Prehistoric palaeodemographics and regional land cover change in eastern Iberia

Fyfe, R.M.[1], Woodbridge, J.[1], Palmisano, A.[2], Bevan, A.[2], Shennan, S.[2], Burjachs, F.[3], Legarra Herrero, B.[2], García Puchol, O.[4], Carrión, J.S.[5], Revelles, J.[6], Roberts, N.[1]

1 School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth, PL4 8AA, UK
2 Institute of Archaeology, University College London, 31-34 Gordon Square, London, WC1H 0PY, UK
3 ICREA Barcelona, Catalonia, Spain; Rovira i Virgili University (URV), Tarragona, Catalonia, Spain; Institut Català de Paleoecologia Humana i Evolució Social (IPHES), Campus Sescelades URV, W3, 43007 Tarragona, Spain
4 PREMEDOC Research Group, Departament de Prehistoria, Arqueologia I Història Antiga, Universitat de València, Avenida Blasco Ibañez 28, 46010, València, Spain
5 Departamento de Biología Vegetal, Facultad de Biología, Universidad de Murcia, 30100 Murcia, Spain
6 Departament de Prehistoria, Universitat Autonoma de Barcelona, 08193 Bellaterra, Spain

Abstract

Much attention has been placed on the drivers of vegetation change on the Iberian Peninsula. Whilst climate plays a key role in determining the species pools within different regions and exerts a strong influence on broad vegetation patterning, the role of humans, particularly during prehistory, is less clear. The aim of this paper is to assess the influence of prehistoric population change on shaping vegetation patterns in eastern Iberia and the Balearic Islands between the start of the Neolithic and the late Bronze Age. 3385 radiocarbon dates have been compiled across the study area to provide a palaeodemographic proxy (radiocarbon summed probability distributions: SPD). Modelled trends in palaeodemographics are compared with regional-scale vegetation patterns deduced from analysis of 30 fossil pollen sequences. The pollen sequences have been standardised with count data aggregated into contiguous 200-yr time windows from 11000 cal. yr BP to present. Samples have been classified using cluster analysis to determine the predominant regional land cover types through the Holocene. Regional human impact indices and diversity metrics have been derived for northeast and southeast Spain and the Balearic Islands. The SPDs show characteristic boom-and-bust cycles of population growth and collapse, but there is no clear synchronism between northeast and southeast Spain other than the rise of Neolithic farming. In northeast Iberia patterns of demographic change are strongly linked to changes in vegetation diversity and human impact indicator groups. In the southeast increases in population throughout the Chalcolithic and early Bronze Age result in more open landscapes and increased vegetation diversity. The demographic maximum occurred early in the 3rd millennium cal. BP on the Balearic Islands and is associated with highest levels of human impact indicator groups. The results demonstrate the importance of population change in shaping the abundance and diversity of taxa within broad climatically-determined biomes.

Keywords

Radiocarbon SPD, palaeodemographics, prehistory, pollen, land cover, human impact, diversity, Spain, Holocene

INTRODUCTION

Much attention has been placed on Holocene vegetation change, and on the drivers of that change, in the Iberian Peninsula. Much of that focus has been on the role of climate in determining vegetation trajectories, particularly in regions where moisture availability is a key factor in the macroecological patterning exhibited by more arid regions (Carrión et al., 2010b). Climate inevitably does play an important role in influencing and determining the species present across different regions (Carrión et al., 2010a), and climatic change can exert a strong influence on broad vegetation dynamics. For example, many pollen sequences describe an increase in mesic woodland associated with a relatively wetter mid-Holocene phase (e.g. Carrión et al., 2001a, 2001b; Carrión et al., 2004; Carrión et al., 2007; Aranbarri et al., 2014). Increasing aridity then resulted in expansion of sclerophyllous and xeric communities (Carrión et al., 2010; Pérez-Obiol et al., 2011). The role of humans in influencing vegetation change, particularly in earlier archaeological periods, is by contrast less straightforward, especially at the regional level. In more recent periods, since 1500 cal. yr BP, the influence of anthropogenic forcing on vegetation in eastern Iberia can be clearly demonstrated and linked to increasing land degradation caused by grazing pressure (Carrión et al., 2001a; Carrión et al., 2004; Aranbarri et al., 2014). In addition, research over the last few years has also uncovered increasing evidence for the impact of earlier societies on land cover in eastern Iberia. According to Carrión et al. (2010a) human settlement and land use has played a role in shaping vegetation patterns since the mid-Holocene through land conversion for agriculture, mining, and grazing. For example, Revelles et al. (2015) describe pronounced changes in deciduous woodland cover and maintenance of cleared landscapes from the early Neolithic in northeast Spain, in close proximity to known early Neolithic archaeological settlements. It is likely that whilst climate controlled broad geographical patterning on vegetation (e.g. by controlling fundamental species distribution and influencing competition between species), this was overprinted by human disturbances, at least at the local scale (Castro et al., 1994, 1998). There is thus a need to further explore the role of past populations on land cover change.

Radiocarbon dates from archaeological sites are increasingly used as proxies for past demographic change, through the use of summed probability distributions (radiocarbon SPD, also known as summed calibrated date probability distributions: SCDPD, Shennan et al., 2013). The basis of the approach is summarised in several places (e.g. Shennan and Edinborough, 2007; Shennan et al., 2013; Palmisano et al., 2017) and assumes that change in the number of radiocarbon dates in a defined region is a useful proxy for demographic trends. Balsera et al. (2015b) presented the first attempt at prehistoric palaeodemographics using radiocarbon dates for the whole of Iberia, drawing on 4402 dates from 1167 archaeological sites. They identified the characteristic 'boom and bust' cycle of population growth and subsequent contraction at the start of the Neolithic (c.7250 cal. yr BP) observed elsewhere in Europe (Shennan et al., 2013). Subsequent studies have applied the approach in the Iberian peninsula (e.g. Bernabeu et al., 2014; García Puchol et al., 2015). Lillios et al. (2016) explored regional trends in demographic change from three sub-regions of the Iberian Peninsula (northwest, northeast and southeast) using dates from settlements and burials across the Chalcolithic and Bronze Age and García Puchol et al. (2017) mapped spatial and temporal patterns in radiocarbon SPD to show dynamics of the final hunter gatherers and the first farmers. These studies noted clear differences in regional demographic trends, but record increases in population as inferred from the radiocarbon SPD in spite of inferred increases in aridity during the sixth and fifth millennia cal. BP. These sub-regional inferences are extended by Blanco-González et al. (2018), who suggest inter-regional differences in climate as a potential explanatory variable for regional demographic differences. The characteristically mediterranean southeast and northeast regions are described as having small demographic responses to known climate events (e.g. the 4.2 ka cal BP event) in comparison to regions more influenced by Atlantic climatic conditions. Blanco-González et al. (2018) call for further regional work in Iberia on subsistence economies, demographic trends and ecological transformations, signalling that understanding past land cover and demographic change is a priority research area.

The aim of this paper is to test how far regional vegetation changes and ecological transformation within eastern Iberia can be explained by archaeologically-derived records of prehistoric demographic change. Regional trends in vegetation through the Holocene will be derived from synthesis of multiple pollen sequences, and inter-regional comparisons made between the northern and southern regions. Data from the Balearic Islands will also be compared to the mainland: islands are useful as experimental laboratories where it can be shown they are isolated from human impact. Current evidence suggests that the Balearic Islands of Mallorca and Menorca were not settled until around 4320 cal. yr BP (Burjachs et al., 2017; Pérez-Jordà et al., 2018). Following colonisation the Balearic Islands are connected to Iberia but are a distinct region. Data from these islands can thus provide valuable reference conditions for natural (pre-human colonisation) vegetation dynamics, and for exploring the impact of known settlement and population expansion trends.

METHODOLOGY AND MATERIALS

Palaeo-demographic data

Prehistoric demographic data is inferred from a summed probability distribution approach utilising radiocarbon dates as surrogates for population (Shennan et al., 2013). Radiocarbon dates from archaeological sites were compiled from existing online databases and electronic and print publications (Martínez et al., 1997; Manen and Sabatier, 2003; Weninger et al., 2009; Van Strydonck and de Roock, 2011; Hinz et al., 2012; Aranda Jiménez et al., 2015; Balsera et al., 2015a, 2015b; Manning et al., 2015; Lillios et al., 2016; Oms et al., 2016; Paulsson, 2017; Vermeersch, 2017). Dates are stored in a georeferenced database following Palmisano et al. (2017). A total of 3885 uncalibrated radiocarbon dates from 814 sites have been collected. All the radiocarbon dates are from archaeological contexts, with the majority being samples of bone, charcoal and wood. Radiocarbon dates obtained from marine samples such as shell are not included to avoid the complicated issues arising from unknown or poorly understood marine reservoir offsets. Fewer than 20 dates have standard deviations greater than 300 years. Biases caused by multiple dates from the same archaeological phase at a site are accounted for by aggregating uncalibrated radiocarbon dates from the same site that are within 100 years of each other and dividing by the number of dates that fall in this bin (Timpson et al., 2014). The probabilities from each calibrated date are combined to produce a summed probability distribution (SPD). The resulting summed probabilities are binned into 200-year time windows to match the time windows used in the analysis of pollen sequences. Archaeological periods are defined from literature, but it should be noted that archaeological periodisation for the Balearic Islands is distinct from the Iberian mainland. All dates are given in calibrated years before present (cal. yr BP). The timing of archaeological periods varies across mainland Iberia, but broadly the first Neolithic cultural material is dated to 7550-7450 cal. yr BP, and the peninsula experienced a rapid transition process from the Mesolithic to the Neolithic (García Puchol et al., 2009; López de Pablo and Gómez Puche, 2009; García Puchol and Salazar-García, 2017). Neolithic culture was established across northeast Spain by 7250 cal. yr BP (Oms et al., 2018). The subdivisions of Antolín et al. (2015) are used for the Neolithic periods: early Neolithic (7350-6450 cal. yr BP), middle Neolithic (6450-5150 cal. yr BP) and late Neolithic/Chalcolithic (5150-4250 cal. yr BP); the start of the late Neolithic is slightly later in southeast Spain. The Bronze Age is divided into three periods following Lull et al. (2013): early Bronze Age (4250-3500 cal. yr BP); late Bronze Age (3500-3250 cal. yr BP) and final Bronze Age (3250-2850 cal. yr BP).

