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Consilience in practice: social–ecological dynamics of the Lake Volvi region (Greece) during the last two millennia

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ABSTRACT: The Lake Volvi area, part of the region of Macedonia (northern Greece), is a biodiversity hotspot, located in the central part of a major communication corridor connecting the western and eastern parts of the Balkans. The sediment succession from Lake Volvi is investigated here to provide a unique high-resolution pollen and geochemical record for the last 2000 years combining palaeoecological and historical methods, implementing the concept of consilience. The palaeoecological data document the environmental dynamics since the occupation of the area by the Romans. The vegetation changes reveal the development of wetland habitats and the variations of the mixed deciduous oak and thermophilous–mesophilous forests, as well as cereal cultivation, grazing and arboriculture, whose intensity varied over time. Archaeological data are available for the 1st millennium CE, but detailed historical evidence becomes accessible from the 13th century CE onwards through Byzantine and Ottoman documents. Both historical and palaeoecological data indicate that the 16th century was the period of strongest population pressure on the environment of the Volvi region. However, for other periods, it is possible to observe disagreements between the proxies. We demonstrate that these contradictions can be resolved with a more complex understanding of the region's social–ecological dynamics. © 2024 The Author(s). *Journal of Quaternary Science* Published by John Wiley & Sons Ltd.

KEYWORDS: environmental history; historical demography; historical geography; human impact; land use; Late Holocene; Macedonia; palynology

Introduction

The Balkan Peninsula has been recognized as a key area for the study of vegetational dynamics (Willis, 1994; Griffiths et al., 2004; Panagiotopoulos et al., 2013; Sadori et al., 2015, 2016a; Donders et al., 2021; Glais et al., 2023). Its rich biodiversity is based on different factors such as climate, geology, hydrology and orography that contributed to shaping the present-day landscape. The natural ecosystems have been shaped by a combination of natural processes such as climatic changes, tectonic activities, erosional events and human activities. Macedonia is emblematic of the Balkans, due to its position in the homonymous peninsula as well as its geomorphology and plant diversity, strongly affected by human activity since the Neolithic (Kotsos and Urem-Kotsou, 2016). From the Roman times onwards, Macedonia became the key area for establishing control over the entire Balkans and over the strategically important corridors of east–west communication in the northern Mediterranean.

Palynological records from Macedonia are quite abundant, but the majority of them focus on the Lateglacial and Early Holocene, and they also have low temporal resolution (Sadori et al., 2023). Within the region, the palaeoenvironmental dynamics of the last millennia are described in detail only for Tristinika marsh (Panajiotidis and Papadopoulou, 2016), Lake Dojran (Masi et al., 2018), Paliouras lagoon (Masci et al., 2022) and Livaditis bog (Kouli, 2020). Climatic data show significant temperature and precipitation variabilities (Labuhn et al., 2018; Xoplaki et al., 2018; Finné et al., 2019) and the distinctive geomorphology of the region (e.g. Francke et al., 2013; Glais et al., 2016) makes the last millennia in Macedonia an ideal period to investigate landscape evolution. Lake Volvi lies in the heart of this region, along the crucial section of the land route connecting the Bosphorus with the Adriatic coast, historically known as the Via Egnatia.

The Volvi region therefore provides a rare case study of complex societal dynamics linked to major historical

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developments (in particular the phases of economic and political integration/disintegration) whose environmental impacts on the local scale can be studied thanks to a robust high-resolution palaeoenvironmental record of Lake Volvi we present here. In this way, thanks to the mobilization of historical, archaeological and environmental data, this study is an experiment in realizing inter-disciplinary consilience (Izdebski et al., 2016, 2022; Sessa, 2019), demonstrating both its benefits and its limits. Consilience stems from the belief in the unity of knowledge and assumes that different lines of evidence, originating from diverse disciplines, should unite in a coherent vision of a problem under study, whether it concerns aspects of the past, or some modern natural or social phenomenon (McCormick, 2011). In this paper, we argue and demonstrate, using the case study of Lake Volvi, that unity does not mean unanimity: consilience occurs both when the different lines of evidence converge, but also when they diverge and reveal new insights, otherwise invisible, into the studied phenomenon.

Study area

Site description

Lake Volvi is the second largest natural lake in Greece. Situated in Central Macedonia, it is located about 35 km east of the city of Thessaloniki (Fig. 1). The lake lies at 37 m a.s.l., has an elongated shape and covers an area of 69 km^2 with a mean depth 13.5 m (Gantidis et al., 2007). Lake Volvi and the adjacent Lake Koroneia are located in the tectonic origin Mygdonia Basin (Kastridis and Kamperidou, 2015) and are remnants of the former Mygdonia Lake, which filled the basin at the end of the Pleistocene. The basin is surrounded by mountain ranges, Mt. Vertiskos to the north and Mt. Holomontas to the south (Karagianni et al., 1999). Lake Volvi has been classified as meso- to eutrophic and its status is mainly influenced by agricultural runoff and farming activities (Fytianos and Lourantou, 2004). It is fed by rainfall, surface and ground water, and thermal springs. A small artificial channel connected Lake Volvi and Lake Koroneia, but today the flow is interrupted due to the low water level of Lake Koroneia (Boli et al., 2015). The main outlet of Lake Volvi, Richios River, connects the lake to the Aegean Sea to the east, outflowing in the Strymonic Gulf (Kaiserli et al., 2002; Kolokytha and Malamataris, 2020).

The surrounding area consists mainly of cultivated land, riverine and lacustrine forests, and scrublands. It is protected by the Ramsar convention for its importance as wetland habitat and has been designated as Special Areas of Conservation for wild fauna and flora (Gantidis et al., 2007). The pioneer pollen sequence from Volvi provided by Bottema (1974) evidenced the high value of the site for palaeovegetation reconstruction.

Climate and vegetation

The climate at Lake Volvi is typical Mediterranean with hot summers and mild winters. Average annual temperature is 13 °C. January is the coldest month (mean temperature of 4 °C) and June the warmest (mean temperature of 22 °C). Mean annual precipitation around the lake is ~445 mm. Precipitation is uniformly distributed throughout all the seasons (Bottema, 1974; Stefanidis et al., 2011).

The catchment areas of Lakes Volvi and Koroneia show high biological diversity at species and habitat levels. The present wetland habitat of this lake system is considered of great ecological and economic importance and therefore characterized by Greek law as a Natural Protected Reserve. The following description uses the nomenclature present in the cited papers in order to avoid misunderstanding. Reed beds of *Phragmites australis* (Cav.) Trin. ex Steud., *Arundo donax* L., *Typha latifolia* L., *Typha angustifolia* L., *Scirpus lacustris* L. and *Sparganium erectum* L. grow around the lakes and the riverbanks (Konstandinidis and Tsiourlis, 2003). Two important riparian forests surround the southeastern shores of Volvi Lake and play an important role in aquatic and terrestrial biodiversity even though intense human activities are severely degrading the habitats. Regarding the Lake Volvi basin, Apollonia and Rendina riparian forests extend from the estuary of the Melissourgos stream to the southern shores and on the east side of Lake Volvi in the valley of Rihios river. Among the riparian tree species, *Alnus glutinosa* L., *Platanus orientalis* L., *Populus alba* L., *Salix alba* L., *Salix* × *fragilis* L., *Populus nigra* subsp. *nigra* L., *Ulmus minor* L., *Fraxinus ornus* L., *Pyrus spinosa* Forssk., *Juglans regia* L. and *Ficus carica* L. are present. Shrub species include *Rubus canescens* DC., *Ruscus aculeatus* L., *Phytolacca americana* L., *Vitex agnus-castus* L., and numerous climbing species such as *Clematis vitalba* L., *Hedera helix* L., *Rubus* L. spp. and *Tamus communis* L. (Efthimiou et al., 2014). Farming and agricultural activities intensely disturb the ecosystem. Deciduous oak forests, with *Quercus pubescens* Willd., *Quercus frainetto* Ten., *Fraxinus ornus* L., *Carpinus orientalis* Mill., *Ostrya carpinifolia* Scop., *Crataegus monogyna* Jacq. and *Rosa canina* L. along with *Fagus moesiaca* (K.Malý) Czeczott, have been largely cleared for agricultural purposes (Konstandinidis and Tsiourlis, 2003), but still cover hills and lowlands. Crop fields of cereals, mostly wheat and maize, forage, vegetables and tobacco extend from the limit of the wetland covering all the lowland areas (Koutrakis and Blionis, 1995). Mediterranean shrubland is discontinuous and gives way to cultivated fields and settlements. The vegetation on the hills both north and south of the lake is characterized by extensive cover of evergreen oaks *Quercus coccifera* L. and *Quercus ilex* L. accompanied by characteristic Mediterranean evergreen species such as *Pistacia lentiscus* L., *Phillyrea media* L., *Olea europea* L. var. *sylvestris* (Mill.) Hegi, *Erica arborea* L., *Erica manipuliflora* Salisb., *Arbutus unedo* L. and *Rhamnus alaternus* L., and phryganic species such as *Cistus* L. spp., *Genista acanthoclada* DC. and *Osyris alba* L.

Castanea sativa L. forests in association with *Fagus* × *taurica*, *Quercus frainetto*, *Fraxinus ornus* and *Quercus pubescens* occur on the east side of the lake area and can even be found at sea level near Strymonikos gulf. Stands of *Pinus maritima* Mill. with *Pinus halepensis* Mill. subsp. *halepensis*, *Pinus pinea* L. and *Pinus halepensis* Mill. subsp. *brutia* (Ten.) Holmboe can be found due to reforestation in small areas of the Rentina Valley that is located east of the lake (Konstandinidis and Tsiourlis, 2003).

Historical setting

During the last 2000 years the Lake Volvi region was controlled by a succession of large imperial formations: Roman, Byzantine and Ottoman. In a way, its history was an alteration of periods of (usually stable) integration into large Eastern Mediterranean empires and longer periods of disruption when the whole of Macedonia was becoming a war zone between regional powers competing for control of the Balkans.

The Romans conquered entire Macedonia in 168 BCE and transformed it from a hitherto independent kingdom into a new province of their empire. The Lake Volvi region continued to function within this framework for almost 600 years, until the 4th centrury (c.) CE with the period of the 1st–2nd c. CE being the most peaceful and politically stable throughout the long Roman rule (Dunn 2004). In the late 4th/early 5th c. CE the

Figure 1. Lake Volvi (Central Macedonia, Greece) and its geographical context. Top: location of Lake Volvi and other pollen sites mentioned in the text; bottom: detail of the Mygdonia Basin (in red, according with Giusti et al., 2019) with the coring site in Lake Volvi indicated by the yellow star. Basemap: Google © Landsat/Copernicus SIO, NOAA, U.S. Navy, NGA, GEBCO. [Color figure can be viewed at wileyonlinelibrary.com]

northern Balkans became a war zone separating the (Eastern) Roman state and the invading Germanic and steppic political groups and nomadic empires, although Macedonia still remained for most part under Roman control until the early 7th c. CE. As a result, despite periods peace, Macedonia was periodically threatened by endemic raiding, which also applies to the Lake Volvi region due to its proximity to Thessaloniki and the lower Strymon valley, two major foci of Roman (Byzantine) military and political control. Moreover, new ethnic groups (Slavs) migrated into the region and substantial cultural change occurred. The sources – both written and archaeological – for this period are limited and hence the details of this process are not well understood (Korres 2007; Curta, 2011).

After several centuries of insecurity, in the early 11th c. CE, the political and military situation of the Central Balkans stabilized, as the whole of the Balkans was conquered by the Byzantine Empire (the direct successor state to the Eastern branch of the Roman Empire). For the next two centuries the situation was more peaceful until, around 1200 CE, the Byzantine Empire partially collapsed, losing its capital Constantinople to Western European invaders ('Latins') and allowing for the emergence of a new Bulgarian state in its Balkan provinces. For the following two centuries, political control of Macedonia was disputed between several regional powers, whereas inter-regional trade integration was increasing thanks to the activities of the Italian merchant republics such as Venice and Genoa (Curta, 2011). In the late 14th c. CE, the region was conquered by the Ottomans (a Turkic dynasty from northwestern Anatolia that gradually conquered the entire Eastern Mediterranean). This started a new period of peace that lasted for several hundred years, with some substantial social unrest occurring periodically in the 17th–18th c. CE (Kotzageorgis, 2007; Kolovos and Kotzageorgis, 2015). While in the late 19th c. CE Macedonia became involved in wars between the Ottoman Empire and the new Balkan states, it was only in 1912 CE that it was annexed by the modern Kingdom of Greece. The last major warfare in the region took place soon afterwards, during the First World War, when it became a major frontline.

Materials and methods

Geochemistry, chronology and palynology of the sediment core

A 707-cm-long continuous sediment succession (core V8-11) was recovered from the western subbasin of the lake (40°40′57.9″N, 23°25′55.2″E; Fig. 1). The succession is constituted by cores extracted by gravity and piston corers (UWITEC, Austria) in June 2019 using a floating platform. Sedimentological and geochemical analyses including X-ray fluorescence (XRF) analysis, total inorganic carbon (TIC), total carbon (TC), total nitrogen (TN) and total sulphur (TS) measurements were performed at the University of Cologne (Germany). XRF analysis was performed on the half cores with a resolution of 2.5 mm, with 6-s exposure time, 30 mA and 30 kV for each measurement, using an ITRAX µXRF scanner (COX Analytics, Sweden) equipped with a chromium anode. Data processing was performed using QSpec 6.5 software (Cox Analytical Systems). Samples for TC, TN and TS were freeze-dried and homogenized, and sub-samples were then analysed with a Vario Micro Cube combustion CNS Analyzer (Elementar, Co., Germany). Samples were disaggregated with an ultrasonic processor to measure TC and TIC with the DIMATOC 2000 (Dimatec, Co., Germany) and total organic carbon (TOC) was calculated by subtracting TIC from TC.

