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A long-term perspective on biomass burning in the Serra da Estrela, Portugal

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Abstract

Fire is currently perceived as a major threat to ecosystems and biodiversity in the mountains of the Mediterranean region. Portugal's highest mountain range, the Serra da Estrela, is one of the country's most important protected areas and also the most fire-prone. We present a ~14000-year fire history based on microscopic charred particles in an infilled glacial lake to better understand the antiquity of biomass burning and its effects on Mediterranean vegetation at the Atlantic margin. Results indicate the continuous occurrence of fire in the Serra da Estrela over the period of the record. Two periods of increased fire activity – around 12000–11000 calendar years before the present (cal. a BP) and 3500–2500 cal. a BP – were accompanied by major vegetation changes and followed by long periods of vegetation stabilisation. Cross-correlation analyses reveal that post-fire succession consistently began with herbaceous vegetation, followed by forest and shrubland stages. Past successional trends were often markedly different to those observed at present. Holocene climatic changes, including shifts in the North Atlantic Oscillation, played a pivotal role in the vegetation development and fire history of the Serra da Estrela. In the late Holocene, human use of fire became a major agent of vegetation change, accelerating the Holocene decline of forests.

Keywords

Fire history; Iberian Peninsula; Late Quaternary; Mediterranean; palaeoecology

1. Introduction

Fire is intrinsically linked to Mediterranean-type ecosystems. Mediterranean plant species present a variety of adaptations to frequent fire, having insulating bark, fire-enhanced germination or the ability to resprout after burning (Grove and Rackham, 2001; Allen, 2008). At the same time, uncontrolled fires in Mediterranean vegetation may have catastrophic consequences for human health, economies, natural resources and life itself, constituting major challenges for management authorities in fire-prone regions worldwide (Bowman et al., 2011).

Fire is currently a major management issue in Portugal, as the country has the highest density of ignitions in Southern Europe (Moreira et al., 2010). Fires are especially frequent and widespread in the country’s protected areas and are therefore considered to pose a major threat to nature conservation and biodiversity (ICN, 2006). The frequency of large fires in these areas appears to have increased during the last few decades, a trend linked, in part, to abandonment of rural land and subsequent accumulation of fuel (Moreira et al., 2010; Jansen, 2011).

Although fire is undoubtedly one of humankind's most ancient tools, our collective fear of wildfires and their capacity for destruction has promoted an attitude of repulsion rather than of understanding. Bowman et al. (2011) argue that we need to know much more about the human dimension of fire regimes, both now and in the past, to reduce the damage caused by fires. The importance of a long-term perspective is particularly great when it comes to fire and the conservation of biodiversity (Tinner and Kaltenrieder, 2005; Colombaroli et al., 2007, 2009; Gil-Romera et al., 2010). High-diversity ecosystems are the product of long periods of evolution and diversification in response to climate, soils, disturbances and plant–animal interactions. The histories of fire and biodiversity in fire-prone ecosystems may be strongly intertwined.

Europe's mountains have been identified as environments with an elevated risk of losing biodiversity in the face of predicted climate change (Gitay et al., 2002). This risk could be especially high in the Mediterranean region, which is considered a "hyper-hot" hotspot for plant diversity (Myers et al., 2000; Sanz-Elorza et al., 2003). In this paper, we present a record of microscopic charred particles from lake sediments from the Serra da Estrela mountain range, Portugal. The Serra da Estrela is a Natural Park and is currently the most fire-prone natural area in Portugal (ICN, 2006). Our aims are to: i) determine the antiquity of fires in the ecosystems of the Serra da Estrela, ii) compare the charcoal record to pollen data to gauge fire's effects on the vegetation, and iii) examine how relationships between fire, climate and humans developed through time.

2. Regional setting

The Serra da Estrela is an isolated granitic massif of the Central Iberian Cordillera located in the centre-north of Portugal. Its peak, Torre, is the highest point in continental

Portugal (1993 m). The range is formed of Hercynian granites which intruded through the surrounding Precambrian–Cambrian schist/greywacke sedimentary complex. Subsequent tectonic movements and erosion have shaped the range, which, broadly speaking, consists of two NE–SW-oriented plateaux, separated by the U-shaped Zêzere Valley and surrounded by deeply incised glacial and fluvial valleys (Fig. 1; ICNB, 2007). Soils on the granitic plateaux are lithosols (rankers), with more developed cambisols occurring over schist bedrock at lower elevations.

The climate of the Serra da Estrela is Mediterranean, transitional between hot-summer and warm-summer types (Csa and Csb in the Köppen classification: AEMet and IM, 2011). The height of the range, combined with its uninterrupted interception of westerly airstreams, lend the Serra da Estrela's climate a distinctly Atlantic character. At Penhas da Saúde (1383 m), annual precipitation averages 2900 mm (ICNB, 2007). Average annual temperature at the same elevation is 9.2ºC (AEMet and IM, 2011), dropping to 3–4ºC at the highest elevations (Mora et al., 2001). Snow cover on the high plateaux may persist for up to 90 days (ICNB, 2007).

The Serra da Estrela, on account of its unique physical and biological characteristics, constitutes a distinct biogeographical area within the Mediterranean region – the *Sector Estrelense* of Costa et al. (1998). Three bioclimatic belts are distinguished (Pinto da Silva and Teles, 1999; ICNB, 2007): 1) a **meso-mediterranean** zone below 900 m elevation, in which remnant forests of oak (*Quercus rotundifolia, Q. suber* and *Q. pyrenaica*) and Portuguese laurel (*Prunus lusitanica*) exist alongside maquis vegetation, agricultural fields, vineyards, olive groves and extensive plantations of *Pinus pinaster*; a **supra-mediterranean** belt between 900 and 1600 m, with remnant woods of *Quercus pyrenaica*, chestnut groves, shrublands and some rye cultivation; and 3) an **oro-mediterranean** belt above 1600 m, in which juniper scrub, mat-grass lawns, heaths, pastures and aquatic communities are found (for further details, see Costa et al., 1998; Pinto da Silva and Teles, 1999). The vascular plant flora of the Serra da Estrela is diverse and includes some 7 endemics, 27 protected species and 92 species of conservation interest; of these, 8 species are considered to be at imminent risk of local extinction (Costa et al., 1998; Pinto da Silva and Teles, 1999; ICNB, 2007).

The vegetation history of the Serra da Estrela during the Late-Glacial and Holocene has been relatively well studied through pollen analysis (Romariz, 1950; Janssen and Woldringh, 1981; van den Brink and Janssen, 1985; van der Knaap and van Leeuwen, 1995, 1997). The latter authors produced a detailed, 14800-year vegetation history from the Charco da Candieira site, based on analysis of 301 pollen samples and 30 radiocarbon dates. Six phases of vegetation development were distinguished:

LG: 14800 to 11600 calendar years before the present (cal. a BP) – Alternation between steppic vegetation and open forests in response to Late-Glacial climatic oscillations;

A: 11600 to 9500 cal. a BP – Development of xerothemic oak-dominated forests under warm, dry climates and in the absence of human influence;

B: 9500 to 6400 cal. a BP – Spread of mesothermic forests under a cooler, moister climate, with little human influence;

C: 6400 to 3400 cal. a BP – Forest dynamics affected by grazing and deforestation;

D: 3400 to 970 cal. a BP – Large-scale deforestation, followed by partial forest recovery;

E: 970 to -40 cal. a BP – Complete deforestation of the Serra da Estrela, accompanied by soil erosion, grazing, burning, agriculture and silviculture.

