



# Environment and settlement - A multiproxy record of holocene palaeoenvironmental development from Lake Wonieść, Greater Poland

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## Abstract

This multi-proxy approach combines results of sedimentological, pollen and diatom studies on sediments of Lake Wonieść, Greater Poland. This enables reconstruction of the natural and anthropogenic drivers of past environmental change. Several steps of lake development are recorded, from a eutrophic to an oligotrophic stage, and with increasing human influence back to a hypereutrophic one. Human influence in the form of eutrophication due to arable farming has been the main driver in the changing ecology of the lake in the second half of the Holocene. The record provides a diachronic perspective of regional “boom and bust” phases of greater or lesser human pressure on the landscape. Early evidence of cereal-type pollen indicates human occupation of areas of chernozem soil during the Linearbandkeramik (LBK) Neolithic period from 5250 cal BC onwards. A clear opening of the landscape occurred during the Trichterbecher (Funnel Beaker) period at ca. 3800 cal BC. From this time onwards, the human influence on the lake can be traced by the geochemical and diatom records. Neolithic, Bronze Age, Iron Age and medieval boom and bust phases of settlement intensity are discussed. A comparison with two other high-resolution lake records from Poland (Lakes Gościąż and Szurpiły) show a good agreement of many of the “boom and bust” phases with Lake Gościąż (“boom” at 3500 and 2150 cal BC, “bust” at 3250, 1560 and 1 BC) and a few even with both, Lake Szurpiły and Lake Gościąż (“boom” at BC and “bust” at 500 cal BC and cal AD 400). This is indicative of supra-regional changes in intensity of land use.

**Keywords** Greater Poland · Holocene · Lake sediment · Settlement history · "Boom and bust" of settlement phases · Pollen · Diatoms · Sedimentology

## Introduction

Palaeoenvironmental archives, like those from Lake Wonieść in Greater Poland, enable a comparison of settlement history with an independent record of land use intensity. The history of the cultural landscape of Wielkopolska (Greater

Poland) dates back to the Stone Age, with variable but generally increasing human influence on the environment over time. Legacies of Palaeolithic and Mesolithic hunter-gatherer-fisher groups indicate the presence of people during the early and middle Holocene. So far, artefacts of the Linearbandkeramik (LBK) people have been found in the region, but just for the late phase of this group, even though the first traces of human activity in the pollen records date back to the early phase of the Early Neolithic. Settlements and graves are further recorded from the Middle Neolithic Trichterbecher culture (TRB) (Szymt 2011). It was during the Early Bronze Age (EBA), however, that one of very few fortified settlements of the northern Únětice groups of Central Europe was established in the Bruszczewo region, on a peninsular in the valley of the river Samica. Bruszczewo is located 7.8 km west of Lake Wonieść. The date of the site, and its position at the eastern boundary of the Únětice area,

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**Fig. 1** The research region in Poland. The rectangle shows the area covered by Figs. 2 and 3

suggest it had an important role in the EBA trade network (Kneisel 2013; Czebreszuk and Müller 2015). The rich archaeological material culture of these groups reflects their position which connected the more northern Baltic area with Central European to the south. The Bronze Age settlement history of Bruszczewo is characterised by two distinct phases; the EBA occupation lasting from ca. 2100 to 1650 cal BC and a Late Bronze Age (LBA)/Iron Age one from ca. 1000 to 500 cal BC (Kneisel 2011). The period around 1600 BC, marking the beginning of the Middle Bronze Age (MBA), is generally characterised by a collapse of the Únětice groups (Kneisel 2012). This indicates that larger scale factors were responsible for the observed reduction in settlement activity. Settlement activities began again in the LBA on the peninsular and continued into the Iron Age. Many findings from the latter period indicate intense settlement at this time. In the Roman Iron Age, items of Roman origin represent contacts with the Roman Empire. The amber trade might have been one reason for the prosperity of the settlement during the Bronze and Iron Age. After the turbulence of the Migration Period, Wielkopolska (Greater Poland) became the core area for the Polish state in early medieval times. During the Middle Ages and into modern times the population increased, with declines at times of pestilence and war, as was typical for Central Europe. Thus the varied history of the region forms the background for the palaeoenvironmental studies of Lake Woniaść.

The focus of this investigations was first on Bronze Age developments, as they were initiated during archaeological excavations near Bruszczewo, in the district of Kościan. However, earlier and later sediments were also analysed in order to reconstruct human environmental impact and

land use changes during various archaeological periods, as well as their influence on internal processes within the lake. Therefore, this study offers an independent perspective on environmental and economic developments through time, and thus estimates the changing settlement activity and intensity in the Bruszczewo area. Furthermore, a comparison with other well-dated palaeoenvironmental records from northern Poland aims for the identification of supra-regional, larger-scale landscape changes.

## Materials and methods

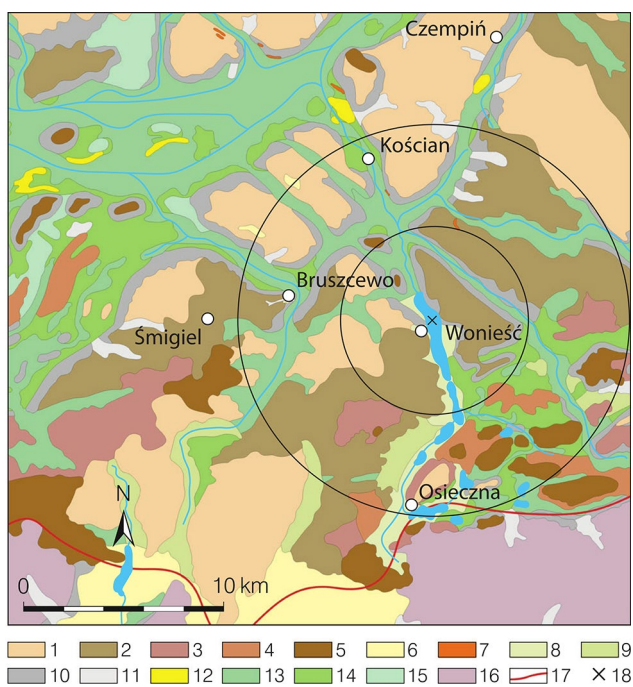
### Site description

Lake Woniaść is located 48 km south-southwest of Poznań in Greater Poland (Fig. 1). Together with a chain of four other lakes it is part of the landscape conservation area of Zbiornik Woniaść. In 1974 the lake level was raised two metres by a retaining wall to the modern level of 67.6 m a.s.l. It now has a surface of 121 ha, a greatest depth of 14.5 m, and an average depth of 6.2 m.

The landscape surrounding Lake Woniaść was formed during the last glaciation (Weichselian or Vistulian) with loamy ground moraine and inland outwash plains and a network of river valleys in glacial channels partly filled by lakes (Kondracki 2001; Hildebrandt-Radke 2010; Hildebrandt-Radke et al. 2011). The geomorphological map (Fig. 2) shows the distribution of valleys and moraine hills to the east and a flat plateau to the west of Lake Woniaść.

The soil map (Fig. 3) shows the dominance of sandy soils in the east and pseudo-podzolic soils to the west of the lake. On the plateau, chernozem (black earth) is also distributed in patches, forming the best farming land in the lake catchment.

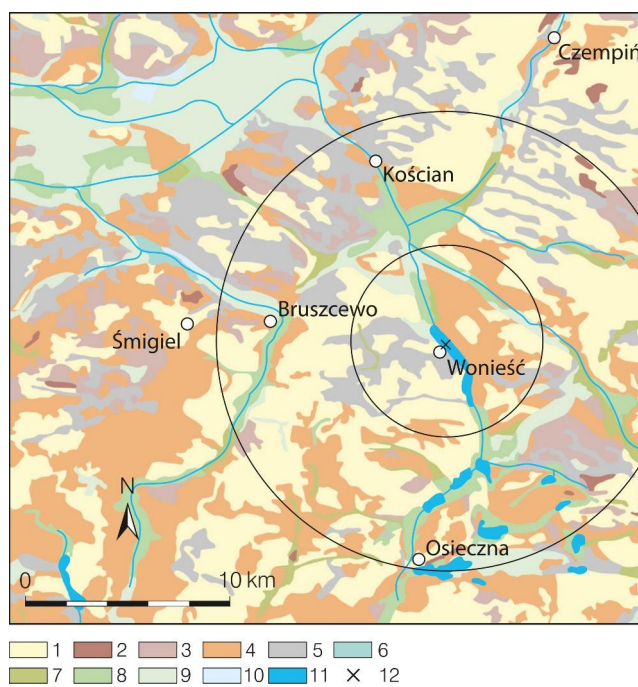
The potential natural vegetation communities of the area are described by Matuszkiewicz et al. (1995). The woodlands on dry loamy soils would be a *Galio-Carpinetum* vegetation association of *Quercus* and *Carpinus* woods. More sandy dry soils would be covered by *Querco-Pinetum* woods of pine and oak and some wetter spots by a *Calamagrostistio-Quercetum*. The sandy river valleys would carry a *Salici-Populetum* and with better soil conditions a *Fraxino-Alnetum* alder carr would grow in the valleys. In the surroundings of Lake Woniaść, all types of woodland have been mapped, with mainly the *Galio-Carpinetum* woods on poorer soils in the north and richer conditions in the south.



**Fig. 2** Geomorphology of the Wonieść region (after Hildebrandt-Radke 2013, based on Krzysztofka 1989, 1993 and Krygowski 1972) 1, flat moraine plateau, Weichselian/Vistulian glaciation; 2, undulating moraine plateau, Vistulian glaciation; 3, hilly moraine upland, accumulative in origin; 4, hilly moraine upland, erosive in origin; 5, moraine hills; 6, glacial outwash plain; 7, eskers; 8 glacial channels with flat bases; 9 glacial channels with uneven bases; 10, terraces and valley slopes; 11, small valleys and streams cutting higher land; 12, aeolian land forms; 13, flood plain; 14, middle terrace with dunes; 15 high terrace; 16 the Morenovo high plateau of the central Polish glaciation, flat moraine plateau, Warta/Saale glaciation; 17, the extent of the Leszno phase, Vistulian glaciation; 18 coring position in Lake Wonieść

