



The impact of Lusatian Urnfield and subsequent prehistoric cultures on lake and woodland ecosystems: insights from multi-proxy palaeoecological investigations at Bruszczewo, western Poland

Piotr Kołaczek¹ · Monika Rządziejewicz² · Monika Karpińska-Kołaczek¹ · Iwona Hildebrandt-Radke³ · Mariusz Gałka⁴ · Mateusz Jaeger⁵ · Jutta Kneisel⁶ · Jakub Niebieszczański⁷

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Abstract

The Lusatian Urnfield culture (LUC, Lausitzer Kultur, kultura łużycka) was one of the most important cultural developments during the Late Bronze and Early Iron Age of central-eastern Europe, 1500–500 BC. In this article, we focus on the impact of the LUC and later cultures on the terrestrial and aquatic ecosystems at Bruszczewo on a microregional scale and within the broad context of analogous processes in central-eastern Europe. We did high resolution multi-proxy analyses of pollen, non-pollen palynomorphs (NPPs), diatoms and plant macrofossils, supplemented with a lithological and geochemical study of lake and peat deposits from near the archaeological site. The results revealed that between ca. 1020 and 920 BC, woodland clearance took place, possibly connected with farming. This probably contributed to the spread of the weeds *Xanthium* cf. *strumarium* and *Convolvulus arvensis* in the newly created disturbed habitats. Woodland clearance and other human activities contributed to better preservation of diatoms in the lake sediments, probably as a result of increased acidity in this environment. Diatoms, especially taxa preferring eutrophic waters and tolerant of large amounts of dissolved organic matter, were the most frequent at that time. Climate deterioration associated with the 2.8 ka event probably lessened human impact around the lake shore. The diatom records suggest prolonged ice cover on the lake and/or colder springs at that time. Another intensification of human impact occurred at ca. 530 BC and was probably related to activity by people of Pomeranian culture (kultura pomorska, Pommerellische Gesichtsurnenkultur). Later, from ca. 330 BC, arable farming activity declined and grazing was suggested by an abundance of coprophilous fungi spores which, however, should not be regarded as definitive indicators of pasture.

Keywords Lusatian Urnfield culture · Human impact · 2.8 ka event · Diatom analysis · Pollen analysis · Lake acidification

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✉ Piotr Kołaczek
pkolacz@amu.edu.pl

¹ Faculty of Geographical and Geological Sciences, Climate Change Ecology Research Unit, Adam Mickiewicz University, Poznań, Ul. Bogumiła Krygowskiego 10, 61-680 Poznań, Poland

² Faculty of Geographical and Geological Sciences, Biogeochemistry Research Unit, Adam Mickiewicz University, Poznań, Ul. Bogumiła Krygowskiego 10, 61-680 Poznań, Poland

³ Faculty of Geographical and Geological Sciences, Anthropocene Research Unit, Adam Mickiewicz University, Poznań, Ul. Bogumiła Krygowskiego 10, 61-680 Poznań, Poland

⁴ Department of Biogeography, Paleoeecology and Nature Conservation, Faculty of Biology and Environmental Protection, University of Lodz, Ul. Stefana Banacha 1/3, 90-237 Łódź, Poland

⁵ Institute of European Culture, Adam Mickiewicz University, Poznań, Ul. Józefa Kostrzewskiego 5–7, 62-200 Gniezno, Poland

⁶ Institute of Pre- and Protohistoric Archaeology, Kiel University, Leibnizstraße 3, 24118 Kiel, Germany

⁷ Faculty of Archaeology, Adam Mickiewicz University, Poznań, Ul. Uniwersytetu Poznańskiego 7, 61-614 Poznań, Poland

Introduction

The Lusatian Urnfield culture (LUC, Lausitzer Kultur, kultura łużycka) was one of the most important cultural phenomena during the Late Bronze Age (LBA) and Early Iron Age (EIA) of central-eastern Europe, both in terms of its vast extent as well as its time span (Dzięgielewski 2017; Kaczmarek 2017). This cultural period spanned approximately 1500–500 BC. In theory, such a long-lasting prehistoric culture, dependent on agricultural subsistence, should be perfect for investigating human impact on the landscape on a millennial scale. However, the number of studies on the effects of the LUC on palaeoenvironmental records is limited to several case studies in central-eastern Europe (for example, Nowaczyk and Okuniewska-Nowaczyk 1992; Niewiarowski and Noryśkiewicz 1999; Harding et al. 2004; Jahns et al. 2013; Kneisel et al. 2019; Gałka et al. 2022). Among the many LUC settlements explored so far, many of them are situated in the vicinity of or within lakes, fens, oxbow lakes or wet meadows (former wetlands) (Chochorowski et al. 2000; Dzięgielewski 2017). Hence, their impact should be recorded by various kinds of palaeoecological proxy evidence (Bakels 2020; Wieckowska-Lüth et al. 2021) as wetland deposits are environmental archives for various micro- and macrofossils connected to human presence (for example, Moore et al. 1991; Birks 2001; Birks and Birks 2006; Shumilovskikh and van Geel 2020). Moreover, among the consequences of a rising population is a change from woodlands into open land, dominated by cultivated fields, meadows, pastures and ruderal areas (Meyerson 2003). A spread of landscapes created by humans may have allowed native plants to enter new habitats and/or increased the dispersal of new taxa introduced by human migrations and economic exchange, and/or promoted the evolution of new taxa adjusted to environments modified by human activity (Lambdon et al. 2008; Hejman et al. 2013; Bellini et al. 2022). The period of the LUC was a time when numerous native taxa started to spread in arable land and/or ruderal habitats and new taxa appeared in the floras of central-eastern European regions (Lityńska-Zajac 2005; Lityńska-Zajac and Wasylikowa 2005). Woodland clearances and agricultural activities in a lake and/or wetland catchment can stimulate various types of erosion (Dreibrodt et al. 2010), and more people and livestock produce more nutrients (Chislock et al. 2013; Davies et al. 2022) which can be expected to influence the nutrient status of adjacent lakes and wetlands. Developments by past societies may have generated an environmental loop in which lakes attracted people and stimulated development of settlements, which in turn contributed to changes in the quality of water as a result of the

influx of nutrients and pollutants (Chislock et al. 2013), and finally may have led to limitation of settlements.

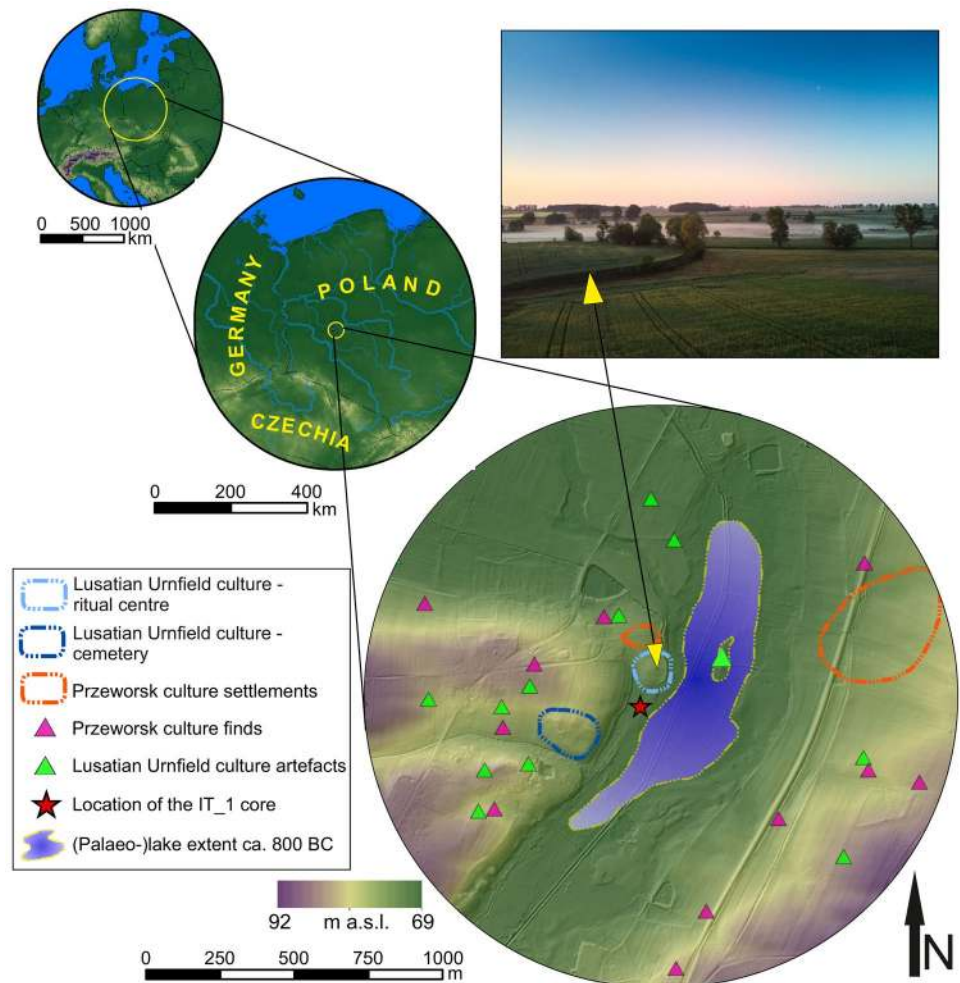
In this article, we focus on the long-lasting impact of LUC and successive cultures on terrestrial and aquatic ecosystems at a microregional scale in Bruszczewo and within the broad context of analogous processes at the time of the LUC domination in central-eastern Europe. Bruszczewo, located in the southern part of Wielkopolska (Greater Poland, central-eastern Europe; Czebreszuk and Müller 2015; Czebreszuk et al. 2015; Niebieszczański et al. 2022) is a multi-cultural site, in which evidence of the LUC has been found in the form of a ritual centre, a cemetery and traces of human activity on an island in the former lake (Niebieszczański et al. 2022). Archaeological knowledge of the LUC at Bruszczewo is, on the one hand, extensive, as three sites were discovered there during excavations in the past, but on the other hand, the exact chronology and human impact on the local ecosystem remain unclear, apart from preliminary near-site and on-site palynological recognition by Haas and Wahlmüller (2010) and an off-site record from a nearby lake, Wonieść (Dörfler et al. 2023). Hence, to fill this knowledge gap, in our research we undertook a multi-proxy study of the deposits at this site. We applied high-resolution investigations including analyses of pollen, non-pollen palynomorphs (NPPs), diatoms and plant macrofossils, and supplemented these with a lithological and geochemical study of the deposits. We aimed first to reconstruct the impact of the LUC and successive cultures on the local wooded and open vegetation as well as changes in land management, including the appearance of new taxa associated with humans; secondly, to understand the links between changes in the lake and those in water quality as a result of human impact and/or global and regional climate changes.

Geographical and archaeological settings

Site setting, a palaeogeographical view

The LUC complex of sites in Bruszczewo lies on the western slope of the Samica river valley, a minor tributary of the river Obra in western Poland, Wielkopolska (Fig. 1). The main morphological feature of the area is the valley, which originated in the late Weichselian, when the retreating glacier and its subglacial meltwaters created a tunnel valley. The Bruszczewo site is situated in the middle part of the river course, where its valley is flat-bottomed and runs from north to south (Fig. 1). It is filled with Holocene peat overlying gyttja, underlain by glaciofluvial sands and tills. The Holocene deposits vary from about 4 m thick in the eastern part to more than 9 m in the central and western parts of the valley (Niebieszczański et al. 2024). Glaciofluvial sands also appear on the land

Fig. 1 Maps showing the location of the study area at Bruszczevo. The largest scale map (below, on right) shows the location of the IT_1 core and archaeological features. Upper right, the position of the LUC ritual centre (arrowed) and the Samica river valley (photo by Marcin Sokalski). Digital elevation models obtained from ASTER DEM GRID (after usgs.gov) and ISOK DEM (after geoportal.gov.pl)



surface in the central part of the valley where there is an oblong esker (Niebieszczański et al. 2022). According to previous research (Niebieszczański et al. 2024) the valley has undergone significant landscape changes since the end of the Pleistocene. Around 18,000 BC, shortly after the retreat of the ice sheet from this area, an extensive lake formed and occupied the basin until at least ca. 200 BC, at which time some lake remnants still survived (Niebieszczański et al. 2024). The lake was gradually transformed into a rich fen that occupied the valley floor until at least medieval times. From that time up to the 19th century AD, the sedimentation pattern was controlled mostly by seasonal flooding of the Samica until this river was regulated and it now follows an artificial channel.