It is not currently possible to use radiocarbon date distributions as a reliable palaeodemographic proxy after the end of the Bronze Age as the number of available dates for this period is too low:

relative dating via cultural material gradually replaces radiocarbon in the development of site chronologies. Iberia came into contact with the Phoenicians and Greeks during the Iron Age (from the 9th century BC, ~2700 cal. yr BP) and colonies such as *Emporion* on the coast of Catalonia were established (founded in 2475 cal. yr BP). This brought eastern Iberia into the realm of written history. Carthaginian colonies such as Cartagena came under Roman rule following the 2nd Punic War (late 3rd century BC, ~2200 cal. yr BP). The Romans dominated the Iberian Peninsula until the 5th century AD (1500 cal. yr BP). After a period of Visigothic rule, almost the whole of eastern Iberia was conquered by Islamic Moors soon after ~700 AD (1250 cal. yr BP). The Christian conquest was a slow process, not completed until the fall of Granada in 1492 AD (458 cal. yr BP). Both Moslem and Christian Medieval periods saw a significant growth in population in Iberia and laid the economic foundations of the modern Spanish state.

Modern and fossil pollen datasets

Pollen count data from the European modern (Davis et al., 2013) and fossil pollen databases (EPD version Oct. 2017: Leydet, 2007-2017) were combined with additional fossil records provided by a network of data contributors to compile a dataset of 257 fossil records and 1798 modern pollen surface samples spanning the Mediterranean region. Pollen sequences with reliable chronologies (Giesecke et al., 2014) were selected for analysis and new sediment core chronologies were constructed for additional records using the ‘bacon’ R package (Blaauw & Christen, 2011). The pollen count data from each site were summed into 55 contiguous 200-year time windows between the periods 11000 and -65 cal. yr BP. Descriptions of the methodological approaches developed and applied to the pollen datasets are provided in Woodbridge et al. (2018) and Fyfe et al. (2018) along with detailed information on the harmonisation of the pollen taxonomy. The approach has allowed the identification of key vegetation types across the Mediterranean region as a whole. This paper draws on a sub-set of 30 fossil sequences from 27 pollen sites and 112 modern surface samples for Mediterranean Spain (Figure 1).

Palaeoclimate datasets

The closest and most complete non-palynological proxy-based records for which data are available from eastern Iberia are used as palaeoclimate indicators for comparison with radiocarbon SPD and pollen-inferred land cover and indices. Datasets have been normalised around their mean and standard deviation to produce z-scores as described in detail in Finné et al. (in review). For northeast Spain a multiproxy record of lake level and salinity has been used from Lake Estanya (Morellón et al., 2009). The lake level record from Laguna de Medina (Reed et al., 2001) is used for southeast Spain. There is no published proxy-climate dataset currently available from the Balearic Islands.

Pollen data analysis

An unsupervised data-driven approach was used to assign pollen samples to vegetation cluster groups for all modern and fossil sites within the Mediterranean (Fyfe et al., 2018; Woodbridge et al., 2018). The approach is based on the similarity of assemblages using Ward's hierarchical agglomerative clustering method (Ward, 1963). Analysis was undertaken using the 'Rioja' R package (Juggins, 2015). A phytosociological classification approach was used to identify the frequent and abundant pollen taxa within each cluster group based on its median and interquartile range (IQR). Interpretive name descriptors were given to each vegetation cluster using the phytosociological classification tables along with comparisons with other classification systems, land cover types defined by remote sensing and the results of previous studies (see Woodbridge et al., 2018).

Non-metric multidimensional scaling (NMDS) was applied to the Spanish fossil datasets (using taxon percentage data aggregated into 200-year time windows) to explore major patterns. NMDS was run using the 'vegan' R package (Oksanen et al., 2016). Data were square-root transformed, and dissimilarity was calculated using Bray-Curtis. Simpson's diversity index (Simpson, 1949) was calculated for each pollen sample and aggregated by region. Three pollen indicator groups were used to summarise key changes in the datasets and identify possible human impact in the records. This included: (a) the average non-arboreal pollen sum (%NAP); (b) the OJC index (sum of *Olea*, *Juglans, Castanea*), an established Mediterranean tree-crop indicator group (Mercuri et al., 2013a); and the anthropogenic pollen index (API: sum of *Artemisia, Centaurea*, Cichorioideae and *Plantago*, cereals, *Urtica* and *Trifolium* type) proposed by Mercuri et al. (2013b). For the OJC index the taxon Oleaceae was grouped with *Olea*. Analysts have routinely separated taxa within the Oleaceae family (e.g. *Fraxinus*, *Phillyrea*); Oleaceae is considered most likely to represent poorly-preserved *Olea*. *Artemisia* is included within the API to facilitate comparison with results from other Mediterranean regions, and the value of the API more broadly is discussed later.

RESULTS

Palaeodemographic change in eastern Iberia

The summed probability distribution (SPD) for radiocarbon dates for all 3885 dates (1438 sites) are shown on Figure 2a. Deviations above or below a null model based on a simple theoretical model of population growth and plateau are highlighted, indicating periods with population growth or decline outside a 95% envelope of the long-term logistic trend. An increase in population is inferred at the start of the Neolithic at 7500 cal. yr BP and the whole of the sequence between 7500 and 6000 cal. yr BP is above the logistic range. The population trend departs significantly over the long-run from a logistic model of population growth (p-value 0.001) at 5600-5300 (end of the Middle Neolithic) and 5000-4700 cal. yr BP inferring population decline. Between these periods the trend indicates population increase at the start of the late Neolithic/Chalcolithic (around 5300-5000 cal. yr BP). Further significant increases in population occur from the early Bronze Age (Argaric period in southeast Spain, c. 4100 cal. yr BP) with population declining towards the start of the late Bronze Age (at 3500 cal. yr BP). Significant population increases occur during the late Bronze Age (at 3200 cal. yr BP) and during the final Bronze Age (3000 cal. yr BP). There are insufficient dates within the Iron Age (after 2500 cal. yr BP) for meaningful interpretations.

Regional divergences from the Eastern Iberia dataset are shown on Figures 2b-d. Northeast Spain includes 1076 radiocarbon dates from 376 sites. We assess to which degree the demographic patterns of each sub-region depart from the pan-regional trend via a permutation test following Crema et al. (2016). This method statistically assesses differences between the SPD of radiocarbon dates within each sub-region and the overall pan-regional average. Population is significantly above the overall pan-regional average throughout the Neolithic, with notable increases at the start of the Neolithic (at 7500 cal. yr BP) followed by a small decline towards the end of the early Neolithic (at 6700 cal. yr BP). A population increase is visible at the start of the late Neolithic/Chalcolithic period. The Bronze Age SPD is significantly below that of the whole dataset, and by the Iron Age the time series starts to become unreliable. There is an increase during the early Bronze Age (from 4000 cal. yr BP) and a decline at the start of the late Bronze Age.

In southeast Spain, the 1219 dates from 306 sites largely follow the general background SDP trends, with the exception of a statistically-significant positive deviation (a population increase and greater than the pan-regional average) at the start of the Neolithic, and a significant negative deviation (population decrease and lower than the pan-regional average) during the middle Neolithic (6100-5900 cal. yr BP). SDP-inferred population is significantly higher throughout the late

Neolithic/Chalcolithic and the early Bronze Age. SPD-inferred population rises steadily, with the peak in population recorded around 3700 cal. yr BP. Significantly lower populations are inferred from the late Bronze Age on.

For the Balearic Islands 1590 radiocarbon dates from 778 sites are used (Figure 2D). The Balearic Islands have a much later date for the start of farming than mainland Iberia, and were the last major Mediterranean islands to be colonised (Burjachs et al., 2017). Prior to the Bronze Age the islands are believed to be uninhabited. Step-wise increases in the SPD are recorded during the late Neolithic (at 4800 cal. yr BP), at the start of the early Bronze Age (4200 cal. yr BP) at the start of the late Bronze Age (3400 cal. yr BP) and during the final Bronze Age (3000 cal. yr BP). From 3400 cal. yr BP the SDP for the Balearic Islands is above the pan-regional trend.

