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Human impact recorded in lake environment (Charzykowskie Lake, N Poland) during the last 6,200 years

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ABSTRACT:

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Based on geochemical and biological investigations of a 6-m-long sediment core, a reconstruction of the environmental conditions in Charzykowskie Lake (northern Poland) is presented. The analyzed sediments consist of fine calcareous detritus gyttja interbedded by lake marl. The results of palynological analysis document the vegetation development around and in the studied lake and confirm the middle and late Holocene age of the sedimentation of the deposits. The identification of 22 taxa of subfossil Cladocera shows the biodiversity of the fauna and reflects the changes in the trophic and water level. The concentrations of various chemical elements suggest the origin of the sediments. Geochemical, including isotope, and biological data, made it possible to reconstruct the environmental conditions, as well as traces of human influence over the last *ca.* 6,200 years. Four stages of human impact have been documented by the pollen data. The first traces of human groups in the vicinity of Charzykowskie Lake are preserved in sediments from about 4,000 years ago. The human activity is poorly recorded in the Cladocera and in the geochemical compositions of the lake sediments, probably due to the size and depth of the lake and its isolation.

Key words: Holocene; Lake sediments; Geochemistry; Subfossil Cladocera; Pollen, Human impact; N Poland.

INTRODUCTION

The period of the last *ca.* 6,200 years has been the subject of numerous palaeoecological studies (eg. Tanţău *et al.* 2011; Bos *et al.* 2012; Kinder *et al.* 2019; Rösch *et al.* 2021). Over this time, climate changes were not as abrupt and large as when compared to those at the beginning of the Holocene and did not cause fundamental changes in the lake environment. The observed changes are often a consequence of the shallowing of the reservoirs as a result of the filling of the lake basin with sediments and/or overgrowing of the banks, as well as of changes in the hydrological network. During this period, an additional factor appears, associated with the appearance and activity of groups of people, which is gaining more and more importance.

We present new results and interpretations of pollen, cladoceran and geochemical investigations of the middle–late Holocene sediments of Charzykowskie

Lake (northern Poland). The aim of this study was a reconstruction of the environmental conditions based on the lake deposits in northern Poland (Tuchola Forest), particularly the changes in water level, trophic state and water temperature, and human impact during the last 6,200 years.

Charzykowskie Lake is a very large Polish lake surrounded by a forest. It is located in the buffer zone of the Bory Tucholskie National Park, also within the Zaborski Landscape Park, where it is partially isolated from human influences. We were interested in the question of the possible influence of the presence and activity of human settlements, and how it might have affected the lake environment in the past, as recorded in the lake sediments. Moreover, our second aim was to compare our results with the research results from the nearby small Skrzynka Lake (Apolinarska *et al.* 2012) and thus to observe local variations in the evolution of the lake ecosystem resulting from the different sizes of these lakes.

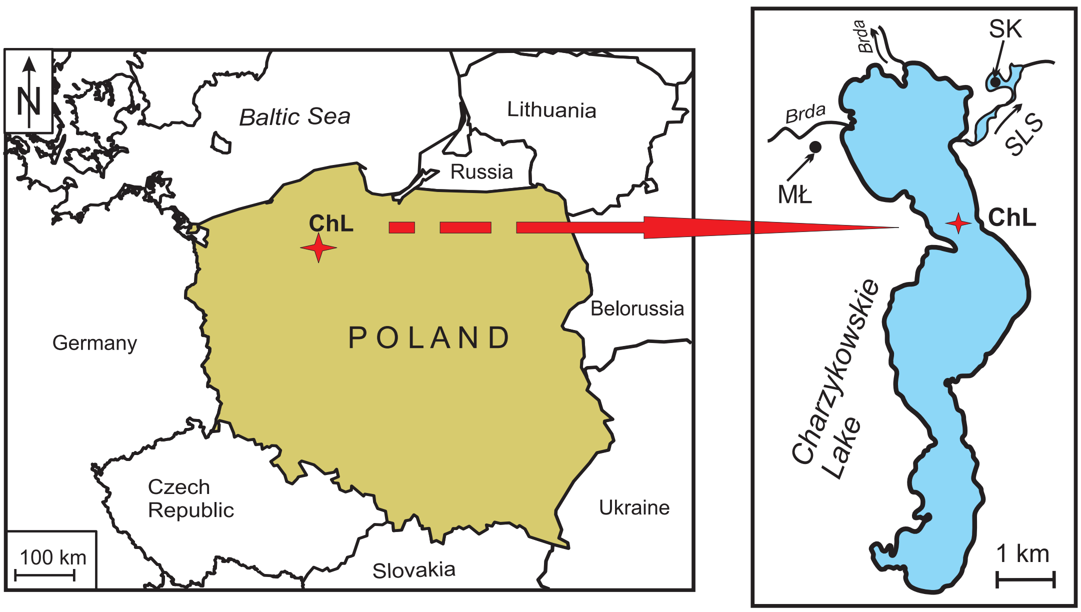
STUDY SITE AND MATERIALS

Charzykowskie Lake is located at an elevation of 121 m a.s.l, near Chojnice, in the Tuchola Forest, northern Poland (Text-fig. 1). It is one of the largest lakes of Pomeranian Lakeland in Poland (1336 ha). Its maximum depth is 30.5 m, and its average depth is 9.8 m. The water volume is an estimated 134,533.2 m^3. The water pH is 8.4, and the conductivity is 300 µS/cm (Jańczak 1997). Charzykowskie Lake fills a large glacial channel with a N-S orientation and measures 10 km long by 2.4 km wide (Jańczak 1997).