Currently, the valley floor supports meadows and pastures, while the river rarely floods due to the embankments along its channel. The slopes above the valley are mostly arable fields, with some pine woods on the western slopes.

Archaeological settings

The Bruszczevo microregion is known for its Bronze Age settlement history. In earlier studies, the emphasis was mainly on the Early Bronze Age (EBA), when the area was inhabited by people of the Únétice culture who established a fortified settlement on a sandy hillock on the western plain beside the former lake (e.g., Czebreszuk and Müller 2004, 2015; Czebreszuk et al. 2015). Of the numerous studies relating to the EBA in Bruszczevo, some also included later settlement periods, such as the LUC (Kneisel 2011; Ignaczak 2015). The archaeological record of the LUC at Bruszczevo revealed the presence of 1, a large (> 1 ha) Urnfield cemetery on the western slopes, 2, undefined settlement remains on the sandy hillock, 3, numerous artefacts on the island (esker) in the central part of the lake (Niebieszczański et al. 2022) and 4, numerous isolated finds in the fields in the former lake shore area. Little is known about the cemetery because only a limited area was excavated and no ^{14}C dates were obtained from there (Ignaczak 2015). Surface finds of potsherds, connected with LUC burials, allow us to estimate

the extent of the site on the western slopes. To the south, the cemetery probably extends into the present-day woodlands (Fig. 1).

The most intriguing part of the settlement complex is on the western plain beside the palaeolake. After the abandonment of settlement by the Únětice people at ca. 1600–1500 BC, the area was uninhabited for several hundred years. During this time, a deep ditch separating the EBA settlement from the hinterland was partially filled with natural sediments (Bork 2010). The new LUC settlers occupied the same hillock as the Únětice people and dug pits on its surface, which contained pottery and also the bones of wild and domesticated animals as well as of humans. They partially deepened the EBA ditch of the settlement (Ignaczak 2015). However, traces of houses were not recorded during excavations. The pottery found in pit backfills was regarded as resembling more a funeral type of activity than waste from a settlement. Animal bones found in features had numerous traces of preparation and processing (Makowiecki and Drejer 2010; Iwanek and Piontek 2015). The lack of houses, the presence of a funerary pottery and signs of consumption might, according to the researchers (Ignaczak 2015), point to the site as being more ritual than domestic in character.

So far, ^{14}C dating at this site is not sufficient to provide any details of the time spans of the various occupation periods at the site. Only two dates were obtained from one pit and these were separated by a few hundred years, $2,720 \pm 35$ ^{14}C BP (Ki-5906) and $2,450 \pm 50$ ^{14}C BP (Ki-5607) (Czebreszuk et al. 2015). The pottery assemblages date the functioning of the pits to the very late stages of the Bronze Age (Montelius V period, 900–700 BC) and the beginning of the EIA (Hallstatt C, 800–660 BC). However, some pottery types, as well as finds from the peat zone, suggest that the site may date from as early as 1200 BC (Diers 2010).

Evidence of human activity was also discovered in the central part of the valley plain, where the esker was an island during the LBA and EIA. There, the surface survey revealed numerous LUC pottery fragments in molehills, as well as in samples from cores on the higher part of the island, which suggested LUC occupation there (Niebieszczański et al. 2022). Also, in the wider area of the Bruszczevo microregion, many surface finds, mostly of pottery, suggest extensive human occupation around the lake (Fig. 1).

Material and methods

Coring, core lithology and chronology

The sediment core IT_1 used in the present investigations was obtained near the archaeological site, on a former peninsula 50 m to the south of the western shore of the palaeolake at 70.4 m a.s.l. The 600 cm long profile was obtained with

an Instorf corer with a 5 cm diameter chamber, 50 cm long. The lowermost part of the profile consisted of fine detritus/calcareous gyttja that continued to 255 cm, where fen peat was present (Niebieszczański et al. 2024). For this study, deposits from 361 to 184 cm depth in this core and spanning ca. 1420–190 BC were selected to study the effects of LUC occupation on the surrounding environment. Sediment slices 1 cm thick were taken to be subsampled for the various analyses. The chronology of profile IT_1 as published by Niebieszczański et al. (2024) is used here (Fig. 2). Calendar dates were obtained from the model as μ values (rounded to 10 years) and are expressed as BC (calibrated years).

Lithology and geochemistry

Pollen, non-pollen palynomorphs and plant macroremains were the main palaeoecological proxies used in this study.

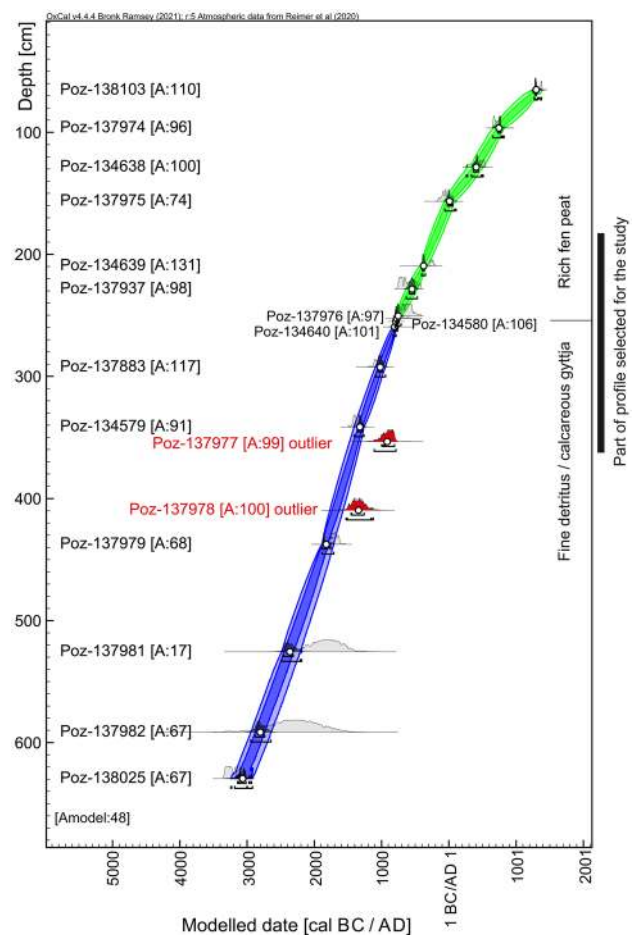


Fig. 2 Bayesian age-depth model for the IT_1 profile (Niebieszczański et al. 2024, modified). The model was produced using OxCal v. 4.4 (Bronk Ramsey 1995, 2006), applying the *P_Sequence* function (parameters: $k_0=0.5$, $\log_{10}(k/k_0)=1$ and *interpolation* = 1) (Bronk Ramsey 2008; Bronk Ramsey and Lee 2013) and the IntCal20 calibration curve (Reimer et al. 2020)

The lithology and geochemistry were studied in a limited number of samples. Carbon (C), nitrogen (N) and sulphur (S) were analysed in 14 samples, selected metallic elements (Cu, Zn, Pb, Ni, Mn, Fe, Mg, Cr, Na, K, and Ca) and phosphorus (P) in 25 samples, grain sizes in 40 samples and CaCO_3 in 10, using standard laboratory procedures (ESM 1).

Pollen, non-pollen palynomorphs (NPPs) and plant macrofossil analyses

For pollen analysis, 64 samples of 1 cm^3 were selected (pollen spectra from 18 samples were published by Niebieszczański et al. 2024). The pollen samples were prepared using standard laboratory procedures (Berglund and Ralska-Jasiewiczowa 1986; ESM 1). Plant macrofossils were examined in 45 samples, with a minimum of 2 cm^3 sample size, using material that was available after sampling for other analyses. Macrofossil data from 19 of these samples have been published in Niebieszczański et al. (2024) (ESM 1).

Diatoms

For diatom analysis, 64 samples of 1 cm^3 were used, from the same depths as for pollen analysis. Sample processing and analyses followed Battarbee (1986). At least 300 diatom valves per sample were analysed with a light microscope using oil immersion at $1,000\times$ magnification. Identification keys by the following authors, Lange-Bertalot and Krammer (1987); Lange-Bertalot and Metzeltin (1996); Krammer and Lange-Bertalot (2008a, 2008b, 2010, 2011); Hofmann et al. (2011); Lange-Bertalot et al. (2011), as well as AlgaeBase by Guiry and Guiry (2023) were used. The diatom ecological groups were arranged with OMNIDIA v. 4.2 (Lecointe et al. 1993, Denys 1991 and van Dam et al. 1994). We considered the following indicator parameters: habitat category (Denys 1991), preference for pH, trophic state (van Dam et al. 1994) and dominant taxa with abundance over 2%.

Data presentation

The diagrams were drawn using Tilia (Grimm 1992), with pollen percentages based on the total terrestrial pollen sum (TTP, ESM 1). The pollen assemblage zones were identified with CONISS (Grimm 1987). In distinguishing the diatom assemblage zones (DAZs) all diatom taxa were used, while for the pollen data, local pollen assemblage zones (LPAZs) were distinguished based on terrestrial pollen taxa.

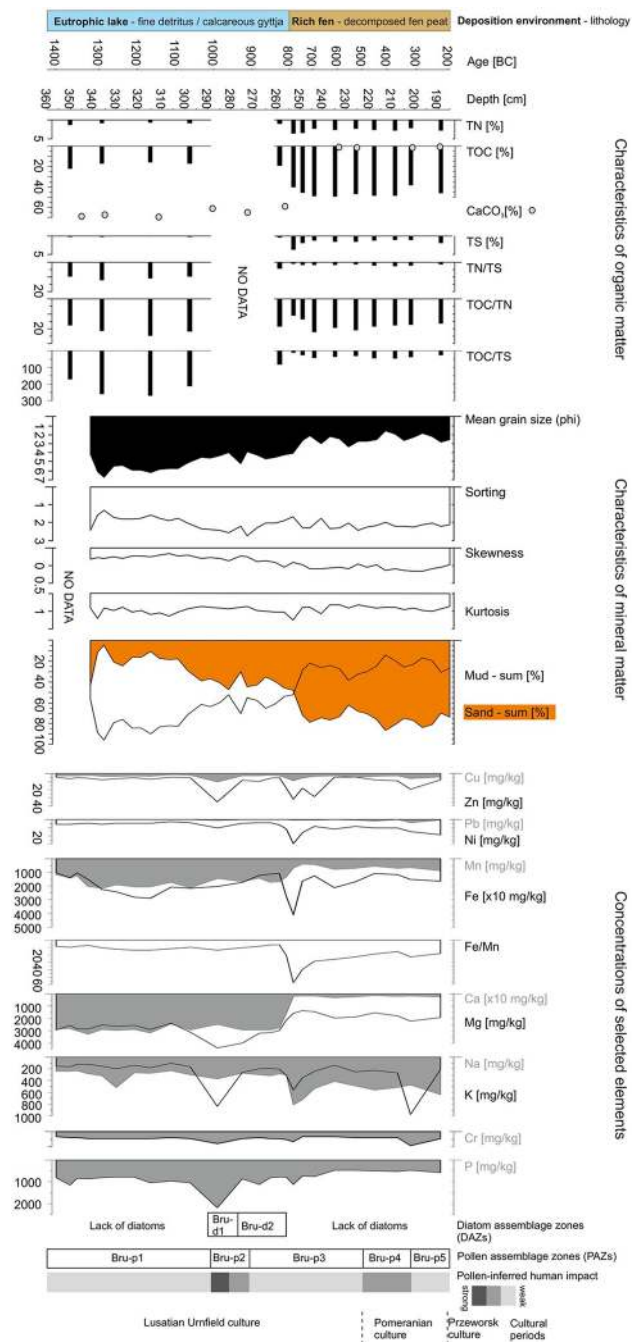


Fig. 3 Bruszczevo, profile IT_1, results of lithological, sedimentological and geochemical analyses. TN, total nitrogen; TOC, total organic carbon; TS, total sulphur; kurtosis, occurrence of outliers