**Coring and sampling**

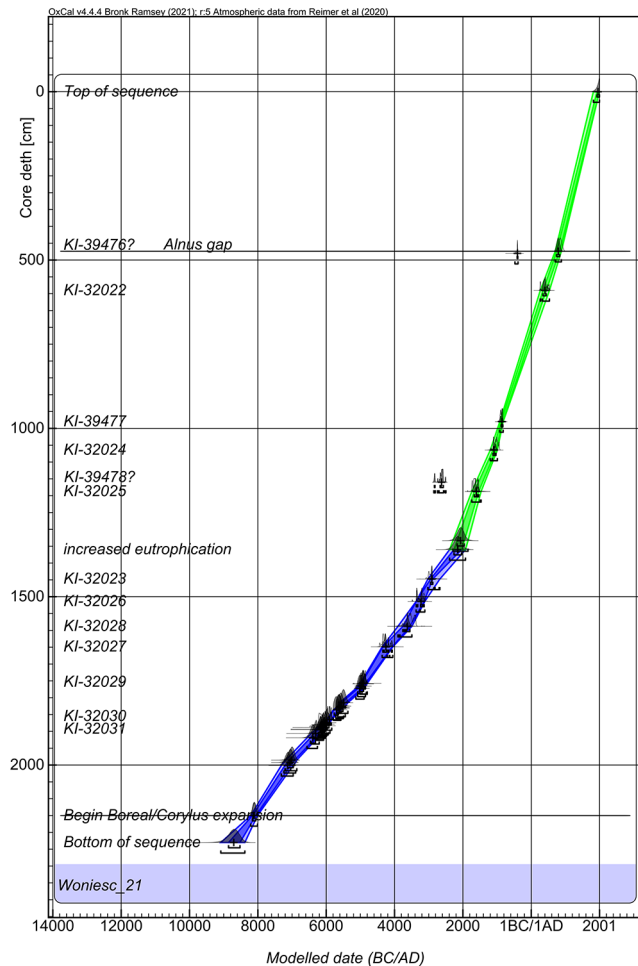
Coring was done in August 2006 from a raft in the middle of the lake with 13.6 m water depth (at N 51°59.815' and E 16°42.327'). The cores were taken using an Usinger coring system (Mingram et al. 2007) with tubes of 2 m length and 8 cm diameter. From 14 m and deeper, a core with a smaller diameter of 5.5 cm was collected. A sediment core with an overall length of 22.46 m was collected in two overlapping parallel sequences. The cores were extruded and cut lengthwise in the field. After being photographed and recorded, the half cores were wrapped in foil and stored in a cold room. Detailed core description, documentation, the creation of the so-called master record and the subsequent subsampling took place in the laboratory. Stratigraphic markers were described from the identification of distinct corresponding changes in the two sediment sequences. These were used to link the lowermost part of the parallel cores to obtain an uninterrupted master record of the early and middle Holocene sediments. In the uppermost part,



**Fig. 3** Soil distribution of the Wonieść region on the basis of agricultural soil maps, 1:100,000 (Institute for Cultivation, Fertilization and Geology in Pulawy 1987). After Hildebrandt-Radke 2013: 1, pseudopodzols; 2, brown soils; 3, leached and acidic brown soils; 4, sandy soils of various origins; 5, chernozem (black earth); 6, gley; 7, silty peat soils; 8, peat and detritus peat soils; 9 detritus and mineral soil; 10, muds; 11, lakes; 12, Lake Wonieść coring position

**Table 1** “Boom and bust” phases of greater or lesser settlement intensity in the record from Lake Wonieść record

LPAZ	Depth [cm]	cal. age	Archaeological period
<b>Boom phase</b>			
Y	298-0	AD 1220-present	Late Middle Ages - Modern Times
V	746–602	100 BC-AD 370	Roman Iron Age
S	986–874	880–515 BC	Late Bronze/Iron Age
Q	1,040–1,008	1020–940 BC	Late Bronze Age
O	1,112-1,092	1290–1210 BC	Middle/Late Bronze Age
L	1,196-1,176	1640–1560 BC	Early/Middle Bronze Age
I	1,358-1,293	2140–1940 BC	Late Neolithic
F	1,562-1,514	3490–3230 BC	Middle Neolithic
<b>Bust phase</b>			
W	602–538	AD 370–580	Late Roman Iron Age
T	874–826	515–360 BC	Pre-Roman Iron Age
R	1,008-986	940–880 BC	Late Bronze Age
P	1,092–1,040	1210–1020 BC	Middle/Late Bronze Age
M	1,176-1,152	1560–1460 BC	Early/Middle Bronze Age
K	1,212-1,196	1690–1640 BC	Early Bronze Age
G	1,514-1,482	3230–3070 BC	Middle Neolithic



**Fig. 4** Age-depth model for Lake Wonieść using Oxcal v. 4.4.4 (Bronk Ramsay 2021)

there were no changes in colour and it was not possible to identify any marker horizons. As the 2 m cores generally tended to expand by 5 to 10 cm due to degassing, a gap of 5 cm has been postulated between each two succeeding core segments. The reconstruction of similar gaps for the lowermost cores, connected by marker horizons, support this approach (Dörfler 2011).

### Core chronology

For an independent dating of the sediment master record, botanical macro-remains were extracted from the sediment and radiocarbon dated. For this, the sediment surfaces of the cores, when cut lengthwise, were carefully examined for potential deciduous leaf remains, which were generally characterised by distinct, well-defined dark layers. By this method, seven leaf fragments and three other plant remains could be extracted that were suitable for AMS dating. Additionally, in three cases pollen concentrates, retrieved by a combination of sieving, chemical treatment and gravity

separation ( $< 120 \mu\text{m}$ , KOH treatment, gravity separation at density of  $> 1.365 \text{ g/cm}^3$ ), were submitted for AMS dating.

In the lowermost 4 m, the sediment showed partly annual laminations. The clear seasonal layering was interrupted several times so no continuous counting was possible. Varve counting was done on high resolution photos using CooRecorder v. 7.1 ([www.cybis.se](http://www.cybis.se)) to estimate the growth rate of these sections. The varve counts resulted in a total of 1,621 years ( $\pm 10\%$ ) in ten well-countable sections between 1977.8 and 1772.6 cm. Results of the  $^{14}\text{C}$  dating and the varve counting are used in the time/depth model (Fig. 4). Two  $^{14}\text{C}$  dates from pollen concentrates were too old compared with the other age estimates and were therefore treated as outliers. For the start and the upper part of the sequence, two pollen stratigraphic events, the *Corylus* expansion at around 8100 cal BC (Nelle and Dörfler 2008) and the *Alnus* decrease around cal AD 850 ( $\pm 50$ ) (Stivrins et al. 2018; Latałowa et al. 2019), were also included in the model as additional age estimates. An OxCal model was applied using a P-Sequence (Poisson distribution), a variable  $k$  value ( $k_0 = 5$ ) (Bronk Ramsay 2021) and the IntCal20 calibration curve (Reimer et al. 2020). Dates mentioned in the text relate to the modelled median values of the time-depth model, rounded to full decades. The results of the  $^{14}\text{C}$  dating are summarised in ESM Table 1. The presented ages differ slightly from the modelled age ranges published by Dörfler (2011). Therefore there are minor changes in the proposed dates, mainly for the middle Holocene.

### Geochemical and lithological analyses

Geochemical measurements were done every 8 cm and lithological analyses every 4 cm. The granulometric composition of the deposits was assessed with a Fritsch laser particle size analyser after organic matter had been removed with  $\text{H}_2\text{O}_2$ . Three size classes were distinguished; sand ( $> 63 \mu\text{m}$ ), silt ( $< 63$  and  $> 2 \mu\text{m}$ ) and clay ( $< 2 \mu\text{m}$ ). Loss on ignition was measured by heating samples in a muffle furnace at  $560^\circ\text{C}$  for 6h. For the geochemical analyses, extraction of trace elements was carried out using a 1:3 mixture of nitric and hydrochloric acid according to the Polish norm ISO 11,466. Copper, iron, cobalt, lead, cadmium, nickel and chromium were assessed by atomic absorption spectrometry (AAS) using an acetylene flame, sodium and potassium with atomic emission spectrometry (AES) in an air-acetylene flame, and calcium in an acetylene-dinitrogen monoxide flame. Phosphorus was determined colorimetrically by reaction with ammonium molybdate and a photometer (Hildebrandt-Radke 2013). The geochemical diagram was drawn with Tilia (Grimm 1990) and the record was divided into ten geochemical zones (GZ I to X).



## Pollen analysis

Pollen analysis was carried out at various sampling resolutions according to the needs of this research. The early Holocene sediments from 2,229 to 1,810 cm were sampled at an interval mainly of 64 cm. Between 1,810 and 982 cm samples were analysed every 4 cm. The later rapidly deposited sediments above 982 cm were analysed at 16 cm intervals. The samples were prepared with standard methods using acetolysis (Moore et al. 1991). Pollen identification and nomenclature follows Beug (2004). In total, 279 samples were counted at a magnification of 400× to a minimum number of 500 arboreal pollen per sample. Identification of Cerealia and other difficult taxa was done at 1000× using phase contrast. Relative pollen percentages have been calculated from the sum of total terrestrial pollen (TTP). Local pollen assemblage zones (LPAZ) were distinguished according to major and minor changes in the pollen composition and the diagrams drawn using Tilia v. 2.0.49 (Grimm 1990).

In order to identify important gradients in the dataset, statistical ordination was applied to a modified dataset consisting of the main 27 terrestrial pollen taxa, which were recorded in at least 50% of the pollen spectra or had a relative representation of > 1% in at least one spectrum. Different categories of Cerealia type pollen (*Hordeum*-, *Triticum*-, *Avena*-, and *Cerealia*-type indet.) were regarded as a single pollen type. Principal component analysis (PCA) was done using Pcord v. 5 (McCune and Mefford 2006). As various phases of the record show very different values for the first axis, this process was carried out in three intervals, each representing a relatively homogenous woodland composition. The resulting three slightly overlapping curves were merged by fitting the mean of the overlapping sections as described by Feeser et al. (2016, 2019).

## Diatom analysis

The subsampling interval for diatom studies was 16 cm. Sample processing and analyses followed Battarbee (1986). For this, 1g of dried sediment was treated with 10% HCl to remove calcium carbonate and washed with distilled water, then boiled in 30% H<sub>2</sub>O<sub>2</sub> to remove organic matter and repeatedly washed with distilled water. At least 300 diatom valves per sample were analysed with a light microscope using oil immersion at 1,000×. For identification, a selection of published keys was used (Lange-Bertalot and Metzeltin 1996; Lange-Bertalot et al. 2011; Krammer and Lange-Bertalot 2008a, b, 2010, 2011; Hofmann et al. 2011).

The ecological groups of the diatoms were determined using Omnidia v. 4.2 (Lecointe et al. 1993) and the resulting groups were distinguished according to Denys (1991) and

van Dam et al. (1994). We considered the following indicator parameters: habitat category (Denys 1991), preference for pH, saprobic level (dead organic matter), and trophic state (nutrients) (van Dam et al. 1994). The total phosphorus (TP) concentration was reconstructed from changes in diatom species composition (DI-TP), using the European Diatom Database (EDDI) with Erni v. 1.2 (environmental reconstruction using the Eddi diatom database) (Juggins 2001). The reconstruction of the TP is based on the diatom taxa present at more than 2% of the total. The DI-TP was calculated using the combined TP dataset derived from nine datasets with 477 samples in total, covering a TP range 2–1,189 μg l<sup>-1</sup>, with a mean of 98.6 μg l<sup>-1</sup>. The LWWA (locally-weighted weighted averaging) method with good empirical predictive ability was used (Juggins 2001). The model based on inverse regression had a root mean square error of prediction (RMSEP) of 0.3 μg l<sup>-1</sup> and a coefficient of determination (r<sup>2</sup>) of 0.71.

