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Reconstructing post-crisis recovery in the hinterlands of Constantinople: A high-resolution first-millennium CE pollen record from Lake Yeniçağa (NW Türkiye)

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ABSTRACT: Facing a novel plague pandemic, military invasions, and political–economic transformations, societies of the eastern Roman (Byzantine) empire had to adapt to a variety of pressures and new ways of exploiting their natural environments during the mid-1st millennium CE. As a result, the rural economy of Anatolia transitioned from the intensive mixed-farming regime of the Graeco-Roman era to a more varied medieval agricultural system. We reconstruct here for the first time this transition in a region of Anatolia located close to Constantinople through pollen analysis of a sediment core from Lake Yeniçağa, dated to between ~2300 and ~1200 cal a BP. After discussing data for the Hellenistic–Roman era, we document repeated attempts at the recovery of mixed farming during the 6th to 8th c. CE. These attempts were only successful toward the end of our study period, with the stabilization of the military situation in the region, as is also visible in the written sources that we analyze in parallel in this paper. Crucially, this model of land exploitation was also constrained by the climatic oscillations that reflected its transitional location between the Aegean, Central Anatolian, and Black Sea climate regions. Thus, our study provides a perfect illustration of the interplay between environment and society in relation to the primary production sector (agriculture), in the dynamic context of a strong elite presence in the nearby capital city.

KEYWORDS: Anatolia; hagiography; landscape and climate change; Late Holocene; pollen

Introduction

In the Mediterranean basin and the surrounding regions, landscapes have been shaped by the long-term interaction between climatic changes and human activities (Grove and Rackham, 2001). In particular, during the Late Holocene, natural ecosystems have been transformed by strong human actions with alternating cycles of intense land use for agricultural production and forest recovery when the economy or demography were in crisis (Butzer, 2005). One of the most significant periods of such social, political, and economic crisis occurred at the end of Antiquity, when the Roman world disintegrated and the Mediterranean experienced a period of instability (Horden, Purcell, 2000; Haldon, 2016). The process of the "Fall of the Roman Empire" took almost three centuries, beginning in the 5th c. CE in the West and ending in the 7th c. in the East, with the new Arab caliphate conquering most of the Eastern Roman lands (Rapley and Heather, 2023). Only western Anatolia—part of modern Türkiye—remained under the full control of what remained of the Eastern Roman Empire, but it suffered continuous Arab raiding (Haldon, 1997). Consequently, Anatolia became a mosaic of different landscape types, mostly showing signs of rewilding or agricultural extensification and simplification, with some continuation of the earlier Hellenistic–Roman mixed agriculture in the more secure locations, as revealed by pollen and bioarchaeological data from numerous sites across Türkiye (Izdebski, 2013; Marston and Castellano, 2025).

Although the number of palynological studies in modern Türkiye is now significant, most of these records have focused on the long-term dynamics from the Late Glacial throughout the entire Holocene, with a consequent low temporal resolution (Sadori et al., 2023). Moreover, palynological sites are not distributed evenly across Anatolia: there is a relative wealth of data in the mid- and high-altitude regions of central and southwestern Anatolia, but the regions closer to Constantinople (modern Istanbul), the capital of the Eastern Roman (Byzantine) Empire, are not so well documented.

In northwestern Anatolia, the pollen sequences come from the lowlands close to the main urban centers (e.g., Küçük Akgöl and Lake Sapanca near Nicomedia, Lake Iznik near Nicaea, Melen near Prusias and Hypium; Bottema et al., 1995; Leroy et al., 2010; Ülgen et al., 2012), whereas data from more

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rural areas even at higher elevation are more limited (e.g., Lake Çubuk, Lake Abant, Lake Melen; Bottema et al., 1995; Ocakoğlu et al., 2016). None of these sequences has sufficient resolution (with ranges from 100 to 300 years) to permit a meaningful discussion of their relationship to past political, demographic, and economic dynamics, and as a result it is difficult to reach unambiguous conclusions about the land cover dynamics in the parts of Anatolia that were adjacent to the political, religious, economic and cultural center of the entire Eastern Roman Empire, the capital city of Constantinople. The city was one of the largest in Late Antiquity (300–700 CE), with population estimates varying from 300,000 to 500,000 inhabitants (Morrisson, 2004). Even if it became smaller by an order of magnitude in the early medieval period (700–900 CE, estimated ca. 30–50 000 inhabitants), it was still one of the few large urban centers of the entire Mediterranean world (Malamut, 2006). Its impact on the surrounding landscape must have been important, but this is still neither well documented nor understood in detail (Mango et al., 1995; Crow and Turner, 2009).

This study presents an attempt at gaining a deeper understanding of landscape dynamics in the region during the period of the post-antique crisis and recovery in the Mediterranean by analyzing in high resolution the sediments from Lake Yeniçağa (NW Türkiye). This site has already been the subject of previous coring activities and pollen investigations, but the published sequences have not produced well-dated evidence for human–environment interaction during our period of interest (Beug, 1967; Bottema et al., 1995; Beug and Bottema, 2015). Our aim is therefore to present a detailed reconstruction of the vegetation history of northwestern Anatolia during the ancient to medieval transition (ca. 500–800 CE) based on new pollen data now available from Lake Yeniçağa. These are then compared against independent records of societal change from documentary sources and proxy data on past variations in hydro-climatic conditions.

Site setting

The site (40°46′32″ N 32°1′30″ E, 989 m a.s.l.) is a shallow freshwater lake surrounded by marshy areas, lying close to the North Anatolian tectonic fault zone south of the Pontic Mountains (Fig. 1). It fills a depression of karstic and, probably, tectonic origin located ca. 35 km east of Bolu, which is bordered by high mountains to the northeast (Gökçeler Daği, 1911 m a.s.l.) and the southwest (Köroğlu Dağları, 1709 m a.s.l.; Tanaglu and Inandik, 1954). The climate is typical of the sub-Euxinian belt of north-central Türkiye, with an average temperature of 0.1°C in winter and 19.7°C in summer, and total annual precipitation of 534 mm (Akman and Ketenoğlu, 1986). Considering rather low precipitation values evenly distributed over the year (spring: 156 mm, summer: 96 mm, autumn: 112 mm, winter: 170 mm; data from Bottema et al., 1995), the Bolu area is part of the rain shadow of the Black Sea region (Mayer and Aksoy, 1986). It is located ca. 250 km from Istanbul/Constantinople.

The vegetation of northern Türkiye comprises mostly broadleaved deciduous forests growing on the northern mountain slopes, where humidity is higher, and coniferous forests occupying the southern exposures (Mayer and Aksoy, 1986; Atalay et al., 2014). The former type is dominated by *Fagus orientalis* Lipsky in association with *Carpinus betulus* L., *C. orientalis* Mill., *Castanea sativa* Mill., deciduous *Quercus*, *Acer cappadocicum* Gled., *Crataegus pentagyna* Waldst. & Kit. ex Willd. and various *Sorbus* species; the latter is composed of *Abies nordmanniana* (Steven) Spach and *A. bornmuelleriana* Mattf. together with *Pinus sylvestris* L. and *P. nigra* subsp. *pallasiana* (D. Don). Toward the increasingly steppic regimes of central Türkiye, where precipitation progressively reduces and summer drought is prolonged, *Quercus pubescens* subsp. *anatolica* O. Schwarz predominates associated to *Pyrus elaeagnifolia* Pall., *Paliurus australis* Gaertn. and pines; when precipitation is below 400 mm/year, steppes of *Artemisia*, *Astragalus*, *Globularia*, *Onosma*, *Thymus*, *Salvia,* and *Marrubium* prevail. In the lowlands bordering the Black Sea, Colchisian forests of *Quercus ilex* L., *Pinus brutia* Ten., and *Laurus nobilis* L. are present, together with Mediterranean elements such as *Phillyrea media* L., *Arbutus unedo* L., and *A. andrachne* L. Under natural conditions, the riverine forests are primarily formed by *Alnus glutinosa* (L.) Gaertn. and *Fraxinus excelsior* L.; on wet soils, *Smilax excelsa* L. and *Vitis vinifera* subsp. *sylvestris* (C.C. Gmel.) Hegi are also present up to 1600 m a.s.l. (Davis, 1965–1988).

As described in previous studies (Beug, 1967; Bottema et al., 1995; Beug and Bottema, 2015), the area around Lake Yeniçağa is today almost treeless and used for agro-pastoral activities. At low altitudes, scattered oak shrubs and pinewoods occur, whereas above 1200 m a.s.l., beech and fir forest predominates.

PALAEOCLIMATE

Lake Yeniçağa lies at the junction of three climate regions as defined by instrumental records (Iyigun et al., 2013), namely Black Sea, Central Anatolia, and Western Anatolia–Aegean transition. Whereas the latter two regions are summer-dry and Mediterranean in character, the first one receives summer-season precipitation of Black Sea origin. There are no independent palaeoclimate data from Yeniçağa itself, so we compare its pollen and NPP record against lake and cave sequences in adjacent regions (Fig. 1). For the Black Sea climate region, a key record derives from Sofular Cave, where we use the $\delta^{13}C$ data from U-series dated speleothems (Fleitmann et al., 2009; Göktürk et al., 2011). The $\delta^{18}O$ signal from this site is heavily influenced by source area effects due to Black Sea waters being isotopically enriched relative to those in the Mediterranean Sea (see also discussion in Morgan et al., 2025). For central Anatolia, hydro-climatic changes are recorded in stable isotope, diatom, elemental chemistry, and carbonate mineralogy data from Lake Nar in Cappadocia, dated by counting of annual varve layers (Jones et al., 2006; Dean et al., 2015). This site also has a detailed palynological record of land cover change during the 1st millennium CE (England et al., 2008). Although Lake Nar is located some distance from Yeniçağa, its $\delta^{13}C$ and $\delta^{18}O$ records are similar to the $\delta^{13}C$ signal from Sofular Cave, implying a common climate driver across both regions. This includes an overall shift from drier to wetter climatic conditions in the decades around ~500 CE. For the Western Anatolia–Aegean transition region, hydro-climatic changes are registered in elemental chemistry Itrax profiles from Lake Iznik (Ülgen et al., 2012), which also has a detailed pollen sequence, and Lake Çubuk stable isotopes (Ocakoğlu et al., 2016). These two sites show contrasting trends over the 6th to 8th c. CE, suggesting site-specific effects or mis-dating at one or both sites. In the discussion that follows, we compare these four palaeohydro-climate sequences against palynological indicators of water depth, and hence lake-level variations, at Yeniçağa, along with terrestrial pollen indicators of past vegetation and land cover.

None of these records provides unambiguous temperature data, although warmer conditions would have, *inter alia*, increased evapotranspiration and hence reduced soil moisture availability and contributed to hydro-climatic conditions (and

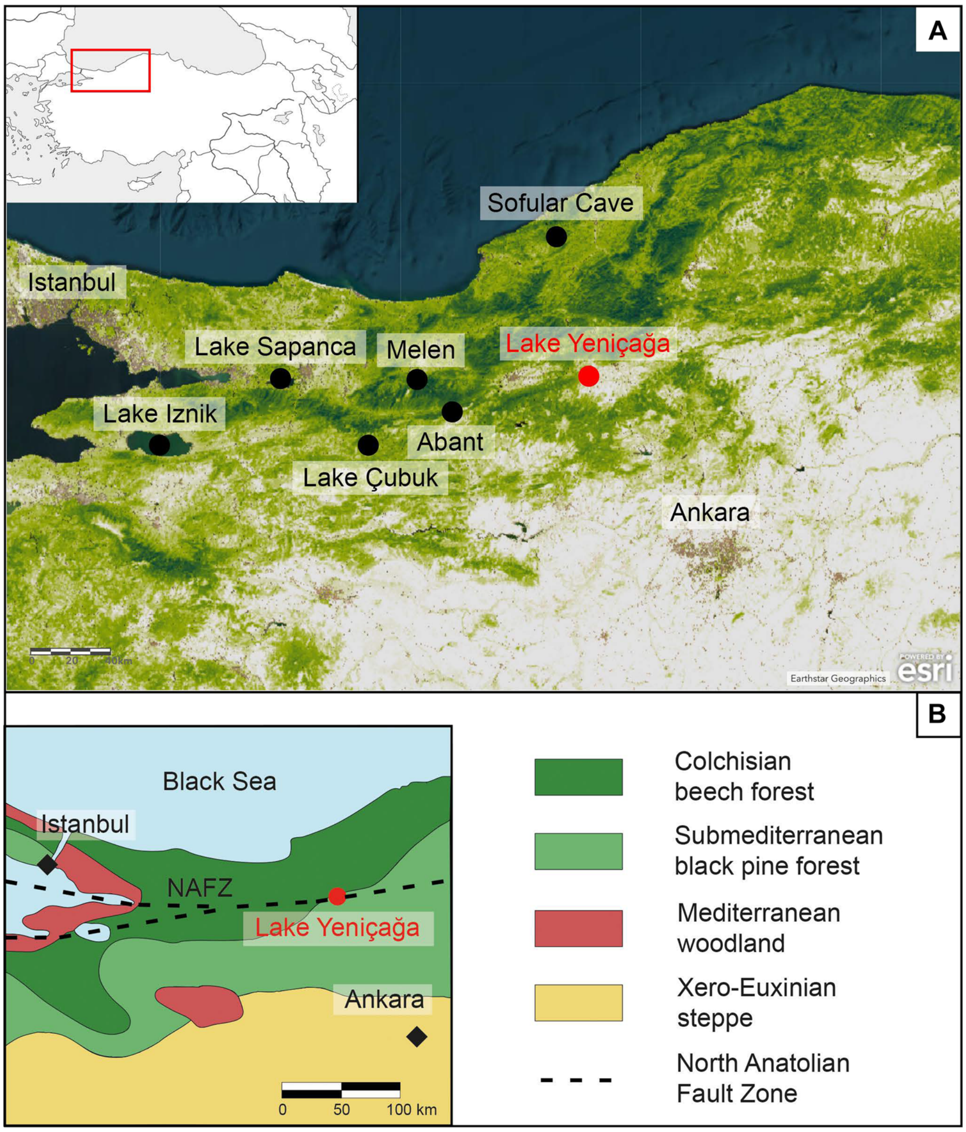

Figure 1. The study area in NW Türkiye. (A) Location of Lake Yeniçağa and other sites mentioned in the text on the land map of the 2020 Global canopy vegetation height. Produced by EcoVision Lab in the ETH Zurich Department of Civil, Environmental and Geomatic Engineering in 10 m resolution (Lang et al., 2023). (B) Vegetation zones of NW Türkiye following Mayer and Aksoy (1986), with indication of the North Anatolian Fault Zone in relation to the study site. [Color figure can be viewed at wileyonlinelibrary.com]

vice versa). Dendroclimatological reconstructions, notably from the Alps, show that some decades during the opening centuries CE were warmer in summer than the 20th-century mean (Luterbacher et al., 2016). By the mid-530s, summer temperatures had declined sharply, marking the start of a century-long period labeled the Late Antique Little Ice Age (Büntgen et al., 2016).