The upper 150 cm of the sediment succession was sampled for analysis of natural (^{210}Pb) and artificial (^{137}Cs/^{241}Am) radionuclides. The analysis was carried out by gamma spectrometry with a Canberra Ge-well detector at Leibniz Institute for Baltic Sea Research (Germany) following Moros et al. (2017).

Accelerator mass spectrometry (AMS) radiocarbon dating was carried out on four terrestrial plant macro-remains taken along the cores and one bulk sediment sample from the bottom of the sequence. The samples were dated at the CIRCE laboratory at the University of Campania 'Luigi Vanvitelli' (Italy). Calibration of the conventional ^{14}C ages to calendar years was made on based on the IntCal20 calibration curve (Reimer et al., 2020) and refer to an uncertainty level of 2σ. The age depth model of core V8-11 was built combining the radionuclide ages for the last ~ 100–150 years, three AMS radiocarbon ages that are considered to be reliable and using Clam (Blaauw, 2010) in the R console (v.1.3.1093).

Pollen analyses were carried out at Sapienza University of Rome (Italy) on 66 samples. A small amount of dry sediment (~0.50 g) was taken for each sample and chemically processed with HCl (37%), HF (40%) and NaOH (10%) to extract palynomorphs from the sediments (Fægri and Iversen, 1989, modified). A known amount of exotic *Lycopodium* spore tablets was added to estimate pollen, non-pollen palynomorphs (NPPs) and charcoal concentrations (Stockmarr, 1971). Pollen grains were counted and identified under a light microscope at 400× and 630× magnification with the help of atlases (Reille, 1992, 1995) and reference pollen collection. Percentages were calculated on different pollen sums. The pollen sum includes all terrestrial pollen types, excluding aquatic plants, ferns and NPPs. Diagrams of pollen percentages and concentrations were plotted using the TILIA program (Grimm, 2011). Constrained cluster analysis (CONISS) was applied together with interpretation of the data to determine pollen zones on terrestrial pollen taxa.

Cereals were identified following Andersen (1979), applying the correction factor for glycerol jelly (Fægri and Iversen, 1989). Among the family Asteraceae, Asteroideae and Cichorioideae subfamilies have been distinguished, and Cichorieae is the only European indigenous subfamily (Florenzano et al., 2015). *Ostrya*/*Carpinus orientalis* comprise both *C. orientalis* and *Ostrya carpinifolia* (Blackmore et al., 2003). Pollen grains of the genus *Quercus* were divided into three groups according to their morphology, following Smit (1973). The *Sparganium* group includes all the Typhaceae except the pollen of *Typha latifolia*. Algae of the genus *Pediastrum* were identified following Komárek and Jankovská (2001). The cultivated trees *Castanea*, *Juglans* and *Olea* (OJC) were grouped following Mercuri et al. (2013) and a Local Pollen Pastoral Indicators (LPPI) curve was adapted from Mazier et al. (2006) including Asteroideae, Cichorieae, *Galium*, Ranunculaceae and *Potentilla*. Microcharcoals were classified into three size groups (10–50, 50–125 and >125 µm) measuring the length of the shorter axis. The size of the charred particles indicates the geographical distance of fires (Whitlock and Larsen, 2002; Sadori and Giardini, 2007).

Byzantine and Ottoman documentary sources

Geospatial historical data were extracted from the available Byzantine and Ottoman documents preserved in archives in Greece and Turkey. After reading the documents and recording the relevant qualitative and quantitative information they contain in spreadsheets, exact coordinates of the recorded villages and locations were established on the basis of existing studies of the historical geography of the Volvi region.

The Volvi region was surveyed for taxation reasons by Ottoman authorities from the mid-15th c. CE onwards, while for the preceding centuries (13th–14th c. CE) some of the agricultural activities were recorded in the various documents preserved in the archives of Mount Athos monasteries in Halkidiki (Smyrlis, 2005, 2006). The monasteries preserve documents related to their properties in villages and on rural lands, and since there were several other landowners holding properties in the area of Volvi (e.g. emperors, aristocrats, bishops), the monastic archives do not allow for a comprehensive reconstruction of land use. Rather, they provide information on the overall trends and specific foci of agricultural activities, owned by the monasteries.

The Byzantine monastic documents from the Athonite archives were accessed through a modern critical edition of the documents (*Archives de l'Athos*, from Lefort 1982, Lefort et al., 1986). In addition, we searched available archaeological reference studies for the Volvi region in the Byzantine period (Lefort, 1982; Lefort et al., 1986; Kolovos, 2000; Karagianni, 2010; Belke et al., 2022; Soustal et al., 2022) and we identified one further location of agricultural activities, unattested in the monastic documents, but dated with an original Greek inscription *in situ*. The resulting Byzantine data are stored in Supplement S1.

The results of the Ottoman fiscal surveys, which in turn provide much more systematic information, were collected in taxation registers (*tahrir defterleri*) (Table S5). These registers record revenues designated to meet the salaries of the military class or end up in the treasury of the sultan in Istanbul. This primary archival source is invaluable as it offers contemporary quantitative data on a village level including (i) demographic figures, namely adult male or widow-headed households, and bachelors, and (ii) *per capita* taxes and imposts on agricultural production, craft industry and market. Information from the taxation registers was extracted directly from the original Ottoman manuscripts.

In the late 17th and early 18th c. CE, the demographic trends of the area can be reconstructed on the basis of two registers that record Christian fiscal units encumbered with the poll-tax (*cizye defterleri*) and one register that lists households levied with extraordinary taxes (*avarız defteri*).

The different nature of the Ottoman sources necessitated the employment of different coefficients on taxable units to reach an estimate of the actual population. The population for the years 1478, 1527 and 1568 CE was calculated by employing a multiplier of 3.515 (mean of 2.72–4.31) on the total number of adult males – heads of households and bachelors – recorded in the *tahrir defter*s (Erder, 1975, 297, table 4); the Christian *cizye*-households of 1697 CE were multiplied by 4.62, that is 3.5 individuals per household, on average, plus 20% of the assumed unregistered households, and 10% of the additional Muslim ones, which are not recorded in this type of register (Darling, 1996, 101; Kolovos and Kotzageorgis, 2015, 141–42); finally, the *avarız*-households of 1722 CE were multiplied by 10.5, that is 3 actual households per *avarız*-household, plus 3.5 individuals per household, on average (Darling, 1996, 101). Cereal production was calculated on the basis of tithe, which worked at one-eighth of the total harvest. Table 1 shows the metric equivalence units used in this study, while for the calculation of the tax's worth in grams of silver (allowing for comparison of original values expressed in contemporary coinage, which underwent inflation) they are for one Ottoman *akçe*: 0.85 in 1478 CE, 0.66 in 1527 CE and 0.61 in 1568 CE (Pamuk, 2004, 455). The resulting Ottoman data are given in Supplement S2.

Table 1. Table of equivalence to translate cereal production units reported in the Ottoman registers. The metric equivalence used has been selected following Kallek (2022, 568) and Taşkın (2005, 90–93).

Ottoman unit of measurement	Metric equivalent (kg)
keyl (wheat)	25.659
keyl (other cereals)	23.093
müdd (wheat)	513.12
müdd (other cereals)	445.0

Results

Lake sediments

Chronology and sediment analysis

The age–depth model is based on five tie points including the date of core recovery at the top of the sediment succession, the radionuclide date and three radiocarbon dates from terrestrial plant remains (Fig. 2, Table 2).

Artificial radionuclides (^{137}Cs) are first detected in the sample taken at 91.5 cm. Until the Chernobyl disaster the only widespread source of ^{137}Cs and ^{241}Am was fallout from atmospheric nuclear weapons testing (e.g. Appleby, 2008). The appearance of ^{137}Cs and ^{241}Am in sediments identifies the depth representing 1954 CE, the date in which the radionuclides were widely distributed for the first time due to weapons testing (e.g. Pennington et al., 1973). Here, the depth representing 1954 CE is found between 95.5 and 91.5 cm core depth (Fig. S1). The ^{210}Pb$_{unsupp.}$ and ^{137}Cs profiles indicate a decrease in sedimentation rate with increasing TOC content in the upper part of the core.

Of the five radiocarbon dates, three were included in the age–depth model (Table 2). Considering the reliability of these dates provided on terrestrial plants, the date on bulk organic sediment DSH1011_SO (696.5 cm, 3350–2106 cal a BP) has been excluded. In fact, the hard-water effect does not impact

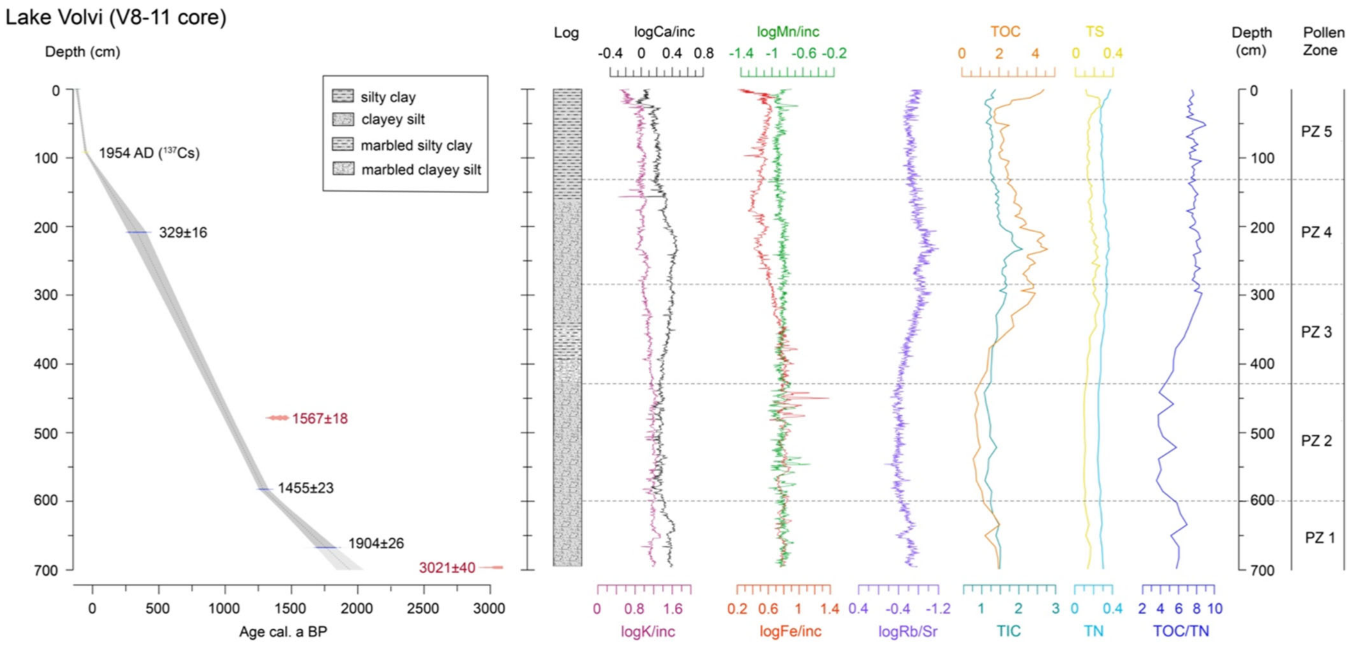

Figure 2. Age–depth model, lithological description and geochemical data of core V8-11 from Lake Volvi (Central Macedonia, Greece). On the left, the age–depth model provided through Clam (Blaauw, 2010; calibrated with IntCal20); ages in red have been discarded. On the right, the sediment succession description and geochemical data plotted against depth. [Color figure can be viewed at wileyonlinelibrary.com]

the terrestrial plants but could strongly impact the organic carbon as well as shells. Sample DSH9649_WO (478.5 cm, 1524–1408 cal a BP) provides an age reversal, and it has been excluded because it probably has been re-deposited. From 667.5 cm to the bottom of the sediment succession, the age–depth model is based on the extrapolation provided by the software. The dates mentioned in the text refer to mean values of the standard deviation that is used to quantify the amount of uncertainty in the provided age. It is the 2σ interval equivalent to the 95% confidence interval, as shown in Fig. 2. Only in specific parts of the discussion (paragraph 5), when the chronological framework is essential for the comparison with historical events, are the dates provided with the 1σ interval that is a 68% confidence level that the true age falls within the given range.

Lithological, sedimentological and geochemical characteristics of the core are summarized from the bottom upwards in Table 3 and in Fig. 2. The limits of the lithological properties (e.g. grain size) are gradual and only marginally support the zonation of the sediment succession. The succession is therefore divided into five zones (PZ: pollen zone) mainly following the changes in pollen assemblage as better described in the next subsection.

All XRF data are plotted as log ratios (Weltje and Tjallingii, 2008). To compensate for organic matter and water contents in the sediments, K, Fe, Mn and Ca peak area counts were normalized by incoherent (inc) scatter (e.g. Marshall et al., 2011; Wagner et al., 2018). The Rb/Sr ratio has been plotted on an inverted axis to better illustrate the correlation with TIC and TOC.