Pollen clusters: synthesis

The 27 pollen sites used in the analysis are divided into three groups (Figure 1; Table 1), covering northeast Spain (7 sites), southeast Spain (12 sites) and the Balearic Islands (8 sites). The results of the hierarchical clustering are presented on Figure 3. The clusters follow the division of Mediterranean pollen assemblages into the 16 groups described in detail in Woodbridge et al. (2018). Not all clusters described by Woodbridge et al. (2018) are represented in the Spanish pollen datasets. The main clusters identified in the Spain pollen are 1.1 (sclerophyllous parkland), 1.3 (steppe parkland), 4.0 (pine forest), 5.1 (pine woods) and 5.2 (pine steppe). The pine clusters are differentiated on the basis of the proportions of pine and the co-occurring taxa within each group. Other groups of note include 1.2 (evergreen shrubland: Oleaceae) and 6.1 (deciduous oak woods). There are clear temporal changes in the representation of the clusters. Sclerophyllous parkland and pine woods are dominant from 11000-9000 cal. yr BP. From 9000 cal. yr BP pine forest and pine steppe both increase, co-incident with decline in pine woods. From 8000 cal. yr BP sclerophyllous parkland declines whilst the number of sites classified as steppe parkland increase. Between 9000-3400 cal. yr BP deciduous oak woods are recognised, but not outside of this time period, and alder woods (8.1) are recognised between 4800-3200 cal. yr BP. Evergreen shrubland (Oleaceae) becomes continuously recognised around 5200 cal. yr BP, declining after 2400 cal. yr BP but rising in the last millennium. Pine steppe has a step-wise increase at 4800 cal. yr BP, and steppe parkland rises at 3000 cal. yr BP. The pine forest group is not recognised after 1400 cal. yr BP.

There are insufficient pollen sites within the northeast and southeast mainland regions to make proportions of clusters in each time window meaningful. Comparison between the Balearic Islands and the mainland show that on the mainland sclerophyllous scrub is limited to the early Holocene (pre-8000 cal. yr BP). In contrast sclerophyllous scrub dominates and persists on the Balearic Islands. The Balearic Islands have a very restricted number of cluster groups, with evergreen shrubland (Oleaceae) from 5800 cal. yr BP, and steppe parkland not appearing until after 2000 cal. yr BP. Pine groups are only sporadically recognised, with pine steppe best represented between 4800-2000 cal. yr BP.

Analysis of pollen data

The low numbers of pollen sites in each mainland region make comparison of the cluster-based results difficult because when cluster results are amalgamated for a region values can be highly influenced by individual sites. Regional differences in vegetation patterns are thus explored using non-metric multidimensional scaling. Performing NMDS with three axes resulting in a stress of 0.175. Biplots of taxon scores for axes 1 and 2 and axes 1 and 3 are shown on Figure 4, with taxa grouped by broad ecological meaning (sclerophyllous taxa, non-sclerophyllous arboreal taxa, the OJC group (plus *Vitis*), the API group, and other herbaceous taxa). Taxa in the OJC group plot together in the ordination space, close to the centre of the plot. The API taxa are widely dispersed along axis 1, but are tightly grouped on axis 2 (Figure 4a). The exception is *Plantago lanceolata* that lies distant from all other taxa, low on axis 2. There is no clear separation between sclerophyllous and non-sclerophyllous taxa on either biplot, and herbaceous taxa are widely dispersed. These patterns are likely to be a function of the highly heterogeneous nature of Mediterranean vegetation.

Biplots of site scores for each 200-year time window show groupings of sites from 9900-100 cal. yr BP (Figure 5a,b; labelled version in Supplementary Information). The plots show a clear separation between the Balearic Islands and the mainland sites for most of the Holocene, with the sites on the Balearic Islands inhabiting the upper left quadrant. Between 9900-4900 several mainland sites plot within the same ordination space as the Balearic Island records, demonstrating similar pollen assemblages (Antas, San Rafael and Elx). Creixell remains grouped within the Balearic sites throughout the entire period. From 6300-5300 cal. yr BP a distinct grouping of sites occurs in the lower left quadrant of the biplots. This includes the high elevation sites in southeast Spain (Baza, Gador, Siles, Sabinar and Villaverde) but also includes the mid-elevation site at Navarrés and the northeast Spain site Lake Banyoles. Beyond the grouping of the Balearic Islands sites and the high elevation sites there are no other clear groupings in the dataset that persist through time. Mainland sites from the southeast and northeast occupy similar areas of the biplots (e.g. see biplots for 6900 and 3300 cal. yr BP).

The difference in position of site across the three NMDS axes (chord distance) between adjacent time intervals is used as an estimate of the rate of change in pollen assemblages. Values are averaged for each region to examine region-scale drivers of vegetation change (demographic and climatic change). These mean chord distances are shown on Figure 6 alongside key pollen indices (NAP sum, the OJC and API indices and Simpson's diversity index), the radiocarbon SPD and regional climate records. Low values for mean NMDS chord distances imply stability in vegetation, whilst higher values indicate greater changes in assemblages between time windows. In northeast Spain NMDS chord distance scores show distinct increases starting at 7500 cal. yr BP (peak at 7100 cal. yr BP), at 5100 cal. yr BP (peak at 4500 cal. yr BP) and at 3100 cal. yr BP. Between these peaks values return to low levels implying stable vegetation between time windows. The increase at 7500 cal. yr BP is coincident with increases in the NAP sum, a rise in Simpson's diversity index and the first peak in the radiocarbon SDP. The rise in mean NMDS chord distance score at 5100 cal. yr BP is coincident with an increase in radiocarbon SDP values. The rise in mean NMDS chord distance score at 3100 cal. yr BP corresponds with an increase in NAP sum, the first continuous OJC index curve and an increase in the API. The Simpson's diversity score suggests that diversity is highest from 6000 cal. yr BP, with greatest diversity at 500 cal. yr BP.

The summary metrics for southeast Spain indicate a much higher NAP sum compared to northeast Spain during the early Holocene (around 40% for southeast Spain compared to 20% for the northeast sequences). The API also shows high levels, in excess of 10% during the early Holocene when human impact should be minimal. The mean NMDS chord distances show some suggestion of cyclic behaviour over millennial timescales, but peaks are more muted than in northeast Spain. Peaks occur around 9100, 7500, 6300, 4100 and 700 cal. yr BP. The most notable change in the indices is an increase in the NAP sum from around 5500 cal. yr BP, which is coincident with a small step-increase in the API index, a major rise in the Simpson's diversity index and the major increase in the radiocarbon SPD. The Simpson's diversity index falls to low levels at 2300 cal. yr BP from a peak at 3500 cal. yr BP. It then increases again, peaking at 1500 cal. yr BP, coincident with a second increase in the NAP sum.

In the Balearic Islands, the mean NMDS chord distance is highest at the start of the records (at 8700-8300 cal. yr BP) and drops to 'baseline' values centred around 0.4. This is much higher than values for northeast and southeast Spain, which have baselines around 0.2. An isolated peak in mean NMDS chord distance scores for the Balearic Islands occurs at 2900 cal. yr BP, with increasing scores from 3500 cal. yr BP. The peak coincides with the maximum radiocarbon SPD value. Neither the OJC nor API trends bear any relationship to the radiocarbon SPD. The Simpson's diversity scores are broadly stable but decline from 3500 cal. yr BP.

Correlation between palaeodemographics, palaeoclimate and pollen-based indices

Correlation matrices for each region, for key pollen indicators shown on Figure 6, radiocarbon SPD and regional climatic records are given on Tables 2-4. Correlation is assessed using Spearman's Rank Correlation Coefficient (R-values) and statistically-significant results ($p<0.05$) are highlighted. In northeast Spain significant positive correlations are found between radiocarbon SPD and the NMDS chord distance, NAP sum and OJC index. The NAP sum is also positively correlated with the OJC index, API and Simpson's diversity. Simpson's diversity is also positively correlated with the OJC index. In southeast Spain the radiocarbon SPD is negatively correlated with the OJC index, and positively correlated with Simpson's diversity. Simpson's diversity is also positively correlated with the NAP sum, but negatively correlated with the OJC index. In the Balearic Islands radiocarbon SPD is positively correlated with the NAP sum, the OJC index and Simpson's diversity, even major changes in demographics and pollen indices do not appear to align (Figure 6). The NAP sum is positively correlated with the OJC and API, and OJC index with Simpson's diversity.

DISCUSSION

Palaeodemographic trends in eastern Iberia, 10000-2500 cal. yr BP

Clear palaeodemographic changes are seen in eastern Iberia through the compilation of archaeological radiocarbon dates and the production of summed probability distributions (Figure 2a). The start of the Neolithic across the whole study region is clearly marked by a step-wise increase in the summed probability distributions at 7500 cal. yr BP. This accords well with the established timing of the Mesolithic/Neolithic transition in eastern Iberia (García Puchol et al., 2009; Fernández-López de Pablo and Gómez-Puche, 2009; García Puchol and Salazar-García, 2017; Oms et al., 2018). There are regional differences between the north and south study areas, with a more abrupt increase in the northeast, and a more gradual, and marginally earlier, increase in the southeast. Oms et al. (2018) suggested full expansion of the Neolithic in the northeast was marginally delayed from the littoral locations favoured by the first Neolithic areas. The significant demographic expansion in Figure 2 agrees with general radiocarbon-based models of population growth across Iberia as a whole (Balsera et al., 2015b) and in more detailed regional analyses that shows the earliest Neolithic population expansion in the east of the peninsula (Drake et al., 2017). In the northeast (Figure 2b) a decline in the SPD around 6700 cal. yr BP implies a 'bust' following the demographic boom of the earlier Neolithic, a feature also recognised by Drake et al. (2017) in their regional analysis, and a pattern that follows trends identified in temperate Europe (Shennan et al., 2013). The pattern is replicated in the southeast with a shorter boom phase. The causes of the boom and bust phenomena in Europe remain unclear, but a longer Neolithic 'boom' in the north east might reflect more successful agrarian strategies in the less arid northern regions around the Ebro valley and the foothills of the Pyrenees.