Biomass burning is acknowledged as an important cause of Holocene vegetation changes in the Serra da Estrela, as suggested by the presence of macroscopic charcoal layers in soil profiles (Braun-Blanquet et al., 1952) and sediments from peatbogs around Lagoa Comprida (van den Brink and Janssen, 1985). The latter were dated to approximately 3500 cal. a BP, corresponding to the period of large-scale deforestation (van den Brink and Janssen, 1985). However, the spatial scale of the fires represented by the charcoal layers could be much smaller than the scale of the vegetation changes, as macroscopic charcoal particles are considered to represent local fires (Clark and Royall, 1995).

3. Material and methods

Charco da Candieira (or Lagoa da Candeeira) is an infilled lake situated in a hanging valley on the western side of the Zêzere Valley (40º20'37"N, 7º34'41"W). At 1400 m elevation, it is the lowest of the glacial lakes of the Serra da Estrela. The site covers approximately 0.8 hectares and its surface dries completely in summer (Costa et al., 2004). The lake basin is considered to have been degraded by rye cultivation and grazing until recently (Costa et al., 2004) and is today surrounded by rocky slopes and scrub vegetation (with a prevalence of *Genista, Cytisus,* and *Erica* species, *Calluna vulgaris* and *Juniperus communis*). A complete list of plant species in and around the site is given by van der Knaap and van Leeuwen (1995).

The samples analysed in the present paper were collected in 1985 and subjected to detailed palynological analysis (van der Knaap and van Leeuwen, 1995, 1997). Subsequently the sample residues (in silicone oil) were archived in glass vials at Utrecht University, the Netherlands. In 2011, we re-mounted the residues of all 293 samples from the central lake core and counted microscopic charred particles at 400× magnification on a Leitz Dialux microscope (we were unable to find the 8 '*Molinia* tussock' samples analysed by van der Knaap and van Leeuwen, 1995). Particles were identified according standard criteria and grouped into two size-classes: 5–50 µm and 50–250 µm (see Blackford, 2000).

In quantifying microscopic charcoal, Finsinger and Tinner (2005) demonstrated that counting 200 items (charcoal particles and *Lycopodium* marker spores) is sufficient to obtain a result with a <5% error if the ratio between charcoal and marker spores lies between 0.1 and 0.91. Due to the enormous quantity of charred particles in the Candieira material (ratio between 7 and 1460), we adapted this method by counting the total number of charcoal particles in each field-of-view until a total of at least 200 particles was reached; thereafter only fields-of-view and *Lycopodium* marker spores were counted to reach a minimum of 50 spores. The number of fields-of-view was then used to correct the charcoal counts and calculate charcoal concentrations (particles cm^{-3}).

Prior to further analysis, a new age–depth model was produced for the Candieira record using a Bayesian approach implemented in OxCal 4.1.7 (Markov chain Monte-Carlo analysis: Bronk Ramsey, 2009) and based on the previously published radiocarbon dates (van der Knaap and van Leeuwen, 1995, 1997). Model acceptability was assessed using A_{model} and $A_{overall}$ statistics (Bronk Ramsey, 2009).

Temporal relationships between charcoal and pollen abundance were analysed using time-series analysis (Green, 1981), implemented in the program PAST 2.11 (Hammer et al., 2001). Pollen proportions, charcoal concentrations and pollen and charcoal accumulation rates were re-sampled at 48-year intervals (median sample resolution), detrended using a Lowess smoother and the residuals cross-correlated. Sixteen of the most common and indicative pollen taxa were analysed during four periods of relatively constant sediment accumulation: 1500–3500, 4500–6500, 7500–9500 and 11500–13500 cal. a BP.

Multivariate numerical analysis of the charcoal and pollen data was performed using Principal Components Analysis (PCA) and Detrended Correspondence Analysis (DCA) in the program PC-Ord (McCune and Mefford, 1999). Stratigraphic diagrams were drawn in Tilia 1.7.16 (Grimm, 1992).

4. Results

The age–depth model for the Candieira sequence is shown in Fig. 2. This model has acceptability indices of 63.5% (A_{model}) and 63.3% ($A_{overall}$). Estimated errors (1σ) range from 36 to 119 years for individual interpolated samples, with an average of 75 years for the entire sequence. The model is very similar to the previously published models (van der Knaap and van Leeuwen, 1995, 1997) and places the pollen-derived Pleistocene–Holocene boundary (950 cm depth) between 12067 and 11703 cal. a BP (2σ). Age ranges for each of the pollen zones are given in Fig. 2.

Charcoal concentrations are very high throughout the Candieira record (Fig. 3), averaging 11 million particles per cm^3 of sediment and reaching peaks of up to 59 million. Considering that all of the data included in the global charcoal analysis of Power et al. (2008) had less than 10 million particles per cm^3 of sediment, the Candieira values are exceptionally high. The highest total charcoal concentrations and accumulation rates are found in the pollen zone representing large-scale deforestation (D, Fig. 3), while the lowest values are associated with the Late-Glacial (LG, Fig. 3).

Pollen percentages most correlated with total charcoal concentrations over the entire record include *Erica arborea* (*r*: 0.58), *E. australis*-type (0.56), Poaceae (0.56), *Plantago lanceolata*-type (0.52) and *Genista*-type (0.48). *Pinus* pollen, which is most abundant in Late-Glacial sediments, is negatively correlated with charcoal (*r*: -0.53). If the Holocene section of the record is considered alone, the strongest positive correlates with charcoal are taxa representing herbs and shrubs (e.g. Poaceae, Asteraceae, *Erica, Genista*-type and *Plantago lanceolata*-type), while the strongest negative correlates are arboreal taxa (e.g. *Quercus, Salix, Taxus* and *Pinus*).

Candieira's microcharcoal assemblages are clearly dominated by smaller charcoal particles (5–50μm). Larger particles (50–250μm) constitute only a small proportion of the assemblages (average 4%), but exhibit a slightly different temporal trend to the smaller particles. Peak accumulations of larger charcoal particles, with more than 10^5 particles per cm^3 per year, occur at approx. 11400, 11300, 8100, 7300, 4550, 4450, 1550, 1300 and 1100 cal. a BP.

Time-series analysis of pollen and charcoal accumulation rates produced similar results for different taxa, suggesting interdependence between the variables. Fine-scale variations in sedimentation rates could explain this pattern (Colombaroli et al., 2009). Cross-correlations of pollen percentages and charcoal concentrations are less affected by sedimentation rates and a selection of these is shown in Fig. 4.

During the earliest period analysed (13500–11500 cal. a BP), Poaceae is positively correlated with charcoal at zero lags, indicative of an immediate response. Grasses are then succeeded by *Genista*-type, *Calluna* and *Alnus* at 1 lag (approx. 50 years after a charcoal peak). *Juniperus* and *Genista*-type exhibit positive responses at 5 lags (approx. 250 years). *Pinus* responds positively at 11 lags (approx. 550 years).

From 9500–7500 cal. a BP, upland herbs respond positively to charcoal at 1 lag, followed by *Alnus* at 2–3 lags, with *Betula* (not shown) at 2 lags. *Quercus*, which dominates the pollen spectra of this period, responds positively to charcoal at 5–6 lags and Poaceae follows at 7–8 lags, accompanied by *Genista*-type. Herbs, *Erica, Calluna* and *Alnus* respond collectively at 10–12 lags and *Quercus* exhibits a strong positive response at 14–16 lags.