Pollen, NPPs and charcoals

The state of pollen preservation is good, with indeterminate pollen grains that never exceed 6%. A total of 54 taxa have been identified among the spermatophytes with a mean of 44 taxa per sample; in total 80 taxa including aquatic plants, spores and NPPs have been observed throughout the sediment succession. Total pollen concentration varies between 5682 and 225 970 pollen grains per gram of sediment. The mean temporal resolution is 49 years throughout the sequence.

The results of pollen analysis are discussed as percentage and concentration diagrams, including microcharcoals, NPPs, and non-pollen microfossils (e.g. bacteria, algal, fungal, animal remains). Constrained cluster analysis of the terrestrial

Table 2. Results of dating of core V8-11 from Lake Volvi (Central Macedonia, Greece). ^{14}C AMS dates on plant remains and bulk organic material, in addition to the age derived from ^{137}Cs analysis at the top of the sediment succession. Calibration is based on the IntCal20 curve (Reimer et al., 2020).

ID_lab number	Sequence depth (cm)	Type	Radiocarbon age	Age, cal a BCE/CE (2σ)	Age, cal a BP
	91.5–95.5	^{137}Cs		1954 CE	
DSH10342_WO	208.5	Wood	329 ± 16	1494–1602 CE	456–348 BP
DSH9649_WO*	478.5	Wood	1567 ± 18	426–542 CE	1524–1408 BP
DSH9653_WO	582.5	Wood	1455 ± 23	567–649 CE	1383–1301 BP
DSH10651_WO	667.5	Seed	1904 ± 26	64–215 CE	1886–1735 BP
DSH1011_SO*	696.5	Bulk	3021 ± 40	1400–1156 BCE	3350–2106 BP

*Dates excluded from the age–depth model.

Table 3. Lithological, sedimentological and geochemical characteristics of core V8-11 from Lake Volvi (Central Macedonia, Greece). The core is described according to the zones. Description starts from the bottom to the top of the core following chronological order. Core depth and the corresponding time framework are reported.

Zone	Description
PZ 1 696.5–600.5 cm (ca. 1970–1430 cal a BP)	Greenish grey clayey silt with distinct bright lenses around 650 cm. TIC, TOC and TS show a decreasing trend towards the top of this unit. This trend is also observed in the Ca/inc and Rb/Sr ratios, which show a minimum around 650 cm (ca. 1700 cal a BP) followed by a maximum around 633 cm (ca. 1600 cal a BP). The TOC/TN ratio shows the same minimum and maximum, but not a clear decreasing trend towards the top of the unit. K/inc shows an opposite trend. The minimum in TIC, TOC, TS and Rb/Sr corresponds to a maximum in K/inc. Fe/inc and Mn/inc ratios remain constant with several minor minima and maxima (more pronounced in the Mn/inc ratio).
PZ 2 592.5–424.5 cm (ca. 1390–930 cal a BP)	Greenish grey to dark greenish grey mostly massive to marbled silty clay to clayey silt, with several bright layers and lenses of calcite. TIC, TOC, TS as well as TOC/TN have the lowest contents throughout the record. The Ca/inc ratio and the Rb/Sr ratio show a similar pattern. Fe/inc and Mn/inc show major high-frequency oscillations, especially where bright lenses and layers occur in the sediment. K/inc shows similar oscillations, but maxima and minima show an anticorrelation to the Fe/inc and Mn/inc ratios.
PZ 3 408.5–280.5 cm (ca. 890–570 cal a BP)	Very dark greenish grey to greenish black massive to marbled clayey silt and silty clay. Biogeochemical data as well as Ca/inc show a gradual but steady increase, while K/inc and Rb/Sr show a decrease and Fe/inc is decreasing towards the top of the unit. Mn/inc shows a slight increase in this PZ. Mn/inc and Fe/inc no longer show a correlation.
PZ 4 268.5–128.5 cm (ca. 540–120 cal a BP)	Clayey silt dominates in the lower part, while it fines upwards to silty clay. Very dark greenish grey to greenish black sediments. Broad peak of TIC, with values exceeding 2.5% in the lower part of PZ 4, which is also visible but less pronounced in the TOC and TS contents as well as the Ca/inc and Rb/Sr ratios. All proxies decline towards the top of this zone. TOC/TN ratio remains around a value of about 8. K/inc shows an overall decrease, with some fluctuations. Fe/inc ratios show an overall increase, while Mn/inc ratios decrease towards the top of this unit.
PZ 5 116.5–0 cm (ca. 80 cal a BP– 2019 CE)	Fine-grained unit composed mostly of silty clay. Greenish black sediments in the lower part of the unit and dark greenish grey deposits near the top of the core. All biogeochemical data continue the decreasing trend in the lower part of the unit and show a pronounced peak near the top of the core. Fe/inc, Mn/inc and K/inc show a distinct minimum near the top of this zone.

pollen taxa has been provided using CONISS (Grimm, 2011) and it supports the construction of the pollen zones described in Table 4.

Documentary sources

Agricultural activities and settlements detailed in the Byzantine monastic documents

In the Byzantine written and archaeological evidence, we identified 10 locations of precisely dated settlements or agricultural activity (Fig. 3). At five of these locations, specific agricultural activities were recorded (four of them related to the cultivation of both cereals and fruit trees). Regarding chronology, the vast majority of the records are dated to the period 1250–1350 CE, while only a few locations have records for the following century (three locations in 1350–1400 CE, four locations in 1401–1450 CE) and for only one of them is information on agricultural activities available. This suggests a major decline in human activity following 1350 CE, possibly related to the plague pandemic that started with the Black Death in 1347–1348 CE (Kostis, 2020, 307–308, 317–318) and the catastrophic warfare of the mid-14th c. CE (Fine, 1996, 321–327; Treadgold, 1997, 771–777; Nicol, 1972, 217–261). Most of the monastic landholdings were concentrated to the south and east of the lake, perhaps reflecting the main settlement foci in the Volvi region in

Table 4. Pollen description of core V8-11 from Lake Volvi (Central Macedonia, Greece). Summary of pollen results according to the zones. Description starts from the bottom to the top of the core following chronological order. Core depth and the corresponding time framework are reported.

Zone	Description
PZ 1 696.5–600.5 cm (ca. 1970–1430 cal a BP)	High arboreal vegetation (max. 73%). Forests are characterized by *Quercus ilex* type (22–33%), *Quercus robur* type (6-22%), *Ostrya/Carpinus orientalis* (1–8%) and *Pinus* (1–8%). Herbs are dominated by Poaceae (11–23%), Fabaceae (1–6%) and Scrophulariaceae (0–3%). Concentration of charcoal fragments is low. Notable presence of anthropogenic taxa. Pollen concentration shows a medium value of 43 545 pollen grains g^{-1}.
PZ 2 592.5–424.5 cm (ca. 1390–930 cal a BP)	Gradual decrease of arboreal plants affecting mainly *Quercus robur* type and the other mesophilous trees and *Pinus*, which reaches 0% at 512.5 cm (1158 cal a BP). *Quercus ilex* type prevails among the arboreal taxa (24–41%). Ericaceae (1–8%) and *Juniperus* (0–4%) show an expansion. Poaceae (12–34%), Fabaceae (1–13%) and Scrophulariaceae (0–4%), along with Amaranthaceae (0–4%), prevail among the herbs. Increase of anthropogenic taxa and coprophilous fungi with some fluctuations and decrease at the end of the zone. Charcoal fragments are scarce. Pollen concentration ranges between 5711 and 44 990 pollen grains g^{-1}.
PZ 3 408.5–280.5 cm (ca. 890–570 cal a BP)	Arboreal vegetation reaches its maximum (70–79%) due to an expansion of *Quercus ilex* type (26–46%) together with *Ostrya/Carpinus orientalis* (5–10%). *Pinus* increases (3–10%) together with *Fagus* (1–5%). Herbaceous vegetation continues to be dominated by Poaceae that reaches the lowest values (9–15%). Fabaceae (0–1%) and Scrophulariaceae (max. 3%) drop abruptly. Amaranthaceae (0–3%) and *Artemisia* (0–3%) show an increasing trend along the zone. Anthropogenic taxa show a decrease. High total pollen concentration (135 297 pollen grains g^{-1} on average).
PZ 4 268.5–128.5 cm (ca. 540–120 cal a BP)	Reduction of tree values from 184.5 cm (306 cal a BP; 48–79%). Mesophilous trees: *Quercus robur* type (4–16%), *Carpinus betulus* (max. 3%), *Corylus* (max. 1%) and *Fraxinus excelsior* (max. 1%) show increasing values while *Quercus ilex* type (15–28%) reduces. Poaceae (13–25%) and Amaranthaceae (2–6%) are the main representatives of herbs with the increase of *Artemisia* (1–8%) and Cyperaceae (1–3%). Continuous presence of anthropogenic and synanthropic taxa. Charcoal concentration is quite high. Pollen concentration fluctuates between 34 442 and 194 288 pollen grains g^{-1}.
PZ 5 116.5–0.5 cm (ca. 80 cal a BP– 2019 CE)	*Quercus robur* type (4–19%) and *Quercus ilex* type (5–16%) dominate among trees. *Pinus* reaches the highest percentage value of the sequence (18%). *Olea* (max. 4%) records a marked increase. Poaceae (11–24%) and Amaranthaceae (2–9%) remain the most abundant taxa among the herbs accompanied by synanthropic taxa: Cichorieae (max. 3%), *Plantago lanceolata* (max. 6%) and *Rumex* (max. 2%). Pollen concentration oscillates between 38 640 and 161 067 pollen grains g^{-1}.

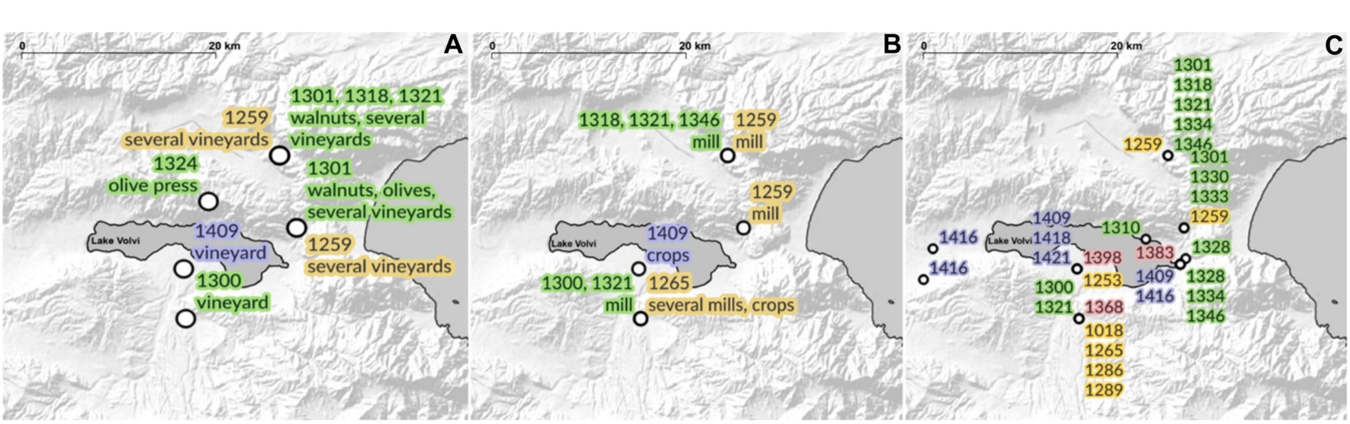

Figure 3. Agricultural activities and settlements attested to in the Byzantine monastic documents and in the Byzantine archaeological records in the Volvi area. (A) Fruit tree cultivation, (B) agricultural activities related to cereals and (C) settlements (no labels). Colours distinguish between 50-year periods: 1250–1300 CE or before (yellow), 1301–1350 CE (green), 1351–1400 CE (red) and 1401–1450 CE (violet). Dates refer to the exact years of the activity/settlement mentioned in the documents/inscriptions. The underlying data are available in Supplement S1. Basemap: © 2014 Esri. [Color figure can be viewed at wileyonlinelibrary.com]

the period 1250–1350 CE. During this period, mixed agriculture including cereal farming and walnut, olive and as vine cultivation is well attested to for the Volvi region.

Demography and agriculture in the Ottoman registers

The Ottoman documents provide information on population numbers in the 15th–18th c. CE (Fig. 4) and agrarian production in the 15th–16th c. CE (Fig. 5). In total, 61 exact locations with quantitative data were obtained from all the registers and several historical trends could be established. We observed ubiquitous population growth in the Volvi region in the 16th c. CE, with the most significant increase taking place between the registers of 1478 and 1527 CE and further increase between 1527 and 1568 CE. A sharp demographic decrease in the Volvi region (−57%) occurred between 1568 and 1697 CE. Accordingly, 20 settlements were identified as abandoned in 1697 CE. Four of these settlements possibly regrouped around Pazar-ı Cedid/Pazargâh (today's Apollonia), a town founded by the Grand Vizier Sokollu Mehmed Pasha in the 1570 s that became the local capital to the south of the lake (Kolovos and Kotzageorgis, 2015, 143). Its name translates to 'New Market' or 'New Marketplace', indicative of its function as the local market town.

