea* since 5900 cal. yr BP and xerophytic taxa since c. 5500 cal. yr BP suggest that climate was already drier during the onset of zone G2. Another consideration is human disturbance. However, any influence of human activity on the vegetation is improbable since Neolithic settlement was very sparse and only episodically sedentary in the lowland region (Cámalich and Martín, 1999; Nocete, 2001).

Given a formerly drier climate, why did deciduous oak forest not establish before? The occurrence of three episodic expansions of deciduous *Quercus* during G1 (Figure 6) suggests that competition between oaks and pines started several centuries earlier, perhaps at c. 6800 cal. yr BP. In this context, we hypothesize that the establishment of deciduous oak forests was hampered by the resilience of the established pine communities until c. 6060 cal. yr BP, when a permanent invasion took place.

**Decline of deciduous oak forests, anthropogenic disturbance mid- to and late-Holocene aridification trend**

The microcharcoal record (Figure 5) envisages a picture of fire incidence broadly related with hydroclimatic variation. Microcharcoal particles are especially abundant from c. 4200 cal. yr BP, reaching maxima values between c. 2100 and 1600 cal. yr BP. This pathway is not altered taphonomically, that is, there is a good correlation between the curves of the two categories of microcharcoal particles (Figure 5).

From 3940 there was a rapid decline in deciduous oaks with a

corresponding large increase in *Pinus* and evergreen oaks. The factor controlling this dramatic change is most probably fire, and in particular the frequency of the fire events. The most outstanding pattern that emerges from the microfossil charcoal records concerns the frequency of major episodes of fire. On average, these occur each 300–400 years from the bottom up to *c.* 4100–4200 cal. yr BP, then changing to each 100–200 years until the top of the sequence (Figure 5). This major change to higher fire frequency precedes a replacement of deciduous *Quercus* by *Pinus* and evergreen *Quercus*. This picture of disturbance-mediated invasion agrees with current ecological studies that describe the vulnerability of deciduous oak forests to recurrent fire events (Chuvieco, 1999).

It is interesting that this change towards more sclerophyllous vegetation occurs during the Prehistoric Argaric period (*c.* 4250–3600–3500 cal. yr BP) (Hernando, 1999). Archaeological literature tends to support enhanced intensity of human impacts in the region during the former Los Millares period (*c.* 5400–4250 cal. yr BP), including the occurrence of lowland and midland forest destruction and matorralization (Lull, 1983; Chapman, 1991). It has been postulated, for example, that a higher frequency of seeds, grinding stones and other macrolithic tools per volume of excavated deposit in Argaric settlements would point to an increase in agricultural production during the Los Millares phase (Castro *et al.*, 1999). Palaeoanthracological evidence has been indicated to testify to wider clearance, increased exploitation of woody species, and advanced pasturage (Rodríguez-Ariza, 1992; 1995), while pollen analyses in open-site excavation beds from river valleys show increased heliophytes, sparser pines and anthropogenic indicators (*Cerealia*, *Plantago*, *Polygonum*, *Vitis*) (López, 1988; Davis and Mariscal, 1994). Furthermore, the Argaric termination, in sharp contact with an ulterior, more dispersed Final Bronze pattern of settlement (*c.* 3500–2900 cal. yr BP), is viewed as socio-economic collapse, an anthropogenically induced environmental catastrophe that could have taken place as fast as within 30 years (Castro *et al.*, 1999) (Figure 6).

From the archaeological and archaeobotanical records, the fire-induced replacement of deciduous oak forest in Gádor could plausibly be linked to human activities. However, the association of fire and a drier climate is also supported, in this case by the significant positive correlations between microcharcoal and *Artemisia*, xerophytes and *Pseudoschizaea*, and the significant negative correlations between microcharcoal and deciduous *Quercus* and other mesophytes (Table 2). A hypothesis of broad climatic influence must therefore be outlined, although this might be better assessed through a multisite study.

