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Environmental conditions in the SE Balkans since the Last Glacial Maximum and their influence on the spread of agriculture into Europe

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Abstract

The Thracian Plain in the SE Balkans was one of the main corridors through which Neolithic agriculture spread into continental Europe. Previous studies have invoked rapid sea-level and climatic changes to explain the timing of agricultural expansion. We present a new record of vegetation, fire and lacustrine sedimentation from Bulgarian Thrace to examine environmental change in this region since the Last Glacial Maximum. Our record indicates the persistence of cold steppe vegetation from ~37,500 to 17,900 cal. a BP, semidesert vegetation from ~17,900 to 10,300 cal. a BP, forest-steppe vegetation from ~10,300 to 8900 cal. a BP, and mixed oak woods from ~8900 to 4000 cal. a BP, followed by widespread deforestation, burning and grazing. Early-Holocene forest expansion in Bulgarian Thrace closely followed changes in the Black Sea's regional moisture balance and appears to have been influenced by solar-forced changes in seasonality. We suggest that climatic aridity and/or enhanced seasonality – lasting until at least ~8900 cal. a BP – could have delayed the spread of early agriculture from the Aegean coast into the continental lowlands of the Balkans and thence into the rest of Europe.

Keywords: pollen; charcoal; magnetic susceptibility; late Quaternary; early agriculture; Neolithic transition

1. Introduction

Climate changes during the late Pleistocene and early Holocene triggered major migrations of species and biomes in temperate latitudes (Roberts, 1998). A potential example of this is the spread of Neolithic farming into Europe, which resulted in the transmission of technology, cultural traditions, genetic heritage and multiple plant and animal species from Western Asia. The degree to which environmental change influenced this complex and essentially cultural event remains the topic of a vast scientific debate (e.g. Weninger et al., 2006; Turney and

Brown, 2007; Bocquet-Appel et al., 2009; Haak et al., 2010; Özdoğan, 2011; Pross et al., 2011; Magyari et al., 2012). It has been argued that rapid environmental changes, such as the 8200 cal. a BP climatic event and Black Sea flood, had major impacts on the Neolithic transition (Ryan et al., 1997; Weninger et al., 2006; Turney and Brown, 2007; Pross et al., 2011). While the precise timing of the arrival of Neolithic agriculture in SE Europe remains contentious, there is general agreement that farming reached the Aegean coast somewhat earlier than the Balkans' inland valleys and plains (Boyadziev 1995, 2009; Perles, 2004; Turney and Brown, 2007; Reingruber and Thissen, 2009; Pinhasi et al., 2012).

Geographical factors mean that the Thracian Plain is one of the probable corridors through which agriculture made its way into the rest of Europe (Bocquet-Appel et al., 2009; Özdoğan, 2011). The first agricultural settlements in Bulgarian Thrace date to around 8000 cal. a BP (Boyadziev, 1995, 2009). Until now there has been no direct palaeoenvironmental evidence from this area to enlighten debate about the causes of the apparent delay in agricultural expansion.

Here we present a late-Quaternary pollen, non-pollen palynomorph, magnetic susceptibility and charcoal record from a site that was formerly Bulgaria's largest inland water body. Our aim is to address the following questions:

1. How did the vegetation of the Thracian Plain respond to climate changes since the Last Glacial Maximum?
2. Could the environment have influenced the Neolithic transition to agriculture?
3. Is Neolithic and later human activity registered palaeoecologically?

1.1. Regional setting

The Thracian Plain is a fertile basin wedged between the mountain chains of the Balkans and the coastlines of the Aegean, Marmara and Black Seas. Throughout its history, the plain has acted as a cultural conduit between East and West, criss-crossed by trade routes and rich in archaeological remains. It was one of the main routes by which agriculture made its way into Europe from Western Asia, and was home to Europe's earliest metalworking cultures (Renfrew, 1978; Bailey, 2000; Bocquet-Appel et al., 2009; Haak et al., 2010). Archaeobotanically, six Neolithic sites on the Thracian Plain and adjacent foothills have been analysed, showing that the full range of Near Eastern crops was cultivated here (Marinova 2006; Leshtakov et al. 2007).

In contrast to other parts of Europe, surprisingly little is known about the environmental context of early agriculture on the Thracian Plain. Previous palynological studies of Bulgaria's past vegetation have focussed on the mountains (e.g. Tonkov et al., 2011; Marinova et al., 2012) or on present-day coastlines (e.g. Filipova, 1985; Bozilova and Beug, 1992). Mountain sites were too remote from early farming populations to directly register the arrival of agriculture and pastoralism in the region, while the coastal sites began to form as sea-levels rose 8000–6000 years ago, usually missing the early-Holocene advent of agriculture altogether. The lowlands, where most of the Neolithic settlements were situated, lack detailed palaeoenvironmental records (Marinova and Thiebault, 2008; Marinova et al., 2012). The few pollen data that exist from Bulgaria's Thracian Plain miss the early Holocene altogether (Filipovitch and Stojanova, 1990; Magyari et al., 2008; Tonkov et al., 2008a, 2009).

These studies unanimously assert that the Thracian Plain was dominated by oak forests prior to clearing associated with agriculture, but none provide direct palynological evidence that would support such a claim. Oak pollen never exceeds 20% in mid to late Holocene pollen records from Sadovo and Straldzha, leading the authors of these studies to conclude that the Thracian Plain's oak forests were destroyed prior to ~4000 cal. a BP (Filipovitch and Stojanova, 1990; Tonkov et al., 2008a, 2009). Chapman et al. (2009) suggest that oak trees grew around the Ezero wetlands (Fig. 1) in the early-mid Holocene, but present pollen and macrofossil diagrams covering a later period (3200–2200 cal. a BP) and indicating deforested, agricultural landscapes. Only marine sediments from the Black Sea provide good evidence for the early-mid Holocene expansion of *Quercus*; the timing of subsequent deforestation is unclear, however, with some marine and coastal records showing an abrupt decline in *Quercus* around 6000 cal. a BP and others showing no decline at all (Bozilova and Beug, 1994; Atanassova, 2005; Filipova-Marinova et al., 2011, 2012; see also Shumilovskikh et al., 2012). In the marine cores, moreover, palaeoecological responses to human impact, climatic changes and sea-level rise can be difficult to disentangle (Filipova-Marinova et al., 2011; Shumilovskikh et al., 2012).

2. Material and methods

2.1. Site description

The Straldzha Mire is located in the Karnobat Lowlands at the foot of the Stara Planina Mountains (Fig. 2). These lowlands are part of the pre-Balkan sunkland that extends westward to the Bulgarian capital, Sofia (Georgiev, 1991). The mire occupies a large, shallow depression underlain by Pleistocene silts and gravels and is surrounded by low hills of Upper Cretaceous limestones, marls and volcanic deposits (Stoyaneva and Michev, 2007; Tonkov et al., 2008a). The mire formerly covered an area of around 14,000 ha (Bonchev, 1929), making it the largest freshwater wetland basin in Bulgaria.

Early 20th century botanists recorded that the Straldzha Mire was a diverse reed-swamp dominated by *Phragmites australis*, with floating islands in areas of open water, a thick peat layer and halophilous vegetation distributed around the margins (Stoyneva and Michev, 2007; Tonkov et al., 2008a). Artificial drainage of the Straldzha Mire proceeded from 1932 to 1939, initially by deepening the bed of the Marash, a creek that runs along the western edge of the mire. Expansion of the canal system continued and, by the 1960s, the mire was completely drained (Stoyaneva and Michev, 2007).

The area around the mire, like most of Bulgarian Thrace, is thought to have once been vegetated by oak forests (*Q. cerris, Q. pubescens* ssp. *pubescens, Q. frainetto* and *Q. robur*), with *Ulmus minor* and *Fraxinus angustifolia* ssp. *oxycarpa* communities distributed over floodplains

(Bondev, 1991). Today, few remnants of these forest communities remain and the entire lowland is an agricultural landscape.

The climate of Bulgaria's Thracian Plain is transitional between Mediterranean and continental zones, with two precipitation maxima: in winter and May-June (Fig.2). Average annual precipitation amounts to 540 mm and the average temperature is 12 ºC, reaching an absolute maximum of 38 ºC (Gâlâbov, 1973).

2.2. Sampling and analytical techniques

In March 2008, we dug a trench 520 cm deep and 30 cm wide into the side of the "Straldja" tile factory's quarry in the lowest part of the Straldzha Mire (Fig. 2; 42º37'49"N, 26º46'12"E, 138 m a.s.l.).The quarry is located near the 'Gyola' area where Tonkov et al. (2008a, 2009) obtained their late Holocene pollen record. Samples ~20cm^3 in size were taken at 5-cm intervals until a depth of 140 cm from the surface and thereafter at 20-cm intervals. The samples were immediately sealed in plastic bags and stored in a refrigerator.

Subsamples of 1cm^3 were extracted for pollen analysis, combined with *Lycopodium* spore tablets (University of Lund), treated with 10% HCl, density separation in sodium polytungstate (s.g. 2.0) and acetolysis for 1 minute, prior to being mounted in glycerol and identified at 400× magnification. At least 200 (average 600) terrestrial pollen were counted in each sample. Pollen identifications were made with reference to Moore et al. (1991) and Reille (1999). Non-pollen palynomorphs were classified according to Jankovská and Komárek (2000), van Geel (2001) and van Geel and Aptroot (2006).