In addition, accounts of contemporary travellers describe desolation and banditry, especially in the areas north and the east of the lake in the second half of the 17th and early 18th c. CE, in accordance with the population shift to the south (Fig. 4). For instance, the famous Ottoman traveller Evliya Çelebi, who visited the area in 1667 CE, describes the lands to the north of Lake Koroneia as deserted; he adds that the villagers, suffering under bandit groups and the oppression of the Ottoman authorities, abandoned their villages and became rebellious highlanders (Kahraman et al., 2003, 43). At the turn of the 18th century, in 1707 CE, the French missionary Père Braconnier describes the pass of Rentina, which connects Volvi with Strymonic Gulf to the east, as 'Val des Voleurs' (Valley of Thieves) (Souciet, 1755, 344; Roussos-Milidonis, 1989, 48).

Trends of cereal production generally agree with the demographic dynamics, showing a strong increase between 1478 and 1527 CE, and sustained growth into 1568 CE (Fig. 5). Cultivation was mostly concentrated on the lowlands around and to the west of Lake Volvi, as well as in the flatlands of the mountain basin located north of the lake. In terms of the composition of cereal production, the importance of wheat increased significantly between 1478 and 1527 CE. During this period, the interlake plain between lakes Volvi and Koroneia (to the east of Lake Volvi) also experienced a major increase in animal husbandry. It is also notable that this area has the highest proportion of oats, which at that time were not consumed by people, but rather used as fodder for domestic animals, in particular horses.

According to the Ottoman registers, the cultivation of olives and the production of olive oil was not widespread (Fig. S2, based solely on the 1568 CE register). The only significant site of olive oil production at that time seems to be located in the immediate vicinity of the village Beşyakoz *alias* Beşik, today's Megali Volvi (the only settlement on the northwestern shore of the lake). This may suggest the continuity of olive cultivation in this area since the early 14th c. CE (when the olive press is attested to in the same area with the inscription dated to 1324/25 CE; Karagianni, 2010, 117, # 39). A tax of 20 akçes (17 g of silver) was also levied on olives in 1478 CE (MM17748, p. 22) in the same village and thus again attests to the continuation of olive cultivation. In 1568 CE, the tax of 25 000 akçes (15 250 g of silver; note akçe devaluation since 1478 CE) derives from an olive grove which borders the village and from another one that belonged to the Vlatadon Monastery in Thessaloniki (TKGM186,

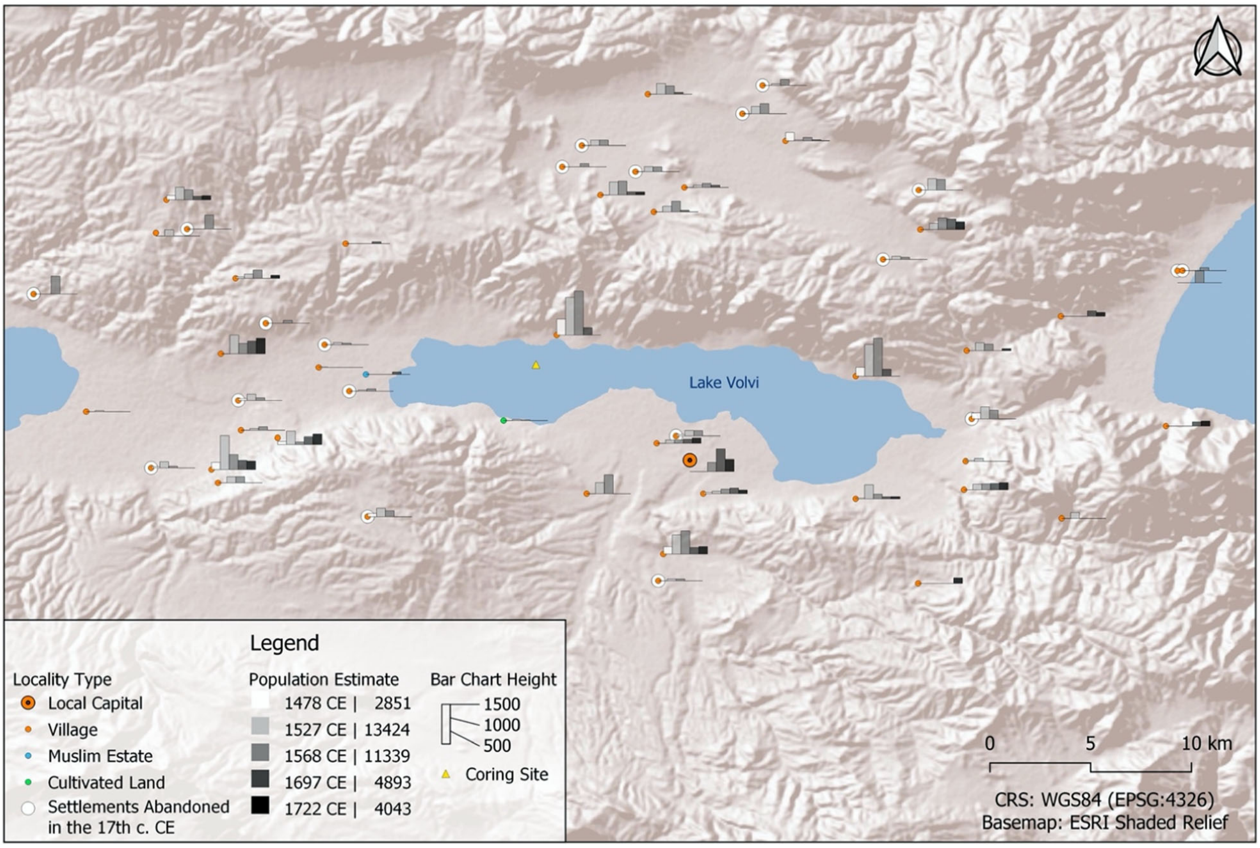

Figure 4. Population dynamics in the Lake Volvi region in the 15th–18th c. CE. Demographic estimation for each different type of locality. The number of inhabitants is displayed according to the age of the cadastres listed in Table S5. The underlying data are available in Supplement S2. Basemap: © 2014 Esri. [Color figure can be viewed at wileyonlinelibrary.com]

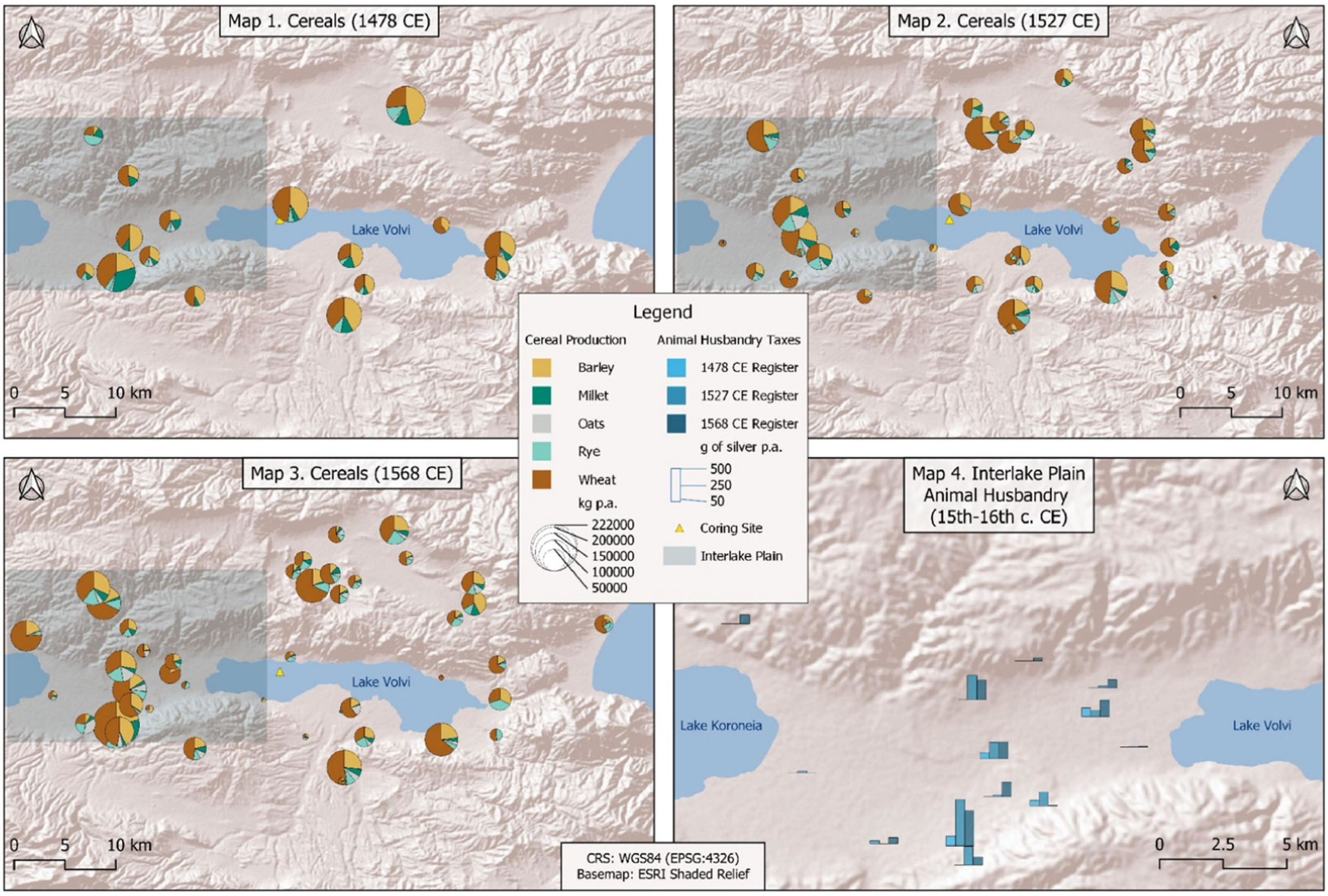

Figure 5. Cereal production and animal husbandry in the Lake Volvi region in the 15th-16th c. CE. Maps A, B and C show the estimation of cereal kilograms produced per year (p.a.) at different times. Map D presents the quantification of the taxes paid for animal husbandry (grams of silver) according to the localities and different registers. The map shows animal husbandry recorded in the plain located between Lake Volvi and Lake Koroneia. Based on the Ottoman registers listed in Table S5. The underlying data are available in Supplement S2. Basemap: © 2014 Esri. [Color figure can be viewed at wileyonlinelibrary.com]

f. 51b). Judging from other estates of the monastery in the area, we are inclined to suggest that the monastic grove may well have existed for at least a century, but was not surveyed and recorded in earlier registers, as it had been granted tax exemption by the Sultans (Kolovos, 2000, II, 162). In 1575 CE, this monastic olive grove was sold to a Turk named Hacı Mehmed for 20 000 akçes (Vasdravellis, 1955, III, 17–18; Stogioglou, 1971, 199). However, in the 14th–16th c. CE, this was probably still relatively small-scale cultivation confined to a few olive groves. Olive cultivation only became dominant in modern Halkidiki after the end of the 17th c. CE, and particularly during the last two centuries (Kolovos and Kotzageorgis, 2015).

Regarding vine cultivation (Fig. S3), there is a major growth in its extent between 1478 and 1527 CE, with further substantial increases into 1568 CE. In contrast to the olive cultivation, vineyard taxes are attested to throughout the Volvi region and their major spatial expansion occurred in 1478–1527 CE. Finally, noticeable cultivation of walnut (Fig. S4) was quite limited and restricted to the northeastern part of the Volvi region, as also seems to have been the case in the 14th c. CE (Fig. 3).

Discussion

Social–ecological dynamics in the first millennium CE

The first millennium CE in the Volvi region is characterized by stark contrast between the high levels of human impact during the period of stable Roman rule (the first four centuries), and the long and dynamic process of decline in human presence that culminated in the almost complete abandonment of the area in the 9th–10th c. CE.

The pollen record of Lake Volvi starts at ca. 20 BCE (1970 cal a BP) with a mosaic of vegetation: the Mediterranean vegetation dominates with *Quercus ilex* type (evergreen oaks) and is accompanied by scarce maquis elements; the mixed deciduous forest is characterized by deciduous oaks; the mountain belt is characterized by *Abies* (fir), *Betula* (birch) and *Fagus* (beech). The riparian vegetation is clearly represented as well, with trees such as *Alnus* (alder), *Platanus* (plane-tree) and *Fraxinus excelsior* (European ash), and possibly *Ulmus* (elm) and *Ostrya*/*Carpinus orientalis* indicate water availability in the soil as well as high values of Poaceae undiff. (wild grass), Cyperaceae, ferns and aquatic plants (Figs. 6 and 7). This remarkable richness in different vegetation types is characteristic of the entire southern Balkans and it is the consequence of the geomorphology and climate of the territory. Around 50 BCE (2000 cal a BP), at Lake Dojran, ca. 80 km to the northwest, the same elements have been recorded with a dominance of mesophilous vegetation (Masi et al., 2018).