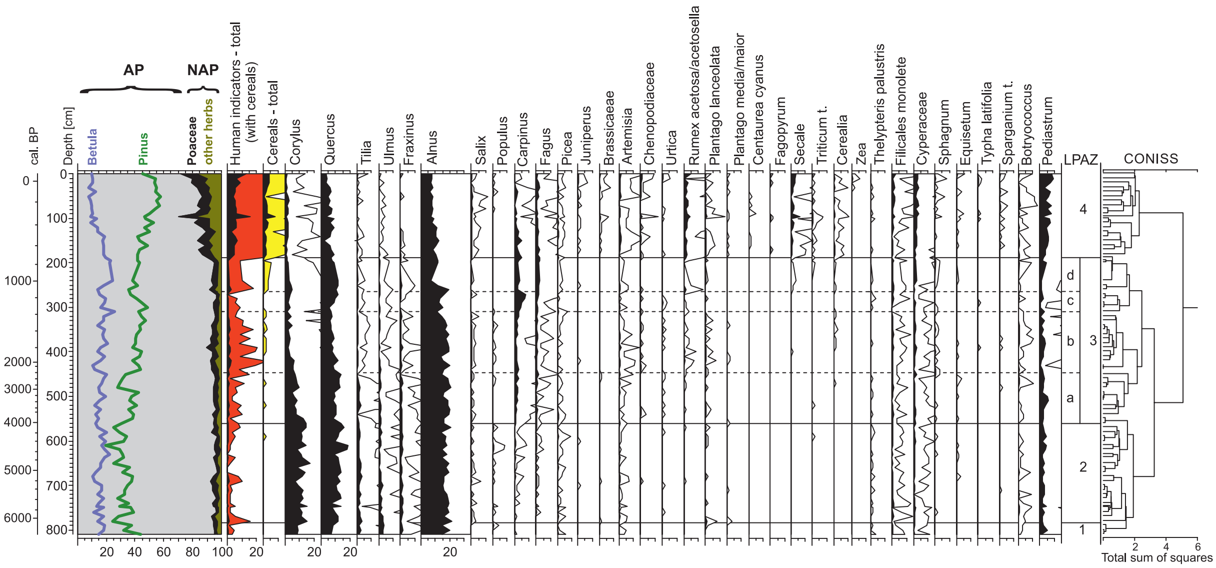
Charzykowskie Lake is located in the northwestern part of the Brda outwash plain, which accumulated during the Pomeranian stage of the Weichselian glaciation approximately 16,200 yr BP (Kozarski 1995). The Brda outwash plain consists of sands and gravel underlain by glacial tills and/or Neogene deposits that crop out in morainal plateaus and along river valleys (Galon 1953; Nowaczyk 2015).

The lake sediments were sampled in March 2006 using a Livingstone type corer (Tobolski 2010). The sampling point was located a significant distance from the mouth of the Brda River and the Seven Lakes' Stream, in the northern lake basin (Text-fig. 1). The water depth at the sampling point was 8.4 m. The total length of the sediment core was 14.2 m. The sediments are composed mainly of calcareous, detritus gyttja partially interbedded with lake marl. The $CaCO_3$ content decreases from above 80% to 20% (Mirosław-Grabowska and Zawisza 2014). The sediment core was sliced every 5–10 cm and was subject to numerous paleoecological analyses (pollen, isotopes and subfossil Cladocera).

In this paper, the results of paleolimnological analysis of the 800-cm section of the upper sediments, accumulated during the middle and late Holocene, are presented. The age of the sediments was determined based on the radiocarbon and pollen data. The results of isotopic and subfossil Cladocera analyses of the



Text-fig. 1. Location of Charzykowskie Lake. ChL – drilling point of sediment core; SLS – Seven Lakes' Stream; MŁ – Małe Łowne peat bog; SK – Skrzynka Lake (Apolinarska *et al.* 2012).



Text-fig. 2. Percentage pollen diagram of the Charzykowskie Lake sediments (selected taxa). AP – grey area; NAP – olive and black areas; LPAZ – Local Pollen Assemblage Zones.

600-cm section of the bottom sediments, which accumulated during the Late Glacial and early Holocene, have already been published (Mirosław-Grabowska and Zawisza 2014).

CHRONOLOGY

Two samples of terrestrial plant macrofossils from depths of 177 cm and 848 cm b.l.f. were collected. The radiocarbon dating was performed in the Poznań Radiocarbon Laboratory. Ages of 660±80 BP (upper sample) and 5740±60 BP (lower sample) were obtained. The radiocarbon ages were calibrated using OxCal 20. The calibrated ages of these samples are in stratigraphical order. The age depth model prepared using the Tilia program was basis on the sediment chronology. Based on these data and palynological data, the age of the sediments and time frames of the chronozones were determined: the Atlantic/Subboreal – 5,750 yr cal BP, Subboreal/Subatlantic – 2,550 yr cal BP (Walanus and Nalepka 2010; https://www.adamwalanus.pl/Kalib14C.html).

