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Impacts of climate and humans on the vegetation in northwestern Turkey: palynological insights from Lake Iznik since the Last Glacial

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Abstract. The Marmara region in northwestern Turkey provides a unique opportunity for studying the vegetation history in response to climate changes and anthropogenic impacts because of its location between different climate and vegetation zones and its long settlement history. Geochemical and mineralogical investigations of the largest lake in the region, Lake Iznik, already registered climate-related changes of the lake level and the lake mixing. However, a palynological investigation encompassing the Late Pleistocene to Middle Holocene was still missing. Here, we present the first pollen record of the last ca. 31 ka cal BP (calibrated kilo years before 1950) inferred from Lake Iznik sediments as an independent proxy for paleoecological reconstructions. Our study reveals that the vegetation in the Iznik area changed generally between (a) steppe during glacials and stadials indicating dry and cold climatic conditions, (b) forest-steppe during interstadials indicating milder and moister climatic conditions, and (c) oak-dominated mesic forest during interglacials indicating warm and moist climatic conditions. Moreover, a pronounced succession of pioneer trees, cold temperate, warm temperate, and Mediterranean trees appeared since the Lateglacial. Rapid climate changes, which are reflected by vegetation changes, can be correlated with Dansgaard-Oeschger (DO) events such as DO-4, DO-3, and DO-1, the Younger Dryas, and probably also the 8.2 event. Since the mid-Holocene, the vegetation was influenced by anthropogenic activities. During early settlement phases, the distinction between climate-induced and human-induced changes of the vegetation is challenging. Still, evidence for human activities consolidates since the Early Bronze Age (ca. 4.8 ka cal BP): cultivated trees, crops, and secondary human indicator taxa appeared, and forests were cleared. Subsequent fluctuations between extensive agricultural uses and regenerations of the natural vegetation become apparent.

1 Introduction

The reconstruction of past climatic and environmental conditions is crucial to understand the living conditions and migration processes of former societies. After the first spread of modern humans into Europe during the Last Glacial (e.g., Benazzi et al., 2011; Higham et al., 2011), different population dynamics into and out of Europe followed. These population dynamics also include the spatial expansion of farming and husbandry, which happened between ca. 11 600 and 5500 years ago. The Marmara region, situated between the Mediterranean Sea and the Black Sea at the principal corridor of human dispersal from Africa via the Middle East to the Balkans, functioned as an important bottleneck for all migrated societies (Richter et al., 2012).

The Last Glacial is characterized by unstable climatic conditions changing between stadial (and glacial) conditions and milder interstadial conditions. Several rapid climate changes described as Dansgaard-Oeschger (DO) events (Dansgaard et al., 1982) and Heinrich events (Heinrich, 1988; Bond et al., 1992) occurred. DO events are associated with an abrupt warming followed by a gradual re-cooling, which are well documented in the Greenland ice core records (e.g., NGRIP members, 2004). Heinrich events are associated with cold periods (also called Heinrich Stadials (HS); Sanchez Goñi and Harrison, 2010), when ice-rafted debris deposited in the

North Atlantic due to massive discharges of icebergs (Bond et al., 1992). Climatic imprints related to DO events and HS are documented in many northern-hemispheric records (e.g., Hemming, 2004; Sanchez Goñi and Harrison, 2010; Müller et al., 2011; Panagiotopoulos et al., 2014; Pickarski et al., 2015). However, the magnitude, nature, and duration of each event might have varied from region to region (Sanchez Goñi and Harrison, 2010). Therefore, further records, also in Turkey, are needed to establish a complete picture of the influence of rapid climate changes on environmental conditions (Fletcher et al., 2010).

Lake Iznik, the largest lake in the Marmara region, serves as a valuable archive to study the relationship between vegetation, climate, and anthropogenic activities. The detection of human impacts on the vegetation is particularly interesting because the eastern Marmara region has a long occupation history, and archaeological settlements are in close proximity to Lake Iznik (e.g., Roodenberg and Roodenberg, 2008).

Previous studies reconstructed the paleoenvironmental and tectonic history of the Iznik Basin and investigated Lake Iznik's recent and paleo-limnology since the late Pleistocene based on seismicity, sedimentology, geochemistry, and mineralogy (Alpar et al., 2003; Franz et al., 2006; Öztürk et al., 2009; Roeser et al., 2012; Ülgen et al., 2012; Viehberg et al., 2012; Roeser, 2014). Those studies also revealed climate-related changes of the lake level and the lake mixing (Roeser et al., 2012; Ülgen et al., 2012; Roeser, 2014). A preliminary pollen analysis inferred from Lake Iznik sediments was published by Ülgen et al. (2012). The pollen record, which is only presented in ecological plant groups, encompasses the last 2400 years. A palynological investigation of sediments from Lake Iznik encompassing the late Pleistocene to late Holocene was still missing.

To provide a better view on the environmental conditions in the Marmara region during the last ca. 31 000 years, we investigated the pollen assemblage and selected non-pollen palynomorphs (NPP) of a ca. 18 m composite profile from Lake Iznik. It comprises a continuous and undisturbed sediment record with a robust chronology (Roeser et al., 2012; Ülgen et al., 2012; Roeser, 2014). Here, we present a new vegetation and climate study, which also concerns human activities in the catchment area of Lake Iznik.

2 Study area

2.1 Regional setting

Lake Iznik (Turkish: İznik Gölü) is located in the southeast of the Turkish Marmara region (Fig. 1). The Marmara region is a tectonically active area surrounding the Marmara Sea. Lake Iznik lies at the middle strand of the North Anatolian Fault, which is the boundary between the Anatolian and Eurasian plate (Öztürk et al., 2009).

With a surface area of 313 km^2, 32 km in length and 12 km in width, Lake Iznik is the largest lake in the Marmara region (Fig. 2). Lake Iznik is situated 85 m above present mean sea level (m a.s.l.) and reaches a maximal water depth of 80 m (Wester, 1989; Franz et al., 2006). The alkaline freshwater lake receives fluvial input from five main rivers (Nadir, Kuru, Kara, Kiran, and Sölöz), while the only output stream is Karsak (Viehberg et al., 2012). The catchment area is about 920 km^2 (Wester, 1989). Several mountain ridges surround the Iznik Basin: Samanli Mountains in the north, Gemiç Mountains in the southwest, and Katirli Mountains in the south. Their summits range from 810 to 1293 m a.s.l. (Öztürk et al., 2009).

2.2 Current climate

Lake Iznik's catchment area is situated in a climatic transition zone, which is influenced by the Mediterranean climate and the Pontic climate. Warm, dry summers and mild, moist winters are typical for the Mediterranean climate (Köppen, 1900). In contrast, the Pontic climate is characterized by an absence of summer drought due to higher precipitation throughout the year and lower mean temperatures (Kürschner et al., 1997). The annual average air temperature at the Iznik Basin is around 14.4 °C, and the monthly average minimal air temperature never drops below 0 °C (Wester, 1989; Table 1). Since Lake Iznik is surrounded by mountain ranges, one can find notable lower average temperatures close by (Akbulak, 2009). Most precipitation falls in winter and spring, whereas June to September are arid months. A gradient in precipitation from west to east is characteristic not only for the Iznik Basin (Orhangazi – Iznik; Table 1) but also for the whole region (Aegean Sea/Marmara Sea – Central Anatolia; Mayer and Aksoy, 1986; Wester, 1989). Precipitation can rise up to about 1200 mm in higher elevations near Lake Iznik (Akbulak, 2009). The prevailing wind direction is west in summer and east in autumn and winter. The wind is unstable in spring and changes directions (Wester, 1989).

2.3 Current vegetation

The potential natural vegetation of northwestern Anatolia is divided into five vegetation zones, from which three directly influence the catchment of Lake Iznik (Fig. 3).

A band of Euxinian and sub-Euxinian mesic deciduous and mixed forest extends along the southern and eastern coasts of the Black Sea (Zohary, 1973; Shumilovskikh et al., 2012). In northwestern Anatolia, it reaches into Thrace (European Turkey) and south of the Marmara Sea almost to the Aegean Sea. The forest is dominated by oriental beech (*Fagus orientalis*) and deciduous oaks (Zohary, 1973). Other important summer-green trees include *Fagus sylvatica*, *Alnus glutinosa*, *Acer campestre*, *Populus tremula*, *Carpinus*, *Fraxinus*, and *Ulmus* (Mudie et al., 2002). Conifers like *Pinus sylvestris*, *P. nigra*, *Abies nordmanniana*, and *Picea orientalis* are present in low altitudes, but they become more fre-

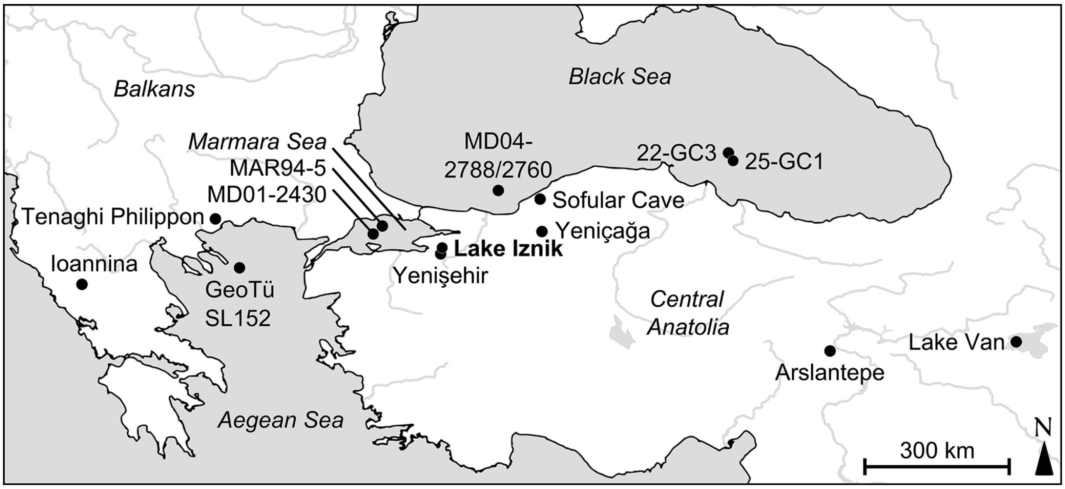

Figure 1. Regional overview modified from Roeser et al. (2012). Dots indicate Lake Iznik (this study) and paleo records mentioned in the discussion: Ioannina (Lawson et al., 2004), Tenaghi Philippon (Tzedakis et al., 2004; Müller et al., 2011), GeoTü SL152 (Kotthoff et al., 2008), MAR94-5 (Mudie et al., 2002), MD01-2430 (Valsecchi et al., 2012), Yenişehir (Bottema et al., 2001), MD04-2788/2760 (Kwiecien et al., 2009), Sofular Cave (Fleitmann et al., 2009; Göktürk et al., 2011), Yeniçağa (van Zeist and Bottema, 1991), 22-GC3 (Shumilovskikh et al., 2012), 25-GC1 (Shumilovskikh et al., 2014), Arslantepe (Masi et al., 2013), and Lake Van (Wick et al., 2003; Litt et al., 2009).