The pattern of radiocarbon-inferred population demographics for southeast Spain from the late Neolithic/Chalcolithic to the late Bronze Age is similar to that of Lillios et al. (2016). Lillios et al. (2016) do not observe major deviations from a null model based on logistic growth for the southeast, and observe pronounced differences between population trends in the southeast, southwest and northwest. In the southeast settlement aggregation is observed in landscape survey and excavation (Blanco-González et al., 2018), and it is widely accepted that populations increased by up to as much as three times from late Neolithic levels with the development of the Argaric Bronze Age society in southeast Iberia (Aranda Jiménez et al., 2014). The results show a long period growth that peaks around 4000 cal. yr BP. Lillios et al. (2016) do not present radiocarbon SPD from the northeast across the late Neolithic/Chalcolithic and Bronze Age, but the region is included in the synthesis of Blanco-González et al. (2018). Our results confirm those of Blanco-González et al. (2018) and indicate strong interregional differences in SPD-inferred demographic patterns: the major increases and declines in population in the southeast are not reflected in patterns in the northeast. Within the northeast the late Neolithic/Chalcolithic is characterised by continuity in cultural practice (including subsistence, settlement and technology) until c.4400 cal. yr BP (Blanco-González et al., 2018), although increases in the radiocarbon SPD do not occur until 4000 cal. yr BP (Figure 2a).

The precise timing of the first settlement on the Balearic Islands is not well defined (Burjachs et al., 2017), but unequivocal evidence for human presence exists from the late Neolithic/Chalcolithic period (Ramis et al., 2002). From 4300-3800 cal. yr BP sedentary cultures are well known. No published radiocarbon SPD for the islands is known. The pattern in Figure 2d shows a small increase at 4700 cal. yr BP signalling early but low levels of cultural material, followed by increasing population levels after 4200 cal. yr BP. Radiocarbon-inferred populations continue to increase through the Bronze Age reaching a peak in the Iron Age (c.2500 cal. yr BP) and are associated on the easternmost Balearic Islands (Mallorca and Menorca) with the indigenous Talaiotic Culture. Pérez-Jordà et al. (2018) indicate that the earliest settlers came with a complete agricultural package, including domesticated animals, cereals and legumes, with strong similarities to the Catalonian (northeast) subsistence traditions.

Human impact on vegetation dynamics in eastern Iberia

Assessing human drivers of vegetation change in Mediterranean regions is confounded by the multiple potential factors that can cause vegetational change, in particular climatic variations (Carrión, 2002). There has also been much debate over the role of climate in cultural and demographic change within Iberia (e.g. Fernández-López de Pablo and Gómez-Puche, 2009; Bernabeu et al., 2016; Blanco-González et al., 2018), implying that separation of these drivers of land cover change may be difficult. In spite of this the strong demographic signals that have emerged from the synthesis of radiocarbon dates can be compared to transformed pollen data to assess the extent to which population changes can explain changes in palaeovegetation patterns.

Northeast Spain

The results from northeast Spain indicate a significant correlation between the radiocarbon-inferred palaeodemographics and key human impact indicators (Table 2, Figure 6a). Increased population levels are associated with higher total NAP values, suggesting increasing levels of open ground, and the correlation with the OJC index implies higher levels of tree cropping associated with higher population levels. This does not mean taxa within the OJC group are domesticated early in Prehistory, and previous work does not demonstrate full domestication of these taxa until the third millennium cal. yr BP (Rodríguez-Ariza and Montes Moya, 2005). Prehistoric societies are likely to have transformed vegetation to promote such useful wild resources (e.g. Rowley-Conwy and Layton, 2011). The positive relationship between demographic increases and rates of change is consistent with human transformation of land cover in response to higher population levels. There are insufficient pollen sites to evaluate changes in the dominant land cover types (clusters) between the northeast and southeast of Iberia; however, the overall pattern from the mainland sites shown on

Figure 3 implies fragmentation of pine-dominated vegetation communities and an expansion of pine steppe (cluster 5.2), particularly from 5000 cal. yr BP, and steppe parkland (cluster 1.3) during the earlier Neolithic period. Recent links between cultural transitions and climatic change have been made (e.g. Cortés-Sánchez et al., 2012, Bernabeu Aubán et al., 2016), and episodes of abrupt climate change such as the 4.2 ka cal BP event have been linked to changing land use strategies and population levels (Blanco-González et al., 2018). More favourable climatic conditions may have been one of a series of factors that promoted population expansion, presumably as a consequence of improved agrarian conditions. The Neolithic archaeobotanical datasets demonstrate permanent fields rather than shifting cultivation (Antolín et al., 2015). Gathering of wild food through the Neolithic period indicates intensive but sustainable exploitation of both domesticated and wild resources (Antolín and Jacomet, 2015), a pattern also seen in other parts of Europe (e.g. Bevan et al., 2017).

It is not possible to compare pollen-inferred land cover changes with archaeologically-inferred population levels after ~2500 cal. yr BP. However, the main pollen classification changes after this time involved tree crops and anthropogenic indicators rather than overall tree cover. Most of the Holocene decline in arboreal pollen in northeast Iberia occurred during prehistoric rather historic times, notably between 7300 and 2500 cal. yr BP. This process of forest loss was almost certainly multi-causal, but the results presented here indicate that human agencies potentially contributed to this process soon after the arrival of Neolithic farming.

Southeast Spain

In contrast to the correlations between past population and vegetation indices in the northeast there are no statistically significant positive relationships observed in the southeast, other than between population levels and vegetation diversity. Increased openness in the landscapes (i.e. higher NAP values) also results in greater diversity, although this correlation (+0.337) is not statistically significant. This pattern can be expected if a greater degree of openness signifies a greater number of different vegetation communities. Previous work at the European scale has indicated latitudinal gradients in diversity, with highest diversity levels in the most southern regions of Europe and this pattern has previously been observed using Holocene pollen data (Silvertown, 1985). The significant negative relationship between OJC and demographics demonstrates, at least in part, the difficulty in separating wild from domesticated taxa. Finds of wild olive in Iberia have been recognised during the Neolithic (Antolín and Jacomet, 2015), but intensification of olive production for trade does not begin until the Roman period in eastern Spain (Terral and Arnold-Simard, 1996, and see Langgut et al., in review). The value of these human impact indices, including the API, is thus questionable in this sub-region. Many of the indicator taxa used are characteristic of disturbed open ground, and *Artemisia* can also be a strong indicator of arid conditions. These are exactly the conditions that are found in southeast Spain through the early Holocene, a region which includes the most arid part of Europe. In the analysis for southeast Spain, the API shows high values at the start of the Holocene (Figure 6), reducing to their lowest values before climbing again from around 6000 cal. yr BP. It seems logical to interpret increases in the API with human impact, particularly as after 7500 cal. yr BP; however, this is clearly a complex indicator group that includes natural disturbance factors including fire and climatic factors, such as aridity.

In spite of the lack of correlation between NAP sum and radiocarbon SPD across the whole record in southeast Spain, the major rise of population from the Chalcolithic to the late Bronze Age (between 5500-3500 cal. yr BP) is strongly aligned with increases in these openness indicators, and this appears to strongly control vegetation diversity. The NMDS chord distance indicates greater change in vegetation assemblages through this period also. The increase in population levels by possibly up to three times through the Argaric period thus had a major impact on vegetation character in the region. Per capita human impact also increased at the start of Bronze Age, as metallurgy led to exploitation of Iberia's abundant mineral resources. Mining and copper/bronze smelting has been reported from the start of the 5th millennium BP (Murillo-Barroso et al., 2017), but the major increases in production associated with the Argaric culture would have led to increased use of wood fuel, and hence in deforestation. The imprint of Chalcolithic and Argaric culture population and economic rise can be seen in the mean NAP sum in the southeast Spanish pollen records, which declined progressively between 5000 and 3700 cal. yr BP. It also led to a shift from pine forests/woods (clusters 2 and 3) to more open pine steppe (cluster 6). The demographic collapse during the late Bronze Age (from 3500 cal. yr BP) only led lead to a temporary reversal in the trajectory of vegetation change. There was a minor re-expansion of arboreal vegetation between 3600 and 3000 cal. yr BP. The limited scale of vegetation recovery may be a consequence of degradation of the landscape through grazing, combined with higher aridity, resulting in bioclimatic limits to the growth of woody vegetation (Carrión et al., 2007; Pérez-Obiol et al., 2011). It is not possible to compare human population trends and pollen-inferred land cover change after ~2500 cal. yr BP using the data presented here. However, in many pollen records from southeast Spain, it is precisely at this point in time that large-scale human transformation of vegetation cover becomes clearly detectable, for example at Mar Menor on the coast of Murcia (Azuara, 2018).

Balearic Islands

Several important contributions discuss both the general vegetation history (Burjachs et al., 2017) and patterns of land use (Pérez-Jordà et al., 2018) in the Balearic Islands. Burjachs et al. (2017) established that groups of islands have differences in their vegetation histories, notably between the eastern Gymnesian islands (Mallorca and Menorca) versus the western Balearic Islands of Ibiza and Formentera. These broad patterns are supported by the analysis presented here. Changes in vegetation assemblages between 6000 and 5000 cal. yr BP in the overall cluster-based analysis (Figure 3c) have been attributed to regional climatic change by Burjachs et al. (2017). This might explain increases in the NAP sum, and the OJC index from 6000 cal. yr BP (Figure 6), reflecting a cooling trend and increasing aridity limiting growth of mesic woodland. This demonstrates the sensitivity of vegetation in the western Mediterranean to natural climatic variability, at least through the early to mid-Holocene. Comparison of pollen indices against continuous proxy-based climate records from the Balearic Islands is currently not possible owing to a lack of published regionally-relevant climate records (see Finné et al., in review, for a more complete discussion on Mediterranean climate and teleconnections).