A diatom percentage diagram was calculated and drawn with Tilia (Grimm 1990). Principal component analysis (PCA) with Canoco 4.5 was applied to the diatom assemblages from increasing depths to define the direction of assemblage variation in time (Lepš and Smilauer 2003).

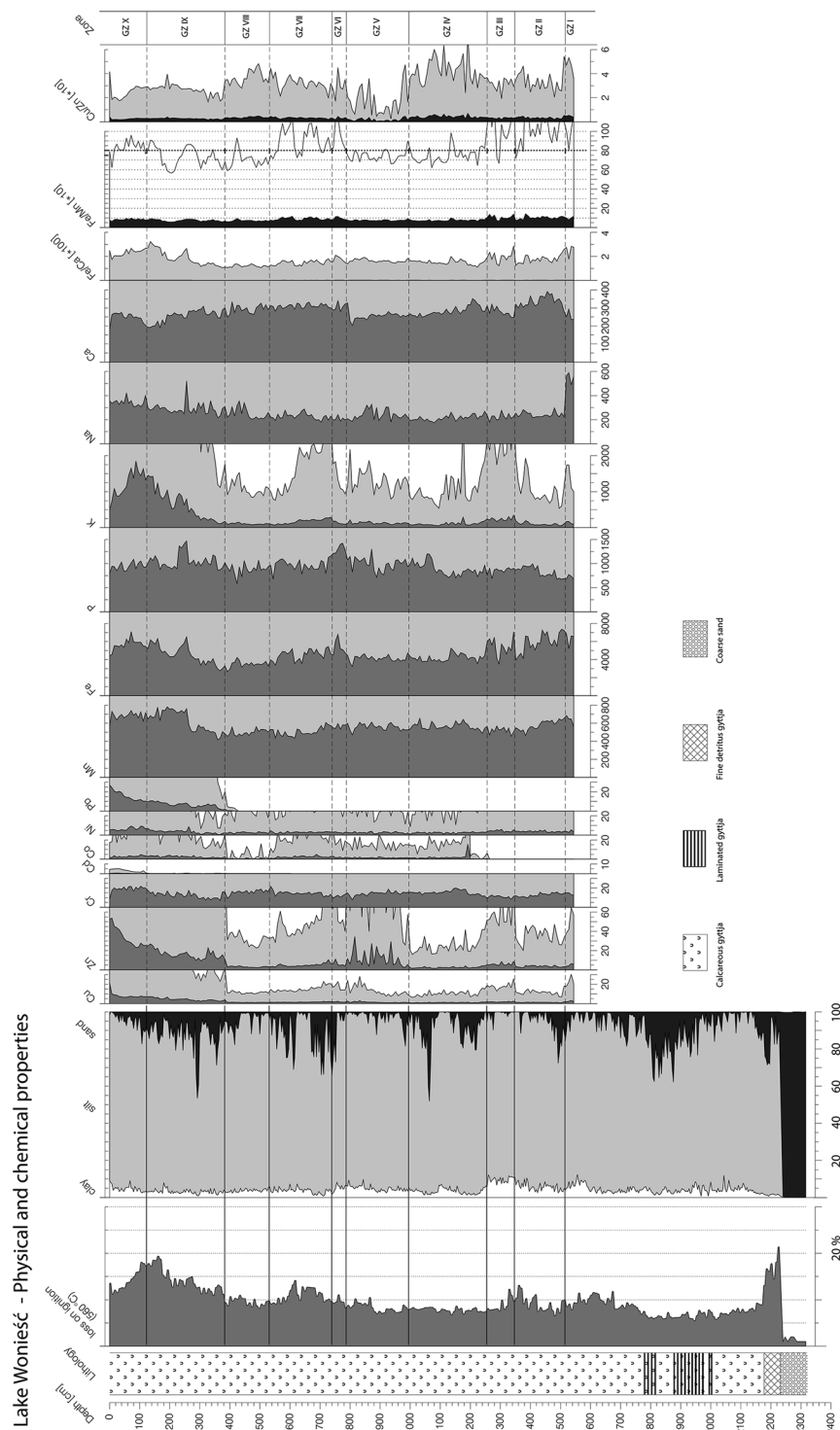
## Results

### Core chronology

The radiocarbon dating results are given in ESM Tables 1 and Fig. 4, which provide an overview of the time-depth development of the sequence. It starts with a relatively high sediment accumulation rate, averaging 1.3 mm/year between 22.3 and 13.6 m (ca. 8700 to 2160 cal BC). As was visible in the laminated sections, the sediment accumulation rate fluctuates between 1.0 and 1.7 mm/year in this section. With the start of distinct eutrophication of the lake at 1,360 cm (ca. 2160 cal BC) the average sediment accumulation rate rises to 3.3 mm/year.

### Geochemical and lithological analyses

Sedimentation began in the early Holocene at a depth of 2,230.7 cm, with an olive-brown organic gyttja (organic mud), overlying coarse sand. From 2,175 cm onwards, the sediment was a light grey calcareous gyttja, rich in organic silicates (diatoms) and other organic detritus. In ten easily distinguished sections between 2001.0 cm and 1772.6 cm, there was a clear seasonal layering from diatom blooms in spring, a dominance of precipitated calcium in summer, and clay and microscopic detritus deposited in winter. The



**Fig. 5** Loss on ignition, particle size analyses and geochemical element distribution results from from Lake Wonieść [Values as g/kg (calcium), otherwise mg/kg]

results of the geochemical and lithological analyses are given in Fig. 5.

Values for loss on ignition (LOI) display a low organic content in the lake sediment; on average it is around 9%

of the dry weight, while minerogenic material and calcium make up about 91% on average. As the organic component reflects the growing conditions for algae, it is mainly influenced by temperature and the availability of nutrients. The

high organic content values in the early Holocene (2,240 to 2,180 cm) coincide with rapid warming and high availability of nutrients during this phase. The samples from between 2,180 cm and 1,800 cm, representing the middle Holocene, show generally stable conditions, with only slowly decreasing LOI values. The values change slightly during the late Atlantic climate optimum, with the potential beginning of arable farming at around 5500 BC (1,800 cm). From the occurrence of the first *Cerealia* pollen onwards, the LOI values start to increase. The increase in organic content indicates good (warm) growing conditions that might have been additionally supported by a slight eutrophication by nutrient input into the lake.

Particle size analyses show a clear dominance of the silt fraction between 2 and 63  $\mu\text{m}$ . Clay particles have a minor contribution, but with clearly increasing values in parallel to settlement phases. Fluctuations of the clay content can be linked with “boom and bust” phases of greater and lesser human land use, but from 750 cm onwards (ca. 130 cal BC) the values do not exceed 5%, which might have been dependant on the particular kind of land use. From ca. 1 BC onwards, we regularly see high values in the sand fraction, which might indicate stronger erosion and input of more coarse minerogenic material, as also shown in the loss on ignition values. However, as calcium particles are included in the grain size analyses, the sand fraction may also include large autochthonous calcite crystals (formed there), indicating both the potential erosion of relatively large quartzite particles and their deposition in the centre of the lake, as well as potentially good growing conditions for calcite crystals. Both kinds of particles need high turbulence in the water for sand to be transported to the centre of the lake and for calcite to be formed there during the summer. Thus, the sand fraction can give us information about the turbulence of the water during the Holocene.

The chemical elements were analysed in the uppermost 1,552 cm of the core (ca. 3400 cal BC to present). The dominant element is calcium, as expected for a hard water lake, with values between 250 and 350 g/kg dry weight. Certain elements show a distinct pattern that allows for a subdivision of the diagram into ten chemical zones (GZ I to X).

The first zone (I; 1,552–1,524 cm) includes four samples with high Na, K, Zn and Cu, and relatively low Ca values. Apart from Ca, these elements decrease at the transition to the second zone (II; 1,524–1,356 cm). In the third zone (III; 1,356–1,264 cm), Cu, Zn and K again have higher values, and Ca relatively low values. At the end of zone three, Co occurs with low values. Zone four (IV; 1,264–1,004 cm) is defined by lower values of Cu, Zn and K, as well as a rapid increase in Co and higher values of Cr. The transition to zone five (V; 1,004–796 cm) is marked by a strong increase in Zn. The strongly fluctuating Zn values decrease at the

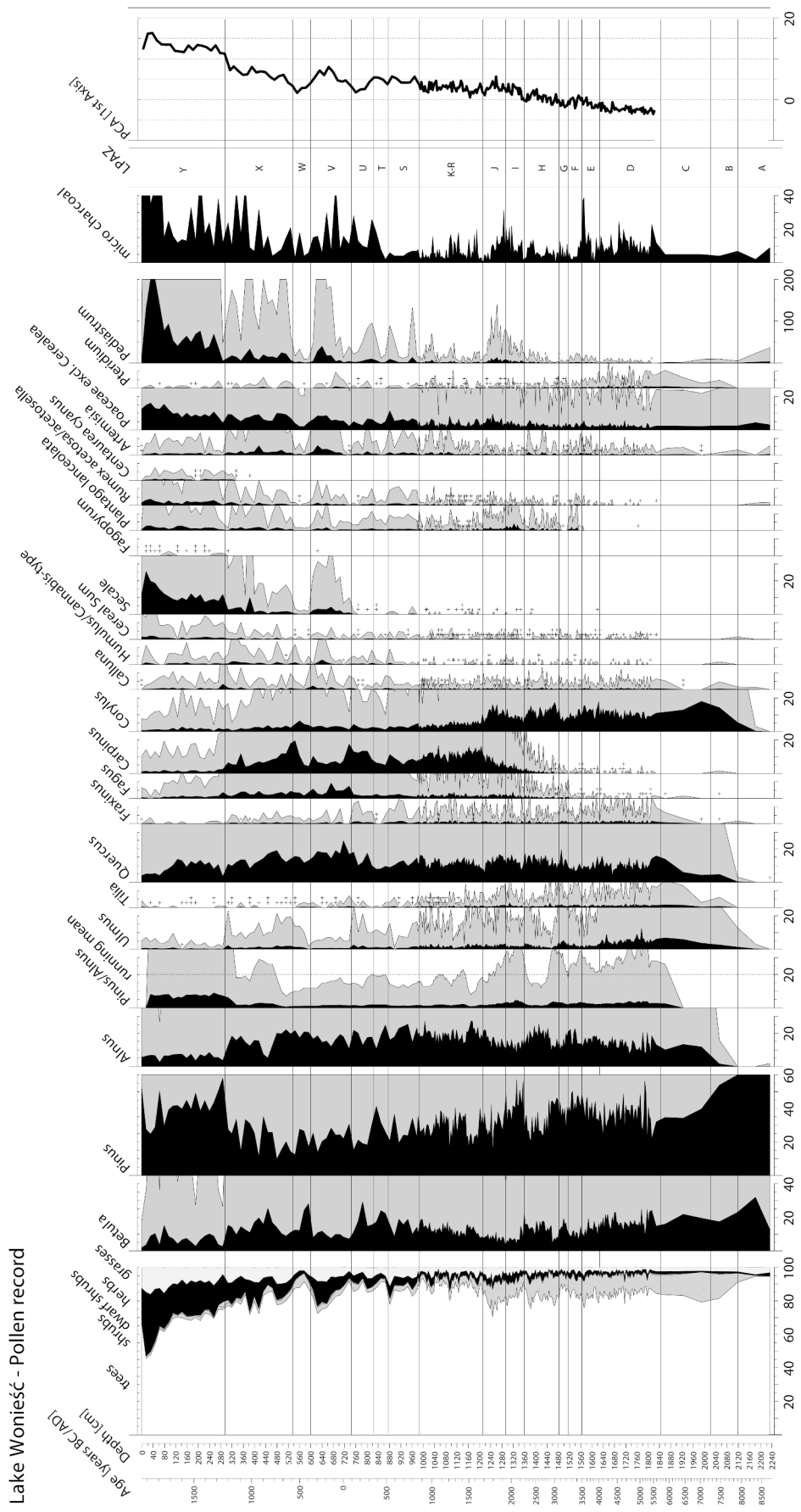
transition to zone six (VI; 796–748 cm), together with a distinct increase in Ca values and a maximum in P values. Zone seven (VII; 748–540 cm) is characterised by higher Co and K values, and a still high Ca content. Zone eight (VIII; 540–428 cm) shows minimum values of Zn, Co and K. Zone nine (IX; 428–132 cm) starts with a strong increase in Cu, Zn, Co and Pb. K rises continuously in this zone from values around 0.1 g/kg to 1.5 g/kg, showing a continuously growing input into the lake basin. In the last zone (X; 132–0 cm), these values decrease slightly, but Zn and Pb increase continuously, and Cd is recorded with values up to 0.5 mg/kg. These geochemical signals reflect changes in land use and hydrological conditions very well.