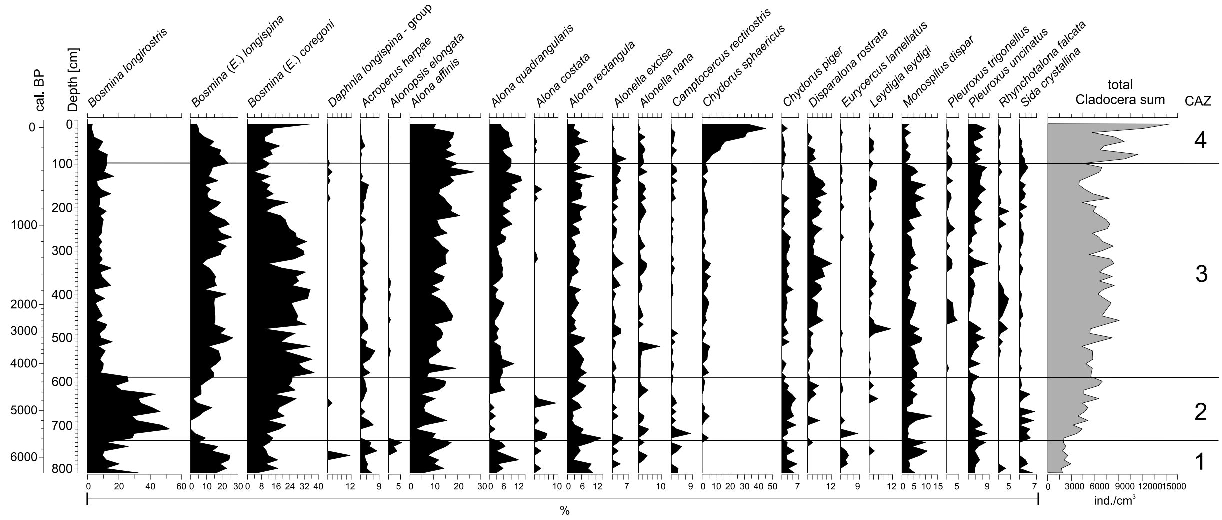
METHODS

Pollen analysis

A total of 86 samples (each 1 cm^3 in volume) were prepared for pollen analysis using standard procedures (Berglund and Ralska-Jasiewiczowa 1986). For taxonomical identification pollen keys (eg. Beug 2004) were used. At least 500 pollen grains of terrestrial plants were counted for each sample. The sum AP + NAP (arboreal pollen and nonarboreal pollen) was calculated. Pollen grains of the local aquatic and telmatic plants were excluded from the total sum. The identification of the pollen grains was carried out by K. Tobolski (2010). The interpretation of the results and division into local pollen assemblage zones (LPAZ), as well as their description were made by M. Obremska (Text-fig. 2). Zonation was confirmed by CONISS cluster analysis (Grimm 1991). Pollen indicators of human impact include Chenopodiaceae, *Urtica, Rumex acetosa/acetosella, Plantago lanceolata, Plantago media/major, Centaurea cyanus, Fagopyrum, Zea, Secale cereale, Triticum*-type, Cerealia.

Cladocera analysis

The Cladocera analysis was conducted on 78 samples from 0–810 cm b.l.f. Sediments were prepared for Subfossil Cladocera analysis in a laboratory of the Institute of Geological Sciences according to the standard method proposed by Frey (1986). One cc of fresh sediment was boiled in 10% KOH solution and left for 20 minutes with a magnetic stirrer to eliminate organic matter. Later, the residuum was treated with 8% HCl to eliminate carbonates and then washed and sieved using a 38 µm sieve and diluted in 10 cm^3 of distilled water. For every microscope



Text-fig. 3. Cladocera relative abundance from Charzykowskie Lake sediments. CAZ – Cladocera Assemblage Zones.

slide, 0.1 ml of final solution was used. The extracted remains were identified using Zeiss Axio Scope A.1 light microscope. Two slides from each sample were counted (minimum 200 remains). In each sample, all skeletal elements (head shield, shell, postabdomen, claw, ephippium) were counted. Identification of Cladocera remains was based on Flössner (1972, 2000) and Szeroczyńska and Sarmaja-Korjonen (2007). The results of the qualitative and quantitative analyses are presented in relative abundance diagrams (Text-fig. 3). Cladocera zones (CAZ) were distinguished based on significant changes in Cladocera relative abundance and species composition and indicated in the diagram by horizontal lines. Classification of Cladocera habitat preferences was based on Hann (1990) and Fryer (1985, 1993) publications.

Geochemical analysis

Geochemical analyses of 40 samples of carbonate sediments from depths of 0–810 cm b.l.f. included content of selected metals (Na, K, Ca, Mg, Fe, Mn, Cu, Zn) and P content determinations (Text-fig. 4). All geochemical analyses of the samples were performed at the Regional Research Center for Environment, Agricultural and Innovative Technologies, John Paul II University of Applied Sciences in Biala Podlaska. The samples for geochemistry analysis were mineralized in a closed microwave reaction system using Anton Paar Multiwave PRO with concentrated HCl and HNO_3 (3:1). Mineralized samples were analyzed using ICP OES spectrometer (SPECTROBlue). Operating parameters for ICP OES instrument were: coolant flow: 12 l/min; auxiliary flow: 0.90 l/min; nebulizer flow: 0.78 l/min.; pump speed: 30 Rpm; number of measurements: 3. Standards used: Bernd Kraft Der Standard Spectro Genesis ICAL Solutions and VHG SM68-1-500 Element Multi Standard 1 in 5% HNO_3.

Stable isotope analysis

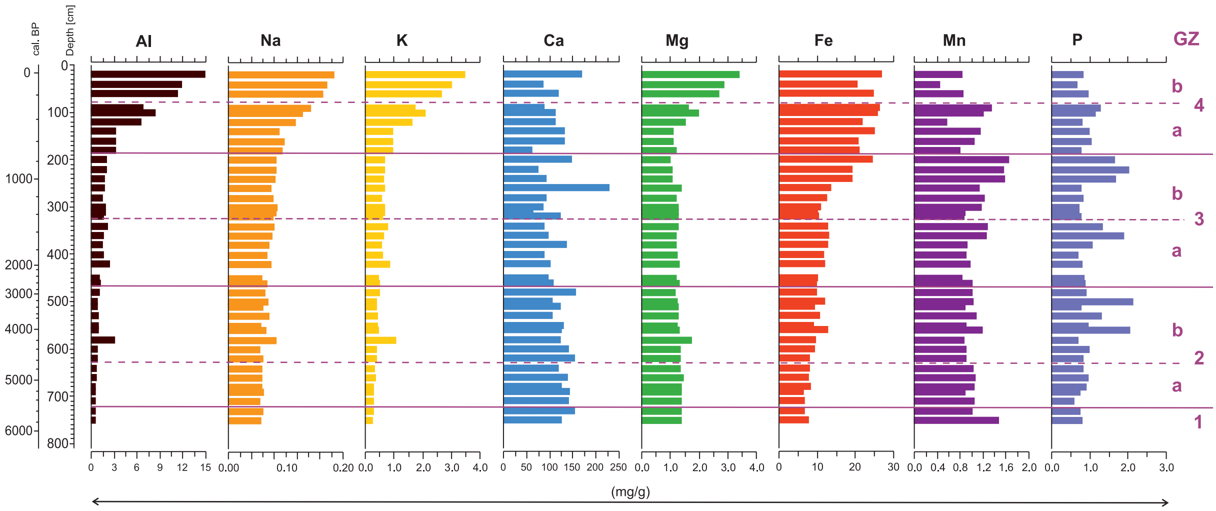
Analyses for oxygen and stable carbon isotopes were performed on 78 samples of carbonate sediments from depths of 0–810 cm b.l.f. using the classical phosphoric acid method (McCrea 1950). The isotopic compositions were measured using a Finningan MAT Delta+gas spectrometer spectrometer at the Institute of Geological Sciences in Warsaw, Poland. The oxygen and carbon isotope ratios are presented in standard delta notation ($\delta^{18}O$, $\delta^{13}C$) versus the V-PDB standard and are presented in the form of curves of variation of $\delta^{18}O$ and $\delta^{13}C$ (Text-fig. 5). The analytical error was ±0.1‰ for $\delta^{18}O$ and ±0.05‰ for $\delta^{13}C$.