Historical background

The region of Lake Yeniçağa was situated in the easternmost part of the ancient region of Bithynia. From the 4th c. BCE it belonged to the independent Kingdom of Bithynia until the conquest by Alexander the Great (334 BCE). During the Hellenistic Period, it maintained its independence, with local kings who enjoyed great influence among different Anatolian monarchs. The capital city of Nicomedia, on the Sea of Marmara, was established by King Nicomedes I in 264 BCE and became one of the most important political and commercial centers of northwestern Anatolia (Paganoni, 2019). Under the last Bithynian king, Nicomedes IV (94–74 BCE), the region lost its autonomy to Mithridates VI of Pontus and was incorporated into the Kingdom of Pontus, until all of northern Anatolia was conquered by the Roman Republic in 63 BCE. Named *Bithynia et Pontus*, this province flourished under Roman rule, with an intense urban Romanization process, evident in both social structure and architecture (Bekker-Nielsen, 2008). The establishment of an integrated Mediterranean economy brought northern Anatolia into an imperial production system of specialized agricultural products due to the favorable environmental conditions and the efficiency of Roman maritime transportation (Roberts et al., 2018).

From 295 CE, the region was part of the late Roman province of *Honorias*, one of the three administrative units established from the previous larger province after the reforms of Emperor Diocletian I and the first separation between the western and eastern parts of the Roman Empire. It belonged to the *Dioecesis Pontica* (314 CE) and the capital was settled in Claudiopolis, the modern city of Bolu. During the Late Roman period, the economic significance of the Eastern Mediterranean provinces grew, especially after the rise of Constantinople as the capital city of the entire Empire under Constantine I (330 CE) (Haldon, 1999). In the lowlands north of the Pontic Mountains, an exponential increase in the number of settlements compared to Roman times reveals the emergence of an industrial-scale production of olive oil (Cassis et al., 2018). In the mountains, the settlement pattern followed the previous Roman model consisting of main urban centers surrounded by extensive estates and villages (Roberts et al., 2018).

Following the first wave of Arab conquests between 634 and around 642 CE, when the Eastern Roman Empire lost most of its East Mediterranean provinces, Anatolia became the core land of the remnant Roman state (generally referred to as the Byzantine Empire in modern scholarship, although the largely Greek-speaking inhabitants of Constantinople and Anatolia continued to call themselves Romans). This Roman successor state was by the later 7th c. reorganized into new military and administrative divisions (by the 9th c. referred to as *themata*, or themes), along with a revised fiscal system focused on the provision of grain and other staples to the army defending Anatolia (Brandes, 2002). While the rural and urban archeology of northern Anatolia points to a major decline in settlement density and urbanization, it only allows limited conclusions due to the difficulty of dating mostly locally produced ceramics and lack of research interest in medieval period sites until recently (Izdebski, 2013). The only published archeological rural site from northern Anatolia, however, suggests the emergence of a new and simpler type of material culture, village-focused rural settlement patterns, with a preference for defensible locations. Many such rural settlements accumulated greater wealth and by the 10th and 11th c. indicate a stronger elite presence. From the 1070s, however, both Byzantine state and society in Anatolia collapsed as a consequence of the Turcoman migration and Seljuk invasion (Cassis, 2017). Until this time, however, the evidence of the written sources and sigillography (official and personal seals used in documents otherwise lost) reveals that Byzantine Anatolia had developed strong aristocratic families whose status was based on extensive landed estates—an aristocracy, however, of whom many escaped to Constantinople, never to return, after the Seljuk invasion (Cheynet, 1990, 2016).

Methods

Lithology, dating, and age-depth model

A new sediment core (YG15) of 900 cm was recovered in 2015 with a Livingstone-type stationary piston corer, from the marsh west of the lake (Fig. 1). For this study, the upper 220 cm of the core was used for lithological description and palynological analyses. Within this interval, the sediment composition transitions from organic-rich sediment with abundant plant remains to sediment mixed with gray clay and lake mud. This lithological variation has been classified into four distinct units: Unit I (10–52 cm), Unit II (52–140 cm), Unit III (140–150 cm), and Unit IV (150–220 cm) (Table 1). As expected, depth increase and prolonged sedimentation resulted in changes in organic matter content and color in the Yeniçağa sediments (Fig. 2). However, the most significant transformation occurs within Unit IV (150–220 cm), which represents a transitional phase between two organic-rich sediment intervals. Below 220 cm (220–900 cm) sediment is generally characterized by high organic matter and plant remains, with color variations ranging from dark brown to light brown.

A total of nine AMS ^{14}C dates were performed on organic-rich sediment and pollen grains at the Tübitak Marmara Research Center (MAM) in Türkiye and the Center for Isotopic Research on Cultural and Environmental Heritage (CIRCE) in Italy (Table 2). ^{14}C samples at 10 cm (TUBITAK-1637: 1.0243 ± 0.0036 F^{14}C) and 19 cm (TUBITAK-1638: 1.0321 ± 0.0029 F^{14}C) refer to post-bomb dates and suggest a gap in sedimentation between 19 cm and 40 cm (DSH9858_PE: 1199 ± 25 BP), probably due to the intentional removal of peaty deposits for economic activities in the lake area. For this reason, the age-depth model has been provided for the core section 40–217.5 cm. It is based on six AMS ^{14}C dates (for the excluded ones, refer to Table 2) and has been developed using the interpolation method of the Clam R package (v4.1.1) (Blaauw, 2010) with the IntCal20 calibration

Table 1. Lithology of core YG15 from Lake Yeniçağa.

Lithological unit	Depth by core sections (cm)	Main lithological description	Detailed lithological description
Unit I (10–52 cm)	10–60 cm Core A	Organic-rich sediment	10–20 cm: Less organic material and denser lake mud; 0–42 cm: Very dark, organic-rich material with abundant plant remains; 42–52 cm: Very light brown sediment, rich in organic material and plant remains, mixed with a low amount of lake mud.
Unit II (52–140 cm)	50–100 cm Core B	Organic-rich sediment mixed with lake mud	52–100 cm: Light brown sediment mixed with increasing density of lake mud, also containing abundant plant material.
	90–140 cm Core A	Organic-rich sediment mixed with lake mud	90–140 cm: The sediment from 52–100 cm is repeated; light brown sediment mixed with increasing density of lake mud, also containing abundant plant material.
Unit III (140–150 cm)	130–180 cm Core B	Transition from organic-rich sediment mixed with lake mud to a highly characteristic dense and gray clay-lake mud sediment	140–150 cm: Transition from organic-rich sediment mixed with lake mud to a highly characteristic dense and gray clay-lake mud sediment; 150–156 cm: Residual gray clay sediment with very low organic lake sediment content; 156–180 cm: Sediment mixed with gray clay and lake mud.
Unit IV (150–220 cm)	170–220 cm Core A	Sediment mixed with gray clay and lake mud	180–214 cm: Sediment mixed with gray clay and lake mud; 214–220 cm: Light brown clay mixed with lake mud.

Description of lithological units from the sediment interval 10–220 cm of the study core.

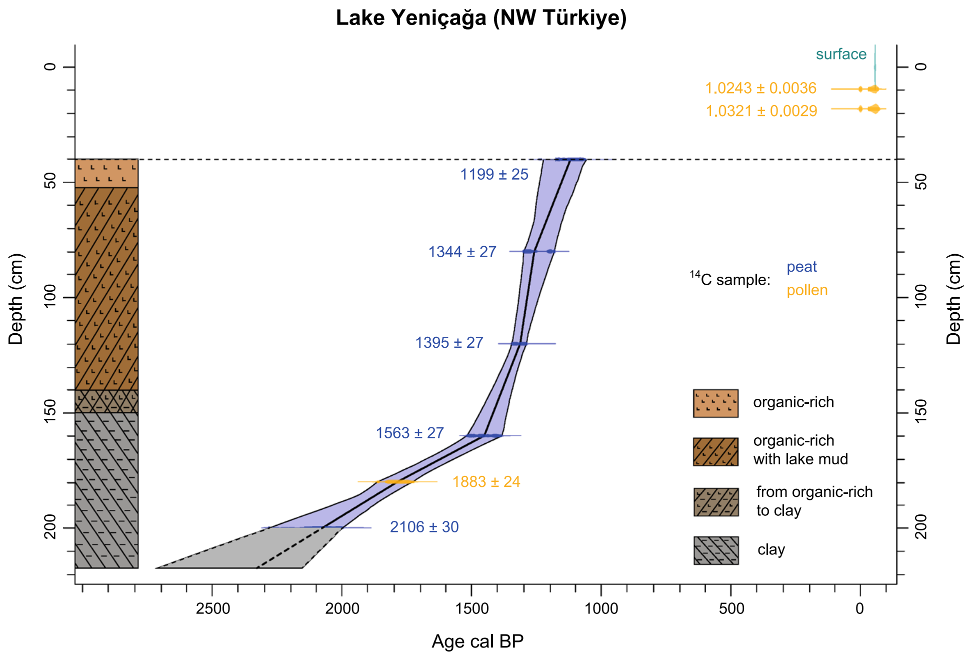

Figure 2. Sedimentological and chronological sequence of core YG15 from Lake Yeniçağa (northern Anatolia). Lithological units (left) and age-depth model (right) of the sediment interval 40–217.5 cm from which pollen samples have been analyzed. The model has been developed through interpolation with the Clam 4.1.1 R-package (Blaauw, 2010) and is based on six AMS^{14}C ages calibrated with IntCal20 (Reimer et al., 2020). From 200 to 217.5 cm, the model has been extrapolated. [Color figure can be viewed at wileyonlinelibrary.com]

Table 2. Radiocarbon dating of core YG15 from Lake Yeniçağa.

Depth (cm)	Lab ID	Material	Radiocarbon age	Age cal a BP (2σ)	Age CE (2σ)
10[a]	TUBITAK-1637	Pollen	1.0243 ± 0.0036	(−5)–(−66)	1955–2016
19[a]	TUBITAK-1638	Pollen	1.0321 ± 0.0029	(−5)–(−64)	1955–2014
40	DSH9858_PE	Peat	1199 ± 25	1241–1058	709–892
80	DSH9859_PE	Peat	1344 ± 27	1304–1176	646–774
120	DSH9860_PE	Peat	1395 ± 27	1347–1285	603–665
160	DSH9861_PE	Peat	1563 ± 27	1521–1422	429–528
180	TUBITAK-1639	Pollen	1883 ± 24	1865–1722	85–228
200	TUBITAK-0712	Peat	2106 ± 30	1903–1748	47–202

AMS ^{14}C dates from organic-rich sediment and pollen samples from the study core. Calibration is based on the post-bomb atmospheric NH1 curve (Hua et al., 2022) and the IntCal20 curve (Reimer et al., 2020) through the OxCal program (v4.4.4) (Bronk Ramsey, 2021).
[a] Data excluded from the age-depth model.

curve (Reimer et al., 2020) (Fig. 2). From 200 cm to the bottom of the study section, the model results from the extrapolation provided by the software. Ages are expressed as cal a BP and CE/BCE.

Pollen, NPP, microcharcoal analyses

New pollen analysis was carried out on 38 sediment samples taken at variable sampling intervals. The peaty material was chemically processed with standard ABA treatment in order to remove mineral and organic matters (Fægri and Iversen, 1989; Moore et al., 1991). *Lycopodium* spores were added to estimate pollen, NPPs (Non-Pollen Palynomorphs), and microcharcoal concentrations (Stockmarr, 1971). Pollen morphology has been identified by using atlases (Moore et al., 1991; Reille, 1992, 1995; Beug, 2004), and reference pollen samples. The following distinction of *Quercus* species is based on the morphological features of pollen grains (Smit, 1973; Hayrapetyan and Bruch, 2020) in addition to the natural distribution of oaks in Türkiye (Uslu and Bakış, 2012): *Q. robur* type includes the deciduous oaks (*Q. robur* L., *Q. petraea* L. ex Liebl., *Q. frainetto* Ten., *Q. infectoria* Olivier, *Q. pubescens* Willd., *Q. macranthera* Fisch.et C.A.Mey. ex Hohen., probably also *Q. hartwissiana* Stewen, *Q. virgiliana* Ten.); *Q. cerris* type groups the semi-evergreen oaks (*Q. cerris* L., *Q. ithaburensis* subsp. *macrolepis* (Kotschy) Hedge & Yalt., *Q. trojana* P. B. Webb); *Q. ilex* type refers to the evergreen oaks (*Q. ilex* L., *Q. coccifera* L.). *Pinus* includes both montane and thermophilous species. Cerealia-type has been grouped in three pollen morphotypes (*Avena/Triticum*, *Hordeum* group, *Secale cereale*) following Andersen (1979) and Beug (2004), although some wild species coexist with barley in the *Hordeum* group. According to Florenzano et al. (2015), the fenestrate pollen type is peculiar of Cichorieae tribe within Asteraceae. NPP remains were identified with the support of Shumilovskikh and van Geel (2020), and the nomenclature follows Miola (2012).

