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Pollen-inferred regional vegetation patterns and demographic change in Southern Anatolia through the Holocene

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Abstract

Southern Anatolia is a highly significant area within the Mediterranean, particularly in terms of understanding how agriculture moved into Europe from neighbouring regions. This study uses pollen, palaeoclimate and archaeological evidence to investigate the relationships between demography and vegetation change, and to explore how the development of agriculture varied spatially. Data from 21 fossil pollen records have been transformed into forested, parkland and open vegetation types using cluster analysis. Patterns of change have been explored using non-metric multidimensional scaling (nMDS) and through analysis of indicator groups, such as an Anthropogenic Pollen Index, and Simpson's Diversity. Settlement data, which indicate population densities, and summed radiocarbon dates for archaeological sites have been used as a proxy for demographic change. The pollen and archaeological records confirm that farming can be detected earlier (around 7000 cal. yr. BP) in Anatolia in comparison with other parts of the Mediterranean. Dynamics of change in grazing indicators and the OJCV (*Olea, Juglans, Castanea,* and *Vitis*) index for cultivated trees appear to match cycles of population expansion and decline. Vegetation and land use change is also influenced by other factors, such as climate change. Investigating the early impacts of anthropogenic activities (e.g. woodcutting, animal herding, the use of fire and agriculture) is key to understanding how societies have modified the environment since the mid-late Holocene, despite the capacity of ecological systems to absorb recurrent disturbances. The results of this study suggest that shifting human population dynamics played an important role in shaping land cover in central and southern Anatolia.

Keywords
Anatolia; Archaeology; Pollen; Demography; Land cover; Vegetation

Introduction

The vegetation history of Anatolia

Southern Anatolia can be broadly divided into three main sub-regions, namely the coastal zone, the Taurus Mountains with intramontane lake basins, and the inner Anatolian plateau (Iyigun et al., 2013). The modern landscape of Anatolia has developed over many millennia as a result of complex interactions between climate, human land use, natural and anthropogenic fire, and other factors, such as competition and species interactions. The late-Pleistocene landscape of inner Anatolia was characterised by species-rich savannah-type grassland, which was replaced in the early Holocene by *Quercus*-dominated parklands and wood pastures of lower diversity (Asouti and Kabukcu, 2014) in to the mid-Holocene. In the wetter uplands of southwest Turkey, mixed conifer-deciduous forests replaced the *Artemisia*-chenopod steppe of the last glacial period (van Zeist and Bottema, 1991).

Archaeobotanical and archaeozoological evidence demonstrates that plant and animal domestication developed earlier in Southwest Asia than in Europe, in particular within the Levant, showing that this was an important centre of agricultural origins (Colledge et al., 2004; Fuller et al., 2012). The first major human impact on ecosystem dynamics in southern Anatolia is not, however, detectable in pollen records until later in the Holocene (e.g. Eastwood et al., 1998). The so-called Beyşehir Occupation Phase (BOP) (van Zeist et al., 1975; Bottema et al., 1986; 1990; Eastwood et al., 1998; Roberts, 2018), which developed most extensively between 3500 and 1300 cal. yr. BP with varied start dates detected between regions, is distinguished as a period of pronounced anthropogenic land-cover change. This phase began in the second and first millennia BC (~3000 ± 800 cal. yr. BP) with declining forest cover and increasing pasture land, cereals and cultivated trees, such as olive and walnut (Eastwood et al., 1998; Roberts et al., 2018b). In southwest Turkey, Eastwood et al. (2007) identified that increased humidity coincided with pollen evidence for increasing human impact and intensification of agriculture during the BOP. Vegetation changes into the Hellenistic, Roman and early Byzantine periods (Table 1: based on Allcock, 2017) reflected increasing evidence of human activity as documented in numerous studies. For example, Vermoere et al. (2002) identified synchronous periods of late Holocene deforestation and cultivation within pollen records from Turkey, although this was accompanied by dissimilarities in the timing of agricultural phases. The BOP was followed by a period of land abandonment after AD 650 (1300 cal. yr. BP) and re-forestation, notably during the Arab-Byzantine wars of the 7th-10th centuries AD (England et al., 2008; Izdebski, 2013; Roberts et al., 2018a; Roberts et al. 2018a).

Cultural and demographic change in Anatolia

Human demographic change and associated land use has played a key role in shaping Holocene landscape alterations in central and southern Anatolia (Allcock and Roberts, 2014; Allcock, 2017; Roberts et al., 2018a; 2018b). There is evidence of a break in settlement in central Anatolia during the Younger Dryas (Baird et al., 2018), which suggests that populations reacted more slowly to the improved climate that permitted the development of agricultural activity in the early Holocene in surrounding areas, such as the Levant (Roberts et al., 2018b; Palmisano et al., this volume). The Neolithic and related social changes during the early Holocene were associated with periods of population growth (Roberts et al., 2018b). In an assessment of long-term socio-environmental dynamics in central Turkey, Allcock (2017) identified human settlement changes that reflect the transformation of society from rural communities during the Neolithic to complex centralised polities, such as the Hittite, Persian and Roman Empires (Table 1), which builds upon a body of existing literature (e.g. Dalfes et al., 1997; Izdebski et al., 2016). She also highlighted how some periods of social change were associated with climatic or environmental instability, supporting earlier research (e.g. Wilkinson, 1997; McIntosh et al., 2000; Marro and Kuzucuoglu, 2007; Kuzucuoglu, 2015).

The four major settlement cycles described by Allcock (2017) roughly correspond to the Neolithic, Bronze Age, Iron Age-Classical, and Medieval-Modern periods. The most intense period of human occupation in Cappadocia occurred during Late Roman times (4th to 7th centuries AD) with evidence of decreased settlement continuity from the mid-7th century (Roberts et al., 2018a). Between Hellenistic and Late Roman times the numerous cities of southern Anatolia were surrounded by agricultural land (Izdebski, 2013). However, a major demographic decline was identified between AD 650 and 900 in central and southwestern Anatolia associated with social and climatic changes. In the pollen record, this corresponded with a decline in the production of cereal and tree crops, and pastoral activity marking the end of the BOP (Roberts et al., 2018a). This was followed by regional differentiation in land use, such as agro-pastoralism in central Anatolia and cultivation of olives and other tree crops in western Anatolia.

Cultural change and climate

Climate trends in semi-arid regions, specifically variability in precipitation patterns, play an important role in socio-economic and cultural change, as water is a limited resource (Jones et al., 2006; Dean et al., 2015; Berger et al., 2016). The adoption of agriculture has been linked to the onset of the favourable early Holocene climate, and subsequent periods of drought throughout the Holocene are reflected in archaeological records with evidence of social adaptations to reduced rainfall for crop production (e.g. Staubwasser and Weiss, 2006). A shift in seasonal climate was identified by Lewis et al. (2017), which could be linked to solar-forced climate change beginning ~8600 cal. yr. BP. They describe changing water balance as an important factor influencing observed cultural changes at the Çatalhöyük archaeological site (located in south-central Turkey) in the Late Neolithic/Early Chalcolithic period and provide evidence for wet winter/early spring conditions during the Early Holocene, reduced seasonality and possibly reduced local summer evaporation after 8300 cal. yr. BP (Lewis et al., 2017). Discontinuity in settlement patterns is often correlated with shortage of water, which would have left settlements vulnerable to any changes in climate (Lewis et al., 2017; Roberts, 2018a). The climate of southern Anatolia has altered significantly throughout the Holocene with many studies demonstrating periods of prolonged drought and significant shifts between wet and dry conditions (e.g. Woodbridge et al., 2011; Dean et al., 2015). Three lake sediment oxygen isotope ($\delta^{18}O$) records derived from carbonates and diatoms (Nar Gölü only) provide an independent framework for Holocene hydro-climatic change, namely Gölhisar in southwest Turkey (Eastwood et al., 2007) and Nar Gölü and Eski Acıgöl in central Anatolia (Dean et al., 2015; Roberts et al., 2001). Similarly to the trends described by Lewis et al. (2017) these records indicate a wetter early Holocene climate.

This study examines vegetation dynamics and human population change across south-central and southwest Anatolia during the last eleven millennia, and addresses two key research questions: 1) what role have changing human populations and past climate trends played in shaping long-term land cover change in southern Anatolia?, and 2) what can be learnt about the impacts of past landscape management through understanding past demographic and vegetation change?

Methods

Pollen-inferred vegetation change

Fossil pollen datasets from 21 records across 14 sites within southern Anatolia have been analysed (Fig. 1 and Table 2) and different approaches employed to identify key patterns of vegetation change. Most of these records are from the intermontane “lake district” of southwest Turkey, with three from central Anatolia, and only one from the coastal zone. This spatial bias means that human landscape changes in the fertile coastal plains of Pamphylia (around modern Antalya) and Cilicia (around modern Adana) are not registered in regional pollen data. Published pollen records also cover different timespans, with only a few sites spanning the whole Holocene. The limited number of early Holocene pollen records means that regional syntheses of vegetation clusters may not be representative of the case study area’s predominantly intermontane landscape ecology prior to 7000 cal. yr. BP; however, as previously mentioned, major landscape alterations as a result of human activity are typically not detectable until the later Holocene in Anatolia. Cluster analysis and community classification, which involved calculating the median and interquartile range of all pollen taxa within samples that fall into each cluster group (Perez et al., 2015) were used to identify major vegetation groups in Mediterranean-wide modern and fossil pollen datasets (Davis et al., 2013; Leydet et al., 2007-2017). This paper focuses on a sub-set of these sites from Anatolia for continuous 200-year time windows throughout the Holocene. The pollen-based methods employed are described in detail in Woodbridge et al. (in press) and Fyfe et al. (2018), which also involved most of the indices described here. Simpson’s index and non-metric multidimensional scaling (nMDS) have been used to explore patterns of diversity change and major variation in the datasets along with the percentage of Arboreal Pollen (AP%). nMDS is an unconstrained ordination technique providing insights into high-dimensional datasets, and is explained in detail in Legendre and Legendre (1983) and McCune and Grace (2002). When applying nMDS the number of axes are chosen before analysis, which avoids hidden axes of variation unlike other ordination techniques. In this study a two dimensional ordination was chosen and Bray-Curtis dissimilarity was used to calculate the distance matrix for ordination. Simpson’s index has been calculated for each pollen sample using pollen percentage data. This index takes both species richness and evenness into account and is often used to explore diversity change in pollen datasets (e.g. Morris et al., 2014; Woodbridge et al., in press). An API (Anthropogenic Pollen Index: *Artemisia, Centaurea,* Cichorioideae, *Plantago,* cereals, *Urtica* and *Trifolium* type) (Mercuri et al., 2013a), an indicator group for cultivated trees (OJC: *Olea, Juglans, Castanea*) (Mercuri et al., 2013b) with the addition of *Vitis* (OJCV), and a group of pastoral land use indicators (*Artemisia*, Chenopodiaceae, *Plantago lanceolata* and *Plantago major/media*, Asteroideae, Cichorioideae, *Cirsium*-type, *Galium*-type, Ranunculaceae and *Potentilla*-type) (adapted from Mazier et al., 2006) and grazing indicators (*Plantago lanceolata, Rumex* *acetosa*-type and *Sanguisorba*) (Roberts et al., 2018a) were also calculated to explore changes in the pollen data in relation to human land use. Oleaceae undiff. was grouped with *Olea* within the OJCV index as this taxon is most likely to represent degraded *Olea* grains, and other taxa within the Oleaceae family are routinely differentiated (e.g. *Fraxinus, Phillyrea*). Although many of these indicator groups are based on published literature that describe the taxa as 'anthropogenic indicators', many of these taxa are not only associated with anthropogenic activity, such as Chenopodiaceae Asteroideae and Cichorioideae, which indicate natural steppe vegetation. The pastoral indicator group was developed using pollen sites in France, so is less informative about landscape change in Anatolia, but has been included to aid comparisons between case study regions within a Mediterranean-wide synthesis (Roberts et al., this volume).