Results and interpretation

Lithology and geochemistry

The transition from gyttja to peat is at about 255 cm in core IT_1 (ca. 810 BC) and these two sediment types differ substantially in their physical and geochemical properties, as

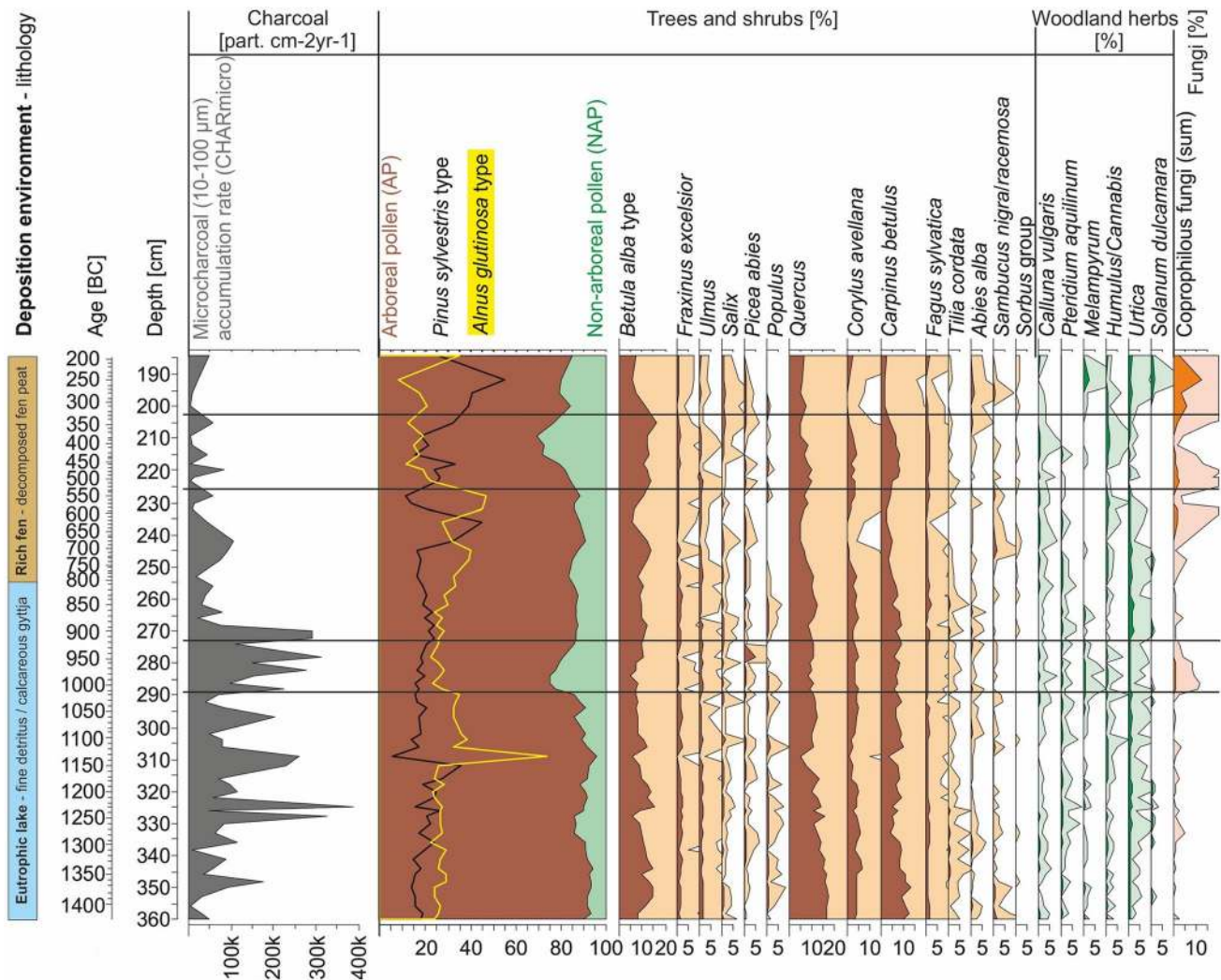


Fig. 4 Bruszczewo, profile IT_1: Results of pollen, spore, non-pollen palynomorph and microcharcoal analyses showing changes in terrestrial ecosystems. The percentages are of the total terrestrial pollen sum (TTP), which is AP and NAP, excluding aquatic and wetland

taxa, cryptogams and NPPs. Lighter colours are used in individual curves to show values magnified by 10. *Abbreviations:* *excl.* excluding; *undiff.* undifferentiated

expected (Fig. 3). The gyttja has higher CaCO_3 (average: 65.4%) and its total organic carbon/total sulphur (TOC/TS) ratio is also higher (81.6–269.4), whereas its TOC is distinctly lower (16.9–22%). The peat has higher TOC (38.2–49.3%), total nitrogen (TN 2.2–3.6%) and sulphur (TS 1–3.6%), distinctly lower values of TOC/TS (11.1–44.4) and CaCO_3 (mean value 0.9%). This dataset shows that the gyttja represents oxidising conditions, substantial CaCO_3 content and a highly decomposed organic matter component with smaller values of TOC/TN (Kuhry and Vitt 1996; Malmer and Wallén 2004). The highest TS values were from the bottom-most peat layer and are associated with the maximum Fe/Mn ratio. The increase in TS concentration is related to the degree of decomposition of organic matter (Herranen

2010) and the bacterial reduction of sulphates in this layer by redox activity (Bottrell and Novak 1997).

The fine detritus/calcareous gyttja at 361–255 cm (ca. 1420–810 BC) has greater concentrations of Mn (1,191–2,184 mg kg^{-1}), Ca (162,246–328,685 mg kg^{-1}) and Mg (2,160–4,468 mg kg^{-1}), in contrast to the fen peat at 255–184 cm (ca. 810–190 BC), which was richer in Na (411–976 mg kg^{-1}) and Ni (8.4–29.8 mg kg^{-1}) (Fig. 3). In the gyttja deposit, Mg, K, Zn and P values have peaks at 286 cm (ca. 1000 BC). In the case of Mg and P, this may signify higher productivity from photosynthesis. Even though the P values might have been affected by remobilization of phosphorous by plants rooted in the gyttja (Bojakowska 2016), the P peak at 286 cm coincides with higher productivity as indicated by biotic proxies such as

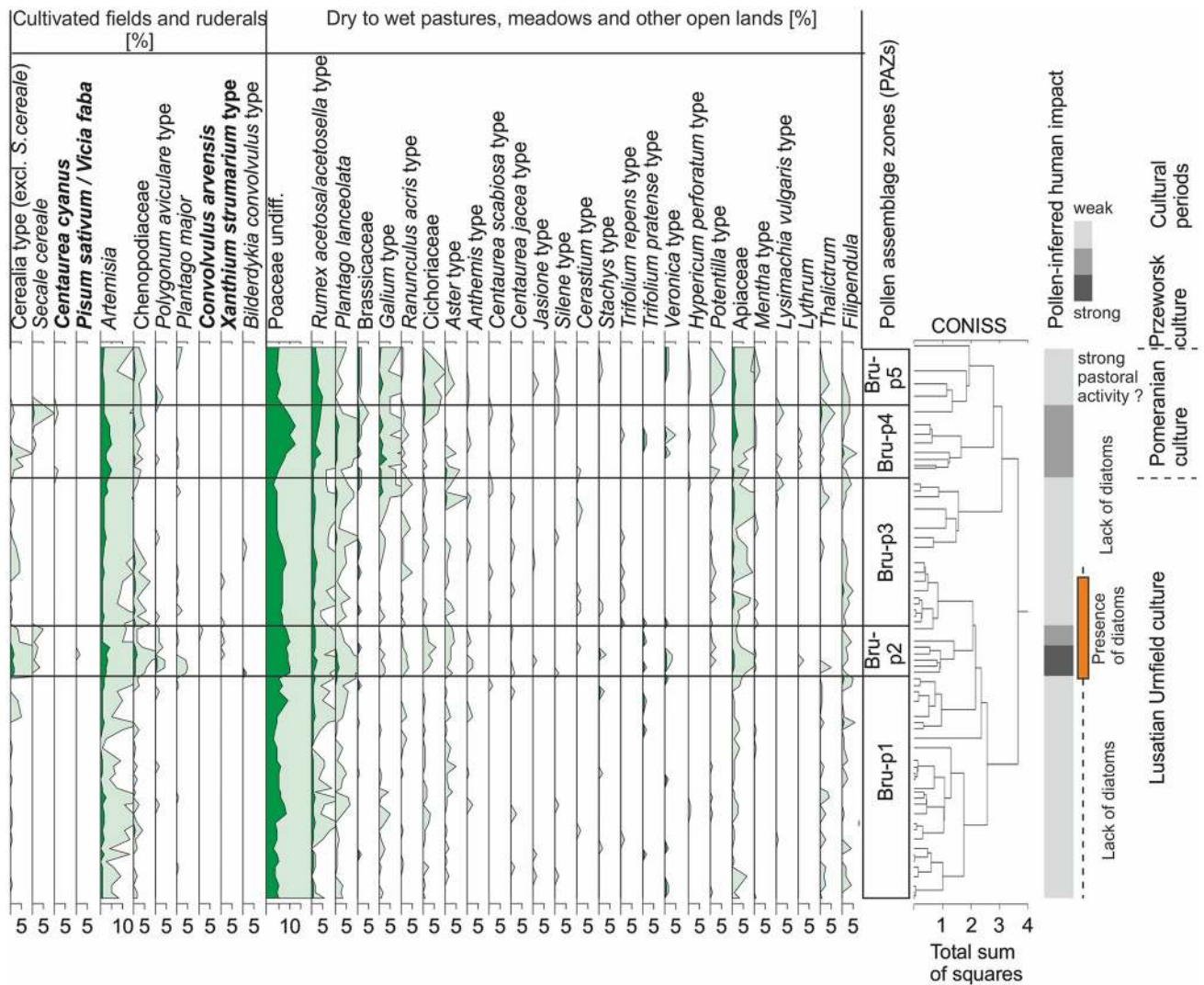


Fig. 4 (continued)

the diatom data. The distinct peaks of Cu, Zn, Ni, Fe, Na, K and P at 255 cm coincide with the transition from gyttja to peat. These high values may be related to the supply of organic (Zn and P) and mineral (Ni, Fe, Na and K) matter from the catchment at the early stage of fen development (Borówka 2007; Clark et al. 2014). The Fe/Mn ratio is lower in the gyttja (6.3–20.5) compared with the peat (15.6–57.9; maximum at 253 cm) (Fig. 3). In general, higher Fe/Mn ratio values suggest less oxygenated conditions (Stewart and Fergusson 1994; Żarczyński et al. 2019). The transition to fen peat caused a rapid increase in this ratio which suggests that the peat became inundated as it began to accumulate. Later fluctuations in the lake water level and better peat aeration were probably the causes of lower Fe/Mn ratios.

The gyttja has a higher mud fraction (52.2–96% of the mineral component), while the peat has a higher sand

fraction (61.6–86.5% of the mineral component) (Fig. 3). The particle sizes in Krumbein phi values range between 1.3 and 2.8 with no obvious trend. Mean grain size reduces towards the upper part of the profile (range 6.7–1.6 phi), whereas skewness values rise gradually (from –0.34 in gyttja to 0.16 in peat), while in the peat the values are relatively stable. In the gyttja, apart from plant detritus, there is a silt fraction with coarser, sandy fractions (negative skewness). The detritus origin may be largely from soil, as shown by the TOC/TN ratio (Contreras et al. 2018). In the peat part of the section, the organic sediments contain sand, which probably arrived in flooding events, but possibly also from erosion from the slopes. High K values support the latter idea (Borówka 1992).