Even more pronounced than pine forests of stage G1, deciduous oak forests would have demonstrated little change to climatic

change. However, if we consider the curves of Asteraceae, *Lygeum*, *Artemisia*, Chenopodiaceae, *Ephedra fragilis*, Lamiaceae and *Thymelaea* in the context of the variation of xerophytes versus mesophytes, the onset of arid conditions during *c.* 5500–5100 cal. yr BP are visible. This interpretation is further supported by evidence from the palaeolimnological record. Increased *Pseudoschizaea* at the expense of Zygnetaceae and Cyperaceae is likely to reflect progressively longer seasonal desiccation since *c.* 5900 cal. yr BP. *Pseudoschizaea* peaks at *c.* 5000, 3800 and 2300 cal. yr BP, which parallels xerophytic maxima at *c.* 5100, 3700 and 2300 cal. yr BP (Figure 5).

Correlation with regional and extraregional climate proxies strengthens the climatic argument (Figure 6). Regional vegetation during the mid-Holocene attains a mesophytic optimum, maximum forest development and xerophytic minimum. In contrast, the late Holocene emerges as a generally dry, pyrophytic period of pine forests and spread of xerophytic communities, under the context of dry spells, and shallowing and desiccation of lakes, cessation of peat accumulation and diminishing soil moisture in valley bottoms (Carrión, 2001a). This picture is visible in the palaeoecological records of San Rafael, Antas, and Roquetas de Mar in lowland coastal Almería (Figure 1) (Yll *et al.*, 1994; Pantaleón-Cano *et al.*, 2003), in the most continental region of the Segura Mountains (Carrión *et al.*, 2001a; 2001b; Carrión, 2002b), and in a number of western Mediterranean sites (Valero and González, 1999; Jalut *et al.*, 2000). A return to widespread aeolian sediment mobilization after 5000 cal. yr BP is recorded in the Sahara (Swezey, 2001). Given this long-term climatic influence, deciduous oak forests in Sierra de Gádor would have withstood growing aridification beyond a millennium, becoming replaced only after fire disturbance. As discussed above, to establish whether these fires were provoked by man, climate or both is largely non-testable.

### Competitive interactions between pines and evergreen oaks

Since there is clear-cut correlation between *Pinus* increases and evergreen *Quercus* decreases throughout the zone G3, it is suggested that abrupt oscillations of both taxa do reflect a competitive balance changed periodically, plausibly by fire disturbance. Lags between the shifts of *Pinus* and evergreen *Quercus* average 50 years approximately. The period of highest microcharcoal concentrations starts at *c.* 2050–2100 cal. yr BP, just before the G3–G4 transition (*c.* 1760 cal. yr BP) towards longer persistence of *Pinus* (Figure 5). The Pearson coefficient shows higher correlation of charcoal with *Pinus* than evergreen *Quercus* (Table 2).

Hence, it appears that fire events during the stage G3 favoured a rapid replacement between pines and evergreen oaks, while

**Table 2** Pearson correlation coefficient for pollen taxa percentage values and microcharcoal concentration at Gádor (see the methods section of the text for definitions of 'Other mesophytes' and 'Xerophytes')

	Dec. <i>Quercus</i>	Ev. <i>Quercus</i>	<i>Q. suber</i>	<i>Pinus</i>	<i>P. pinaster</i>	<i>Artemisia</i>	Other mesophytes	Xerophytes	<i>Pseudoschizaea</i>
Ev. <i>Quercus</i>	-0.306**								
<i>Q. suber</i>	-			+0.298**	+0.278**		+0.250*		
<i>Pinus</i>	-0.636**								
<i>P. pinaster</i>	+0.607**			-0.239*					
<i>Artemisia</i>	-0.579**			+0.205*	-0.537**		-0.667**		
Other mesophytes	+0.902**	-0.284**		-0.380**	+0.655**				
Xerophytes	-0.645**			+0.268**	-0.574**	+0.954**	-0.717**		
<i>Pseudoschizaea</i>	-0.561**	+0.234*			-0.422**	+0.498**	-0.689**	+0.518**	
Microcharcoal	-0.561**			+0.340**	-0.480**	+0.469**	-0.593**	+0.515**	+0.356**

\*Meaningful at the 0.05 level.