Archaeologically-inferred demographic change

Archaeological data have been obtained for a total of 1426 sites and 3804 excavated or surveyed settlements (occupation periods) (Fig. 1) to construct records of past demographic change using established methods (Palmisano et al. 2017). Archaeological sites have been recorded, where possible, as georeferenced points per time-slice (unprojected WGS84). For the purposes of this paper, we have chosen to deal exclusively with those places identified as human habitation sites or possible habitations, and hereafter then we use the terms 'site' and 'settlement' interchangeably to refer to this subset. The settlement data covers the time period 9900 to 1100 cal. yr. BP and summed radiocarbon dates extend from 11000 to 6100 cal. yr. BP, as there are no data available covering times prior to or more recent than these periods. A spatial database of archaeological sites has been created through a comprehensive review, standardisation, and synthesis of settlement data from reports and gazetteers relating to 52 archaeological surveys carried out throughout all three sub-regions of southern Anatolia, although there are some notable geographical gaps, such as the Pamphylian coastal plain (see SI 3 for a complete list of references). Although the archaeological surveys carried out in Anatolia show a spatially variable intensity of investigation, most of them fall within the "extensive" category (0.4 to 5 sites per km sq.). Topographic variability is another issue to be considered in the Anatolian context as mountainous fringes and areas with rugged topography are marginal zones that have not commonly received as detailed archaeological attention as lowland areas for a series of practical reasons, such as difficult terrain and dense vegetation cover. Another issue is represented by the gap of the Middle Chalcolithic occupation in southwest Anatolia and the Burdur plain due to recognition and visibility problems related to either a poor knowledge of Middle Chalcolithic pottery assemblages or colluvium deposits covering floodplain sites (see Vandam, 2015). A major caveat is represented by the estimated size of settlements that in most cases indicate only the overall extent of mounds, but neither the size for a particular chronological phase nor the extent of the surrounding lower town. Therefore, the results derived from the analyses of the estimated settlement sizes have to be interpreted cautiously, as constituting evidence only about the patterns exhibited by relatively large, sedentary farming communities. The methods used in this paper to infer demographic trends from radiocarbon dates and archaeological settlement data build largely on previous works that seek to address issues such as "wealth-bias" of particular site phases (Timpson et al., 2014), the artefacts in SPD plots due to radiocarbon calibration curves (Williams, 2012; Weninger et al., 2015), and temporal uncertainty in archaeological site-phases and periods (see Crema, 2012; Palmisano et al., 2017).

Within the analyses of the archaeolgical data, the 'site count' was calculated and the estimated 'site sizes' were summed for 200 year-time steps in order to assess how population changes across time every 200 years. Bearing in mind that archaeological cultures result in larger or shorter time spans according to the dating precision of archaeological artefacts, we applied a probabilistic approach known as aoristic analysis to deal with the temporal uncertainty of occupation periods (Crema, 2012; Palmisano et al., 2017). In addition, to mitigate the discrepancy between wide chronological uncertainties and narrower likely site durations, we applied Monte Carlo methods to generate 'randomised start of occupation' periods for sites with low-resolution information (Crema, 2012; Palmisano et al. 2017). The resulting probabilistic distributions of site frequencies through time, based on the aoristic sums and Monte Carlo simulations, provide useful comparisons with the raw site frequency data and the summed settlement sizes. Consequently, the SPD of radiocarbon dates are binned into 200-year time slices to match the time windows used in the analysis of pollen sequences. We also calculated the median of the envelope of the randomised start date of sites, which is the result of a 1,000 randomised start occupation date for sites, and binned this into 200-year time slices.

Palaeoclimate datasets

The palaeoclimate datasets (Fig. 1 and Table 2) derive from lakes in central and southern Anatolia and provide records of $\delta^{18}O$ inferred hydroclimate (Nar Gölü: Dean et al., 2015, Eski Acıgöl: Roberts et al., 2001 and Gölhisar Gölü: Eastwood et al., 2007). The records have been resampled to the same temporal resolution and converted to z-scores to allow inter-site comparisons and calculation of an average z-score for the region (see Finné et al., this volume, for further details).

Results

Vegetation, climate and demographic trends

The patterns of vegetation cluster group change (Fig. 2) indicate an increase in sclerophyllous parkland (cluster 1.1) and pine steppe (cluster 5.2) after around 8000 cal. yr. BP, which coincides with a decline in deciduous oak parkland (cluster 6.2). However, the limited number of pollen sites in the earlier Holocene make interpretations more restricted for these vegetation cluster groups. One of the most striking trends in the pollen cluster group results is the increase and decline in pasture/wetland (cluster 3.0) between 4500 and 1300 cal. yr. BP. This cluster is dominated by Cyperaceae pollen, and probably reflects a combination of increased upland grazing land, as indicated by the abundance of grass and grazing indicators in this cluster group, and local wetland sedge communities. In the last ~1800 years, there has been a significant expansion in pine woodland (cluster 5.1). The archaeological demographic proxy record indicates that population started increasing in the Early Chalcolithic (~8000 – 7500 cal. yr. BP) and grew substantially during the Bronze Age (~5000 – 3100 cal. yr. BP), which was punctuated by cycles of 'boom and busts' throughout the Bronze Age (see Fig. 3). A dramatic increase in population then occurred in the Hellenistic and Roman periods (see Table 1 for a summary of Anatolian archaeological periods).

Pollen indicator groups offer a useful approach to explore key changes in vegetation community dynamics over time in line with cultural shifts. Fig. 4 shows that arboreal pollen (AP%) has varied between 30 and 70% throughout the Holocene with a steady decline from 9000 to 2400 cal. yr. BP and an increase after this time. There is a marked rise in cultivated trees between ~5000 and ~1500 cal. yr. BP demonstrated in the OJCV index. The API indicates an increase in anthropogenic activity from 6500 cal. yr. BP, while grazing pollen indicators steadily increased from 8500 cal. yr. BP and declined in the most recent 1500 years. Simpson's index suggests that diversity increased in the early Holocene with consistent values throughout the records and a recent decline since 1500 cal. yr. BP. Statistically significant relationships between the pollen and archaeological datasets (Table 3) are demonstrated most clearly for the pasture/wetland vegetation cluster (3.0), which shows a strong positive relationship with the demographic proxies, and significant negative relationships between AP% and demographic change, indicating that larger populations were associated with increased pasture/wetland vegetation and a decline in the abundance of trees. A decrease in AP% could lead to decreased evaporation from vegetation and potentially higher run-off. Nevertheless, the Cyperaceae increase suggests lower lake levels, which could indicate drier climatic conditions or possibly human interference with catchment hydrology. There are also highly positive and significant relationships between the demographic proxies and the OJC / OJCV and API indices and grazing indicators, which reflect human land use. nMDS axis scores summarise major variation in the pollen datasets and indicate periods of greater change around 6000 and 2000 cal. yr. BP (Fig. 4). The nMDS scores are significantly correlated (p-value <0.05) with the demographic proxies (Table 3) indicating that major change in the pollen data corresponds with demographic shifts.

When patterns within individual pollen records are examined in more detail, variability between sites is clearly identifiable. The results of two separate analyses are presented in Fig. 5 (sites ordered from left to right reflecting SW to NE location): AP% (shown on the x axis for each site), which indicates how open or closed the landscape is, and the cluster analysis derived 'vegetation clusters' are presented as symbols. Sites on the Anatolian plateau indicate greater abundance of grassland/parkland (1.4) throughout the Holocene (e.g. Eski Acıgöl) while those in the southwest Anatolian Lake District indicate that sclerophyllous parkland (1.1) or woodland dominated the landscape (e.g. Karamık, Beyşehir and Ağlasun). Similar vegetation shifts are shown between records, such as pine woods (5.1) moving to pine steppe (5.2), and several records indicate an increase in pasture/wetland (3.0) from ~4000 cal. yr. BP (e.g. Gölhisar, Ovagöl, Bereket and Pınarbaşı). Grass was abundant in the pollen records during the early Holocene; however, there is no clear relationship between grass abundance and the summed probability distribution (SPD) of radiocarbon dates for this period (Fig. 6). During the Beyşehir Occupation Phase (BOP) there was a clear increase in the OJCV index across most sites from 3500 to 1500 cal. yr. BP, which is also reflected by peaks in the demographic proxies around these times (Fig. 7). The increase in the OJCV index began earliest in the one pollen record available from the coastal zone (Ovagöl).

Within the palaeoclimate datasets (Fig. 4) higher (more positive) z-scores indicate wetter climatic conditions, while lower (more negative) values relate to drier climate. The average z-scores across all three sites show wetter conditions in the early to mid-Holocene (until ~5000 cal. yr. BP), which is followed by drier conditions until ~1500 cal. yr. BP. Values then increase again indicating a shift to wetter climate during Medieval times and then decline signifying a more recent drying phase in the last ~500 years, corresponding to the Little Ice Age. Spearman's rank correlations between the pollen, archaeological and palaeoclimate datasets indicate strong statistically significant negative relationships between all of the climate records and the demographic proxies with *r*-values up to -0.78 (Table 3). The clearest significant relationships between the climate and pollen datasets are with the pasture/wetland cluster (3.0), which shows a negative relationship indicating that pasture/wetland was more abundant when climate was drier. There are also significant relationships with a number of the pollen indicator groups, such as OJCV, API and grazing indicators, which are all negatively correlated with climate (Table 3). Pollen nMDS scores are significantly correlated with the climate records indicating that major patterns in the pollen datasets reflect climate trends.

Discussion

Demographic change, cultural transitions and landscape dynamics

Although efforts have been made to define a study region with good data coverage and congruence of datasets (pollen, archaeology and climate) the records from different data types may be clustered within some areas and not represented in others. Consequently, patterns are likely to be influenced by sub-regional dissimilarities in climatic, geographic, social and cultural history. The influence of these dissimilarities on the results and interpretations has been taken into account when interpreting patterns within and between the datasets, and sites are also shown individually in addition to the regional synthesis to illustrate site level differences and characteristics (Figs. 5-7). The results presented here have allowed a broad scale comparison of long-term demographic and vegetation change, and they suggest that shifting human population dynamics played an important role in shaping land cover in central and southern Anatolia, as evidenced by the significant positive relationships between anthropogenic pollen indicator groups (API, OJCV and grazing indicators) and population increases (Fig. 4 and Table 3). Abundance of vegetation cluster 1.4 (parkland/grassland) is evident during the early Holocene (Fig. 3), which coincides with increased burning in the landscape of southern Anatolia, as demonstrated by Turner et al. (2010). The individual pollen records also indicate that grassland cover reached a maximum during the early Holocene (Fig. 6). This early grassland phase could have resulted from a combination of climate change and the influence of human land use, but most studies do not detect clear human impacts on vegetation until the later Holocene in Anatolia. Natural and anthropogenic use of fire, which is restricted by the availability of biomass for burning in drier sites on the Anatolian plateau, could have maintained grasslands, with climate appearing to act as a pacemaker for burning (Turner et al., 2008); however, these relationships require further investigation.