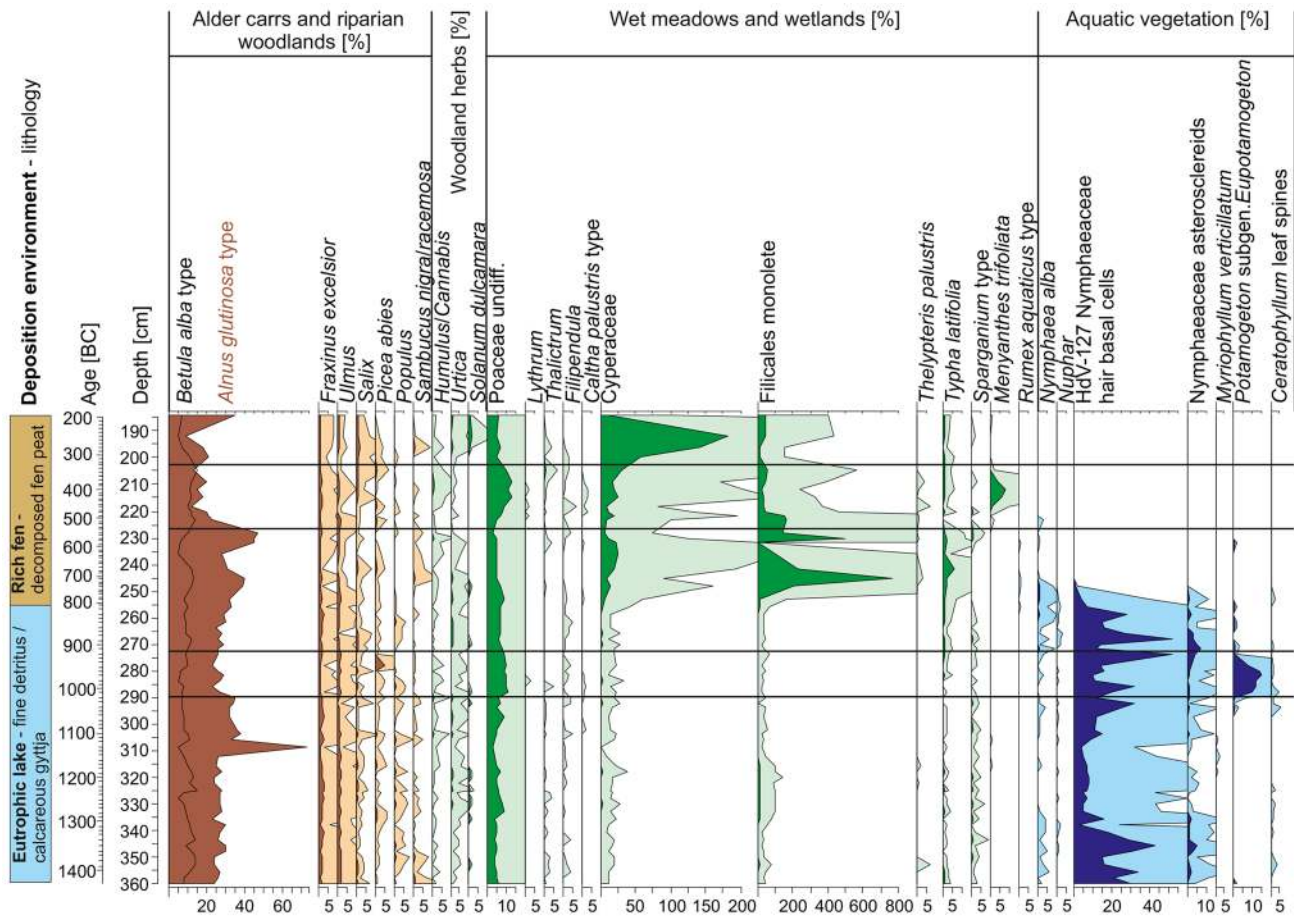


Fig. 5 Bruszczewo, profile IT_1: Results of pollen, spore and non-pollen palynomorph analyses showing changes in lake and rich fen ecosystems. The percentages are of TTP as for Fig. 4. Lighter colours

are used in individual curves to show values magnified by 10. *Abbreviations:* carb. & s. high organic carbon content and saprophytic; sp. species; subgen. subgenus; undiff. undifferentiated; var. variety

Ecosystem changes as evidenced by pollen, non-pollen palynomorphs (NPPs), plant macrofossils and microcharcoal

The analyses revealed five stages of variable human impact on the vegetation that correspond to the five local pollen zones calculated by CONISS. As well as concentrating on human impact, the descriptions of the LPAZs also consider wetland and aquatic pollen taxa and the data from spores, algae, other NPPs and microcharcoal (Figs. 4, 5).

Zone Bru-p1; 360–289 cm (ca. 1420–1010 bc)

At around 1500 bc, the promontory in Bruszczewo was already abandoned by people of the Únětice culture who had lived there during the Early Bronze Age (Czebreszuk and Müller 2015; Czebreszuk et al. 2015). The archaeological evidence suggests ca. 1100 bc as the possible starting point for the occupation of the site by the Lusatian Urnfield

culture (LUC) people. Apart from the Bruszczewo promontory, there may also have been settlements elsewhere around the lake (Szambelan 2022).

During this period, *Quercus* (4.9–17.2%), *Carpinus betulus* (5.4–13.3%), *Corylus avellana* (1–5.9%) and *Pinus sylvestris* (pollen types: 5.7–35.2%, 4,966–17,109 grains $\text{cm}^{-2} \text{year}^{-1}$, Fig. 4, ESM 2) were the main woodland components in moderately moist habitats, but *Fagus sylvatica* (0.7–2.2%) and *Tilia cordata* (pollen types: 0–1%) were more scattered. Under an open tree canopy and in openings in dry and moderately moist woodlands, *Pteridium aquilinum*, *Calluna vulgaris* and *Melampyrum* were abundant. The wet surrounding areas were occupied by alder (*Alnus glutinosa* type: 22.6–73.2%; 6,720–221,640 grains $\text{cm}^{-2} \text{yr}^{-1}$) and birch (*Betula alba* type: 5.6–15.5%; grains 2,229–17,822 $\text{cm}^{-2} \text{yr}^{-1}$), with some *Fraxinus excelsior* (1–2.6%), *Ulmus* (0.1–1.8%) and *Salix* (0.1–1.1%) (Fig. 3, ESM 2). In the understorey of the wet woodlands, there was *Sambucus nigra/racemosa* and in the herb layer,

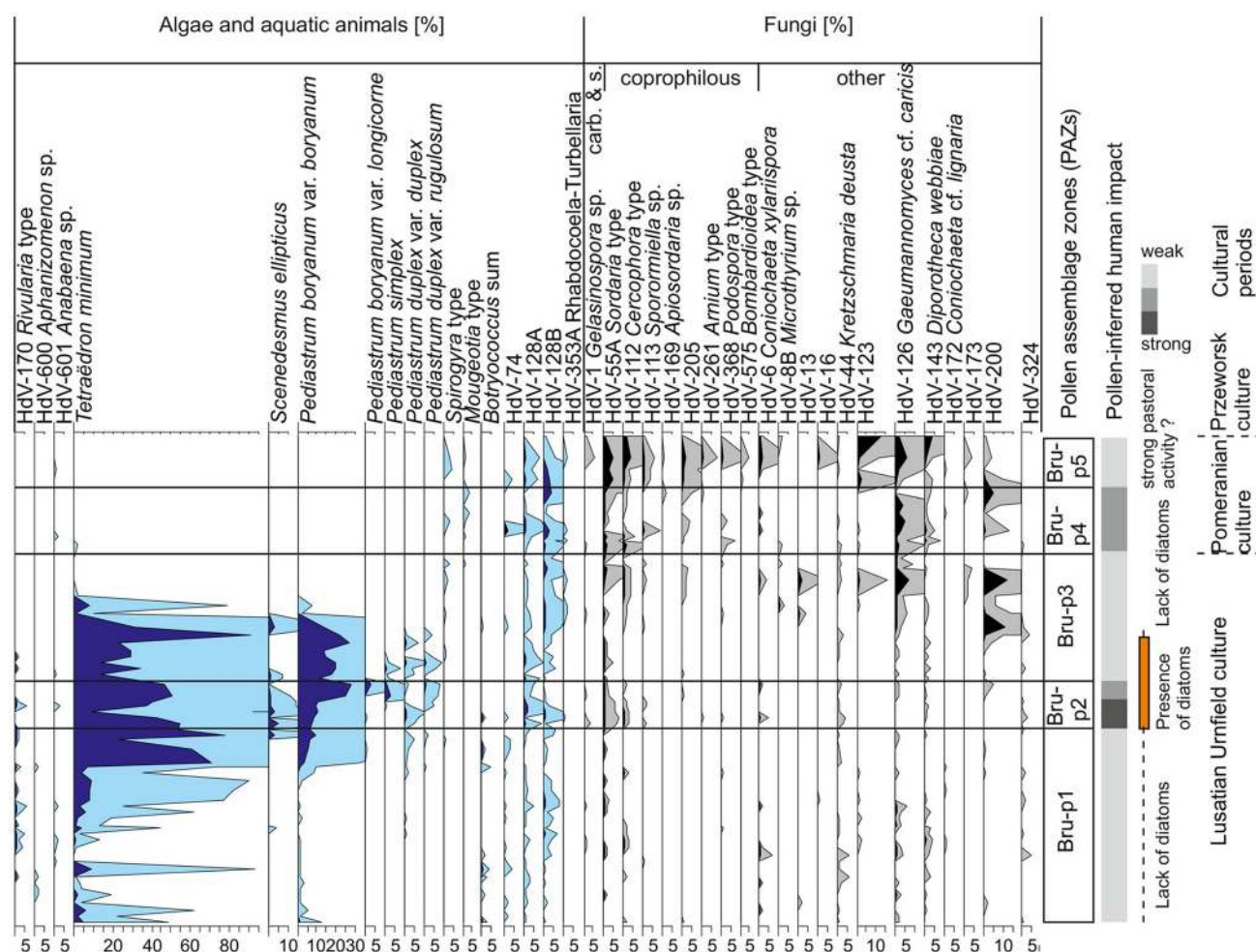


Fig. 5 (continued)

Urtica (0.1–1.5%), *Humulus/Cannabis* (0–1%) and *Solanum dulcamara*. Open habitats are indicated by relatively high NAP values (6.1–14.4%) in which Poaceae dominate (2.6–9.2%), probably from grasses in wetlands associated with the shallowing lake as well as ones growing on dry mineral soils. Additionally, *Artemisia* (0.1–2.8%) and *Rumex acetosalacetosella* type dominated in ruderal habitats as well as in dry areas. *Plantago lanceolata* (0–0.9%), as well as scattered records of coprophilous fungi (0–0.5%), may indicate that some of the newly created open areas were used extensively for pasture (Makohonienko et al. 1998). Other indicators of moderately to fairly wet meadows include Apiaceae, *Thalictrum*, *Filipendula*, Cichoriaceae and *Galium* type which occur in most samples. The presence of cultivated fields is indicated by Cerealia type pollen (0–0.5%) in most samples. The microcharcoal accumulation rate ($\text{CHAR}_{\text{micro}}$, 510–326,494 particles $\text{cm}^{-2} \text{yr}^{-1}$) indicates high fire activity in this period, with four distinct peaks. One, at ca. 1280–1250 BC, coincided with woodland clearance shown by a decline in AP values of ca. 4–5%. The high

fire activity, at least partly caused by humans, contributed to woodland openness and gaps.

The eutrophic lake had *Nymphaea alba* and *Nuphar lutea* floating on it, whose local presence in aquatic vegetation (Figs. 5, 6), apart from pollen and macrofossils, is further emphasised by Nymphaeaceae hair basal cells (HdV-127: 2.4–42.6%) (Fig. 5). From ca. 1100 BC, the amounts of the algae *Tetraëdron minimum* (up to 78%, 30,704 cells $\text{cm}^{-2} \text{yr}^{-1}$) and *Pediastrum boryanum* var. *boryanum* (up to 9.7%, 3,567 coenobia $\text{cm}^{-2} \text{yr}^{-1}$) increased distinctly (Fig. 5, ESM 2), which probably marked increasing productivity related to lake shallowing and woodland clearance (AP declines).