RESULTS

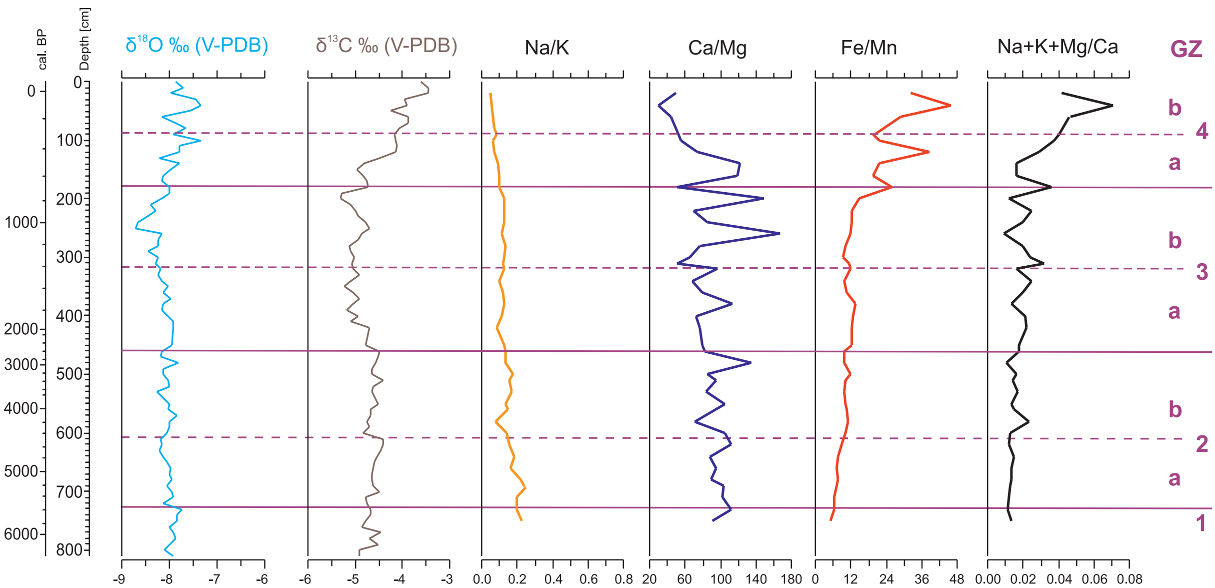
Pollen analysis

LPAZ 1 *Ulmus*: to 6,000 yr cal. BP (below 780 cm)

A characteristic feature of this zone is the highest proportion of *Ulmus* pollen grains (max. 3.9%) in the profile (Text-fig. 2). Pollen of all the main components of mixed deciduous forests such as *Quercus*, *Corylus*,



Text-fig. 4. Results of the analysis of selected chemical elements of the Charzykowskie Lake sediments. GZ – Geochemical Zones.



Text-fig. 5. Results of oxygen and carbon isotope analysis and geochemical ratios of the Charzykowskie Lake sediments. GZ – Geochemical Zones.

Tilia and *Fraxinus* are present continuously, in addition to a high percentage of *Alnus* (up to 20.5%). Only one coniferous species – pine – was noted and its value reaches 43.6% as maximum during this zone. The share of NAP was low (5% on average). The top boundary of this LPAZ is marked by an increase of *Quercus* and *Corylus.*

LPAZ 2 *Quercus–Corylus*: 6,000–4,000 yr cal. BP (780–560 cm)

At the beginning of zone 2 there is a visible increase in the percentage of *Quercus* (from 8.7% to 11.6%) and *Corylus* (from 8.1% to 15.2%) pollen grains, while the proportion of *Ulmus* decreases (from 3.6% to 2.7%) and gradually declines. The total share of AP does not change. Within this zone the pollen grains of two new species of trees appeared: *Carpinus* and *Fagus*, but their values are still very low (below 0.5%). At LPAZ 2 the first pollen grains of *Rumex acetosa/acetosella, Plantago media/major* and *Plantago lanceolata* were noticed. The single pollen grains of *Triticum*-type appear at the end of this zone. The top boundary of this LPAZ is marked by a decline of *Corylus* and an increase *Carpinus*.

LPAZ 3 *Quercus–Carpinus*: 4,000–700 yr cal. BP (560–198 cm)

A characteristic feature of this phase is the visible gradual decline of the *Corylus* curve and fluctuations of the *Quercus* and *Carpinus* curves. Due to *Quercus* and *Carpinus* percentage variability this phase is divided into four subzones:

Subzone a – 4,000–2,400 yr cal. BP (560–450 cm)

The value of *Carpinus* pollen grains increases and ranges from below 1% up to 3%. The share of *Corylus* visible declines from 12.8% to 7% at the top of subzone. The percentage of *Quercus* pollen grains is between 8.5–12.5%. At the same time there is a noticeable increase in the proportion of *Pinus* pollen grains. The proportion of NAP is similar to the previous phase but the regular appearance of *Urtica, Rumex acetosa/acetosella* and *Plantago lanceolata* as well as the presence of single pollen grains of *Triticum*-type and Cerealia undiff. is noticeable (distinctive).