No important changes are found in Volvi arboreal vegetation as well as in the sedimentation for the entire PZ 1 (ca. 20 BCE – 520 CE, 1970–1430 cal a BP) and indicate a stable phase. Carbonate minerals, which can partly be quantified by TIC and Ca/inc ratio (the amount of calcite), play an important role in the biogeochemical cycles that involve the movement and transformation of carbon through various components of the Earth's system (Talbot, 1990, Müller et al., 2022) and can be used as archives of past climate changes. The good correlation between TOC and TIC implies that carbonates are mainly of

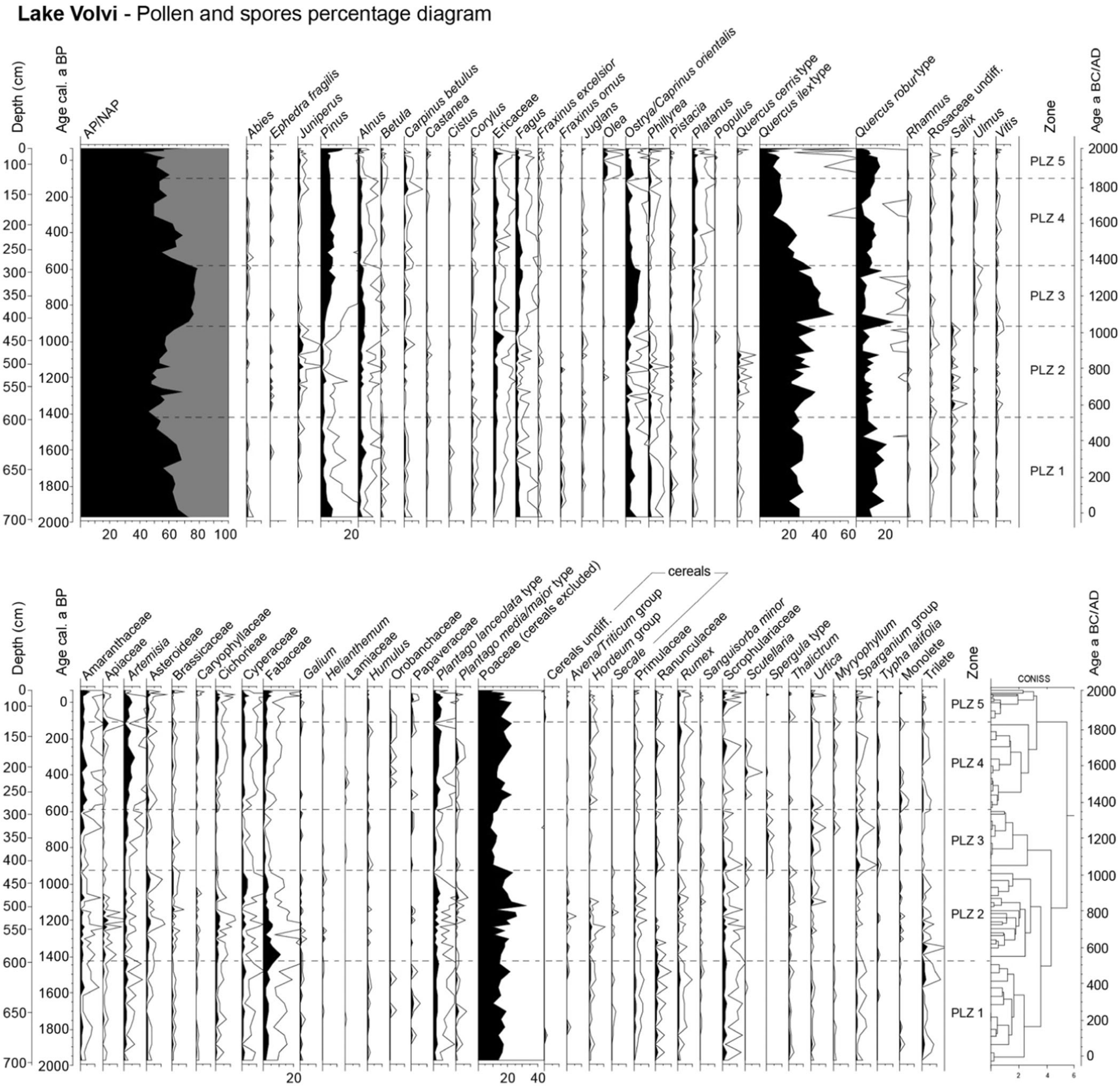

Figure 6. Pollen and spore percentages of core V8-11 from Lake Volvi (Central Macedonia, Greece). Percentage diagrams of selected arboreal, non-arboreal, aquatic and spore taxa and CONISS. Curve magnification 5×.

authigenic origin (Figs. 2 and 8) and thus may represent the productivity in the lake. High productivity may indicate favourable conditions for the growth of organisms within the lake and also the relatively high biomass production in the surrounding area. The relatively stable TIC and K/inc ratio (referring to clastic input) hence may reflect a relatively stable climate, with a slight decrease of lake productivity, which corresponds to a higher proportion of clastic, terrigenous input and a TIC minimum at 650 cm (ca. 250 CE, 1700 cal a BP) (Fig. 8). This event correlates to a maximum in the clastic input (K/inc ratio) indicating a dilution effect with less carbonate content. An increase of fine sediments evidenced by the Rb/Sr ratio (indicating clay content) is probably the result of weathering processes promoted by humid conditions and precipitation or human activities which can also influence the Rb/Sr ratio through erosion of the catchment. Soil erosion is also confirmed by *Glomus* in the pollen assemblage, a mycorrhizal fungus (Fig. 7). Other sites in the Balkans show contrasting climatic data (Zanchetta et al., 2012; Sadori et al., 2016a; Finné et al., 2019) with Lake Prespa (Leng et al., 2010) and Lake Dojran (Francke et al., 2013) recording drier conditions around 2000–1400 cal a BP, whereas a wetter climate characterized Southern Greece (Finné et al., 2014; Boyd, 2015; Seguin et al., 2020; Emmanouilidis et al., 2022). At the same time, in the first–second century CE, once the entire Balkans were integrated under Roman rule under Emperor Augustus, Macedonia experienced a period of prosperity and settlement expansion that must have increased erosion levels in the Volvi catchment (Vanderspoel, 2010).

Pollen data show continuous cereal cultivation since the beginning of the sequence and all along PZ 1 (ending at ca. 510 CE, 1440 cal a BP). Cereal pollen percentages are very low, but significant, as cereals are low pollen producers. The continuous presence of cereals suggests similar land use in Roman times. Highest values of cereal pollen concentration occur around the mid-2nd c. CE (159 CE, the confidence

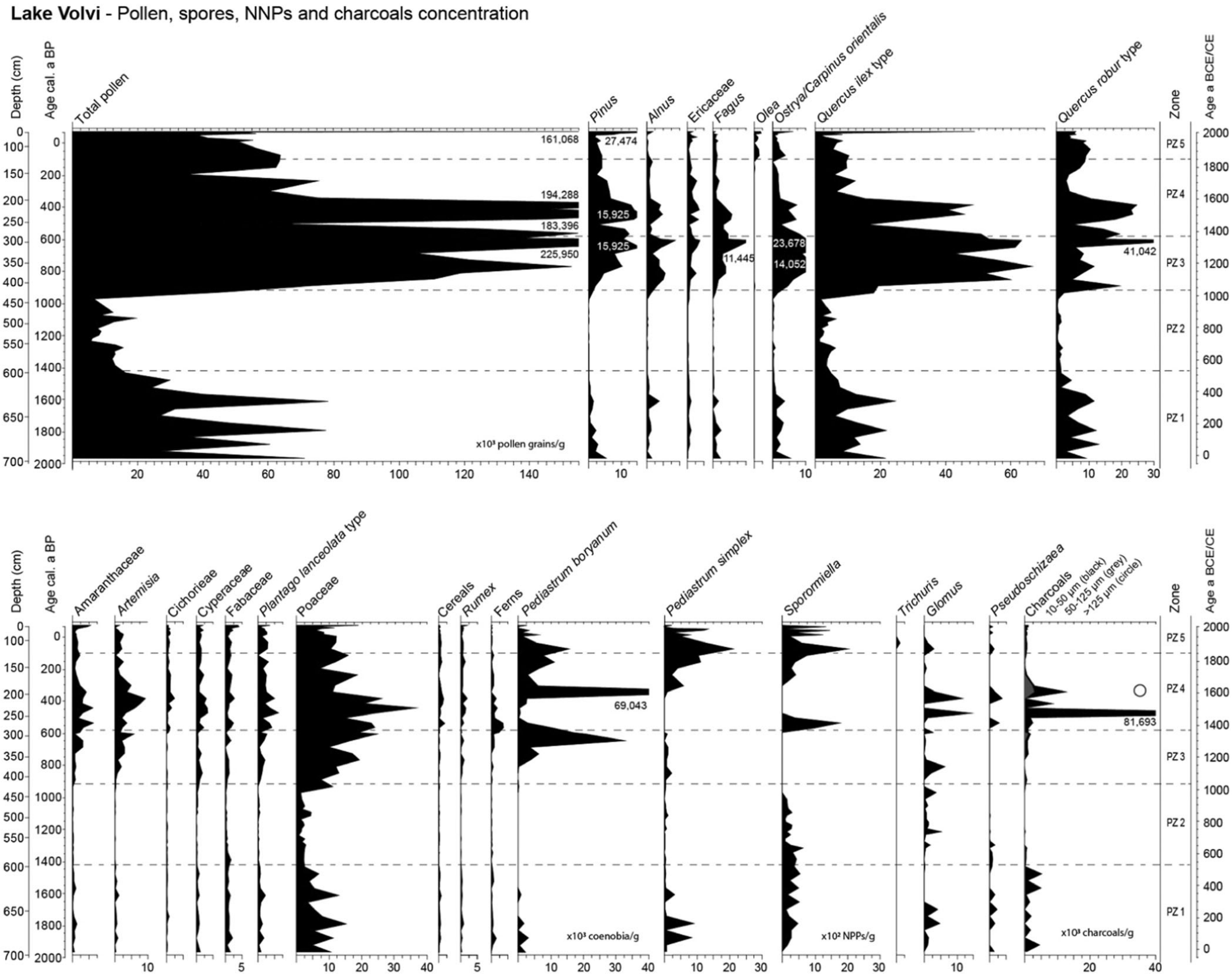

Figure 7. Pollen, NPPs and charcoal concentrations of core V8-11 from Lake Volvi (Central Macedonia, Greece). Pollen, NPP and microcharcoal concentration diagram of selected taxa.

interval 1σ is 112–206 CE, see 'Chronology and sediment analysis' for details) and in the 4th c. CE (337 CE, 1σ: 309–365 CE), both time intervals coinciding with the most prosperous and peaceful political–economic conditions in the Roman Eastern Mediterranean. In addition to cereal cultivation, pollen taxa indicative of disturbed or degraded landscapes, mainly related to pasturelands (e.g. *Plantago lanceolata*, *Urtica*, *Rumex;* Figs. 6 and 8), suggest that the lands around the lake were strongly exploited for pastoral activities (see the local pollen pastoral indicators curve in Fig. 8). Spores of the coprophilous fungus *Sporormiella* further confirm the widespread presence of livestock (Fig. 7).

Arboriculture, which includes *Olea* (olive), *Juglans* (walnut) and *Castanea* (chestnut), was fairly well developed with discontinuous and occasional attestation in the pollen record (Figs. 6 and 8). The strong agricultural exploitation in the Volvi region in Roman times is similar to trends observed throughout Macedonia and Greece as a whole (Kouli et al., 2018). In the nearby site of Tristinika marsh, agriculture is well attested to since the Archaic period (Panajiotidis and Papadopoulou, 2016); at Lailias (Gerasimidis and Athanasiadis, 1995) and Orestias (Kouli and Dermitzakis, 2010), cereal cultivation is attested to during the 1st century CE. Similar patterns are also observed in southern Greece: at Vravron an increase in cereals occurred at 200–400 CE (1750–1550 cal a BP; Triantaphyllou et al., 2010, Kouli, 2012). Anthropogenic influences are highlighted also in many other Macedonian sites such as the Beles Mountains (Panajiotidis and Gerasimidis, 2013), Lake Dojran (Masi et al., 2018) and Paliouras lagoon (Masci et al., 2022). It is interesting to note that the well-developed human occupation does not concern the mountainous areas of northern Greece as attested to at Paiko (Gerasimidis et al., 2008), Voras (Gerasimidis et al., 2009) and Flambouro (Gerasimidis and Panajioditis, 2010) (all sites shown on Fig. 1).

The discussion of viticulture using pollen data is challenging. We decided to not include the *Vitis* (grapevine) pollen curve in the cultivated plants, as wild grapevines constitute part of the natural landscape, still growing on the riverbanks today. Bottema (1974) attributes *Vitis* pollen from the Volvi sequence to the presence of wild grapevine (*Vitis vinifera* var. *sylvestris*) on the basis of ecological associations; however, the discovery of wine amphorae from the Roman Imperial age to Byzantine times from the site of Arethousa, north of Lake Volvi, together with the findings of grape pips, treading floors for wine production and a mosaic representation (Silver, 2017; Hamari, 2020), suggest that the continuous curve of *Vitis* in the Volvi sequence should indicate viticulture on the hills around the area (Fig. 3). It is well known that cultivation and trade of wine were widely spread across southern Greece and Anatolia (Izdebski et al., 2015; Dodd, 2020) and the hills of the Volvi basin might have been a suitable place for grape cultivation.