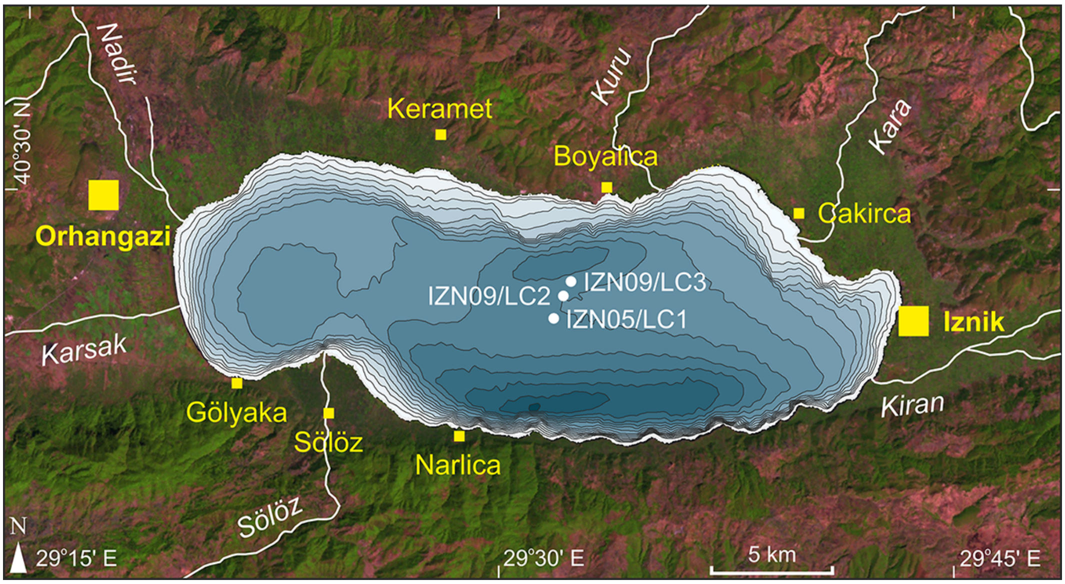

Figure 2. Lake Iznik with bathymetric curves in 5 m intervals modified from Roeser et al. (2012). Dots indicate the coring locations, and squares indicate settlements.

quent in higher altitudes (Zohary, 1973). The Pontic forest is associated with more than 600 mm mean annual precipitation (Roberts and Wright, 1993). Zohary (1973) divided the vegetation zone into an Euxinian type near the coast and a more continental sub-Euxinian type. The rain shadow of the Pontic Mountains favors the latter type, which is characterized by a high amount of *Carpinus* and *Pinus nigra*. The natural tree line near Lake Iznik reaches an elevation of about 2000 m (Louis, 1939).

The Aegean coasts and southeastern coasts of the Marmara Sea are characterized by a climax of Mediterranean woodland. According to Zohary (1973), there is an evergreen subzone from sea level to an elevation of 1000 m and an oro-Mediterranean subzone reaching up to 1600 m. The evergreen subzone is dominated by *Quercus calliprinos*, *Olea europaea*, *Ceratonia siliqua*, *Myrtus communis*, *Phillyrea media*, *Arbutus*, and *Pistacia*. But there are also some deciduous and coniferous elements like *Quercus infectoria*, *Q. ithaburensis*, *Styrax officinalis*, *Crataegus azarolus*, *Spar-*

Table 1. Average climate data and elevation of Iznik and Orhangazi (Wester, 1989; see Fig. 2 for the locations).

	Elevation (m a.s.l.)	Air temperature (°C)			Precipitation (mm)			Evaporation (mm)
		year	Jan	Jul	year	Nov–Apr	May–Oct	year
Iznik	88	14.4	6.9	23.8	552	351	201	718
Orhangazi	95	14.4	5.2	24.2	743	507	236	648

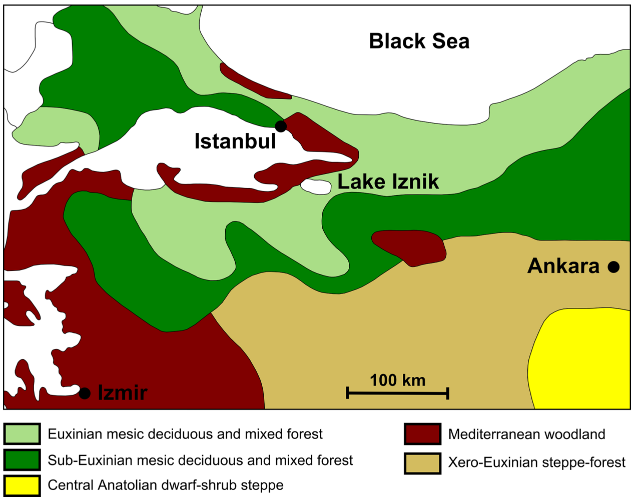

Figure 3. Natural potential vegetation of northwestern Turkey redrawn from Zohary (1973).

tium junceum, *Juniperus phoenica*, and *Pinus brutia* (Zohary, 1973; van Zeist et al., 1975). The oro-Mediterranean subzone is dominated by summer-green trees and conifers. Important elements are deciduous oaks (mainly *Quercus cerris*) and pines (mainly *Pinus nigra*). Additionally, the range of characteristic arboreal taxa includes: *Ostrya carpinifolia*, *Castanea sativa*, *Fraxinus ornus*, *Cotinus coggygria*, *Fontanesia phillyreoides*, *Acer*, *Juniperus*, *Cornus*, *Buxus*, several Rosaceae (e.g., *Crataegus monogyna*), and several Fabaceae (e.g., *Colutea arborescens*; Zohary, 1973).

However, the potential natural vegetation differs considerably from the vegetation one will find nowadays, which is shaped by human activities of several thousand years (Mayer and Aksoy, 1986). Due to agriculture (e.g., olive cultivation, cereal cropping, and husbandry), forests were cleared, large areas were overgrazed, landscapes were burned, and soils eroded (Zohary, 1973; Mayer and Aksoy, 1986). Former Mediterranean woodlands degraded to macchia vegetation with *Arbutus*, *Juniperus*, *Pistacia*, *Phillyrea latifolia*, *Spartium junceum*, and evergreen oaks (Kürschner et al., 1997; Atalay et al., 2014). In case this xeromorphic shrub vegetation were further overexploited, it degraded to phrygana vegetation. These are open landscapes with herbs and dwarf shrubs, which are often thorned (Kürschner et al., 1997). An important element of the Eastern Mediterranean phrygana is the dwarf shrub *Sarcopoterium spinosum*, which benefits from land degradation and extensive grazing (Le Houèrou, 1981; Bottema and Woldring, 1990).

3 Material and methods

3.1 Core setting, composite profile, and age-depth model

For the current study, a composite profile was constructed by using different sediment cores, which were collected in two separate coring campaigns. All of these cores descended from the central sedimentary ridge of Lake Iznik, which separates the northern and the southern basin, at a water depth of ca. 50 m (Fig. 2). The cores were recovered from floating platforms with the help of percussion piston corers (Roeser et al., 2012; Ülgen et al., 2012).

Sediment samples for pollen analyses originated from different cores: core IZN05/LC1 (coring location: 40°26.033 N, 29°31.999 E; recovered in summer 2005) from the composite profile IZN05/SC4E&LC1 (Ülgen et al., 2012) and cores IZN09/LC2 (coring location: 40°26.57 N, 29°32.35 E) and IZN09/LC3 (coring location: 40°26.92 N, 29°32.61 E; both recovered in autumn 2009) from the composite profile IZN09/LC2&LC3 (Roeser et al., 2012).

The composite profiles IZN05/SC4E&LC1 and IZN09/LC2&LC3 could be clearly correlated through Ca / Ti and Ca / Fe ratios, respectively, each supported by lithology (Ülgen et al., 2012: Fig. 5; Roeser et al., 2012: Appendix A). The tie point between the two composite profiles is a tephra from a Vesuvius eruption, an Avellino Pumice (AP) tephra, which was geochemically identified in both records (Ülgen et al., 2012; Roeser et al., 2012). The tephra was dated to 3945 ± 10 a cal BP (Sevink et al., 2011). The finding at Lake Iznik represents the easternmost evidence for the AP tephra, which is an important chronostratigraphic marker for a direct comparison with other paleo records (Çağatay et al., 2015), e.g., Lago Grande di Monticchio, Italy (Allen et al., 2002; Wulf et al., 2004) or Lake Shkodra, Albania and Montenegro (Sulpizio et al., 2010; Sadori et al., 2015). The final composite profile has a composite length of ca. 18 m (Roeser et al., 2012). The age-depth model from Roeser (2014) was extended with dates from core IZN05/LC1 (Ülgen et al., 2012) in order to expand it to recent times (Roeser et al., 2016).