Archaeological trends for the early Holocene inferred from radiocarbon date densities (Roberts et al., 2018b) show a likely increase in population around 10300 cal. yr. BP continuing until ~7500 cal. yr. BP (Fig. 6). This corresponds to the Neolithic and early Chalcolithic periods, when farming and sedentary village life were adopted in this region (Table 1). Previous studies also demonstrate evidence of abundant *Pistacia* in the early Holocene particularly in dry, high elevation areas, which is clearly demonstrated at site Eski Acıgöl (SI 1), and also demonstrated in archaeological charcoal records of burned pistachio wood (Asouti and Kabukcu, 2014). The trends identified by Allcock (2017) for Cappadocia match the wider regional population trajectories identified in the archaeological site survey data (Fig. 3). The Early Bronze Age and Classical (Hellenistic-Roman-Early Byzantine) population peaks are clearly visible in the settlement density data shown in Figs. 3 and 4.

The grassland phase was followed by the development of open oak parkland (~8500 cal. yr. BP) that may have been managed by people (Figs. 4 and 5). According to Asouti and Kabukcu (2014) these semi-arid oak woodlands, associated with increasing abundance of deciduous oak parkland (cluster 6.2), represent one of the earliest anthropogenic vegetation types in Southwest Asia as a consequence of prehistoric landscape practices and was not simply part of the ‘natural’ Anatolian vegetation. Therefore, this could imply that a pre-Neolithic base-line vegetation was absent in this region; by contrast, Holocene forest cover was much more extensively developed in the uplands of southwest Anatolia. However, the increase in oak parkland also reflects climatic changes and whether or not human populations would have been large enough to initiate detectable impacts on woodland cover at this time remains a matter of debate.

Throughout the Holocene different vegetation types emerge (Fig. 3), which can be interpreted in relation to changes in land use practices, such as increased sclerophyllous parkland (cluster 1.1) from 8400 cal. yr. BP. Evidence of early farming activity has also been identified in pollen records from archaeological sites, for example, Eastwood et al. (in review) identified very high percentage of *Cerealia* pollen grains deposited over a short time period (~300 years) during the Early Chalcolithic at Çatalhöyük in Anatolia. This early Holocene phase was followed by dominance of clusters 1.1 (sclerophyllous parkland) and 6.2 (deciduous oak parkland) until 4500 cal. yr. BP, and was then followed by an increase in Cyperaceae (shown in cluster 3.0: pasture/wetland) and tree crops indicated by the OJCV index (Fig. 4) from ~5000 cal. yr. BP. Lakes became shallower and dried out during periods of climatic desiccation (Fig. 4) leading to increased Cyperaceae marshland. Cyperaceae also increased due to upland grazing at this time. The increase in the OJCV index that occurred earliest in the one pollen record available from the coastal zone (Ovagöl) suggests that systematic cultivation of tree crops, such as olive, started in the Eu-Mediterranean zone, and only later moved into the interior Oro-Mediterranean zone.

Demographic changes coincide with some, but not all, of the vegetation changes identified in the pollen records. The SPD of radiocarbon dates from archaeological sites only covers the early to mid-Holocene and indicates a steady increase in population between 10400 and 7800 cal. yr. BP, followed by declining population (Fig. 6). Asouti (2017) highlighted a myriad of factors that contributed to land use strategies in Southwest Asia during the early Holocene including natural agencies, such as climatic seasonality, and human factors, such as the experiences, community behaviours and mobility of people. Human land use could be reflected by the increase in parkland/grassland (cluster 1.4) in central Anatolia during this time (Fig. 3), although, the delayed reestablishment of forests in the early Holocene in Turkey has also been attributed to climatic factors (Bottema et al., 1990; van Zeist and Bottema, 1991; Djamali et al., 2010). The relationships between demographic trends, human land use behaviours and vegetation changes are not straightforward and it is uncertain whether human impacts by pre-Neolithic and Neolithic communities were large enough to cause widespread changes in the natural vegetation. Although detectable at an individual site level, such settlements and populations may have been too sparse and low in number to affect the region-wide landscape and other factors will also have influenced landscape change, such as seasonality of precipitation (Djamali et al., 2010; Lewis et al., 2017).

Oak parkland was maintained in central Anatolia until about 4000 cal. yr. BP, after which time it was largely replaced by pastureland and by tree and cereal crops (Roberts, 2018b). This is demonstrated by the grazing indicator curve and OJCV index, which provides a simple anthropogenic signal, but which can also be influenced by taxa not associated with human land use, such as wild olive (Fig. 4). The Anthropogenic Pollen Index (API) is more difficult to interpret, since the ruderal plant taxa that contribute to this index would have responded to natural (e.g. climatic) as well as human disturbance in this region. Both south-central and southwest Anatolia experienced the Beyşehir Occupation Phase (BOP) of agrarian land use, which also involved arboricultural practice and increases after around 5000 cal. yr. BP before declining again at 1500 cal. yr. BP, indicating that tree crop cultivation, although spatially variable, was most significant during this period.

Initial human impact on regional vegetation in the uplands of southwest Anatolia is detectable somewhat later than on the plateau, most notably in late Chalcolithic times. At Ağlasun, in particular, a decline in deciduous oak woodland and an increase in anthropogenic pollen taxa at around 6000 cal. yr. BP (Fig. 5) has been attributed by Bakker et al. (2012) to clearance by early farming communities. The BOP, most extensively developed between 3500 and 1300 cal. yr. BP, represents the clearest example of human-induced land cover change in southern Anatolia during the Holocene. This phase was followed by a period in many pollen records that indicates ‘rewilding’ of the landscape with an increase in pine trees. This is reflected in the vegetation summary diagram (Fig. 3) showing an increase in pine and mixed woods and decline in open/parkland vegetation. The pine forest and pine woods cluster groups are frequently represented in individual pollen sequences since the mid and late Holocene (e.g. Gölhisar, Gravgaz, and Sogut) in the south-west of the case study region and are also represented in the higher elevation sites (e.g. Beyşehir and Hoyran) towards the north-east of the case study area. Roberts et al. (2018a) concluded that in Cappadocia (central Anatolia) the post-disturbance trajectory also took the regional socio-ecological system to a new and different state, rather than returning to a previous one, in this region dominated by agro-pastoralism (England et al., 2008).

Many previous studies have focussed on shorter time periods (e.g. Izdebski et al., 2015), small scale (i.e. site specific) comparisons between pollen and archaeological records, and identified similar timing in evidence of human occupation and the presence of land use pollen indicators (England et al., 2008). Within the current study there are distinct differences between the pollen sites in the southwest and those on the central Anatolian plateau. The southwest is more mountainous and forested whereas the plateau is drier. During the late Holocene a marked increase in AP% is evident, mainly in the last 1500 years, particularly involving pine woods/forests, which indicates reforestation of areas previously used for agricultural land use. This is also shown in the cluster results (4.0, 5.1 and 5.2: Fig. 3). A decline in population coincides with times of turbulence caused by conflict on the eastern frontier of the Byzantine Empire when much of southern and central Anatolia was deliberately de-populated and militarised (England et al., 2008; Izdebski, 2013; Haldon, 2016).

Significant relationships have been identified between the climate records and the demographic trends (settlement proxy), however, these relationships are complex and reflect many natural and cultural factors. The negative relationship between pasture/wetland and climate implies that when climate is drier, lake levels are lower and more habitats are created that support wetland plants (e.g. Cyperaceae). The synthesised pollen datasets analysed in this study do not appear to show any clear changes during the 9.3 and 8.2 ka climatic events, although they can be recognised in proxy-climate records from sites such as Nar Gölü (Dean et al., 2015). The 4.2 and 3.2 ka climatic events (e.g. Kaniewski et al., 2008) have been linked to societal collapse with centennial-scale drought intervals identified in palaeoclimate records during these periods (e.g. Dean et al., 2015; Massa and Şahoğlu, 2015). Population dynamics drawn from archaeological data seem to corroborate this picture in addition to the strong negative correlations ($r = \sim -0.70$) between palaeoclimate and demographic proxies (Table 3). The fact that some pollen taxa reflect both anthropogenic and non-anthropogenic factors complicates the interpretation of the indicator groups. Flohr et al. (2016) predicted four different potential societal 'responses' to sudden climatic change: collapse/decline of societies; long distance migration; adaptation; and no impact. The significant relationships between the OJCV index, API and grazing indicators and the climate records indicate that people may have adapted to long-term climatic shifts, for example, through diversification of subsistence practices. Flohr et al. (2016) suggested that the lack of a large-scale, severe impact that can be detected on Southwest Asian societies can be explained by the existence of such adaptation strategies and/or by the resilience of early farming communities. In more recent historical periods (the last two thousand years), a number of studies demonstrated that the impact of climatic changes on societal and landscape transformations was relatively limited. Adverse changes in climate conditions did not coincide with major transformations in the landscape and society (Izdebski 2013; Haldon et al. 2014; Izdebski et al. 2016). Rather, a major landscape change, marking the end of the BOP, which took place in southern Anatolia around the 7th century AD has been linked to the collapse of the Eastern Roman (early Byzantine) political and socio-economic system, which required adaptation of social practices and landscapes across Anatolia and much of the eastern Mediterranean. Similar studies of the later historical periods reported lack of clear connections between climatic instability and socio-economic factors as well as landscape change during the Medieval Climate Anomaly (Xoplaki et al., 2016). However, a severe multi-year drought that occurred in Anatolia in the 1590s (AD) led to a prolonged social crisis and expansion of steppe pastures (White, 2011). Several episodes of ‘social crises’ occurred through this and the following century as a consequence of a complex combination of social and cultural factors. The increase in cluster 3.0 (pasture/wetland) between 4500 and 1300 cal. yr. BP is likely to have been due both to climatic desiccation (including the 4.2 and 3.2 ka dry events), and to population rise and the development of pastoralism during Bronze Age to Classical times.

Other factors may also have influenced vegetation patterns, such as geomorphological changes (Kuzucuoğlu et al., 2018) and the impacts of long-term human impact and extreme climatic conditions upon soil properties and thus site-conditions for vegetation growth (e.g. Van Loo et al., 2017, who identified that soil erosion was driven by anthropogenic activities rather than climate change in southwest Turkey). Soil exhaustion in the past may have caused changes in vegetation composition not directly related to human impacts or climate. Furthermore, vegetation recovery following human impact or climate change may be delayed or even halted when specific ‘tipping points’ are not crossed. This might be related to site specific environmental conditions making some sites more resilient than others and resulting in new equilibrium vegetation composition. For example, Kaniewski et al. (2007) stress how contemporary land cover shows strong legacy effects of past human impact.

Landscape management

Understanding past demographic and vegetation change may provide useful information about the impacts of landscape management. Asouti and Kabukcu (2014) highlight how information about the origin and evolution of the Anatolian semi-arid oak woodlands is potentially of importance for reconstructing the changing ecologies and geographical distributions of domesticated crop species. Land use strategies that encourage the establishment and spread of deciduous oaks include sheep herding, controlling competing arboreal vegetation and woodland management (Asouti and Kabukcu, 2014). These practices could have affected landscapes in the mid-Holocene when, as our regional pollen synthesis shows, deciduous oak parkland (cluster 6.2) was more abundant in the landscape; this vegetation type is still abundant in Cappadocia at present. In central Anatolia, this parkland ecosystem also includes economically important tree taxa, such as almond and wild fruit trees that are poorly represented in pollen diagrams (Woldring and Cappers, 2001). According to Gross (2012), poorly-considered development projects are threatening biodiversity in Turkey and wildlife corridors provide opportunity to support conservation progress. Restoring biodiversity to its condition in, for example, earlier stages of the Holocene depends not only on reducing livestock grazing and wood-fuel cutting, but also on incorporating these into a more sustainable system of socio-ecological management such as existed prior to the Iron Age.