The iron to manganese ratio (Fe/Mn) reflects the redox conditions in the deep part of the lake. Strong deep water exchange in dimictic lakes, in which the surface and bottom water temperatures equalise twice a year allowing mixing, results in a higher content of Mn oxides, whereas incomplete water circulation and stronger stratification of the lakes water result in higher Mn solution and thus lower values in the sediment (Garbe-Schönberg et al. 1997). This ratio is therefore a good indicator for phases of increased water circulation caused by stronger winds, alternating with phases of incomplete or only temporary circulation. Overall, eight phases can be identified with a discrimination ratio of 8. Four phases show Fe/Mn values between 6 and 8, and four phases between 8 and 11. Low values indicate stronger circulation and higher values less circulation with oxygen at the bottom of the lake (Żarczyński et al. 2019). Stronger redox conditions occurred between 1,550 and 1,236 cm, 796 and 564 cm, 300 and 252 cm, and 180 and 20 cm. The opposite, oxic conditions, occurred between 1,236 and 796 cm, 564 and 300 cm, 252 and 180 cm, and between 20 and 0 cm.

## Pollen analysis

The pollen diagram shows selected taxa on a depth scale and it provides an overview of the development of natural vegetation during the Holocene and also of human-induced vegetation changes (Fig 6). Twenty five local pollen assemblage zones (LPAZ, lettered A–Y) are identified and they are described in ESM Table 2. The core section with zones D to R and a closer sampling interval, is presented separately (ESM Fig. 1). The following section discusses human impact and considers the different lines of proxy evidence.

After the rapid expansion of *Pinus* (pine) and *Betula* (birch) in the early postglacial period (LPAZ A), the spreading of warmth-demanding deciduous trees and shrubs began with *Corylus* (hazel) and continued with *Ulmus* (elm), *Quercus* (oak), *Tilia* (lime) and *Alnus* (alder) in LPAZ B. *Fraxinus* (ash) in LPAZ C, *Carpinus* (hornbeam), and *Fagus* (beech) followed rather later in LPAZ G with a distinct





◀ **Fig. 6** Pollen percentage diagram from Lake Wonieść, based on total terrestrial pollen and taxa scores from the first axis of a PCA for the main 27 terrestrial pollen taxa. Exaggeration by 10×

temporal delay. The final establishment of hornbeam and beech lasted several centuries and was accompanied by a decrease in elm, lime, and hazel. Very typical for the region, given its continental climate, are the high values of *Carpinus* that reach more than 10% of the pollen sum in the middle and late Holocene.

The first human influence can be detected in the form of regular occurrences of Cerealia-type pollen from 1,794 cm (ca. 5250 cal BC, LPAZ D) onwards. This indicates potential cereal growing from this early stage of the Neolithic onwards. This is noteworthy, as no settlements from this time have been identified so far in this region. Since the Linearbandkeramik (LBK) people generally preferred areas with chernozem (black earth) soils, those places to the west of Lake Wonieść are most likely to have been the areas of settlement in this period. As these soils are nowadays intensively farmed and deeply ploughed soils, the chance of detecting traces of early farmers in this area is low. The evidence from the pollen record, however, is generally in good agreement with the archaeological evidence, which indicates a spread of LBK groups into these lowlands around 5200 cal BC (Czebreszuk and Szmyt 2011). Single Cerealia pollen grains, detected in addition to the regular counts of 500 arboreal pollen grains, occur from 5500 cal BC onwards but these could also be pollen transported from a long distance, as from Kujawy, 120 km to the north-east, where Neolithisation started around 5400 cal BC (Czebreszuk and Szmyt 2011; Makohonienko et al. in press), even though cereal pollen, apart from *Secale* (rye), is produced and distributed only in small amounts. Most of the early Cerealia-type pollen grains have been identified as *Triticum*-type type under phase contrast, so the wild grass *Glyceria* can be excluded as a potential origin for these grains. Between 4800 and 4100 cal BC, in the time of Late Danubian groups, single cereal pollen grains continue to occur even though no traces of settlement are known so far in the Lake Wonieść region. It is during the Trichterbecher (Funnel Beaker) Culture (TRB, 4100 to 2800 cal BC) when a strong transition occurred in the woodland, with the decline of *Ulmus* and an increase of *Corylus* around 4020 cal BC (LPAZ D/E). This transformation is most probably a consequence of live-stock farming, with cattle grazing in the woods (Feeser et al. 2019). There are further Cerealia-type records around the same time. About 530 years later, at around 3490 cal and the widespread BC, a steep increase in *Plantago lanceolata* (ribwort plantain) and other anthropogenic indicators marks an economic change, with opening of the still widespread natural woodlands (LPAZ E/F) and more arable farming. From this time onward, a strong human component is visible in the environmental development of the land around

the lake. Beside the general trend of increasing human pressure on the landscape, several phases of settlement abandonment and woodland regeneration can be identified in the pollen record. As the intensity of land use reflects human pressure on the environment and is thus also an indicator for population density (Feeser and Dörfler 2015), we interpret such phases of woodland clearance and regrowth as phases of greater or lesser regional settlement or human population density. At ca. 3230 cal BC, after c. 260 years of strong human influence on the landscape (LPAZ F), a ca. 160 year long phase of woodland regeneration occurs, indicating a decline in human pressure and most probably also in population (LPAZ G). *Betula* has a short maximum period as a pioneer tree and *Ulmus* regenerated as well. At the same time, *Corylus* values decrease, indicating a decline of hazel, probably due to a less open woodland or a more closed woodland canopy.

The subsequent opposite development is expressed by the curves of these taxa in the following LPAZ H. *Ulmus* decreases strongly again and *Corylus* reaches high values synchronous with anthropogenic indicators. As a light-demanding shrub, hazel benefited from the opening of the woodland structure, which might even have encouraged a good yield of nuts. This increase in settlement indicators in LPAZ H is accompanied by the spread of *Carpinus* in the woods with a mass expansion starting at around 2140 cal BC. At the same time, a spread of *Fagus* and a slight increase in *Tilia* occurred. During this part of the Bronze Age, we again see distinct fluctuations in settlement intensity. Changes in woodland composition are shown by some records, such as the rise of *Carpinus* and the decrease of *Corylus*, as well as variations in anthropogenic indicators that characterise this development. Towards the end of the Bronze Age, at around 880 cal BC, a strong increase in settlement indicators such as *Rumex acetosa/acetosella*-type (sorrel) is visible. At ca. 100 cal BC a first strong increase in *Secale* values marks the introduction of this new cereal to the Iron Age economy. *Ulmus* and *Carpinus* decrease, and *Fagus* expands at this time. The pronounced settlement phase of LPAZ V is replaced by a minimum of settlement indicator values in LPAZ W from AD 370 to 580, according to the time-depth model. This is an early date for this period that is accompanied by a woodland regeneration and is linked to economic crises during the late Roman Iron Age and early Migration Period. A new increase of settlement activities is seen in LPAZ X, starting around AD 580. However, it is not before AD 1220, according to the time-depth model, that opening of large areas of woodland and the widespread cultivation of *Secale* as a winter crop started in the region around the lake (LPAZ Y).

The ratio of *Pinus* and *Alnus* deserves special attention. The pollen record shows distinct variations in the curves of pine and alder, most often in opposite directions. Pine represents drier conditions, but alder indicates dampness. Both trees reflect very different habitats and so they do not influence each other directly. Their alternating records can be used as evidence for regional climate variation: As alder usually grows in wet valleys and on lake shores, it is dependent on a sufficient water supply. Pine, on the other hand, grows on sandy and loamy soils and it reflects dry habitats and benefits from dryer conditions in its competition with deciduous trees, if the dry phase is long enough. Thus, the two pollen records can be used to distinguish between drier and wetter phases of climate. In the Central European climate, the dry phases represent a more continental climate and wet phases a more oceanic one. As single samples may vary due to short term changes, a five-sample running mean of the values has been calculated. Ratios with more than twice the values of *Pinus* compared to *Alnus* reflect drier phases and values below 2 show wetter phases. According to this, we can distinguish between a relatively dry middle Holocene and a wetter phase in LPAZ *H* lasting for nearly 860 years (ca. 3000 to 2140 cal BC). After a short dry phase (LPAZ *I* 2140 to 1940 cal BC) the climate seems to have become generally wetter according to increasing alder and decreasing pine values. For the last 1,200 years and up to the present, this value is not meaningful, as the *Alnus* gap at around AD 850 (Stivrins et al. 2018; Latałowa et al. 2019) and the transformation of alder carrs into meadows after Germanic occupation have strongly influenced the representation of *Alnus*.