From 6500–4500 cal. a BP, upland herbs exhibit a strong positive response to charcoal at zero lags, mirrored by the strong negative responses of *Quercus* and *Cerealia*-type. *Erica* and Poaceae show significant negative responses at 1 lag, while *Pinus* and *Betula* both produce significant positive responses at 1–3 lags. An inversion of this pattern is observed after 6 lags (approx. 300 years), following a positive *Genista*-type response at 5 lags. A strong *Juniperus* response appears at 13 lags.

From 3500–1500 cal. a BP, *Pinus* and *Quercus* no longer exhibit significant responses to charcoal over the first 10 lags, whereas upland herbs and *Cerealia*-type show a significant positive response at 1–2 lags. As in the previous period, *Erica* and Poaceae respond negatively to charcoal at 1 and 2 lags respectively. *Alnus* has a significant positive response at 3–5 lags, followed by *Juniperus* and *Pteridium* at 6 lags (not shown), *Calluna* and *Genista*-type at 7–8 lags and Poaceae at 8–9 lags.

Both PCA and DCA produced similar results on the first axis, as shown in Fig. 6. DCA axis 1 is influenced by the relationship between negatively correlated taxa such as *Erica, Alnus, Ranunculus, Plantago lanceolata*-type and *Pteridium* on the one hand, and positively correlated taxa like *Pinus, Artemisia, Calluna, Juniperus* and Chenopodiaceae on the other. PCA axis 1 is negatively correlated with *Quercus*, *Pteridium* and *Taxus,* while positive correlates are almost identical to those of the DCA.

5. Discussion

5.1. Problems of interpretation

Despite the clear evidence for repeated fires in the Candieira record, some important uncertainties must be taken into account. Firstly, the source-area of microscopic charcoal is difficult to define and may amount to hundreds to thousands of metres, depending on particle size, wind velocity and site characteristics (Whitlock and Larsen, 2001). It is difficult to say whether the fires recorded in the Candieira sediments represent local fires in the lake catchment or more regional events. The prevalence of small particles (<50μm) suggests that most of the charcoal derives from regional fires, although over-representation of fine particles can also be caused by catchment processes and sample preparation. Secondly, the transition from lake sediment to wetland sediment at 175-cm depth adds further uncertainty to the source of the charcoal. Lake sediments probably incorporate a greater regional component than wetland sediments due to mixing processes in the water column. Wetland vegetation may directly contribute charcoal to the sediment when the vegetation is burnt and may also trap charred particles amongst its foliage (Tolonen, 1986; Whitlock and Larsen, 2001). Increases in sediment bulk density (Fig. 3) could be an indication of erosion events, which have the potential to introduce secondary charcoal into the sedimentary record. Finally, some fire peaks may have been missed because sediment sampling was not contiguous.

5.2. Antiquity of biomass burning in the Serra da Estrela

Braun-Blanquet et al. (1952, p. 319) speculated that soil charcoal in the Serra da Estrela represented biomass burning from “hundreds, if not thousands, of years ago”. Our data from Charco da Candieira confirm that fires have occurred with regularity since at least 14,000 cal. a BP. Indeed, even the name ‘Candieira’ is thought to relate to the deliberate burning of the vegetation by pastoralists, hunters and charcoal producers (Batista, 1988).

Two major shifts in fire regime can be inferred from the charcoal record; the first at the beginning of the Holocene (~12000–11000 cal. a BP) and the second in the mid-late Holocene (~3500–2500 cal. a BP). During each of these periods, charcoal accumulation in Candieira increased quite dramatically, followed by a slight decline and subsequent establishment of a new equilibrium. Both shifts are accompanied by major changes in the palaeovegetation, demonstrating a long-standing link between fire incidence and vegetation change in the Serra da Estrela.

Low fire activity around the Serra da Estrela during the steppe vegetation phase of theYounger Dryas is consistent with the interpretation of low fuel availability on the Iberian Peninsula during stadial periods (Daniau et al., 2007). Holocene fire histories from the SW Mediterranean region indicate that fire activity was relatively high during the early Holocene, declined during the mid Holocene and increased again after ~5000 cal. a BP (Carrión, 2002; Tinner et al., 2009; Vannière et al., 2011; Carrión et al., 2012). The Candieira fire history shares aspects of these trends and most closely resembles records from sites in SE Spain and the west coast of Sicily, especially in relation to the major increase in fire activity between ~3500–2500 cal. a BP (Carrión et al., 2007; Tinner et al., 2009; Gil-Romera et al., 2010).

Unlike most fire histories from the Mediterranean region, the Candieira record gives no indication of millennia-long periods in the mid Holocene when fire activity subsided. Charcoal is constantly present in relatively high concentrations. There are, however, shorter periods from which major charcoal peaks are lacking, i.e. approx. 10500–10000, 9000–8500, 7000–6500, 4500–4000, 2500–2000 cal. a BP. These may simply be sections of the core in which charcoal peaks were missed, although the regular spacing of these intervals could point to an underlying fire cycle. The 4500–4000 cal. a BP reduction is recorded throughout the Mediterranean region (Vannière et al., 2011).

5.3. Fire's impact on the vegetation

Given the antiquity and recurrence of biomass burning in the Serra da Estrela, it is likely that fire has shaped the vegetation to a substantial degree. As noted above, the two most important vegetation changes – early Holocene afforestation and mid-late Holocene deforestation – are accompanied by major shifts in fire regime and arrival at new metastable states (sensu Oldfield, 1983).

On millennial timescales, correlations between charcoal and pollen can reveal the response of vegetation structure to fire activity (e.g. Tinner et al., 2009). Heathland taxa are positively correlated with charcoal in the Candieira record overall, whereas woodland taxa are negatively correlated, suggesting a strong link between Holocene fire activity, forest decline and heathland development in the Serra da Estrela. Similar relationships are observed in other mountain ranges of the Iberian Peninsula (Carrión et al., 2007; Morales-Molino et al., 2011).

On shorter timescales of hundreds of years, the interactions between charcoal and pollen abundances may hold a great deal of ecological information on plant species responses to fire (Green, 1981; Walker, 1982; Colombaroli et al., 2007, 2009). The Candieira pollen record is sufficiently detailed and well-dated to allow close examination of population dynamics within discrete sections of the Late-Glacial and Holocene.

In interpreting the time-series results (Fig. 4), it is important to take into consideration the potential source-area of the charcoal and pollen. *Pinus, Olea* and *Alnus* pollen in the Candieira sediments probably derive mostly from lower elevations several kilometres from the site, whereas *Quercus, Taxus* and *Cerealia*-type may come from somewhat closer sources, and *Erica*, *Calluna, Genista*-type, *Pteridium* and the dominant upland herbs are thought to come from an area ranging from tens of metres to a few kilometres around the site (van der Knaap and van Leeuwen, 1995). The origin of the charcoal is more difficult to define, though the prevalence of small particles suggests a predominantly regional source.

In the four periods studied by time-series analysis, upland herbs appear to be the first taxa to respond positively to a fire event, as indicated by positive correlations between charcoal and pollen abundance at 0 or 1 lag (each lag representing a period of approximately 50 years). The only exception to this is during the Late-Glacial, when the correlation is positive but non-significant. The 'upland herbs' group includes non-wetland taxa and is dominated by *Rumex acetosella*-type and various Apiaceae, Asteraceae, Fabaceae and Liliaceae, which feature in post-fire vegetation succession in the Serra da Estrela (Jansen, 2011). Poaceae were excluded from the group because grasses occur in the wetland vegetation of Charco da Candieira (van der Knaap and van Leeuwen, 1995).