Strong positive correlations between the radiocarbon SPD and human impact indicator groups (NAP sum and OJC) are a result of the rank-order correlation approach used: the highest values of demographics coincide with the highest levels of NAP and the OJC index, although the patterns are not immediately obvious from the curves presented (Figure 6C). Once again, the utility of indices of human impact that are based on naturally-occurring taxa, particularly those whose abundances relate to a wide variety of disturbance processes, is questionable for periods before demonstrable human impact. Pérez-Jordà et al. (2018) do not find strong evidence for *Olea* cultivation on the Balearic Islands until the Iron Age. *Olea* is present and can be locally abundant in the sclerophyllous vegetation of the islands, as such it has been argued that consumption could be a result of gathering of wild fruits (and see Langgut et al., in review).

CONCLUSIONS

The synthesis of pollen data and comparison with a proxy for palaeodemographics demonstrates regional differences in the impact of population change on vegetation across eastern Iberia and the Balearic Islands. In northeast Iberia patterns of demographic change are strongly linked to changes in vegetation diversity and human impact indicator groups. In the more arid southeast relationship patterns in human impact indicator types and past population demographics are less clear, but the rise in population through the Chalcolithic and early Bronze Age Los Millares and Argaric cultures results in more open landscapes and increased vegetation diversity. Vegetation diversity decreases as population levels fall, but the landscape remains open, presumably as a result of soil degradation and increasing aridity into the late Holocene. On the Balearic Islands, prior to initial human colonisation, climate was the primary pacemaker of vegetation in the early and middle Holocene.

There was no clear synchronism between demographic trends in the three sub-regions of eastern Iberia between 10000 and 2500 cal. yr BP, other than the rise in population on the mainland at the start of Neolithic farming ~7600-7300 cal. yr BP. In northeast Iberia population grew rapidly after this time and stayed high, whereas in southeast Spain the main demographic rise occurred much later (after 5300 cal. yr BP) and population subsequently declined (after 3500 cal. yr BP). While regional population in southeastern Spain peaked soon after the start of the Argaric culture, on the Balearics the demographic maximum occurred early in the 3rd millennium cal BP, during the early Iron Age Talaiotic Culture. As we can assume that these three sub-regions experienced a broadly similar climatic history, it can be inferred that climate changes were not the main pacemaker for long-term demographic trends for eastern Iberia as a whole, even though they must have contributed to societal changes in a variety of ways. For example, the 4.2 ka abrupt climate event coincided with, and may have influenced, the transition between the Late Chalcolithic Los Millares culture and the Early Bronze Age Argaric culture in southeast Iberia (Lull et al., 2015). However, it had no detectable consequences for demographic trends in this sub-region, with inferred population reaching a peak just after 4200 Cal yr BP. Nor does the pollen evidence analysed here indicate that this short-lived dry phase had any clearly detectable direct consequences for vegetation in eastern Iberia.

Human impact indicator groups are challenging to interpret for many Mediterranean regions, as they include many taxa found within the natural vegetation. Patterns in these indicator groups are simpler to interpret during the early Holocene prior to the first farming communities (when vegetation is driven by climate and natural disturbance processes) and the late Holocene (when vegetation is largely controlled by human transformation). Disentangling the relative importance of natural and anthropogenic impact in the mid-Holocene is more difficult. Pollen diversity in all regions is strongly related to radiocarbon-inferred population levels, and the NMDS chord distance shows a strong relationship with prehistoric demography. This supports the assertion of Carrión et al. (2010a) that human impacts should result in greater rates of change in vegetation. The analysis presented here supports a role for climatic forcing of vegetation at the large scale, but clearly demonstrates the importance of population changes in shaping the abundance and diversity of taxa within broad biomes.

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Table 1: sites used within the Spain case study analysis *indicates dataset from the EPD

Site#	SiteName	site code	LatDD	LonDD	Elevation	Region	References/contributor
1	Amposta	AMPOSTA	40.704	0.597	5	NESpain	Pérez-Obiol 2007, Pérez-Obiol et al 2011
2	Creixell	CREIXELL	41.166	1.440	5	NESpain	Burjachs and Schulte 2003, Carrión 2012, Burjachs and Expósito 2015
3	Laguna Salada Chiprana*	N-SAL	41.233	-0.166	150	NESpain	EPD dataset: no citation
4	Lake Banyoles* Banyoles SB2	BANYOLES	42.133	2.750	175	NESpain	Pérez-Obiol and Julià 1994 Revelles et al 2015
5	Hoya del Castillo*	N-CAS	41.250	-0.500	250	NESpain	Davis and Stevenson 2007
6	Laguna Guallar*	N-GUA	41.400	-0.216	330	NESpain	Davis and Stevenson 2007
7	Salada Pequeña*	N-PEQ	41.033	-0.216	360	NESpain	EPD dataset: no citation
8	Roquetas de Mar*	ROQUETAS	36.7944	-2.588	5	SESpain	Pantaleón-Cano et al 2003
9	San Rafael*	SANRAFA	36.773	-2.601	5	SESpain	Pantaleón-Cano et al 2003
10	Elx (Alacant)	ELX	38.174	-0.752	10	SESpain	Burjachs et al 1997, Carrión 2012
11	Antas*	ANTAS	37.208	-1.823	10	SESpain	Pantaleón-Cano et al 2003
12	Navarrés *	NAVARRES, NAVA 1+2, NAVARRE3	39.070	-0.680	225	SESpain	Carrión and Dupré-Olivier 1996; Carrión and van Geel 1999
13	Salines (Alacant)	SALINES	38.500	-0.888	500	SESpain	Giralt et al 1999, Carrión 2012, Burjachs et al 2016
14	Villaverde	VILLAVERDE	38.800	-2.220	890	SESpain	Carrión et al 2001a
15	Siles	SILES	38.440	-2.510	1050	SESpain	Carrión et al 2001b
16	Sabinar	SABINAR	38.200	-2.116	1130	SESpain	Carrión et al 2004
17	Gador	GADOR	36.930	-2.910	1650	SESpain	Carrión et al 2003
18	Cañada de la Cruz	CANADACRUZ	38.066	-2.700	1650	SESpain	Carrión et al 2001b
19	Baza	BAZA	37.233	-2.700	1850	SESpain	Carrión et al 2007
20	Prat de Vila (Eivissa)	PRATDEVILA	38.915	1.435	5	Balearic	Burjachs et al 2017
21	Albufera Alcúdia (Majorque)*	ALCUDIA	39.792	3.119	5	Balearic	Burjachs et al 1994, Burjachs et al 2017
22	Es Grau (Menorca)	ESGRAU	39.948	4.258	30	Balearic	Burjachs 2006
23	Son Bou*	SONBOU	39.924	4.027	15	Balearic	Yll et al 1997
24	Algendar*	ALGENDAR	39.940	3.958	20	Balearic	Yll et al 1995
25	Cala'n Porter*	CPORTER	39.870	4.131	25	Balearic	Yll et al 1997
26	Hort Timoner*	HTIMONER	39.875	4.126	40	Balearic	Yll et al 1997
27	Cala Galdana*	GALDANA	39.900	4.000	50	Balearic	Yll et al 1995
A	Laguna de Medina	-				SESpain	Reed et al 2001
B	Lake Estanya	-				NESpain	Morellón et al 2009

Table 2: Northeast Spain Spearmans' Rank Correlation Coefficient r-value matrix for the period 10000-2500 cal. yr BP. Shaded boxes indicate p<0.05.

	14C SPD	NMDS chord distance	NAP sum	OJC index	API	Simpson's diversity	Estanya z-score
14C SPD	1.000	**0.269**	**0.647**	**0.408**	0.324	0.287	-0.013
NMDS chord distance		1.000	0.228	0.031	0.128	0.092	-0.009
NAP sum			1.000	**0.415**	**0.747**	**0.607**	0.029
OJC index				1.000	0.265	**0.521**	-0.153
API					1.000	**0.424**	0.0153
Simpson's diversity						1.000	-0.265
Estanya z-score							1.000

Table 3: Southeast Spain Spearmans' Rank Correlation Coefficient r-value matrix for the period 9000-2500 cal. yr BP. Shaded boxes indicate p<0.05.

	14C SPD	NMDS chord distance	NAP sum	OJC index	API	Simpson's diversity	Laguna de Medina z-score
14C SPD	1.000	0.338	0.008	**-0.585**	-0.152	**0.387**	0.115
NMDS chord distance		1.000	0.035	-0.220	-0.090	0.156	0.135
NAP sum			1.000	-0.322	**0.466**	**0.431**	0.232
OJC index				1.000	-0.073	**-0.354**	-0.189
API					1.000	0.068	0.098
Simpson's diversity						1.000	0.073
Laguna de Medina z-score							1.000

Table 4: Balearic Islands Spearmans' Rank Correlation Coefficient r-value matrix for the period 9000-2000 cal. yr BP. Shaded boxes indicate $p<0.05$.