### Diatom analysis

The study of the diatom flora of Lake Wonieść enabled a reconstruction of the development of this lake. Due to insufficient preservation of the diatoms in the oldest deposits of the core, the record starts at a depth of 2,071 cm. As the preservation of diatoms in the upper part was very good, 182 taxa could be identified, of which 158 belong to Pennales and 24 to Centrales. The commonest and most indicative taxa are shown in Fig. 7 and autecological units in ESM Fig. 2. As indicative parameters, the life form, the pH requirements, the saprobity (dead matter requirement) and the trophic (nutrient) state were taken into account. Based on the changes in the taxon composition and the proportions of the various ecological groups, the data are divided into ten local diatom assemblage zones (LDAZ), which represent total phosphorus (TP) values between 10.25 and 112.59 µg/l. Features of the zonation are summarised in ESM Table 3.

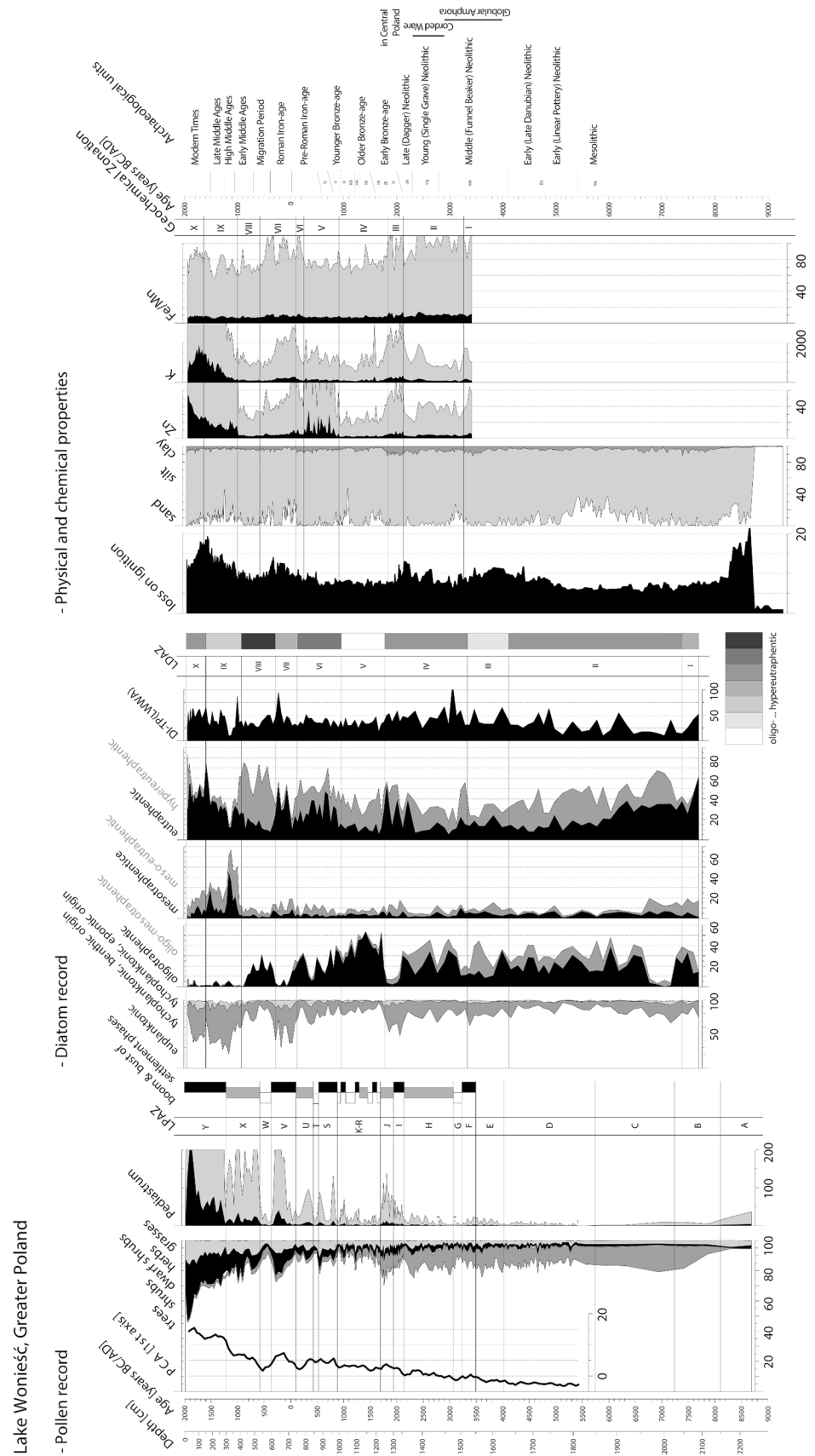
Regarding the life forms, typical euplanktonic (free floating or open water) taxa dominate, based on the classification of Denys (1991), as is typical for deep lakes with steeply sloping shores and a narrow rim of shallow water along the shoreline. In the upper part of the core, there is an increase of tychoplanktonic species (brought from elsewhere), such as *Pseudostaurosira brevistriata*, *Staurosira construens* and *Staurosirella pinnata*. Variations in the relative amounts of euplanktonic and tychoplanktonic taxa indicate phases of either low water level, a greater visibility due to clear water conditions and more water turbulence, transporting the residues of benthic (deep water) taxa into the deposits from the catchment forming on the lake bed. Such phases with more tychoplanktonic taxa occur in LDAZ III, the second half of LDAZ IV, as well as in LDAZ VII, IX and X. Regarding the pH range, taxa with positive or neutral alkali requirements dominate the record as is typical for a calcareous environment. Taxa of circumneutral water decrease continuously in the course of the Holocene and there are occasional occurrences of acidophilous diatoms also, with a general decreasing trend towards the later phases. The group of alkaliphilous taxa representing calcareous water has its maximum values in the uppermost samples and in LDAZ VII, LDAZ VI, the top of LDAZ IV and LDAZ I, contemporary with maxima in the eutrappent species. As is typical for a clean freshwater lake, the amount of dead organic matter (saprobity) is represented by oligo- and beta-mesosaprobous taxa. Alpha-mesosaprobous species, which need plenty of dead material, increase slightly from LDAZ VII onwards but stay at very low levels until modern times. The trophic state of the lake as reflected by the diatom record shows the strongest variations. Whereas taxa of oligotrophic conditions with few nutrients have high values in the middle Holocene layers of LDAZ I to V, they are replaced by those of eutrophic and very eutrophic water with plenty of nutrients from LDAZ IV onwards. Most of these variations mirror the development of anthropogenic indicators in the pollen record, which indicates a strong human influence in the environmental development of the lake from the Neolithic onwards.

## Interpretation and discussion

### Comparison of the results from the different methods

A comparison of the various results allows for an interpretation of both natural changes and those caused by humans (Fig. 8). As human activity has influenced not just the woodland composition but also the hydrological and ecological conditions of the lake, the interpretation will mainly





**Fig. 8** Comparison of pollen, diatom and geochemical records from Lake Wonieść plotted against linear time scale and with archaeological periods according to Szmyt (2011), Rassmann (2004), and Kneisel (2012)



indicators shows that it reflects the general trends of increasing and decreasing human pressure on the landscape very well. The differences in levels of human disturbance are also reflected in the curve of *Pediastrum* (a green alga, which is not included in the PCA), but no species or type identification was made, so the curve shows the values of all *Pediastrum* species. This record shows the eutrophication of the lake from the Late Neolithic onwards, with values increasing in parallel to those of anthropogenic indicators, and decreasing at times of lesser human pressure. *Pediastrum* occurs in lakes under various ecological conditions (Jankovská and Komárek 2000). The similarities in the occurrences of eutraphentic (high nutrient) diatoms and the records of herbs and grasses are taken as a confirmation of the indicative value of these algae for eutrophication or nutrient status of the lake.

Responses to early Holocene climate change occur in parallel in the lithology, such as varve preservation, terrigenous (soil) detrital flux and from diatoms, suggesting a firm link between internal lake processes and the deposition of sediment into it, as well as the sensitivity of diatom composition and detrital input to climate change (Woszczyk et al. 2014; Słowiński et al. 2017; Zawiska et al. 2020).

Sedimentation started in the early Holocene (LPAZ A) with a sandy gyttja and small amounts of clay compounds. The pollen record shows the typical succession of trees and already very low values of herbs and grasses. With the start of the Holocene, the sediment shows a fast transition from sandy gyttja to an olive-brown organic gyttja, as also indicated in the LOI curve with values up to 20%. Diatoms are not preserved from this early phase. The diatom record starts at a depth of 2,071 cm (LDAZ I, ca. 7500 cal BC), with high values of benthic diatoms indicating shallow water conditions and a peak of hypereutraphentic taxa indicating nutrient-rich water conditions in the early Holocene. The increases in the abundance of these taxa and in clay content indicates that the process of eutrophication was intensified by erosion of soil into the lake (Bogaczewicz-Adamczak 1990). Around 1,950 cm (ca. 6700 cal BC) planktonic taxa increase, showing a rising water level. Relatively high values of oligotraphentic diatoms indicate calcium rich but nutrient poor conditions at this stage of lake development. Hypereutraphentic diatoms have minimum values and oligotraphentic ones maxima. Accordingly, the sediment accumulation rate is high, with values around 1.4 mm/year. With the establishment of a deciduous mixed oak woodland and its stabilisation of the soils by vegetation cover, the nutrient input into the lake decreased. Stable conditions in the woodland during LPAZ D (ca. 5740–4120 cal BC) continued, with values of oligotraphentic diatoms remaining high and a low sediment accumulation rate of 1.1 mm/year on average in LDAZ D. Regular pollen occurrences

of *Calluna* (heather), *Artemisia* (mugwort) and other herbs indicate areas with more open woodland, most probably with a high proportion of pine in drier places. High values of pine in comparison to alder (a pine-alder ratio above 2) are interpreted as an indication of a continental climate during this phase, with warm dry summers and cold winters. In LPAZ D the first indications of human activities occur in the form of regular Cerealia-type pollen. The increasing sediment accumulation rate from around 1.1 to 1.4 mm/year indicates some potential eutrophication of the lake, but the diatom record still has high values of oligotraphentic taxa. The start of the next phase, LPAZ E (ca. 4020–3490 cal BC), is characterised by a distinct *Ulmus* decline that marks the transition from the Atlantic to the Subboreal. In the diatom record, a short peak of acidophilous taxa and of oligotraphentic species occurs (LDAZ III). It is accompanied by a decrease of planktonic and an increase of tychoplanktonic diatoms. This could indicate a low water level at this climatic transition time. LPAZ E also reflects the transition to the TRB Neolithic, with farming as the main subsistence practice. Eutrophication is also reflected in the LOI curve as an indicator of the organic content. Maximum values are reached between 1,620 cm and 1,570 cm, representing the beginning of the Middle Neolithic. In the following LPAZ F, a new type of Neolithic land use practice occurs that is characterised by regular occurrence of *Plantago lanceolata*. After a first phase with mainly animal husbandry and small-scale crop growing in LPAZ E and potentially in LPAZ D, in LPAZ F larger plots of fields were cultivated for growing cereals. The clay content and to a slight degree also *Pediastrum* starts to rise and the sediment accumulation rate increases during this phase, indicating a higher productivity due to erosional processes or nutrient inwash. LPAZ F (ca. 3490–3230 cal BC) represents a Neolithic TBK settlement phase, with the first moderate openings in the woodlands, even though arboreal taxa prevail. The sediment accumulation rate increases slowly from 1.1 mm/year to values around 1.7 mm and later on to 2 mm/year. This increased deposition is accompanied during the next 2,000 years by a gradual decrease of oligotraphentic taxa and a contemporaneous increase of eutraphentic and hypereutraphentic diatoms.