Zone Bru-p2; 289–273 cm (ca. 1010–920 BC)

This zone represents the beginning of LUC activity at Bruszczewo. The ritual centre and adjacent cremation cemetery were probably created at this time (Czebreszuk and

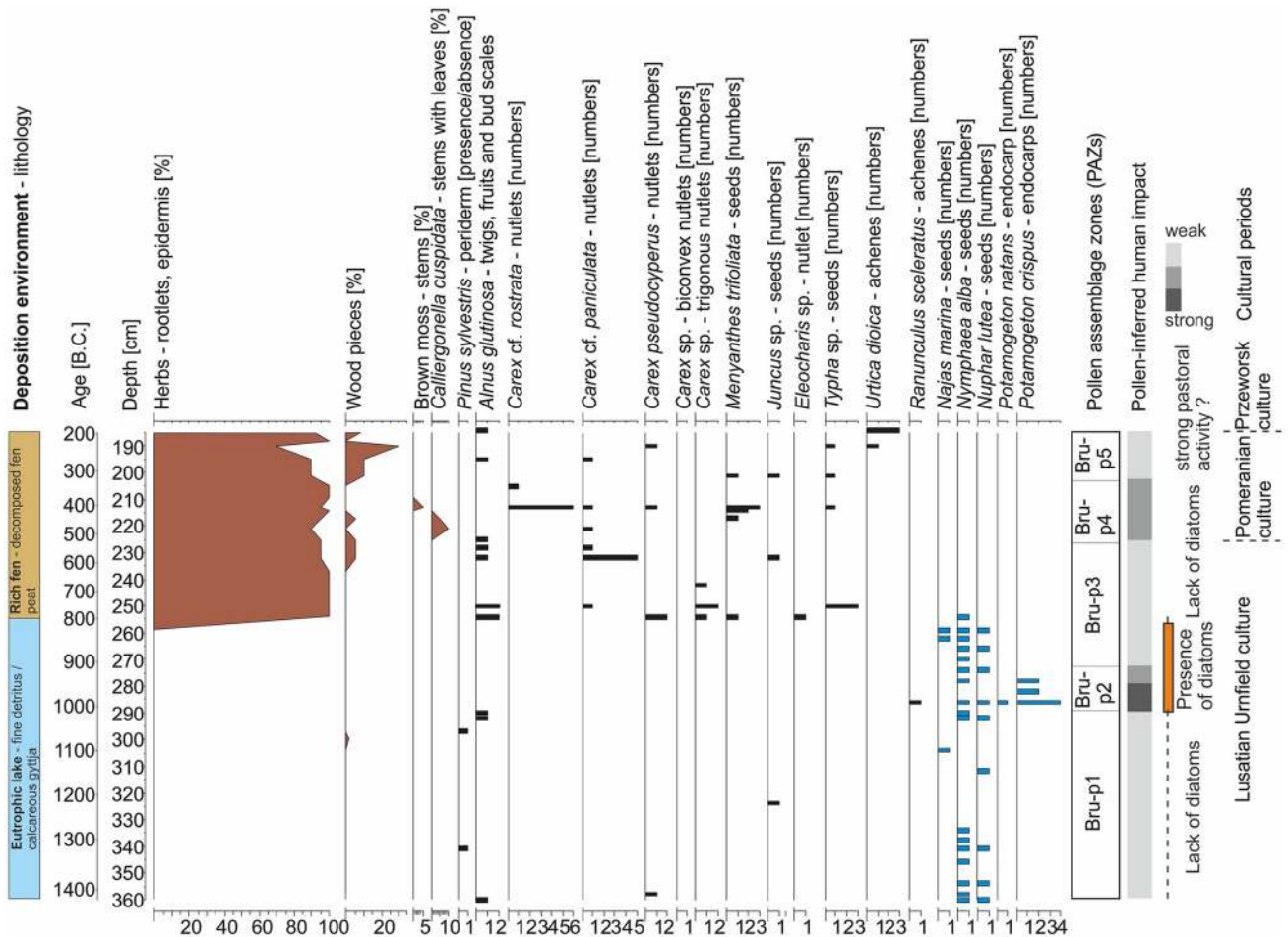


Fig. 6 Bruszczewo, profile IT_1: Results of plant macrofossil analysis. Brown mosses, all Bryopsida except *Sphagnum*

Müller 2015; Czebreszuk et al. 2015; Ignaczak 2015), but the exact date is uncertain (Ignaczak 2015).

The pollen data indicate an increase in human activities that resulted in significant woodland clearance at the beginning of the zone and then recovery of trees in the later part (AP: 75–86%) (Fig. 4). Among the trees, alder (*Alnus glutinosa* type: 23.1–28.5%) and *Fraxinus excelsior* reduced. Cultivated fields became more extensive and/or were situated closer to the lake shore, as indicated by distinct increases in *Cerealia* type pollen (0.2–1.6%) and the regular presence of *Secale cereale* (0.1–0.5%) which appeared for the first time in the profile. The single pollen grain of *Vicia faba* or *Pisum sativum* points to the growing of beans or peas (Fig. 4). An increase in ruderal habitats and perhaps their closeness to the lake shores is suggested by *Artemisia* (1–3.3%), *Chenopodiaceae* (0.2–1.4%), *Polygonum aviculare* type (0–0.4%), *R. acetosalacetosella* type (0.8–1.9%) and *Plantago major*. An increase in taxonomic richness in the ruderal communities is suggested by the first records for *Xanthium strumarium* type, *Bilderdykia convolvulus* type and *Convolvulus arvensis*. Similarly, areas potentially used as pastures are reflected by

an increase in coprophilous fungi (0.3–1.2%; mainly *Sordaria* type) which corresponds with high NAP and *P. lanceolata* values. The palynological analysis, overall, indicates that there was human occupation close to the lake shore, which no doubt also influenced the microcharcoal record, which has higher values compared with the previous zone (Bru-p1). The woodland recovery detected in the later part of this zone was probably further from the lake. Eutrophic lake conditions are indicated by the constant presence of *Nymphaeaceae* hair basal cells (HdV-127; 10–52%). Other aquatic plants included *Potamogeton crispus* and *P. natans* (Figs. 5, 6) which are recorded as macrofossils and *Eupotamogeton* pollen (0.2–15%). Eutrophic conditions are confirmed by high values for *Tetraëdron minimum* (9.2–46.7%) and increased representation of most *Pediastrum* taxa (Fig. 5).

Zone Bru-p3; 273–225.5 cm (ca. 920–530 BC)

During the period represented by zone Bru-p3, neither the archaeological data nor the relevant radiocarbon dates indicate the end of the ritual centre, its abandonment or its

destruction (Czebreszuk and Müller 2015; Czebreszuk et al. 2015). The distribution of LUC artefacts around the former lake suggests continuing occupation.

Though human impact probably declined (AP increased to 90.4%; Fig. 4), farming activity continued in the catchment, as indicated by *Cerealia* type records in most samples. At the same time, a decline in human impact probably enabled regeneration of woodlands, with some exceptions. At ca. 820–720 BC, *Cerealia* type pollen is more regularly recorded, coinciding with a period of woodland clearance seen in reduced AP. Ruderal and other plant communities favoured by human activity are indicated by regular records of *Rumex acetosa/acetosella* type, *Plantago major*, *Artemisia*, *Chenopodiaceae* and even single *Xanthium strumarium* type and *Bilderdykia convolvulus* type pollen records. The decline of human impact explains, at least partly, the decrease in fire activity at ca. 890 BC (declining $\text{CHAR}_{\text{micro}}$ from 289,250 to 2,130 particles $\text{cm}^{-2} \text{yr}^{-1}$) (Fig. 4, ESM 2). The decrease in pollen indicators of human impact might be connected with the change from lake to rich fen which took place in this period. The main tree that spread in this period was alder (*Alnus glutinosa* type: 25.4–47%), suggesting that the wet lake edge habitats were occupied by alder carr. The spread of *Alnus* coincides with synchronous declines of *Quercus*, *Carpinus* and *Corylus*. The alder canopy might have limited influx of pollen from other kinds of woodland in the catchment area such as patches of regenerating woodlands in areas that had previously been affected by human activity. The same process might have affected microcharcoal accumulation, as lake terrestrialisation, spread of alder and $\text{CHAR}_{\text{micro}}$ decline are synchronous developments (Fig. 4). If this is correct, then the data may lead to underestimation of fires and human activity.

The alder spread at the same time that the rich fen developed at the coring site, at ca. 790 ± 30 BC (Niebieszczański et al. 2024). This process is reflected by a rapid decline in abundance of Nymphaeaceae hair basal cells (HdV-127), *Tetraëdron minimum*, *Pediastrum boryanum* var. *boryanum* and an increase in Cyperaceae (pollen: 1.3–25%; macrofossils of *Carex* cf. *paniculata*, *C. pseudocyperus* and *Eleocharis* sp.), Filicales monoete (max. 499%; probably including spores of *Thelypteris palustris*) and *Typha latifolia* (0.1–1.8%). Together with the expansion of Poaceae (probably *Phragmites australis*) and Cyperaceae (probably *Carex* sp.), the fungal NPP *Gaeumannomyces* cf. *caricis* (HdV-126: max. 7.2%) and HdV-200 (max. 12.8%) became more frequent (Figs. 5, 6). The lake level was fluctuating and there was periodical water stagnation marked by algae and related NPPs such as *Spirogyra* type, *Mougeotia* type, *Botryococcus* and HdV-128 A and B. With the start of peat accumulation, coprophilous fungi became more frequent, which might be an effect of increased availability of dead

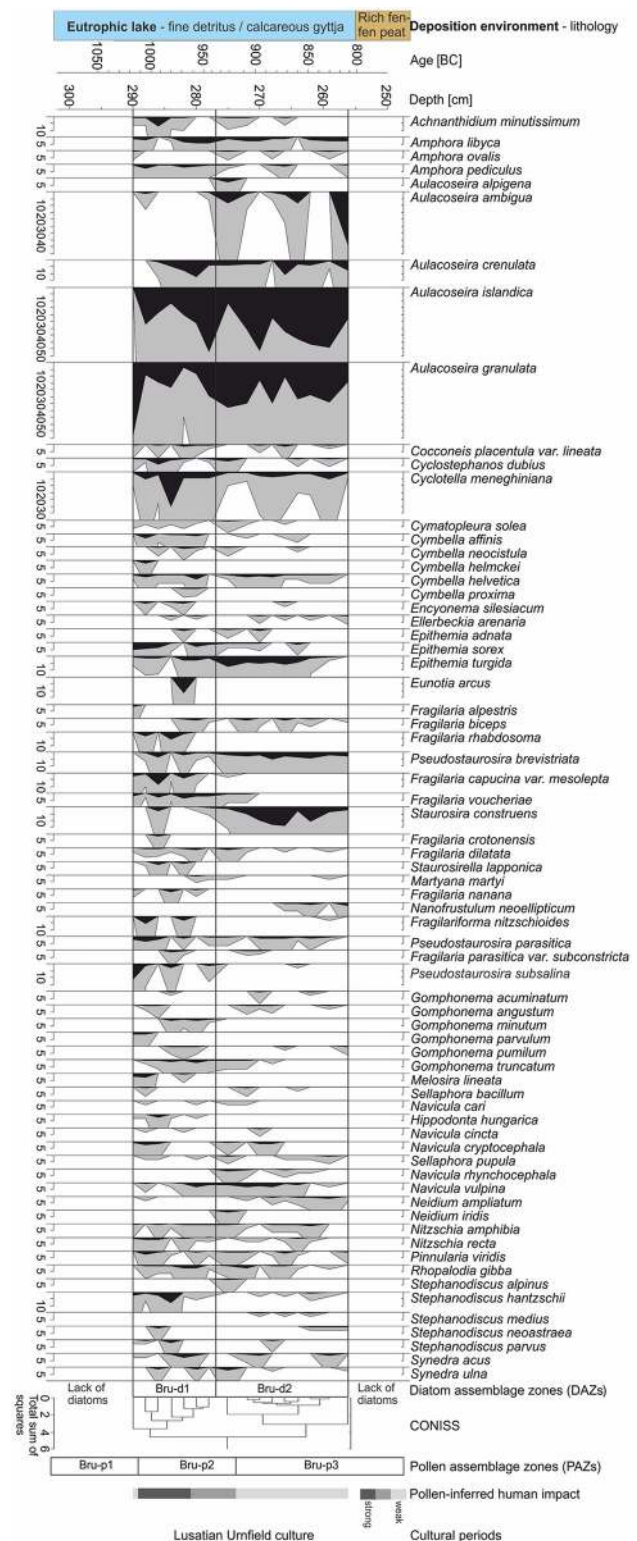


Fig. 7 Bruszczevo, profile IT_1: Results of diatom analysis. Lighter colours are used in individual curves to show values magnified by 10

organic matter and/or more frequent presence in the fen of grazing livestock (Figs. 4, 5).