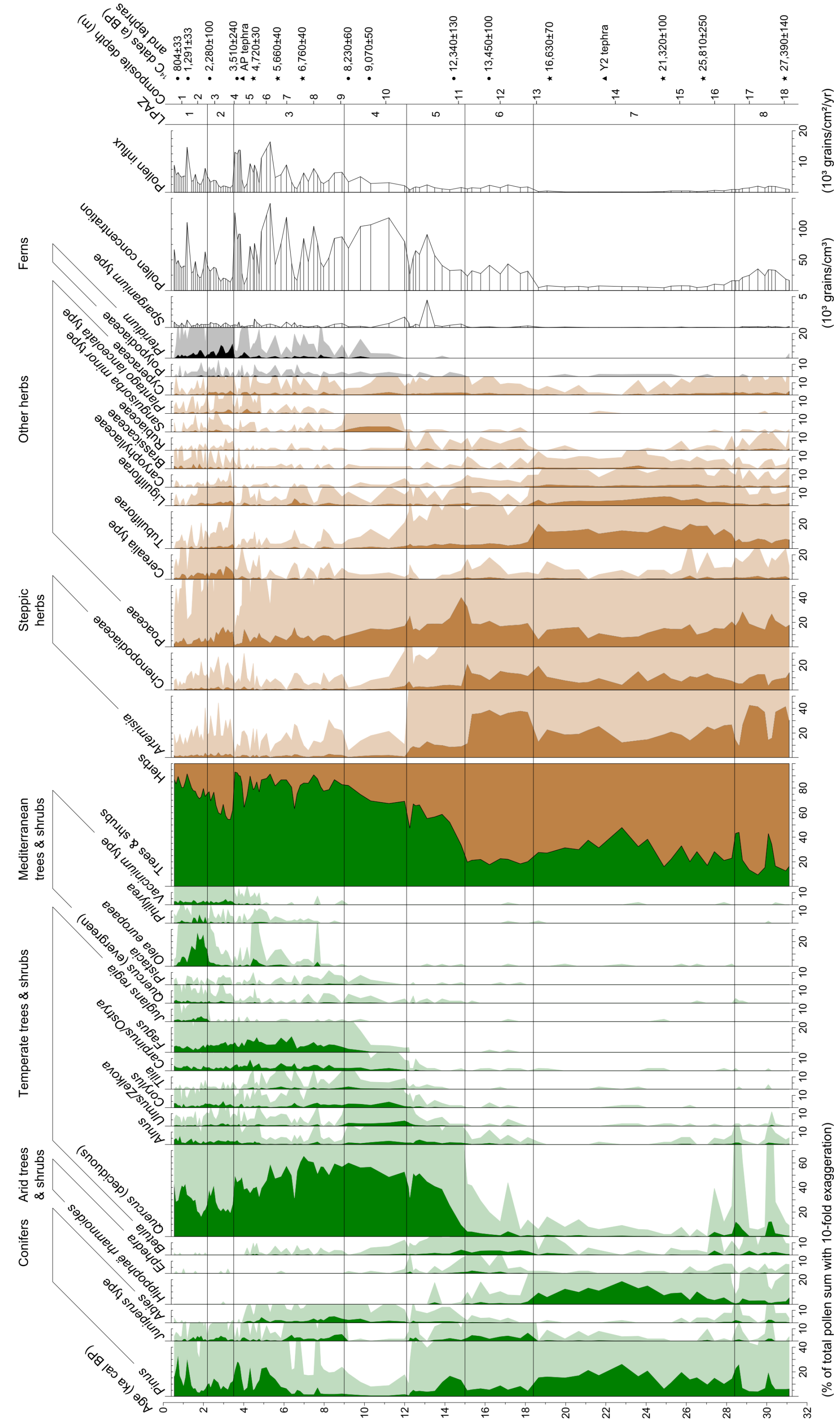

Figure 4. Pollen diagram inferred from Lake Iznik sediments with selected terrestrial plants in percentages, selected aquatic plants in concentrations, total pollen concentrations, total pollen influxes (pollen accumulations), and local pollen assemblage zones (LPAZ). Radiocarbon dates from plant remains (circles) and bulk organic (stars) as well as tephra positions according to Ülgen et al. (2012) and Roeser (2014) are marked.

3.2 Palynological analyses

33 sediment samples from core IZN05/LC1 were taken in a mean resolution of 12.6 cm ranging from the uppermost part of the core (0.51 m composite depth) to the AP tephra (4.58 m composite depth). After a first low-resolution screening of the composite profile IZN09/LC2&LC3, additional samples were processed in sections where climatic events were already known from geochemical analysis (Roeser et al., 2012; Roeser, 2014), the temporal resolution was very low, or palynological events were detected. Finally, 78 sediment samples from composite profile IZN09/LC2&LC3 were taken in a mean resolution of 17.5 cm ranging from the AP tephra to the end of the record (18.14 m composite depth). All samples had a sediment volume of mostly ca. 4 cm^3 (sampled with plastic syringes).

For the pollen preparation of the 111 sediment samples, we followed a standard protocol described in Faegri and Iversen (1989). The chemical treatment included 10 % hot hydrochloric acid (HCl) to remove carbonates (10 min), 40 % hydrofluoric acid (HF) to remove silicates (at least 48 h), 10 % hot HCl (10 min), glacial acetic acid ($C_2H_4O_2$), hot acetolysis with 1 part concentrated sulfuric acid (H_2SO_4) and 9 parts concentrated acetic anhydrite ($C_4H_6O_3$) to remove cellulose (max. 3 min), and $C_2H_4O_2$. Coarser particles than 200 µm and finer particles than 10 µm were removed by sieving and ultrasonic sieving, respectively. Lycopodium tablets with 18 584 $\pm$ 371 spores were added to each sample as markers to calculate absolute pollen and NPP concentrations (Stockmarr, 1971). With the help of the concentration and sedimentation rates, influx (pollen accumulation) rates were calculated. Samples were preserved in glycerol and were stained with safranine.

Microscopic analyses were carried out with Zeiss Axio Lab.A1 light microscopes using a magnification of 400. The pollen reference collection of the Steinmann Institute (University of Bonn) and palynomorph keys (Faegri and Iversen, 1989; Moore et al., 1991; Reille, 1995, 1998, 1999; Chester and Raine, 2001; Beug, 2004) were used for the palynomorph identification. We mainly followed Beug (2004) for the nomenclature of pollen types. A minimum of 500 terrestrial pollen grains were counted in each sample (joint analyses by Phoebe Niestrath (0.51–4.58 m) and Andrea Miebach (4.58–18.14 m)). Obligate aquatic plants were excluded from the total pollen sum to exclude local taxa growing in the lake (Moore et al., 1991). Furthermore, destroyed, immature, and unknown pollen were excluded from the total pollen sum, which was used to calculate percentages of the pollen assemblage. Pollen types were grouped as follows: conifers, arid trees and shrubs (*Ephedra*, *Haloxylon*, *Hippophaë rhamnoides*), Mediterranean trees and shrubs (*Celtis*, *Ceratonia siliqua*, *Fraxinus ornus*, *Olea europaea*, *Phillyrea*, *Pistacia*, evergreen *Quercus*, *Vaccinium* type), temperate trees and shrubs (all other trees and shrubs), steppic herbs (*Artemisia*, Chenopodiaceae), and other herbs.

Pollen diagrams were prepared with Tilia, Version 1.7.16 (© 1991–2011 Eric C. Grimm). A stratigraphically constrained cluster analysis using a square root transformation was applied by CONISS (Grimm, 1987). All taxa with more than 2 % of the total pollen sum and the sum of arboreal pollen (AP) were used for the cluster analysis. On this basis and visual pattern, local pollen assemblage zones (LPAZ) were determined.

4 Results and discussion

Selected pollen and spore data are presented in Fig. 4. According to the present age-depth model (Roeser et al., 2016), the temporal resolution of the record varies between 1139 and 57 years with an average of 278 years. Eight local pollen assemblage zones (LPAZ) were defined and are summarized in Table 2. The LPAZ are in agreement with previously defined lithological units, which are known to relate to specific climate phases (Roeser et al., 2012; Roeser, 2014). A complete pollen diagram with all taxa can be found in the Supplement.

4.1 MIS 3-2 transition: ca. 31.1–28.4 ka cal BP (LPAZ 8)

Lake Iznik's LPAZ 8 corresponds to the transition of Marine Isotope Stages (MIS) 3 and 2 (definition after Lisiecki and Raymo, 2005). The pollen assemblage documents a predominance of steppe vegetation with dwarf shrubs, herbs, and grasses dominated by wormwood (*Artemisia*), Tubuliflorae, Chenopodiaceae, and Poaceae (Fig. 4). Such a vegetation composition suggests generally dry and cold conditions. Still, climatic conditions allowed limited occurrences of arboreal taxa, especially pines (*Pinus*). Low to moderate pollen concentrations suggest a rather sparse vegetation cover.

However, two distinct rapid vegetation changes are evident, which are characterized by an increase of grasses (Poaceae) followed by a spread of pines, deciduous oaks (*Quercus*), and Cupressaceae (*Juniperus* type). Moreover, cold-tolerant trees like alders (*Alnus*) and firs (*Abies*) occurred in limited amounts. The decrease of steppic elements and arid-tolerant trees like common seabuckthorn (*Hippophaë rhamnoides*) together with a spread of trees and shrubs suggests increasing available moisture and higher temperatures, i.e., interstadial conditions. The vegetation was probably similar to today's xero-Euxinian steppe forest (Fig. 3), which is characterized by 300–600 mm mean annual precipitation (Roberts and Wright, 1993). These rapid vegetation changes can be correlated to Dansgaard-Oeschger (DO) events DO-4 and DO-3 (definition of term after Rasmussen et al., 2014). DO events originated in the North Atlantic and were transferred by atmospheric and oceanic circulations into the Eastern Mediterranean (Tzedakis et al., 2004). During DO interstadials, the Iznik basin was probably climatically advantaged for the spread of trees and shrubs, especially in low altitudes and at south-

Table 2. Local pollen assemblage zones (LPAZ) with composite depths, ages, the number of pollen samples, the temporal resolution, main components of the pollen assemblage (AP: arboreal pollen, NAP: non-arboreal pollen, percentages refer to the total pollen sum and give minimal and maximal values for the respective LPAZ), pollen concentrations (PC), definitions of lower boundaries (LB), and the inferred dominant vegetation type.