Pollen percentages have been calculated on the sum of terrestrial spermatophytes, *Pinus* excluded. For macrophyte and fern percentages the sums include terrestrial spermatophytes and, in turn, each considered palynomorph (Berglund et al., 1986). Pollen and NPP concentrations have been calculated per volume of sediment (pollen-NPPs cm^{-3}). Pollen and NPP influx, which correspond to the amount of pollen grains, spores, and other palynomorphs incorporated annually per unit of sediment, have been obtained by dividing the concentration values by the sedimentation rates given by the age-depth model (pollen-NPPs year^{-1} cm^{-2}; Berglund et al., 1986). By using the TILIA software, diagrams have been drawn against depth and time, and refer to the core section 40-217.5 cm. CONISS cluster analysis has been provided considering Arboreal Pollen (AP) and Non-Arboreal Pollen (NAP) taxa with values higher than 2% (Grimm, 1992). The statistical analysis in combination with visual inspection support the pollen zonation. In order to interpret palynological data in the light of historical evidence, ecological constraints have been applied to group pollen and NPPs. Anthropogenic indicators have been selected from Behre (1981), Mercuri et al. (2013), Berger et al. (2019) and are discussed considering their natural distribution in the study region.

Following Sadori and Giardini (2007) and Whitlock et al. (2010), microcharcoals have been counted and sorted in different dimensional classes by measuring their short axis to reconstruct regional fires (10–50 μm), fires that occurred at the landscape/regional scale (50–125 μm), and local fires (more than 125 μm). Data are presented as concentration values (charcoals cm^{-3}).

Principal Component Analysis (PCA) has been performed on pollen percentage data to (i) quantify environmental trends and (ii) possibly identify the main drivers of vegetation changes. The ordination method has been first applied to taxa considered for CONISS since it integrates cluster analysis: clustering is based on pairwise distances among taxa following the stratigraphic succession, whereas ordination considers the variability of the whole association matrix (Legendre and Legendre, 2012). Secondly, the numerical technique has been used on ecological plant groups and anthropogenic indicators.

Results

Palynological data

The entire pollen sequence covers the time interval ca. 380 BCE–830 CE (2330–1120 cal a BP), with a mean temporal resolution of 38 years (Fig. 2). For the ancient-to-medieval transition period (500–830 CE/1450–1120 cal a BP), the resolution is much higher, with an average of 15 years. Pollen preservation is good across the sequence, except for two barren samples at 173.5–175.5 cm, which are not included in the results. Indeterminate pollen grains, that is, broken or degraded, do not exceed 16%. The mean count of terrestrial spermatophytes, *Pinus* excluded, is 248 pollen grains/sample. A total of 111 pollen taxa have been identified, including 42 arboreal, 54 herbaceous, and 15 aquatic taxa. AP including *Pinus* prevail up to 87% of the total pollen count. Pollen concentration is variable and ranges from 1010 (at 167.5 cm–ca. 370 CE/1580 cal a BP) to 288,410 (at 103.5 cm–ca. 660 CE/1290 cal a BP) pollen cm^{-3}.

The mean count of NPPs is 427. A total of 34 taxa have been recognized, and they have been selected for this study following their ecological value as reported in the literature (see Methods). Concentration of NPPs varies between 50 (at 167.5 cm–ca. 370 CE/1580 cal a BP) and 459,260 (at 201 cm–ca. 150 BCE/2100 cal a BP) NPPs cm^{-3}. Percentage and concentration values of pollen and NPPs are plotted in Figs. 3 and 4. Accumulation rates of pollen grains and other palynomorphs are not affected by a substantial dilution effect, and the relative influx diagram is presented in Fig. S1.

Five pollen zones, named from YPZ 1 (bottom) to YPZ 5 (top), have been interpreted, and the transitions among different environments are supported by PCA (Fig. 5). The positive scores from Component 1 (55.3%) correspond mainly to forest and cold-resistant taxa, and the negative ones correspond to herbaceous taxa; the positive pollen Component 2 (32%) includes Cyperaceae and dry-resistant taxa, and the negative one groups Poaceae and water-demanding taxa. Additional PCA of ecological pollen groups in comparison with anthropogenic indicators is shown in Fig. 6: the ordination discriminates mesophilous and hygrophilous taxa from Mediterranean, xeric and synanthropic taxa (Component

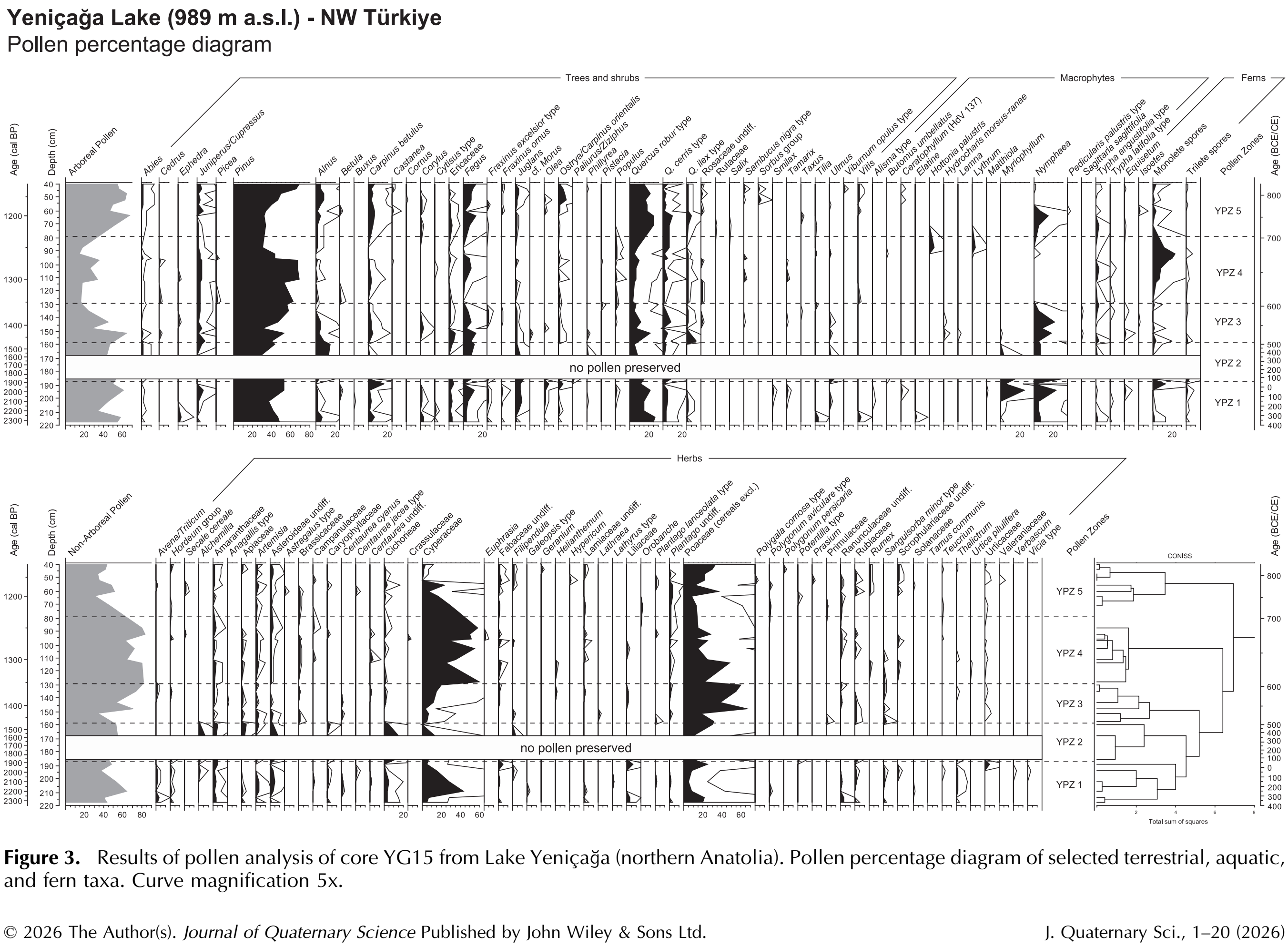

Figure 3. Results of pollen analysis of core YG15 from Lake Yeniçağa (northern Anatolia). Pollen percentage diagram of selected terrestrial, aquatic, and fern taxa. Curve magnification 5x.

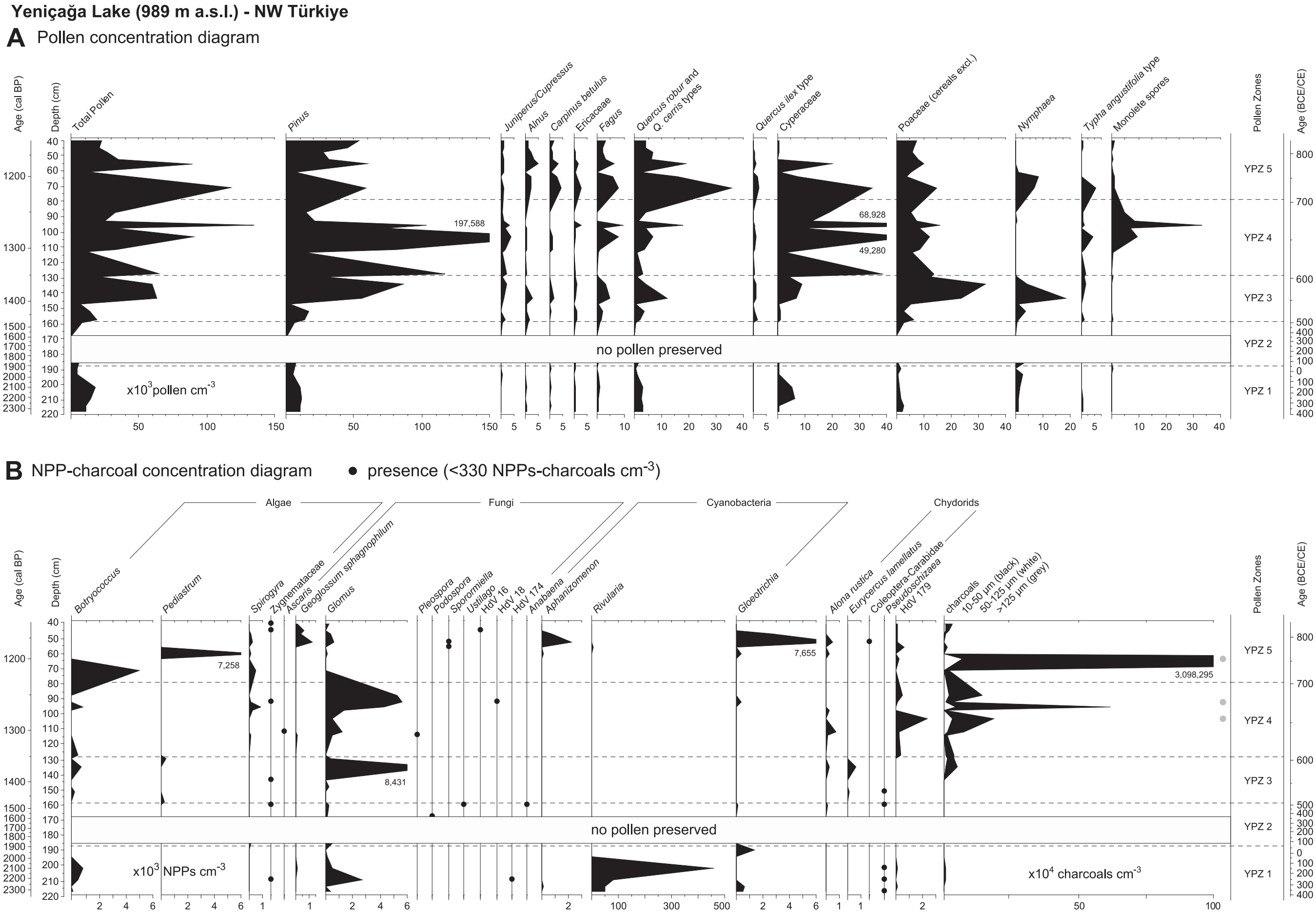

Figure 4. Results of pollen analysis of core YG15 from Lake Yeniçağa (northern Anatolia). Pollen (A) and NPP-charcoal (B) concentration diagrams of selected taxa.