Microscopic charcoal (<200 µm) was quantified on pollen slides using the point-count method (Clark, 1982), while macroscopic charcoal (>250 µm) was quantified using a modification of the 'Oregon sieving method' (Long et al., 1998; Mooney and Tinner, 2011). A known volume (~2 cm^3) of sediment was placed in dilute (4.2%) sodium hypochlorite (bleach) for 24 hours (Rhodes 1998) and then washed through a 250 µm sieve. The captured material was hand-sorted to remove extraneous material and the charcoal photographed using a high-resolution digital camera. Charcoal concentrations were quantified using image analysis software (Scion Image 4.0.3.2). This resulted in the concentration of macroscopic charcoal >250 μm, expressed as an area (mm^2 per cm^3). Charcoal particles of this size should predominantly reflect local fire events (Long et al., 1998; Whitlock and Larsen, 2001; Conedera et al., 2009). Charcoal concentrations were then converted to an influx (also known as charcoal accumulation rates or CHAR), by normalising for the deposition time of the sample.

Dual-frequency magnetic susceptibility measurements were run on a Bartington MS2 magnetic susceptibility meter following the protocols outlined by Dearing (1999) and Herries and Fisher (2010). Additional mineral magnetic analysis was undertaken on a Magnetic Measurements Variable Field Translation Balance (VFTB), including isothermal remanent magnetisation (IRM) acquisition curves and backfields, hysteresis loops and thermomagnetic curves. These mineral magnetic measurements provide information on changes in the magnetic minerals present (i.e. magnetite, maghaemite and haematite), their magnetic grain size and concentrations, thus allowing changes in sediment source and alteration to be identified and the driving forces behind magnetic susceptibility changes to be established.

Since the upper part of the Straldzha quarry record may have been disturbed or truncated by quarrying activities, we obtained additional cores from three locations on the mire (Fig. 2) where material excavated during construction of drainage canals preserved the original sediment surface. The cores were collected with an Eijkelkamp auger. Samples from the westernmost site (canal core, Fig. 2) were taken at 10-cm intervals (5-cm intervals around sedimentological changes) and pollen extracted as described above, although *Lycopodium* markers were unavailable at the time. Results were plotted using Psimpoll (Bennett, 2004).

2.3. Numerical analyses

Pollen data were analysed numerically to elucidate the palaeoclimatic significance and palaeovegetational context of the results. We used Detrended Correspondence Analysis (DCA: Hill and Gauch, 1980) and minimum variance cluster analysis (Ward, 1963) to compare preexisting pollen data to the new record. We made use of data publicly available through the European Pollen Database (Fyfe et al., 2009) and selected a number of representative records from the Bulgarian mountains and the Black Sea area (Fig. 1) in order to compare geographical and altitudinal patterns in vegetation development. Pollen taxonomy was standardised to a base of 99 taxa (see supplementary information), resulting in some loss of information. This standardisation was necessary to remove the influence of different pollen-taxonomic systems (e.g. differentiation of *Quercus* morphotypes). Analyses were implemented in the program PC-Ord (McCune and Mefford, 1999). A combination of minimum variance clustering and indicator species analysis (Dufrêne and Legendre, 1997) was used to determine an optimum number of groups. We selected the maximum number of groups in which each group had at least one statistically significant indicator (p=0.001; Monte Carlo test, 1000 permutations). Results were plotted on timescales provided in the European Pollen Database or, in the case of Lake Varna, from the original publication (Bozilova and Beug, 1994).

2.4. Chronology

Thirteen Accelerator Mass Spectrometer radiocarbon dates were obtained for the Straldzha profiles. In the absence of macrobotanical material for dating, five of the radiocarbon determinations were made on pollen concentrates extracted using the Australian Nuclear Science and Technology Organisation's procedure based on Brown et al. (1989). The remaining samples were cleaned to remove rootlets and pre-treated by acid washing in dilute HCl, then organic residues were dated. An age-depth model was constructed for the quarry section using Markov chain Monte-Carlo analysis, a Bayesian statistical approach to age modelling implemented in OxCal 4.1.7 (Bronk Ramsey, 2009), based on the IntCal09 calibration curve (Reimer et al., 2009). The age-depth model was extended by linear extrapolation to cover the entire quarry section (Fig. 3). Sediment accumulation rates in the upper part of the record were also applied to the upper metre of the canal core. The lowermost sample in the core was statistically matched with the beginning of palaeovegetation phase 4 (Section 3.2) and the intervening ages interpolated from the AMS date at 110-cm depth (Fig. 3).

3. Results

3.1. Sediment description and mineral magnetics

Sediment descriptions for the two Straldzha Mire records appear in Table 1. The most important change in the sedimentary sequence occurred around 125 cm in the quarry section, where the grey to orange-brown sediments laid down under oxidising conditions (Unit III) were overlaid by darker peaty silts and lighter lake marls (Units IV and V). Additional cores collected near drainage canals showed Unit VII to be ~25 cm thicker in the western part of the Straldzha Mire compared to the east. In several fields near the quarry this top layer has been lost completely, exposing the underlying light-grey marl (Unit VI). The canal core is more likely to represent the full sedimentary sequence of this unit.

Magnetic susceptibility measurements (X_{LF}; Fig. 4) broadly follow lithological changes, exhibiting medium and variable values ($0.31–0.15\times10^{-6}m^3kg^{-1}$) in the silty units (I–III), low and stable values ($0.11–0.08\times10^{-6}m^3kg^{-1}$) in the marl sediments (IV–VI, and VII in the canal core) and very high values ($1.25–0.64\times10^{-6}m^3kg^{-1}$) in the disturbed surface sediments (Unit VII in the quarry record; Unit VIII in the canal core). The magnetic mineralogy of the Straldzha sediments is dominated by varying proportions of: (1) authigenic and detrital ferrimagnetic material, principally magnetite, and (2) paramagnetic material that is mainly due to the presence of paramagnetic iron-bearing, but generally unoxidised, clay minerals (see supplementary information and Table 1). The basal silt units have much higher amounts of ferrimagnetic material, consisting of both magnetite and maghaemite of likely detrital origin. The marls have very little ferrimagnetic material and are dominated by paramagnetic material, possibly authigenic. The disturbed surface sediments are dominated by large amounts of ultra-fine grained magnetite, consistent with ferrimagnetic enhancement via pedogenesis. High magnetic susceptibility is related to the draining of the mire.

3.2. Numerical analyses and pollen stratigraphy

A pollen diagram, depicting both the quarry section and core, is shown in Fig. 4 (see also supplementary information). Like the core of Tonkov et al. (2008a, 2009), collected nearby, pollen preservation in the sediments was variable. We attribute this to the alkalinity of the sediments, the continental climate and the fact that the wetland was artificially drained some decades ago.

Cluster analysis (Fig. 5; supplementary information) was used to group the pollen record into five palaeovegetation phases (Fig. 4), the names of which are based on the assumed ecological preferences of the indicator taxa listed in Table 2. DCA axes 1 and 2 explain 46% and 20% of variance respectively and produced results in strong agreement with the cluster analysis (supplementary information). Axis 1 gives high scores to samples abundant in deciduous tree taxa (especially *Quercus*) and low scores to samples with abundant coniferous taxa (especially *Pinus*). Given the present-day ecology and distribution of the tree species represented, this axis perhaps best reflects a winter temperature and/or rainfall seasonality gradient. Axis 2 gives high scores to samples with abundant tree taxa and low scores to the most important xerophytic taxa, Chenopodiaceae and *Artemisia*. This axis is thus most easily attributed to a moisture gradient.

3.2.1. Cold steppe phase (517.5–167.5 cm, quarry section)

The lowermost zone is dominated by the pollen of herbs and grasses, with an abundance of *Artemisia* (24–37%) and Poaceae (8–25%). Chenopodiaceae, *Ranunculus*-type and *Polygonum aviculare*-type are well represented. *Pinus* is the most abundant arboreal pollen type (3–26%), but *Quercus*, *Betula, Juniperus* and *Celtis* also occur throughout. *Pediastrum* is abundant (up to 12 times the terrestrial pollen sum).

3.2.2. Semidesert phase (167.5–105 cm, quarry section)

At the beginning of the second zone, *Artemisia* and arboreal pollen decline and Chenopodiaceae rises to a peak, completely dominating the pollen assemblage (58–69%). Toward the end of the zone, arboreal pollen begins a resurgence led by *Quercus, Corylus* and *Ulmus*. At the same time, charred particles, dung-inhabiting fungi and various indicators of shallow water (*Typha latifolia*-type, *Gleoetrichia*-type, and *Spirogyra*-type) increase, while magnetic susceptibility declines.

3.2.3. Forest-steppe phase (105–55 cm, quarry section)

A suite of grassland taxa (e.g. *Allium, Centaurea, Dipsacus, Filipendula*-type, *Galium*-type, *Heracleum*-type, *Sanguisorba minor*) increases in the third zone against a background of slowly rising *Quercus* values and the constant presence (<1%) of *Pistacia*. Spores of dung-inhabiting fungi (*Sporormiella* and *Sordaria*) and charred particles decline through this zone.

3.2.4. Oak woods phase (55–20 cm, quarry section; 170–105 cm, canal core)

Quercus increases rapidly in the fourth zone, this time reaching its highest proportions for the entire record (up to 52%). Average pollen concentrations of *Quercus* are three times higher than in the previous zone, while *Ulmus* and *Corylus* concentrations double (supplementary information). Charcoal, Chenopodiaceae, grassland taxa and dung fungal spores are reduced. *Potomogeton* and *Pediastrum* occur throughout.

3.2.5. Deforestation phase (20–0 cm, quarry section; 105–65 cm, canal core)

The final zone shows a sharp decline in *Quercus, Corylus* and *Ulmus*, and an increase in charred particles, dung fungal spores, Poaceae and *Plantago lanceolata*-type. The canal core, which is regarded as a more complete representation of this phase, indicates that deforestation was preceded by the late succession of *Fagus* and *Carpinus* and followed by considerable peaks in *Salix, Alnus* and fern spores, and a temporary recovery of *Quercus*. All of these taxa decrease toward the end of the zone, when Chenopodiaceae, *Triticum*-type and macroscopic charcoal increase.