Pollen records from Anatolia show clear evidence of environmental recovery following disturbance, most obviously in the post-BOP period. At Nar Gölü in Cappadocia, this included a significant re-expansion of oak woodland and decline in soil erosion after ~1300 cal. yr. BP (England et al., 2008; Roberts et al., in review). In the uplands of southwest Anatolia, the re-wilding process favoured expansion of pine trees rather than the mixed conifer-broad leaf forests of the mid-Holocene (Fig. 3) (see Richardson (2000) for a review of the ecology and biogeography of *Pinus*). The recent dominance of pine has probably been due to a combination of factors including soil loss during and after the BOP, along with continued grazing/browsing pressure from transhumant livestock herding, although open *Juniperus* woodland is also favoured by grazing. The relationships between population, land use and vegetation change are complex and understanding regional trajectories of change can provide information about the characteristics of vegetation resulting from different management practices and changing demographic pressures over time.

Conclusion

This study has highlighted the long-standing human transformation of vegetation in southern Anatolia. The early emergence of Neolithic agriculture meant that the oak parkland ecosystem of central Anatolia co-evolved as a consequence of natural and anthropogenic factors, including burning, grazing and wood cutting, and which may therefore have been maintained as a semi-natural agro-ecosystem. While changing human populations clearly influenced vegetation patterns, they did so in combination with other external controls, such as climate change. Hence the increase in sedge pollen (cluster 3.0: pasture/wetland) between 4500 and 1300 cal. yr. BP is likely to have been due both to climatic desiccation, including the 4.2 and 3.2 dry events, and demographic increase and the creation of upland pastureland during Bronze Age to Classical times. The precise timing of shifts in population and impacts on vegetation patterns do not show regular repetitive patterns over time. Pollen indicator groups such as cultivated trees (OJCV) and grazing indicators display significant positive relationships with demographic trends, especially during the BOP, and highlight how greater production of food would have been required for larger populations. Modern land management could benefit from improved understanding of the regional relationships between land use and vegetation change, and knowledge of how past land use practices promoted the resilience and potential for recovery of certain vegetation types, such as deciduous oak parkland.

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Figures

Fig 1 Locations of modern pollen (grey) and fossil pollen (green) sites, archaeological (blue) and radiocarbon sites (red) and palaeoclimate records (black triangles). The topographic map is shown for the region of south-central Anatolia analysed within this study. Site numbers are provided with the fossil sites (see Table 2 for further information).

Fig 2 Pollen-inferred vegetation cluster groups presented as percentage of pollen samples (time windows) assigned to each vegetation cluster group for sites in south-central Anatolia, and archaeological datasets (11000 cal. yr. BP – modern). The summary diagram shows amalgamated values of broad cluster groups and the grey area highlights a period of low pollen site numbers.

Fig 3 Normalised demographic trends for south-central Turkey based on settlement data (raw count, total area, aoristic weight and randomised start date) for the period 10000-1000 cal. yr. BP with key archaeological periods highlighted.

Fig 4 Pollen indicator groups: arboreal pollen (%AP), sum of *Olea, Juglans, Castanea* and *Vitis* (OJCV), anthropogenic pollen index (API), summed grazing indicators, non-metric multidimensional scaling (nMDS) axis scores, and Simpson's diversity index averaged for all sites in the study area (11000 cal. yr. BP to modern). Archaeological demographic proxies from settlement data: total estimated area of sites and number of sites (randomised start date) (9900 to 1100 cal. yr. BP). Normalised (z-scores) $\delta^{18}O$ hydroclimate (palaeoclimate) proxy records with average and standard deviation.

Fig 5 Sum of Arboreal Pollen (%AP) for each fossil pollen site plotted with vegetation cluster groups (symbols) (11000 cal. yr. BP to present). Sites 1 to 18 are located in southwest Anatolia and sites 19 to 22 are located on the Anatolian Plateau.

Fig 6 Poaceae (grass) % for pollen sites covering the early Holocene presented with summed probability distribution (SPD) (11000 to 6000 cal. yr. BP).

Fig 7 OJC (*Olea*, *Juglans* and *Castanea*) index for the period 6000 cal. yr. BP to present for each pollen record presented with archaeological demographic proxies from settlement data: total estimated area of sites and number of sites (randomised duration) (6000 to 1100 cal. yr. BP).

Supplementary Information 1 Percentage of a) *Cerealia* (cereal) pollen types and b) *Pistacia* (pistachio) pollen for each pollen record for the period 11000 cal. yr. BP to present.

Supplementary Information 2 a) Anthropogenic Pollen Index (API) and b) grazing indicators (*Plantago lanceolata, Rumex acetosa-type, Sanguisorba)* for each pollen record for the period 11000 cal. yr. BP to present.

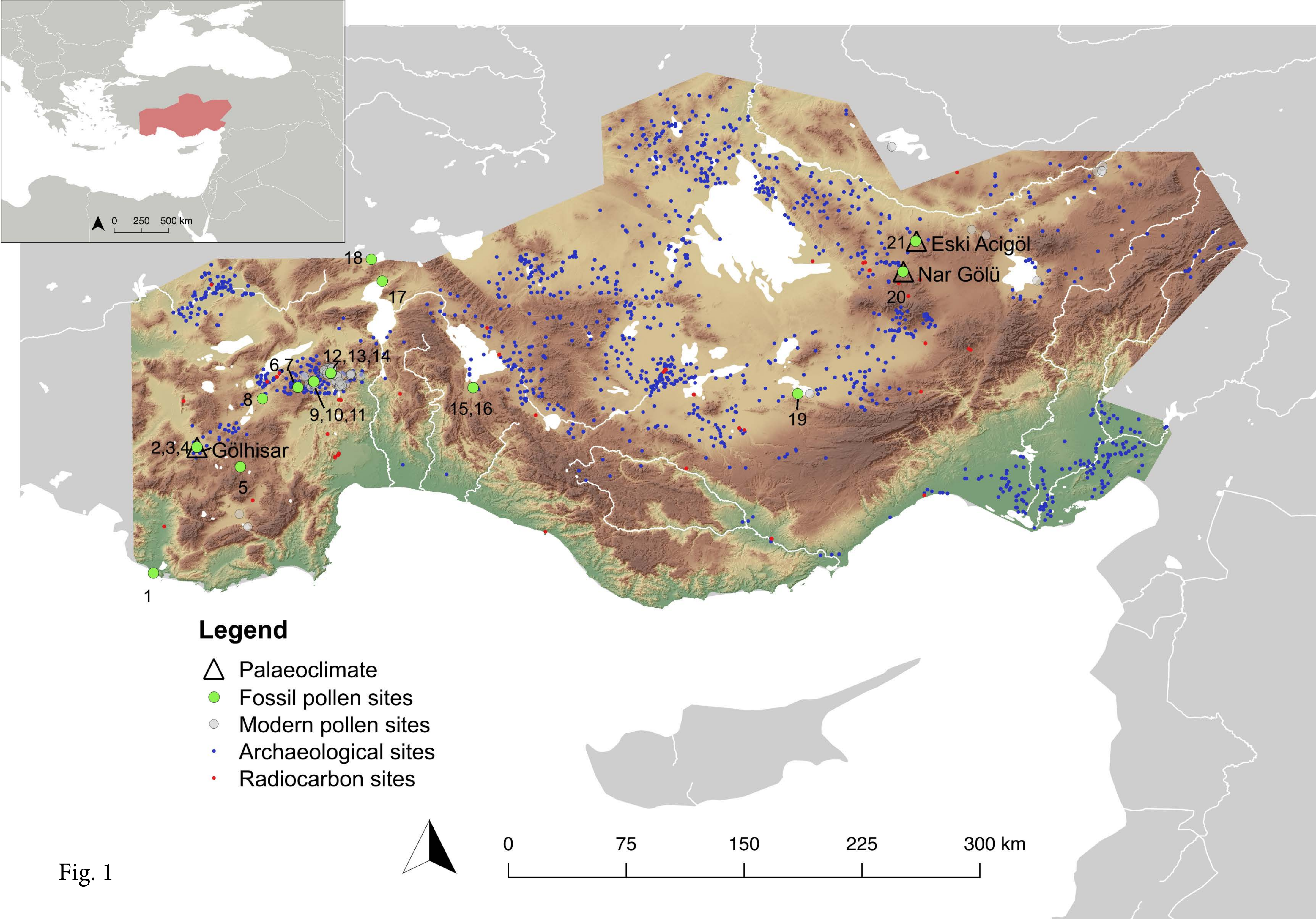
Supplementary Information 3 Archaeological datasets and references for settlement data used in this study.

Tables

Table 1 Archaeological periods in central and southwest Anatolia (based on Allcock, 2017). The Beyşehir Occupation Phase (BOP) most extensively covers the period from 3500 until 1300 cal. yr. BP.

Table 2 Metadata for fossil pollen and palaeoclimate records from central Anatolia.

Table 3 a) Spearman's Rho correlations between the pollen and archaeological datasets (upper value within each cell: *r*-value and lower value: *p*-value) (significant correlations are shaded grey) (9900-1100 cal. yr. BP). b) Spearman's Rho correlations between the pollen, archaeological and palaeoclimate z-score datasets (upper value within each cell: *r*-value and lower value: *p*-value) (significant correlations are shaded grey) (for corresponding time periods)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17
12,13,14
6,7
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19
21
Eski Acigöl
Nar Gölü
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Legend
△ Palaeoclimate
● Fossil pollen sites
● Modern pollen sites
• Archaeological sites
• Radiocarbon sites
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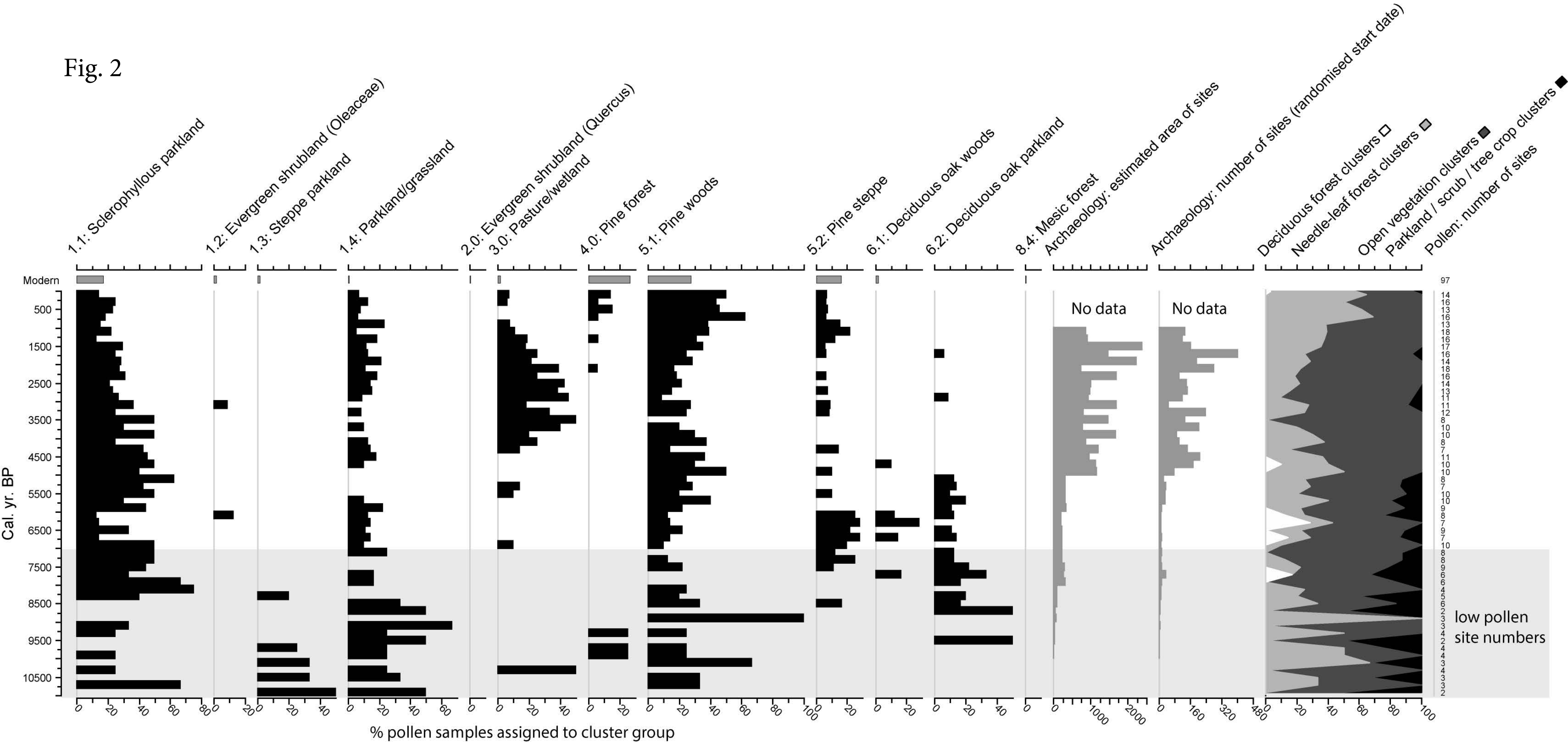
150
225
300 km