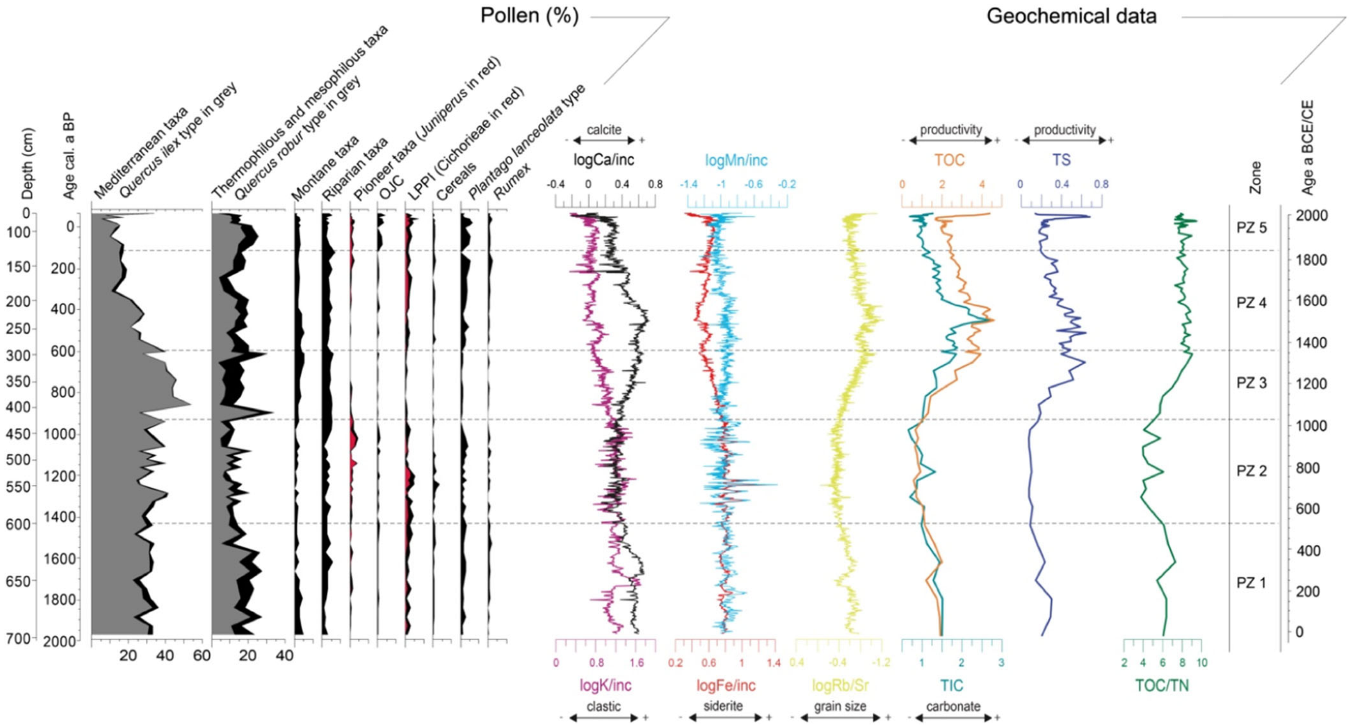

Figure 8. Comparison of different proxies from core V8-11 of Lake Volvi (Central Macedonia, Greece). Pollen percentage diagram of ecological groups and selected taxa. Mediterranean: *Cistus*, *Fraxinus ornus*, *Phillyrea*, *Pistacia*, *Quercus ilex* type, *Rhamnus*. Thermophilous and mesophilous: *Carpinus betulus*, *Corylus*, *Fraxinus excelsior*, *Ostrya/Carpinus orientalis*, *Quercus cerris* type, *Quercus robur* type, *Tilia*, *Ulmus*. Montane: *Abies*, *Betula*, *Fagus*. Riparian: *Alnus*, *Platanus*, *Populus*, *Salix*. Pioneer: *Ephedra*, *Juniperus*, Rosaceae. Cereals: *Avena/Triticum* group, *Hordeum* group, *Secale*, cereals undiff. OJC: *Olea*, *Juglans*, *Castanea*. LPPI: Asteroideae, Cichorieae, *Galium*, Ranunculaceae, *Potentilla*. Pollen data are aligned with geochemical data plotted according to the chronology. [Color figure can be viewed at wileyonlinelibrary.com]

Important changes happen in the 6th c. CE, at the beginning of PZ 2 (ca. 560–1020 CE, 1390–930 cal a BP). During this pollen zone, a slight shift in the arboreal vegetation is recorded. Thermophilous and mesophilous taxa, especially deciduous *Quercus* (oak) and *Ostrya/Carpinus orientalis* (European hop-hornbeam/oriental hornbeam), show a contraction (Fig. 6). Concurrently, the progressive reduction of montane taxa and conifers, in particular *Pinus* (pine), and the gradual expansion of pioneer taxa, evidence a change in the proportion of the taxa (Figs. 6 and 8).

Interestingly, the pollen concentration drops abruptly at the beginning of the zone and recovers sharply at its end. The decline involves all pollen taxa, as well as ferns and algae. This important change is recorded also in the sedimentological data. TOC has the lowest values in the entire sequence, showing a more oligotrophic state and less biomass, confirming the signal given by pollen and algae concentrations. Low TOC/TN values confirm the reduction of the organic content of the lake due to the slight terrestrial plant contribution and an increase in microbial decay processes. In addition, a modification in the lithology of the lake is visible in the higher Rb/Sr ratio values (referring to grain size), which point to a change toward clayey sediments and probably an intensification of soil erosion due to wet climatic conditions (Fig. 8). Erosional processes, suggested by the drop in pollen concentration as well as by changes in geochemistry and sedimentology, are also confirmed by the presence of NPPs *Glomus* and *Pseudoschizaea* in the pollen assemblage (Fig. 7). This erosion process could be linked to selective opening of the landscape that mainly affected the mesophilous and thermophilous plants (first *Ostrya*/*Carpinus orientalis* and *Quercus robur* type). Another possible scenario, however, may be suggested by the high fluctuations of Fe/inc and Mn/inc values that could indicate strong fluctuations in bottom water redox conditions (Fig. 8). Well-oxygenated bottom water conditions may have sporadically occurred as a result of increased wind stress, lower summer temperatures or distinct shifts in bottom water flows. Then, the lower concentration of all pollen taxa, which express the depletion of pollen in the sediment, could be related to the oxidation of pollen grains in the more oxygenated water (in other words, not all the pollen that reaches the bottom of the lake can be preserved in these unexpected conditions because the presence of oxygen reduces the number of pollen grains that were then trapped in the sediment). Low TIC and TOC values reflecting scarce productivity might be also connected to climatic oscillation. Holocene climatic changes are small and can be often blurred by several natural forcing and non-climatic factors. In particular, the LALIA (Late Antique Little Ice Age) is recorded as a cooling event the temporal extent of which is not well defined yet and may vary from region to region (Büntgen et al., 2016; Margaritelli et al., 2020; Peregrine, 2020). Moreover, in the Balkans it coincided with pandemics, human migration and political instability (Sarantis, 2016), which may have blurred this short climatic oscillation. In the Eastern Mediterranean speleothems show contrasting patterns: Uzuntarla cave indicates a cooler period between 500 and 600 CE (Göktürk, 2011) while Kocain cave records a wetter phase at ca. 330–460 CE followed by an arid period in the 5th century (Jacobson et al., 2021). Therefore, cereal and arboriculture contraction as well as the small decrease of evergreen and deciduous in the 6th century may be associated with several events that here seem more closely related to hydrogeological factors that affected the water basin which coupled with numerous raids and possible plagues waves could have masked the LALIA event.

Along PZ 2 low arboreal percentages are associated with a very peculiar pattern of anthropogenic pollen indicators (both cultivated and synanthropic), with related changes in pioneer taxa such as *Juniperus* (juniper) at the end of the zone. It is worth emphasizing that during the whole zone the uncertainty in the age–depth model remains relatively small with 1σ probability of ca. ±20 years, allowing the analysis of the changes in the landscape with semi-centennial precision.

At the transition between PZ 1 and PZ 2, a significant change in the anthropogenic indicators marks the end of Roman prosperity. Over the samples dated to 470 CE (1σ: 450–483 CE), 514 CE (1σ: 494–533 CE) and 559 CE (1σ: 539–577 CE), cereal declines to a null. Also in 559 CE, the indicators of olive, walnut and chestnut cultivation experienced a significant and sustained drop, implying that during the second half of the 6th c. CE olive and walnut cultivation in the Volvi region lost significance compared to during Roman times. Still, the drop in indicators of cultivation, both for fruit trees and for cereals, during the second half of the 6th c. CE shows remarkable similarities to the decline in the cereal pollen observed in the greater Halkidiki region, and the Tristinika marsh high-resolution record (Panajiotidis and Papadopoulou, 2016). This decline coincides with the first 6th c. CE outbreaks of plague recorded in Eastern Roman written sources (so-called Justinianic Plague, or the beginning of the First Plague Pandemic).

There is no written evidence for the presence of plague in Macedonia at that time, nor has any ancient DNA (aDNA) data been obtained from Macedonia so far. However, given that the aDNA evidence has demonstrated that the plague was present in the 6th–7th c. CE in regions where no written evidence for it exists, including Central Europe, its presence in Macedonia is not implausible (cf. Mordechai et al., 2019; Keller et al., 2019). Moreover, *The Chronicle of Marcellinus Comes* reports that the plague had already devastated the broader region of Illyricum (the western Balkans) by 543 CE (Marc. com. 543: Croke, 1995, 50), and it was present in Constantinople in 542 CE (Dewing, 1914, 451–73). Considering Volvi's location on the Via Egnatia, one of the major Balkan communication routes at this time, the area would presumably have been highly affected. Therefore, one of the most significant drops in human activity signs in our record during the first millennium CE is probably related to otherwise undocumented 6th c. CE plague outbreaks.

Another factor in the agrarian downturn from the mid-6th c. CE might have been the intense period of Balkan raiding by Hun and Sclaveni groups from north of the Lower Danube from 539 top 559 CE (Sarantis, 2016, 101–109, 240–47, 278–97, 336–48). These invasions were launched primarily with the aim of plundering the manpower and material resources of the Balkan provinces. Later, the Balkans were struck by an even longer period of endemic raiding by Avar and Sclaveni groups from 579 to 626 CE (Whitby, 1988, 138–84; Pohl, 2018, 163–98 and 280–305). Macedonia was affected on numerous occasions, and Thessaloniki was besieged and its environs ravaged in 586 CE, 604 CE, 620 CE and 622 CE (Lemerle, 1981, 46–73, 85–104). Thus, the mid-6th c. CE collapse probably resulted from a combination of plague and enemy raiding, and perhaps other syndemic diseases, such as malaria (Newfield, 2017) – and it was clearly already underway in the later 5th c. CE.

Importantly, stable land use in the earlier 4th–6th c. CE period is confirmed by archaeological finds. In Apollonia, on the southern shores of the lake, an early Christian basilica (dated possibly to the 4th/5th/6th c. CE) has been excavated, suggesting continued agrarian prosperity (Karagianni, 2010, 115, # 33). In the northeastern part of the lake shore, an early Christian cemetery dating to the late 5th to mid-6th c. CE has been found (dating based on numismatic finds; Karagianni, 2010, 117, # 39). Also during this period, probably 5th–6th c. CE, a late Roman stronghold was constructed at Rentina, immediately to the east of the lake, overseeing communication over the road leading to the Strymon delta and further to Constantinople (Karagianni, 2010, 127–128, # 56; however, the identification of this site with the Justinianic 6th c. fortress named Artemision, described by Procopius in his *On Buildings* IV 3,27–30, is unsupported, given that Procopius' description of Halkidiki is generally not preserved due to the *lacuna* in the manuscript in IV 3,20: Flusin, 2000, 13–15). The use of the fortress of Rentina in the 5th–6th c. CE confirms continued strategic interest in the Volvi region, through which passed the aforementioned Via Egnatia. However, there is no archaeological confirmation of significant Eastern Roman activity in the area after the 6th c. CE, again indicating the scale of collapse.

During the 7th–8th c. CE, the Byzantine authorities withdrew from most Balkan regions, with the exception of a handful of coastal cities, including Thessaloniki (Curta, 2011, 94–134), as a result of prioritization of the desperate fight for the empire's existence against the armies of Sassanid Persia and then early Islam in Anatolia. An economic collapse in most Balkan regions followed this imperial withdrawal with the decline or abandonment of settlements, the major demographic downturn, and the end of monetary exchange and long-distance commerce (Curta, 2021, 65–66). However, despite this political and economic collapse, and potential further outbreaks of plague, cereal cultivation (mostly barley) recovers in the Volvi pollen sequence in the 7th c. CE. Also pastoral land management is attested to from ca. 600 to 780 CE (1350–1170 cal a BP) by the curves of pollen pastoral indicators at local scale (LPPI), of *Rumex* (docks), *Urtica* (nettle) and *Plantago lanceolata* type (mainly represented by ribwort plantain), and the continuous attestation of the coprophilous fungus *Sporormiella* (Figs. 6–8). Scarceness of *Olea* pollen continues from the beginning of the sequence with a short interval of discontinuous presence from ca. 750 to 830 CE (1200–1120 cal a BP) when very low percentage values attest to the present of groves in the proximity of the lake (Fig. 6). Nonetheless, the low percentages of *Olea* reflect the prevalence of cereal cultivation as detected in other Greek sites (Kouli, 2012; Panajiotidis and Papadopoulou, 2016; Weiberg et al., 2019; Emmanouilidis et al., 2022). Altogether, there emerged a new form of a less intrusive, probably transhumant pastoralism (which included cereal cultivation, as attested to for many late mediaeval Turcoman nomads as discussed in the next section). These nomad communities probably operated at both lower and higher altitudes. This represents a major shift from the Roman agricultural mode of the previous centuries. Could it perhaps be associated with the presence of a new group in this area? In addition to Slavs, Bulgars and Avars – known for their nomadic lifestyle – migrated to regions surrounding Thessaloniki from the late 7th c. CE (Pohl, 2018, 331–34). 'Scythians', possibly Bulgars or another 'Turkic' nomadic group, were settled in the Strymon area sometime after 688 CE (*De Them.* 2.3: Haldon, 2021, 183).