Betula and *Alnus*, which are both pioneer taxa (van der Knaap and van Leeuwen, 1995), feature prominently in Holocene post-fire successions, usually appearing shortly after the initial appearance of herbfields. Fire is unlikely to be the main reason for the long-term *Betula* decline in the Serra da Estrela (cf. van den Brink and Janssen, 1985). *Betula* is thought to have occurred along mountain streamsides and near the margins of mountain lakes (including Charco da Candieira), while *Alnus* probably occurred in lower-elevation forests and riparian zones (van der Knaap and van Leeuwen, 1995).

In the Holocene periods analysed, *Erica* often responds negatively to fire over the first 4 lags (approx. 200 years). This response is unexpected, as heaths are important in post-fire succession in the Serra da Estrela today (Jansen, 2011). Macrofossil evidence demonstrates that *Erica arborea* was present near Charco da Candieira from as early as 8800 cal. a BP, despite low pollen representation at that time (van der Knaap and van Leeuwen, 1995). Pollen filtration (Tauber, 1967) by dense *Salix* and *Betula* thickets that developed around the site after fire could explain this phenomenon, as *Erica* species are insect-pollinated and have poor pollen-dispersal capacity. It is also conceivable that low-statured *Erica* shrubs were at a competitive disadvantage to taller deciduous species (such as *Quercus* and *Betula*) and occupied marginal habitats until complete deforestation took place in the late-Holocene (phase E).

Positive *Erica* and *Genista*-type responses at longer lag times (>6 lags) in some periods could suggest that these taxa are favoured by repeated burning, considering that major charcoal peaks occur approximately 300 years apart (a similar frequency of microscopic charcoal peaks was observed during the mid-Holocene at 1530 m elevation in the Sierra de Gádor in Almeria: Carrión et al., 2003, 2012). Alternatively, ecological succession to treeless vegetation may occur after the senescence of oak forests.

Oaks (deciduous *Quercus*) generally respond negatively to fire in the short term, but recover long after fire (approx. 250 years), exhibiting the classic ‘climax’ response (see

Green, 1981). However, oak behaviour differs from period to period. The significant pre-fire increase at 11500–13500 and 1500–3500 cal. a BP could suggest that fire occurrence was partly related to the accumulation of biomass. In the early-mid Holocene, when *Quercus* was dominant, initial post-fire recovery is only significant in the earlier phase (B: 7500–9500 cal. a BP) and post-fire decline is only significant in the later period (C: 4500–6500 cal. a BP). A second phase of significant oak recovery is observed after a much longer duration – approx. 700 years in phase B and 800 years in phase C. No recovery is observed in phase D. Oak forests clearly had a greater capacity for post-fire regeneration during the early Holocene. Fire and grazing pressure are major factors inhibiting oak forest development in the Serra da Estrela today (Jansen, 2011). Deciduous oaks tend to be more susceptible to post-fire mortality (Catry et al., 2010) and less tolerant of grazing than evergreen oaks (Grove and Rackham, 2001). Under these impacts, the Candieira area’s late-successional vegetation may have switched from climax oak forest to plagioclimax broom scrub (Fig. 4).

The role of *Pinus* in the Candieira record is poorly understood because much of its pollen could have arrived from distant pine populations via long-distance pollen transport (van der Knaap and van Leeuwen, 1995). Reduction of oak forest cover would therefore increase the proportion of long-distance *Pinus* pollen, explaining why negative oak responses to fire are synchronous with positive pine responses (Fig. 4) and vice versa. The only definitive evidence for pine populations around Charco da Candieira comes in the form of macrofossils and stomata of *Pinus* cf. *sylvestris*, which reached its upper altitudinal limit in the middle of phase LG but died out completely after the Late-Glacial (van der Knaap and van Leeuwen, 1997). The *Pinus sylvestris* decline throughout Portugal is attributed to an unfavourable Holocene climate and the influence of fire (Figueiral and Carcaillet, 2005). A few pines (possibly *P. pinaster*) entered into forest dynamics in the period 4500–6500 cal. a BP, constituting an intermediate successional stage between herbfields and scrub vegetation.

The post-fire response of grasses shows remarkable consistency through the Holocene. Poaceae macrofossils were found throughout Candieira's Holocene sediments, suggesting that grasses were part of the wetland vegetation (van der Knaap and van Leeuwen, 1995). Grasses may have been shaded out by the post-fire development of deciduous vegetation, as indicated by the similarity between Poaceae and *Erica* responses to fire through the Holocene (Fig. 4).

Cereal pollen, which appears sporadically before 6000 cal. a BP and frequently thereafter, responded to fire in a similar fashion to the other Poaceae in the period 4500–6500 cal. a BP, but exhibits a completely different behaviour in the period 1500–3500 cal. a BP (Fig. 4). The changing response of cereal pollen to fire in more recent millennia is likely to relate to agricultural practices (see Section 5.4).

Post-fire vegetation succession in the present-day broom scrub communities of the Serra da Estrela has been studied by Jansen (2011) using a botanical approach. His model, which includes supra-mediterranean (middle elevation) and oro-mediterranean (higher elevation) variants, is shown in Fig. 5 alongside the successional trends deduced from time-series analysis of the Charco da Candieira pollen and charcoal data. It must be remembered that these data are a palynologically biased picture of the vegetation in which some taxa are over-represented (e.g. *Alnus*), while others are not represented at all (e.g. *Prunus lusitanica*). Also, the pollen-to-charcoal comparison represents response to fire, not necessarily the plant community that develops after fire. Nevertheless, there is a striking similarity between the modelled post-fire trajectory for the oro-mediterranean zone and the Late-Glacial pollen response.

The Holocene stages are influenced by the over-representation of wind-pollinated taxa such as *Betula* and *Alnus*, as well as the under-representation of insect-pollinated *Erica* and *Genista*. Uncertainty concerning the source of Poaceae pollen (wetland *vs* upland vegetation) in the Candieira record means that Jansen's (2011) initial stage of 'open grasslands' is represented palynologically by upland herbs. Pollen data from the early and late Holocene indicate subsequent succession to a pioneer birch-woodland stage that is not observed in the present day. *Betula alba* is associated with *Quercus pyrenaica* forests (Pinto da Silva and Teles, 1999) and may have played a much more important role in the supra-mediterranean zone prior to complete deforestation. The subsequent *Alnus* stage is also not observed at present and reflects recovery of riparian forest, probably at lower altitudes. In the early Holocene, this stage is followed by oak forests, while in the late Holocene a succession to juniper scrub is observed (similar to Late-Glacial dynamics). In both cases, scrub, grassland or heathland vegetation appears as a final stage, either because of recurrent fire or because of the senescence of oak and juniper communities. The mid-Holocene (4500–6500 cal. a BP) successional trend deduced from pollen is quite different, involving a pine-woods stage not observed at present. Subsequent succession to broom scrub and then heathland is in good agreement with the Jansen (2011) model.

These observations indicate that grassland, scrub and heathland communities are important in the long-term vegetation dynamics of the Serra da Estrela and are not simply the product of recent deforestation. Moreover, oak forest requires hundreds of years to recover after fire and it seems that its capacity for recovery has declined through the Holocene. Oak was dominant in the early Holocene when vegetation dynamics were largely governed by successional cycles. Changed climatic conditions and disturbance regimes have favoured the expansion of treeless vegetation.