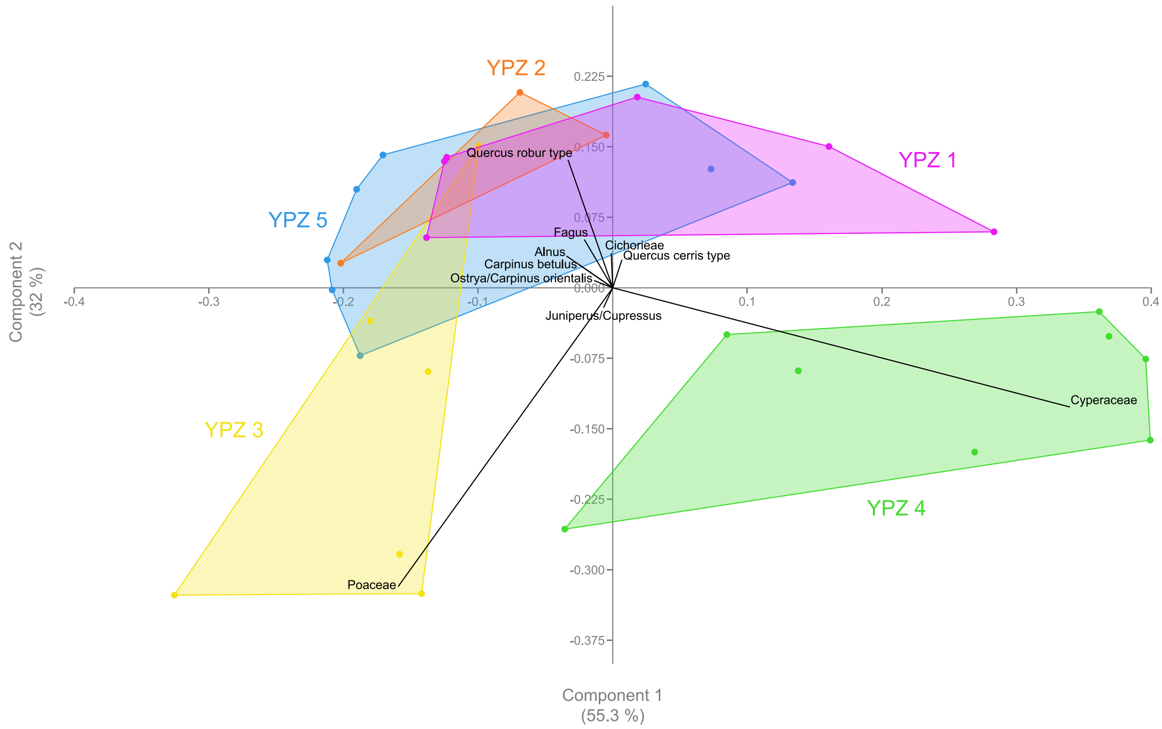

Figure 5. Results of statistical analysis of core YG15 from Lake Yeniçağa (northern Anatolia). Scatter biplot of Principal Component Analysis (PCA) of pollen percentages. The ordination uses the first two components (87.3% of the total variance) and is applied to the same pollen taxa of CONISS analysis. A comparison with local pollen zones identified by means of clustering is presented. Only pollen taxa that mainly contribute to the ordination are shown. [Color figure can be viewed at wileyonlinelibrary.com]

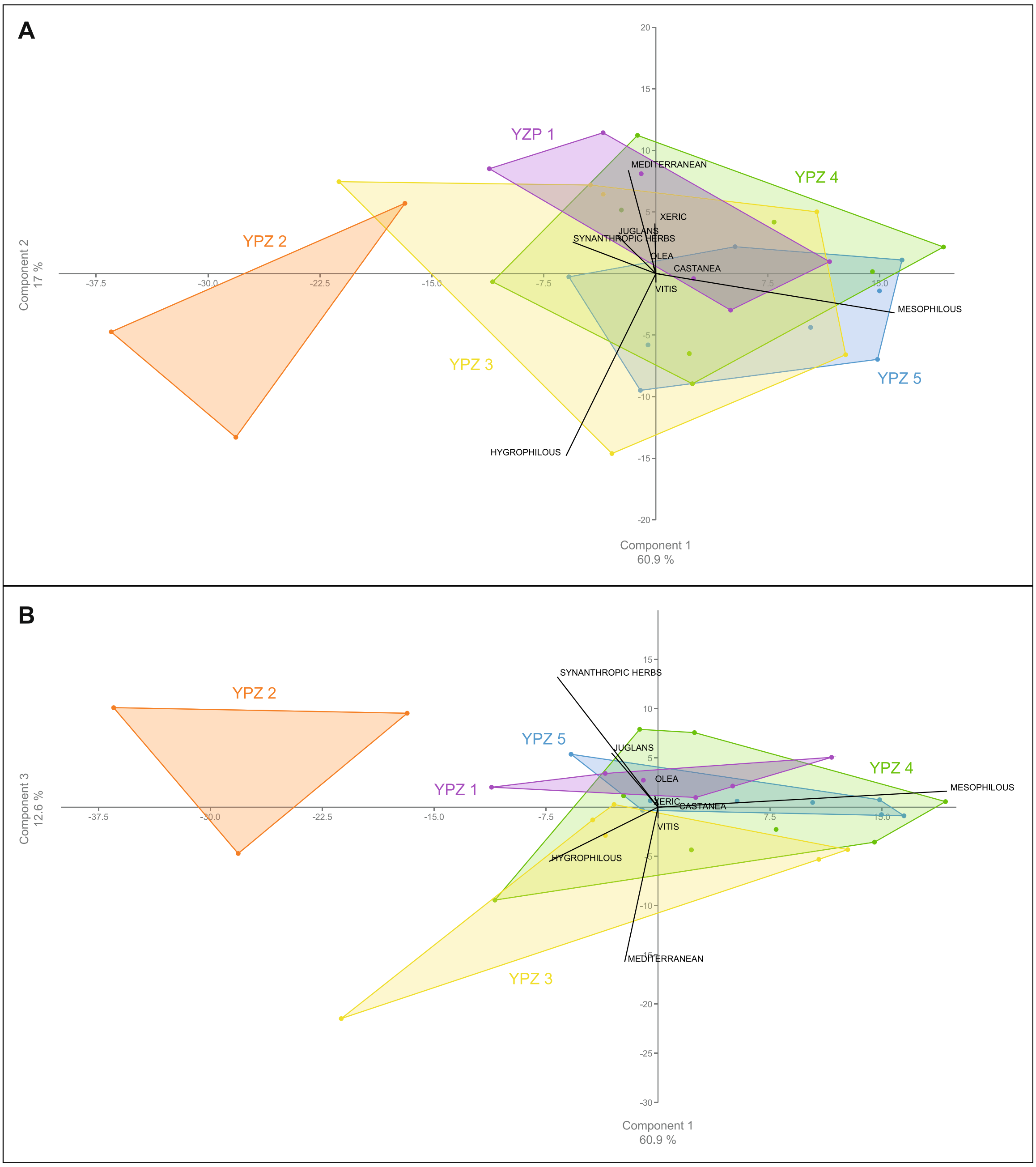

Figure 6. Results of statistical analysis of core YG15 from Lake Yeniçağa (northern Anatolia). Scatter biplots of Principal Component Analysis (PCA) of pollen percentages comparing ecological groups and synanthropic plants. The ordination uses the first three components (90.5% of the total variance) and is compared with local pollen zones identified by means of cluster analysis. (A) Component 1 (60.9%) versus Component 2 (17%); (B) Component 1 (60.9%) versus Component 3 (12.6%). [Color figure can be viewed at wileyonlinelibrary.com]

1: 60.9%), whereas the remaining variance of the data explains for the difference between cold-deciduous forest and other natural/anthropogenic environments (Component 2: 17%; Component 3: 12.6%).

YPZ 1: 217.5–189.5 cm, ca. 380 BCE–30 CE (2330–1920 cal a BP)

AP dominates, and *Pinus* oscillates from 37% to 54%. Total pollen concentration decreases after reaching 28 550 pollen cm^{-3} at 201.5 cm (ca. 150 BCE/2100 cal a BP). The mean number of pollen taxa is 36. The main arboreal taxa are *Quercus robur* type (12%–26%), *Carpinus betulus* (1%–17%), *Fagus* (0%–11%), and *Quercus cerris* type (0%–5%). Ericaceae (1%–5%) represent Mediterranean vegetation, whereas *Alnus* (max 6%) prevails among riparian trees. Arboreal synanthropic taxa are dominated by *Juglans* (max 6%) throughout the zone, with peaks of *Vitis* (3%) at 213.5 cm (ca. 320 BCE/2270 cal a BP) and *Olea* (5%) at 189.5 cm (ca. 30 CE/1920 cal a BP). Herbs are mainly represented by Cyperaceae (5%–42%) and Poaceae (5%–24%). Cultivated plants are well attested by cereals, reaching the highest value of the sequence (*Avena/Triticum*, max 3%; *Hordeum* group, max 1%), and legumes (*Vicia* type, 1%; *Lathyrus* type, <1%), in association with *Centaurea cyanus* (<1%). At the end of the zone, Urticaceae has a peak of 5%.

Among water plants, *Myriophyllum* (0%–25%) and *Nymphaea* (0%–24%) prevail. Apart from *Glomus* (2640 NPPs cm^{-3}) in association with *Pseudoschizaea*, NPP concentration is made by the cyanobacterium *Rivularia*, increasing up to 457,260 NPPs cm^{-3} at 201.5 cm (ca. 150 BCE/2100 cal a BP) and afterward disappearing. The concentration of microcharcoals is not relevant throughout the zone.

YPZ 2: 188.5–159.5 cm, ca. 30–500 CE (1920–1450 cal a BP)

AP shows a decreasing trend caused by the reduction of *Pinus* (29%–54%). Pollen concentration tends to zero, and the mean number of pollen taxa reduces to 23, also considering the lack of pollen at 173.5 and 175.5 cm. *Quercus robur* type decreases up to 5% at 159.5 cm (ca. 500 CE/1450 cal a BP) and Ericaceae contract (max 4%). In contrast, *Alnus* increases and reaches the highest value of the sequence (15%) at the end of the zone, in association with the high abundance of *Fagus* (7%–11%). *Juglans* is the only synanthropic tree attested in the zone and shows a similar reducing trend (from 7% to 2%). NAP is dominated by Cichorieae (5%–15%), Cyperaceae (0%–13%), and Asteroideae (2%–8%) from the beginning to 167.5 cm (ca. 370 CE/1580 cal a BP) and by Poaceae (29%) until the end of the zone. Cereal pollen (*Hordeum* group, 2%) is only present at 185.5 cm (ca. 90 CE/1870 cal a BP) together with Rubiaceae (2%).

Nymphaea (7%–29%) and *Myriophyllum* (0%–15%) dominate aquatic vegetation but significantly reduce toward the end of the zone. Among NPPs, *Glomus* is present in very low concentration (max 420 NPPs cm^{-3}) together with sporadic remains of *Pseudoschizaea* and *Podospora*. Microcharcoal concentration is not relevant.

YPZ 3: 158.5–129.5 cm, ca. 500–600 CE (1450–1350 cal a BP)

AP oscillates although its decrease is confirmed, in contrast with the growth of *Pinus* (31%–59%). Total pollen concentration abruptly increases up to 118,930 pollen cm^{-3}, and the mean pollen variability expands (29 taxa). *Quercus robur* type (4%–21%), *Fagus* (2%–13%), and *Quercus cerris* type (0%–8%) dominate but reduce throughout the zone, together with the significant drop of *Alnus* pollen (max 8%). Mediterranean trees and shrubs are represented by *Quercus ilex* type (0%–9%) and Ericaceae (0%–6%). Among arboreal synanthropic taxa, *Juglans* (1%–2%) is weakly attested and *Olea* appears at 147.5 cm (ca. 540 CE/1410 cal a BP). Herbs are dominated by Poaceae (17%–66%) and, to a lesser extent, Cyperaceae (3%–19%). Cereals appear in the upper part of the zone (*Avena/Triticum*, max 1%; *Hordeum* group, max <1%), although other synanthropic taxa are present (Rubiaceae, max 2%; *Plantago lanceolata* type, 2%; *Plantago* undiff., max 1%; *Centaurea cyanus*, max 1%).

Nymphaea (3%–22%) is the main aquatic taxon, followed by *Typha angustifolia* type (0%–4%). *Glomus* abruptly increases and reaches the highest value of the sequence (8430 NPPs cm^{-3}) at 134.5 cm (ca. 590 CE/1360 cal a BP), in association with chydorid remains of *Eurycercus lamellatus* (630 NPPs cm^{-3}). A reduced concentration of microcharcoals is only attested at the end of the zone (max 48,060 charcoals cm^{-3}).

YPZ 4: 128.5–87.5 cm, ca. 600–680 CE (1350–1270 cal a BP)

AP displays the lowest percentage, following the general reduction of *Pinus* although it expands significantly between 111.5 cm (ca. 650 CE/1300 cal a BP) and 97.5 cm (670 CE/1280 cal a BP), reaching the highest value of the sequence (71%). Pollen concentration increases up to 288,410 pollen cm^{-3} at 103.5 cm (ca. 660 CE/1290 cal a BP), and the mean pollen variability is attested to 27 taxa. *Quercus robur* type reduces up to 4%, combining with all the other arboreal taxa, apart from *Juniperus* (2%–5%) and especially *Fagus*, whose increase is recorded from 103.5 cm to 95.5 cm (ca. 670 CE/1280 cal a BP). Synanthropic trees almost disappear. The rapid growth of Cyperaceae in combination with the drop of Poaceae affects NAP. Among synanthropic herbs, *Centaurea* undiff., *Plantago* undiff., Ranunculaceae undiff., *Rumex*, and Rubiaceae show values <2%.

Water plants almost disappear, except for *Typha angustifolia* type (max 4%) in the lower part and *Hottonia palustris* (5%) and *Lythrum* (max 4%) in the upper part of the zone, whereas monolete spores increase up to 25% at 92.5 cm (ca. 680 CE/1270 cal a BP). NPPs are dominated by *Glomus* (max 5620 NPPs cm^{-3}), HdV-179 (max 2350 NPPs cm^{-3}), and chydorid remains of *Alona rustica* (max 700 NPPs cm^{-3}). Microcharcoal concentration abruptly increases up to 620,360 charcoals cm^{-3} at 95.5 cm, and the fraction larger than 125 μm is found.