LPAZ	Depth (m)	Age (ka cal BP)	No. of pollen samples/ temporal resolution (years)	Pollen assemblage	Dominant vegetation type
(1) *Olea europaea* LPAZ	0.51–2.65	0.6–2.2	17/102	AP: predominance with increasing trend: 71.4–91.6 %, high amounts of deciduous *Quercus* and *Pinus*, maximum of *Olea europaea* (0.6–28.3 %), plateau of *Juglans regia*. NAP: Poaceae (2.2–7.8 %) and Cerealia type (0.5–5.9 %) are most abundant. PC: moderate to high. LB: increase of *Olea europaea* and *Juglans regia*, decrease of deciduous *Quercus*	Mixed forest with some Mediterranean elements; strong anthropogenic exploitation on the natural vegetation and fruit and cereal cropping
(2) Cerealia type LPAZ	2.65–3.97	2.2–3.5	11/116	AP: predominance with rapid decrease followed by an increasing trend: 54.5–77 %, mainly deciduous *Quercus*, *Pinus*, and *Fagus*. NAP: Poaceae (4–16.5 %) and Cerealia type (2.4–11 %) are most abundant. PC: low to moderate. LB: increase of NAP, Poaceae, Cerealia type, Liguliflorae, Tubuliflorae, and *Vaccinium* type, decrease of AP, deciduous *Quercus*, *Pinus*	Mixed forest with some Mediterranean elements; strong anthropogenic exploitation on the natural vegetation and cereal cropping
(3) Deciduous *Quercus* LPAZ	3.97–9.16	3.5–9.0	32/179	AP: predominance: 63.2–93.1 %, mainly deciduous *Quercus*, *Fagus*, and *Carpinus/Ostrya*, increasing but unstable values of *Pinus*, peak of *Olea europaea* (0–6.9 %). NAP: Poaceae (1.5–16.3 %) is most abundant, peak of Liguliflorae (0–5.9 %). PC: rapid fluctuations between low and high. LB: increase of *Juniperus* type, decrease of *Sanguisorba minor* type, *Ulmus*/*Zelkova*, and *Alnus*	Diverse deciduous and mixed forest dominated by oaks with an increasing influence of pines
(4) *Sanguisorba minor* type LPAZ	9.16–10.27	9.0–12.1	5/664	AP: predominance with increasing trend: 67.5–82.2 %, mainly deciduous *Quercus*, plateau of *Ulmus*/*Zelkova*. NAP: Poaceae (9.8–17.1 %) and *Sanguisorba minor* type (0.2–4.5 %) are most abundant. PC: high. LB: increase of AP and deciduous *Quercus*, decrease of *Artemisia*	Full development of deciduous forest dominated by oaks, which get successively accompanied by cool-temperate and warm-temperate species
(5) Poaceae-deciduous *Quercus* LPAZ	10.27–11.13	12.1–15.0	10/314	AP: strong increase up to predominance: 33.7–67.1 %, mainly due to strong increase of deciduous *Quercus* (9.7–51.8 %), peak of *Pinus*, increase of *Alnus*. NAP: initial predominance but with rapid decrease, two peaks of Poaceae (13.5–40.6 %), weak peak of Chenopodiaceae (2–7 %). PC: moderate to high with one peak. LB: increase of AP, deciduous *Quercus*, and *Pinus*, decrease of NAP and Chenopodiaceae	Establishment of oak-dominated woodland (with one weak and one stronger setback) and a decreasing influence of steppe
(6) *Artemisia*-*Juniperus* type LPAZ	11.13–12.91	15.0–18.4	8/428	AP: *Pinus*, *Juniperus* type, *Betula*, and deciduous *Quercus* are most abundant, maximum of *Ephedra* (0.2–2.6 %). NAP: predominance: 77.4–82.3 %, mainly *Artemisia*, Poaceae, and Chenopodiaceae. PC: moderate. LB: increase of *Artemisia*, *Juniperus* type, and *Betula*, decrease of Tubuliflorae, Liguliflorae, *Hippophaë rhamnoides*, and *Pinus*	Productive dwarf shrub steppe with scattered stands of pioneer trees
(7) *Hippophaë rhamnoides*-Tubuliflorae LPAZ	12.91–16.55	18.4–28.4	18/554	AP: high amounts of *Pinus* (6.5–26.4 %), maximum of *Hippophaë rhamnoides* (1.7–18.9 %). NAP: predominance with stable assemblage and abundance: 52.1–83.9 %, mainly *Artemisia*, Tubuliflorae, Poaceae, Chenopodiaceae, and Liguliflorae. PC: very low. LB: increase of NAP, *Artemisia*, and Tubuliflorae, decrease of AP and deciduous *Quercus*	Open steppe with very low vegetation cover
(8) *Artemisia*-deciduous *Quercus* LPAZ	16.55–18.14	28.4–31.1	11/259	AP: *Pinus* (4.2–26.3 %) and deciduous *Quercus* (0.6–12.5 %) are most abundant and peak twice. NAP: predominance with rapid fluctuations: 56–90.6 %, mainly *Artemisia*, Poaceae, Chenopodiaceae, and Tubuliflorae. PC: low to moderate. LB: not defined (end of record)	Fluctuation between open dwarf shrub steppe and forest steppe with scattered trees and shrubs

facing slopes. The complex topography allowed plants to move in altitudinal direction and resulted in many microhabitats with probably favorable microclimates. However, the warm and moist phases were not strong or long enough to allow the occurrence of warm temperate trees and Mediterranean sclerophylls. The rapid but short-term expansion of trees and shrubs indicates that glacial refuge areas for temperate taxa were nearby.

The sparse vegetation cover in the Iznik area during stadial conditions is supported by low loads of terrestrial organic material into Lake Iznik documented by geochemical indicators, e.g., low ratios of total organic carbon and total nitrogen (TOC / TN; Roeser, 2014; Fig. 5). During DO-4 and DO-3, the lacustrine bioproductivity and endogen carbonate production, which are expressed by the calcium/titanium (Ca / Ti) ratio, increase simultaneously with arboreal pollen (AP) percentages in response to increased summer temperatures (Roeser et al., 2012; Fig. 5). Thus, our new pollen data set complements and confirms the former identification of DO events based on multi-proxy analysis (Roeser, 2014). An almost absence of the green algae *Pediastrum* and *Botryococcus* and the occurrence of dinoflagellate cysts of *Spiniferites cruciformis* at Lake Iznik (Fig. 5) suggest a low aquatic bioproductivity and oligotrophic conditions (low nutrient level; Jankovská and Komárek, 2000; Kouli et al., 2001). Increasing *Spiniferites cruciformis* amounts might be a result of higher water temperatures (Shumilovskikh et al., 2014).

The comparison of this study to vegetation studies from the southern Black Sea (Shumilovskikh et al., 2014; Fig. 6) and the Marmara Sea (core MAR94-5; Mudie et al., 2002) suggests a rather uniform vegetation in northwestern Turkey. However, higher pollen concentrations and higher abundances of AP in core MAR94-5 suggest a denser vegetation and more favorable conditions for tree growth in the central Marmara region (Mudie et al., 2002). The spread of deciduous oaks during DO events seems to be a general pattern in the northeastern Mediterranean, although several pollen records do not show a response to every interstadial. In fact, climatic conditions during DO-3 and DO-4 were probably still too harsh or favorable conditions were too short-lasting that several records do not show significant changes in the vegetation (Fletcher et al., 2010 and references therein).

A temporal offset of the Lake Iznik record is recognized by comparing it to the NGRIP δ^{18}O record (NGRIP members, 2004; Fig. 6) and the isotopic record from the well-dated Sofular Cave in northern Anatolia (Fleitmann et al.,

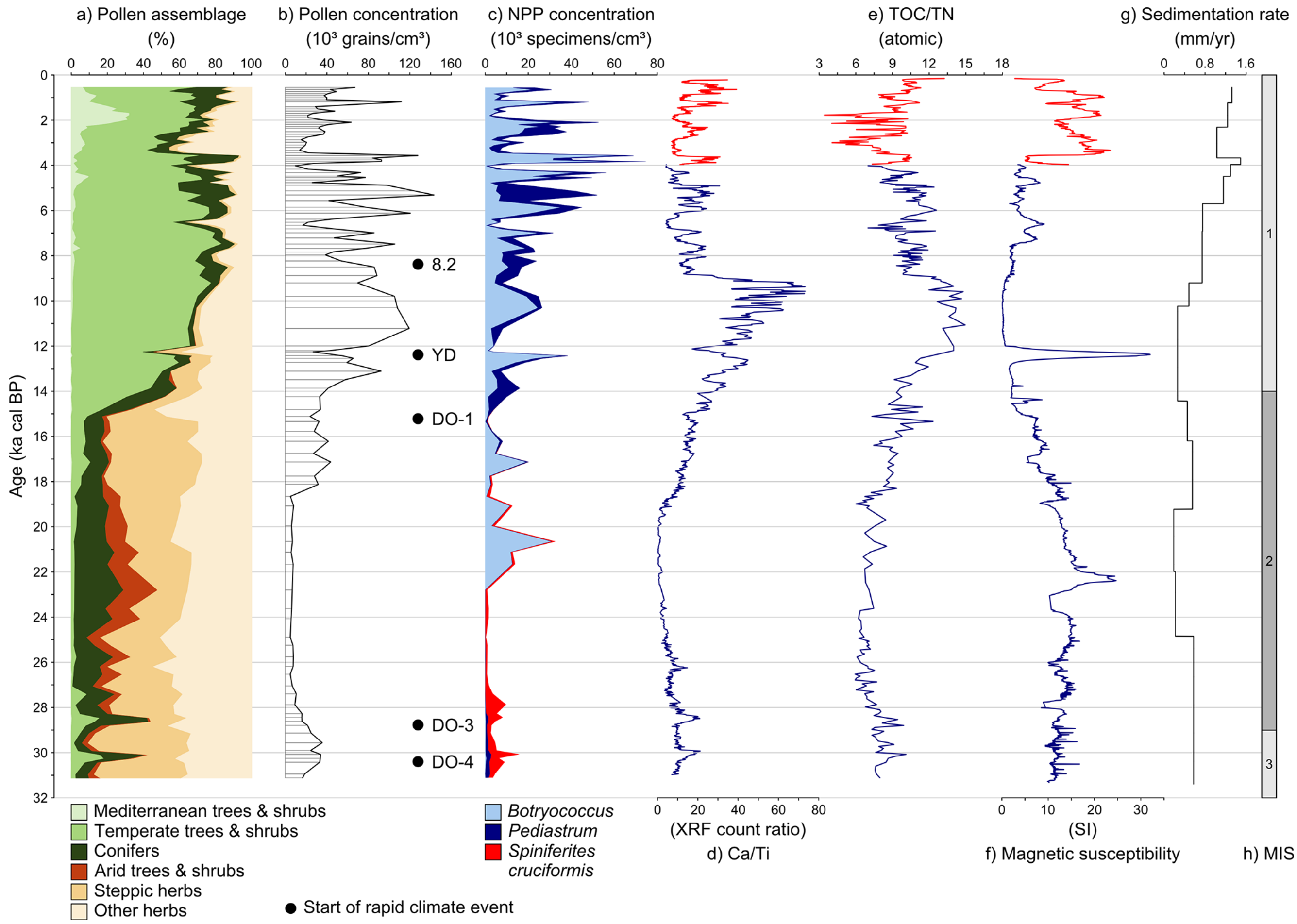

Figure 5. Comparison of different proxies inferred from Lake Iznik sediments: (a) pollen assemblage, (b) total pollen concentrations, (c) non-pollen palynomorph (NPP) concentrations, (d) calcium/titanium (Ca / Ti) ratios (represent the lake-wide endogen carbonate precipitation; relative changes between the red curve (Ülgen et al., 2012) and the blue curve (Roeser et al., 2012) are comparable), (e) total organic carbon/total nitrogen (TOC / TN) ratios (relate to catchment vegetation cover and are influenced by the distance to the shoreline; hence, differences between the red curve (Ülgen et al., 2012) and the blue curve (Roeser, 2014) most likely result from different coring locations), (f) magnetic susceptibility (relatable to the detrital input and the diagenetic remobilization of iron and sulfur; changes between the red curve (Ülgen et al., 2012) and the blue curve (Roeser et al., 2012) are most likely analytical artefacts), (g) sedimentation rates (Roeser et al., 2016), (h) marine isotope stages (MIS; Lisiecki and Raymo, 2005). Dots mark Dansgaard-Oeschger events (DO), the Younger Dryas (YD), and the 8.2 event.