3.3. Age-depth model

Radiocarbon dating results are provided in Table 3. Three dated points were initially excluded from the age-depth model, having both low organic content and large error margins. Residual carbonates adhering to the pollen grain walls may explain the discrepancy between ^{14}C ages for pollen concentrates and bulk sediment samples (Kilian et al., 2002). Using the remaining points, performance statistics indicated poor agreement between the data and the model (agreement index A_{model} 12%), especially in relation to samples Wk-32001 and Wk-32002. Exclusion of Wk-32001 increased the model's agreement index to a more acceptable level (A_{model} 58%). This model (Fig. 3) places the Pleistocene–Holocene boundary around 128–130 cm, close to the lithological change and initial oak pollen increase at 125 cm.

4. Discussion

4.1. Late Quaternary vegetation on Bulgaria's Thracian Plain

Two important considerations should be taken into account in interpreting the palaeovegetation record from Straldzha Mire. The first concerns the age-depth model. Considerable uncertainty is attached to the pre-Holocene section, which is affected by low organic content, possible old carbon effects and overlapping ages for different sediment depths. We cannot exclude the possibility that intervals of rapid sedimentation and/or hiatuses occurred during this period (e.g. Magyari et al., 2008; Tonkov et al., in press), although certain features of the pollen record (discussed below) suggest continuous sedimentation. The second consideration is that the pollen source-area of large sites (>100 ha) is dominated by a regional pollen component (Jacobson and Bradshaw, 1981; Sugita, 2007). Palaeovegetation records from such sites are representative of a large spatial area, estimated at ~10^4–10^5 km^2 (Sugita, 2007), and recent modelling suggests even greater areas may be involved (Theuerkauf et al., 2012). Only large-scale vegetation changes are thus expected to register in the Straldzha pollen record.

4.1.1. Cold steppe phase (~37,500–17,900 cal. a BP)

An *Artemisia*-dominated cold steppe phase occurred from the beginning of the Straldzha quarry record until ~17,900 cal. a BP. This phase corresponds to pollen spectra dated to Marine Isotope Stages (MIS) 2 and 3 in the Tenaghi Philippon record (Müller et al., 2011) and also occurs in pollen records from the Black Sea (Atanassova, 2005; Shumilovskikh et al., 2012) and the mountains of SW Bulgaria (Fig. 5). Similar pollen assemblages appear in the earliest part of the Ezero record (Magyari et al., 2008), dated around 15,000 cal. a BP, and were interpreted as a landscape of dry steppe and wooded steppe. Plant macrofossil data from Ezero indicate that arboreal taxa such as *Juniperus, Celtis, Quercus, Betula* and certain Rosaceae were present on the Thracian Plain, but their presence is hardly evident from pollen data perhaps because of reduced pollen production under glacial conditions (Magyari et al., 2008; Feurdean et al., 2012; see also Willis, 1994). Similar patches of xeric woodland were probably present around the Straldzha Mire, since the same pollen taxa occur during the cold steppe phase and the eastern Balkans is regarded as one of the probable refugial areas for deciduous thermophilous trees (Krebs et al., 2004; Leroy and Arpe, 2007; Bozilova et al., 2011). The presence of *Betula*, however, seems to indicate a climate considerably colder than at present (Tarasov et al., 1998; Magyari et al., 2008). The magnetic susceptibility and mineralogy of this period suggests that detrital input into the lake alternated with derived, pedogenically enhanced sediments, and this potentially reflects colder but variable climatic conditions consistent with deposition during MIS 3 and into MIS 2. Ordination results also suggest climatic variability through this phase (Fig. 6).

Pine trees were also present in the region throughout the last glacial period. *Pinus* pollen concentrations did not vary substantially from the Pleistocene to the Holocene (supplementary information), suggesting that much of the *Pinus* pollen in Straldzha Mire was blown in from distant sources. The lowest arboreal pollen contribution (7.5%) is recorded at the earliest part of the cold steppe phase, corresponding to the grey silt band around 35,000 cal. a BP. Similar minima, dated to ~39,000 cal. a BP (mid MIS 3), are recorded at Lake Prespa (Leng et al., in press) and Tenaghi Philippon (Müller et al., 2011), possibly reflecting a regional climatic fluctuation. Higher arboreal percentages (up to 35%), especially of *Pinus*, in the later part of the phase are most likely to reflect the expansion of frost-tolerant woodland during MIS 2 (Müller et al., 2011).

The Straldzha Mire probably existed as an ephemeral lake during the cold steppe phase. The lake water was colonised by *Potomogeton* and coccal green algae (mostly *Pediastrum kawraiskyi* and *Botryococcus*). *P. kawraiskyi* is common in Lateglacial sediments from Europe and is generally associated with large lakes and cool conditions (Jankovská and Komárek, 2000). Strong evaporation occurred during the full glacial, indicated by the presence of gypsum crystals in the sediments.

4.1.2. Semidesert phase (~17,900–10,300 cal. a BP)

The subsequent Chenopodiaceae-dominated phase straddles the Pleistocene–Holocene transition, taking in the Lateglacial and early Holocene. A fundamental change in the environment of the Thracian Plain occurred between 17,900 and 13,200 cal. a BP, as indicated by a major shift in pollen assemblages and magnetic mineralogy (Fig. 4). This shift coincides with the expansion of deciduous *Quercus* around Tenaghi Philippon, interpreted as an indication of increasing moisture and less severe winters (Müller et al., 2011). The lack of any corresponding *Quercus* expansion around Straldzha may be attributed to a substantial decrease in moisture, as suggested by the ordination results; there was also no apparent temperature rise (Fig. 6). This interpretation is corroborated by the magnetic mineralogy, which demonstrates declining ferrimagnetic enhancement of externally derived soils, as would be expected in drier and/or colder climates. Reduced precipitation could also decrease sediment and magnetic input to the lake, further diminishing magnetic susceptibility.

The prevalence of Chenopodiaceae pollen suggests that the Lateglacial climate of Bulgarian Thrace was not analogous to that of the Last Glacial Maximum. Chenopodiaceae may have even been prominent in the halophyte vegetation of the Straldzha Mire: *Atriplex prostrata* ssp.

calotheca, Camphorosma monspeliaca and *Sueda maritima* were recorded around the margins of the mire prior to 20th-century drainage (Tonkov et al., 2008a). It is possible that these halophytes occupied larger areas of the mire basin during the Lateglacial, with vegetation similar to that of present-day saline lakes in semidesert and steppe areas (Connor et al., 2004; Magyari et al., 2012). Hydrological changes are indicated by magnetic susceptibility measurements (Fig. 3), the decline of green algae and the appearance of cyanobacteria (*Gleoetrichia*), perhaps indicating a carbonate-enriched, shallow lake (Chmura et al., 2006).

However, similarly aged Chenopodiaceae peaks occur in several pollen records from the Black Sea (Atanassova, 2005; Filipova-Marinova et al., 2012), at middle elevations in the Rhodope Mountains (Huttunen et al., 1992; Stefanova et al., 2006b) and even in the Veleka River refugium in SE Bulgaria (Filipova-Marinova, 2003). This suggests that the Lateglacial expansion of Chenopodiaceae at Straldzha was more than simply a local-scale phenomenon. Chenopodiaceae dominance is not, however, seen in Lateglacial pollen records from the Rila and Pirin Mountains, SW Bulgaria. At these high-elevation sites, Chenopodiaceae is always subdominant to *Artemisia* (Fig. 5; Bozilova and Tonkov, 2000; Stefanova et al., 2006a; Tonkov et al., 2008b, in press). The same applies to most areas surrounding the Mediterranean (e.g. van Zeist and Bottema, 1991; van der Knaap and van Leeuwen, 1997; Lawson et al., 2004, 2005; Müller et al., 2011). Only in the continental interiors of Western Asia does Chenopodiaceae prevail over *Artemisia* in pollen spectra of Younger Dryas age (e.g. van Zeist and Bottema, 1991; Wick et al., 2003; Djamali et al., 2008; Connor, 2011; see also El-Moslimany, 1990). Hence the Lateglacial and early Holocene of Bulgarian Thrace were most likely characterised by pronounced continentality and drought.

A regional increase in fire occurrence during the early Holocene also appears to be related to this pattern (Fig. 4; Turner et al., 2008, 2010; Magyari et al., 2012; Panagiotopoulos et al., in press). Microscopic charcoal concentrations rise during the early Holocene (Unit III–IV transition). This increase does not produce any obvious peak in magnetic susceptibility because microscopic charcoal likely entered the lake via aerial deposition from regional fires. The magnetic mineralogy, however, changes significantly at this time, displaying a gradual transition from deposits dominated by detrital inputs to those dominated by authigenic formation. As the Holocene progresses (Unit IV), magnetic susceptibility increases slightly, probably corresponding to minor variations in detrital inputs. As with the pollen, the charcoal and magnetic records remain consistent with enhanced climatic seasonality or aridity.