YPZ 5: 86.5–40.5 cm, ca. 680–830 CE (1270–1120 cal a BP)

AP definitely increases, as shown by *Pinus* (from 34% to 70%). Total pollen concentration contracts and oscillates (20,760–149,630 pollen cm^{-3}), and the mean number of pollen taxa is 34. *Quercus robur* type (14%–25%) prevails among arboreal taxa, together with *Fagus* (1%–13%), *Carpinus betulus* (4%–7%), *Quercus cerris* type (<1%–10%), and *Ostrya/Carpinus orientalis* (0%–8%). *Alnus* increases up to 9% at 52.5 cm (ca. 790 CE/1160 cal a BP), whereas pollen of Mediterranean plants is present throughout the zone (*Quercus ilex* type, 1%–4%; Ericaceae, 0%–2%). A variety of arboreal synanthropic taxa is attested (*Juglans*, max 3%; *Olea*, max 2%; *Vitis*, max 1%). NAP is mainly dominated by Poaceae (8%–33%) and Cyperaceae (0%–29%) with opposite trends. Cereals are represented by *Hordeum* group (max 1%), *Secale cereale* (max 1%), and *Avena/Triticum* (<1%), whereas Cichorieae (max 3%) and *Plantago* undiff. (max 3%) prevail among other synanthropic plants.

Following the increase of *Nymphaea* up to 16% at 63.5 cm (ca. 750 CE/1200 cal a BP), aquatic plants almost disappear. The lower part of the zone is also characterized by the presence of green algae (*Pediastrum*, 7260 NPPs cm^{-3}; *Botryococcus*, 5070 NPPs cm^{-3}), whereas the upper part by cyanobacteria (*Gloeotrichia*, 7660 NPPs cm^{-3}; *Aphanizomenon*, 2230 NPPs cm^{-3}) and fungi (*Geoglossum sphagnophilum*, 1250 NPPs cm^{-3}; *Glomus*, 560 NPPs cm^{-3}). The highest microcharcoal concentration (3,168,150 charcoals cm^{-3}) is recorded at 63.5 cm.

Historical data

Historical sources for the early medieval period in the Byzantine Empire are very limited compared to Late Antiquity, but they include several testimonies on agriculture practiced in Anatolia. The historiographic writings (mostly chronicles) are primarily interested in political events in the capital and the wars the Empire was involved in on its borders, so they contain only glimpses of the social dynamics in the countryside (the most important chronicles are those of Theophanes and Nicephorus (de Boor, 1963; Mango, 1990). One of the key textual sources dated to this period is the *Farmer's Law* (Greek *Nomos georgikos*): a short legal collection of regulations pertaining to rural life, of unclear origin and purpose (Medvedev, 1984; Chitwood, 2017; Humphreys, 2017). It reveals a lively and closely-knit village world, with shared tax responsibility and elements of mixed agriculture. For Bithynia, the most relevant text that complements the *Farmer's Law* is the *Life of Philaretos the Merciful*, an 8th c. saint, written in the first half of the 9th c. (Rydén, 2002). Philaretos is depicted by his hagiographer—his grandson Niketas—as a rich layman who had given out all his belongings to help the poor after which his (and his family's) fate was completely reversed when some imperial envoys asked his granddaughter to marry a young emperor.

The first few sentences of the vita contain a description of Philaretos's properties and are probably one of the most frequently interpreted passages in the whole history of modern Byzantine studies (Kazhdan, 1994). The text reads as follows:

"In the land of the Paphlagonians there was a man called Philaretos, and this man was the most noble of the men in Pontos and the Galatian region, the son of George, a farmer as the name says. He was very rich and had many livestock: six hundred head of cattle, one hundred yoke of oxen, eight hundred mares in the pastures, eighty saddle horses and mules, twelve thousand sheep and he had forty-eight estates abounding in land, all separate, very beautiful and of great value, for in front of each one of them there was a well gushing forth from a hilltop, capable of watering everything that needed water from it in abundance. And he had many slaves [perhaps: household servants – AI] and very great possessions". (trans. Rydén, 2002)

While apparently detailed, this description is modeled on the Book of Job and cannot be taken at face value (Rydén, 2002). Philaretos's property to a large extent reproduces the composition of Job's riches (and the loss of flocks that happens to Philaretos resembles Job's story as well, to the extent that both heroes lose most of their property due to a hostile raid). Even the general impression that livestock was the most important source of wealth should be treated carefully: the Book of Job in the mainstream Greek translation (the Septuagint) contains a description of Job's riches (Job 1,3): "And his livestock consisted of: seven thousand sheep, three thousand camels, five hundred yoke of oxen, five hundred mares [asses] in the pastures, and a very great body of servants, and he had great works [pastures? farms?] on [his] land." (trans. AI). Moreover, Philaretos's grandson Niketas, the author of the text, was brought up in Constantinople and had spent 20 years in monasteries away from Paphlagonia. He was unlikely to know at first hand the conditions on the ground.

The socioeconomic interpretation of this saint's life thus remains controversial. Some historians have argued that this text attests to the continuity of the Roman villa-type economy (ancient large estate) (as in Lemerle, 1979). Others, in contrast, have suggested that it documents the beginnings of the process in which new, mostly military elites dependent on the gold salary payments from the imperial court accumulated land and gradually created a new estate economy in Byzantine Anatolia (as in Harvey, 1989 or Kaplan, 1992).

In both the *Farmer's Law* and the *Life of Philaretos*, there are several references to the tillage of the land. Philaretos is portrayed at a later stage as a farmer working on his own field with a yoke of oxen (Phil. 68–69). The cultivation of the land is also the dominant rural activity in the *Farmer's Law*: plowing (*NG* 1, 2, 4, 11, 13) and sowing (*NG* 1, 2, 4, 13) are mentioned several times, harvesting—once (*NG* 52). There is also a hint that Byzantine farmers set fire in order to extend or revitalize their fields (*NG* 56–58).

Viticulture also features as one of the most important agricultural practices in the *Farmer's Law*. The proper care of a vineyard is described in the regulations, which forbid damaging such plantations (*NG* 12, 16, 18), as well as various ways of storing wine (*NG* 69–70). The text also describes the custom of letting the animals graze a vineyard after the harvest (*NG* 79). Interestingly, establishing a vineyard is considered to be a venture comparable to the construction of a house (probably because of the scale of the material investments involved) (*NG* 21), which explains why, at three distinct locations in the *Farmer's Law*, there are whole sets of regulations punishing various types of damage to a vineyard (whether inflicted intentionally by a human, or by a farmer's cattle) (*NG* 12, 16, 18; then 38; finally, 50–59, esp. 50–51). Viticulture is also attested in the early 10th c. *Life of Eustratios of Agauros*, a saint who died during the reign of Basil I (867–886 CE) (Papadopoulos-Kerameus, 1897, 1898; *Dumbarton Oaks Hagiography Database* 37): a monk had to keep guard in a vineyard during the harvest period (the monastery was in all probability located in southern Bithynia) (p. 386, l. 8–9).

Vine and hazel appear as well in the *Life of Philaretos*, not in the description of the saint's estates, but in a dream of the author, Niketas, presented in the final part of the life of his grandfather. Niketas dreamt of "grapes as big as the size of a tall man" along with large pomegranate-trees, plus date-palms and hazel with fruit like "wine-jars holding twelve measures each" (Phil. 844–51). Interestingly, hazelnuts are today one of the key crops in northern Türkiye. The *Farmer's Law* also contains a few other references to fruticulture: pruning trees (*NG* 22); cultivating them (*NG* 32; 33; 39); hiring a guard for an orchard (*NG* 33). A vegetable garden adjacent to a house is referred to also (*NG* 31). Olive groves, in contrast, are not mentioned at all in the *Farmer's Law*, which could be an indication of a landscape where olive cultivation was not practiced due to climatic/geographical conditions, as in northern Türkiye. On the other hand, it may reflect the more general collapse of olive oil production in Anatolia in the wake of the Arab invasions, related to market fragmentation and shrinkage (Fiołna et al., 2025).

As for pasturing activities, their predominant form seems to have been collective herding of oxen. One herdsman took care of oxen belonging to several farmers (*NG* 23–29). The shepherds were either hired (*NG* 34) or they were slaves (*NG* 71–72). Oxen were expensive and usually not many of them were owned by one farmer—contrary to sheep, which always appear in the plural in the *Farmer's Law* (cf. also the story of a poor farmer losing his only yoke of oxen; Phil. 81–83). In the same text, there are also several detailed regulations which punish the theft of oxen (*NG* 38–45), clearly an animal of sufficient worth to risk stealing (*NG* 42). Moreover, every farmer was obliged to take care of the oxen of others if he found a lost animal (*NG* 43).

The last prominent product of the village economy was wood. Woodland was a valuable resource and could be possessed by a farmer (*NG* 17; 20). Working in woodland was part of the agricultural calendar, and there was a particular "woodcutting time" (*NG* 22). Wood was not only gathered in order to provide fuel or construction materials for villagers, but it was traded as well as subject to state corvee (*Life of Eustratios*, p. 390, l. 4; De Cer., 319. 58–59 and 66–67 ed Dagron and Flusin, 2020: t. III; Dunn, 1992).

Discussion

The Hellenistic period (330–60 BCE)

The earliest levels of the new high-resolution pollen record of Lake Yeniçağa contain important information on the long-term development of local vegetation and land cover during Graeco–Roman Antiquity. From the beginning of the Hellenistic period, the region of Lake Yeniçağa was characterized by woodlands of pines and mesophilous trees (mainly dec. *Quercus, Carpinus betulus, Fagus, Corylus*) (Fig. 3). This needle-leaved and broad-leaved montane vegetation represents the coniferous forest, which dominated drier habitats at higher elevations, and the cold-deciduous forest spread in more humid habitats at lower altitude, as attested in the near Lake Çubuk and other Late Holocene pollen records of NW Türkiye (Bottema et al., 1995; Miebach et al., 2016; Ocakoğlu et al., 2016). The presence of Mediterranean elements, like Ericaceae and evergreen *Quercus*, reveals patches within the Black Sea forest on the southern slopes of the inner mountain valleys (Fig. 3). Such xerophilous enclaves, which are common in the Marmara region (see Lake Iznik; Miebach et al., 2016), seem to represent a peculiarity of the Yeniçağa landscape with respect to other mountain areas of the Bolu province (Bottema et al., 1995; Ocakoğlu et al., 2016). Toward the 4th c. BCE, the expansion of mesophilous vegetation associated with hygrophilous trees (mainly *Alnus*) attests to wet conditions in the area. Poaceae, which mainly refers to the *Phragmites* lacustrine belt, also expanded, suggesting the spread of reeds due to the high water level of the lake (Fig. 7). The role of reed pollen as an indicator of the water column has already been stressed by Bottema and colleagues (1995) for the sediment sequence of Lake Melen. At ca. 260 BCE, a contraction of mesophilous and hygrophilous forests is recorded and, together with the abrupt increase of Cyperaceae (closely resembling *Carex* pollen type; Beug, 2004) and *Artemisia*, indicates the onset of drier conditions (Figs. 3 and 7). In particular, the spread of sedges is confirmed by higher concentration values and since they grow behind reeds in wet soils is clear evidence of the reduction of the lake level (Fig. 4; Sadori et al., 2013). The alternating prevalence of reeds and sedges along the entire Yeniçağa pollen record, as already shown by Beug (1967), confirms that fluctuations of water level, and consequently lake size, caused the expansion of different lacustrine belts at the coring site. These two lake environments are clearly discriminated by PCA (Fig. 5). Considering also the presence of NPP remains growing in shallow water, the local hydrological change at ca. 260 BCE was probably fostered by a regional climatic trend toward arid conditions, attested by the stable isotope records of Lake Çubuk and Sofular Cave and affecting the Eastern Mediterranean at various extent (Fig. 7; Schilman et al., 2001; Kaniewski et al., 2007). These climatic constraints also impacted on land use in the lake area as attested by anthropogenic pollen: cultivation of cereals with higher water demand (*Avena/Triticum*: up to 3% at ca. 320 BCE) as well as grapevine (*Vitis*: 3% at ca. 320 BCE) benefited from the wetter climate until ca. 260 BCE, when the drop in precipitation probably forced the abandonment of viticulture and the selection of crop species more adaptable to water stress, such as barley (*Hordeum* group: 1%). In addition, the higher abundance of annual weedy plants (*Centaurea cyanus*, *Polygonum aviculare* type) would suggest that most of the fields were converted into fallow land, within a rotational production system more suitable to a changing climate (Behre, 1981; Fig. 3). The possibility that *Vitis* pollen from the wetter phase would have been produced by wild plants which formed the undergrowth of the riverine forest should be not excluded, also considering the low pollen productivity of the cultivated ones (Bottema et al., 1995; Arnold, 2002). Besides, the contribution of this taxon to synanthropic plants is not statistically significant (Fig. 6). Nonetheless inaperturate pollen grains of *Vitis* which are mainly produced by wild grapevines have not been recognized, for this reason we consider this taxon a primary anthropogenic indicator (Berger et al., 2019; Mercuri et al., 2021).