Fig. 1

Fig. 2


1.1: Sclerophyllous parkland
1.2: Evergreen shrubland (Oleaceae)
1.3: Steppe parkland
1.4: Parkland/grassland
2.0: Evergreen shrubland (Quercus)
3.0: Pasture/wetland
4.0: Pine forest
5.1: Pine woods
5.2: Pine steppe
6.1: Deciduous oak woods
6.2: Deciduous oak parkland
8.4: Mesic forest
Archaeology: estimated area of sites
Archaeology: number of sites (randomised start date)
Deciduous forest clusters □
Needle-leaf forest clusters ▨
Open vegetation clusters ◆
Parkland / scrub / tree crop clusters ◆
Pollen: number of sites
Modern
97
Cal. yr. BP
500
1500
2500
3500
4500
5500
6500
7500
8500
9500
10500
No data
No data
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low pollen site numbers
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0 20 40 60 80 100
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0 1000 2000
0 160 320 480
0 20 40 60 80 100
% pollen samples assigned to cluster group

Fig. 3

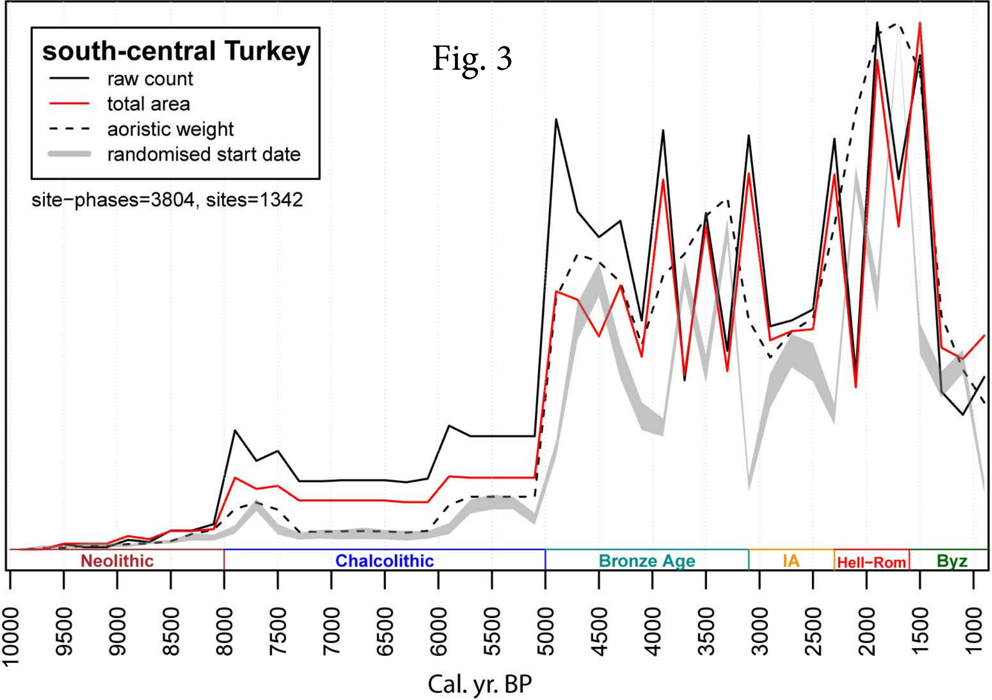
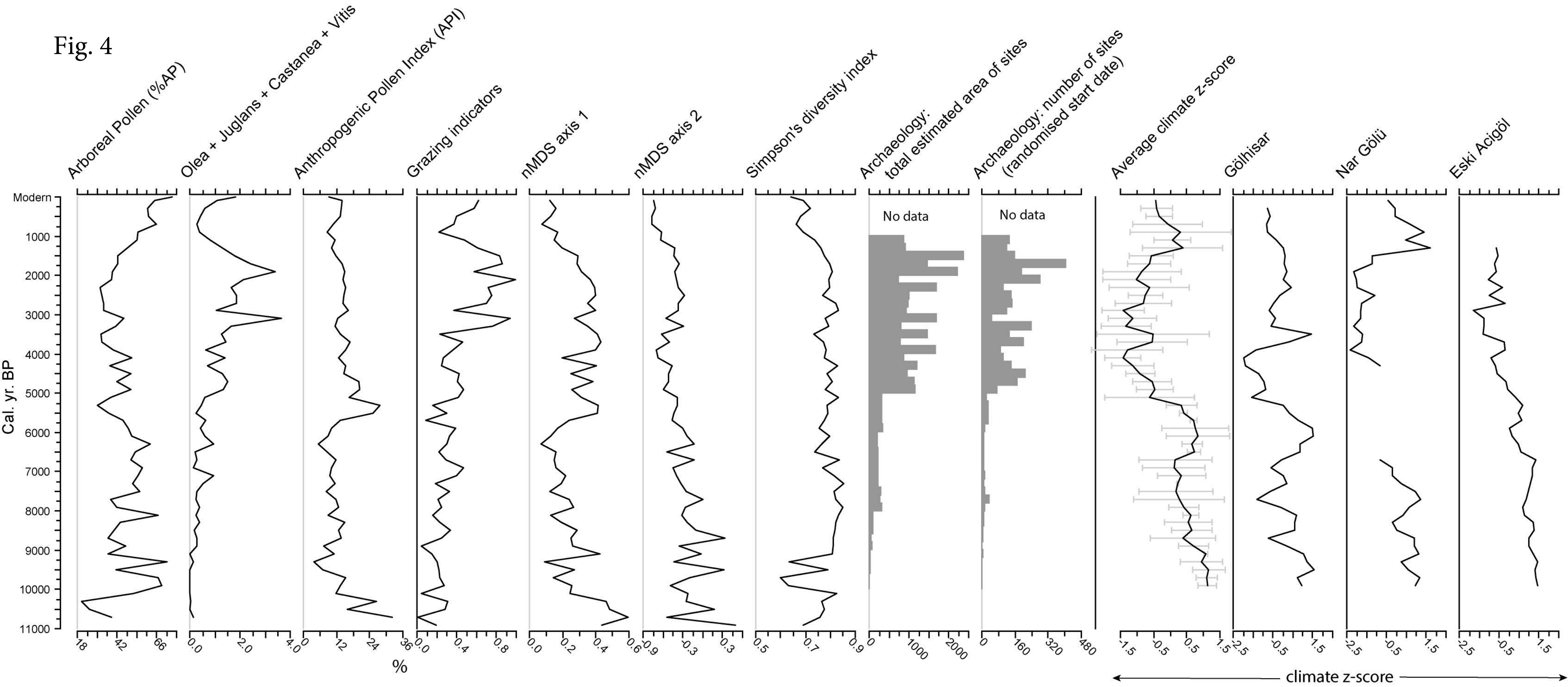

south-central Turkey
raw count
total area
aoristic weight
randomised start date
site−phases=3804, sites=1342
Neolithic
Chalcolithic
Bronze Age
IA
Hell−Rom
Byz
10000
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
Cal. yr. BP

Fig. 4


Arboreal Pollen (%AP)
Olea + Juglans + Castanea + Vitis
Anthropogenic Pollen Index (API)
Grazing indicators
nMDS axis 1
nMDS axis 2
Simpson's diversity index
Archaeology: total estimated area of sites
Archaeology: number of sites (randomised start date)
Average climate z-score
Gölhisar
Nar Gölü
Eski Acigöl
Modern
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
Cal. yr. BP
No data
No data
18
42
66
0.0
2.0
4.0
0
12
24
36
%
0.0
0.4
0.8
0.0
0.2
0.4
0.6
-0.9
-0.3
0.3
0.5
0.7
0.9
0
1000
2000
0
160
320
480
-1.5
-0.5
0.5
1.5
-2.5
-0.5
1.5
-2.5
-0.5
1.5
-2.5
-0.5
1.5
climate z-score