Subzone b – 2,400–1,400 yr cal. BP (450–310 cm)

A further decrease in the content of *Corylus* pollen grains is visible (from 7.1% to 1.4%). The proportion of *Quercus* gradually decreases from 12.5% to 7.2%. In the central part of the subzone, the percentage of *Carpinus* pollen grains decreases and falls to a minimum of 0.7%. At the same time, the proportion of *Pinus* pollen grains and NAP slightly increases (33.7–42%, and up to 10.1%, respectively). The increase in the proportion of NAP next to Poaceae is evident in the presence of *Artemisia, Urtica,* Chenopodiaceae, *Rumex acetosa/acetosella* and *Plantago lanceolata.* There also appears a periodic curve of Cerealia undiff. and the first pollen grain of *Secale cereale.*

Subzone c – 1,400–1,050 yr cal. BP (310–260 cm)

Here, the most significant increase in the share of *Carpinus* is observed (to a maximum of 8.1%). At the same time, the proportion of *Quercus* increases to 11.7%, while the percentage of *Pinus* pollen grains decreases significantly (48.5% to 37.2%). In this subzone, the curve of Cerealia undiff. disappears.

Subzone d – 1,050–700 yr cal. BP (260–198 cm)

After a maximum in the proportion of *Carpinus* pollen grains in subzone c, there is a sharp drop in their percentage from 8.1% to 3.6% in this subzone. The share of *Alnus* pollen grains also declines noticeably (19.3% to 10.7%). The proportion of *Quercus* decreases slightly from 11.7% to 7.2%. In contrast, the *Fagus* share increases from 1.2% to 2.5%. The percentage of NAP reached 9.7%. Continuous curves of *Secale cereale, Triticum*-type and Cerealia undiff. appear. The top boundary of LPAZ 3 is marked by an increase of *Pinus* and NAP.

LPAZ 4 *Pinus*-NAP: 700–0 yr cal. BP (198–0 cm)

In zone 4, there is a very significant increase in the percentage of *Pinus* pollen grains (maximum of 57.5%) and NAP (from 12.7% to a maximum of 29.8%). The composition of NAP is dominated by Poaceae (4.3–11.9%) and is characterized by a high proportion of anthropogenic plant indicators, especially *Rumex acetosa/acetosella* (1.2–4.2%) and cereals, with a dominance of *Secale cereale* pollen grains (0.5–6.3%).

Cladocera analysis

In the studied sediment sequence 22 Cladocera species were identified in total, belonging to four families: Bosminidae, Daphniidae, Chydoridae and Sididae. Through the last 6,000 years, specimens from the planktonic family Bosminidae were the most widespread and abundant species, with mean relative abundance *ca.* 50%. Among littoral species, the genus Alona (*Alona affinis, Alona quadrangularis* and *Alona rectangula*) was the most noticeable and reached a relative abundance of 23%, whereas *Chydorus sphaericus* was gaining importance in the youngest sediments with mean relative abundance of 17%. (Text-fig. 3).

The changes in the Cladocera population and species composition in the studied part of Charzykowskie Lake's sediment core (late Atlantic period to modern times) allow us to distinguish four Cladocera Assemblages Zones (CAZ), which also reflect lake-development stages. The results obtained are shown in relative abundance diagrams (Text-fig. 3).

CAZ 1: to 5,600 yr cal. BP (810–730 cm)

Zone CAZ 1 – remains of twenty-one Cladocera taxa, both pelagic and littoral, were found in the sediment. The total sum of Cladocera remains was the lowest throughout the entirety of the studied sedimentary sequence and reached *ca.* 2,200 individuals in one cc. Predominant species were three Bosminidae taxa, which belonged to planktonic species with a mean share of 47%. Among littoral Cladocera, plant-sediments-associated species were dominant, particularly *Alona affinis* (11%), *Alona quadrangularis* (6%), *Alona rectangula* (7%). The rare species of *Alonopsis elongata* appeared in the upper part of this zone.

CAZ 2: 5,600–4,300 yr cal. BP (730–590 cm)

Zone CAZ 2 – the number of Cladocera individuals deposited at one cc significantly increased (*ca.* 5,000 yr cal. BP), whereas the number of Cladocera species was very similar to the previous zone (20 taxa). The predominant species was *Bosmina longirostris*, which during this zone reached its maximum (34%) in the studied core. It is also worth noting that during this time *Bosmina (E.) longispina* reached its minimum (*ca.* 6%). Littoral Cladocera taxa constituted 40% of the total Cladocera sum.

CAZ 3: 4,300–350 yr cal. BP (590–100 cm)

Zone CAZ 3 is the longest zone distinguished in the studied sediments. The number of Cladocera individuals was increasing in the beginning of the zone and then remained constant with the average amount 6,700 individuals in one cc. The number of Cladocera species was very similar to that in the two previous zones and reached 21 taxa. Cladocera living in the open-water zone, namely *Bosmina* (*E.*) *longispina* and *Bosmina* (*E.*) *coregoni*, were dominant and constituted more than 40% of the total Cladocera sum. Littoral species lived in plant-sediment-associations and were numerous, among which the following were most noticeable: *Alona affinis* (13%), *Alona quadrangularis* (5%), *Alona rectangula* (5%). Since the middle part of CAZ 3, sediment-associated species became an important element of the Cladocera littoral environment, reaching a mean share of 12% (e.g. *Disparalona rostrata* – 6%; *Monospilus dispara* – 5%).

CAZ 4: 350 yr cal. BP – present (100–0 cm)

Zone CAZ 4 was deposited during the last 350 years. This zone is characterized by a significant increase in Cladocera density, up to 12,000 individuals in 1 cm^3 (mean 9,600), with the presence of 21 Cladocera taxa. During this time, planktonic taxa (mostly Bosminidae) recorded a decline (mean share 33%), whereas species living in plant-sediment-association were numerous (31%), represented mostly by the Aloninae subfamily. Cladocera living in the sediment noted a decline (mean share 7%). Since *ca.* 250 years ago, a significantly increased share of *Chydorus sphaericus* was observed, which reached its maximum in the studied core (45%).

GEOCHEMICAL AND ISOTOPE ANALYSIS

Four geochemical zones (GZ1–GZ4) were distinguished based on the variations in the chemical composition of the sediments and in isotopic variability (Text-figs 4, 5).