While the Candieira fire history does not extend into more recent times, vegetation changes during the last thousand years (i.e. further expansion of heathland, felling of oak woods, rye cultivation and establishment of pine, eucalypt and olive plantations; see van der Knaap and van Leeuwen, 1995) have again altered the relationship between fire and vegetation. While the response of individual taxa to fire appears to be quite conservative, as indicated by similar responses in different Holocene periods, the vegetation as a whole may respond to changed disturbance regimes in ways that are difficult to predict.

The good news for plant biodiversity is that fire is not a new disturbance in the Serra da Estrela and today's indigenous flora is relatively resilient to burning. Our observations suggest that policies of total fire exclusion (e.g. ICNB, 2009) are unsustainable in the Serra da Estrela and emphasis should instead be placed on reducing the damage caused by large-scale wildfires, which have deleterious effects on habitats and biodiversity (Jansen, 2011). Prescribed fire regimes can play a pivotal role in biodiversity management, but must be supported by ecological knowledge and ecosystem monitoring (Allen, 2008).

5.4. Interactions between fire, climate and humans

The Holocene fire history of the Mediterranean region is regarded primarily as a reflection of climatic changes (Carrion, 2002; Vannière et al., 2011; Lionello, 2012; cf. Tinner et al., 2009).

Interpretation of pollen records from Portugal has given rise to two opposing models for the Holocene palaeoclimate. Based on numerous pollen profiles from lakes along the west coast of Portugal, Queiroz (1999) proposed a wet early Holocene, dry mid

Holocene and hyper-wet late Holocene. Conversely, van der Knaap and van Leeuwen (1995) interpreted the Candieira record as indicating a dry early Holocene and wet mid-Holocene. Interpretation of palaeovegetation in strictly climatic terms is rendered difficult by the influence of sea-level changes ('inundation phases') at the coastal sites (Mateus, 1992; Queiroz, 1999; Queiroz and Mateus, 2004) and prehistoric human impacts on the vegetation throughout the region (Mateus, 1992; van der Knaap and van Leeuwen, 1995; Queiroz, 1999). In addition, Mediterranean climates are characterised by their seasonality, an aspect which has not hitherto emerged from the Portuguese palynological data.

Numerical analyses of the Candieira pollen data (Fig. 6) demonstrate that the vegetation history reflects the major climatic fluctuations of the Late-Glacial – including the Older Dryas (Heinrich event 1), Bølling–Allerød interstadial (Greenland interstadial 1) and Younger Dryas – although the radiocarbon age model here appears too young (van der Knaap and van Leeuwen, 1997). Holocene vegetation changes are more difficult to interpret. The PCA result, which closely follows oak pollen percentages, bears some resemblance to the reconstructed winter-temperature curve from Lake Tigalmamine in Morocco (Cheddadi et al., 1998) and possibly reflects the sensitivity of *Quercus* species to winter temperatures (Colombaroli et al., 2009). The DCA result takes a different course that appears to track the overall trend in increasing warm-season sea-surface temperatures off West Africa (deMenocal et al., 2000). This DCA axis is influenced by the gradual increase in pollen from heathland species, such as *Erica* and *Genista*, which have morphological adaptations to temperature variations, desiccating winds and seasonal drought, as well as the ability to resprout after fire (Jansen, 2011). Temperature might be expected to register palaeoecologically in a mountain area such as the Serra da Estrela, although prehistoric human impacts on the vegetation may potentially override the climatic signal. Gil-Romera et al. (2010) suggest that the early Holocene was characterised by reduced temperature seasonality in SE Iberia, in agreement with the trends reconstructed here.

Another climatic signal of interest is the increase in pollen accumulation rates from approximately 13800 to 9700 cal. a BP (Fig. 6). High pollen concentrations during this period are also observed in a marine record from the Alboran Sea (Fletcher and Sanchéz Goñi, 2008). These were interpreted as a reflection of increased biomass in response to precession-driven changes in seasonality (Fletcher and Sanchéz Goñi, 2008). The development of the Serra da Estrela's xerothermic forests during the early Holocene may be linked to this precession pattern, which has had a pervasive influence on the Quaternary vegetation history of the Mediterranean region (Tzedakis, 2007; Gil-Romera et al., 2010). Precession, however, has no discernable impact on the fire history from Candieira.

Likewise, the Candieira pollen record provides no clear signal of Holocene aridity, possibly because the Serra da Estrela rarely experiences drought in the usual Mediterranean sense of the term. Independent evidence for aridity coincident with increased late-Holocene fire activity in the Serra da Estrela comes from the multi-proxy quantitative palaeoclimatic reconstructions from the Azores (Björck et al., 2006), pollen data from southern Portugal (Fletcher et al., 2007), lowered lake levels in southern Spain and Northern Africa (Lamb and van der Kaars, 1995; Reed et al., 2001; Carrión, 2002), as well as widespread sedimentation hiatuses in interdunal lakes in western Portugal (Queiroz and Mateus, 2004). A drier climate may have initiated paludification of Charco da Candieira itself, which switched from a lake to a seasonally dry pond around 3400 cal. a BP (van der Knaap and van Leeuwen, 1995). Arid phases peaking at the beginning of the Holocene (palaeovegetation phase A) and between ~3500–2500 cal. a BP (phase D) may have been the trigger for major fires in the region and the subsequent reorganisation of the vegetation of the Serra da Estrela (Fig. 6). Major increases in fire activity are registered across the Mediterranean zone of the Iberian Peninsula between ~3500–2500 cal. a BP, indicating a coherent regional pattern (Stevenson and Harrison, 1992; Carrión, 2002; Carrión et al., 2007, 2012; Gil-Romera et al., 2010; Vannière et al., 2011; see also Rius et al., 2011).

Cyclic aridity phases in SW Europe are thought to be closely linked to variations in the North Atlantic climate system (Reed et al., 2001; Davis and Stevenson, 2007; Fletcher et al., 2007; Vannière et al., 2011), specifically the cooling events identified by Bond et al. (1997). In the Candieira record, major peaks in large charcoal particles at approx. 11400–11300, 9700, 8100, 4500, 2700 and 1300 cal. a BP overlap temporally (2σ) with 'Bond events' at approx. 11100, 9400, 8100, 4200, 2800 and 1400 cal. a BP, respectively (Fig. 6). The reason that these events registered as local fires, rather than the regional fires indicated by smaller charcoal particles, may be that North Atlantic cooling events had a greater effect on the Serra da Estrela's supra- and oro-mediterranean belts than on the lower elevations due to orographic interception of westerly air-streams.

While Holocene climatic changes may have been the driving force behind vegetation change and fire incidence in the Serra da Estrela, human impacts cannot be disregarded, especially in more recent millennia. Van der Knaap and van Leeuwen (1995) used palynological indicators of anthropogenic activity and forest disturbance in the Candieira record to place the earliest signs of human activity in phase B (9500–6400 cal. a BP). The first *Cerealia*-type pollen occurs in the Candieira record at ~10000 cal. a BP and it is present almost continuously from 8500 to 7400 cal. a BP. Considering that the earliest agricultural settlements in Portugal date to around 7400 cal. a BP (Zilhão, 2001; Zeder, 2008), these occurrences may reflect pollen of steppe grasses (van der Knaap and van Leeuwen, 1995). Other traditional anthropogenic indicators, such as *Rumex acetosella*-type and *Plantago lanceolata*-type (Behre, 1981), are not particularly helpful in the Candieira record as they occur throughout the Late-Glacial and Holocene.