Thereafter the rapid increase in precipitation recorded at Lake Çubuk in northwestern Türkiye contributed to the expansion of mesophilous and hygrophilous trees in the study area, with an abrupt peak of NPPs suggesting eutrophication of the lake water at ca. 150 BCE (Fig. 7). Such a process, confirmed by the spread of *Botryococcus* among algae, was possibly fostered by the movement of organic-rich sediments into the basin through runoff waters during wet seasons, possibly by some erosion events attested by the presence of *Glomus* spores in the previous level (Fig. 4). Moreover, higher temperatures contributed to the accumulation of nutrients in the water body, in addition to the high level of human activities in the area testified by the increasing abundance of anthropogenic pollen like cereals and walnut (Fig. 3). *Juglans*, although it is native to Türkiye, can be considered a synanthropic plant as confirmed by PCA of Yeniçağa pollen data (Fig. 6; Mercuri et al., 2013; Pollegioni et al., 2017). In particular its spread (6%), already attested in the previous study of Beug (1967) (see the pollen diagram in Beug and Bottema, 2015), confirms the onset of walnut cultivation in northwestern Anatolia from lowlands to mountain areas during Classical-Hellenistic times (Bottema et al., 1995; Miebach et al., 2016; Ocakoğlu et al., 2016). In

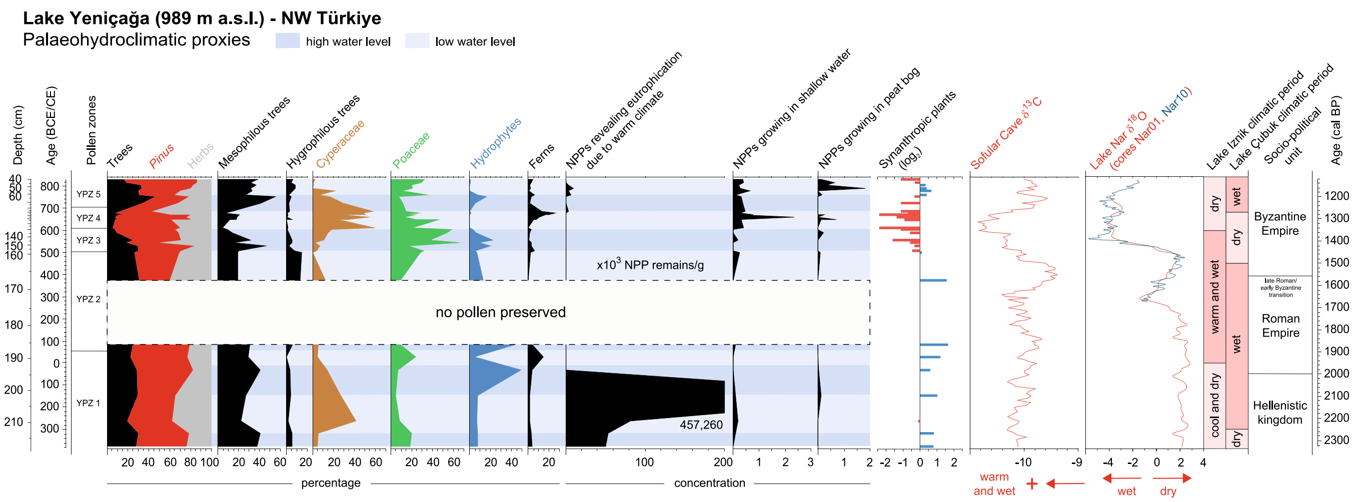

Figure 7. Palaeohydroclimatic proxies from Lake Yeniçağa (northern Anatolia). Percentage and concentration diagram of pollen/NPP ecological groups plotted against age and aligned with regional palaeoclimatic data (Jones et al., 2006; Fleitmann et al., 2009; Göktürk et al., 2011; Ülgen et al., 2012; Dean et al., 2015; Ocakoğlu et al., 2016). Mesophilous trees: *Carpinus betulus, Corylus, Fagus, Quercus robur* type, *Quercus cerris* type; Hygrophilous trees: *Alnus, Fraxinus excelsior* type, *Populus, Salix*; Hydrophytes: *Nymphaea, Myriophyllum*; NPPs revealing eutrophication: *Anabaena, Aphanizomenon, Gloeotrichia, Pediastrum, Rivularia*; NPPs from shallow water: *Spirogyra*, Zygnemataceae, HdV 174, HdV 179; NPPs from peatbog: *Alona rustica*, Coleoptera-Carabidae, *Geoglossum sphagnophilum*, HdV 16; Synanthropic plants: *Olea, Juglans, Vitis, Avena/Triticum, Hordeum* group, *Secale cereale, Centaurea cyanus, Centaurea jacea* type, *Centaurea* undiff., Cichorieae, *Plantago lanceolata* type, *Plantago* undiff., Ranunculaceae undiff., Rubiaceae, *Rumex, Urtica pilulifera*, Urticaceae. Dark blue areas represent period of increasing water level, light blue areas of decreasing water level. [Color figure can be viewed at wileyonlinelibrary.com]

this respect, evidence from Lake Yeniçağa contribute to disclose how walnut was diffused by the Greeks and then the Romans across the Mediterranean, in accordance with pollen data from Anatolia (e.g., Eastwood et al., 1999; Wick et al., 2003) and the Balkans (e.g., Masi et al., 2018; Masci et al., 2024; Vignola et al., 2022). Apart from agriculture, human pressure on the lake catchment was represented by herding practices, whose development is clearly shown by the increasing presence of Asteroideae, Cichorieae, *Lathyrus* type, *Plantago lanceolata* type, *Plantago* undiff. (Fig. 3). The coterminous decrease of *Pinus* pollen could also be ascribed to pastoral activities on the mountain slopes as well as by lumbering, in accordance with the reconstruction provided by Bottema and colleagues (1995) for the vegetation dynamics around Lake Yeniçağa during the mid-/late Holocene (Fig. 3). This model of land use combining tree cultivation, cereal farming, and pastoralism was common in NW Türkiye even at higher elevation and corresponds with the so-called Beyşehir Occupation (BO; Bottema and Woldring, 1990) phase, a Late Holocene event broadly recorded in Anatolian and Greek sites from the Iron Age up to the Byzantine period (Bottema et al., 1995; Kaniewski et al., 2007; Ocakoğlu et al., 2016; Şenkul et al., 2018; Biltekin et al., 2025).

The early Roman period (60 BCE–100 CE)

The period of wetter climatic conditions continued during the early Roman period, from ca. 30 BCE to ca. 90 CE, when the highest amount of hydrophyte pollen (up to 50%) is recorded (Fig. 7). Water plants with roots anchored at the lake bottom and floating or submerged leaves, such as water lilies (*Nymphaea*) and watermilfoils (*Myriophyllum*), require high enough water column to grow (0.5–1.5 m) and represent the lacustrine vegetation growing before reeds, toward the center of the lake. Considering this ecological evidence, their spread clearly reveals favorable hydroclimatic conditions at a local scale, resulting in the maximum extension of the Yeniçağa water body. The abundance of pollen of mesophilous trees (mainly *Quercus robur* type and *Fagus*) confirms that precipitation increased at that time. Nonetheless, an abrupt contraction of aquatic vegetation occurring at ca. 30 CE coincides with the increase in Poaceae pollen and fern spores: this evidence may reveal the reduction of the water level, with the expansion of wet soils in the coring site previously occupied by the lake environment (Fig. 7). Actually, if excluding any taphonomic or sedimentological process compromising the representativeness of pollen spectra, an event occurring in the Yeniçağa area could be possibly postulated. In this respect the concurrent spread of more thermophilous species, like hornbeams (*Carpinus betulus*, *Ostrya/Carpinus orientalis*), together with Mediterranean xerophytes, like Ericaceae and *Olea*, seems to indicate a renewed period of warmer and drier conditions that contributed to a change in the composition of vegetation (Fig. 7). Mediterranean species could have been also released by a change in land use, especially for olive which is a cultivated tree: PCA shows that only a low variance of data explains for difference between Mediterranean and synanthropic taxa, suggesting how this vegetation change might have been led by different drivers (Fig. 6).

At a regional scale climatic instability is attested for northwestern Anatolia until the 1st c. CE, with a prolonged dry period recorded by Çubuk and Sofular stable isotope values from ca. 2150 to 1900 cal a BP (200 BCE–50 CE). At Lake Iznik, geochemical data confirm drier conditions, in association with the prevalence of pollen from herbaceous vegetation with steppe elements until 1950 cal a BP (1 CE; Miebach et al., 2016) (Fig. 7). Although pollen resolution of the lower part of the Yeniçağa sequence does not allow identification of short-term environmental fluctuations, anthropogenic pollen types reveal a change in land use: pastoral indicators decrease from ca. 30 BCE (e.g., Asteroideae, Cichorieae, *Plantago lanceolata* type, *Plantago* undiff.) and suggest the reduction of herding practices in the mountains. Fast-growing trees probably spread as attested by the abundance of *Pinus* pollen (Fig. 3; see also Bottema et al., 1995; Ocakoğlu et al., 2016), although other palynological sequences of Türkiye and the Balkans reveal the intensive use of pine wood during Roman times (e.g., Panagiotopoulos et al., 2013; Masi et al., 2018; Şenkul et al., 2018; Biltekin et al., 2025).

More in general, pollen data from Lake Yeniçağa agree with the palaeoenvironmental and socioeconomic dynamics reconstructed for Anatolia during the so-called Roman Warm Period (RWP or Roman Climatic Optimum; Lamb, 1995). This is a generally warm and humid climatic phase that occurred at ca. 300 BCE–300 CE and was probably influenced by changes in solar irradiance. It is considered a key period for the development of Roman culture in the Mediterranean and beyond (Bond et al., 2001; McCormick et al., 2012), although its significance for the Roman Empire's economic development has recently come into question (Haldon, 2016). Thus, although most of the proxies have recorded warmer and wetter conditions (e.g., Desprat et al., 2003; Migowski et al., 2006; Magny et al., 2007; Zanchetta et al., 2007; Esper et al., 2012), evidence of more cold and/or arid climate are attested all across the basin (e.g., Schilman et al., 2001; Mangini et al., 2005; Piva et al., 2008; Taricco et al., 2009; Büntgen et al., 2011) and there was no Mediterranean-wide pattern of single "benign/optimal climate" (Labuhn et al., 2018). In Anatolia, the former (warm and humid) conditions are evidenced at Lake Iznik in the northern region, as well as at Bereket and Lake Van from western to eastern regions (Wick et al., 2003; Kaniewski et al., 2007; Ülgen et al., 2012), whereas the latter (cold and/or arid) appeared toward inner areas (Lakes Nar and Tecer; Kuzucuoğlu et al., 2011; Dean et al., 2015). These regional variations probably reflect broader fluctuating trends during the course of the RWP, indicated in the vegetation changes that occurred around Lake Yeniçağa in the 1st c. CE (Margaritelli et al., 2016). In particular, the increase in temperature, especially during winter, enabled the intentional growth of *Olea* trees in the inland of northern Anatolia that is outside their natural distribution range, and even at mid-high altitudes thanks to the influence of the Black Sea. For this reason, the peak of *Olea* pollen in the Yeniçağa record (5% at ca. 30 CE) may well reflect the intensification of olive cultivation in the Roman province of *Bithynia et Pontus* more widely during the early Imperial period, associated in turn with the expansion of olive monoculture in western Anatolia (Doğan et al., 2025; Fiołna et al., 2025). Palaeoenvironmental and historical studies in Anatolia as well as the Balkans have largely focused on the Roman tendency to locate large-scale olive groves in lowlands along the coast, even though signs of increasing olive cultivation in the upland valleys come from southwestern Anatolia (Kaniewski et al., 2009; Leroy et al., 2010; Roberts et al., 2018; Langgut et al., 2019; Vignola et al., 2022; Fiołna et al., 2025) and, now, from the upland region in which Lake Yeniçağa is located. In contrast to cereal pollen percentages that decrease slightly, the high percentage value of *Juglans* during the Roman period (up to 7% at ca. 90 CE; Fig. 3) confirms that local arboriculture became subject to more intensive cultivation regimes, focused on the most marketable food products of the highlands (such as nuts and oil). This evidence as resulted from other palynological sequences of northwestern and central Anatolia (e.g., Lake Abant, Lake Melen, Lake Iznik, Lake Çubuk, Lake Sülük;

Bottema et al., 1995; Miebach et al., 2016; Ocakoğlu et al., 2016; Biltekin et al., 2025) suggests that the BO phase at Lake Yeniçağa peaked during the Hellenistic and Roman occupation.

The ancient-to-medieval transition (400–800 CE)

The pollen record provides no palynological evidence in the interval 167–185 cm, corresponding to the period from the 2nd to mid-4th c. CE (90–370 CE), because pollen preservation is lacking for samples at 173.5 and 175.5 cm. This is most probably the result of oxidation processes affecting pollen grains enclosed in lake sediments. Based on lithological features of the Yeniçağa sediment sequence, a distinct transformation representing a significant change in the lake ecosystem occurred in Unit IV, specifically within the depth range of 156–180 cm (Table 2). In addition, the drop of pollen concentration from levels immediately before and after the barren interval also indicates changes in the lake environment. All this evidence reflects a dry climate and seems to correlate with an episode of more arid conditions recorded at 350–450 CE by positive stable isotope values of Sofular Cave and Nar Lake (Fig. 7). The same oscillation may be attested closer to the study area by the Çubuk palaeoclimatic proxy from 1780 to 1650 cal a BP (170–300 CE; Ocakoğlu et al., 2016). If the climate is assumed to have been the main driver of changes visible in our record, a lowering of the water level with an exposure of soils at the coring site might be postulated, causing pollen deterioration. Nevertheless, it is interesting to note that the entire lower part of the sequence, from the bottom to ca. 160 cm (500 CE), is characterized by slow sedimentation and very low pollen concentration, in comparison with the upper part of the core (Figs. 2 and 4). Since the same pollen preservation was observed between the studied samples, this pattern may result from several factors: (i) a difference in the climate seasonality of the Black Sea region affecting the rain shadow in the Bolu area, with lower winter precipitation on the top of the mountains in earlier periods that transported low amounts of sediment with pollen into the lake after snow smelting (Mayer and Aksoy, 1986); (ii) the tectonic activity of the North Anatolian Fault Zone (NAFZ) along which the Bolu area is located, causing a change in the soil inwash as reconstructed for another lacustrine sequence on the same active branch (Leroy et al., 2010); (iii) the different temporal resolution of the lower part of the sequence with respect to the Byzantine interval (38 vs. 15 years on average), of which the pollen samples might have recorded fluctuations in the local hydroclimatic system at different scales (from decennial to annual); (iv) a difference in human pressure on the environment, with extensive agro-pastoral activities during the Hellenistic and Roman periods reducing the plant biomass in the Yeniçağa area (Fig. 4).