2009; Fig. 6). Fleitmann et al. (2009) already described an age difference for the onset of DO-4 and DO-3 of the Sofular Cave compared to the NGRIP data of 586 and 277 years, respectively. The temporal offset of Lake Iznik's record is even larger. Although timing and amplitude of climate changes and its impact on vegetation can differ from region to region, slight inaccuracies in the lower part of the current age-depth model for Lake Iznik are likely.

4.2 Pre-LGM and LGM: ca. 28.4–18.4 ka cal BP (LPAZ 7)

A steppe vegetation predominated in the Iznik area during the pre-LGM and LGM (Last Glacial Maximum, i.e., the period with maximal global ice volume dating back to 23–19 ka cal BP according to Yokoyama et al., 2000 and Tzedakis, 2007). The abundance of the arboreal species *Hippophaë rhamnoides* suggests a cool and dry steppe (Tarasov et al., 1998), which is supported by a very low vegetation productivity (low pollen concentration and influx; Fig. 4). In contrast to adjacent LPAZs, a significant increase in percentages of the herbaceous Tubuliflorae and Liguliflorae as typical open-land indicators (Litt et al., 2012) is evident. The vegetation composition and the extremely low vegetation productivity suggest that precipitation rates were very low, probably comparable with 100–300 mm annual precipitation of today's Central Anatolian dwarf shrub steppe (Roberts and Wright, 1993; Fig. 3). Pollen influx values of all taxa

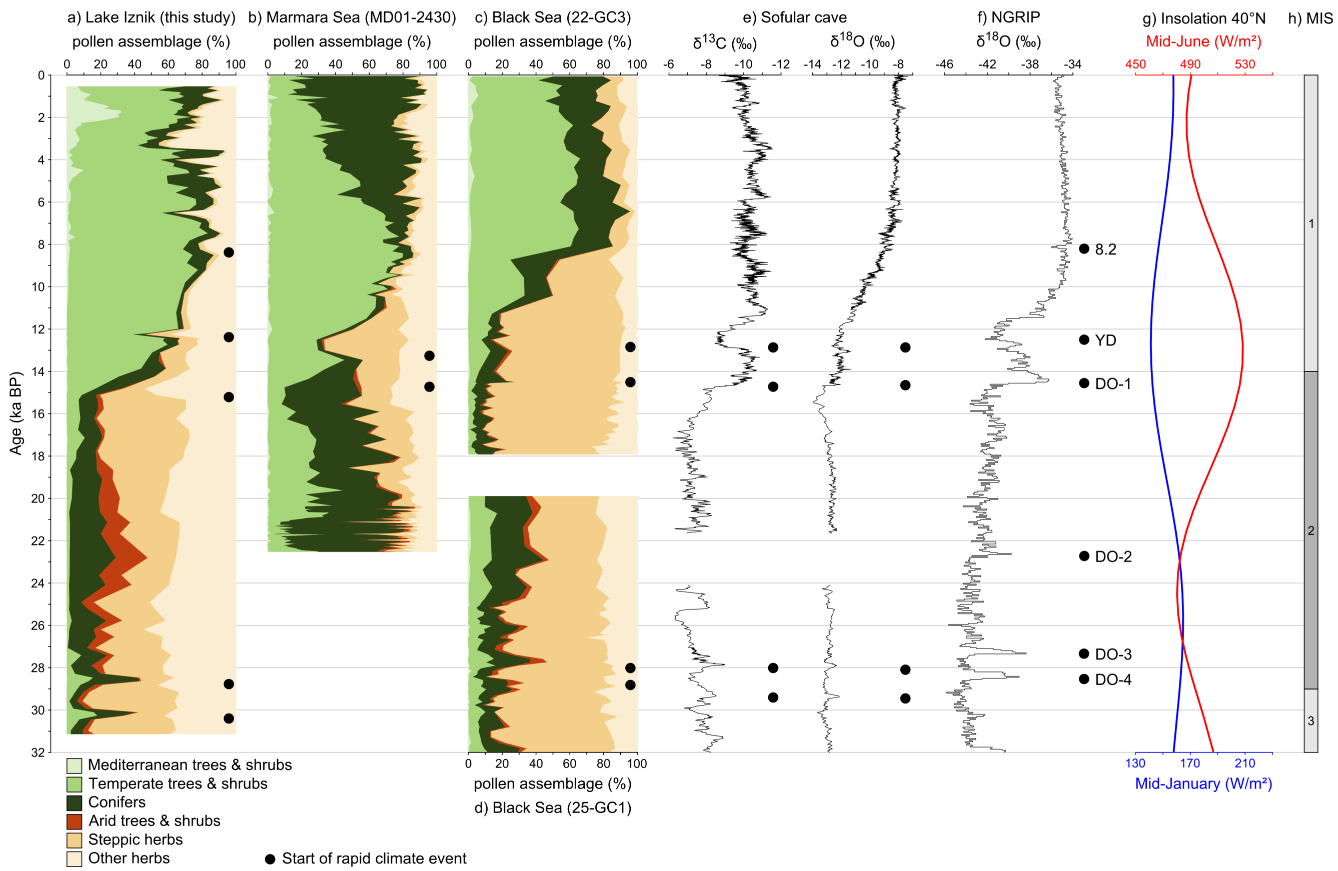

Figure 6. Comparison of pollen assemblages from (a) Lake Iznik (this study), (b) Marmara Sea, core MD01-2430 (Valsecchi et al., 2012), (c) Black Sea, core 22-GC3 (Shumilovskikh et al., 2012), and (d) Black Sea, core 25-GC1 (Shumilovskikh et al., 2014) with (e) isotope data from Sofular cave (Fleitmann et al., 2009), (f) isotope data from Greenland (NGRIP members, 2004), (g) mid-June and mid-January insolation (Berger, 1978; Berger et al., 2007), and (h) marine isotope stages (MIS; Lisiecki and Raymo, 2005). Dots mark Dansgaard-Oeschger events (DO), the Younger Dryas (YD), and the 8.2 event.

are lower than in adjacent LPAZ, which indicates that high percentages are not a result of increased pollen amounts of the concerned taxa but result from statistical effects. The high AP ratio must therefore be interpreted with cautions. Nevertheless, some taxa like Tubuliflorae, Liguliflorae, *Hippophaë rhamnoides*, and *Pinus* were more abundant compared to other taxa. This could be explained as follows (1) they were not as much effected by the harsh conditions as other taxa, (2) these plants lived in special habitats where microclimatic conditions were more favorable, or (3) pollen grains were transported by long distance. Due to the low pollen production by the upland vegetation of the Iznik area during LPAZ 7, the proportion of long-distance transported pollen is much larger (especially for *Pinus*; van Zeist et al., 1975; Faegri and Iversen, 1989).

The geochemical and sedimentological results from Lake Iznik indicate a low lacustrine bioproductivity coupled to a low endogen carbonate production (low Ca / Ti ratios) as a result of lower summer temperatures during the LGM (Roeser et al., 2012; Fig. 5). The deposition of dropstones within a clay matrix suggests the occurrence of at least a partial ice cover of Lake Iznik (Roeser, 2014). Still, the water conditions allowed the occurrence of *Botryococcus* (Fig. 5), which has a wider ecological tolerance than *Pediastrum* and can also survive in very cold or nutrient poor waters (Jankovská and Komárek, 2000). Peaking values of the magnetic susceptibility are ascribed to the deposition of the Y2 tephra (Roeser et al., 2012; Fig. 5), which is related to the ca. 22 ka cal BP Cape Riva eruption of Santorini (Pichler and Friedrich, 1976; Eriksen et al., 1990). It is an important chronostratigraphic marker in the Eastern Mediterranean (Çağatay et al., 2015).

In general, most paleoclimate records and models of the Eastern Mediterranean agree on cold and arid conditions during the LGM (van Zeist and Bottema, 1988; Robinson et al., 2006; Tzedakis, 2007; Valsecchi et al., 2012 (Fig. 6); but also see Şenkul and Doğan (2013) for another conclusion). Likewise the pollen record from the southern Black Sea indicates colder and drier climatic conditions compared to today, although an increased moisture availability compared to MIS

3 allowed the expansion of woodland (Shumilovskikh et al., 2014; Fig. 6).

However, ambiguous data are present for the millennia prior to the LGM, including the detection of rapid climate events. Although many high-resolution Eastern Mediterranean pollen records generally document vegetation changes in response to DO events, DO-2 (23.3–22.9 ka cal BP; Rasmussen et al., 2014) is not registered by the majority of records (Fletcher et al., 2010 and references therein). Compared to other DO events, the amplitude of the δ^{18}O curve from North Greenland in response to DO-2 is in fact quite low (NGRIP members, 2014; Fig. 6). However, the Tenaghi Philippon pollen record indicates the spread of pines in response to DO-2 (Müller et al., 2011). A vegetation response to DO-2 is not visible in Lake Iznik's pollen record because the environmental advantages did probably not cross a critical threshold for tree growth in the eastern Marmara region (but also note the rather low temporal resolution of samples; Table 2). Likewise, there is no unambiguous evidence for a vegetation change in response to Heinrich Stadial 2 (26.5–24.3 ka cal BP; Sanchez Goñi and Harrison, 2010) in Lake Iznik's pollen record. Environmental changes related to this rapid climate event were documented in some Eastern Mediterranean records, e.g., from the northwestern Black Sea (Kwiecien et al., 2009) and the Dead Sea (Torfstein et al., 2013). However, other records, e.g., from the Tenaghi Philippon site (Tzedakis et al., 2004) and the southern Black Sea (Shumilovskikh et al., 2014; Fig. 6) do not indicate a vegetation response related to Heinrich Stadials. In areas where tree populations were already close to their climatic tolerance limit, differences between harsh Heinrich Stadials and other stadials might not be detected because even moderate stadial conditions could cross the ecological threshold for tree growth (Tzedakis et al., 2004). This explanation could also pertain for the catchment of Lake Iznik. Still, a higher sampling resolution might result in the detection of rapid climate changes of centennial scale during that time.