In the lowest part of the studied sediments (geochemical zone GZ1) concentrations of lithophile components Al, Na, K, and Mg are very low, at *ca.* 0.6 mg/g, 0.06 mg/g, 0.3 mg/g, and 1.4 mg/g, respectively (Text-fig. 4). The Fe content is 7–8 mg/g, while Mn is present at 1–1.5 mg/g. The deposits are rich in Ca (up to *ca.* 154 mg/g). Content of P is above 0.8 mg/g. The concentrations of Cu and Zn are below the detection limit.

In the overlying deposits (geochemical zone GZ2a), the concentrations of most elements are similar to those in the earlier geochemical zone GZ1: Al of 0.5–0.7 mg/g, Na of 0.06 mg/g, Mg of 1.4 mg/g, Fe of 6–8 mg/g. The Mn amount decreases to 0.9–1 mg/g. Ca content varies from 118 to 142 mg/g. A slight increase in amount of K (to 0.4 mg/g) and P (to 1 mg/g) is observed. In the upper part of this geochemical zone (subzone GZ2b), the concentrations increase slightly for Al, up to *ca.* 1 mg/g. Mg content is of *ca.* 1.4 mg/g. A slight increase in the amount of Na (to 0.8 mg/g) and Fe (to 13.5 mg/g) is observed. The Ca amount varies from 104 to 156 mg/g, K – from 0.4 to 1 mg/g, Mn – from 0.9 to 1.2 mg/g and P – from 0.7 to 2.1 mg/g.

In the next geochemical zone (GZ3), the amount of Al increases to 2.1 mg/g and K to 0.07–0.08 mg/g. The concentrations of some elements are constant: Na of 0.08–0.09 mg/g and K of 0.7 mg/g. The Ca content varies from 65 to 228 mg/g, while that of Mg from 1 to 1.3 mg/kg. An increase in the amounts of Fe (to 24 mg/g), Mn (to 1.7 mg/g) and P (to above 1.6 mg/g) is observed.

In the uppermost sediments (geochemical zone GZ4), a significant increase in most elements is noted. The concentration of Al rises to *ca.* 15 mg/g, Na to 0.2 mg/g, K to 3.5 mg/g, and Mg to 3.4 mg/g. The content of Fe varies from 20 to 27 mg/g, with Ca between 63–170 mg/g. The amounts of Mn and P vary from 0.5 to 1.2 mg/g and from 0.8 to 1.3 mg/g, respectively.

The oxygen isotope ratio varies between -8.7 and -7.3‰, whereas the carbon isotope ratio oscillates between -5.3 and -3.5‰ (Text-fig. 5). The lowest analyzed deposits (below a depth of 720 cm) are characterized by an increasing value of $\delta^{18}O$, from -8.1 to -7.7‰. At that time the $\delta^{13}C$ values vary from -4.9 to -4.5‰ (geochemical zone GZ1, Text-fig. 5). Next, up to a depth of 460 cm (GZ2), the $\delta^{18}O$ values oscillate around -8‰. The lower values of -8.2‰ occur at a depth of 630 cm. The $\delta^{13}C$ values lightly increase from -4.9 to -4.4‰ (depth of 610–620 cm) and from -4.8 to -4.5‰ (depth of 460–600 cm). The oxygen isotopic values systematically decrease to -8.4‰ (depth of 260–460 cm, geochemical zone GZ3a, Text-fig. 5). The carbon isotopic values drop to – 5.2‰, followed by an increase to -4.7‰. Then

$\delta^{18}O$ suddenly decreases to -8.7‰ (depth of 250 cm, geochemical zone GZ3b) and starts to rise to -8‰. $\delta^{13}C$ falls to -5.3‰. The uppermost sediments (from depth of 180 cm, geochemical zone GZ4, Text-fig. 5) are characterized by varying values of $\delta^{18}O$, from -8.2 to -7.3‰ (maximum of values), and the increasing values of $\delta^{13}C$, up to -3.5‰ (maximum of values).

INTERPRETATION AND DISCUSSION

The results of the geochemical, including isotopes, Cladocera and pollen analyses helped us to reconstruct the environmental conditions around and in the Charzykowskie Lake, during the last 6000 years. We especially focused on the traces of human activity and human impact on the ecosystem of this area.

The final phase of the Atlantic period (to *ca.* 5,750 yr cal. BP)

At that time the vegetation documented favorable climatic conditions and was represented by multispecies deciduous and mixed forests with oak, lime, elm and hazel (LPAZ 1, Text-fig. 2). Alder covered the shores of the lake. In this period the lake was large, without a clearly marked rush zone. The open water zone was dominated by *Eubosmina*: *Bosmina (E.) longispina* and *Bosmina (E.) coregoni* species, indicating a large volume for the lake (CAZ 1, Text-fig. 3).

Also at that time, the calcareous-rich deposits (calcareous gyttja and lake marl) accumulated. The gyttja was poor in lithophile elements such as Al, Na, K and Mg, and metals (Fe, Mn, Cu, Zn). The very low values of Fe/Mn ratio confirm the prevailing oxidizing conditions in the lake (Borówka and Tomkowiak 2010; Mendyk *et al.* 2016). The constant values of both $\delta^{18}O$ (approximately -8‰) and $\delta^{13}C$ (*ca.* -4.8‰) of these carbonates reflect the invariable isotopic composition of the lake water (Text-fig. 5). Within the same period, stable hydrologic conditions and/or a fast sedimentation rate are suggested. Our results are similar to those obtained in the nearby located Skrzynka Lake (Apolinarska *et al.* 2012). In addition, we observed a slight positive trend in $\delta^{18}O$ values, which were likely associated with warming conditions.