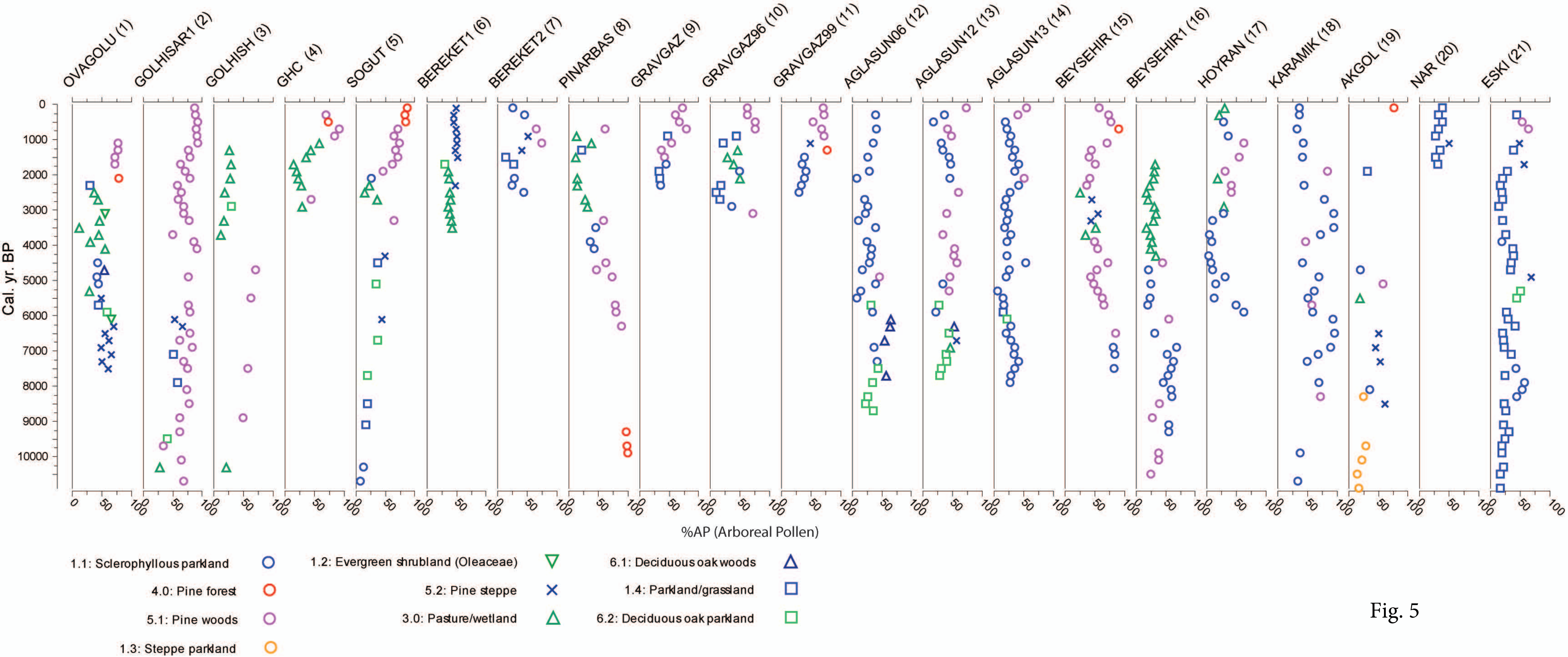

OVAGOLU (1)
GOLHISAR1 (2)
GOLHISH (3)
GHC (4)
SOGUT (5)
BEREKET1 (6)
BEREKET2 (7)
PINARBAS (8)
GRAVGAZ (9)
GRAVGAZ96 (10)
GRAVGAZ99 (11)
AGLASUN06 (12)
AGLASUN12 (13)
AGLASUN13 (14)
BEYSEHIR (15)
BEYSEHIR1 (16)
HOYRAN (17)
KARAMIK (18)
AKGOL (19)
NAR (20)
ESKI (21)
Cal. yr. BP
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
0
50
100
%AP (Arboreal Pollen)
1.1: Sclerophyllous parkland ○
4.0: Pine forest ○
5.1: Pine woods ○
1.3: Steppe parkland ○
1.2: Evergreen shrubland (Oleaceae) ▽
5.2: Pine steppe ×
3.0: Pasture/wetland △
6.1: Deciduous oak woods △
1.4: Parkland/grassland □
6.2: Deciduous oak parkland □

Fig. 5

Fig. 6

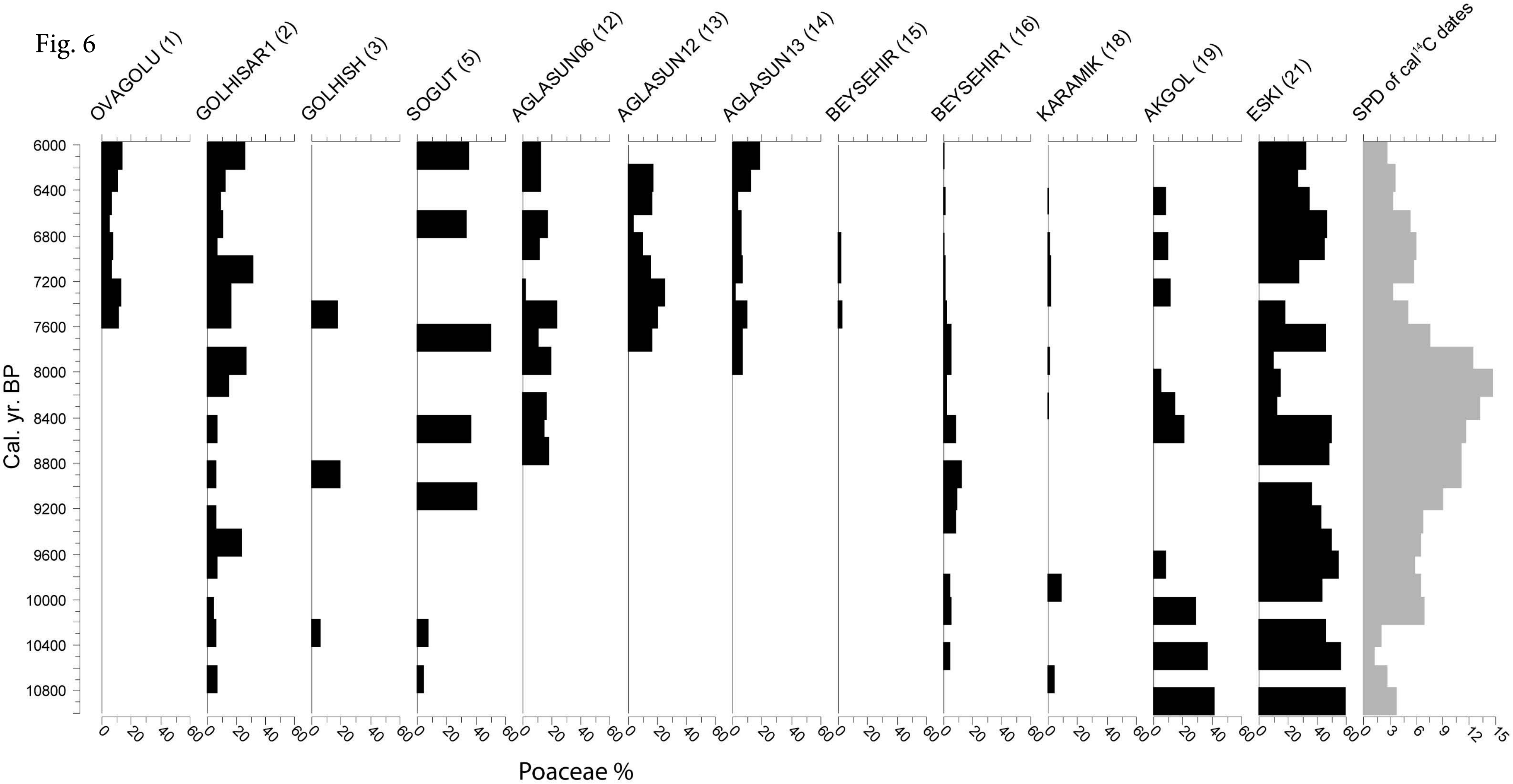

OVAGOLU (1)
GOLHISAR1 (2)
GOLHISH (3)
SOGUT (5)
AGLASUN06 (12)
AGLASUN12 (13)
AGLASUN13 (14)
BEYSEHIR (15)
BEYSEHIR1 (16)
KARAMIK (18)
AKGOL (19)
ESKI (21)
SPD of cal14C dates
Cal. yr. BP
6000
6400
6800
7200
7600
8000
8400
8800
9200
9600
10000
10400
10800
0
20
40
60
0
3
6
9
12
15
Poaceae %

Fig. 7

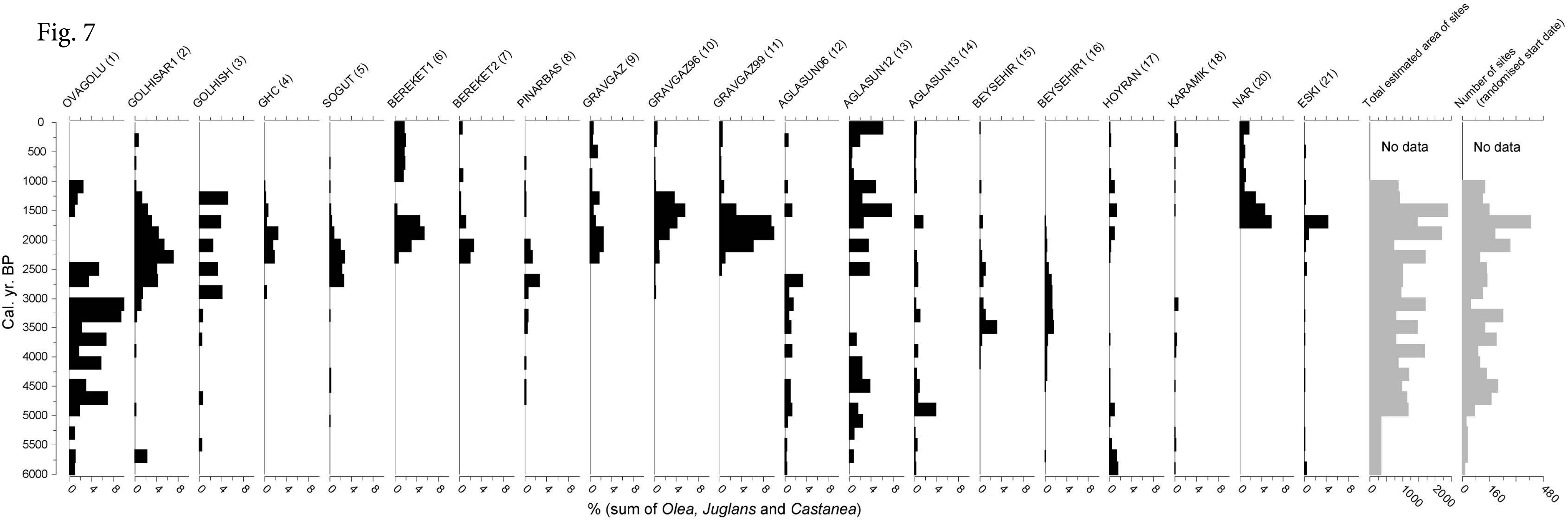

OVAGOLU (1)
GOLHISAR1 (2)
GOLHISH (3)
GHC (4)
SOGUT (5)
BEREKET1 (6)
BEREKET2 (7)
PINARBAS (8)
GRAVGAZ (9)
GRAVGAZ96 (10)
GRAVGAZ99 (11)
AGLASUN06 (12)
AGLASUN12 (13)
AGLASUN13 (14)
BEYSEHIR (15)
BEYSEHIR1 (16)
HOYRAN (17)
KARAMIK (18)
NAR (20)
ESKI (21)
Total estimated area of sites
Number of sites (randomised start date)
No data
No data
Cal. yr. BP
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
0 4 8
0 1000 2000
0 160 480
% (sum of *Olea*, *Juglans* and *Castanea*)

Table 1 Archaeological periods in central and southwest Anatolia (based on Allcock, 2017). The Beyşehir Occupation Phase (BOP) most extensively covers the period from 3500 until 1300 BP.