The timing and duration of Lateglacial and early-Holocene aridity in the region is strongly linked to summer insolation (Wright et al., 2003; Stefanova et al., 2006b; Tzedakis, 2007; Leng et al., in press). The Straldzha record suggests that the summer insolation maximum overrode the effect of the North Atlantic circulation in the continental lowlands of the Balkans. The Bølling-Allerød interstadial and Younger Dryas stadial, both temperature events that are clearly registered in the Rila and Pirin Mountains (Atanassova and Stefanova, 2003; Stefanova et al., 2006a; Tonkov et al., 2008b, 2011), had a minor impact on the vegetation of the Rhodope Mountains (Huttunen et al., 1992; Bozilova et al., 2011) and no substantial effect on the vegetation of the Thracian Plain. This could reflect differences in how vegetation at different altitudes responds to climate. Around Lake Prespa, western Balkans, trees at lower altitudes were “relatively unaffected” by the Younger Dryas, while higher elevation pines responded strongly (Panagiotopoulos et al., in press). The Younger Dryas often has an ambiguous signal in isotopic and palynological records from the Black Sea region (Badertscher et al., 2011; Filipova-Marinova et al., 2012; Shumilovskikh et al., 2012; see also Bottema, 1995). Aridity, not temperature, seems to have been the key factor limiting lowland forest development during the Straldzha semidesert phase.

4.1.3. Forest-steppe phase (~10,300–8900 cal. a BP)

The vegetation of the third phase must have been relatively open, based on the diversity of xeric and mesic herbs represented in the pollen record. Similar herbaceous taxa are represented in most of the pollen diagrams from Bulgaria that cover the early Holocene (e.g. Bozilova and Tonkov, 2000; Tonkov et al., 2002, 2008b, in press; Stefanova and Ammann, 2003; Stefanova et al., 2006a; Bozilova et al., 2011). Typically, Holocene afforestation in the mountains of

Bulgaria was led by *Betula*, followed by *Quercus*, then *Ulmus* and *Tilia*, and somewhat later by *Corylus*. Holocene succession around Straldzha Mire was quite different, as could be expected of a lowland area. *Betula* does not play a prominent role, while *Corylus, Ulmus* and *Quercus* increase simultaneously. Marine pollen records from the Black Sea show much the same succession (Atanassova, 2005; Filipova-Marinova et al., 2012), indicating a distinct pattern of lowland landscape development.

The forest-steppe phase is relevant to the discussion of climatic, fire and grazing controls on post-glacial forest succession, since it clearly reflects the pattern – widespread in the Eastern Mediterranean, Black and Caspian Seas region – of a delayed oak forest expansion in the early Holocene, accompanied by elevated proportions of *Pistacia* pollen (van Zeist and Bottema, 1991; Roberts and Wright, 1993; Willis, 1994; Wright et al., 2003; Filipova-Marinova, 2003; Stevens et al., 2006; Panagiotopoulos et al., in press). Previous studies posited that afforestation was delayed by dry early Holocene climates, contradicting evidence for wet climates from lake-levels, isotopic analyses and speleothems (Roberts et al., 2011; cf. Chen et al., 2008). Prehistoric human activities may have also played a role in stalling forest expansion (Roberts, 2002).

Changes in the seasonal distribution of rainfall may explain the apparent contradiction between lake-level and palynological proxies. Djamali et al. (2010) show that penetration of the Indian Summer Monsoon can have profound effects on the seasonality of rainfall in Western Asia, by blocking spring rainfall and promoting a more Mediterranean, winter-dominated precipitation regime. They suggest that increased monsoonal influence until ~6300 cal. a BP limited the spread of plant species that rely on spring rains. On the Mediterranean coast, a wet climate with enhanced Mediterranean characteristics (wet winters and dry summers) persisted from 9500 to 7800 cal. a BP, followed by a trend toward drier, less seasonal climates until 5000 cal. a BP (Peyron et al., 2011). For the same period, pollen records suggest increased summer moisture in the Central Balkans and Hungarian Plain (Magyari et al., 2010; Panagiotopoulos et al., 2012).

Early-Holocene climatic zones in SE Europe appear to have been quite different to what we observe at present (Wright et al., 2003).

Around Straldzha Mire, which at the time was a carbonate-rich lake with predominantly authigenic sedimentation, oak forest expansion stalled for 2500–3000 years after its initial Holocene advance (Fig. 5). A delay of 2800 years was also observed at Shiroka Polyana in the Rhodope Mountains (1400 m a.s.l.; Stefanova et al., 2006b), as well as at Skala Wetland in the Stara Planina (470 m), a site 20 km north of Straldzha Mire, where a substantial oak pollen increase (from <1% to 38%) occurred between levels dated to 9100 and 7600 cal. a BP (Connor, unpubl. data). Early-Holocene delayed afforestation is also observed in recent high-resolution pollen records from the southern Black Sea, with maximum tree pollen percentages achieved only after 8000 cal. a BP (Fig. 7; Shumilovskikh et al., 2012; Filipova-Marinova et al., 2012). The delay was therefore widespread and substantially longer than its counterpart on the Aegean coastline or in the Bulgarian mountains, where rainfall was perhaps less of a limiting factor. At Tenaghi Philippon, for example, arboreal pollen exceeds 50% around 11500 cal. a BP and 75% around 10,000 cal. a BP (Müller et al., 2011); on Bulgaria's Thracian Plain the same thresholds were crossed around 8600 and 6800 cal. a BP respectively, demonstrating prolonged early-Holocene aridity. *Pistacia* pollen, the hallmark of this phase in the Balkans and western Asia (Willis, 1994; Roberts et al., 2011), is present in small but constant quantities (<1%) throughout the forest-steppe phase. *Pistacia* pollen also appears sporadically between ~10,000–7000 cal. a BP in pollen records from other areas on or around the Thracian Plain (i.e. Kupena: Huttunen et al., 1992; and Arkutino and Varna: Bozilova and Beug, 1992, 1994), while *P. terebinthus* is recorded in Neolithic archaeobotanical assemblages from Bulgaria (Marinova, 2009). *Pistacia*'s poor pollen productivity (Roberts, 2002) implies that *P. terebinthus* shrubs took part in the early Holocene vegetation of the Thracian Plain, which also included a mixture of deciduous oaks, rosaceous shrubs and grassy meadow communities. Importantly, charcoal concentrations and the occurrence of dung-inhabiting fungi are reduced during the forest-steppe phase, so grazing and fire were perhaps not the main factors stalling the expansion of oak.

4.1.4. Oak woods phase (~8900–4000 cal. a BP)

Around 8700 cal. a BP, *Quercus* commenced a rapid expansion and meadow vegetation contracted, creating a forest landscape that persisted until ~4000 cal. a BP. Increased representation of *Corylus, Ulmus* and *Tilia* pollen indicates that other forest species increased simultaneously with oak, while *Pistacia* and other xerophytes declined. Changes in climatic seasonality and monsoonal forcing may explain the expansion of oak forest around the Straldzha Mire, but it also corresponds to a period of sea-level rise in the Black Sea (see also Filipova-Marinova et al., 2012; Shumilovskikh et al., 2012). This enormous body of water has had a strong bearing on the Holocene climate of the surrounding lands, clearly demonstrated by the link between sea level and oxygen-isotope signatures in stalagmites from Sofular Cave (Fig. 6; Fleitmann et al., 2009; Badertscher et al., 2011). It is likely that the Black Sea's influence on regional atmospheric humidity was sufficient to allow oak forests to expand, overriding the signal of solar-forced climatic changes. Its effects may have been felt as far as the Rila Mountains, where a marked change in diatom assemblages coincides with *Quercus* expansion around 8800 cal. a BP (Lotter and Hofmann, 2003).

At the end of the Straldzha oak woods phase, *Carpinus betulus* and *Fagus* make a belated arrival. These two taxa tend to appear relatively late in Bulgarian pollen records (e.g. Huttunen et al., 1992; Tonkov et al., 2002; Stefanova and Ammann, 2003), except those from coastal refugia (Bozilova and Beug, 1992, 1994; Filipova-Marinova, 2003). Fire occurrence also appears to have increased toward the end of the oak forest phase, reflecting a pattern observed across the Eastern Mediterranean region (Vannière et al., 2011).

4.1.5. Deforestation phase (~4000 cal. a BP onwards)

A phase of deforestation represents the final stage in the vegetation history of Bulgaria's Thracian Plain and is more faithfully registered in the canal core than in the quarry section. The only other pollen records from the plain, Sadovo and Straldzha-1, begin around 4000 cal. a BP and indicate that deforestation had already occurred by that time (Filipovitch and Stojanova, 1990; Tonkov et al., 2008a). Deforestation, accompanied by fires and grazing, eliminated *Ulmus* from the Straldzha region. *Corylus* and *Quercus* also declined, but both managed a brief recovery, which was also attended by peaks in light- and moisture-demanding pioneer species (*Salix, Alnus* and Polypodiaceae). Cluster analysis associated this recovery stage with grasslands (Fig. 5). Subsequent fires (occurring locally, judging from the abundance of macroscopic charcoal) appear to have removed most of the regrowth, forming something like the present-day landscape. A gradual increase in magnetic susceptibility is seen at this time that likely reflects increased erosion due to deforestation. The timing of major deforestation on the Thracian Plain, from about 4000 cal. a BP, agrees with previous studies from the Balkans (Willis, 1994), but is rather late in terms of the greater Eastern Mediterranean region, where earlier, large-scale clearances are detected around 5000 cal. a BP (Roberts et al., 2011).