4.3 Post-LGM: ca. 18.4–15 ka cal BP (LPAZ 6)

The onset of LPAZ 6 corresponds to the termination of the LGM and is marked by a ratio change of steppe components in Lake Iznik's pollen record: mainly *Artemisia* displaces Tubuliflorae, Liguliflorae, Brassicaceae, Caryophyllaceae, and *Hippophaë rhamnoides* (Fig. 4). The occurrence of *Ephedra*, a genus, which is associated with the desert biome (Prentice et al., 1996), points to seasonal moisture deficiencies. However, increasing pollen concentrations and decreasing open steppe indicators (especially Tubuliflorae and Liguliflorae) suggest a denser vegetation. The general higher plant productivity was supported by increased summer insolations (Berger, 1978; Berger et al., 2007; Fig. 6) implying higher temperatures and longer growing seasons. Moreover, pioneer trees of the Cupressaceae family (*Juniperus* and/or *Cupressus sempervirens*) and birch (*Betula*) formed open forests patches, which were accompanied by pines and successively also by deciduous oaks. The development of an open woodland with *Juniperus*, *Pinus*, *Betula*, and *Quercus* is typical for the pre-temperate phase of a glacial–interglacial cycle in southern Europe and corresponds to a climatic warming (Tzedakis, 2007).

Steadily increasing Ca / Ti ratios at Lake Iznik result from an increasing lacustrine bioproductivity in response to milder climatic conditions (Roeser et al., 2012; Fig. 5). The denser catchment vegetation contributes to an increased terrestrial proportion of accumulated organic matter, which is reflected by increasing TOC / TN ratios (Roeser, 2014; Fig. 5) and is supported by a decreasing magnetic susceptibility (Roeser et al., 2012; Fig. 5).

An ongoing dominance of steppe vegetation during the post-LGM is reflected in many Eastern Mediterranean records. Still, regional variations occurred: while eastern Anatolia was dominated by a cold semi-desert steppe with almost no arboreal taxa (Litt et al., 2009), more trees (primary pines) occurred in northern Turkey (van Zeist and Bottema, 1991; Shumilovskikh et al., 2012; Fig. 6), and the amount of arboreal pollen was even higher in the Aegean region (Kotthoff et al., 2008) and in Greece (Lawson et al., 2004; Müller et al., 2011). In contrast to our study, Kwiecien et al. (2009) and Valsecchi et al. (2012) proposed harsher climatic conditions during the post-LGM compared to the LGM for northwestern Turkey in response to Heinrich Stadial 1 (18–15.6 ka cal BP; Sanchez Goñi and Harrison, 2010). Valsecchi et al. (2012) suggested colder and/or drier conditions in the Marmara region due to increased pollen percentages of steppic plants and decreased percentages of temperate trees (Fig. 6).

4.4 Lateglacial: ca. 15–12.1 ka cal BP (LPAZ 5)

The onset of LPAZ 5 is characterized by shortly peaking values of Poaceae followed by an enormous increase of deciduous oaks and a peak of *Pinus* pollen amounts (Fig. 4). Simultaneously, steppe components like Chenopodiaceae decrease abruptly. The change in the vegetation composition suggests warmer and moister climatic conditions. A similar pattern was already found during DO-3 and DO-4 in Lake Iznik's pollen assemblage. Likewise, this vegetation change corresponds to DO-1, which can be used as a synonym for the Lateglacial Interstadial (Bølling-Allerød) and started ca. 14.6 ka cal BP according to the NGRIP record (Rasmussen et al., 2014). Pioneer forests of *Betula* and *Juniperus/Cupressus sempervirens* got successively replaced by temperate summer-green trees going along with a rapid forest expansion. However, pollen concentrations indicate that the forest expansion and the spread of oaks was somewhat slower than percentages may suggest. Therefore, the full development of the forests in the catchment of Lake Iznik did not take place before the early Holocene.

During LPAZ 5, two retreats in the forest expansion are noticeable. A peak of *Artemisia* together with a decrease of AP and a slowdown of the *Quercus* expansion indicate a weakening of favorable climatic conditions for tree growth and a short-term stagnation of forest expansion around ca. 13.3 ka cal BP. The period might correspond to a cooler sub-event during DO-1 (Rasmussen et al., 2014). The second forest retreat within LPAZ 5 (around ca. 12.3 ka cal BP) is much more pronounced. An abrupt decline of several trees and shrubs (with the exception of *Ephedra*), an expansion of mainly Chenopodiaceae and Poaceae, and a decrease of pollen concentrations mark a period of dryer and/or cooler climate in the catchment of Lake Iznik. This climate change is associated with the Younger Dryas (YD).

The rapid increase of deciduous oaks at ca. 15 ka cal BP coincides with a rapid rise of *Pediastrum* (Fig. 5), which indicates increasing lake water temperatures or a higher nutrient supply to the lake (Jankovská and Komárek, 2000). Increasing TOC / TN values might support a general higher biomass, although increasing proportions of terrestrial organic material in Lake Iznik can be related to phases of lower lake levels as indicated by independent proxies (Roeser, 2014; Fig. 5). The enhanced endogen carbonate production clearly outlines increasing summer temperatures (higher Ca / Ti ratios; Roeser et al., 2012; Fig. 5).

During DO-1, a short phase of lower algae concentrations (Fig. 5), lower Ca / Ti ratios (Roeser et al., 2012; Fig. 5), and lower TOC / TN ratios (Roeser, 2014; Fig. 5) also lead to the interpretation of a rapid cooling, which is expressed by the short-term stagnation of forest expansion. During the YD, the retreat of forests relates to lower summer temperatures (lowering Ca / Ti ratios) and colder water temperatures (low NPP concentrations). A 2 cm thick layer of coarse sediments possibly represents a timely coincident distal deposition of a mass movement. This coarser layer is overprinted by iron monosulfides expressed by a peak in the magnetic susceptibility (Roeser et al., 2012; Fig. 5). The YD is condensed in Lake Iznik's sediments due to low sedimentation rates. According to the well-dated NGRIP chronology (Rasmussen et al., 2014; NGRIP members, 2004; Fig. 6) and varve chronologies from Lake Van (Wick et al., 2003) and Europe (Litt et al., 2001), the YD phase lasted about 1100 to 1200 years.

The spread of deciduous oaks in response to the onset of DO-1 is a common pattern in the Eastern Mediterranean. It is registered in many pollen records from northwestern Turkey and Greece, e.g., from Tenaghi Philippon (Müller et al., 2011), Ioannina basin (Lawson et al., 2004), the Marmara Sea (Valsecchi et al., 2012; Fig. 6), and the southern Black Sea (Shumilovskikh et al., 2012; Fig. 6). In addition, rapidly increasing δ^{13}C values from Sofular Cave indicate the spread of trees and shrubs at the southern Black Sea coast since 14.6 ka cal BP (Fleitmann et al., 2009; Fig. 6). By contrast, the spread of deciduous oaks in other parts of the Near East started after the Pleistocene-Holocene boundary (Bottema, 1995). For example at Lake Van (eastern Turkey), a slow oak steppe-forest expansion suggests dry spring and summer conditions (Wick et al., 2003; Litt et al., 2009), and at the western Black Sea coast, a steppe vegetation dominated until the early Holocene (Atanassova, 2005).

The retreat of mesic forests and the spread of steppic vegetation is a typical expression of the Younger Dryas in the Marmara region (Mudie et al., 2002; Valsecchi et al., 2012; Fig. 6) and in general in the Eastern Mediterranean (Bottema, 1995; Rossignol-Strick, 1995). Also rapidly decreasing δ^{13}C values from Sofular Cave indicate the retreat of trees and shrubs at the southern Black Sea coast since 12.9 ka cal BP (Fleitmann et al., 2009; Fig. 6). In the pollen record from the southern Black Sea, the YD is less strongly expressed although a retreat of trees is still evident (Shumilovskikh et al., 2012; Fig. 6).

4.5 Early Holocene: ca. 12.1–9 ka cal BP (LPAZ 4)

The lower boundary of LPAZ 4 coincides with the Pleistocene-Holocene boundary, which was dated to 11.7 ka cal BP (e.g., Walker et al., 2008). The early Holocene of Lake Iznik's pollen record is characterized by constantly high percentages of *Quercus*, which shows that deciduous oaks were a major element of the landscape. Successively also other trees and shrubs followed. Main components (> 2 %) of the forest succession, which already started during the Lateglacial, were (1) deciduous *Quercus* together with an initial peak of *Pinus*, (2) *Alnus*, (3) *Ulmus*/*Zelkova* (elm/zelkova), (4) *Corylus* (hazel) and *Carpinus*/*Ostrya* (hornbeam), (5) *Abies*, (6) *Fagus* (beech). Constantly high pollen concentrations in LPAZ 4 point to a dense vegetation and a development from open woodland during DO-1 to dense forests during the early Holocene. As a result of the forest expansion, spores of the bracken fern (*Pteridium*) and Polypodiaceae, a family of polypod ferns, become constantly present. In contrast, all NAP components are very rare except for Poaceae and *Sanguisorba minor* type (*Sanguisorba minor* and/or *Sarcopoterium spinosum*), which reaches its highest percentages during LPAZ 4. The abrupt increase of *S. minor* type takes place simultaneously with the first consistence occurrence of *Pistacia* (pistachio) between ca. 11.2 and 12 ka cal BP. *Pistacia* is a poor pollen producer and known for its under-representation in sediments (Rossignol-Strick, 1995; Mudie et al., 2002; Lawson et al., 2004). Hence, low percentages (< 1.2 % at Lake Iznik) are still informative (Lawson et al., 2004). Furthermore, it indicates mild climatic conditions (Rossignol-Strick, 1995) with mean minimum temperatures of the coldest month above 5 °C (Prentice et al., 1996). Frosts, if present at all in the vicinity of Lake Iznik, were reduced in frequency. The warm temperatures went along with the high stand in summer insolation (Berger, 1978; Berger et al., 2007; Fig. 6). The spread of temperate and mesic trees together with the virtual absence of *Artemisia* and Chenopodiaceae also point to an increase of available moisture compared to glacial times.

During the early Holocene, the lake level of Lake Iznik was relatively low (Roeser et al., 2012), which resulted together with summer insolation maxima (Berger, 1978; Berger et al., 2007; Fig. 6) in overall highest Ca / Ti ratios (Roeser et al., 2012; Fig. 5). Also high amounts of terrestrial organic matter are documented in the sedimentary record (high TOC / TN ratios; Roeser, 2014; Fig. 5).