Sheep and goat herding is the traditional mainstay of the Serra da Estrela's economy. Grazing's direct impact on the Serra da Estrela's vegetation and fire history is unknown; along with fires lit by herders to promote pasture, it is probably quite significant (Braun-Blanquet et al., 1952; van der Knaap and van Leeuwen, 1995). The regular occurrence of spores from dung-inhabiting fungi (e.g. *Sporormiella* and *Podospora*: van Geel and Aptroot, 2006) in the Candieira material demonstrates that grazing by wild or domestic animals has a long history in the Serra da Estrela, extending back to the Late-Glacial.

The earliest archaeological site in the Serra da Estrela, Buraco da Moura de São Romão, is located ~9km WNW of Charco da Candieira on the western flank of the mountains and contains Neolithic, Chalcolithic, Bronze Age and Medieval levels (Senna-Martinez, 1993). Analysis of Bronze-Age faunal remains from the 2nd millennium BC provides convincing evidence that pastoral activities, especially sheep and cattle herding, were practised at this time (Cardoso et al., 1998), coincident with widespread deforestation in the Serra da Estrela (van den Brink and Janssen, 1985; van der Knaap and van Leeuwen, 1995). Regional aridity between ~3500–2500 cal. a BP may have intensified occupation of better-watered mountain areas, leading to the clearance of forests for pasture, or a population increase led to the same outcome.

Establishment of Roman roads and settlements in the Serra da Estrela is marked palaeoecologically by the first appearance of *Castanea* pollen in the Candieira record around 2000 cal. a BP. Roman-era activity was concentrated at the foot of the mountains, far from the central plateaux (Alarcão, 1993), and no drastic changes are evident in the pollen record from Charco da Candieira.

The same cannot be said of the Medieval, a period of rapid population growth that led to the expansion of heathland and virtual disappearance of forests. Historical sources attest to the importance of sheep grazing and rye cultivation at higher elevations (Batista, 1988), including in the surroundings of Charco da Candieira (Costa et al., 2004). Cereal cultivation was often practised on common land during the Medieval, alongside animal husbandry, charcoal production, firewood collection, timber harvesting and hunting; deliberate agro-pastoral fires (*queimadas*, in Portuguese) were associated with many of these activities (Batista, 1988).

Substantial amounts (>15%) of *Cerealia*-type pollen in the more recent Candieira sediments are a clear testament to this local activity (Fig. 6). Fire and cereals are strongly related in the period 1500–3500 cal. a BP, with a significant expansion of cereal pollen 50–100 years after fire. This distinctive response is most likely to be a reflection of prehistoric *queimadas*, possibly in the direct surroundings of Charco da Candieira. Recent increases in pine and olive pollen, on the other hand, come from the establishment of extensive plantations in the valleys and lowlands (van der Knaap and van Leeuwen, 1995).

In summary, long-term trends in the fire history from Charco da Candieira can be explained largely by Late-Glacial and Holocene climatic changes, particularly cycles of aridity associated with shifts in the North Atlantic Oscillation. Fire was ever-present in the Serra da Estrela, but, in the hands of prehistoric and historic human populations, it became a major agent of vegetation change, accelerating the Holocene decline of forests.

6. Conclusions

Ever since the ice cap and glaciers retreated, fire has always been an important component of the ecosystems of the Serra da Estrela. Fire has directly shaped the composition of the mountain’s plant communities. Current trends toward increasing fire incidence in the Serra da Estrela present immediate management difficulties, but are nothing new when viewed from a long-term perspective. The Serra da Estrela has witnessed several periods in the past in which fire incidence appears to have increased dramatically due to climatic factors. In each case, the period of increasing fire activity was followed by a much longer period of stabilisation. Although fire itself does not seem to pose a threat to the region’s plant biodiversity, the variety of vegetation responses to fire in the past suggests that changes in climate, land-use and disturbance regimes could have unpredictable outcomes in the future. For this reason it is important to develop a better understanding of fire in the mountains of the Iberian Peninsula, both now and in the historical past.

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Figures

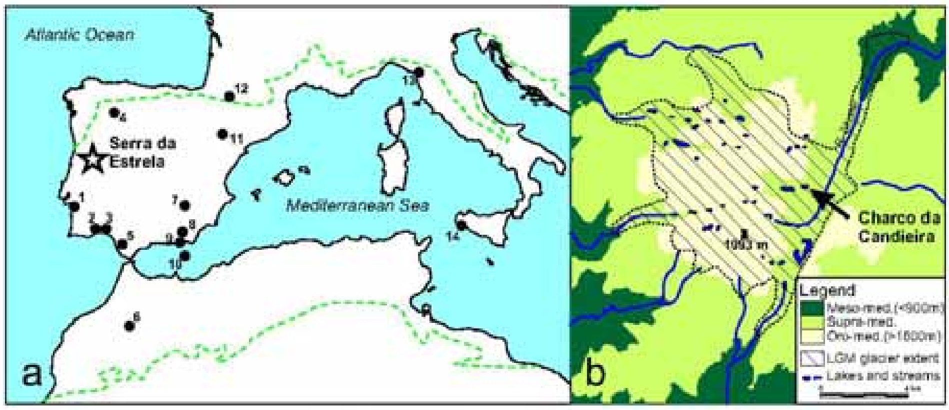

Figure 1. Location of the Serra da Estrela, Portugal (a) and the study site, Charco da Candieira (b). The dashed line in Fig. 1a indicates the bioclimatic limit of the Mediterranean region (after Quézel and Médail, 2003). Other sites mentioned in the text are shown: 1. NW Alentejo (Mateus, 1992; Queiroz, 1999; Queiroz and Mateus, 2004); 2. Guadiana Estuary (Fletcher et al., 2007); 3. Laguna de las Madres (Stevenson and Harrison, 1992); 4. Vallefondo (Morales-Molino et al., 2011); 5. Laguna de Medina (Reed et al., 2001); 6. Lake Tigalmamine (Cheddadi et al., 1998; Lamb and van der Kaars, 1995); 7. Lake Siles (Carrión, 2002; Gil-Romera et al., 2010); 8. Baza (Carrión et al., 2007); 9. Gádor (Carrión et al., 2003); 10. Alboran Sea (Fletcher and Sánchez Goñi, 2008); 11. Central Ebro Desert (Davis and Stevenson, 2007); 12. Lourdes Basin (Rius et al., 2011); 13. Lago di Massaciuccoli (Colombaroli et al., 2007); 14. Gorgo Basso (Tinner et al., 2009). Fig. 1b shows the main bioclimatic zones of the Serra da Estrela (see Section 2), the extent of the most recent glaciation and the distribution of glacial lakes (after Daveau, 1971).