A short phase of woodland regeneration, represented by LPAZ G (ca. 3230–3070 cal BC), shows a short *Betula* (birch) peak as primary woodland followed by a subsequent increase in *Ulmus*, *Tilia*, *Quercus* and *Fraxinus*. Records of Cerealia-type, *Plantago* and Poaceae reach a minimum or are interrupted in this phase. Apart from higher values of planktonic diatom taxa, there is no clear sign in the diatom record or the geochemical composition that could be linked to this short period of settlement abandonment during the Middle Neolithic. After ca. 160 years, anthropogenic indicators

increase again and the values of woodland taxa return to their previous levels. This pattern of phases with decreasing anthropogenic indicators and regeneration of woodland is repeated several times in the following centuries.

The Late Neolithic period show moderate intensity of land use in LPAZ *H*. *Pinus/Alnus* ratios below 2 indicate a more oceanic climate during this time, with little input of nutrients into the water.

There is a strong and rapid increase of all anthropogenic indicators in LPAZ *I* that marks the start of EBA settlement. This phase is represented by a strong decrease of oligotraphentic diatom taxa and an increase in clay content, as well as in Zn and K as indicators of erosion. Higher values of *Pediastrum* also show a green algal bloom due to eutrophication of the lake, which is also represented by a maximum in the LOI at the end of GZ II, corresponding with the Late Neolithic and EBA settlement phase (LPAZ *I* and *J*). The record indicates much greater land use compared with the Middle Neolithic before. It corresponds to the first phase of the Bruszczewo EBA settlement, which lasted from ca. 2100 to 1650 cal BC. The great increase of pine in relation to alder indicates a more continental climate during this phase of increased settlement. This climate change seems to have favoured the fast spread of *Carpinus* (hornbeam) which finally reached higher values than *Corylus*.

With the start of continuous *Pinus/Alnus* ratios below 2 in the final LPAZ *J*, the climate may have changed towards a more oceanic one in LPAZ *K*. The lake level seems to have risen, as shown by maxima in the planktonic diatoms compared with tychoplanktonic ones. However, the Fe/Mn ratio < 8 indicates weak circulation and strong stratification of the water during this phase. As the lake is north-south orientated, westerly winds during more oceanic phases may not have influenced the water circulation as strongly as in east-west orientated lakes. Later, during the end of LPAZ *S* and in LPAZ *T* and *U*, the Fe/Mn ratio indicates stronger circulation. As anthropogenic indicators are relatively high during these phases, and as arboreal pollen is at a relative minimum, the lake might have been more exposed to wind than beforehand. This would be in good agreement with geochemical features found in Lake Żabińskie, northeast Poland (Żarczyński et al. 2019), where loss of woodland caused high wind exposure with stronger water circulation and thus decreasing Fe/Mn ratios.

The short phase of decreasing settlement indicators (“bust”) in LPAZ *K*, that lasted from ca. 1690 to 1640 cal BC, corresponds to the abandonment of the Bruszczewo settlement at ca. 1650 cal BC. As the lake represents regional developments, this can be interpreted as a regional or even supra-regional event (Kneisel 2012). Whereas the occupation of the peninsular did not start at Bruszczewo before 1000 cal BC, the anthropogenic indicators show a recovery

of land use activities as early as in the 16th century cal BC on a regional scale. However, according to the rapidly alternating anthropogenic indicators, the next phases of decreased settlement activity (“bust”) occurred already around 1560 to 1460 cal BC and around 1210 to 1020 cal BC. Thus, only the increased settlement phases of LPAZ *Q* (1020–940 cal BC) and *S* (880 to 515 cal BC) represent the second occupation phase at Bruszczewo, with a regional intensification of land use. Archaeologically, we see a clear increase of Bronze Age finds density in relation to the Neolithic one that indicates an intense land use during this time (Hildebrandt-Radke 2013, Fig. 32). Nevertheless, woodland still covered most of the area surrounding Lake Wonieść, as the arboreal pollen sum averaging 80% indicates. High values of *Corylus* are interpreted as a sign of light, semi open woodland at this time.

If we group the phases of increasing human pressure (“boom” phases) and those of woodland regeneration (“bust” phases), we can identify LPAZ *F*, *I*, *L*, *O*, *Q*, *S*, *V* and *Y* as “boom” phases, and LPAZ *G*, *K*, *M*, *P*, *R*, *T* and *W* as “bust” phases. In between, phases of relative stability indicate times with no drastic changes in land use intensity. According to our chronology this indicates several phases of wealth and growth during the Neolithic, Bronze Age and Iron Age up to modern times, as well as phases of crisis and population decline in the same periods. These trends are summarised in Table 1 and shown in Fig. 8 as black and white bars.

Most of these phases can be connected to particular features of the hydrological or sedimentological and geochemical records. As mentioned above, a maximum of settlement indicators in LPAZ *I* (ca. 2140–1940 cal BC) can be correlated to a maximum in the LOI and to higher values of Cu, Zn, Fe, and K. A synchronous maximum in hypereutraphentic diatoms and in the *Pediastrum* curve indicates eutrophication of the water by arable farming in the surroundings of the lake and a maximum in benthic diatoms indicates a low water level. Indicators of eutrophication like *Pediastrum* and hypereutraphentic diatoms also show the strong influence of people on the environment during the Roman Iron Age. A very strong indication for a “bust” phase is visible in LPAZ *U* (ca. cal AD 370–580), with a clear decline in all settlement indicators. Again, *Betula* values distinctly show regeneration of primary woodland and *Carpinus* its expansion in more mature woodland. Most diatoms and chemical elements which indicate eutrophication decline, but the lake does not show a full recovery to oligotrophic conditions. The settlement gap in the early medieval period (LPAZ *W*) is also reflected in low organic content (LOI). Values start to increase again with the beginning of medieval settlement. At the same time, the temperature started to increase again after the Late Antique Little Ice Age (LALIA) in the 6th and 7th centuries AD (Büntgen et al. 2016). After 200 years of

abandonment, settlement indicators increased again, showing either the regeneration of a small surviving population or new colonisation. A very strong transformation takes place at the change from LPAZ *V* to *W*. An *Alnus* decrease indicates the transformation of alder carrs into wetlands and most other deciduous trees also show lower values. Anthropogenic indicators rise, especially *Secale*, and the alga *Pediastrum* indicates strong eutrophication of the water body. Beside Cu and Zn, Pb also shows a strong increase, indicating some economic activities in the wider region. High values of benthic diatoms indicate a low water level at this time. Just in the uppermost part, from ca. AD 1700 onwards, a rise in Cd shows further pollution of the lake. This might be due to artificial colouring of textiles or leather processing during this time.

### Comparison with other records from Poland

Our results show the potential of lake sediments to provide high resolution records of regional environmental responses to climate change and human impact. The detailed chronology enables a correlation with other high-resolution climate archives on a synchronised time scale.

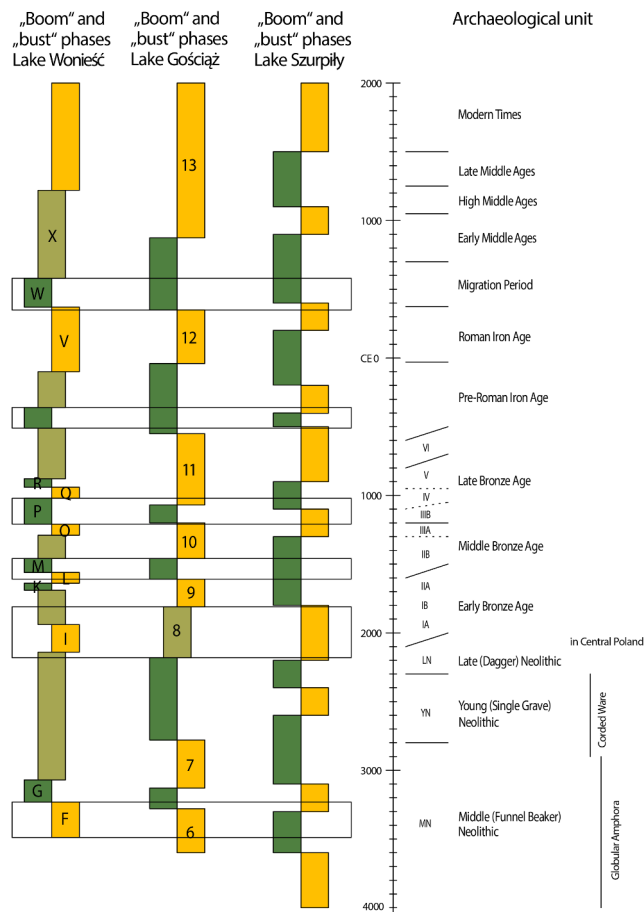
### Comparison with other records from northern Poland

Many pollen records from Poland have been published, but most of them are located to the north of our site. Just a few of these sites are suitable for comparing the settlement intensity and the changes from human activities in the landscape, depending on the sampling resolution, dating and the occurrence of settlement indicators in the record. For comparison we selected two well-dated sequences lying north-east of Lake Wonieść, even though archaeologically and environmentally they represent different regions.

- Lake Gościąż (Ralska-Jasiewiczowa et al. 1998).
- Lake Szurpiły (Kinder et al. 2019).

The settlement history is similar in the two regions around Lakes Gościąż and Wonieść, but at Lake Szurpiły both settlement and vegetation history are different. Lake Szurpiły was chosen for comparison with Lake Wonieść in order to identify factors that may have influenced settlements independently of their cultural affiliation.

The record of the laminated Lake Gościąż (Goslar 1998; Ralska-Jasiewiczowa and van Geel 1998) from central Poland, some 190 km east east-northeast of Lake Wonieść, is one of the best studied and dated in Central Europe. The dating is based on a series of 30 AMS  $^{14}\text{C}$  dates and a correlation of the thickness of the varves with tree ring records



**Fig. 9** “Boom” and “bust” phases of more settlement or less, from the lake records from Lakes Wonieść, Gościąż and Szurpiły. The zones are the original local zonations established by the authors for each site

from Germany that have absolute dates. Thus, the date for the elm decline of 3940 cal BC (4020 cal BC in Lake Wonieść) and the start of the late Roman Iron Age abandonment of settlement at AD 350 ± 70 (cal AD 370 at Lake Wonieść) show the very good agreement of the two records. Even though the absolute values differ, the curves of *Carpinus* have a great similarity with a first maximum at Lake Gościąż at ca. 1660 cal BC (1700 cal BC at Lake Wonieść), a second maximum at ca. 130 cal BC (100 cal BC at Lake Wonieść) and a third one ca. cal AD 650 (cal AD 600 at Lake Wonieść). Thus, the two records can be compared on the basis of a good dating correlation, even though the lamination is irregular in the uppermost metres of the Lake Gościąż core and there are no AMS  $^{14}\text{C}$  dates later than 2980 cal BC.