\*\*Meaningful at the 0.01 level.



increasing fire intensity would have provoked an ulterior stage of pine prevalence during the stage G4 (Figure 6). Fire appears as a regional phenomenon at this time, as suggested in the late-Holocene pollen sequence of the Cañada Larga peat bog (1890 m a.s.l.) in the nearby Sierra de Filabres-Baza (Figure 1), which shows grassland spread since *c.* 2400 cal. yr BP preceded by increases of fire occurrence at *c.* 2700 cal. yr BP (Riera *et al.*, 1995) (Figure 6).

### Pastoralism and the influence of human activities during Roman times: the onset of recent forest depletion

The coetaneous records of sordariaceous fungal spores and *Riccia* spores, and *Polygonum aviculare* pollen, are probably indicative of heavy grazing in the lake catchment since *c.* 1700–1650 cal. yr BP, prior to the grass expansion/forest decline characteristics of zone G5 (Figures 4–6). Sordariaceae are often coprophilous (Lundqvist, 1972). *Riccia* species grow abundantly in the emergent surfaces of regional mountain water bodies within areas of intense grazing. *Polygonum aviculare* can also be related with pastoralism (Carrión and van Geel, 1999; Carrión, 2002b).

The curves and/or continuous occurrences of Genistae (cf. *Echinospartum*, *Erinacea*, *Genista*, *Ulex*), *Berberis hispanica*, *Crataegus monogyna*, *Rhamnus* (cf. *R. saxatilis*), Caryophyllaceae (cf. *Dianthus pungens*), Brassicaceae (cf. *Vella*, *Hormatophylla*) and *Ononis* (cf. *aragonensis*), in phase with Poaceae and Sordariaceae-*Riccia*-*Polygonum* assemblages, suggest expansion of thorny scrub following historical forest clearance and overgrazing on the high-elevation grasslands during the stage G5. Pastoralism would have even occurred extensively in low-elevation areas of Sierra de Gádor, as suggested by the coetaneous spread of thermophilous spiny shrubs such as *Ziziphus lotus*, *Withania frutescens*, *Periploca angustifolia* and *Calicotome intermedia*.

This influential pattern is further supported by charcoal and seed remains of *Olea*, *Vitis* and heliophytic taxa in the excavation sites of the slopes (Rodríguez-Ariza, 1995; Buxó, 1997), and archaeological evidences of great demographic pressure during Roman times (Cámalich and Martín, 1999). This anthropogenic phase still occurs in Gádor with high fire activity, which may now be more clearly connected with slash-and-burn practices, especially from *c.* 1800 onwards, when the charcoal patterns become more irregular (Figures 5–6).

To finish, we emphasize that, in high- and mid-elevation areas of Sierra de Gádor, human activities may have taken place well before the occurrence of conventional anthropogenic pollen indicators. Although arable agriculture (*Vitis*, *Centaurea*?), and arboriculture (e.g., *Castanea*) are noticed very recently (Figure 4), grazing by flock animals may have occurred in Sierra de Gádor many thousands of years before, but left no traces in the landscape. One should not expect agricultural practices to be important at the study-site altitude. In this respect, it is worth stressing that, although less abundant than during the zones G4 and G5, spores of Sordariaceae and *Riccia* do occur since the beginning of the pollen sequence (Figure 4), while *Plantago*, although not being an unquestionable anthropogenic indicator in southern Spain (Pantaleón-Cano *et al.*, 2003), rises slightly since *c.* 3100 cal. yr BP.

### Final remarks and conclusion

We have provided a reconstruction of the local vegetation history of Sierra de Gádor during the period from *c.* 6850 to 1160 cal. yr BP, and a discussion on the controls of vegetation change based on palaeoecological evidences of fire occurrence, human activity and climatic change. We can now shed light on the specific topics of controversy posed in the introduction.