Similar to the rapid spread of forests in the Iznik area at the beginning of the Holocene, also δ^{13}C values from Sofular Cave decrease distinctly (Fleitmann et al., 2009; Fig. 6), which suggests an increase of effective moisture (Göktürk et al., 2011). In accordance to the Lake Iznik record, AP amounts from the Tenaghi Philippon record increase considerably (Müller et al., 2011). However, the pollen records from the southern Black Sea (Shumilovskikh et al., 2012; Fig. 6), the Aegean Sea (Kotthoff et al., 2008), and Lake Van (Litt et al., 2009) suggest a slower forest expansion.

The first consistent occurrence of the *Sanguisorba minor* pollen type and of *Pistacia* at the onset of the Holocene is a typical pattern of pollen records from the Eastern Mediterranean and can therefore be used as a stratigraphic marker (Rossignol-Strick, 1995; Kotthoff et al., 2008; Valsecchi et al., 2012). Our study confirms the stratigraphic character of these pollen types.

4.6 Mid-Holocene: ca. 9–3.5 ka cal BP (LPAZ 3)

The mid-Holocene in the Iznik area was characterized by a general continuing of temperate deciduous forest and mild and warm climatic conditions (Figs. 4, 7). However, the amount of conifers raised. The increased frequency of *Abies* and *Fagus*, which started already at ca. 9.8 ka cal BP but amplifies in LPAZ 3, suggests slightly moister climatic conditions compared to the early Holocene. The abundance of *Abies* was probably even higher than suggested by the pollen percentages because *Abies* is known for its underrepresentation in pollen diagrams (van Zeist et al., 1975). Firs and beeches probably grew in the mountain areas surrounding Lake Iznik.

Several phases of decreased forest cover and simultaneous drops of pollen concentrations and influxes are visible in LPAZ 3. Potential climatic triggers causing these vegetation changes are especially probable for periods when no or few anthropogenic indicator taxa (cultivated plants and non-cultivated plants, which benefit from anthropogenic influences; e.g., Behre, 1990; Bottema and Woldring, 1990; Fig. 7) appeared simultaneously. The most pronounced of these periods are centered at ca. 8, ca. 6.5, and ca. 4.1 ka cal BP. However, the determination of the exact duration of those changes is challenging because possible rapid fluctuations of the sedimentation rate would potentially affect the duration of recorded events and eventually also bias the pollen influx. Such expected rapid fluctuations are generally not accounted for by age-depth models, which reflect rather the average sedimentation. The high synchronicity of pollen concentrations and NPP concentrations support this assumption (Fig. 5).

Several anthropogenic indicator taxa appear in LPAZ 3 (Fig. 7). For instance, a small peak of *Olea europaea* percentages is visible around 7.7 ka cal BP. Still, this is not unambiguous evidence for olive cultivation, because olives are natural components of the Mediterranean vegetation (Zohary, 1973), the increase is just represented by a single sample and therefore needs further investigation, and olive cultivation in the Near East started most likely about a millennium later (Weiss, 2015) and is therefore very unlikely (cf. Sadori and Narcisi, 2001). Although also other anthropogenic indicator taxa can occur naturally in the Marmara region (Zohary, 1973), evidence for human activities consolidates when anthropogenic indicator taxa show higher abundances, several anthropogenic indicator taxa occur simultaneously, and natural forests retreat contemporaneously. Likewise, the first unambiguous evidence for human-induced changes of the vegetation documented in Lake Iznik's pollen record starts at ca. 4.8 ka cal BP. Olives and cereals were most likely cultivated. Although Cerealia type percentages only slightly increase, those changes are still informative due to their underrepresentation in pollen diagrams (van Zeist et al., 1975; Faegri and Iversen, 1989). The increase of the *Plantago lanceolata* pollen type may point to area disturbance or grazing (van Zeist et al., 1975; Behre, 1990). The simultaneous occurrence of *Vaccinium* type pollen, which probably originated from *Erica*, indicates the development of macchia vegetation (Kürschner et al., 1997).

Moister conditions since ca. 9 ka cal BP are also suggested by geochemical analysis from Lake Iznik (Roeser et al., 2012; Roeser, 2014). The abrupt retreat in carbonate accumulation indicates a lake level rise that lasted circa 500 years (decreasing Ca / Ti ratios; Roeser et al., 2012; Fig. 5).

Similar to the Lake Iznik record, also other studies document a moisture rise during the mid-Holocene. An increase in humidity since ca. 9.6 ka cal BP was inferred from the Sofular cave record based on high stalagmite growth rates and low $(^{234}U\,/\,^{238}U)_o$ ratios (Göktürk et al., 2011), while the pollen record from the southern Black Sea indicates moister and warmer climatic conditions since ca. 8.3 ka cal BP due to a rapid spread of temperate forest (Shumilovskikh et al., 2012; Fig. 6).

The 8.2 ka cold event is the most prominent rapid climate change (RCC) at northern high latitudes during the Holocene (Johnsen et al., 2001; NGRIP members, 2004; Fig. 6). Phases with reduced precipitation were described in several Eastern Mediterranean records, but they often lasted longer compared to the sharp and short 8.2 ka event at northern high latitudes (e.g., Staubwasser and Weiss, 2006; Kotthoff et al., 2008; Weninger et al., 2009; Göktürk et al., 2011). The vegetation change in the Iznik area around 8 ka cal BP might also correspond to the 8.2 event. However, the synchronous ap-

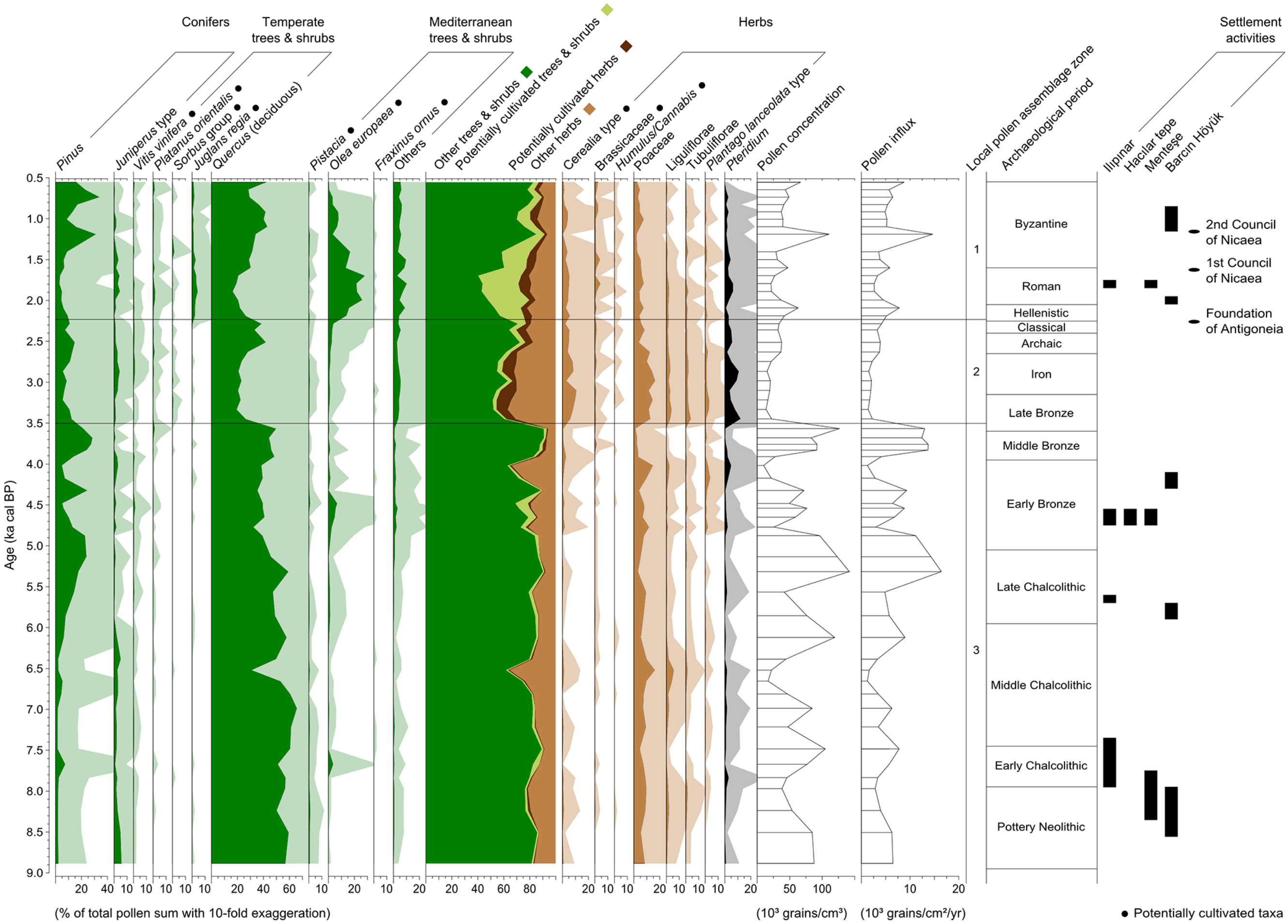

Figure 7. Pollen diagram of the last 9 ka cal BP inferred from Lake Iznik sediments with archaeological periods (Eastwood et al., 1998; Sagona and Zimansky, 2009), settlement activities of archaeological settlements in the vicinity of Lake Iznik (Ilıpınar, Hacılar tepe, and Menteşe after Bottema et al. (2001) and Barcın Höyük after Gerritsen et al. (2013a, b); see Fig 8. for the locations), the foundation of Antigoneia (later Iznik; Abbasoğlu and Delemen, 2003), and the two ecumenical councils of Nicaea (later Iznik; Şahin, 2003).

pearance of several archaeological settlements (Bottema et al., 2001; Gerritsen et al., 2013a, b; Fig. 7; see Fig. 8 for the locations) makes it difficult to separate anthropogenic and climatic influences on the vegetation. Also Bottema et al. (2001) considered human impacts for a contemporaneous destruction of forests in the Yenişehir area, south of Lake Iznik.