	14C SPD	nMDS chord distance	NAP sum	OJC index	API	Simpson's diversity
14C SPD	1.000	-0.095	**0.739**	**0.734**	-0.214	**0.345**
nMDS chord distance		1.000	-0.300	0.019	-0.313	0.049
NAP sum			1.000	**0.762**	0.306	**0.438**
OJC index				1.000	0.138	**0.435**
API					1.000	0.025
Simpson's diversity						1.000

Figure 1: location of pollen samples (sub-fossil and surface samples) and archaeological radiocarbon dates used within the analysis. The division between northeast and southeast Spain is indicated by the dashed line. Pollen site numbers are the same as those in Table 1. Palaeoclimate sequences: (A) Laguna de Medina (Reed et al. 2001); (B) Lake Estanya (Morellón et al. 2009).

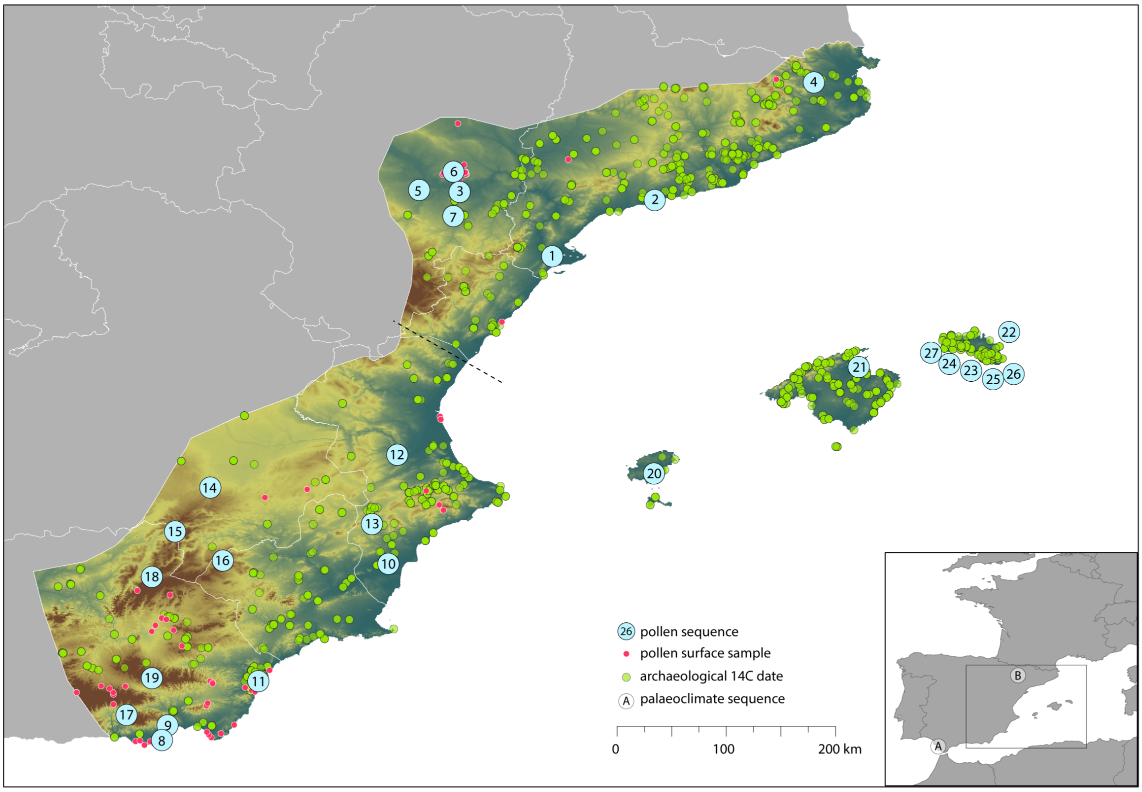


Figure 2: Summed Probability Distributions (SDP) of un-normalised calibrated radiocarbon dates (cal. yr BP). A: all radiocarbon dates against a fitted logistic model (95% confidence); B: north-east Spain, with SDP for all eastern Spain dates; C: south-east Spain, with SDP for all Spain dates; D: Balearic Islands, with SDP for all Spain dates. Vertical bands indicate negative or positive deviations from the null model (panel A) or all Spain dates (B-D).

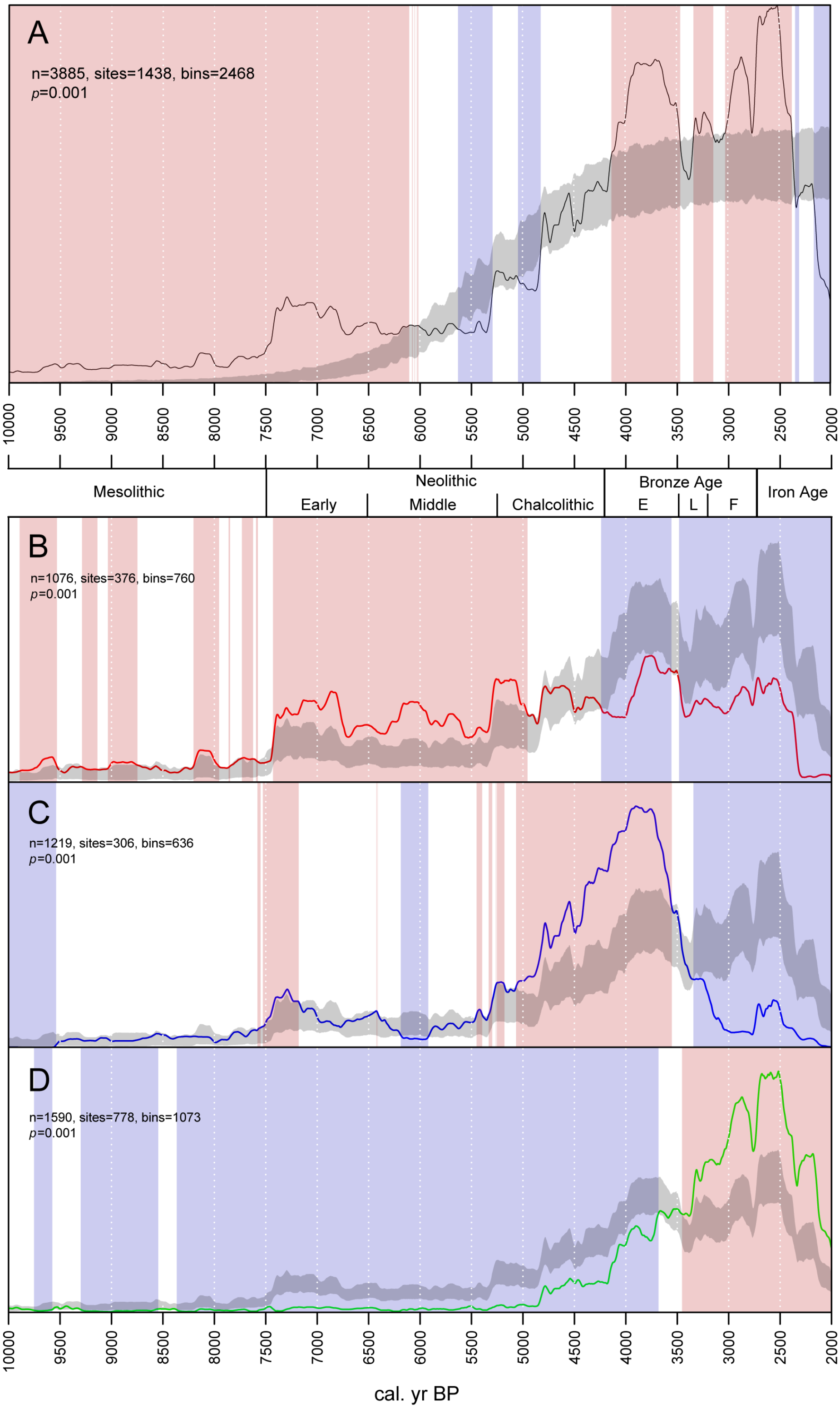


Figure 3: relative proportions of pollen samples within each vegetation cluster in each time window, for (A) all sites, (B) sites on mainland Spain (northeast and southeast regions combined) and (C) Balearic Islands. Radiocarbon summed probability distributions show results for all dates collated. Time windows with insufficient radiocarbon dates for reliable SDP are shown in white.