The final decline occurred in the 9th c. CE, with the second half of the 9th c. and the 10th c. CE seeing no notable human activity in the Volvi region. This period is characterized by some of the lowest values of cereal pollen concentration in the entire record, by an important decrease of local and regional pastoral indicators, as well as of *Sporormiella* from ca. 830 CE (1120 cal a BP) (Figs. 6–8). In addition, this period also saw the expansion of pioneer taxa (e.g. *Juniper*), which suggests almost complete abandonment of the region by human populations (Fig. 8).

When placed in the historical and archaeological context, this socio-ecological collapse again reveals the paradox of the Volvi region's role within Macedonia. During the 9th–10th c. CE, the imperial authorities reasserted control over the southern Balkans by recruiting local warlords and by establishing new administrative units (Oikonomidès, 1994; Haldon, 2021, 164–99). By 904 CE, Thessaloniki was reported again to be a thriving port city (Melville-Jones et al., 2000). On this basis, one would expect agricultural intensification rather than collapse for the Volvi region, located as it was in the heart of Byzantine Macedonia. However, by contrast, it was the rise of the Byzantine power in Macedonia that undermined the conditions of a 'political vacuum' needed for the transhumance form of stateless way of life to thrive around Lake Volvi. The subsequent failure of any alternative new economic system to emerge here could be due to the fact that it fell between two of the new administrative authorities, one based in the Strymon valley to the east, and the other in Thessaloniki to the west. The Byzantine governance of the Balkans was not all-encompassing as it had been in Late Antiquity but fragmented. Consequently, lands farther away from the key military–administrative centre – such as the Volvi region – would not have been positively affected by the rise in the Byzantine state's presence in Macedonia. Moreover, much of southern Macedonia remained the focus of fierce military activity in the 9th and 10th c. CE (Ditten, 1993, 166–71 and 217–21; Hupchick, 2017, 149–220; Stephenson, 2000, 58–79). These areas, distant from the major military hubs, would have been unattractive for new settlement and aristocratic investment.

In brief, the continuation of relatively strong human presence in the 5th and early 6th c. CE, despite the military insecurity of the Central Balkans, is attested to by both archaeological and palynological data. The following phases of the early mediaeval developments in this area can only be reconstructed from the pollen data presented herein. The significant drop in human activities that occurred during the second half of the 6th c. CE is probably associated with some undocumented plague outbreaks across the empire, and to Hun, Sclaveni and Avar raiding. In the following two centuries, the pollen data provide plausible evidence for the existence of a new, transhumance way of living in the Volvi region, generating new ecological dynamics.

Social–ecological dynamics in the second millennium CE

Following the collapse of human activities at the end of the late first millennium CE, the beginning of the second millennium CE is characterized by consolidation of the forest. This phase was preceded by the pioneer vegetation succession, which occurred during the human abandonment phase. In parallel, in the first centuries of the second millennium CE, human activities slowly resumed, yet they did not achieve sustained levels up until the 15th c. CE. The climax of human impact in the entire record falls in the 16th c. CE, after which different agricultural activities continue to a varying degree.

Thus, PZ 3 (ca. 1055–1380 CE, 895–570 cal a BP) is characterized by a marked expansion in percentage and concentration values of the arboreal vegetation, in particular *Quercus ilex* type (evergreen oaks), *Pinus*, *Fagus* and *Ostrya/Carpinus orientalis* (Figs. 6 and 7). Evergreen oaks reach the maximum of the sequence at ca. 1100 CE (850 cal a BP). This expansion of oak forests could have been partially favoured by human management practices. The management of oakwood for grazing and timber is a well-attested practice in Greece (Dimopoulos and Bergmeier, 2004; Kizos, 2014) and it is also attested to in Tristinika, in Halkidiki, during mediaeval times. *Quercus ilex* type shows a decreasing trend starting soon after the mentioned climax, and it is replaced by *Ostrya/Carpinus orientalis*, *Fagus* and *Ulmus* (elm), highlighting a shift toward more humid conditions (Fig. 6). A drop in percentages of Poaceae around ca. 1055 CE (895 cal a BP) could be related to high lake levels attested to also by the wetland communities (riparian trees *Alnus*, *Platanus* and possibly *Ulmus*) that are well represented (Fig. 6). This could be related to the Medieval Climate Anomaly that is characterized, in the Eastern Mediterranean, by wet conditions (Finné et al., 2011). Cereals display only sporadic presence of members of the *Hordeum* group (barley) around 1180–1220 CE (770–730 cal a BP). While the onset of this increase in cereal cultivation may be related to political stability and trade integration in the Byzantine Empire in the 11th–12th c. CE, the discontinuation could be attributed to the Fourth Crusade, the conquest of much of the Aegean by Western Europeans ('Latins'), and the resulting political, military and economic instability. At the same time, it is notable that agriculture reappears toward the end of the 12th c. CE. Apparently, it was long before the military security ensured by the Byzantine conquest of the Bulgarian Empire in the early 11th c. CE that positive demographic and agrarian developments in our study area. However, this mediaeval recovery came too late to stabilize itself, because the Byzantine Aegean descended into political crisis and disintegration in the 13th c. CE.

The small scale and intermittent nature of human activities during the Middle and Late Byzantine times (11th–12th c. CE) is not only visible in the cereal pollen curve, but is also highlighted by all the anthropogenic parameters. A similar decrease is also attested to by the OJC (olive, walnut, chestnut) and LPPI (grazing-associated plants) curves (Fig. 8). A similar diminishment of human imprint on the landscape during Late Byzantine times is evidenced at Tristinika marsh (Panajiotidis and Papadopoulou, 2016), in contrast to southern Greece, e.g. Kotihi and Lerna (Lazarova et al., 2012; Vignola et al., 2022), which did not face a decline of human pressure on the environment (Izdbeski et al., 2015; Kouli et al., 2018). The slight but consistent increase of *Artemisia* followed by Amaranthaceae from ca. 1220 CE (730 cal a BP) in the study area may reflect both the low level of human activity or a shift towards arid conditions. Even though many plants belonging to the family Amaranthaceae are indicative of drought and soil salinization, they also rapidly colonize abandoned arable fields together with ruderal plants (Cordova and Lehman, 2003). The Rb/Sr ratio suggests a dry climate around 1250–1550 CE (700–400 cal a BP) which might be connected to lake level lowering due to a shift towards coarser grain size. Besides, the presence of *Pediastrum boryanum* coenobia points to the occurrence of more eutrophic conditions in Lake Volvi since ca. 1140 CE (800 cal a BP), which is in agreement with the increase in TOC and TS starting around ca. 950 CE (1000 cal a BP). The increase in TOC and TS can be also associated with the Rb/Sr ratio and the occurrence of major erosion in the catchment, probably connected with the abandonment of cultivated and grazed land. Such a change is also attested to by increased TIC contents and Ca/inc ratios (Fig. 8).

The Byzantine monastic documents (Fig. 3) indicate that the majority of the Byzantine agricultural and settlement activity in this area during the 13th–14th c. CE was concentrated in the eastern part of the Lake Volvi catchment, close to Apollonia in the southeast and Rentina in the east. Both sites were active small towns of the middle and late Byzantine period (up to the 14th c. CE at least), with Rentina being a well-protected and fortified settlement (Karagianni, 2010, 115 & 128). These towns established local foci of settlement activity in the eastern part of the catchment, which encouraged continued land exploitation in this area. The western part of the lake catchment, by contrast, seems to have been sporadically exploited (only when more stable political–economic conditions allowed for agricultural expansion). The expansion of thermophilous and mesophilous forests and the continuous presence of riparian vegetation reflects the new land organization of the 13th–14th centuries CE (Fig. 6). In this context, it is not surprising that while the monastic documentary data clearly indicate the massive scale of mortality and agricultural disruption related to the plague outbreaks during the Black Death (mid-14th c. CE), and they pertain to the eastern part of the catchment, the pollen record does not contain a clear signal of the plague's impact for the western part (contrary to the plausible signal of the 6th c. CE plague, during the reign of Justinian, see previous section). This suggests any macro-scale arguments about the plague's impacts based on even the most highly resolved micro-scale local studies, without support from other multiple sources of evidence in the same region (as in, for instance, Izdebski et al., 2022), may be of limited validity, given that even in such a large lake as Volvi the impact of the plague on its eastern side was not recorded in the sediments accumulating in its western basin.

Archaeological findings attested to the presence of infrastructure for olive production north of the lake around 1324–1325 CE (Bakirtzis, 2003; Karagianni, 2010; Fig. 3), owned by the monasteries. The extremely low signals of arboriculture, as evidenced by the OJC curve (Fig. 8), may be related to the contraction of trade networks in the region; in fact, the east area of the Mygdonia basin ceased to be economically connected with Thessaloniki already by ca. 1230 CE (Bakirtzis, 2003). Among cultivated trees, *Vitis* must also be taken into consideration, as monastic documents document that those vineyards existed near the lake in the northeastern and southern areas in the 13th–15th c. CE (Fig. 3; Supporting Information Fig. S3). Wild grapevine is well attested to in the area and the continuity in the Volvi record could be partially related to its presence. As *Vitis* is a low pollen producer (Mercuri et al., 2021), its cultivation can also be inferred by low pollen percentages. The combination of historical data and the pollen presence is here strong evidence for grape cultivation. Byzantine documents (Fig. 3) recorded walnut cultivations in the 13–14th c. CE which are also evidenced later in the 16th c. CE (Fig. S4). According to Bottema (1974) *Juglans* is an important element of the riverine forest and together with *Platanus* is a successor of *Fraxinus excelsior* in that habitat. The continuous presence of *Fraxinus excelsior* and *Platanus* in the Volvi diagram attest to the great importance of wetland forest. An important peak of *Pediastrum* and TS around 1300–1340 CE (650–610 cal a BP) can be related to water eutrophication as a consequence of the increase of organic matter into the lake.

A major turning point in the social and environmental history of the lake Volvi region occurred at the beginning of the 15th c. CE corresponding to the beginning of PZ 4. Within this zone, arboreal pollen shows a selective contraction, mainly in evergreen *Quercus* together with *Ostrya*/*Carpinus orientalis*, while thermophilous and mesophilous taxa do not exhibit any decline (Figs. 6 and 8). The reduction in the arboreal biomass is also registered by the geochemical data (TOC and TS, Fig. 8). The pollen sample dated to 1411 CE (1σ: 1372–1458 CE) displays the highest cereal concentration value of the entire record, almost fourfold the value of any mediaeval sample and almost threefold of any Roman sample. Already in the preceding sample, an increase of the anthropogenic indicators related to pastoralism (e.g. Cichorieae, *Galium*, *Plantago lanceolata*; Figs. 6 and 8) is also observed, supported by the peak of the coprophilous fungus *Sporormiella* in 1411 CE. This expansion of farming and pastoral activities, however, was interrupted soon thereafter: during the following three samples, spanning the 15th and early 16th c. CE (1442 CE, 1472 CE and 1503 CE; 1σ: 1401–1556 CE) the high cereal values were discontinued. These values, while slightly higher than medieval cereal concentrations, were three times lower than the previous sample. High cereal values reappeared again in 1533 CE (1σ: 1488–1588 CE) and 1564 CE (1σ: 1517–1620 CE). This indicates that the 16th c. CE was the period of the most intensive cereal production and demographic pressure in the Volvi region during the entire last 2000 years. In the following three paragraphs we use historical sources to explain the strange pattern represented by the 1411 CE peak in the cereal pollen. It is based on the assumption that our age–depth model is reliable in estimating the actual ages of the sediment pollen samples, and indeed within the range of 1σ confidence intervals our interpretation fits perfectly. The 1σ age probability range, however, represents only a 68% probability that the real age falls into this time interval – if we take into account the 2σ range, which would provide 95% probability, the strange pattern seen in the pollen data could fall much earlier or later (2σ range for the 1411 CE sediment pollen sample is 1350–1469 CE). Still, the coherence between the developments we reconstruct on the basis of the historical documents and the vegetation dynamics visible in the pollen data lend strong support to our interpretation.

When we consider the temporal resolution of the sequence, the time intervals between samples (on average 32 years) represent two human generations. This means that in the late 14th to early 15th c. CE an outburst of agricultural activity occurred in the western part of the Volvi region, but just for the duration of one generation – and in this period our written documentation, in particular in the west of the Volvi region, is practically absent (Figs. 3 and 4). For the following three generations, during the rest of the 15th c. and the early 16th c. the pollen data suggest that population numbers remained low. This is in agreement with the situation recorded in the first Ottoman taxation register, dated to the later 15th c. CE, which shows rather small numbers of inhabitants and villages. The population and agricultural explosion of the 16th c. CE is again clearly visible in both the Ottoman taxation registers (Figs. 4 and 5) and in the pollen data.