According to Roberts et al. (2011), a dry phase took place in the Eastern Mediterranean ca. 6600 years ago. The forest retreat in the Iznik area around 6.5 ka cal BP might correspond to this climate event (note that the age-depth model during this phase is based on radiocarbon dates subjected to reservoir effects; Roeser et al., 2014). However, the magnitude of the vegetation change is large, which leads to the assumption of (additional) anthropogenic influences. Although anthropogenic indicator species are rare and there is no evidence for settlements near Lake Iznik at that time (Fig. 7), the subsequent spread of pines might indicate a permanent open-

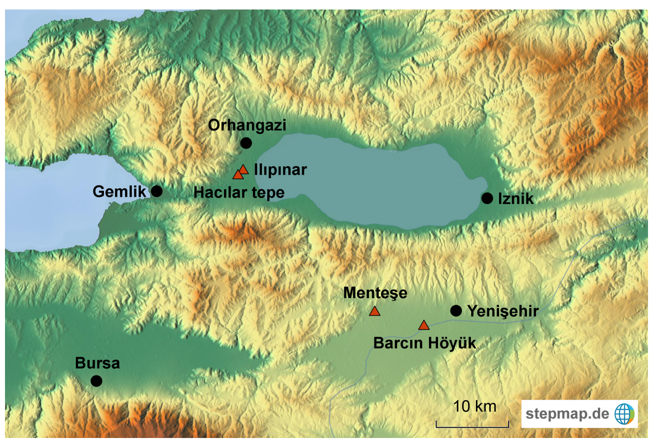

Figure 8. Archaeological settlements (red triangles) in the vicinity of Lake Iznik.

ing of forests by humans. Pines can have a pioneer role in anthropogenic influenced landscapes, and they quickly distribute in abandoned areas (Litt et al., 2012). Though, a similar spreading pattern of *Pinus* is also found in the pollen record from the Marmara Sea (Valsecchi et al., 2012; Fig. 6; note that pines are often considerably over-represented in marine pollen assemblages) and therefore counters against a local vegetation development.

The unambiguous evidence for human-induced vegetation changes in the Iznik area at ca. 4.8 ka cal BP is in accordance with documented settlement activities in the vicinity of Lake Iznik (Bottema et al., 2001; Gerritsen et al., 2013a, b; Fig. 7). Also Bottema et al. (2001) postulated the relationship of these settlements and a deforestation in the Yenişehir area.

According to Mayewski et al. (2004), there is evidence for an RCC at 4.2–3.8 ka cal BP in some paleo records on global scale (the so-called 4.2 ka event). A pronounced aridity prevailed in the Eastern Mediterranean around 4.2 ka cal BP, although timing and magnitude of changes varies considerably among different records (Bar-Matthews and Ayalon, 2011; Finné et al., 2011 and references therein; Masi et al., 2013). The forest retreat around ca. 4.1 ka cal BP in the Iznik area might also be associated with this dry period. However, an extensive cultural network across Anatolia was already established by the end of the Early Bronze Age (Sagona and Zimansky, 2009). Therefore, persistent anthropogenic influences on the vegetation are also possible.

4.7 Late Bronze Age to Classical Period: ca. 3.5–2.2 ka cal BP (LPAZ 2)

During the Late Bronze Age, at ca. 3.5 ka cal BP, an enormous change in the vegetation took place in the catchment of Lake Iznik (Fig. 7). At least since that time, the vegetation development was overprinted by human impacts and the detection of climate influences on the vegetation is hardly possible. Natural forests got cleared, from which mainly deciduous oaks and pines were affected. People probably cleared the low-altitude forests, where *Quercus* and *Pinus* were most likely common as they are today (Atalay et al., 2014). Cereal cropping was an important form of land use, while fruit cultivation played a minor role. Open land vegetation like Asteraceae (mainly Liguliflorae) and grasses benefited from the retreat of forests and from agricultural use including grazing (Bottema and Woldring, 1990; Florenzano et al., 2015). But also Mediterranean taxa like Ericaceae (*Vaccinium* type) and evergreen oaks became rapidly more abundant. The abundance of the *Plantago lanceolata* pollen type and the rapid increase of *Pteridium* indicate a stronger human activity in the catchment of Lake Iznik (van Zeist et al., 1975; Bottema and Woldring, 1990). *Platanus orientalis* (oriental plane) pollen grains are continuously present since ca. 3.9 ka cal BP. The oriental plane is a natural component of the local vegetation and is especially abundant in riparian habitats (van Zeist et al., 1975). It was probably planted to provide shade like it is still done today in Anatolian villages (Eastwood et al., 1998).

A conspicuous palynologically identifiable settlement period firstly described from southwestern Turkey, the Beyşehir occupation phase (BOP), started at ca. 3.4 ka cal BP (van Zeist et al., 1975; Eastwood et al., 1998). Correlating phases in pollen records were subsequently observed in greater parts of Turkey and in the Aegean region (Eastwood et al., 1998; Bottema, 2000). The similar timing of vegetation changes in the Iznik pollen record prompts to a correlation to this phase. Although the assemblage and abundance of cultivated taxa during the BOP varies among the different records (Eastwood et al., 1998; Bottema, 2000), the secondary role of arboriculture in the Iznik area depicts a major difference compared to other records. It is still not fully understood which culture accounted for the observed vegetation changes during the BOP (Eastwood et al., 1998). The Late Bronze Age was the time of the Hittites, who dominated large parts of Anatolia. However, no Hittite sites are known from northwestern Turkey including the Iznik area. The Iron Age in northwestern Turkey was politically shaped by the Kingdom of Phrygia, which was bordered by the Assyrian Empire to its southeast and the Kingdom of Urartu to its northeast (Sagona and Zimansky, 2009).

During the Archaic and Classical Period (ca. 2.6–2.2 ka cal BP) deciduous oaks recovered to a certain extent and open land vegetation as well as *Plantago lanceolata* type became less abundant. Such a pattern may indicate a different form of land use in certain areas. The re-spread of trees might indicate that logging, herding, or intentional burning was reduced (Bottema et al., 2001). Still, cereal cropping continued, which suggests a continuity of colonization and agriculture. At the beginning of the Archaic Period, the dynasty of Lydia displaced the Kingdom of Phrygia (Sagona and Zimansky, 2009). This change in culture and politics coincides with the described change in Lake Iznik's pollen assemblage.

4.8 Hellenistic Period to Byzantine Period: ca. 2.2–0.6 ka cal BP (LPAZ 1)

The uppermost LPAZ is characterized by an abrupt increase of *Olea europaea* and *Juglans regia*, which suggests that walnuts and especially olives were widely cultivated (Fig. 7). While cereal cropping continued like in previous phases, the arboriculture became an important additional agriculture form. Mainly deciduous oaks and pines were cut again. During the Hellenistic Period, the Iznik area was incorporated to the Bithynian Kingdom. Antigoneia (later Nicaea and finally Iznik) was founded at the eastern shore of Lake Iznik (Abbasoğlu and Delemen, 2003).

The maximal percentages of *Olea europaea* and minimal percentages of natural forest elements are found during the Roman Period (ca. 2.05–1.65 ka cal BP). Apparently, the general anthropogenic influence on the vegetation increased (higher amounts of *Pteridium* and lower pollen concentrations probably due to increased erosion), and olive cultivation expanded. In 74 BC (2024 BP), the Iznik area became incorporated into the Roman Empire. Iznik developed very quickly (Abbasoğlu and Delemen, 2003) and was one of the largest cities in the region. Furthermore, the city became famous for hosting a large ecumenical council in 325 AD (1625 BP; Şahin, 2003). Settlement activities are also described for other archaeological sites close to Lake Iznik (Bottema et al., 2001; Gerritsen et al., 2013a, b; Fig. 7).

Olea europaea pollen percentages retreat at ca. 1.3 ka cal BP, which indicates that many olive orchards were abandoned. Percentages of other human indicator taxa decrease as well. Concurrently *Pinus* pollen rise significantly, which suggests the recolonization of abandoned agricultural land by pine forests. Pines probably also benefited from human-induced soil degradation (Roberts, 1990). The AP ratio and pollen concentration reach magnitudes comparable to the mid-Holocene, which indicates that the vegetation still had the ability to recover despite the preceding disturbances. This was also the case at other forested sites in the Eastern Mediterranean (e.g., Ionnania, northwestern Greece). In contrast, in some drier areas (e.g., Central Anatolia) the anthropogenic forest loss was irreversible (Roberts et al., 2011 and references therein).

During the Byzantine Period (1.15–0.8 ka cal BP), a repeated foray of humans is documented in Lake Iznik's pollen record. The cultivation of olives and cereals increased once more, although it did not reach dimensions comparable to earlier times. Pines retreated quickly and strongly again, while deciduous oaks were not affected by the probable forest clearing. Simultaneously, in 787 AD (1163 BP), a second famous ecumenical council took place in Iznik (Şahin, 2003).

The uppermost part of LPAZ 1 shows a less intense human exploitation on the vegetation. The forest recovered and anthropogenic indicator taxa were not very abundant. This study covers the time period until ca. 0.55 ka cal BP (1400 AD) and therefore does not include the last centuries.

5 Conclusions

1. This study reveals the vegetation and climate history of the last ca. 31 000 years inferred from lacustrine sediments of Lake Iznik, the largest lake in the Marmara region. Special emphasis is given to climate variability based on signal analysis of biotic proxies such as pollen.

2. A steppe with dwarf-shrubs, grasses, and other herbs dominated during glacial/stadial conditions indicating dry and cold climatic conditions. In particular between ca. 28.4 and 18.4 ka cal BP (MIS 2), very low pollen concentrations and influx rates (pollen accumulation) suggest a very sparse vegetation cover and a very harsh climate. Therefore, pollen percentages are considerably biased amongst others by long distance transported pollen like *Pinus* pollen.

3. Forest-steppe with scattered stands of trees and shrubs (mainly deciduous oaks and pines) developed during interstadial conditions associated with Dansgaard-Oeschger events 4 and 3.

4. Deciduous oaks spread rapidly since the Lateglacial, which indicates warmer and moister climatic conditions. They were successively accompanied by other deciduous, coniferous, and evergreen trees. The spread of forests suffered a setback during the Younger Dryas caused by cold and/or dry climatic conditions.

5. Subsequent forest retreats were either caused by climatic anomalies (particularly the 8.2 event), human influences, or a combination of both. However, a clear anthropogenic impact on the vegetation is document in Lake Iznik's pollen record since ca. 4.8 ka cal BP. The vegetation development was overprinted by human impacts at least since the Late Bronze Age, which makes it hardly possible to detect climate-induced vegetation changes.

6. Cereals, olives, and walnuts were among the most important cultivars in the Iznik area. Oriental planes were probably planted to provide shade in settlements. Grape vines, mamma-ashes, stone fruit trees of the rose family (*Sorbus* group), pistachios, cruciferous crops (Brassicaceae), hop and/or hemp (*Humulus*/*Cannabis*) may have been cultivated.

7. Phases of different agricultural use alternated with phases of forest regeneration. A strong coincidence of vegetation changes and the regional archaeological history becomes apparent. Rapid fluctuations in pollen concentrations since the mid-Holocene might indicate rapid changes of Lake Iznik's sedimentation rates caused by catchment erosion.

Data availability

The complete pollen and NPP data set is available online at doi:10.1594/PANGAEA.858056.

The Supplement related to this article is available online at doi:10.5194/cp-12-575-2016-supplement.

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