Zone Bru-p4; 225.5–202.5 cm (ca. 530–330 BC)

During the period represented by zone Bru-p4, artefacts of Pomeranian culture type (kultura pomorska, Pommerellische Gesichtsurnenkultur) appeared and became widespread in the Wielkopolska region (Dzięgielewski 2010). However, there is no direct archaeological evidence of the presence of this culture from the excavations at Bruszczevo nor in artefacts found on the surface in this microregion.

Alder woodlands declined (*Alnus glutinosa* type: 12.6–22.5%) and this openness increased pollen transport from *Quercus*, *Corylus*, *Carpinus* and *Fagus* from the upper river terrace of the valley. There was more cultivated land and/or it was closer to the fen edge, as shown by *Cerealia* type and *Secale cereale* which were well represented together with *Centaurea cyanus* which was recorded for the first time. Ruderal communities are reflected in the records of *Artemisia* and *Chenopodiaceae*. Pasture, meadows and/or dry and open rich-fen communities were more widespread, as indicated by increases in percentages of *Poaceae*, *Rumex acetosacetosella* type, *Plantago lanceolata*, *Galium* type and *Apiaceae*. Wet rich fen habitats supported *Menyanthes trifoliata* (0–8.1%). Coprophilous fungi spore values are similar to those at the end of Bru-p3. Even though AP values are the lowest in the profile, low fire activity is indicated by $\text{CHAR}_{\text{micro}}$ values of 3,760–84,850 particles $\text{cm}^{-2} \text{yr}^{-1}$.

Zone Bru-p5; 202.5–184 cm (ca. 330–190 BC)

During this period, the late Pomeranian culture and at its end, the early stage of the Przeworsk culture (kultura przeworska, 3rd century BC–1st century AD) were present in the Wielkopolska region. Two Przeworsk settlements have been recorded to the north and east of the site (Fig. 1; Teska and Michałowski 2017).

During this period the woodlands regenerated, probably in the areas near the rich fen, mainly with pine, (*Pinus sylvestris* type: 25.7–40.7%), then alder (*Alnus glutinosa* type: 8.4–35.3%) and to a lesser extent willow (*Salix* 0.4–1.4%). As in Bru-p3, pollen percentages of *Corylus*, *Carpinus* and *Fagus* declined. The habitats near the coring site were rich in nitrogen, indicated by more frequent occurrences of the nitrophiles *Urtica dioica* and *Solanum dulcamara* (Ellenberg 1974). *Melampyrum* grew in the woodland undergrowth in moderately wet and dry habitats, which might have been affected by grazing (Behre 1981). The great increase in coprophilous fungi might have been a result of decomposition processes in the aerated peat layer and/or increased presence and/or numbers of livestock grazing on the fen surface.

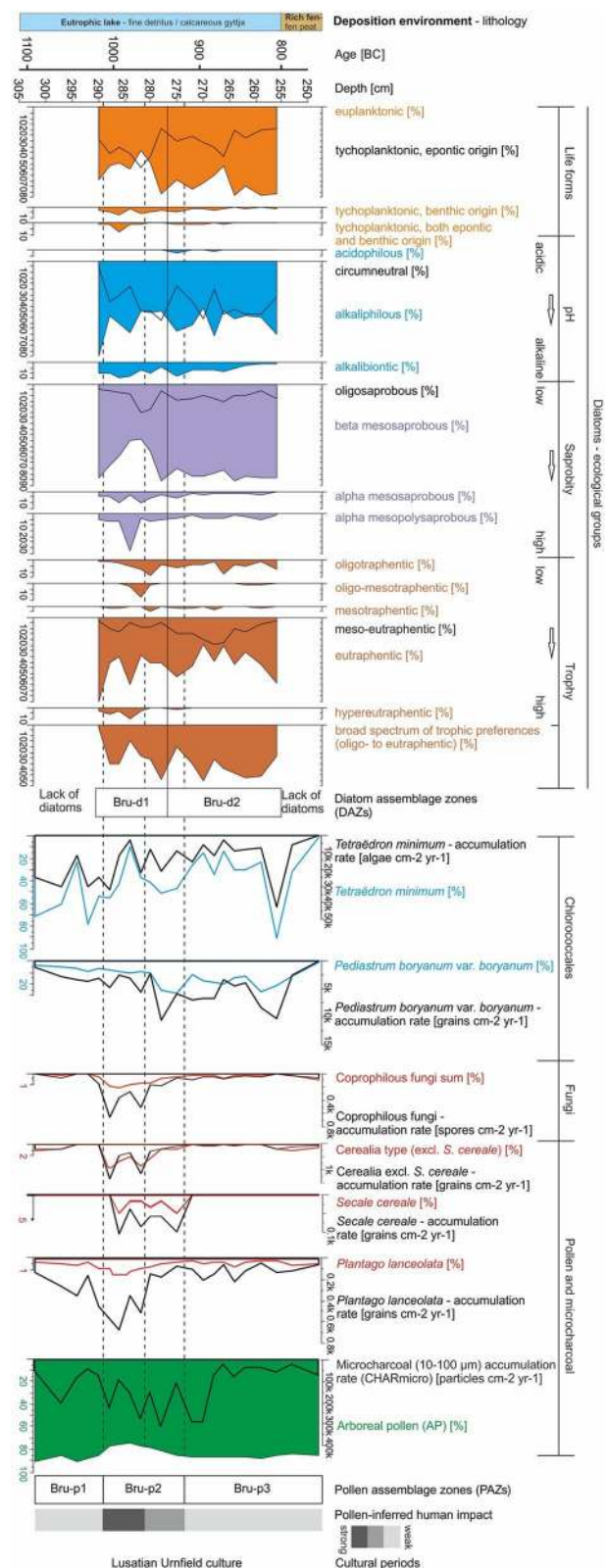


Fig. 8 Bruszczevo, profile IT_1: Summary of results of diatom and palynological analyses. Percentages of diatom ecological groups are calculated separately for life forms, pH, saprobity (organic matter content) and trophic (water nutrient status). The ecological groups of diatoms are explained in the text

Diatoms

In the samples spanning ca. 1420–1020 BC (fine detritus/calcareous gyttja) and 820–190 BC (fine detritus/calcareous gyttja and mostly decomposed fen peat), there was a lack of recognizable diatom frustules. The numbers of diatom valves increased substantially in the layer showing strong woodland clearance and increased farming activity by Lusatian Urnfield culture people, ca. 1020–810 BC (290–256 cm). In only 16 out of 64 samples (25%), however, was it possible to record more than 300 frustules and calculate statistically significant percentages (Figs. 7, 8). The lack of diatoms in the fen peat is a result of a lack of suitable habitats for them there (Gaiser and Rühland 2010; Garcés-Pastor et al. 2017). On the other hand, the absence of diatoms in many of the gyttja deposits may have numerous explanations, such as removal of frustules by water flow, resuspension and reworking of older sediments, grazing by zooplankton, bioturbation and dissolution (Battarbee 1986; Jones 2007; also discussion below).

CONISS analysis suggests two distinct diatom zones, Bru-d1 and 2 (Fig. 7), that are described below.

Zone Bru-d1; 290–276.5 cm (ca. 1020–940 BC)

This zone coincides with the period of the greatest woodland clearance and the highest percentages and pollen accumulation rates of taxa indicating human activities at the end of Bru-p1 and in the earlier part of Bru-p2 (Fig. 8). The dominant taxa were *Aulacoseira islandica* (0–47%; distinct increase towards the top of the zone), *A. granulata* (3.9–53.9%; decreasing trend), *A. crenulata* (0–12.6%) and *Cyclotella meneghiniana* (1–25.5%). More frequent taxa compared with zone Bru-d2 were *Amphora pediculus*, *Cymbella affinis*, *Fragilaria rhabdosoma*, *F. capucina* var. *mesolepta*, *Epithemia sorex*, *Staurosirella lapponica*, *Pseudostaurosira subsalina* and *Stephanodiscus hantzschii* (Fig. 7).

The aquatic habitats were favourable for a range of diatom types including free floating (euplanktonic) diatoms (37.5–76.4%), ones moved around by disturbance (tychoplankton) and/or those released from melting ice (epontic) (19.7–53.9%). The most abundant taxa of more alkaline water (alkaliphilous) steadily declined from 83.7 to 44.7% and were gradually replaced by taxa representing circumneutral water (4.6–51.9%). Taxa representing alkaline conditions also played an important role in the diatom communities (4.1–13.4%). The concentration of dissolved organic matter favoured beta mesosaprobous taxa (60–85.4%) whose biological oxygen demand (BOD) for removing organic matter from water in the process of decomposition by aerobic bacteria is 2–4 mg l⁻¹ (Van Dam et al 1994). However, distinct increases of alpha mesopolysaprobous (BOD 13–22 mg l⁻¹, 33.5%, ca. 980 BC) and later of oligosaprobous

taxa (BOD < 2 mg l⁻¹, max. 24.3%, ca. 970 BC) are linked with the strongest signs of woodland clearance from low AP percentages (Fig. 8). Eutraphentic taxa (34.2–74.8%) that prefer eutrophic water and those with broad ecological tolerance (3.6–48.4%) were most abundant in this zone. The hypereutraphentic taxa, characteristic of very eutrophic water (0.3–10%), had their highest values in the profile, coinciding with the strongest signs of woodland clearance (Fig. 8).

Zone Bru-d2; 276.5–256 cm (ca. 940–820 BC)

This zone corresponds with a period of lower human impact in the later part of Bru-p2 and earlier Bru-p3 (Figs. 7, 8). In general, diatoms were present in low concentrations. *Aulacoseira islandica* (11.7–46.3%) and *A. granulata* (10.6–28.8%) continued to be the most frequent taxa. Their decline is correlated with distinct peaks in *A. ambigua* (max. 40.1%) and *A. crenulata* (10.6%). In this zone, values of *Staurosira construens* (1.6–13.5%) and *Epithemia turgida* (0–7.8%) were distinctly higher than in the previous one. *Amphora lybica*, *Pseudostaurosira parasitica*, *Pseudostaurosira brevistriata* and *Navicula vulpina* had low values but were more frequent (Fig. 7).

Euplanktonic taxa (60.7–82.6%) were more common than in the previous zone. Diatoms of circumneutral (21.8–53.8%) and alkaline water (42.2–66.7%) dominated alternately. Dissolved organic carbon levels favoured beta mesosaprobous taxa (75.2–88.9%). As for the previous zone, eutraphentic taxa (24.4–58%) and ones with broad ecological tolerances (20.5–52.8%) were well represented (Fig. 8).