The surprising trajectory of short-term intensification around 1411 CE followed by several decades of low-level agricultural activity, until the maximum was reached again in the 16th c. CE, can be explained by two co-occurring factors: Turcoman migration and recurrent plague. The first of these is the forced deportation of Turcoman nomads (*yörük*s) from western Anatolia into Macedonia in the 1380 s and 1390 s CE, documented in general terms in the Ottoman written sources (Aktepe, 1951, 300–301; Gökbilgin, 1957, 11–14; Necipoğlu, 2009, 99–100; Kotzageorgis, 2015, 99–100). Detailed information on the nomadic settlement in the Volvi area itself comes only from the 16th c. CE. However, the 17th c. CE traveller Evliya Çelebi reports on the oral histories that local nomadic communities recounted about their origins. They placed their arrival in the Volvi area in the earliest waves of nomadic migrations (Kahraman et al., 2003, 79).

As with most nomads, the *yörük*s were engaged not only in animal husbandry, but also in cereal cultivation, in particular of barley, for human consumption and animal fodder (İnalcık, 1993, 110–111). According to the TT403 register (Table S5), cereal cultivation corresponds to 99.3% of their agricultural taxes; a similar percentage of 94.0% of taxes levied on cereals is attested to for the *yörük*s of Thessaly in the MM10 register (1454/55 CE; Liakopoulos, 2022, 311). Thus, a nomadic immigration, reported by later oral histories, clearly explains the sudden demographic change in the western Volvi area, which at the time was otherwise characterized by a demographic crisis caused by plague. The location of Volvi on the main communication pathway and the lack of previous substantial settlement in the western part of its catchment (as evidenced by the pollen record and the Byzantine documents – Fig. 3) made the southern, northern and interlake lowlands surrounded by hills an obvious place for the nomads to station themselves after their arrival (Dimitriadis, 1980, 390–97; Dimitriadis, 1983, 12; Kotzageorgis, 2015, 113–14; Kalionski, 2020, 102). During the first stages, the *yörük*s were mainly engaged in animal husbandry (as reflected in the pollen sample prior to 1410 CE), but they soon turned to mixed transhumance pastoralists and settled farmers and integrated in the pre-Ottoman settlement and exchange networks (Kolovos and Kotzageorgis, 2015, 139).

While migration would explain the sudden explosion of land use, the second factor, i.e. the high intensity of recurring plague epidemics, could explain the short-lived character of this land use phase. The location in the main communication corridor made the Volvi area dangerous for use as semi-permanent quarters, because of exposure to plague that was circulating along the main communication corridors, including those passing through the region, connecting Constantinople and Thessaloniki. It is therefore not surprising that the land use levels (pollen of cereals and pastoral indicators) reverted to the earlier values in the remaining samples dated to the 15th c. CE. During most of this century, Central Macedonia experienced several major plague outbreaks (Table S6).

As noted already, a significant increase in human pressure occurred again in the 16th c. CE, and this time was more long-lived. The pollen samples dated to 1533 and 1564 CE reflect a new approach to land management, with arable fields of *Avena/Triticum* group (oat/wheat), *Hordeum* (barley) group and sporadically *Secale* (rye). Specialization to a pastoral economy is indicated by the rise of Cichorieae and other taxa related to pastoralism (Figs. 6 and 8). Moreover, the rising curves of the families Fabaceae and Brassicaceae, which include pulses and edible vegetables, suggest an even more diversified type of agriculture; at the same time the rapid increase of percentage values of Rosaceae may be related to different land use practices that include fruit-producing trees (Fig. 6).

This change is related to the political and economic situation of the so-called *Pax Ottomana*. The firm establishment of the Ottomans in the 15th c. CE brought stability and contributed to unprecedented demographic growth. In other mountainous sites of Greece, constant livestock grazing pressure coincides with the establishment of Turcoman nomads (Panajiotidis and Gerasimidis, 2013; Kouli, 2020). Unsurprisingly, the developments visible in the pollen data agree very well with the indications of the Ottoman taxation registers (Figs. 4 and 5). The registers demonstrate the growing importance of wheat between 1478 CE and 1527 CE (Fig. 5), which is also visible in the pollen record: the sample of 1564 CE has the highest oat/wheat concentration, while later samples show only sporadic presence of oat/wheat and renewed domination of barley. This would suggest that the agricultural expansion of the 16th c. CE in the area of Volvi was at least partly related to the demand of the urban and military consumers, who preferred wheat (the perfect cash crop), thus responding to market and fiscal pressures.

The 16th c. CE demographic and agricultural expansion in the Volvi region was relatively short-lived. Pollen data indicate a gradual decline of cereal concentration reaching null around 1700 CE (250 cal a BP), while the registers record significant population decline between the 16th and early 18th c. CE (Fig. 4). The high amount of *Pediastrum* algae from ca.1604 CE (350 cal a BP) suggests increasing eutrophic levels in a period associated with erosional events recorded by the concentration of spores of *Glomus* and *Pseudoschizaea*. Increased erosion could be linked to an intensification of river run-off activity and the increase of humidity during the Little Ice Age (LIA) as documented in the northern Aegean after ca. 1450 CE (Gogou et al., 2016). Similar patterns have been observed in various other locations across Greece including the Drama plain in northern Greece (Lespez, 2003), the northern Aegean marine record (Gogou et al., 2016; Dimiza et al., 2020), Vravron in eastern mainland Greece (Triantaphyllou et al., 2010; Kouli, 2012) and Klisova lagoon in western Greece (Emmanouilidis et al., 2022). The phenomenon of increased rain is quite important and involved most of the Mediterranean area, causing river floods (see figs. 2 and 4 in Sadori et al., 2016b), lake level increase and reduced agricultural practices in central Italy (Sadori, 2018). These data provide compelling evidence of increased riverine run-off during this climatic period. The erosion events are also associated with the abandonment of fields, as erosion levels were often highest in the decades immediately following phases of intense cultivation, which occurred in the 16th c. CE. Soon after, there occurs a peak in charcoal concentration, which suggests ecological and societal instability, visible in an increased frequency of local and regional fires (Fig. 7).

This significant and relatively rapid population and land use decline may again be explained by the risks posed by the location of Lake Volvi in one of the main communication corridors of the Balkans. The Via Egnatia trade route may have again facilitated the proliferation of plague. In 1577 CE, plague is recorded in the axis of Constantinople–Adrianople–Thessaloniki, covering an extended area in Thrace and Macedonia; in 1618–22 CE Thessalonikiis was ravaged by the epidemic; here we also note the disease in neighbouring Serres in 1621–23 CE; another onset that swept through entire northern Greece is dated to 1642 CE (Kostis, 2020, 349, 355, 360–61, 367–68). In general, between 1513 CE and the last recurrence of plague in Thessaloniki in 1838 CE, there were as many as about 60 outbreaks (Kostis, 1998), most of them in the 17th–18th c. CE. Thus, the average frequency of plague outbreaks per century doubled compared to the 15th c. CE (Table S6). This increase in the frequency of epidemics in Macedonia seems to have been a real phenomenon, not just a matter of more abundant documentation available for Macedonia after 1500 CE. As recent aDNA and historical studies have shown, a concurrent divergence of two new *Yersinia pestis* (the bacterium responsible of the plague) lineages appears in the late 15th century CE, one of which was associated with a natural reservoir somewhere in the Ottoman territories (Slavin, 2022; Keller et al., 2023). As a result, there were at least two – and probably more – natural plague reservoirs sending waves across west Eurasia and north Africa, implying more frequent outbreaks than in the previous two centuries. Moreover, we also need to consider the emergence of Thessaloniki as an international trade hub of major importance, connecting Europe and Asia, and attracting constant shipment of goods, people and pathogens (Nehama, 1935; Emmanuel, 1936; Hassiotis, 1997; Varlık, 2014). This increased exposure to plague would both lead to higher mortality, but also encourage emigration from the Volvi area into more isolated and less epidemiologically risk-prone areas.

The Volvi region experienced an important increase in human pressure around 1790 CE (160 cal a BP) with the increase of all the human indicators. At the same time, the rapid increase in pioneer taxa indicates a degraded land ecosystem, which does not strongly affect the riparian forest, but only the hilly areas covered by mixed oak and thermophilous and mesophilous forests.

The presence of *Olea* is not recorded in the pollen data from the 11th c. CE to the 17th c. CE when it is sporadically attested to (Fig. 6), while the Ottoman taxation cadastres attest to olive oil production in the 16th c. CE in exactly the same area where it was located in the Byzantine times (Figs. 3 and S2).

Strong land use consisting of livestock farming, arboriculture and cultivation of cereals is present in the uppermost part of the sequence from ca. 1870 CE (80 cal a BP), at the beginning of PZ 5. The *Olea* pollen curve reached highest values of the sequence in the 19th c. CE (Fig. 6). Nowadays, olive trees on the shores of the lake constitute an important element of the vegetation. By contrast, *Juglans*, which is always present along the sequence, disappears from the pollen record by the 19th century CE, while *Castanea* appears underrepresented compared to the other cultivated trees. Cereals exhibited a distinct increase with a differentiation in the cultivated species. Expansion of the anthropogenic pollen indicators related to pastoralism as well as coprophilous fungi such as *Sporormiella* and the parasite *Trichuris* reveal the importance of animal husbandry practices in the economy that overall may have contributed to the reduction of evergreen oaks (Figs. 6 and 7). A marked increase of *Pediastrum* indicates significant eutrophication of the water, probably a result of the increased cattle farming (Komarek and Jankovská, 2001). In this respect soil erosion markers indicate the intensification of land management as a result of the expanding land use that continues until the present day.

Conclusion

Palynological and sedimentological analyses of Lake Volvi describe the palaeoenvironmental conditions of Central Macedonia for the last 2000 years. The study reveals the significant impact of land use on the region, which has reduced the variability of habitats and vegetation. The area is still characterized by a wetland habitat around the entire Lake Volvi basin, as attested to in the past. In addition, the pollen data from Lake Volvi make it also possible to connect vegetation change with human history. There is general agreement between late Roman archaeology and the pollen data, and later with regard to the climax of human land use in the 16th c. CE during Ottoman rule.

However, we found disagreements between the two types of data – historical and palynological – which after detailed investigation revealed otherwise invisible aspects of the Volvi region's environmental history. Most importantly, the pollen data show that the 16th c. CE population and land use peak was short-lived. In addition, it was preceded by a century-long period of unstable land use related to Turcoman nomadic populations. Other nomadic groups were also active in the Volvi region for about 200 years after the collapse of Roman rule in the mid-6th century CE, as made evident, again, by pollen data.

Placing the pollen data in the historical context reveals also another paradox: while the hypothetical plague outbreaks in the 6th century CE (Justinian's plague) probably caused a rapid decline in land use and population, the well-documented 14th c. CE plague outbreaks (the Black Death) did not significantly alter vegetation in the western part of the Volvi area. The reason was the relatively high settlement density prior to the Justinianic Plague, which stands in stark contrast to the low population numbers in the western part of the Volvi region in the decades preceding the arrival of the Black Death.

In conclusion, our natural scientific–humanistic study of the Volvi region's history demonstrates that consilience should not be understood as convergence. Full alignment of independent lines of evidence coming from different disciplines is not its goal. Rather, while the agreements add to the credibility of the consilient approach and are to be expected with the most significant phenomena (e.g. the 16th c. CE climax in land use and population, or the prosperous Roman centuries), properly contextualized disagreements between data and methods provide new insights that would not be achieved if historical or palaeoecological data were analysed in isolation.

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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.

Figure S1. Artificial (^{137}Cs, ^{241}Am) and natural (^{210}Pbunsupp.) radionuclide profiles of core V8-11 from Lake Volvi (Central Macedonia, Greece). The radionuclide data have been compared with TOC content that evidence a decrease in sedimentation rate in the upper part of the core.

Figure S2. Olive oil taxation in the Lake Volvi region in 1568 CE. The taxation for olive oil production is expressed in grams of silver per year (p.a.). Based on the Ottoman register listed in Supp Table 5. Basemap: © 2014 Esri.

Figure S3. Vineyards taxation in the Lake Volvi region in the 15th-16th century. The taxation for vineyards expressed in grams of silver per year (p.a.). Based on the Ottoman registers listed in Supp Table 5. Basemap: © 2014 Esri.

Figure S4. Walnuts taxation in the Lake Volvi region in the 16th century. The taxation for walnut production is expressed in grams of silver per year (p.a.). Based on the Ottoman registers listed in Supp Table 5. Basemap: © 2014 Esri.

Table S5. Ottoman taxation registers covering the Volvi region. The table reports name, the date to which the documents refer to and the place where the original manuscripts are located.

Table S6. Mediaeval plague outbreaks in Macedonia and the southern Balkans following the Black Death. Locations in Macedonia in bold. Other outbreaks occurred along the main communication corridors that crossed Macedonia and hence suggest possible, unrecorded outbreaks in Macedonia as well.

Abbreviations. AP, Arboreal pollen; AMS, accelerated mass spectroscopy; BCE, Before Common Era; BP, Before Present; c., century; CE, Common Era; LIA, Little Ice Age; LALIA, Late Antiquity Little Ice Age;

NAP, Non arboreal pollen; NPPs, Non-pollen palynomorphs; TOC, total organic Carbon; TIC, total inorganic Carbon; TC, total Carbon; TS, total Sulphur; TN, total Nitrogen; XRF, X-ray Fluorescence.

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Note: References with * are cited in the Supplementary Table 6.

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