Anthropogenic interference in Bulgaria's vegetation is thought to have a long history, dating back to the Neolithic Period (Bozilova and Tonkov, 1990, 1998; Willis and Bennett, 1994). Pollen of cultivated plants, especially cereals, are regarded as primary indicators of anthropogenic activity, while secondary indicators in steppic areas include *Plantago, Rumex, Polygonum aviculare, Urtica, Artemisia,* Chenopodiaceae and the Asteraceae subfamily Cichorioideae (Bozilova and Tonkov, 1998). The application of these indicators, both primary and secondary, to the Straldzha record is confounded because they occur throughout the Lateglacial and Holocene, presumably as a natural part of the vegetation. This issue applies, in varying degrees, to other lowland sites in Bulgaria (Bozilova and Tonkov, 1990; Marinova and Atanassova, 2006; Marinova et al., 2012), and elsewhere in SE Europe (Magyari et al., 2012; Panagiotopoulos et al., in press) and Anatolia (Bakker et al., 2011). The Straldzha Mire is also so large that only extensive landscape modification could be expected to be detected palaeoecologically (Janssen, 1986; Halstead, 2000; Kalis et al., 2003). The intensive, local-scale impacts of the first farmers in SE Europe are most convincingly detected in pollen records from small, adjacent sites located near Neolithic settlements (Andrič, 2007; Magyari et al., 2012). Nevertheless, the almost constant presence of *Vitis, Triticum*-type, *Rumex, Urtica, Cannabis*-type and *Pteridium* through the Straldzha oak-woods phase seems at odds with the inference of a densely forested landscape, and may indeed reflect small-scale human interventions in the vegetation of the Thracian Plain, akin to the intensive 'garden' agricultural model proposed by Bogaard (2004). The only definitive evidence for human impact is the deforestation phase itself, which also includes the occurrence of *Agrostemma githago* alongside *Triticum*-type pollen, as clear signs of cereal cultivation (Behre, 1981; Marinova et al., 2012).

4.2. A model for Bulgaria's Lateglacial and Holocene palaeovegetation

Cluster analysis defines 10 principal pollen-derived associations in the Lateglacial and Holocene history of Bulgaria's vegetation (Fig. 5; Table 2). The data used in defining these groups cover a wide range of environments, including the Black Sea coast, the Thracian Plain, the middle altitudes of the Rhodope Mountains and the higher altitudes of the Rila and Pirin Mountains. The vegetation history of the individual sites has been described in detail in the original publications, but our analysis highlights a number of common features in Bulgaria's vegetation history. Given that the chronology for individual sites is often poor, we compare reconstructions with better dated records where possible (e.g. Tonkov et al., 2006).

4.2.1. Lateglacial (16,000–11,500 cal. a BP)

In the Rila Mountains, the replacement of cold steppe vegetation with meadows and pine woods during the Lateglacial is linked to warming phases (Tonkov et al., 2006, 2011; Bozilova and Tonkov, 2011). In accordance with previous interpretations, our analysis suggests that patches of woody vegetation (pine and birch) occasionally appeared in otherwise open vegetation around Lake Sedmo Rilsko during the Bølling-Allerød interstadial, dated between 15,000 and 12,800 cal. a BP (Bozilova and Tonkov, 2011). The apparent difference in the timing and duration of the meadow phase at Suho Ezero is an artefact of poor dating (Tonkov et al., 2006). The same applies to the Besbog record – subsequent re-coring at the lake's centre produced a complete Lateglacial sequence with woodland expansion between 13,800 and 12,600 cal. a BP and a subsequent reduction during the Younger Dryas (Stefanova et al., 2006a,b). Lateglacial vegetation around Kupena Mire is interpreted as "montane steppe-forest" (Huttunen et al., 1992;

Tonkov et al., in press). Our analysis indicates that grassland and meadow vegetation persisted through the Lateglacial, contrasting with vegetation at both higher and lower elevations (Fig. 5). The brief appearance of semidesert vegetation around Kupena corresponds temporally to the Younger Dryas, but may relate to the summer insolation peak at the same time, which best explains the transition from cold steppe to semidesert vegetation in the lowlands around Straldzha (Fig. 6). Reconstruction of cold steppe in marine core A-159 agrees with Lateglacial aridity and restricted woodland distribution inferred from neighbouring marine records (Atanassova, 2005; Mudie et al., 2002; Filipova-Marinova et al., 2012).

4.2.2. Early Holocene (11,500–8000 cal. a BP)

A major reorganisation of Bulgaria's vegetation occurred during the early Holocene. Deciduous forest communities ascended into the high mountains, favoured by high summer insolation (Stefanova and Ammann, 2003). Although the Besbog record has a hiatus during this period, more recent analysis shows that the deciduous woodland phase lasted until ~7500 cal. a BP in the high mountains (Stefanova et al., 2006a; Tonkov et al., 2008), comparable to the birch woods phase reconstructed for Suho Ezero (Fig. 5). The transition to woodland took considerably longer at lower altitudes – around 9500 cal. a BP at Kupena and 8700 cal. a BP at Straldzha. It is difficult to assess the reconstruction of cold steppe in marine core A-159 because of poor age control and uncertainty about the source-area of the pollen. Other marine records for the early Holocene follow the succession observed at Straldzha (Filipova-Marinova et al., 2012; Shumilovskikh et al., 2012). Temporary indications of aridity observed around 8000 cal. a BP in several lowland records could represent effects of the 8200 cal. a BP event, which is registered palynologically in Black Sea sediments (Filipova-Marinova et al., 2012).

4.2.3. Mid-Holocene (8000–4000 cal. a BP)

In agreement with our reconstruction (Fig. 5), coniferous forests moved into the high mountains during the mid-Holocene (Bozilova and Tonkov, 2000; Stefanova et al., 2006a; Tonkov et al., 2006; Panagiotopoulos et al., in press). Reconstruction of meadows at Besbog conflicts with evidence for pine woods around the site (Stefanova et al., 2006a) and appears to an artefact of Poaceae pollen produced by the lakeshore vegetation. While conifers dominated at higher altitudes, oak forests were widespread at lower elevations. In some places, mid-Holocene vegetation along the Black Sea coast appears to have been quite similar to today's, with forest-steppes persisting in the north (Shabla) and Euxinian 'longoz' forests in the south (Arkutino). This interpretation is supported by other studies from the same areas (Marinova and Atanassova, 2006; Filipova-Marinova, 2003). The two Lake Varna records exhibit substantial differences; salinity changes and prehistoric human impacts are thought to have strongly affected the Arsenala profile (Bozilova and Beug, 1994). Arsenala's 'semidesert' vegetation reconstructed after 5000 cal. a BP may be simply a reflection of saltmarsh vegetation.

4.2.4. Late Holocene (4000 cal. a BP to the present)

Spruce and beech forests played an increasing role in high-elevation vegetation dynamics during the late Holocene (Bozilova and Tonkov, 2000; Stefanova and Ammann, 2003). However, as our reconstruction shows, pines remained dominant around Besbog in the Pirin Mountains (Stefanova et al., 2006a). At Kupena, a series of rapid shifts in forest dominance occurred – from oak to fir to beech to pine – though these are inconsistently represented in different pollen records from the site (Huttunen et al., 1992; Tonkov et al., in press). The reconstruction (Fig. 5) misleadingly places the fir stage into 'birch woods', the closest statistical analogue given the scarcity of *Picea* pollen (supplementary information). Subsequent forest-steppe and pine forest stages are in agreement with the recent history of Kupena (Tonkov et al., in press). In the lowlands, the two Straldzha records display a clear divergence in their reconstructed late-Holocene vegetation (Fig. 5). The earlier record was collected near a spring (E. Marinova, pers. comm.), so halophytes growing locally may have directly contributed to high percentages of Chenopodiaceae pollen, leading to our reconstruction of semidesert vegetation. Differences in sample pretreatment could also offer an explanation. In any case, most of the landscape around Straldzha remained without forest through the late Holocene. Relatively stable late-Holocene vegetation is reconstructed along the Black Sea coast, in accordance with nearby marine pollen records (Atanassova, 2005; Filipova-Marinova et al., 2012).

Bulgaria's vegetation history demonstrates the complex interactions between Mediterranean and continental climate systems, influenced by the Black Sea moisture balance, North Atlantic climate variability, precession-driven insolation variations and the strength of the monsoon system. Vegetation of the high mountains seems to have responded strongly to North Atlantic circulation, probably because orographic rainfall means they are better watered and so the vegetation is primarily limited by temperature. Bulgaria's Thracian Plain is shielded from westerly air streams by the same mountains, so here moisture availability and rainfall seasonality (precipitation *vs* evaporation) were probably the main controls on Lateglacial–Holocene vegetation development. The strong relationship between the oxygen-isotope curve from Sofular Cave (Badertscher et al., 2011) and Straldzha DCA axis 1 (Fig. 6) suggests that the Black Sea's moisture balance was the primary determinant of Holocene forest cover in Bulgarian Thrace.

4.3. Human–environment interactions

The same factors that limited the spread of forests may have also influenced the timing of the introduction of agriculture into the SE Balkans. Some authors have linked the dispersal of agriculturalists through Europe after 8200 cal. a BP to their displacement from the Black Sea basin by rising sea levels (Ryan et al., 1997; Turney and Brown, 2007), or to rapid climatic changes (Weninger et al., 2006). Prior to this time, however, climatic conditions on Bulgaria's Thracian Plain were possibly too dry for agriculture. The Tenaghi Philippon record (Müller et al., 2011) demonstrates that the Aegean coastline was far less arid than Bulgarian Thrace at the beginning of the Holocene, explaining why the earliest agricultural settlements on the European continent may have been established there. Early-Holocene aridity, driven by Black Sea moisture balance and solar forcing, may have been a major deterrent to early agriculture on the Thracian Plain. The mountain barriers of the Balkans, combined with the aridity of the lowland plains, conspired to delay the transmission of agriculture through the eastern Balkans to the rest of Europe.