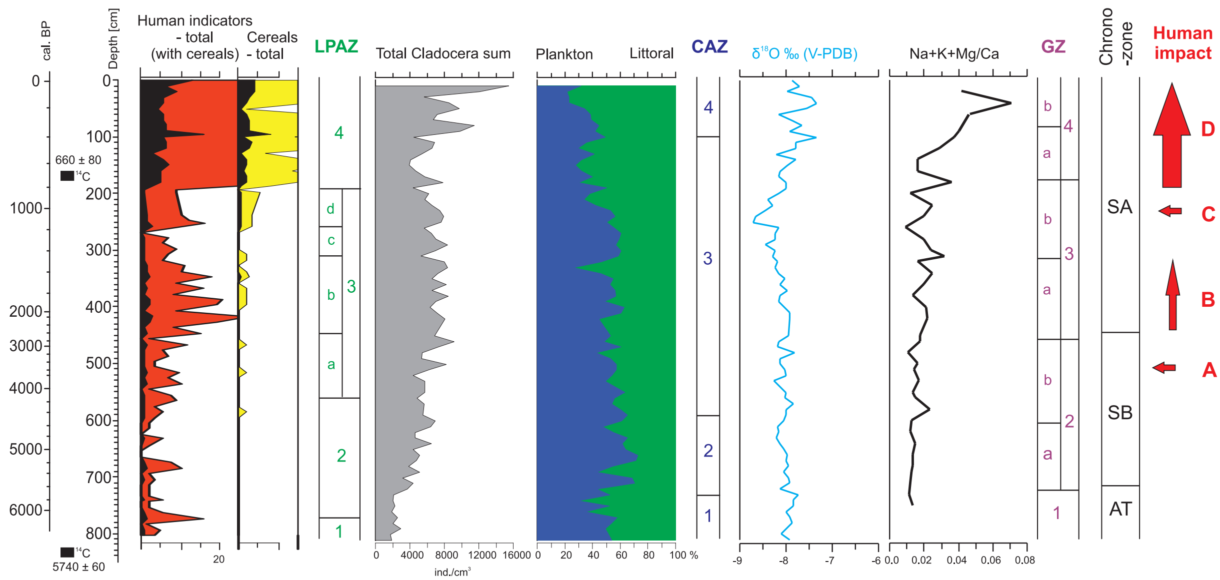
The Subboreal period (*ca.* 5,750–2,550 yr cal. BP)

To *ca.* 4,000 yr cal. BP, the multispecies deciduous and mixed forests still existed, but the plant composition changed. Hornbeam and beech appeared in the forest communities. The shares of oak and hazel significantly rose in contrast to gradually declining elm. The first pollen grains of *Rumex acetosa/acetosella, Plantago media/major* and *Plantago lanceolata,* as well as the single pollen grains of *Triticum*-type appeared, suggesting the first trace of human presence, e.g., in organizing the first pastures (LPAZ 2, Text-fig. 2). The initial human activity was not registered in the composition of aquatic plants or algae. The observations suggest a low penetration of this region by human groups (Text-fig. 6).

Initially (to *ca.* 5,600 yr cal. BP), quite a rare species of Cladocera appeared in the lake, namely, *Alonopsis elongata*, which is typical of Northern areas of Europe, rather than Polish lowlands (Szeroczyńska and Zawisza 2011). The dominance of *Eubosmina* species and the presence *Alonopsis elongata*, which can inhabit the cool waters, indicate a lower temperature and/or an increase in the water level of the lake (Hofmann1984; Szeroczyńska and Zawisza 2011).

About 5,600 yr cal. BP we observed a decrease in $\delta^{18}O$ values of *ca.* 0.5‰, and a positive trend in $\delta^{13}C$ values (Text-fig. 5). The drop of oxygen isotopic values of carbonates can suggest an inflow of "fresh" and cool water, suggested by the Cladocera data, as well as a probable increase in water level (Mirosław-Grabowska and Zawisza 2014, 2018; Mirosław-Grabowska *et al.* 2020). The lack of synchronicity of the oxygen and carbon curves likely reflects the open system of this lake. The still minimal amounts of lithophile elements (Al, Na, K, Mg) and metals (Fe, Mn), in addition to the low Na+K+Mg/Ca ratio, indicate the absence of mechanical denudation in the area surrounding the basin, as well as a lack in the supply of these elements into the lake. The highest Ca concentration in the whole profile was likely caused by groundwater supply.

Between 5,600 and 4,300 yr cal. BP the total Cladocera sum gradually increases (CAZ 2, Text-fig. 3). The most dominant species was *Bosmina longirostris*, which reached its maximum at the studied core. *Bosmina longirostris* is considered a trophic state indicator, and its domination generally suggests higher trophic state (Szeroczyńska 1985; Hofmann 1996; Zawisza and Szeroczyńska 2008). Within this period, the Cladocera living in the littoral zone, among macrophytes, were common. The Cladocera species diversity and total Cladocera sum indicate that at the time good conditions for zooplankton development prevailed, suggesting a trophic state higher than at CAZ 1. The Cladocera species composition suggests significant enrichment of the lake's environment with waters and nutrients. The trophic level of the waters of Charzykowskie Lake reached



Text-fig. 6. Human impact stages on the base of selected biological and geochemical data from the Charzykowskie Lake sediments. LPAZ – Local Pollen Assemblage Zones; CAZ – Cladocera Assemblage Zones; GZ – Geochemical Zones; Chronozones: AT – Atlantic, SB – Subboreal, SA – Subatlantic; A, B, C, D – Human impact stages; red arrows – period of human traces; width of arrow indicates the scale of human activity (non-nominated value).

probably mesotrophic B level during CAZ 2. An increase in trophic level, from oligo/mesotrophic at the Atlantic period to mesotrophic B at the beginning of the Subboreal time, was also noted at Jelonek Lake, which is located in the vicinity of Charzykowskie Lake (Zawisza *et al.* 2016).

Since *ca.* 4,000 yr cal. BP, the development of oak-hornbeam forests took place, with a decrease of hazel shrubs and a slight increase in the pine share, after which the composition of the woodlands was constant. The regular presence of nettle (*Urtica*) and sorrel (*Rumex*), in conjunction with the occurrence of ribwort plantain (*Plantago lanceolate*), are to be associated with human presence (LPAZ 3a, Text-fig. 2). The pollen grains of human indicator plants suggest an initial human activity associated with the grazing of animals (human impact stage A – Text-fig. 6).