Age BP	**BC / AD**	**Period**
900 - present	*AD 1050 - present*	Medieval (Islamic) to modern
1600 - 900	*AD 350 - 900*	Byzantine
~2000-1600	*~50 BC - AD 350*	Roman
~2300 - 2000	*~350 - 50 BC*	Hellenistic
3100 - 2300	*1150 - 350 BC*	Iron Age (including Persian)
3400 - 3100	*1450 - 1150 BC*	Late Bronze Age (Hittite Empire)
4000 - 3400	*2050 - 1450 BC*	Middle Bronze Age (including Old Hittite)
5000 - 4000	*3050 - 2050 BC*	Early Bronze Age
8000 - 5000	*6050 - 3050 BC*	Chalcolithic
10,300 - 8000	*8350 - 6050 BC*	Neolithic
>10,300	*>8350 BC*	Pre-Neolithic

Table 2 Metadata for pollen and climate records from sites in southern Anatolia

	Code	Site Name	Latitude	Longitude	Elevation	Contributor	Site type	Proxy type	Start and end date	N. time windows	Reference
1	OVAGOLU	Ova Gölü	36.26667	29.3	20	EPD	small marsh in drained lake	Pollen	7400-1000	30	European Pollen Database
2	GOLHISAR1	Gölhisar	37.13333	29.6	951	Eastwood	lake	Pollen and climate	10600-200	21	Eastwood W et al. (1999) Quaternary Science Reviews, 18: 671-695.
3	GOLHISH	Gölhisar Gölü	37.13333	29.6	951	EPD	lake	Pollen	8800-1200	11	European Pollen Database
4	GHC	Gölhisar Gölü	37.13333	29.6	951	Eastwood	lake	Pollen	2600-1000	6	
5	SOGUT	Sögüt Gölü	36.9975	29.89833	1400	EPD	drained lake	Pollen	8400-0	20	van Zeist WH et al. (1975) Palaeohistoria, 17: 53-144.
6	BEREKET1	Bereket1	37.54518	30.29506	1410	Kaniewski	marsh	Pollen	2200-0	11	Kaniewski D et al. (2007) Quaternary Science Reviews 26, 2201-2218.
7	BEREKET2	Bereket2	37.54518	30.29512	1410	Izdebski	marsh	Pollen	1400-1200	2	Bakker J et al. (2012) Vegetation History and Archaeobotany, 21: 249-266.
8	PINARBAS	Pinarbasi	37.46667	30.05	970	EPD	lake	Pollen	4600-800	11	European Pollen Database
9	GRAVGAZ	Gravgaz	37.58425	30.40358	1215	Izdebski	marsh	Pollen	1800-0	9	Bakker J et al. (2012) Vegetation History and Archaeobotany, 21: 249-266.
10	GRAVGAZ96	Gravgaz96	37.58425	30.40358	1215	Broothaerts	marsh	Pollen	3000-0	16	Vermoere M et al. (2002) The Holocene 12: 569-584.
11	GRAVGAZ99	Gravgaz99	37.58425	30.40358	1215	Broothaerts	marsh	Pollen	2400-0	13	Bakker J et al. (2013) Climate of the Past 9: 57-87.
12	AGLASUN06	Aglasun06	37.64157	30.52029	1140	Broothaerts	stream	Pollen	8600-200	22	Vermoere M (2004) In: Waelkens M. Studies in eastern Mediterranean archaeology (SEMA 6). Turnhout: Brepols, 1-347.
13	AGLASUN12	Aglasun12	37.64058	30.5225	1140	Broothaerts	stream	Pollen	7600-0	27	Vermoere M (2004) In: Waelkens M. Studies in eastern Mediterranean archaeology (SEMA 6). Turnhout: Brepols, 1-347.

14	AGLASUN13	Aglasun13	37.64258	30.52009	1140	Broothaerts	stream	Pollen	7800-0	32	Vermoere M (2004) In: Waelkens M Studies in eastern Mediterranean archaeology (SEMA 6). Turnhout: Brepols, 1-347.
15	BEYSEHIR	Beysehir Gölü I	37.54167	31.5	1120	EPD	lake	Pollen	7400-0	22	European Pollen Database
16	BEYSEHIR1	Beysehir 77 II III	37.54167	31.5	1120	Woldring	lake	Pollen	4600-1600	22	
17	HOYRAN	Hoyran Gölü	38.275	30.875	920	EPD	lake shore, marsh	Pollen	5800-0	14	European Pollen Database
18	KARAMIK	Kararmik Batakligi	38.425	30.8	1000	EPD	marsh, partly open water	Pollen	9800-0	7	van Zeist W et al. (1975) Palaeohistoria, 17: 53-144.
19	AKGOL	Akgöl Adabag	37.5	33.73333	999	EPD	lake	Pollen	10400-1800	8	Bottema S (1987) Pages 295-310 in Aurenche O et al. eds. Chronologies in the Near East. Oxford, United Kingdom.
20	NAR	Nar Gölü	38.3403	34.45671	1363	Eastwood	lake	Pollen and climate	1600-0	9	England A et al. (2008) Holocene, 18: 1229-1245. Roberts N et al. (2016) Journal of Quaternary Science. 31: 348-362.
21	ESKI	Eski Acigol	38.55028	34.54472	1270	Woldring	lake	Pollen and climate	10800-200	44	Woldring H & Bottema S (2001/2) Palaeohistoria, 43/44.

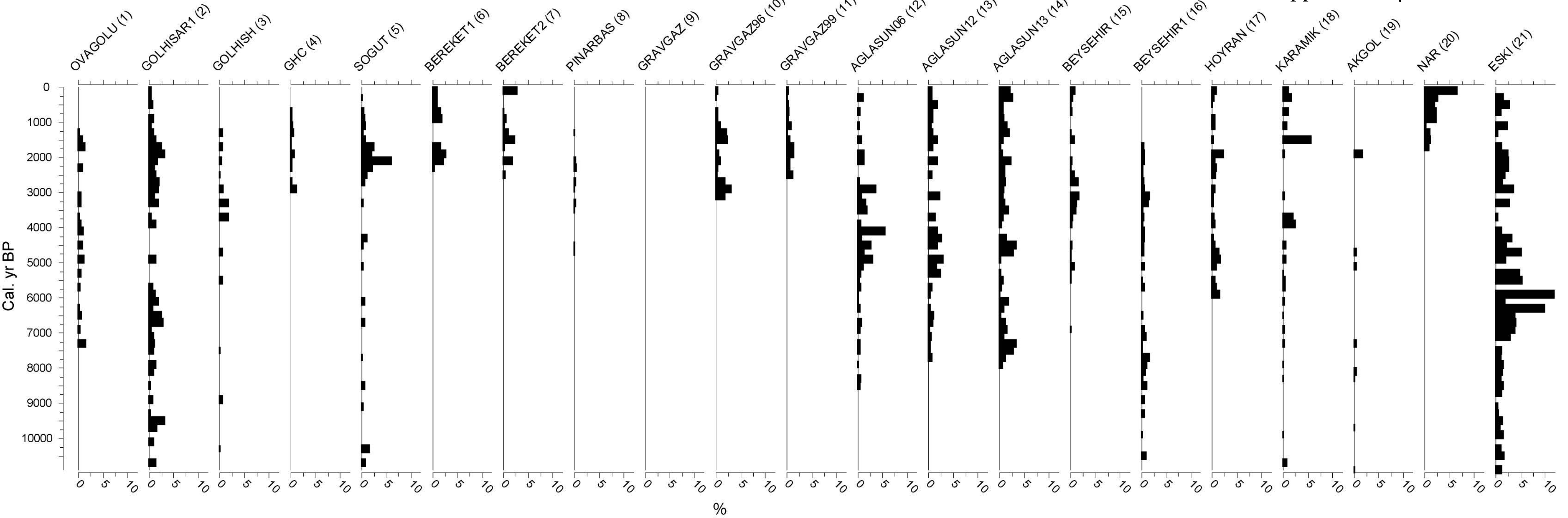
Table 3 a) Spearman's Rho correlations between the pollen and archaeological datasets (upper value within each cell: r-value and lower value: p-value) (significant correlations are shaded grey) (9900-1100 BP)

	Raw count of sites	***Total estimated area of sites***	***Aoristic sum of sites***	***Number of sites***
1.1: Sclerophyllous parkland	0.255 0.091	0.263 0.081	0.223 0.141	0.164 0.281
4.0: Pine forest	-0.304 0.042	-0.296 0.048	-0.208 0.17	-0.19 0.212
5.1: Pine woods	0.303 0.043	0.276 0.067	0.272 0.07	0.23 0.128
1.3: Steppe parkland	-0.3 0.045	-0.3 0.045	-0.292 0.052	-0.283 0.059
1.2: Evergreen shrubland (Oleaceae)	0.095 0.534	0.065 0.672	-0.003 0.987	-0.077 0.613
5.2: Pine steppe	-0.005 0.973	0.017 0.91	-0.052 0.732	-0.031 0.839
3.0: Pasture/wetland	0.664 0	0.693 0	0.73 0	0.731 0
6.1: Deciduous oak woods	-0.1 0.514	-0.135 0.375	-0.099 0.519	-0.069 0.653
1.4: Parkland/grassland	-0.3 0.045	-0.288 0.055	-0.302 0.044	-0.224 0.139
6.2: Deciduous oak parkland	-0.396 0.007	-0.4 0.006	-0.408 0.005	-0.396 0.007
Arboreal Pollen	-0.408 0.005	-0.423 0.004	-0.455 0.002	-0.439 0.003
Non-arboreal Pollen	0.443 0.002	0.451 0.002	0.5 0	0.478 0.001
Oleaceae	0.783 0	0.784 0	0.791 0	0.807 0
OJC	0.855 0	0.853 0	0.863 0	0.854 0
OJCV	0.85 0	0.847 0	0.857 0	0.851 0
API	0.478 0.001	0.454 0.002	0.474 0.001	0.461 0.001
Grazing indicators	0.663 0	0.656 0	0.67 0	0.691 0
Regional pastoral indicators	0.29 0.054	0.267 0.076	0.242 0.109	0.228 0.133
Simpson's diversity index	-0.039 0.798	-0.039 0.801	-0.035 0.821	-0.025 0.869
nMDS axis 1	0.473 0.001	0.48 0.001	0.511 0	0.49 0.001
nMDS axis 2	-0.552 0	-0.553 0	-0.491 0.001	-0.46 0.001

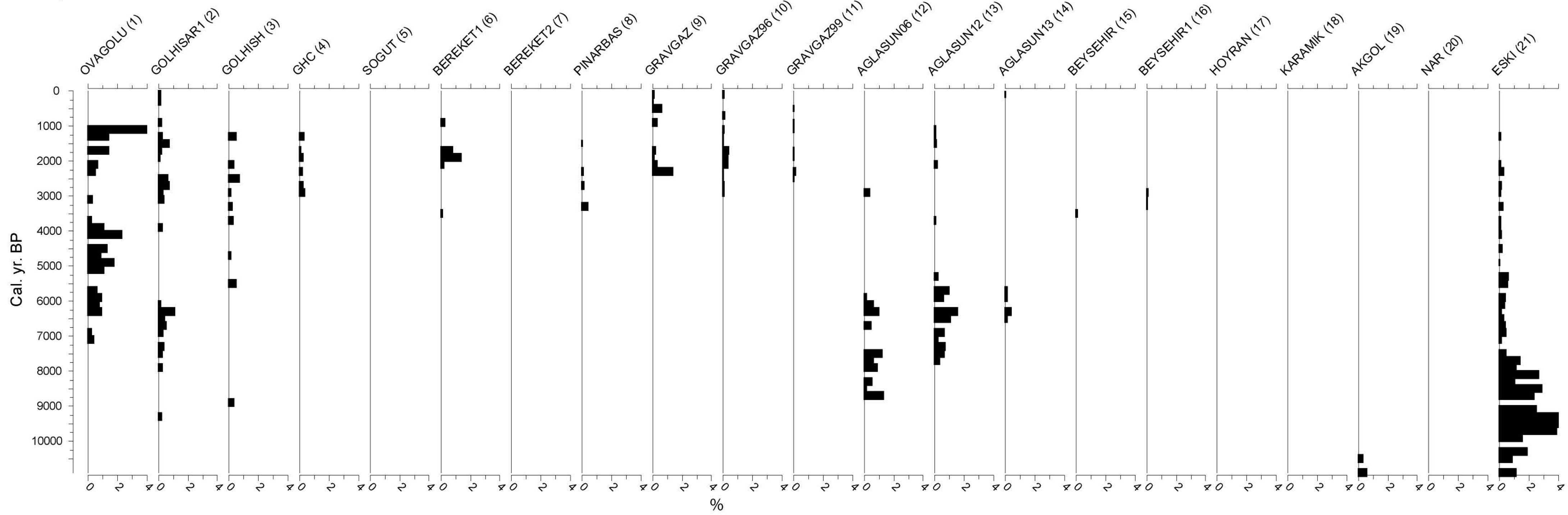
Table 3 b) Spearman's Rho correlations between the pollen, archaeological and palaeoclimate z-score datasets (upper value within each cell: r-value and lower value: p-value) (significant correlations are shaded grey) (for corresponding time periods)