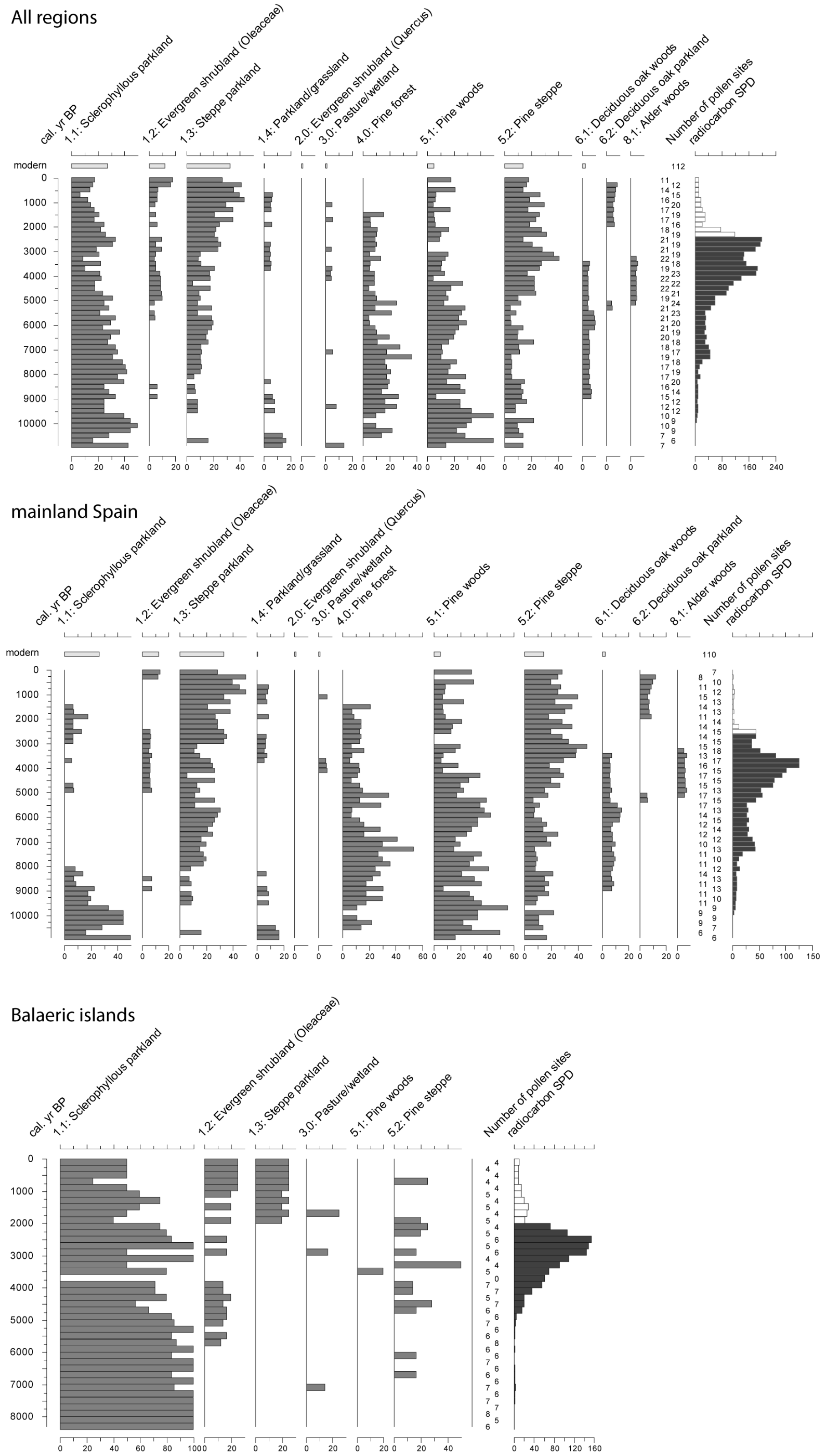


Figure 4: taxa plots from non-metric multidimensional scaling (NMDS) analysis of all sites, showing (A) axis 1 vs 2 and (B) axis 1 vs 3. Taxa are grouped in broad ecological or anthropogenic indicator classes.

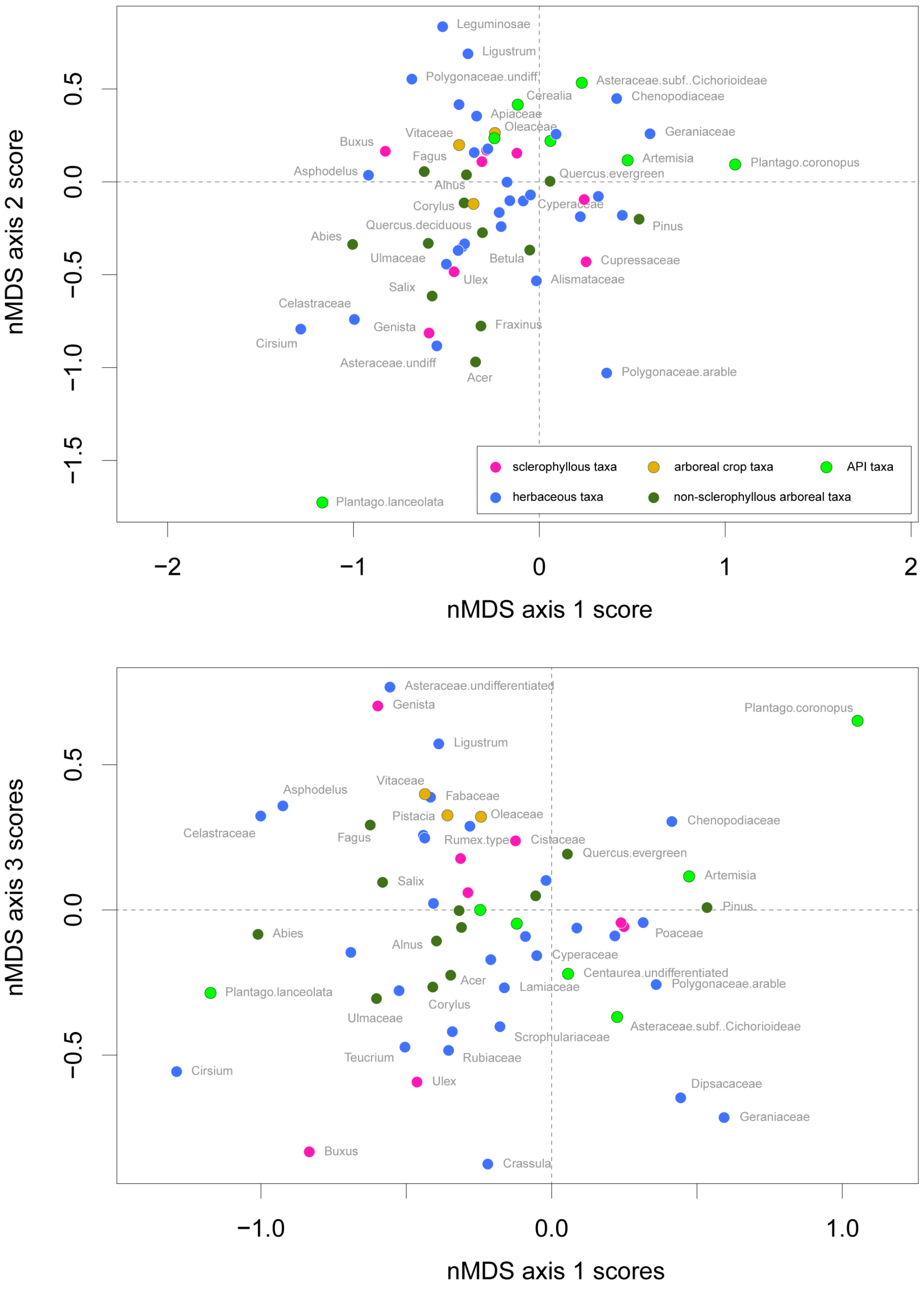
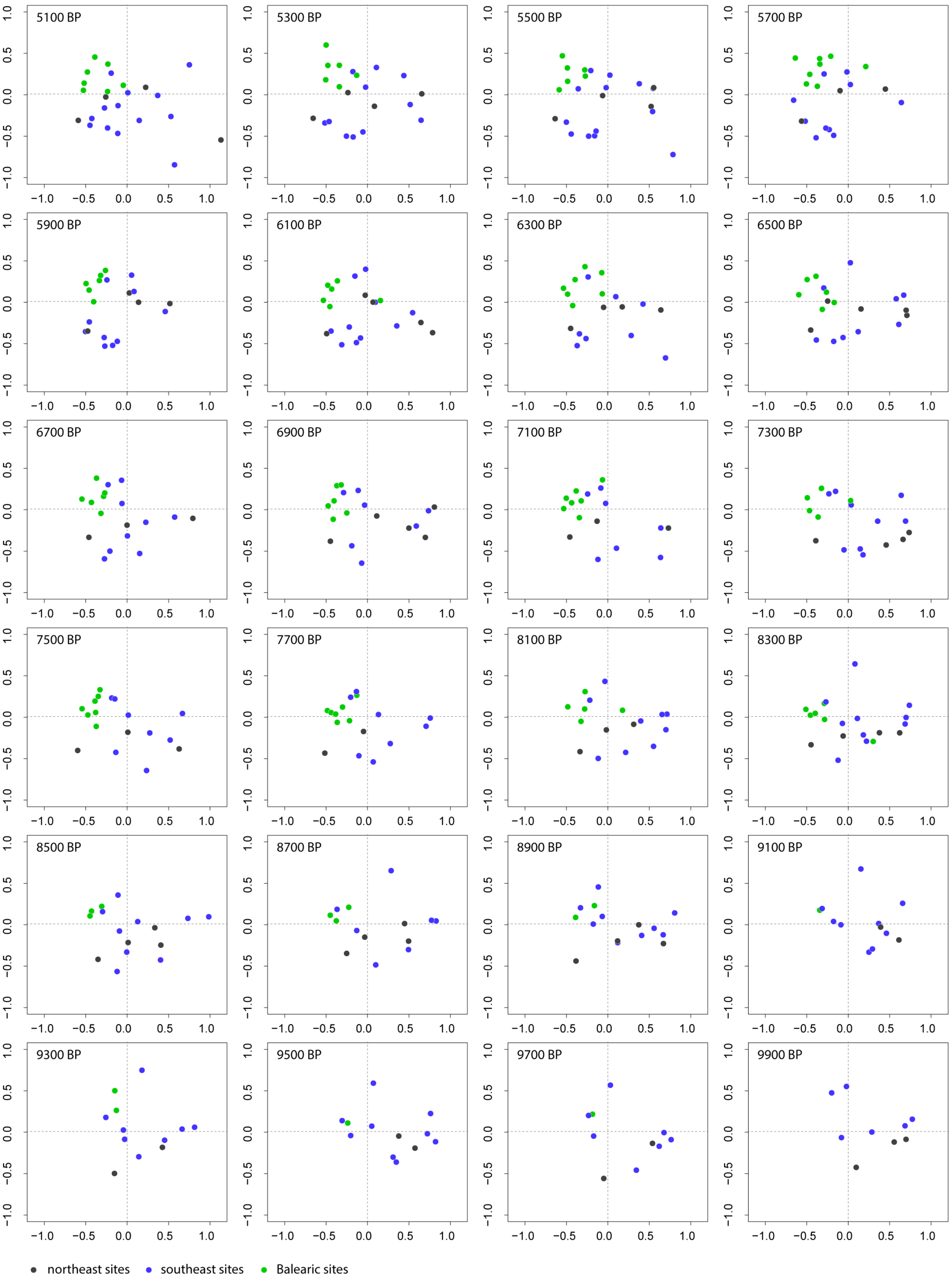