A similar hiatus is present in the spread of agricultural communities to Western Anatolia. Despite the presence of agriculturalists in Central Anatolia at Can Hassan and Aşıklı Höyük and on the coastal margins of the Aegean, no Neolithic settlements prior to the late 7th millennium BC have yet been uncovered in Western Anatolia (Özdoğan, 2011). Shortly after 8400 cal. a BP, numerous agricultural sites appeared across the inner region of Western Anatolia (Özdoğan 2008). It may be that the arid conditions that prevailed on the Thracian Plain also extended to the West Anatolian hinterland and restricted the spread of the Neolithic westward from the Central Anatolian plateau.

It is not surprising to see afforestation progressing alongside the introduction and expansion of agriculture during the Neolithic era on the Thracian Plain. Oak forests appear to have been prevalent around all Bulgarian Neolithic sites from which wood remains have been studied (Marinova and Thiebault, 2008). The impact of the earliest European farmers on the landscape was relatively small (Willis and Bennett, 1994; cf. Magyari et al., 2012). Indeed, interpretation of the weed flora of Bulgarian Neolithic archaeobotanical assemblages indicates that early agriculture did not significantly affect the local oak woodland; instead it created a mosaic of openings for grazing, foraging and farming through intensive garden cultivation (Bogaard 2004; Marinova and Thiebault, 2008).

In the Yambol Region of SE Bulgaria, in which the Straldzha Mire is located, some 52 Neolithic and Chalcolithic archaeological sites are known (Fig. 8; Lichardus et al., 2002; AKB, 2012) Maximum populations for tell settlements in the East Balkans have been estimated at 120–150 persons (Chapman, 1989). Intensive mixed farming (small-scale, labour-intensive cultivation and herding) dominated Neolithic Europe (Bogaard, 2004), requiring ~0.5 ha per person (Milisaukskas and Kruk, 1989; cf. Bogaard, 2004). These estimates suggest that the inhabitants of a large village needed ~60–75 ha of land for agriculture, most of which would have fallen within 1 km of the settlement (Milisauskas and Kruk, 1989). Even if half of the agricultural land was fallow at any given time, the Neolithic population of the Yambol Region would only have required no more than 75 km^2 of cleared land – only about 2% of the region. It must be recognised that the Neolithic archaeological record in the Thracian Plain (including the Yambol Region) is much less complete than that of other areas of the SE Balkans (Boyadzhiev 2009). Nevertheless, the limited agricultural footprint required by all known sites is not likely to be visible in the palaeoecological record of a lake as large as Straldzha was at that time.

The Straldzha record suggests strong human impact, including deforestation, burning, grazing, and erosion, beginning around 4000 cal. a BP, coincident with other major clearances in the Balkans (Willis, 1994). The second millennium BC corresponds roughly to the Middle and Late Bronze Ages in SE Bulgaria, periods that are, unfortunately, poorly attested on the Thracian Plain (Leshtakov, 2002; 2009; Boyadziev, 1998). In the early second millennium (the Middle Bronze Age) many sites were abandoned, including most tells, while stock-breeding appears to have become more mobile (Leshtakov, 2009). Changes in settlement patterns and subsistence strategies become clearer in the latter second millennium (the Late Bronze Age), when more numerous, distributed, and often short-lived settlements were founded across the Thracian Plain and uplands on its periphery (Leshtakov, 2002; 2009; Athanassov, 2011). For the Yambol Region, Fig. 8 indicates the decline of tell settlements and the increasing proportion of short-lived ‘flat’ sites over time. In this figure, the number of tell sites represents a maximum – few new tells are likely to be discovered – while the number of flat sites is a minimum, likely to increase with further archaeological investigation. Evidence from recent surface survey, while hampered by poor chronological control, revealed three previously unknown (Late?) Bronze Age surface scatters in 30 km^2 of the Yambol Region, replacing one Early Bronze Age tell in the study area (Iliev et al., 2012).

Settlement pattern changes are accompanied by long-term changes in subsistence strategies. In addition to increasing mobility of stock-breeding posited by Leshtakov (2009), palaeozoological evidence from north Bulgarian and coastal sites suggest that by the Late Bronze Age cattle bones dominate assemblages from the SE Balkans (Athanassov, 2011; cf. Benecka and Ninov, 2002, for Neolithic trends in the Thracian Plain itself). Metallurgy became a significant economic activity as Thrace entered long-distance trade networks in the Late Bronze Age; copper ingots of all known Mediterranean types can be found in Bulgaria, indicating the degree of economic integration and craft specialisation (Leshtakov, 2009).

Evidence to date, although incomplete, suggests that human impact on the environment during the second millennium BC probably resulted from greater demand for charcoal stemming from increased metal production, combined with a shift in agro-pastoral regimes. Long-lasting villages (such as produce tells), relying upon intensive agriculture, gave way to more numerous but ephemeral settlements, supported by extensive, mobile stock-breeding, largely of cattle. Cultivation also became less intensive, and perhaps shifting. The new regime required the exploitation of a much larger area, including colonisation of new, sometimes marginal, agricultural lands, and it had a greater impact on that land, producing a clearly visible palaeoecological signal (Porozhanov, 1998; Leshtakov, 2009; Athanassov, 2011; cf. Halstead, 2000, for an analogous process in Late Neolithic Greece). Further research, however, is required to clarify the extent, nature, and chronology of human impact on the environment of the ancient Thracian Plain, especially through (1) surface survey (enhanced by an improved understanding of regional prehistoric ceramic fabric chronologies) to clarify settlement patterns, (2) excavation of prehistoric rural sites, including palaeobotany and palaeozoology, to reveal more about subsistence strategies, (3) geological investigation of ancient soils to better understand the scale of agriculture necessary to support attested populations, and (4) local palaeoecological study (e.g. of river terraces) to detect small-scale vegetation disturbances associated with prehistoric farming.

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5. Conclusions

New palaeoenvironmental data from Bulgaria's Thracian Plain suggest that early-Holocene conditions remained much more arid in the continental lowland areas of the Balkans than in coastal or mountain areas. Intensified summer insolation seems to have resulted in extreme warm-season drought and delayed the spread of forests across lowland Thrace for thousands of years until the regional moisture balance of the Black Sea region changed. Early-Holocene aridity, along with other cultural and environmental factors, probably limited the expansion of early agriculture from the coastal areas of Anatolia and Greece. The decline of aridity on the Thracian Plain from 8600 cal. a BP must be seen as one of the potential triggers for agriculture's expansion into continental Europe. Anthropogenic deforestation does not occur until after ca. 4000 cal. a BP, and may have been the result of a combination of new, extensive agro-pastoral regimes and greater fuel demands for metal processing.

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Table 1. Sediment descriptions from the Straldzha Mire. Sharp boundaries appeared between units I–II, II–III, III–IV, VI–VII and VII–VIII; all other boundaries were diffuse.

Unit	Quarry section	Core	Sediment description
VIII	–	0–65 cm	Disturbed sediment excavated during canal construction
VII	0–15 cm	65–110 cm	Black, peaty silt with crumbly texture and gastropod fossils (Planorbidae)
VI	15–80 cm	110–170 cm	Light-grey marl with freshwater bivalve remains (Unionidae)
V	80–100 cm	170–?	Dark-grey marl with freshwater bivalve remains
IV	100–125 cm	–	Black, very compact, silty marl sediments
III	125–465 cm	–	Orange-brown to grey silty sediments with some mottling, vertical cracking and occasional inclusions of small (1–2 mm) quartz pebbles
II	465-500 cm	–	Grey silt band with no mottling
I	500-520 cm	–	Orange-brown silty sediments with gypsum inclusions

Table 2. Indicator taxa for the 10 major pollen associations in Bulgaria's Lateglacial and Holocene vegetation history. These indicators, particularly those with low indicator values (IV), may not be applicable to pollen records other than those analysed (Fig. 5).

Group name	Indicator taxa and indicator values
Forest-steppe	*Centaurea* (20), *Cerealia*-type (32), *Filipendula*-type (19), Lamiaceae (19)
Semidesert	Chenopodiaceae (51), *Cirsium*-type (19)
Grassland	*Linum* (35), Poaceae (32), *Saussurea*-type (18), *Saxifraga* (23), Scrophulariaceae (25), *Taxus* (15)
Cold steppe	*Artemisia* (46)
Oak woods	*Corylus* (23), *Ulmus* (28)
Euxinian forest	*Carpinus betulus* (46), *Fagus* (27), *Fraxinus excelsior* (27), *F. ornus* (27), *Ophioglossum* (24), *Ostrya*-type (58), *Quercus* (30), *Vitis* (14)
Pine woods	*Pinus* (32)
Birch woods	*Betula* (38), *Ranunculus* (27), Rosaceae (24), *Rumex* (28), *Tilia* (24)
Meadows	Asteraceae subfamily Asteroideae (24), Rubiaceae (18)
Fir-spruce forest	*Abies* (46), *Campanula* (27), Ericaceae (21), *Picea* (65)

Table 3. Accelerator Mass Spectrometer radiocarbon ages for the two Straldzha records. Age ranges for the core (marked *) are based on calibrated ages while those for the quarry are based on modelled ages from the Monte Carlo simulation. All ages were calibrated using the IntCal09 database in Calib 6.02 (Stuiver and Reimer, 1993).