	Gölhisar	*Nar Gölü*	*Eski Acıgöl*	*Average z-score*
1.1: Schlerophyllous parkland	-0.16	-0.281	-0.138	-0.204
	0.272	0.083	0.39	0.154
4.0: Pine forest	0.073	0.281	0.341	0.28
	0.617	0.083	0.029	0.049
5.1: Pine woods	-0.279	0.018	-0.023	-0.093
	0.052	0.913	0.886	0.519
1.3: Steppe parkland	0.183	0.159	0.288	0.246
	0.209	0.332	0.068	0.086
1.2: Evergreen shrubland (Oleaceae)	0.128	-0.202	-0.141	0.017
	0.38	0.218	0.378	0.908
5.2: Pine steppe	-0.034	0.043	0.143	0.155
	0.817	0.797	0.374	0.283
3.0: Pasture/wetland	-0.183	-0.73	-0.779	-0.677
	0.209	0	0	0
6.1: Deciduous oak woods	0.005	0.13	0.163	0.176
	0.971	0.431	0.308	0.222
1.4: Parkland/grassland	0.25	0.319	0.343	0.396
	0.083	0.048	0.028	0.004
6.2: Deciduous oak parkland	0.146	0.267	0.452	0.39
	0.317	0.1	0.003	0.005
Arboreal Pollen	0.086	0.451	0.484	0.391
	0.559	0.004	0.001	0.005
Non-arboreal Pollen	-0.108	-0.481	-0.474	-0.403
	0.459	0.002	0.002	0.004
Oleaceae	-0.175	-0.737	-0.644	-0.571
	0.23	0	0	0
OJC	-0.301	-0.719	-0.752	-0.692
	0.036	0	0	0
OJCV	-0.3	-0.725	-0.752	-0.693
	0.036	0	0	0
API	-0.353	-0.528	-0.219	-0.355
	0.013	0.001	0.169	0.011
Grazing indicators	-0.306	-0.596	-0.604	-0.645
	0.033	0	0	0
Regional pastoral indicators	-0.332	-0.392	-0.01	-0.205
	0.02	0.014	0.952	0.154
Simpson's diversity index	-0.179	-0.122	0.036	-0.153
	0.218	0.46	0.824	0.288
nMDS axis 1	-0.091	-0.524	-0.53	-0.415
	0.536	0.001	0	0.003
nMDS axis 2	0.372	0.268	0.406	0.41
	0.009	0.099	0.008	0.003
Raw count of sites	-0.473	-0.754	-0.743	-0.778
	0.001	0	0	0
Total estimated area of sites	-0.46	-0.696	-0.756	-0.758
	0.001	0	0	0
Aoristic sum of sites	-0.415	-0.714	-0.798	-0.775
	0.005	0	0	0
Number of sites	-0.486	-0.662	-0.729	-0.7
	0.001	0	0	0

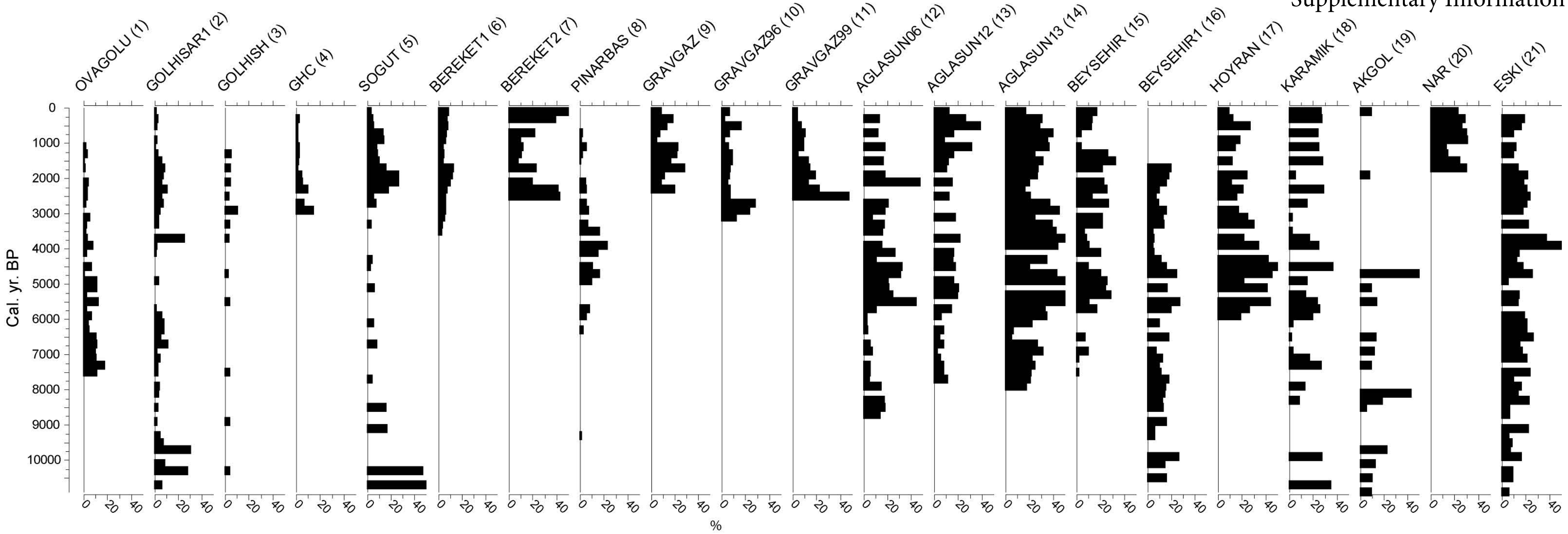
a) *Cerealia*



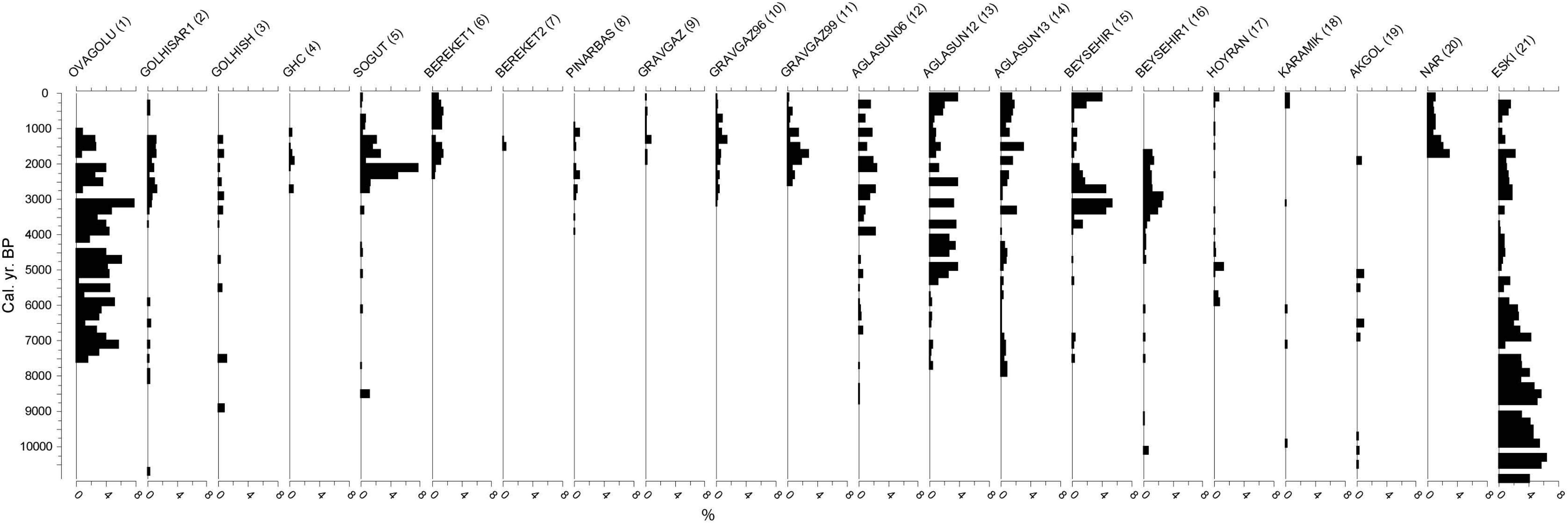
b) *Pistacia*



a) Anthropogenic Pollen Index (API)



a) Grazing indicators (*Plantago lanceolata, Rumex acetosa*-type, *Sanguisorba*)



Supplementary Information 3 Archaeological datasets and references for settlement data used in this study.

Reference	**Season**	**N. sites**
Abay 2011	2003-2009	79
Bahar 1997	1995	22
Bahar 1998	1997	1
Bahar 1999	1997	11
Bahar 2001	1998-1999	21
Bahar 2002	2000	13
Bahar 2003	2001	5
Bahar 2004	2002	3
Bahar 2008	2006	38
Bahar 2009	2007	24
Bahar 2014	2012	18
Baird 2004	1995-96	85
Baird 2005	1995-99	19
Balci and Çakan 2016	2015	10
D'Alfonso 2010	2006-2009	31
Dökü 2013	2012	2
Dökü and Baytak 2015	2013-2014	12
Dökü and Baytak 2016	2015	11
Erbil 2016	2015	16
Erbil et al. 2015	2014	11
French 1965	1963-64	10
French 1970	1958	62
Gülçür 1995	1993	13
Kontani 2012	2011	18
Kontani 2013	2012	16
Kulakoğlu *et al.* 2010	2008	2
Kulakoğlu *et al.* 2011	2009	13
Kulakoğlu *et al.* 2012	2010	21
Harmanşah and Johnson 2012a	2010	9
Harmanşah and Johnson 2012b	2012	15
Harmanşah and Johnson 2013a	2011	21
Harmanşah and Johnson 2013b	2013	3
Harmanşah and Johnson 2015	2014	8
Harmanşah and Johnson 2016	2015	2
Maner 2014	2013	13
Maner 2015	2014	25
Maner 2016	2015	8
Mellaart 1963	1951-1958	104
Omura 1993	1991	7
Omura 1995	1993	31
Omura 1997	1995	33
Omura 1998	1996	23
Omura 2000	1999	62
Omura 2001	2000	9

Omura 2003	2002	9
Omura 2008	2003-2006	156
Özsait 2003	2001	17
Özsait and Özsait. 2013	2011	7
Poblome *et al.* 2015	2014	9
Senyurt 1999	1997	11
Seton-Williams 1954	1951	143
Vanhaverbeke and Waelkens 2003	1993-96	131

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Baird, D. 2004. Settlement Expansion on the Konya Plain, Anatolia. In: W. Bowden, L. Lavan, and C. Machado (Eds.), *Recent Research on the Late Antique Countryside*. Leiden: Brill, 219-246.

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