From ca. 370 CE to the end of the sequence at 40 cm depth the pollen record is continuous. Hygrophilous trees are still abundant (*Alnus*: 13%) and associated with sedges and reeds, suggesting the prevalence of lacustrine vegetation in the coring site, as also confirmed by the occurrence of hydrophytes (Fig. 7). The level of human activity is still evidenced by *Juglans* pollen (5%). In particular the highest abundance of Cichorieae (15%) and Asteroideae undiff. (8%) throughout the sequence testifies to herding practices that might have been taking place in the environs of the lake, exactly when some spores of the coprophilous fungus *Podospora* occur and attest the presence of animals (Figs. 3 and 4; Schlütz and Shumilovskikh, 2017). From ca. 370 to 500 CE the local expansion of riverine forest continued since *Alnus* pollen increased up to 15% and reed vegetation prevailed against rooted water plants (Fig. 7). This abundance of peri-lacustrine plants, in association with algae growing in stagnant and shallow water (Zygnemataceae) and Chydorids living in peat (*Alona rustica*), seems to indicate reduced precipitation and the lowering of the lake level (Fig. 4).

At the same time the woodland composition changed, with *Fagus* dominating among broad-leaved deciduous trees, and *Abies* expanding among conifers (Fig. 3). This prevalence of cold-resistant trees seems to indicate lower temperatures, the effect of which was the natural reduction of forest biodiversity (total arboreal taxa: 18). A possible cooling phase is recorded not far to the west at Lake Çubuk from 450 CE, when $\delta^{18}O$ values in combination with microfaunal and pollen data testify to changing conditions in the lake environment (Ocakoğlu et al., 2016). At ca. 510 CE, however, plant composition developed again and Mediterranean enclaves suddenly expanded (*Quercus ilex* type: 9%, *Juniperus*: 8%, Ericaceae: 4%) in association with species of deciduous forest more tolerant to warm conditions (*Quercus robur* type: 9%, *Carpinus betulus*: 2%, *Ostrya/Carpinus orientalis*: 2%). At the same time the level of human impact around Lake Yeniçağa reduced, as shown by the decrease of *Juglans* (2%) and Cichorieae (5%) pollen. Such a decrease in land use, combined with a short-term episode of higher temperatures, likely resulted in the recovery of woodland with pines growing in abandoned areas (Fig. 3). Importantly, this local palaeoenvironmental reconstruction is not reflected in regional proxies, which record a general trend toward wetter climatic conditions until ca. 1350 cal a BP (600 CE) (Fig. 7; Fleitmann et al., 2009; Göktürk et al., 2011; Ülgen et al., 2012; Ocakoğlu et al., 2016). In addition, pollen data from Lake Iznik reveal that the intensification of arboriculture in the lowlands, the onset of which is recorded from ca. 1500 cal a BP (450 CE), affected oakwoods (Miebach et al., 2016).

From ca. 510 to 600 CE a general phase of lake expansion is clearly attested by the increase of *Nymphaea* and the decrease of *Alnus*, suggesting higher water column with the spread of hydrophytes at the coring site whereas the lakeshore with the riparian tree line moved far away (Fig. 3). The abundance of Poaceae pollen, the highest in percentage (66% at 540 CE) and concentration (32,460 pollen cm^{-3} at 590 CE) but not in influx (Figs. 3, 4, and S1), confirms that the reed belt grew following the increasing water level and characterized the lake environment (Fig. 5). This plant development follows the wet climate highlighted by $\delta^{13}C$ values of Sofular Cave and the sediment data from Lake Iznik, instead of the environmental conditions in the near Lake Çubuk as noted above (Fig. 7). Apart from the climatic influence, water level of Lake Yeniçağa might also have been affected by seismic activity of the NAFZ: at Lake Sapanca on the west a lithological change associated to a disturbance event and increasing pollen amount is exactly recorded before ca. 580 CE (Leroy et al., 2010). At ca. 530 CE the Colchisian vegetation, previously extending up to the Bolu area, changed and evergreen oaks (*Q. ilex* type: 2%) were replaced by Mediterranean shrubs, mainly Ericaceae (6%) but also *Phillyrea* (<1%) (Fig. 3). In view of the fact that mesophilous tree cover increased, as recorded by pollen concentration values, whereas the Sofular palaeoclimatic proxy records dry conditions at that time, the peak in heathers might be related to some change in precipitation seasonality, which affected summer climate in the inner valleys (Figs. 4 and 7). The occurrence of free-floating European frog-bit (*Hydrocharis morsus-ranae*) among water plants seems to confirm stagnant conditions during the warm season, when this species produces pollen (Fig. 3). Moreover, since no hints of intense human pressure are attested by anthropogenic pollen, apart from the presence of weedy plants from abandoned fields (*Centaurea cyanus*: 1%), a climatic cause should be considered (Figs. 3 and 8).

Around the middle of the 6th c. CE, however, at the height of Eastern Roman political and economic expansion, agricultural activities expanded in the area again and brought with them a general reduction of forest cover, probably due to the exploitation of wood sources and the need to develop new cultivated land: at ca. 540 CE pollen concentrations of *Pinus* and mesophilous trees decreased in association with the re-appearance of *Olea* together with *Juglans* (both 1%). The regional climate became rapidly wetter as recorded at Lakes Çubuk and Nar, as well as Sofular Cave, indicating that the decrease in forest biomass may have been associated with enhanced human activity (Figs. 4, 7, and 8). Similar palynological evidence of tree cultivation in northern Anatolia for this period comes from Lake Sapanca and Lake Iznik, where olives, vines, and fruit trees were abundant throughout the lowlands around 1410 cal a BP (540 CE together with cereals; Leroy et al., 2010; Miebach et al., 2016). In this respect a long-distance transport of olive pollen grains from lower areas into the Yeniçağa catchment cannot be ruled out, as stressed for the higher sites of Lakes Abant and Melen (Bottema et al., 1995).

This renewed agricultural activity, which involved the region from coast to upland, lasted a few decades. At Lake Iznik a drop of cultivated taxa is recorded after 1410 cal a BP (540 CE; Miebach et al., 2016). At Lake Yeniçağa pollen from tree crops decreased at ca. 560 CE: walnut continued to grow in its naturalized distribution area without human management, unlike olive trees which were reaching their growing limits (Fig. 8). This reduced human pressure on the environment resulted in the recovery of forest taxa, through a process of reforestation begun by pioneering plants such as Rosaceae (1%). The primary economy evolved into a more sustainable exploitation system, based on fallow lands (*Centaurea cyanus*) and pastures (Asteroideae undiff., Cichorieae, Ranunculaceae undiff., Rubiaceae) (Fig. 3). As there was no military conflict in Anatolia until the 610s CE, when the Persians invaded extensive areas of the Eastern Roman Empire, such decline in the regional scale of agriculture may well have been related to the impact of the so-called Justinianic plague on the rural populace. In the case of Yeniçağa, this would have been its secondary circulation which impacted on the Eastern Roman ecosystems and populations after the 540s (Mordechai et al., 2019).

Following the epidemic ca. 590–600 CE, there is again some short-lived recovery of agro-pastoral activities in the surrounding of Lake Yeniçağa. Crop species (*Avena/Triticum*, *Juglans*) as well as plants growing in pasturelands (mainly Cichorieae, *Plantago*) increase, in contrast to mesophilous trees which reduce both in percentages and concentrations (Figs. 4 and 8). Moreover, at ca. 590 CE the peak in *Glomus* curve would suggest an intensification of land use since plowed fields are highly susceptible to erosion. The resilient land exploitation was common not only in the inner montane valleys like Yeniçağa, but also in high-altitude sites like Çubuk, where a similar anthropogenic pollen assemblage is attested (Ocakoğlu et al., 2016).

From ca. 610 to 680 CE the disappearance of water plants correlates with the maximum increase of Cyperaceae in the sequence, both in percentage (up to 60% at ca. 610 CE) and concentration (up to 68,928 pollen cm^{-3} at ca. 670 CE). In addition, ferns attain their highest values (26% at ca. 680 CE) together with remains of NPPs occurring in shallow water (2347 NPPs cm^{-3} at ca. 660 CE). This evidence indicates a significant reduction in the lake size: the water level progressively declined at the coring site and the sedge belt expanded, whereas reeds moved far away from it as shown by the decrease of Poaceae pollen (Figs. 4 and 7). Such paleoenvironmental change was clearly intensified during the second half of the 7th c. CE, as evident through the PCA ordination (Fig. 5): it should be probably put in relation to the aridification trend attested by some climatic proxies of western, central and northern Anatolia which also affected the level of human activities in the Yeniçağa area (Fig. 8; Jones et al., 2006; Fleitmann et al., 2009; Göktürk et al., 2011 Ülgen et al., 2012).

In the 7th c. CE, the short-term vegetation dynamics recorded by high-resolution pollen data reveal a complex

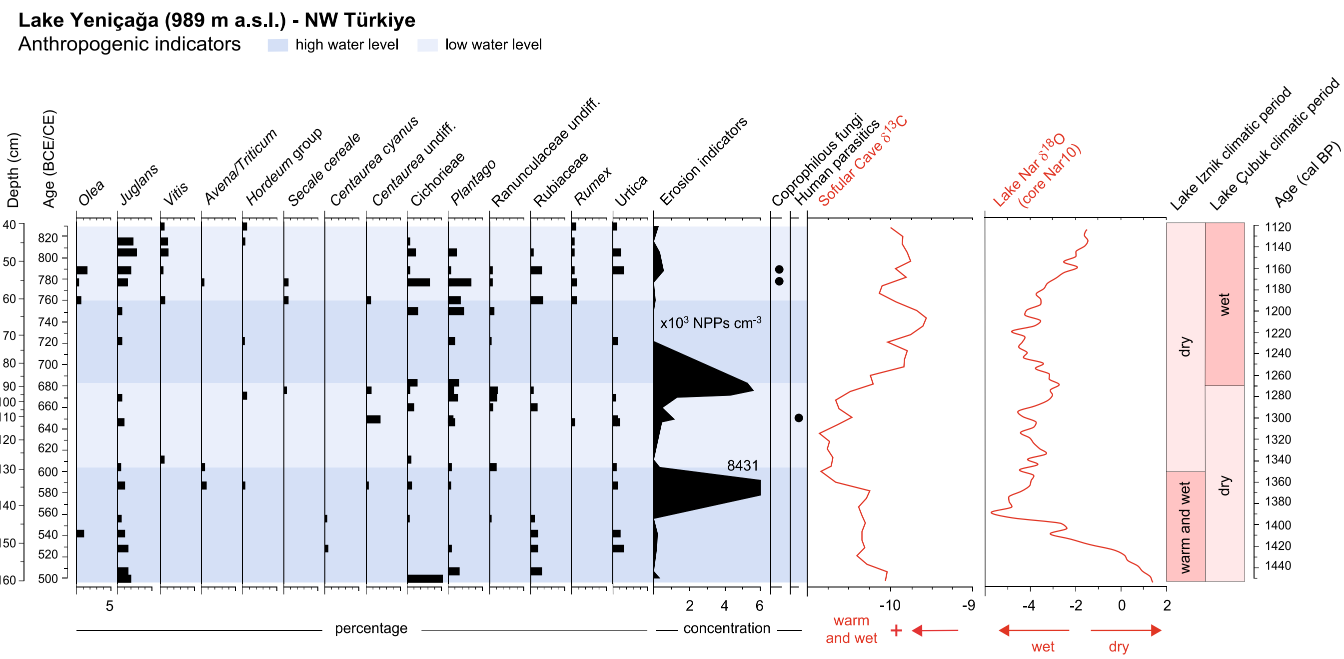

Figure 8. Anthropogenic indicators from Lake Yeniçağa (northern Anatolia) for the period 500–830 CE. Percentage and concentration diagram of synanthropic pollen (Behre, 1981, Mercuri et al., 2013, Berger et al., 2019) and NPP showing human pressure on the environment during the early Byzantine period, compared with regional palaeoclimatic data (Jones et al., 2006; Fleitmann et al., 2009; Göktürk et al., 2011; Ülgen et al., 2012; Ocakoğlu et al., 2016). Erosion indicators include *Glomus* and *Pseudoschizaea*. [Color figure can be viewed at wileyonlinelibrary.com]

relationship between environment, people, and climate during this period. At ca. 610 CE *Carpinus betulus* and *Fagus* are not attested and deciduous oaks reach the lowest percentage value of the sequence (4%), whereas *Betula*, *Cedrus*, and *Picea* (max 1%) appear. In addition, *Pinus* increases both in percentage (64%) and concentration (117,165 pollen cm^{-3}) (Figs. 3 and 4). The abrupt contraction of mesophilous forest was accompanied by the expansion of pinewood and cold-resistant species of Euxine vegetation from northeastern Anatolia (*Betula* sp., *Cedrus libani, Picea orientalis*; Davis, 1965–1985; Atalay et al., 2014), suggesting drier and colder conditions. The attestation of these species in lowland sites, like Lake Melen and Lake Iznik, has been also related to the transport by wind of pollen grains from the inland (Bottema et al., 1995; Miebach et al., 2016). Nonetheless cedar trees (*Cedrus libani*), whose presence in the Yeniçağa area has been already recorded during the Holocene, seem to have recovered from scattered populations strongly impacted by human disturbance in the northern regions of Anatolia (Beug and Bottema, 2015; Biltekin et al., 2015).

Already affected by the plague in the past decade, the primary economy must have been strongly impacted by this climatic deterioration: evidence for cereal and walnut cultivation disappears, probably due to the lower temperatures and recurring frost that affected plant growth, while only limited pastoral activities are attested (Cichorieae: 1%). Yet exceptionally the presence of *Vitis* pollen (1%) indicates local viticulture. Since the arid climate would not have allowed the wild hygrophilous species to grow as previously stated, this must indicate cultivated plants (Fig. 8). At higher elevations agriculture definitely collapsed, weeds expanded on abandoned fields and only herding was practiced during the following decades, as shown by pollen data from Lake Çubuk (Ocakoğlu et al., 2016).