(1) The Sierra de Gádor has certainly seen stages of forest during the Holocene. Unfortunately, the pollen sequence is interrupted at *c.* 1160 cal. yr BP, and we cannot inform about environmental changes that occurred thereafter. However, it is clear that, one millennium ago, there were present several taxa that are now extinct in Sierra de Gádor, such as *Taxus baccata*, *Corylus avellana*, *Betula celtiberica*, *Alnus glutinosa* and *Myrtus communis*. Others, like *Arbutus unedo*, *Buxus sempervirens*, *B. balearica* and *Acer granatense*, have become extremely rare. In addition, historical records and toponimic information suggest there was extensive brush and pine and oak forest cover in several mountain systems of Almería only three centuries ago (Gómez-Cruz, 1991; García Latorre and García Latorre, 1996). Sierra de Gádor became one of the world's chief lead producers since 1822, which would have produced a major impact on tree cover (Grove and Rackham, 2001). The current treeless situation of Sierra de Gádor has been shaped relatively recently.

(2) This new palaeoecological record adds to previous pollen sequences in lowland eastern Andalusia to suggest a general aridification trend since the mid-Holocene (*c.* 5900–5500 cal. yr BP). This conclusion is supported by both xerophyte pollen and microfossil indicators of lake shallowing and desiccation. Extra-regional correlation with north African and other Mediterranean areas is hampered by insufficient chronological control.

(3) It is clear that fire frequency has been a major contingency for the tempo of changes in the forest dominant in Sierra de Gádor. However, both forest decline and replacement of mesophytic by more xeric Mediterranean vegetation are influenced by climatic change, in particular growing aridity during the second half of the Holocene. So, fire events, while being critical on the tempo of vegetation change, remain compatible with the determinism of the climatic system.

(4) Modern vegetation in Sierra de Gádor cannot be adequately understood in absence of the palaeorecord of biotic changes, fire occurrence and anthropogenic disturbance. Several species are relics of the mid-Holocene mesic forests. Over the last two millennia, natural and/or human-set fires, combined with overgrazing, would have pushed mountain forests over a threshold leading to the spread of grassland, thorny scrub, junipers and nitrophilous communities. The Gádor sequence is also pertinent to discern the ecological affinities of several species such as *Maytenus europaeus*, *Chamaerops humilis*, *Myrtus communis*, *Asparagus*, *Phillyrea* (cf. *P. media*) and *Buxus sempervirens/balearica*, which behaved as mesophytes by reaching a maximum during the mid-Holocene (Figure 3). These taxa have declined in Gádor since *c.* 4000 yr BP, and their variation does not correlate that of the xerothermic scrub of *Ziziphus*, *Withania*, *Periploca* and *Calicotome*, which have been phytosociologically related (Peinado *et al.*, 1992). Rather, our findings give support to the ideas by Mota *et al.* (1996) and Cabezudo and Pérez-Latorre (2001) about the importance of the palaeotropical element in the overall composition of the pre-anthropogenic shrub communities of the southeastern coastal mountains.

(5) The magnitude of human impacts on vegetation during the Holocene has been highly variable over southeastern Spain, starting earlier in low-elevation areas and river basins. It seems to us that the environmental problem has not been sufficiently bounded in archaeo-ecological discussions. The evidential basis on which environmental inference has been approached is at best ambiguous and at worst simply not the type of data that could provide reliable answers. It is here where palaeoecological records might hope to provide a remedy. However, archaeological pollen and charcoal will tend to reflect local landscapes, and the own Gádor environmental history, based on a single core, cannot be a panacea. The idea of Argaric collapse as being related to resource exhaust under enhanced aridity is just a hypothesis that needs to be better tested. The problem is one where the spatial scale reaches paramount

importance and, thus, the extent of human impacts in the region can be only adequately approached on the basis of specifically orientated projects.

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