Site	Sample depth (cm)	Laboratory number	Material	Radiocarbon age (^{14}C a BP)	Calibrated age (cal. a BP)	Modelled age range(cal. a BP)
Quarry	25–30	Beta-246649	Organic sediment	5570±40	6354±62	6645–6170
	60–65	OZM-410	Pollen concentrate	8675±45	9643±62	10180–9530
	60–65	Wk-32001	Lake sediment	8855±45	9966±203	10180–9530
	100–105	Beta-246650	Organic sediment	8980±50	10080±161	10500–9650
	125–130	Beta-308484	Organic sediment	9710±40	11156±74	11335–10700
	155–160	Wk-32002	Lake sediment	14696±65	17831±240	18605–16945
	155–160	OZM-411	Pollen concentrate	16000±80	19157±255	19875–18280
	255–260	OZM-412	Pollen concentrate	27090±190	31360±239	32820–30750
	355–360	Wk-32003	Lake sediment	23653±114	28370±378	29515–27570
	355–360	OZM-413	Pollen concentrate	26080±150	30800±313	31395–29625
	455–460	OZM-414	Pollen concentrate	29040±150	33830±640	34800–31910
Core	100	Beta-294415	Organic sediment	3100±30	3316±70	3384–3247*
	110	Beta-300663	Organic sediment	4230±40	4746±118	4861–4796, 4762–4641*

Figure captions

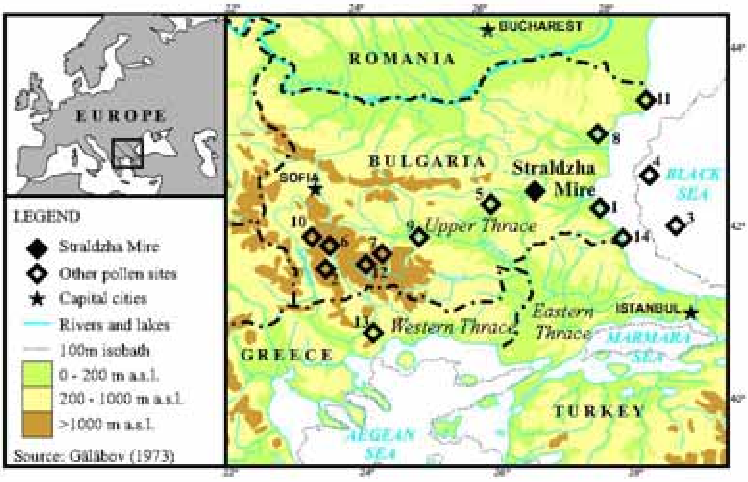

Fig. 1. Map of the Eastern Balkans showing the location of the Thracian Plain, Straldzha Mire and other sites mentioned in the text. 1- Arkutino; 2- Besbog (Pirin Mts); 3- Black Sea A-159; 4- Black Sea GGC-18; 5- Ezero; 6- Dry Lake (Suho Ezero, Rila Mts); 7- Kupena (Rhodope Mts); 8- Lake Varna (Arsenala and Poveljanovo); 9- Sadovo; 10- Sedmo Rilsko; 11- Shabla-Ezerets; 12- Shiroka Polyana; 13-Tenaghi Phillipon; 14- Veleka River.

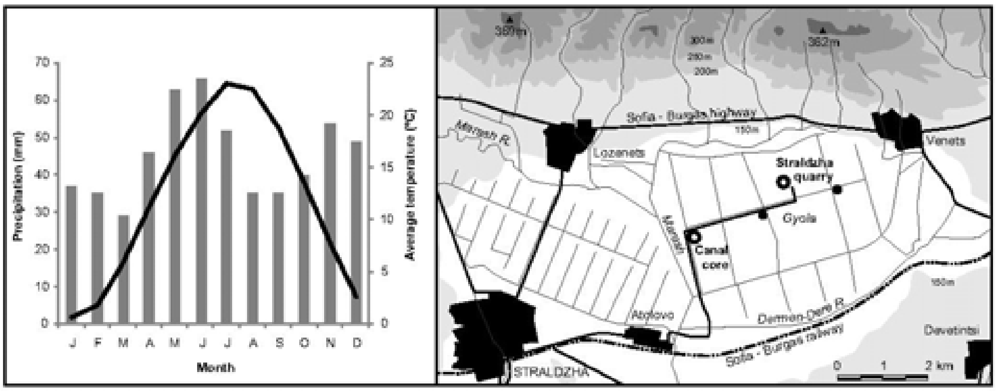

Fig. 2. Climate diagram for Yambol (left) and a map of the Straldzha Mire (right) indicating the location of the Straldzha quarry section and canal core (large circles). Other coring locations are

denoted by small circles. Drainage lines are shown as thin black lines. Source: Gaydarska (2007) and 1985 Soviet topographic map K-35-54 (1:50,000).

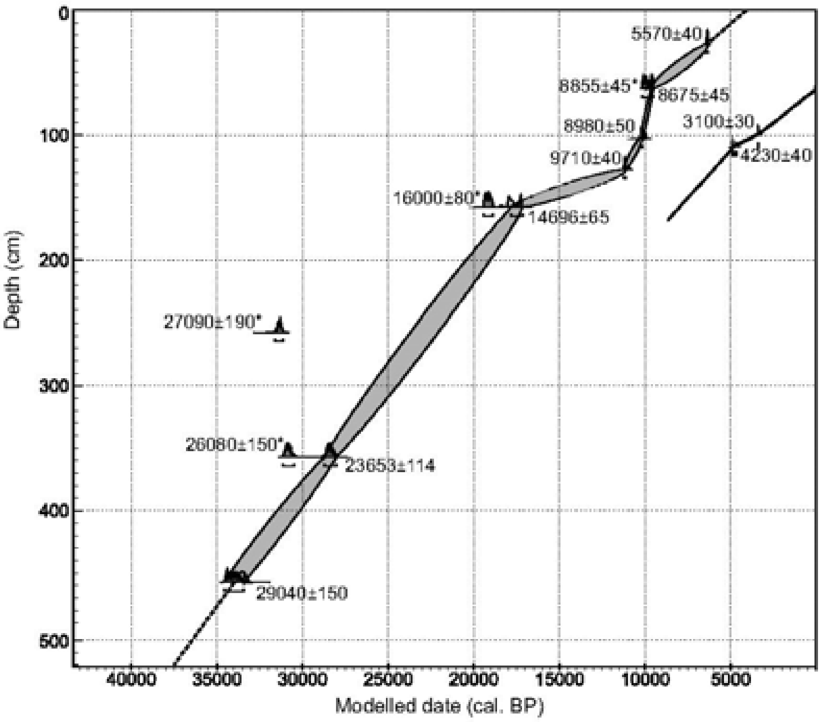

Fig. 3. Age-depth model for the Straldzha quarry record (grey shading) and the canal core (solid black line). Asterisks (*) indicate dates that were not considered in the model. Dashed lines are extrapolations.

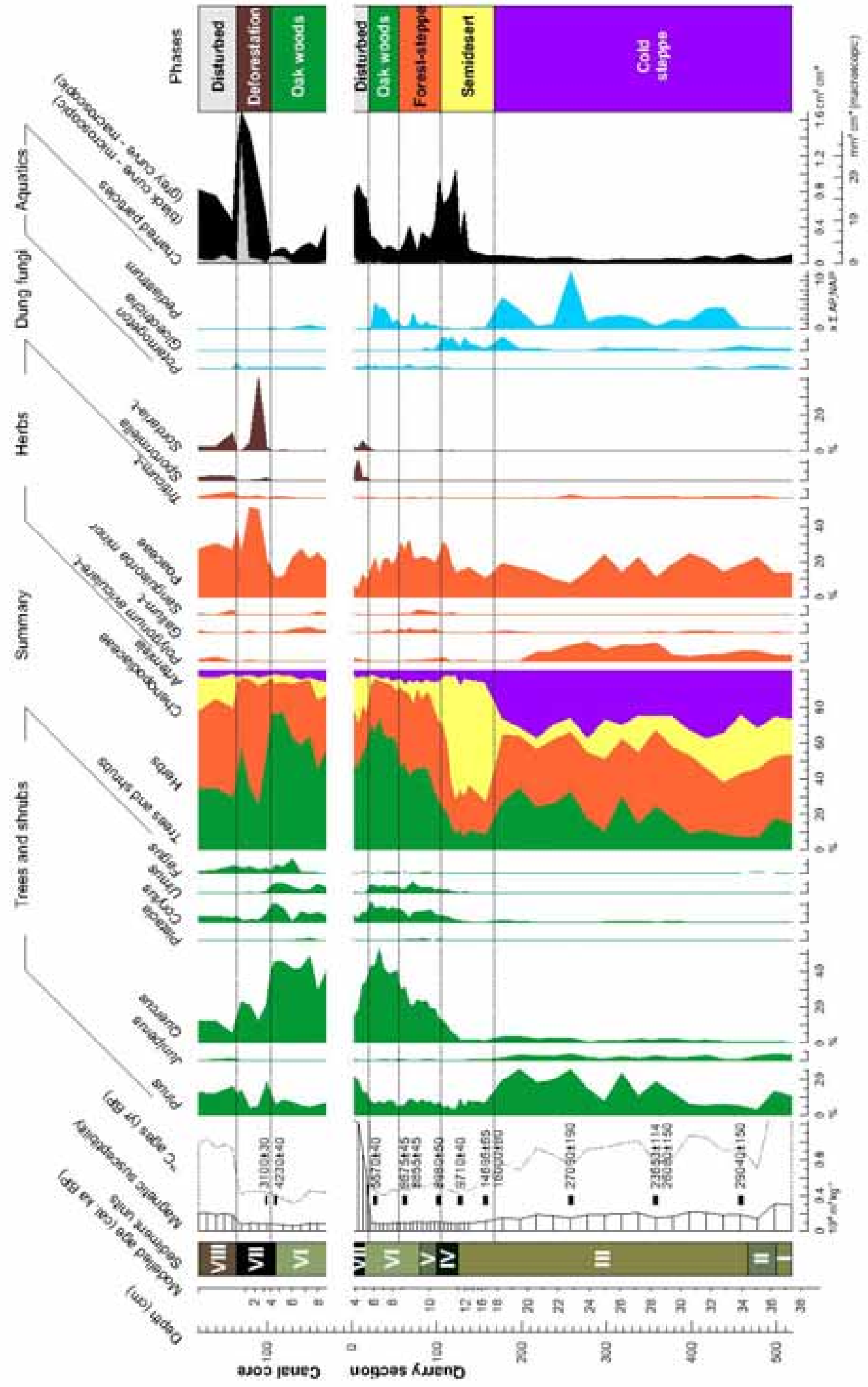

Fig. 4. Stratigraphic diagram from the Straldzha quarry section (bottom) and canal core (top). Modelled ages, depths, sediment units (coloured using photographs of the sediment profile), magnetic susceptibility measurements (dotted line is a 5x exaggeration), pollen and spore

percentages, charred particles (microscopic and macroscopic) and palaeovegetation phases are shown. See supplementary information for the complete dataset.