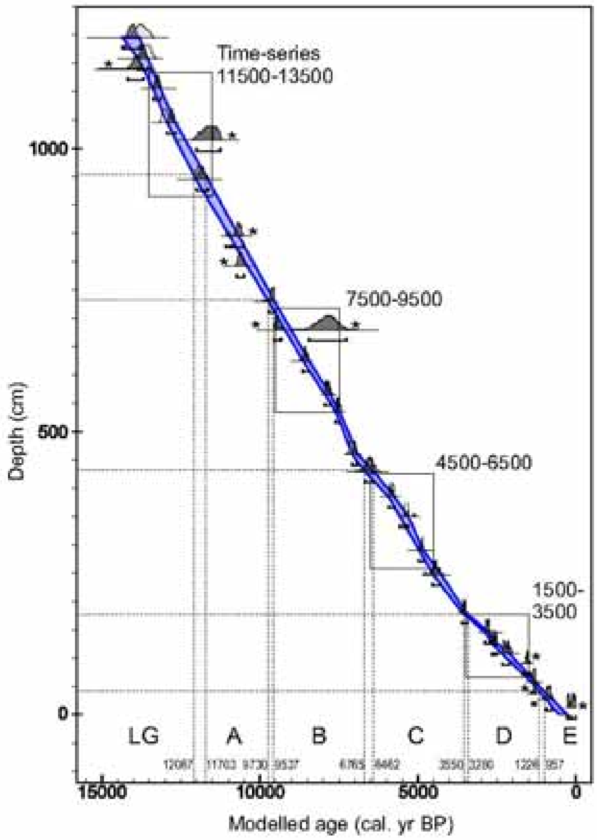

Figure 2. Age–depth model for the Charco da Candieira sediment record showing probability distributions for each dated level, dates excluded from the model (*) and age ranges for each of the palaeovegetation phases (Section 2). Boxed periods were subjected to time-series analysis (Section 5.3; Fig. 4).

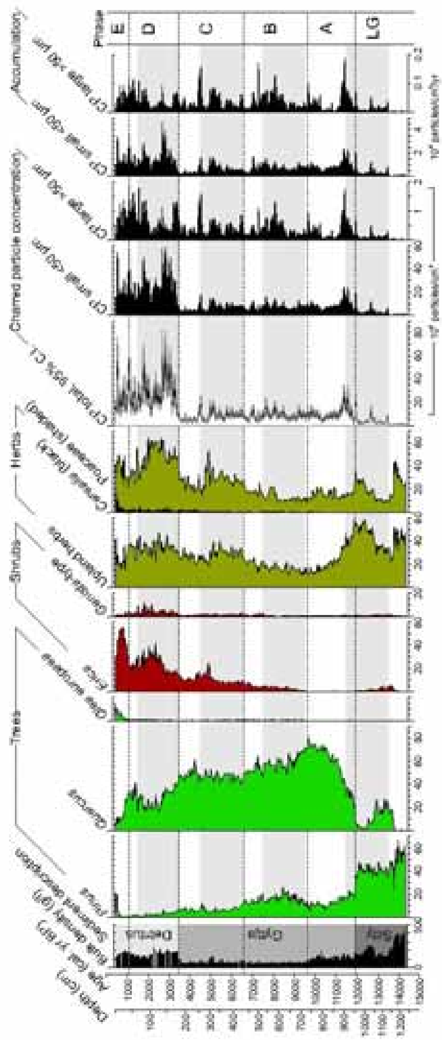

Figure 3. Stratigraphic diagram of proxies analysed in the Charco da Candieira sediment record. From left to right: depths, modelled ages, sediment bulk density (g/l dry weight), sediment description (details in der Knaap and van Leeuwen 1995, 1997), selected pollen percentages, total charred particle concentrations with 95% confidence intervals (estimated from Maher, 1972), concentrations of charred particles 5–50 and 50–250 µm in size, and accumulation rates of the same. Palaeovegetation phases (Section 2) shown at right; grey horizontal bands are time-series analysis periods (Fig. 4).

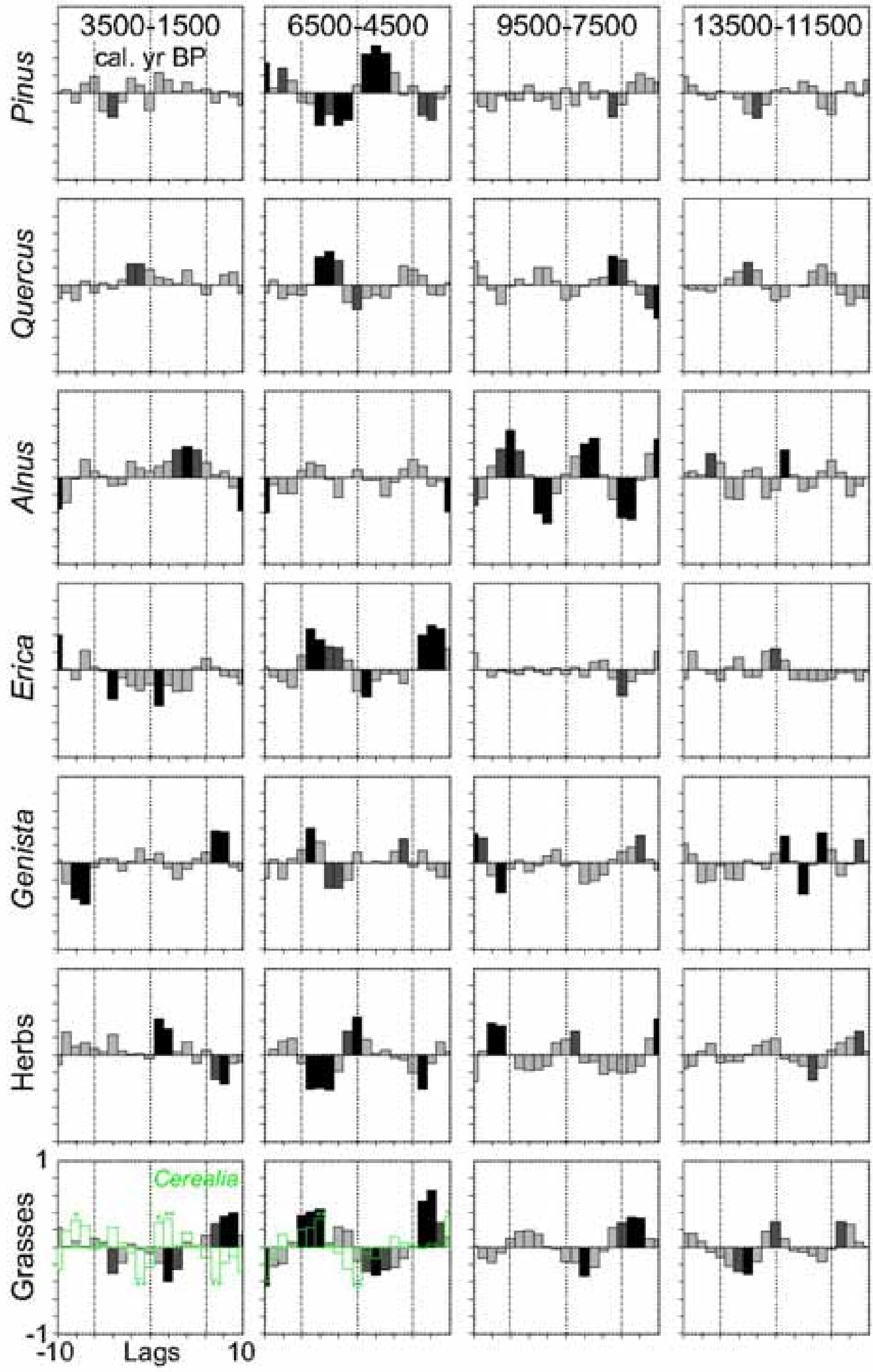

Figure 4. Cross-correlograms of interpolated and detrended pollen percentages (selected taxa) and charred particle concentrations for four periods in the Charco da Candieira record. The vertical axis represents correlation coefficients and the horizontal axis represents lags (each equivalent to 48 years). Statistically significant correlations are

indicated by black columns ($p<0.05$) and dark-grey columns ($p<0.1$). *Cerealia* pollen is represented as hollow columns on the Poaceae graph (** $p<0.05$ and * $p<0.1$). When reading these graphs, a positive correlation at zero lags (centre of each graph) indicates a direct (immediate) correlation between charcoal and pollen abundance. A positive correlation to the right indicates that a charcoal increase leads a pollen increase. A positive correlation to the left indicates that the charcoal lags behind the pollen (see Green, 1981, for full explanation). Dashed vertical lines at 6 lags denote the average period between major charcoal peaks (approx. 300 years).