Summarising the phases of high settlement activity and of abandonment (“boom” and “bust” phases), we can see a first strong increase in settlement indicators at 3500 cal BC. A first decrease is recorded after just 30 years (ca. 3470 cal BC) but the curve lasts, with still high values, until 3260 cal BC, when a peak in the *Betula* curve and a succeeding increase in *Ulmus* indicate woodland regeneration. At Lake

Wonieść the first settlement phase with higher *Plantago lanceolata* values is recorded in LPAZ *F*, dated from 3490 to 3230 cal BC. Thus, this “boom” and “bust” during the final TRB Neolithic seems to be a common phenomenon at the two sites that has also been recorded at many sites in northern Germany (Feeser et al. 2016, 2019). The next phase of increased settlement activities occurred between ca. 3100 and 2800 cal BC at Lake Gościąż (phase 7), followed by a reduction phase from ca. 2800 to 2200 cal BC. The start was also synchronous with that of new settlement activities in the Lake Wonieść region, but here we see just a medium intensity of land use at this stage that lasted until 2140 cal BC. Figure 9 summarises the “boom” and “bust” phases of the different records. It shows both specific and common patterns. Good agreement is also visible, apart from the Neolithic phase mentioned earlier, in the Bronze Age “bust” phase (between settlement phase 9 and 10) from ca. 1600 to 1450 cal BC at Lake Gościąż. At Lake Wonieść, this phase started around 1640 cal BC and lasted to 1560 cal BC. This also relates to the very common decrease of settlement indicators that can be connected to the collapse of the Únětice Culture in the middle of the 16th century BC. At Lake Wonieść, this can be connected to the “bust” phase in LPAZ *M*, dated to 1560 cal BC. Kneisel (2012) has compiled pollen records from northern Poland and eastern Germany for a comparison of events in the 2nd and 3rd millennia BC, and this phenomenon in particular. Most of the records were produced for other purposes and thus the dating is often poor, or in many cases even absent. Nevertheless, there seems to be good agreement that there were decreases in settlement indicators in the middle of the 16th century BC.

Additionally, the start of a “bust” phase in the EBA seems to have very similar dates at the two locations, 1200 cal BC at Lake Gościąż and 1210 cal BC at Lake Wonieść. The next common event is a strong decrease of settlement indicators during the pre-Roman Iron Age that is dated to 550 cal BC at Lake Gościąż and to 515 cal BC at Lake Wonieść. The strong increase of settlement activity in the first century BC is dated to 40 cal BC at Lake Gościąż and to 100 cal BC at Lake Wonieść, and the abandonment phase of the late Roman Iron Age dates to cal AD 350 and 370 respectively. Thus, there are a number of common features, even if the developments in between seem to have been more of local significance.

There is a multi-proxy record from laminated sediments from Lake Szurpiły, northeastern Poland (Kinder et al. 2019). The lake lies 480 km northeast of Lake Wonieść. The sediment is dated by a combination of 14 AMS  $^{14}\text{C}$  dates, varve counts and  $^{210}\text{Pb}$  dating for the uppermost part. The pollen and sediment record shows a strong connection between human activities in the surroundings and the ecological development of the lake. Even though the anthropogenic

indicators are summarised in the pollen diagram, a number of phases of greater or lesser settlement activity can be deduced, as summarised in Fig. 9. In the Neolithic, an increase in ruderal taxa and weeds occurs around 4000 cal BC, but settlement indicators do not reach high values in the Szurpiły record. At the time when settlement indicators increase at Lakes Wonieść and Gościąż around 3600 cal BC, here the indicators start to decrease. Several increases and decreases in human activities in the following millennium which are visible in the Lake Szurpiły record are not reflected elsewhere. The first common feature is an increase in settlement indicators around 2200 cal BC. In the Szurpiły region they started to decrease already at 1850 cal BC, but later at Lake Gościąż at ca. 1600 cal BC and at Lake Wonieść around 1560 cal BC. One common feature is a decrease of settlement intensity at ca. 500 cal BC, at the start of the phase of cooler and wetter climate in the Subatlantic. There is little parallel with other phases of settlement increase and decrease between these sites, apart from the abandonment of settlements at the end of the Roman Iron Age. The decrease of settlement indicators and the start of woodland regrowth occurred at nearly the same time at all three sites. Thus, we can see a few supra-regional phenomena in settlement development, whereas most of the “boom” and “bust” phases seem to be of local to regional significance.

Regarding the driving forces behind these developments we can identify, apart from natural succession of competing species, human impact as an important factor for the state of the vegetation as well as of the lake. The climate would have influenced people as well as the environment, but human resilience seems to have differed from region to region and from phase to phase. No particular factors seem to have influenced environmental changes in the same way. Only very few common patterns are found in all three records, which represent very different environmental and cultural settings. The increase of settlement intensity at 2200 cal BC and the abandonment of settlements in the middle of the first millennium BC and in the middle of the 4th century AD are some of these features. There is more similarity in the records from Lakes Gościąż and Wonieść with common patterns of settlement development, perhaps as these sites are also culturally more similar. Beside the features already mentioned, the dates of the start of intensive Neolithic farming at ca. 3600 cal BC are similar, as well as the settlement gaps around 1600 cal BC and 1200 cal BC.

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## References

- Battarbee RW (1986) Diatom analysis. In: Berglund BE (ed) Handbook of Holocene Paleocology and Paleohydrology. Wiley, Chichester, pp 527–570
- Beug HJ (2004) Leitfaden der Pollenbestimmung für Mitteleuropa und angrenzende Gebiete. Pfeil, München
- Bogaczewicz-Adamczak B (1990) Paleolimnologia jezior Borów Tucholskich w świetle badań kopalnych okrzesek. (Rozprawy i Monografie 150) Wydawnictwo Uniwersytetu Gdańskiego, Gdańsk
- Bronk Ramsey C (2021) Oxcal v4.4.4. <https://c14.arch.ox.ac.uk/oxcal.html>. Accessed 20 September 2021
- Büntgen U, Myglan VS, Ljungqvist FC et al (2016) Cooling and societal change during the Late Antique Little Ice Age from 536 to around 660 AD. *Nat Geosci* 9:231–236
- Czebreszuk J, Müller J (2015) Early Bronze Age defensive settlement in Bruszczewo. New steps towards synthesis. In: Czebreszuk J, Müller J (eds) Bruszczewo III. The settlement and fortification in the mineral zone of the site. *Studien zur Archäologie in Ostmitteleuropa*, vol 13. Habelt, Bonn, pp 413–419
- Czebreszuk J, Szmyt M (2011) Making the Cultural Landscape: Neolithic and Early Bronze Age Communities on Polish Lowland and their Environment. In: Hildebrandt-Radke I, Dörfler W, Czebreszuk J, Müller J (eds) Anthropogenic Pressure in the Neolithic and the Bronze Age on the Central European Lowlands. (*Studien zur Archäologie in Ostmitteleuropa* 8). Bogucki Wydawnictwo Naukowe, Poznań, pp 11–32
- Denys L (1991) A check-list of the diatoms in the Holocene deposits of the western Belgian coastal plain with a survey of their apparent ecological requirements. Professional Paper 1991/2 N° 246. Service Geologique de Belgique, Bruxelles
- Dörfler W (2011) Palaeoecological Reconstruction of the Bronze Age Landscape around Lake Wonieść, Great Poland. In: Hildebrandt-Radke I, Dörfler W, Czebreszuk J, Müller J (eds) Anthropogenic Pressure in the Neolithic and the Bronze Age on the Central European Lowlands. *Studien zur Archäologie in Ostmitteleuropa*, vol 8. Bogucki Wydawnictwo Naukowe, Poznań, pp 67–77
- Feeser I, Dörfler W (2015) The early Neolithic in pollen diagrams from eastern Schleswig-Holstein and Western Mecklenburg – evidence for a 1000 year cultural adaptive cycle? In: Kabaciński J, Hartz S, Raemackers D, Terberger T (eds) The Dąbki site in Pomerania and the Neolithisation of the North-European Lowlands (c. 5000–3000cal bc. Leidorf, Rahden/Westf., pp291–306
- Feeser I, Dörfler W, Czymik M, Dreibrödt S (2016) A mid-Holocene annually laminated sediment sequence from Lake Woserin: The role of climate and environmental change for cultural development during the Neolithic in Northern. *Ger Holocene* 26:947–963
- Feeser I, Dörfler W, Kneisel J, Hinz M, Dreibrödt S (2019) Human impact and population dynamics in the Neolithic and Bronze Age: Multi-proxy evidence from north-western Central Europe. *Holocene* 29:1,596–1,606
- Garbe-Schönberg CD, Zeiler M, Stoffers P (1997) Geochemische Stoffkreisläufe in Binnenseen: Akkumulation versus Remobilisierung von Spurenelementen. In: Matschullat J, Tobschall HJ, Voigt HJ (eds) Geochemie und Umwelt: Relevante Prozesse in Atmo-, Podo- und Hydrosphäre. Springer, Berlin, Heidelberg, pp 291–315
- Goslar T (1998) The record of laminae thickness of the Lake Gościąg sediments, and its correlation with absolutely dated tree-ring width sequences. In: Ralska-Jasiewiczowa M, Goslar T, Madeyska T, Starkel L (eds) Lake Gościąg, Central Poland - A monographic study. W. Szafer Institute of Botany, Polish Academy of Sciences, Kraków, pp 104–110
- Grimm E (1990) TILIA and TILIA-GRAPH: PC spreadsheet and graphics software for pollen data. – INQUA Working Group on Data Handling Methods Newsletter 4:5–7
- Hildebrandt-Radke I (2010) Das geologische Alter und die Hauptphasen der Denudations- und Akkumulationsprozesse vor dem Hintergrund topografischer Verhältnisse des archäologischen Fundplatzes Bruszczewo. In: Müller J, Czebreszuk J, Kneisel J (eds) Bruszczewo II: Ausgrabungen und Forschungen in einer prähistorischen Siedlungskammer Großpolens. *Studien zur Archäologie in Ostmitteleuropa* 6. Habelt, Bonn, pp 16–37. 1
- Hildebrandt-Radke I (2013) Pradziejowa i wczesnohistoryczna antroposjia i jej zapis w środowisku przyrodniczym na przykładzie regionu środkowej Obry (Wielkopolska). (*Studia i Prace z Geografii i Geologii* 30). Bogucki Wydawnictwo Naukowe, Poznań
- Hildebrandt-Radke I, Spychalski W, Lutyńska M (2011) Sedimentological, geochemical and diatom investigations on sediments of Lake Wonieść in the context of climate changes and main stages of the Middle Obra River settlement. In: Hildebrandt-Radke I, Dörfler W, Czebreszuk J, Müller J (eds) Anthropogenic pressure in the Neolithic and the Bronze Age on the Central European Lowlands. *Studien zur Archäologie in Ostmitteleuropa*, vol 8. Bogucki Wydawnictwo Naukowe, Poznań, pp 79–95
- Hofmann GM, Werum M, Lange-Bertalot H (2011) Diatomen im Süßwasser-Benthos von Mitteleuropa. Bestimmungsflora Kieselalgen für die ökologische Praxis. Über 700 der häufigsten Arten und ihre Ökologie. Gantner, Ruggell
- Institute for Cultivation, fertilization and geology in Pulawy (1987) [Institute of Soil Science and Plant Cultivation] Agricultural soil maps, 1:100,000
- Jankovská V, Komárek J (2000) Indicative value of *Pediastrum* and other coccal green algae in palaeoecology. *Folia Geobot* 35:59–82
- Juggins S (2001) The European Diatom Database, user guide, version 1.0. University of Newcastle, Newcastle. <http://craticula.ncl.ac.uk/Eddi/docs/EddiGuide.pdf>
- Kinder M, Tylmann W, Bubak I et al (2019) Holocene history of human impacts inferred from annually laminated sediments in Lake Szurpiły, northeast Poland. *J Paleolimnol* 61:419–435
- Kneisel J (2011) Bronze Age Settlements in Bruszczewo. In: Hildebrandt-Radke I, Dörfler W, Czebreszuk J, Müller J (eds) Anthropogenic Pressure in the Neolithic and the Bronze Age on the Central European Lowlands. *Studien zur Archäologie in Ostmitteleuropa*, vol 8. Bogucki Wydawnictwo Naukowe, Poznań, pp 49–65