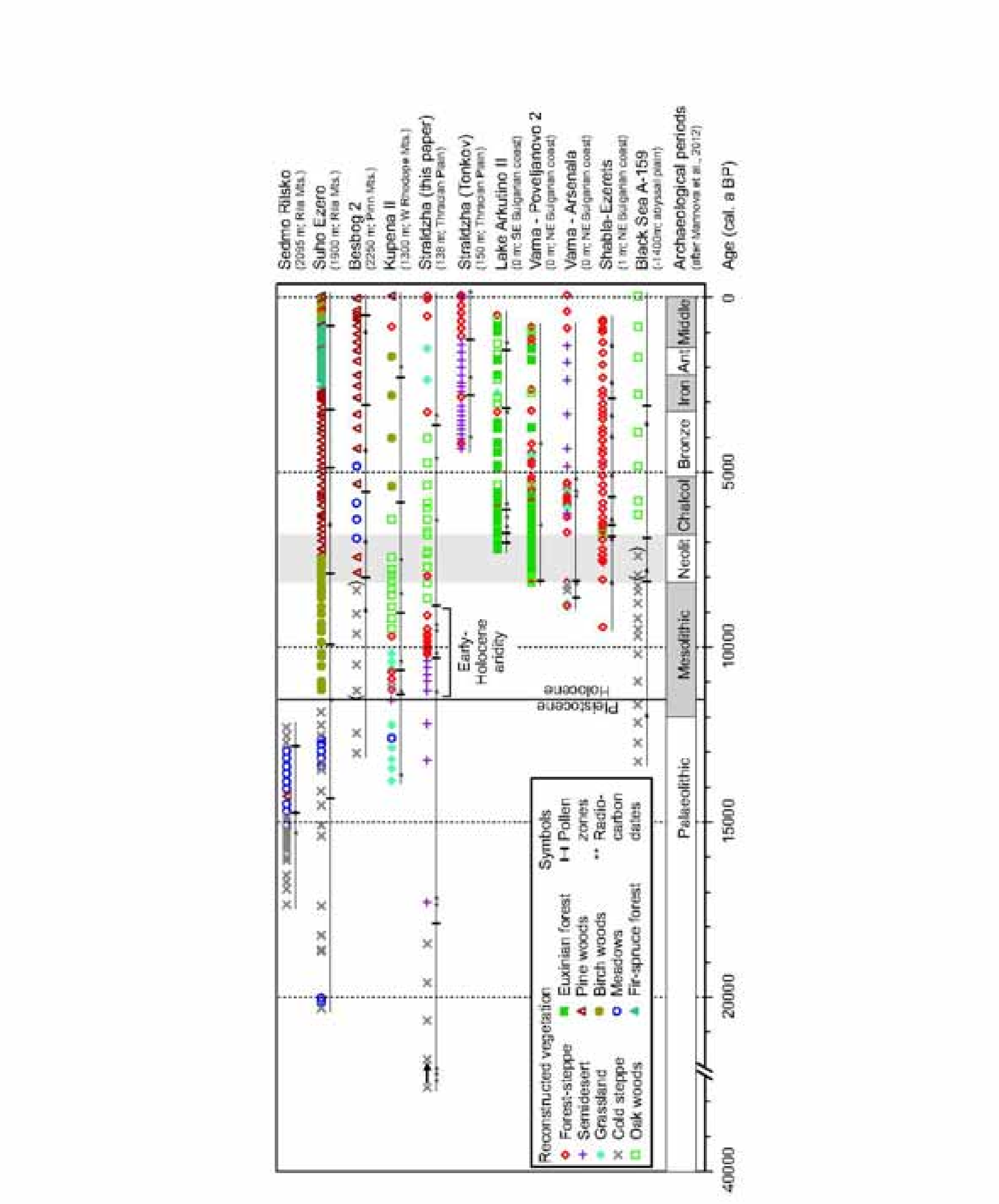

Fig. 5. Cluster analysis results plotted by age, showing the development of Bulgaria's vegetation at different pollen sites through the Late Pleistocene and Holocene. Symbol legend at left. Samples in parentheses are suspected to be too young compared to equivalent samples in more recently published and better dated pollen records from the same or nearby sites

(Stefanova et al., 2006a,b; Filipova-Marinova et al., 2012). Pollen data from this paper, Atanassova (2005), Filipova (1985), Bozilova and Beug (1992, 1994), Tonkov et al. (2008a; 2009), Huttunen et al. (1992), Stefanova and Bozilova (1995), Bozilova and Smith (1979), Bozilova et al. (1986) and Bozilova and Tonkov (2011).

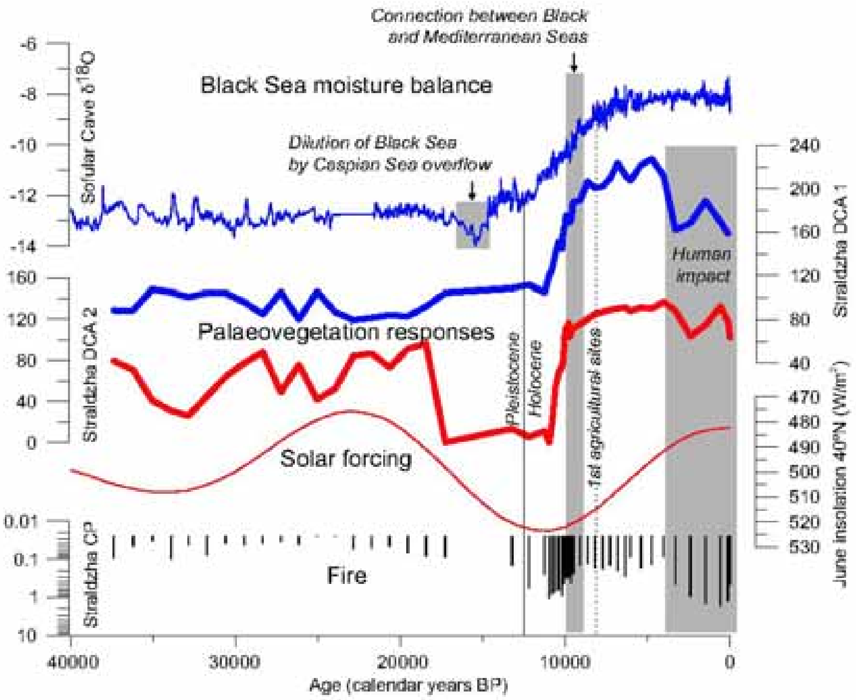

Fig. 6. Response of palaeovegetation around Straldzha Mire (bold curves at centre) to regional climatic changes (Black Sea moisture balance from Fleitmann et al., 2009; summer insolation from Berger et al., 1978). Fire history (microcharcoal, bottom) is also compared to solar forcing. Grey areas indicate periods in which the records were affected by other factors.

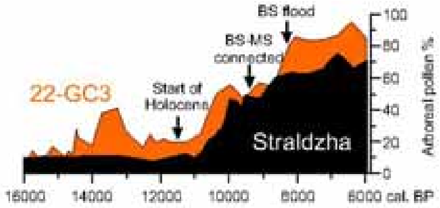

Fig. 7. Comparison of arboreal pollen percentages from Straldzha Mire and Black Sea core 22-GC3 (Shumilovskikh et al., 2012) from 16,000 to 6000 cal. a BP, showing delayed early-Holocene afforestation. Major events in the Black Sea (BS) are also indicated: connection with the Mediterranean Sea (MS: Badertscher et al., 2011) and flood (Turney and Brown, 2007).

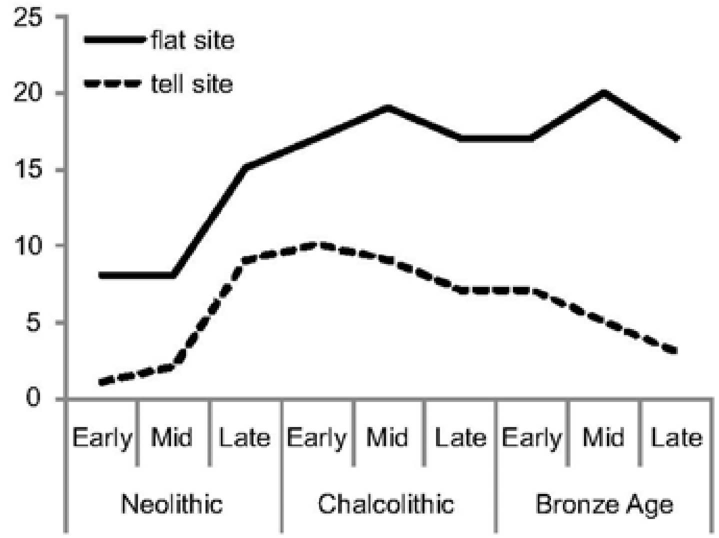

Fig. 8. Prehistoric settlement types in the Yambol Region (after AKB, 2012).

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