Figure 5: site plots from non-metric multidimensional scaling (NMDS) analysis in each time interval. (A) 9900-5100 cal. yr BP; (B): 4900-100 cal. yr BP. Plot shows axis 1 vs 2 scores. Green is Balearic sites, black northeast Spanish sites and blue southeast Spanish sites. [labelled version in Supplementary Information]



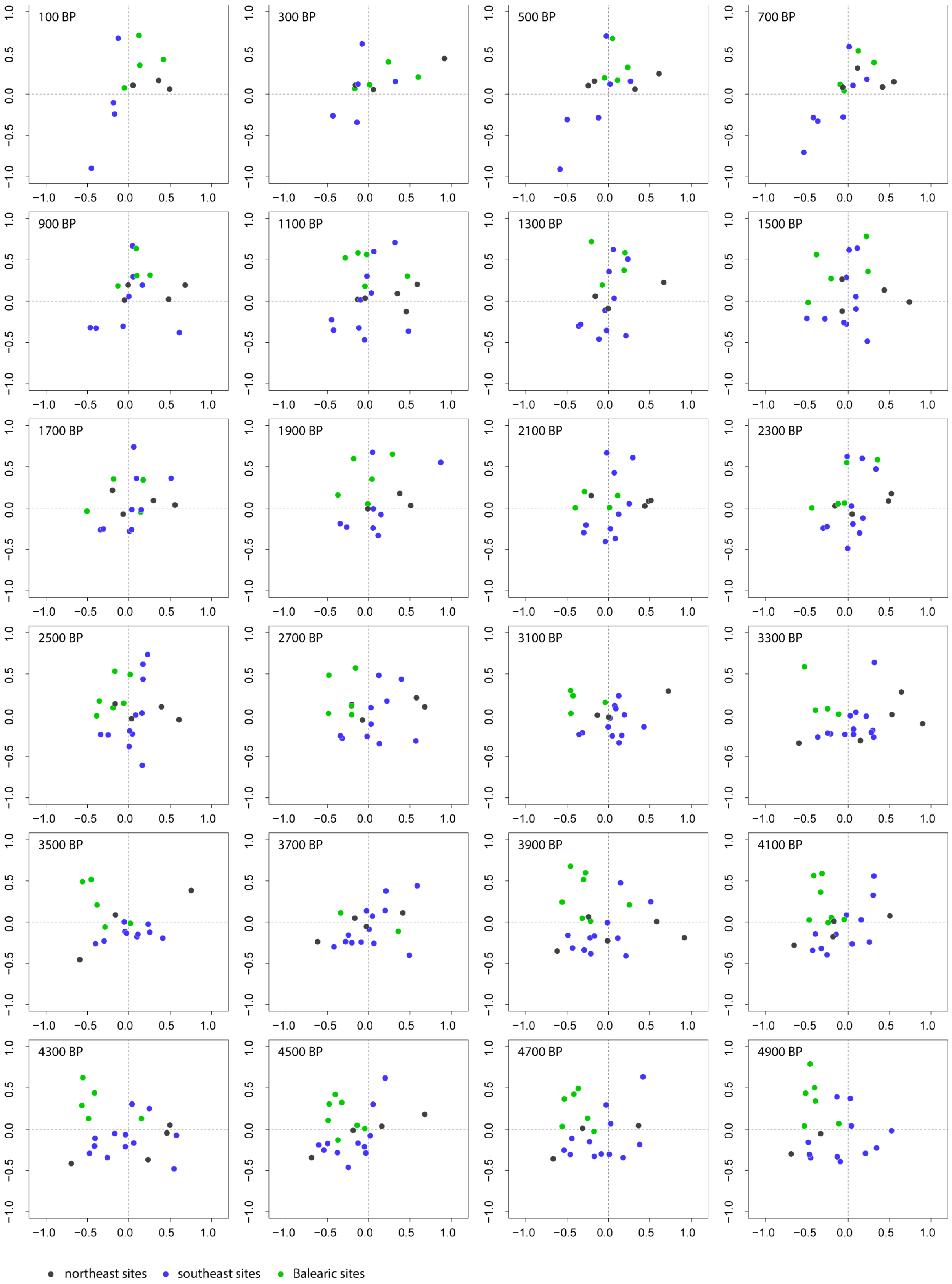
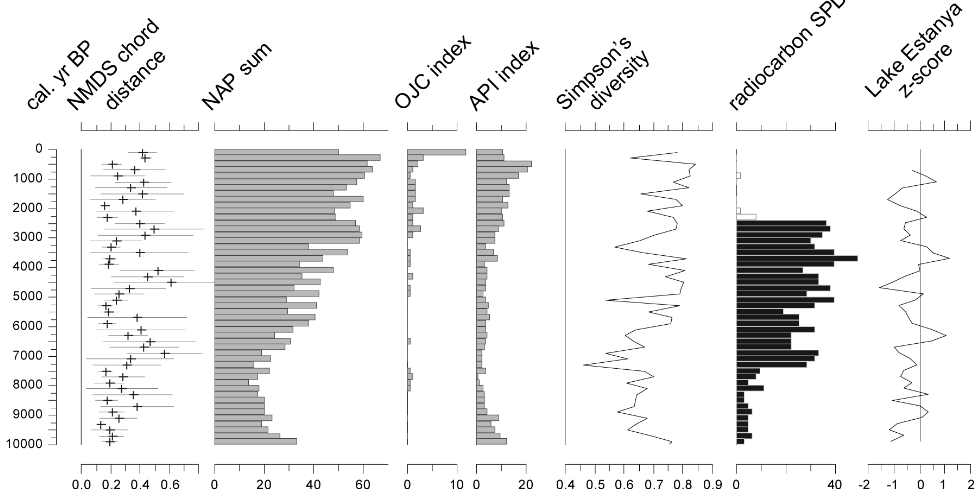
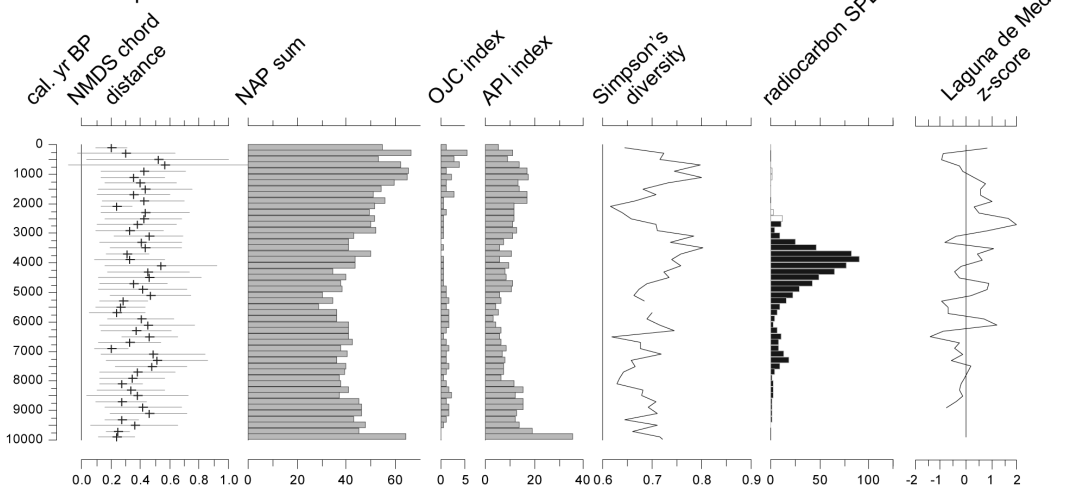

100 BP
300 BP
500 BP
700 BP
900 BP
1100 BP
1300 BP
1500 BP
1700 BP
1900 BP
2100 BP
2300 BP
2500 BP
2700 BP
3100 BP
3300 BP
3500 BP
3700 BP
3900 BP
4100 BP
4300 BP
4500 BP
4700 BP
4900 BP
−1.0
−0.5
0.0
0.5
1.0
● northeast sites
● southeast sites
● Balearic sites

Figure 6: regional plots of pollen assemblage change (mean NMDS chord distance), sum of non-arboreal pollen types, key anthropogenic indicator groups (API and OJC), Simpson's diversity index, radiocarbon summed probability distributions for each region and z-scores for regional proxy-climate records (Lake Estanya: Morellón et al 2009; Laguna de Medina: Reed et al 2001).

Northeast Spain



Southeast Spain



Balearic Islands