Discussion

Palaeoecological data in dating settlement activity: challenges and pitfalls

The Late Bronze (LBA) and Early Iron Age (EIA) occupation in Bruszczewo, when studied by environmental evidence, provides the chance to fill major gaps in the archaeological knowledge of the area. Earlier archaeological and geoarchaeological research on this site concentrated mainly on the Early Bronze Age (EBA); however, later material provided some glimpses into the Lusatian Urnfield culture (LUC) occupation period but did not allow reconstruction of the history of its settlement there. Unfortunately, no chronology of the LUC at the site has been established due to the limited number of ¹⁴C dates and the lack of a chronology from distinctive pottery types from this site. As indicated earlier, the only available ¹⁴C dates are from two samples which are within the Hallstatt radiocarbon plateau, and so these rather imprecise dates are of little use for establishing

a chronology of LUC occupation at the site (Czebreszuk and Müller 2015). The large number of settlements and other archaeological features revealed by the surface survey also lacks precise dating. Also, most of the potsherds were not distinct enough, according to Czebreszuk and Szydlowski (2010), to attribute them to narrow time horizons. There is also no precise chronology for the LUC cemetery near the ritual centre on the promontory at Bruszczewo, nor for the recently discovered LBA/EIA site on the former island in the ancient lake. On the other hand, the palaeoecological data presented here provide important new evidence towards establishing a precise chronology for the site. Palynological data show three phases of LUC settlement activity in the area: (1) before ca. 1010 BC, with dispersed settlement in the wider area with a little stable human impact, (2) ca. 1010–920 BC, the probable development of settlement and farming activity in the shoreline zone and possibly the creation of an LUC cemetery and (3) ca. 920–530 BC, a little stable human impact, perhaps when the ritual centre had lost its importance (Szambelan 2022). The next period of substantial increase of agricultural activity at ca. 530–330 BC is also important for understanding the archaeological chronology. In that period, the local LUC society was influenced by the new social, cultural and economic organization of the Pomeranian culture (Dzięgielewski 2010). Up until now, neither excavations in Bruszczewo nor the surface survey finds have revealed any traces of this culture. This may be the result not only of an actual lack of artefacts, but also of the generalized way of interpreting the maps of the Archeologiczne Zdjęcie Polski (AZP, the Polish Archaeological Record), the main source of archaeological data in Poland. The chronological divisions of cultural units in the AZP are often combined into units of several centuries, so that periods spanning 200 years or less may be merged into wider periods so that artefacts of the Pomeranian culture may be hidden within larger archaeological and chronological units such as the LBA and EIA.

The time horizon at ca. 330 BC shows a potential change in economic strategy, from arable to pastoral farming, which corresponds with the time of the emergence of the Pomeranian culture in Wielkopolska (Dzięgielewski 2010). This process is indicated by the decline and/or disappearance of pollen indicators of cultivated fields with a simultaneous increase in spores of coprophilous fungi (Fig. 4). However, other interpretations may be equally probable: (1) people may have abandoned local settlements and the indications of pastoralism from coprophilous fungi may have come from grazing wild animals; (2) the decaying organic matter in fen peat may have supported more ubiquitous taxa that usually occur on dung as an alternative source of organic carbon (Shumilovskikh and van Geel 2020). A simultaneous increase in *Melampyrum* and Cichoriaceae pollen, which are regarded as indicators of grazed woodlands or pastures

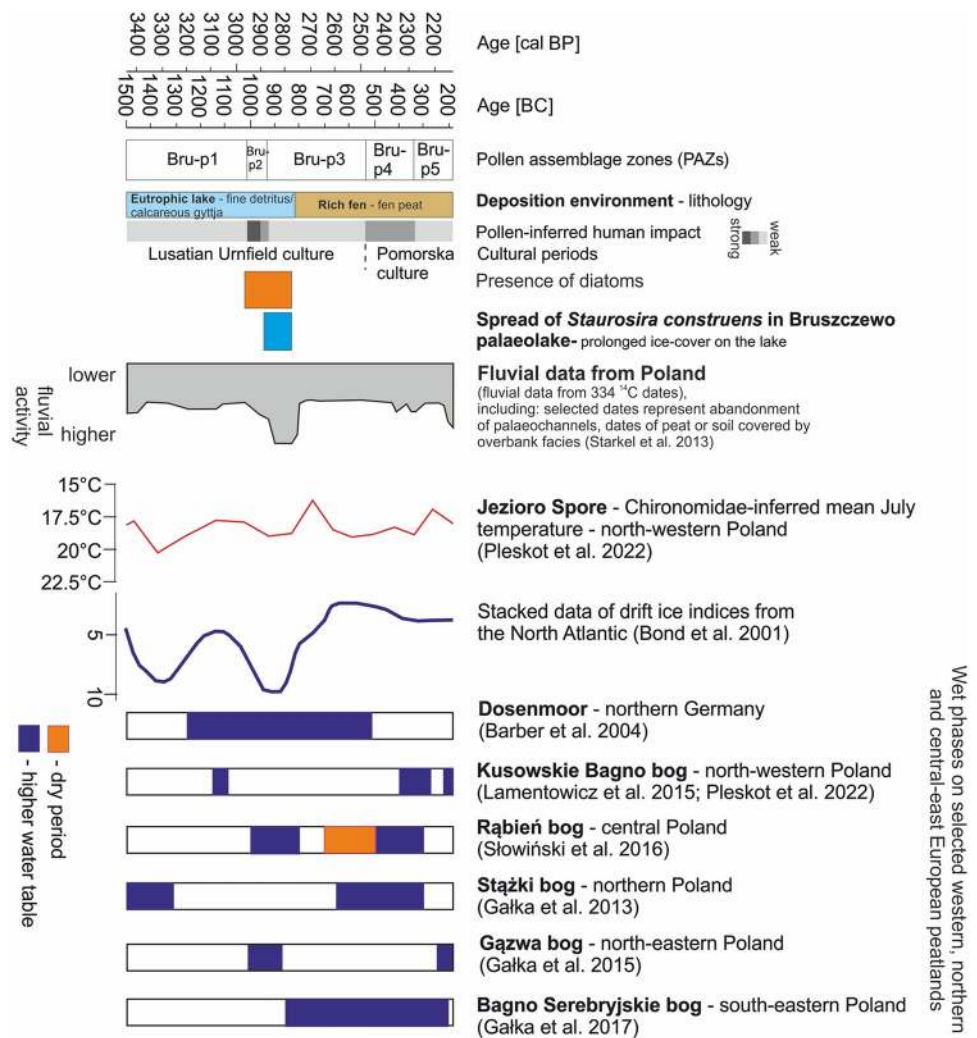
(Behre 1981) together with coprophilous fungi suggest grazing. This finds support in the simultaneous decline of *Plantago lanceolata*, characteristic of mown meadows, pastures and fallow land (Behre 1981) but only lightly grazed (Makohonienko et al. 1998). Davies et al. (2022) suggest that the decline or disappearance of pollen of grazing-tolerant taxa is a reliable indicator of heavy grazing when recorded together with large amounts of coprophilous fungal spores. However, rapid increases in abundance of coprophilous fungi on peatlands are not a straightforward indicator of the biomass of large domesticated and wild herbivores (Davies 2019). All these arguments show that any conclusions about economic transitions between arable and pastoral farming should be drawn from a broad set of indicators.

The effects of Lusatian Urnfield culture settlement on lake water quality

Lack of diatoms in fine detritus/calcareous gyttja

Diatoms are the most sensitive indicators of water quality in our study. They were found only in the layer of fine detritus and calcareous gyttja from ca. 1020–810 BC (Fig. 7), when the signs of much woodland clearance and expansion of farming in the lake catchment were recorded (Fig. 8). Below this horizon and above it only a few unidentified diatom fragments were detected and all bore traces of dissolution (ESM 3). Valve dissolution is listed among the factors responsible for low concentrations of diatoms in sediments (Battarbee 1986; Jones 2007). Alkaline water conditions, which support accumulation of CaCO_3 (Fig. 3), might have contributed to removal of diatoms through dissolution of the frustules, contributing to the lack of records in much of the profile. Moreover, Apolinarska et al. (2012) reported that an increase in the abundance of picoplankton (ca. 0.5–2 μm) which provide potential nuclei for calcite precipitation, might be accompanied by a decrease in diatoms. During the period represented by the layer in which the diatoms were found, the increase in human impact may have resulted in increased delivery of nutrients from cultivated fields near the lake (Fig. 8; Taylor et al. 2013). This could have caused eutrophication and an increase in acidity of the lake water, which would have improved the potential for diatom preservation. A shallow lake water depth of 2 m or less, indicated by the presence of *Nymphaea alba*, *Nuphar luteum* and *Potamogeton natans* (Brzozowski and Pelechaty in press), may have supported this process (Figs. 5, 6). Moreover, diatom composition and ultimately preservation may have been affected by their removal as a result of water flowing through the lake, resuspension and reworking of older sediments, or grazing by zooplankton and bioturbation (Battarbee 1986; Jones 2007). In the case of the palaeolake at Bruszczewo, even if water flowed through it, it was quite large, > 20 ha

Fig. 9 Climate oscillations as reconstructed by various authors at selected sites in western, northern and central Europe (Barber et al. 2004; Starkel et al. 2013; Gałka et al. 2013, 2015, 2017; Lamentowicz et al. 2015; Słowiński et al. 2016; Pleskot et al. 2022) and stacked data on drift-ice indices in North Atlantic cores (Bond et al. 2001) compared with the Bruszczewo record as presented in this paper



(Niebieszczański et al. 2024) and relatively shallow, so the effect of flowing water on diatoms should have been negligible. Water flow should also have affected other planktonic algae such as *Tetraëdron minimum* or *Pediastrum* spp. which were regularly abundant in layers without any diatom valves (Fig. 8). If mixing of sediments through bioturbation is considered, two outlier ^{14}C dates that are later than suggested by the age-depth model might represent some reworking of the sediment from the period ca. 1680–1390 BC (410–353 cm). However, above this layer, up to ca. 1020 BC, the regular succession of ^{14}C dates suggest undisturbed deposits, but yet these too are devoid of diatoms. We do not have other data, such as from Cladocera or other zooplankton, that might indicate their grazing as a factor responsible for the removal of diatoms before they could be deposited and preserved. Stable values for microscopic algae such as *T. minimum* suggest no distinct changes in zooplankton grazing pressure before or after diatom appearance, so such pressure is unlikely to be responsible for the lack of diatoms. There is also a lack of distinct traces of competition between diatoms

and other algae detectable by the palynological analysis. Even if there is a minor decline in the *T. minimum* accumulation rate as diatoms are recorded (Fig. 8), the increase in the amount of *Pediastrum boryanum* var. *boryanum* suggests that any effect by Chlorophyta spp. is minimal. To sum up, valve dissolution seems to be the most reasonable explanation for the lack of diatoms in the interval ca. 1420–1020 BC with fine detritus/calcareous gyttja, although the other factors referred to above cannot be excluded with certainty.

The Lusatian Urnfield culture and the diatom record

Changes in water quality related to increased human impact of LUC people near the Bruszczewo lake shore are clearly shown in the diatom record. In general, beta-mesosaprobous taxa were dominant, which means relatively low or moderate amounts of organic matter in the lake water, with a biological oxygen demand (BOD) of 2–4 mg l⁻¹. Coinciding with the signs of pronounced woodland clearance at ca. 1020–950 BC and a greatly increased emphasis on arable farming, the

largest amount of organic material in the water (BOD: 13–22 mg l⁻¹), eutra- and hypereutrophic taxa were recorded (Fig. 8). This indicates a distinct increase in nutrient levels in the shallow and eutrophic lake environment. The strongest evidence of organic matter from diatoms, from alpha-mesopolysaprobous diatom values of 33.5%, was found from ca. 980 BC, mainly of *Cyclotella meneghiniana* and to a lesser extent *Stephanodiscus hantzschii*. Both taxa are found in eutrophic water rich in phosphorus (P) (Wang et al. 2012; Reavie and Kireta 2015). Wang et al. (2012) showed that *C. meneghiniana* and *S. hantzschii* are more competitive than other diatoms when water turbulence is limited, but *Cyclotella* needs water enriched by orthophosphates. Håkansson (2002) reported the presence of *C. meneghiniana* in various types of water from oligotrophic to polluted. In Brazil, the abundant modern occurrence of this species was recorded in very warm waters, highly polluted by faecal contaminants (Pereira et al. 2010). The simultaneous increase in the accumulation rate of coprophilous fungal spores in the period ca. 1020–950 BC suggests that faecal material may have enriched the lake water with phosphorus (P) and thus compensated for water turbulence in the shallow lake (Fig. 7). The synchronous peaks of magnesium (Mg), zinc (Zn) and potassium (K) indicate the greatest deposition of eroded (clastic) material from the catchment around the lake (Wirth et al. 2013; Welc et al. 2021; Dörfler et al. 2023). At Salet, a lake in north-eastern Poland, the prominent increase in the frequency of *S. hantzschii* has been linked to the changes towards hypertrophy caused by human impact (Gašiorowski et al. 2021). On the other hand, in Wonieść, western Poland, 15 km east of Bruszczewo, the peak of *S. hantzschii* was not related to increased human impact (Dörfler et al. 2023), whereas from Szurpiły (north-east Poland) there are only sporadic records for this species (Kinder et al. 2019). A synthesis by Stivrins et al. (2018), based on studies of lakes in Latvia, indicates that high records of *S. hantzschii* are linked with strong eutrophication.