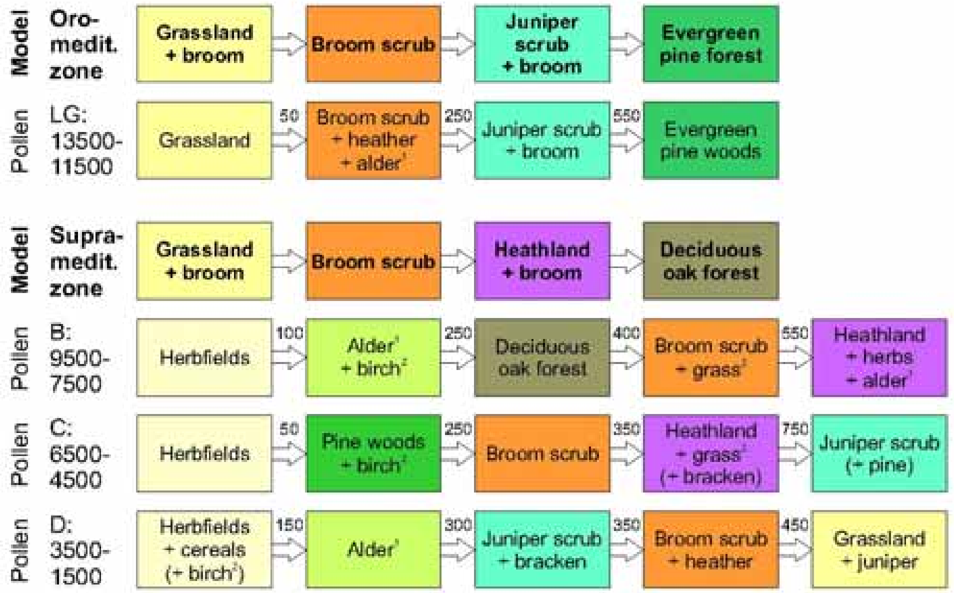

Figure 5. Comparison of a model of post-fire succession in the Serra da Estrela's oro-mediterranean and supra-mediterranean vegetation (Jansen, 2011) with successional trends deduced from time-series analysis of the Charco da Candieira pollen and charcoal record (Section 5.3). Significant post-fire pollen correlations have been translated into vegetation types to aid comparison. Numbers above the arrows indicate the approximate number of years since fire required to reach each stage. Taxa marked 1 are possibly

derived from long-distance pollen transport; taxa marked 2 may have occurred in the local wetland vegetation; taxa in parentheses appear late in the successional stage in which they are included.

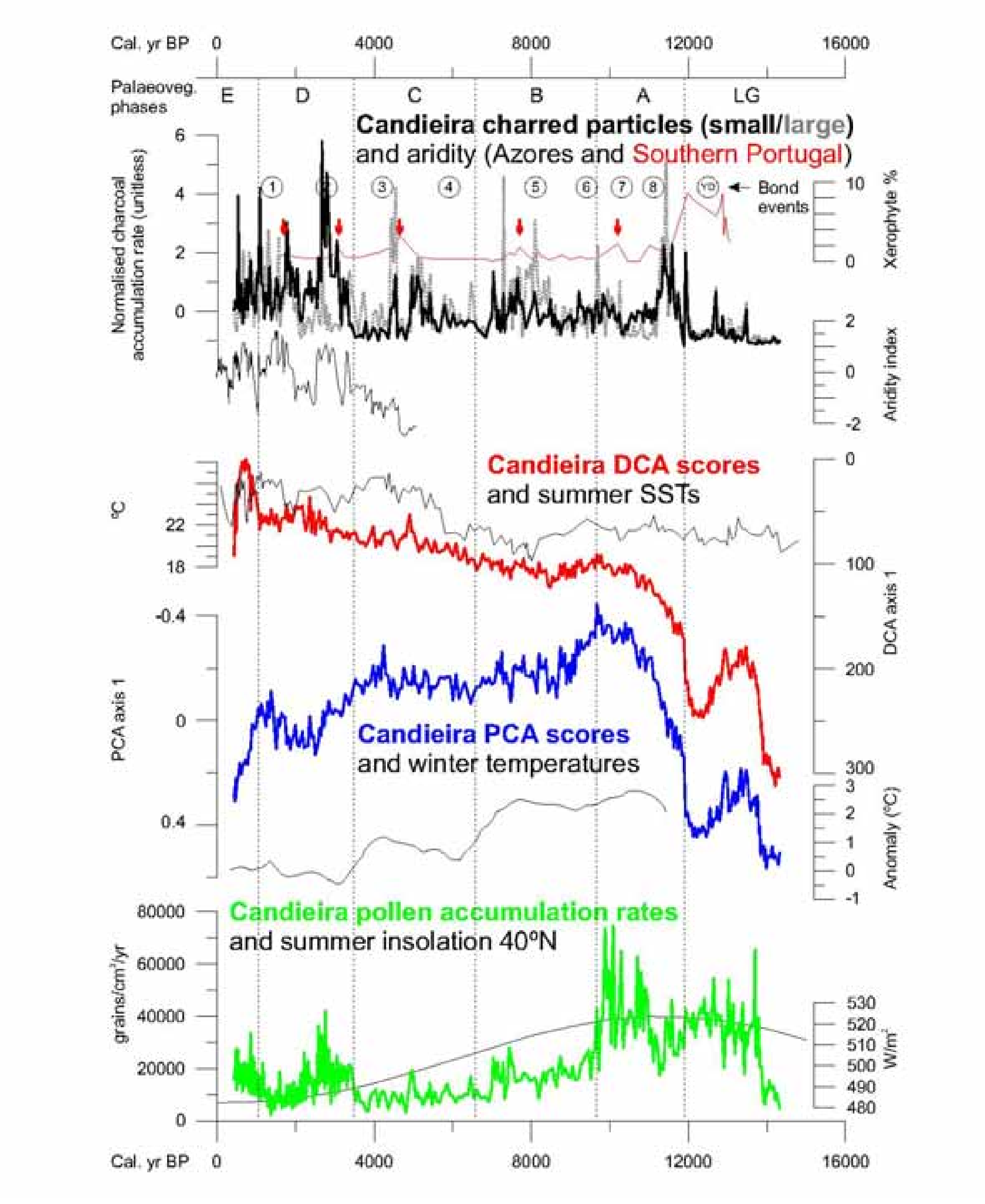

Figure 6. Ordination results (PCA and DCA), normalised charred-particle accumulation rates and dryland-pollen accumulation rates from the Charco da Candieira record (thick

lines) in relation to other palaeoclimatic records mentioned in the text (thin lines). Charcoal data normalised to standard deviation (see Carcaillet et al., 2002). Azorean aridity index redrawn from Björck et al. (2006); arid phases in Southern Portugal from Fletcher et al. (2007); Bond events from Bond et al. (1997); summer sea surface temperatures (SSTs) off West Africa from deMenocal et al. (2000); winter temperatures in Morocco from Cheddadi et al. (1998); and summer insolation at 40ºN from Berger (1978).