- Kneisel J (2012) The Problem of Middle Bronze Age Inception in Northeast Europe - or: Did the Únětice Society Collapse? In: Kneisel J, Kirleis W, Dal Corso M, Taylor N, Tiedtke V (eds) Collapse or Continuity? Environment and Development of Bronze Age Human Landscapes. Habelt, Bonn, pp 209–233
- Kneisel J (2013) Long and close distance trade and exchange at the Baltic Coast during Early Iron Age. In: Alberti ME, Sabatini S (eds) Exchange Networks and Local Transformations. Interactions and local changes in Europe and the Mediterranean between Bronze and Iron Age. Oxbow Books, Oxford, pp 156–168
- Kondracki J (2001) Geografia regionalna Polski. Wydawnictwo Naukowe PWN, Warszawa
- Krammer K, Lange-Bertalot H (2008a) Bacillariophyceae 2: Bacillariaceae, Ephitemiaceae, Surirellaceae. In: Ettl H, Gerloff J, Heyning H, Mollenhauer D (eds) Süßwasserflora von Mitteleuropa vol. 2/2, 4th edn. Fischer, Stuttgart
- Krammer K, Lange-Bertalot H (2008b) Bacillariophyceae 3: Centrales, Fragilariaceae, Eunotiaceae. In: Ettl H, Gerloff J, Heyning H, Mollenhauer D (eds) Süßwasserflora von Mitteleuropa vol. 2/3, 3rd edn. Fischer, Stuttgart
- Krammer K, Lange-Bertalot H (2010) Bacillariophyceae 1: Naviculaeae. In: Ettl H, Gerloff J, Heyning H, Mollenhauer D (eds) Süßwasserflora von Mitteleuropa vol. 2/1, 4th edn. Fischer, Stuttgart
- Krammer K, Lange-Bertalot H (2011) Bacillariophyceae 4: Achnantheaceae, kritische Ergänzungen zu Navicula (Linneolatae) und Gomphonema. In: Ettl H, Gerloff J, Heyning H, Mollenhauer D (eds) Süßwasserflora von Mitteleuropa vol. 2/4, 3rd edn. Fischer, Stuttgart
- Krzysztofka M (1989) Szczegółowa Mapa Geologiczna 1:50 000. Arkusz Koscian (542), Geomorphological map. PiG, Warszawa
- Krzysztofka M (1993) Objaśnienia do Szczegółowej Mapy Geologicznej Polski 1:50 000. Arkusz Koscian. PiG, Warszawa
- Krygowski B (2007) Geomorphologic maps of the Wielkopolska-Kujawska Lowland 1: 300,000. Paleogeografia and Geoekologii Institute, Uniwersytet im. Adama Mickiewicza w Poznaniu, Poznań
- Lange-Bertalot H, Metzeltin D (1996) Indicators of Oligotrophy: 800 taxa representative of three ecologically distinct lake types. In: Lange-Bertalot H (ed) Iconographia Diatomologica: Annotated Diatom Micrographs, vol 2. Ecology, Diversity, Taxonomy. Koeltz Scientific Books, Königstein
- Lange-Bertalot H, Bąk M, Witkowski A, Tagliaventi N (2011) Eunotia and some related genera. Diatoms of Europe, vol 6. Gantner, Ruggell
- Latalowa M, Święta-Musznicka J, Słowiński M et al (2019) Abrupt *Alnus* population decline at the end of the first millennium CE in Europe – The event ecology, possible causes and implications. Holocene 29:1,335–1,349
- Lecoite C, Coste M, Prygiel J (1993) “Omnidia”: software for taxonomy, calculation of diatom indices and inventories management. In: van Dam H (ed) Twelfth International Diatom Symposium. Springer, Dordrecht, pp509–513. [https://doi.org/10.1007/978-94-017-3622-0\\_51](https://doi.org/10.1007/978-94-017-3622-0_51)
- Lepš J, Smilauer P (2003) Multivariate Analysis of Ecological Data using CANOCO. Cambridge University Press, Cambridge
- Makohonienko M, Płóciennik M, Papiernik P et al (in press) Environmental changes during Mesolithic-Neolithic transition in Kuyavia Lakeland, Central Poland. Quaternary International. <https://doi.org/10.1016/j.quaint.2021.11.020>
- Matuszkiewicz W, Faliński JB, Kostrowicki AS, Matuszkiewicz JM, Olaczek R, Wojterski T (1995) Potential natural vegetation of Poland. General map 1:300 000. IGiPZ Polska Akademia Nauk, Warszawa
- McCune B, Mefford MJ (2006) PC-ORD: Multivariate Analysis of Ecological Data, v. 5. MjM Software, Gleneden Beach, Oregon
- Mingram J, Negendank JFW, Brauer A, Berger D, Hendrich A, Köhler M, Usinger H (2007) Long cores from small lakes - recovering up to 100 m-long lake sediment sequences with a high-precision rod-operated piston corer (Usinger-corer). J Palaeolimnol 37:517–528
- Moore PD, Webb JA, Collinson ME (1991) Pollen Analysis. Blackwell, Oxford
- Nelle O, Dörfler W (2008) A summary of the late- and post-glacial vegetation history of Schleswig-Holstein. In: Dengler J, Dolnik C, Trepel M (eds) Flora, Vegetation, and Nature Conservation from Schleswig-Holstein to South America – Festschrift for Klaus Dierßen on Occasion of his 60th Birthday. Mitt AG Geobot Schleswig-Holstein Hamburg, vol 65. Arbeitsgemeinschaft Geobotanik in Schleswig-Holstein und Hamburg, Kiel, pp 45–68
- Ralska-Jasiewiczowa M, van Geel B (1998) Human impact on the vegetation of the Lake Gościąg surroundings in prehistoric and early-historic times. In: Ralska-Jasiewiczowa M, Goslar T, Madeyska T, Starkel L (eds) Lake Gościąg, central Poland: a monographic study. W. Szafer Institut of Botany, Polish Academy of Sciences, Kraków, pp 267–294
- Ralska-Jasiewiczowa M, van Geel B, Demske D (1998) Holocene regional vegetation history recorded in the Lake Gościąg sediments. In: Ralska-Jasiewiczowa M, Goslar T, Madeyska T, Starkel L (eds) Lake Gościąg, Central Poland: a monographic study. W. Szafer Institut of Botany, Polish Academy of Sciences, Kraków, pp 202–219
- Rassmann K (2004) Chronologie – Die zeitliche Ordnung der Dinge als Schlüssel zur Geschichte der Bronzezeit. In: Jöns H, Lüth F (eds) Mythos und Magie: archäologische Schätze der Bronzezeit aus Mecklenburg-Vorpommern. (Archäologie in Mecklenburg-Vorpommern 3) Archäologisches Landesmuseum und Landesamt für Bodendenkmalpflege Mecklenburg-Vorpommern, Lübstorf, pp 39–49
- Reimer PJ, Austin WEN, Bard E et al (2020) The IntCal20 Northern Hemisphere Radiocarbon Age Calibration Curve (0–55 cal kBP). Radiocarbon 62:725–757. <https://doi.org/10.1017/RDC.2020.41>
- Słowiński M, Zawiska I, Ott F et al (2017) Differential proxy responses to late Allerød and early Younger Dryas climatic change recorded in varved sediments of the Trzechowskie palaeolake in Northern Poland. Quat Sci Rev 158:94–106. <https://doi.org/10.1016/j.quascirev.2017.01.005>
- Stivrins N, Buchan MS, Disbrey HR et al (2018) Widespread episodic decline of alder (*Alnus*) during the medieval period in the boreal forest of Europe. J Quat Sci 32:903–907
- Szmyt M (ed) (2011) Prehistory of Wielkopolska: A Guide to Exhibition, 2nd edn. Archaeological Museum, Poznań
- Van Dam H, Mertens A, Sinkeldam J (1994) A coded checklist and ecological indicator values of freshwater diatoms from the Netherlands. Neth J Aquat Ecol 28:117–133
- Woszczyk M, Tylmann W, Jędrasik J, Szarafin T, Stach A, Skrzypczak J, Lutyńska M (2014) Recent sedimentation dynamics in a shallow coastal lake (Lake Sarbsko, northern Poland): Driving factors, processes and effects. Mar Freshw Res 65:1,102–1,115. <https://doi.org/10.1071/MF13336>
- Żarczyński M, Wacnik A, Tylmann W (2019) Tracing lake mixing and oxygenation regime using the Fe/Mn ratio in varved sediments: 2000 year-long record of human-induced changes from Lake Żabińskie (NE Poland). Sci Total Environ 657:585–596. <https://doi.org/10.1016/j.scitotenv.2018.12.078>
- Zawiska I, Dimante-Deimantovica I, Luoto TP et al (2020) Long-Term Consequences of Water Pumping on the Ecosystem Functioning of Lake Sekšu, Latvia. Water 12:1459. <https://doi.org/10.3390/w12051459>