From ca. 610 to 650 CE the decrease in pollen concentration confirms episodes of dryness at the coring site, which might have hindered the preservation of pollen grains in the sediment (Fig. 4). Although open environments with xeric vegetation expanded (*Artemisia*: 2%, *Helianthemum*: 1%), toward the middle of the century climatic amelioration enabled the deciduous forest to recover at the expense of pinewood (*Pinus*: 54%) and the vegetation succession started with pioneer plants (Rosaceae: 1%), followed by mesophilous trees (Figs. 3 and 7). Agro-pastoral activities were also intensified as shown by synanthropic pollen of *Juglans*, *Plantago*, and *Rumex* (up to 1%), together with nitrophilous taxa (Urticaceae, including *Urtica pilulifera*: 1%) and other herbs growing in pastures (Fabaceae undiff.: 2%, Scrophulariaceae undiff.: 1%; Figs. 3 and 8). Within a few years precipitation increased and woodlands expanded again, as recorded by arboreal pollen concentrations and the rapid growth of hygrophilous and mesophilous forests (Figs. 4 and 7). The concurrent expansion of thermophilous deciduous (*Ostrya/Carpinus orientalis*: 2%) and evergreen (*Juniperus/Cupressus*: 5%, *Quercus ilex* type: 2%, *Ephedra*: 1%) species clearly indicates increasing temperature (Fig. 3). The near-disappearance of anthropogenic indicators was likely the result of a combination of climatic instability and the impact of the Persian and Arab warfare on the capital region of Anatolia: pollen data reveal the definitive abandonment of lands where weeds (*Centaurea* undiff.) expanded and erosion processes started to increase. Human frequentation in the area, probably ephemeral, is only attested by a few herbs growing on organic-rich soils (Urticaceae), microcharcoals, and eggs of human parasites (Figs. 3, 4, and 8). The forest expansion continued up to ca. 670 CE, led by pines and mesophilous trees as confirmed by pollen percentage and concentration values; at the same time the alternating contribution of thermophilous species suggests fluctuations of temperature (Figs. 3, 4, and 7). Arboriculture (*Juglans*: max 1%) and herding (Cichorieae, *Plantago*: max 1%) practices started again by local communities but their impact on the local environment was still reduced (Fig. 8).

From ca. 670 to 680 CE woodland was reduced especially the abrupt contraction of pinewoods (minimum of 31% and 14,798 pollen cm^{-3}; Fig. 4), although the local presence of riparian trees (*Populus*: max 2%) and of stable isotope values from Lake Çubuk and Sofular Cave seem to attest a new trend of enhanced precipitation and favorable environmental conditions (Figs. 3 and 7). In this respect, anthropogenic pollen clearly reveals that such a thinning of the woodland was caused by some clearance activities to recover acreage for cereal cultivation and pasture, as confirmed by the presence of large-size microcharcoals. It is worth emphasizing that agriculture replaced arboriculture in the study area with the cultivation of barley and rye (*Secale cereale*: <1%), the latter being the most resistant cereal crop to lower temperatures: the attestation of rye pollen in combination with *Abies* and *Picea* suggests declining spring temperatures, which impacted on the growing season of tree crops (chestnut, walnut) and forced an adaptation of agricultural practice to the changing climate (Figs. 4 and 8). This agricultural recovery was interrupted by the Arab invasions, however, which extended as far as Constantinople. The intensification of erosion processes under wetter conditions, recorded by *Glomus* spores around 680 CE, would suggest such an abandonment of arable fields due to political instability (Jankowiak, 2013; Lilie, 1976).

From ca. 680 to 760 CE an increase in rainfall continues to be recorded by the regional proxies of Lake Çubuk (Fig. 7). The level of Lake Yeniçağa rose, attested by the abundance of water plants, mainly *Nymphaea* and *Typha angustifolia* type, at the coring site, now located far away from the peri-lacustrine belts (i.e., reeds, sedges, and ferns; Fig. 3). At the same time arboreal plant biomass increased, led by the growth of mesophilous woodland vegetation representing the woodland recovery after the previous demographic and economic downturn (Fig. 4). Until ca. 750 CE the slight expansion of pioneer plants like *Corylus* disclosed the succeeding recovery of deciduous oak and beech forests, in the latter case together with the bush species *Taxus*. Apart from cold-resistant species, the presence of thermophilous Euxine vegetation (Ericaceae, *Q. ilex* type) indicates short-term climatic fluctuations at a local scale (Fig. 3).

A forest regeneration seems to have occurred at that time in the rural mountain areas of northwestern Anatolia in the absence of strong human impact, as shown by the Abant pollen record from ca. 690 CE (Bottema et al., 1995). On the contrary, the concurrent indication of a reduction in pinewood cover in the Yeniçağa area (*Pinus*: maximum 34% and 59,619 pollen cm^{-3}) reveals the human imprint on such a vegetation change, since it should be related to new economic activities carried out in the lake area. Indeed, agro-pastoral practices intensified, as recorded by pollen of tree crops (*Juglans*: max 1%), cereals (*Hordeum* group: <1%) and weeds (*Polygonum aviculare* type: <1%), and herbs growing in pasturelands (Cichorieae, *Plantago*: max 2%) (Figs. 3 and 8). Such an attempt at agricultural recovery was, again, short-lived because of the repeated Arab raids attested in these years, that also included taking captives form the rural population and resettling them in the Levant: in 727 the Arabs raided as far as Bithynia and took many captives and booty (Theophanes AM 6218; Nicephorus 61); in 731/2 another raid reached as far as Paphlagonia and took a large number of captives (Theophanes AM 6224). At ca. 760 CE cold-resistant forest contracted to the advantage of thermophilous species (mainly *Juniperus/Cupressus*, *Fraxinus ornus*, *Ostrya/Carpinus orientalis*), whose spread clearly reveals warmer climate (Fig. 3). Apart from the climatic fluctuation, we observe this abrupt decline of mesophilous trees soon after the Arab raiding started, also in the Çubuk area: this probably suggests a concurrent woodland clearance and the establishment of new groves in the area around the lake due to the favorable environmental conditions, as attested by *Olea* and *Vitis* pollen which confirms the recovery of arboriculture in the final part of the sequence (Fig. 8; Ocakoğlu et al., 2016). Among mesophilous species *Castanea* is a potentially cultivated tree, whose diffusion through the Mediterranean basin has been interpreted as the result of intensive exploitation by the Romans (Mercuri et al., 2013). However, it is native to northern Türkiye and appears sporadically in the Late Glacial–Holocene record of Lake Yeniçağa (Davis, 1965–1988; Beug and Bottema, 2015). In addition, PCA confirms it is closer to mesophilous rather than cultivated and other synanthropic taxa (Fig. 6). For all these reasons, it is more feasible that its occasional occurrence during the Late Antiquity was related to broad-leaved vegetation dynamics in the Bolu region (Fig. 3).

From ca. 780 to 830 CE a renewed phase of low water level is shown by the collapse of hydrophytes in combination with the abundance of NPP remains indicating peaty conditions. The contraction of the lake caused the expansion of reed vegetation belt and riparian forest in the coring site, where the shallow water contributed to some eutrophication processes (Fig. 7). These environmental changes were probably driven by an ongoing aridification phase revealed by climatic data from Lakes Çubuk and Nar (Jones et al., 2006; Ülgen et al., 2012; Ocakoğlu et al., 2016). Coniferous and broad-leaved deciduous vegetation recovered from the previous period accompanied by pioneer species (e.g., Rosaceae undiff.), although the maximum expansion of thermophilous trees is attested at this period for the Yeniçağa area, both in percentages and concentrations (Figs. 3 and 4). This forested landscape was mainly characterized by pine, which likely retained its stands in less fertile or less accessible areas, also on higher mountain slopes as confirmed by Çubuk pollen data (Ocakoğlu et al., 2016); in contrast, the level of human pressure in the surrounding of the lake significantly increased. Anthropogenic pollen attests a wide range of economic activities including agriculture (*Avena/Triticum*, *Hordeum* group, *Secale cereale*; max 1%) and arboriculture (*Juglans*, *Olea*: max 3%). In this respect the presence and abundance of pollen from *Sorbus* group (max 3%) is significant: these plants, which grow in the broad-leaved deciduous forest, belong to the pioneer Rosaceae family and could have contributed to the first forest succession, as already postulated for other species (Rosaceae undiff.) at that time. However, they are potentially cultivated trees and their occurrence may be also related to the presence of orchards close to the lake, as supposed at Lake Iznik in the same Byzantine period (Miebach et al., 2016). Herding practices are also attested by the presence of herbs growing in pasturelands (Cichorieae, *Plantago*, *Rumex*: max 3%), as well as by spores of coprophilous fungi, which represented the main economic activity in the Çubuk area (Ocakoğlu et al., 2016). The slight increase in *Glomus* remains might also suggest new land being exploited, resulting in some restrained destabilization of soils (Fig. 8). It is worthy of note that the connection between pine expansion and clearance activity has been already stressed for the rural mountain areas of northwestern Anatolia and leads us to interpret local vegetation changes as a combination of natural and anthropogenic events (Bottema et al., 1995). Anyway, this intensified human pressure on the Yeniçağa landscape continues until the end of the pollen record.

This late 8th c. agricultural recovery visible in the pollen data can now be associated with the account from the *Life of Philaretos*. Regardless of the imitative character of the text, the palaeoenvironmental evidence from Lake Yeniçağa does confirm that the second half of the 8th c. CE was indeed characterized by a sustained recovery of agricultural activity in northwestern Anatolia. Crucially, contrary to the earlier attempts at economic recovery that we can observe in the 7th to earlier 8th c. CE, and thanks to the very high resolution of our pollen data, these late 8th c. CE indications are sustained over several decades, which might well have led to the accumulation of wealth in the hands of local elites—which is exactly the situation that the *Life of Philaretos* describes. It is also possible that locations such as the Yeniçağa area, not far from the capital, were preferred by the office-holding elite of Constantinople and the military, which were receiving salaries in gold from the emperor and would have sought ways to invest their wealth (Brubaker and Haldon, 2011: 575–91, 602–4). In this respect, there is a contrast with regions more distant from the capital, for example at Lake Nar in Cappadocia (England et al., 2008) and Buldan Yayla (Doğan et al., 2025; Fiołna et al., 2025) in southwestern Anatolia where there is a hiatus in agricultural indicators for at least 200 years following the collapse of late Roman agriculture in the 660s CE. The new Lake Yeniçağa record demonstrates quite clearly that this was not the case throughout Anatolia. Crucially, our pollen record also show that Byzantine attempts at agricultural recovery did not focus solely on cereal cultivation and stockraising, but could include a broad suite of tree crops such as nuts (chestnut, hazelnut, walnut) and fruits (apples, cherries, pears, plums), as also demonstrated by the contemporary written sources.

Conclusion

The high-resolution approach to the new pollen sequence from Lake Yeniçağa reveals a dynamic vegetation history in northwestern Anatolia from the Hellenistic period to the Byzantine era. The location of the study site in northwestern Anatolia, a crossroads between different biogeographical and climatic zones, makes its vegetation sensitive to even small variations in climate. One significant conclusion to be drawn from our data is that the important climatic oscillations between the Aegean, Central Anatolia, and Black Sea zones that occurred during the period with which we are concerned affected in particular the forest cover at higher elevations, with significant changes in coniferous and broad-leaved deciduous woodlands.

At the same time, our data also reveal that even during the late Roman period, that is to say, before the 7th to 9th c., when recurrent warfare with the Arabs became part of life in Byzantine Anatolia, the local agricultural landscape was far from being stable. The palynological data, taken in the context of the existing historical and archeological evidence, indicates some significant shifts in land-use only some of which can be clearly attributed to changes in climate; others can be ascribed with a reasonable degree of confidence to anthropogenic factors such as the effects of warfare; and with perhaps less certainty to the demographic impacts of epidemic or pandemic disease. Thus it is entirely possible that it was plague that may have halted agricultural expansion in the Yeniçağa area in the latter half of the 6th c. CE. Importantly, the phase of greatest climatic aridity around 400 CE did not coincide with a period of pandemic or military invasion; if it had, then the survival of the Eastern Roman Empire would have been threatened more severely than it was. On the contrary, the Justinianic plague and subsequent Persian and Arab wars occurred at times when hydroclimatic conditions were relatively favorable for production of most agricultural goods, which may have strengthened societal resilience in northwest Anatolia. Thereafter, despite the collapse of the established Roman economic system, there were repeated attempts at agricultural recovery, that is, intensification of land exploitation in the inner rural areas, at ca. 600, 670, 720, and 760 CE. The first three were disrupted by warfare—first by the Persian, then by the Arab invasions; they were short-lived and did not last longer than 10–20 years. Only the last attempt, starting in ca. 760 CE, was sustained, to the extent that it found its way into the limited literary production of the times. The process of agricultural intensification and the possibility of an associated accumulation of wealth in elite hands in northwestern Anatolia is the context for the story of the 8th c. CE local saint, Philaretos.

This paper exemplifies the unique knowledge gains obtained by combining high resolution palynological analysis of sediment records with historical information for a relatively well-researched period. It also demonstrates that the vicinity of the capital of the Eastern Roman Empire, Constantinople—which meant access to urban food consumers as well as the proximity of elite land investors—was a major factor, along with the unstable climate, that determined the land use history of Lake Yeniçağa. Indeed, it seems reasonable to conclude that such an important economic driver underlay repeated attempts to establish a highly diverse, productive landscape, a strong contrast with the conclusions that may be drawn from other pollen records from Anatolia of comparable resolution.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Supporting information

Additional supporting information can be found in the online version of this article.
supmat.docx.

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