The period ca. 950–810 BC is characterized by a decline of human influence and a change in diatom composition and *Aulacoseira islandica* and *A. granulata* dominated here, but *Epithemia turgida* and *Staurosira construens* had the highest values, and there were single, short-term but distinct peaks of *Aulacoseira ambigua*. *A. granulata* is associated mostly with eutrophic waters in which there is mixing of the water column (Bicudo et al. 2016), as is *A. islandica* (Serieyssol et al. 2009). *A. ambigua* prefers nutrient-rich waters and tolerates water mixing and low light conditions (Bicudo et al. 2016), so short-term increases may be related to a greater density of larger plants in the shallowing lake (Fig. 5). The increase in *S. construens* beginning at ca. 910 BC confirms eutrophic conditions (Beauger et al. 2022), but it may also have been stimulated by prolonged ice cover on the lake and colder springs

(Bradbury et al. 2002; Keatley et al. 2008; Słowiński et al. 2017). Optimum conditions for this species may have been maintained by climate cooling, as it occurred during a period of increased drift ice in the North Atlantic at ca. 2,800 BP; 850 BC (Bond et al. 2001) and/or the solar minimum at ca. 2,800–2,700 BP (850–750 BC; Steinhilber et al. 2009). In general, numerous sites from central-eastern Europe record cooling, often shown as an increase in lake water levels (for example, Barber et al. 2004; Starke et al. 2013; Gałka et al. 2015, 2017; Słowiński et al. 2016). There are also sites without recorded signs of an increase in water levels (such as Gałka et al. 2013; Lamentowicz et al. 2015) (Fig. 9). Moreover, Pleskot et al. (2022) reported no cooling of the summers in western Poland in the period when *S. construens* was recorded at Bruszczewo. A previous study on it revealed that the lake was drying out and no traces of a higher water levels were found (Niebieszczański et al. 2024). Climate cooling may have resulted in people cultivating land further from the lake shores or it probably caused a population decrease and hence lower human impact too. A decrease in nutrient input would have reduced the amount of acidification caused by humans and therefore caused a change towards more alkaline water conditions. Pestryakova et al. (2018) identified *S. construens* as a reliable indicator of alkaline water (pH ~ 8) and a shallower lake would have given rise to higher turbidity and conditions favourable for it (Stivrins et al. 2018). In Salet, it seems that higher precipitation and erosion in the lake catchment during the 2.8 ka event were major causes of nutrient input to the lake, as indicated by the diatom record (Gašiorowski et al. 2021). In the case of our site, higher precipitation is unlikely to have been the factor maintaining high nutrient input despite a decrease in human impact, as the shallowing of the lake occurred at a time of high trophic status. A combination of higher density of aquatic plants and spreading wetland vegetation would have led to high nitrogen (N) demand and contributed, at least temporarily, to nitrogen deficits in the former lake. This, in turn, may have favoured the spread of *Epithemia turgida*, which lives in symbiosis with nitrogen-fixing cyanobacteria (Janson 2002; Stancheva et al. 2013).

To sum up, our study has shown that the diatom assemblages were influenced by the process of lake shallowing and becoming rich fen. Human impact probably distinctly changed the water quality by strong nutrient input towards more circumneutral conditions that influenced the potential for sedimentation of diatom frustules and probably also their taxonomic composition. Moreover, climate cooling may have modified diatom composition directly, by affecting the duration of ice cover on the lake and/or indirectly by limiting human impact near the shoreline

including possibly raising the lake level and/or increasing erosion.

Rare pollen taxa reflect the impact by LUC people on the environment and local flora

The LUC period was marked in the pollen record, not only by a decrease in tree and shrub pollen and an increase in cereal type, but also by records, in this period only, of some very rare pollen types from taxa that nowadays are regarded as weeds and ruderals, notably *Convolvulus arvensis* and *Xanthium strumarium* type. Also, pollen attributable to *Pisum sativum* (pea) or *Vicia faba* (field bean) was identified, showing that legumes were grown. *C. arvensis*, which is rarely recorded in pollen studies, was identifiable to species level. *X. strumarium* type represents in the modern Polish flora a group of taxa mainly of non-central European origin, apart from *X. strumarium* (cocklebur) which has been identified in records from Poland from at least as far back as the Bronze Age (Mueller-Bieniek et al. 2015). So *X. strumarium* is very probably the species that produced this pollen type in our records. Naturally, the results from a single pollen profile do not provide unequivocal proof of the local presence of a plant associated with human activity. However, the fact that these rare pollen taxa were found from the period with the most pollen evidence of human activities suggests that human actions, including the creation of habitats suited to *C. arvensis* and *X. strumarium*, were located close to the coring location. Mueller-Bieniek et al. (2015) dated seeds of *Xanthium* sp. from the Lutomiersk-Koziówki site, central Poland, to 974–819 BC ($2,745 \pm 30$ ^{14}C BP, Poz-43578), from where *X. strumarium* seeds were also recorded from LBA contexts. In the case of Bruszczevo, pollen of *X. strumarium* type was identified in layers dated to ca. 970, 950, 910 and 830 BC (± 30 –40 years). Earlier archaeobotanical studies reported the presence of *X. strumarium* in central Europe from as early as the end of the Bronze Age (Opravil 1983), but none of its macrofossils had been directly ^{14}C AMS dated before Mueller-Bieniek et al. (2015). This taxon has been more frequently recorded as pollen in profiles from central and eastern Europe. Its pollen is very similar to *Ambrosia artemisiifolia* type (Beug 2004; Punt and Hoen 2009). However, it is only in the last 150 years that some North American species of *Ambrosia* have become widespread or even invasive in Europe (Chauvel et al. 2006). Furthermore, records of *X. strumarium* type and other *Ambrosia*-like pollen grains from older contexts are much rarer. Among sites with reliable absolute chronologies, the appearance of *Xanthium* pollen in the varved lake sediments of Gościąg, central Poland, coincided with the time of the LUC in the EIA, which is in the Hallstatt period (profile G1/87; ca. 750–900 BC; Ralska-Jasiewiczowa and van Geel 1998). Pollen profiles from the area occupied

earlier by the LUC and available in the Neotoma database (Nelson et al. 2023) also reveal the first appearances of various *Xanthium* pollen types in the Late Holocene, in most cases together with cereal pollen. In western Poland (central Wielkopolska), single grains of *Xanthium* type pollen were detected from the lake sediments of Jezioro Świętokrzyskie, in layers dating to between ca. 1390 and 270 BC (chronology uncertain, Makohonienko 2000). The earliest appearance of *Xanthium* (*X. spinosum* type), but not accompanied by cereal pollen records, was recorded from the lake sediments of Svitiáz (northwestern Ukraine) at ca. 1740 BC, in the EBA (Schwörer et al. 2022). *Xanthium* pollen was recorded from eastern Germany in somewhat later sediments (ca. 1610 and 836 BC) (Brandt 1996; Jahns 2000; Wolters 2002). In Czechia (Czech Republic), *Xanthium* was recorded from Tišice at ca. 710 BC (Pokorný 2005).

Convolvulus arvensis (field bindweed) was recorded in core IT_1 from ca. 920 BC. According to a review by Lityńska-Zajac (2005), it is known as a weed of cereals from as early as the Hallstatt period. The oldest archaeobotanical records of it come from cultural layers assignable to the LUC (Jaroń 1938; Palmer 2004). Pollen profiles in the Neotoma database (Nelson et al. 2023) reveal the Holocene appearance of *C. arvensis* at various dates from the area of the LUC. At the site of Dury, northern Poland, field bindweed appeared before the beginning of agricultural activity at ca. 5040–3860 BC, chronology uncertain (Kowalewski and Milecka 2003). On the other hand, in Wonieść, situated ca. 15 km from Bruszczevo, the earliest record of *C. arvensis* pollen was dated ca. 830 BC (Dörfler 2011). Its pollen occurred there at the same time as *Cerealia* type and *Secale cereale*, so it relates to the presence of crops during the Lusatian period. In general, other finds of *C. arvensis* pollen are linked to the presence of cereal pollen. The earliest has been dated at ca. 3570 BC from Parížske močiare in Slovakia and identified as *C. arvensis* type (Jamrichová et al. 2014; Nelson et al. 2023). In eastern Germany, Jahns (2000) recorded *C. arvensis* together with cereal type pollen between 3470 and 860 BC (Jahns 2000), but bindweed has also been recorded in samples without any cereal pollen (for example Giesecke 2001).

A single pollen grain of *Pisum sativum* or *Vicia faba* (more precise identification was not possible) from ca. 970 BC was found from Bruszczevo. Macrofossil data from Poland show the earliest records of peas and beans from the Neolithic with scarce finds of *P. sativum* and there are later *V. faba* records from the LUC (Lityńska-Zajac and Wasylukowa 2005). According to the Neotoma database (Nelson et al. 2023), *V. faba* pollen has been recorded from Świętokrzyskie (Wielkopolska) at ca. 610 BC according to the pollen stratigraphy (Makohonienko 2000). *P. sativum* pollen, on the other hand, was found in Czechia but much later, from ca. AD 550 (Pokorný and van der Knaap 2011),

so information relating to this pollen type from the LUC area is still limited.

Our results suggest that prehistoric farming stimulated the spread of *Xanthium* and *Convolvulus arvensis* and increased their local distribution. Judging from the pollen records of other sites in central Europe where they have been found, this process intensified during the Bronze Age. However, both taxa are very rare and easy to overlook, which is evident from an earlier study at Bruszczevo, which did not find them (Haas and Wahlmüller 2010). Our study shows that detailed pollen analyses can provide new records and hence better understanding of the spread of various weeds and crop taxa including legumes such as *Pisum sativum* and *Vicia faba*.

Conclusions

The results of multi-proxy studies at Bruszczevo reveal new information about Late Bronze Age and Early Iron Age human activity and its impact on the environment of the lake and the surrounding land. People of the Lusatian Urnfield culture (LUC) increased their farming activity near the shores of the former lake at Bruszczevo at ca. 1020–920 BC. During this period:

- 1) Human activity probably contributed to an increase in the acidity of the lake water, which enabled preservation of diatom frustules in the sediments, but earlier alkaline conditions had probably hampered this process. At the time of the most pronounced woodland clearance, the amount of diatoms preferring and/or tolerating a high content of organic matter increased. This shows that human activities during this period were linked with or contributed to a substantial release of nutrients into the lake and/or stimulated rapid eutrophication of its waters.
- 2) *Xanthium* cf. *strumarium*, *Convolvulus arvensis* and *Pisum sativum*/*Vicia faba* were recorded at Bruszczevo for the first time as pollen grains. These results are consistent with many other pollen studies from central-eastern Europe where these taxa have been detected, normally in association with cereal pollen, and from as early as the Bronze Age. The Bruszczevo data suggest that *X. cf. strumarium* and *C. arvensis* became widespread as crop weeds and/or ruderals during the LUC period.

The 2.8 ka climate event may have contributed to the weakening of human impact at Bruszczevo which dates to after ca. 940 BC. Moreover, the diatom data suggest prolonged ice cover on the lake and/or colder springs in the period ca. 910–820 BC.

At about 530–330 BC, a second stage of increased woodland clearance and intensification of human impact took

place. This was probably an effect of the activity of the Pomeranian culture people. At ca. 330 BC impact on the local ecosystems was reduced as farming activity declined. A simultaneous increase in coprophilous fungal spores in the peat deposits suggests a change towards pastoral farming. However, this increase might have been at least partly caused by the presence of decaying organic matter that benefited some fungi that are also considered to be coprophilous.

Our study shows that multi-proxy investigations of lake and peat deposits close to archaeological sites enable the dating of settlement phases, especially where archaeological artefacts do not provide reliable chronologies. Moreover, a detailed palynological analysis may add to the knowledge about where, when and how particular plants may have been related to human activity.

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