Terrestrial vegetation changes had no significant influence on the lake environment. At that time, pelagic species from the subgenus *Eubosmina* dominated, in parallel to a decline in the share of *Bosmina longirostis* (9%). The littoral zone was inhabited by quite numerous plant-sediment-association species. The zooplankton composition indicates that during this time the lake was deep, with a considerable open water zone, where planktonic species characteristic of mesotrophic A waters lived. Moreover, the lake had a well-developed littoral zone, with a rich Cladocera zooplankton living among macrophytes. During this period, Charzykowskie Lake's environment was stable and developed under natural climatic condition. The influence of human activities on the lake's waters was very limited. A very similar observation, indicating high stability of the lake conditions during the upper Holocene, was made by Apolinarska *et al.* (2012) at Skrzynka Lake, which discharges into Charzykowskie Lake by the Seven Lakes' Stream.

The Subatlantic period (from *ca.* 2,550 yr cal. BP)

Around *ca.* 2,550 yr cal. BP a transformation of the terrestrial vegetation began. The share of all deciduous trees and shrubs (e.g. *Carpinus, Quercus, Corylus*) reduced (LPAZ 3b, Text-fig. 2) and were partially replaced by pine. The increase of NAP suggests the start of deforestation. The presence of nettle (*Urtica*) and other ruderal plants (i.e., *Artemisia,* Chenopodiaceae) testifies to the human settlement. The appearance of Cerealia, including the first single pollen grain of *Secale cereale* documents the beginnings of agriculture (human impact stage B – Text-fig. 6). At that time, a slight increase in the concentrations of Al, Na, K and Mg, as well as the Na+K+Mg/Ca ratio suggest the supply of mineral materials from the catchment, thus confirming the deforestation process.

During this time the Cladocera community was stable. No human effects on zooplankton have been observed.

About 1,400 yr cal. BP the next reconstruction of woodlands occurred. Hornbeam and oak dominated but the share of pine fell (LPAZ 3c, Text-fig. 2). Lack of cereal pollen grains and a significant decrease in the proportion of the other human indicator plants suggest that there were no human settlements in the vicinity of the lake.

Further changes in the plant composition began about 1,050 yr cal. BP. The share of deciduous trees like hornbeam, oak and alder decreased. More humid conditions preceded the spread of beech (LPAZ 3d, Text-fig. 2). The increase of NAP, especially *Artemisia* and Poaceae testifies to deforestation. Continuous curves of *Secale cereale, Triticum*-type and Cerealia undiff. document the next stage of settlement and agriculture (human impact stage C – Text-fig. 6).

An irregular increase of *ca.* 1.5‰ in $\delta^{18}O$ values and a systematic increase in $\delta^{13}C$ values of *ca.* 2‰ occurred (Text-fig. 5). Such trends may be associated with climatic warming (oxygen isotope) and an increase in the photosynthetic activity of phytoplankton and macrophytes (carbon isotope). Additionally, a drop in the water level could have occurred within the period. Moreover, the higher Ca/Mg ratio suggests: development of vegetation in the lake's surroundings; the replacement of denudation of the catchment by soil leaching processes; and the subsurface transport of soil solutions (Okupny *et al.* 2021).

About 700 yr cal. BP, the further increase of NAP, dominated by *Poaceae*, as well as the increase of pine share, confirm the continuation of fall in woodland cover (LPAZ 4, Text-fig. 2). In more open areas juniper has appeared. The forests were characterized by poorer species composition. The shares of lime, elm and ash decreased. A high proportion of anthropogenic plant indicators, especially *Rumex acetosa/acetosella* and cereals with a dominance of *Secale cereale* document the constant human settlement (human impact stage D – Text-fig. 6). The lake has been surrounded by peat bogs with *Sphagnum*. At that time, shallowing of the lake and the formation of a widespread littoral zone occurred. The rushes with Cyperaceae, *Sparganium* and *Typha latifolia* have grown. The development of hydrophytes and algae (*Pediastrum*) is also noticeable. The human impact could have led to nitrification of habitats, which enabled *Urtica* to spread.

About 650 yr cal. BP, the lithology and geochemical features of the sediments changed. The deposits contained less carbonates (down to 20%, Ca/Mg ratio dropped) and more organic detritus. The concentrations of Al, Na, K and Mg rose, as well as the Na+K+Mg/Ca ratio (Text-figs 5, 6), suggesting the supply of mineral materials from the catchment. The deposits also record an increase in both the iron concentration (to 27 mg/g) and the Fe/Mn ratio (to 45). The highest contents of Al, Mg, K and Fe (Karasiewicz *et al.* 2014) and a very low Na/K ratio (Borówka 1992) confirm the sparse vegetation cover. The increase in the basin erosion ratio of Na+K+Mg/Ca is a geochemical record of deforestation in the catchment area. The increase in supply of Al, Na, K, Mg, and Fe relative to Ca is most characteristic of the Subatlantic period (Okupny *et al.* 2021). The small increase in the Fe/Mn ratio and the higher values of $\delta^{13}C$ suggest the probability of slightly more reducing conditions (or a slightly higher trophic level).

The youngest sediments of Charzykowskie Lake are characterized by the biggest changes in zooplankton composition (Text-fig. 3). The most significant changes were observed in the water trophic state. Since *ca.* 350 years ago, a growth of the total Cladocera sum is observed, caused in most part by the *Chydorus sphaericus* increase, whose presence indicates the higher trophic conditions of the lake. (Hofmann 1996; Szeroczyńska 1998; Shumate *et al.* 2002; Cheng *et al.* 2020) At the time, the share of littoral taxa was the highest in the studied sediment sequence (almost 70%), pointing to an abundance of nutrients in the shallow water area. Such species composition suggests that the lake was affected by an eutrophication process at the time, caused most probably by an increased supply of nutrients into the water from the catchment as a result of human economic activities, predominantly agriculture.

CONCLUSIONS

In the Atlantic period, the mixed-deciduous forests composed mainly of oak, lime, elm, ash and hazel were present. Alder forests inhabited moist places. The Subboreal period was characterized by the appearance of new components in the woodlands, e.g., hornbeam, beech and spruce. In the Subatlantic period, the forest significantly changed. The coniferous trees (especially pine) became dominant.

Base on the palynological data we recognized four stages of human impact in the Charzykowskie Lake's vicinity. The first traces of human presence were recorded in Charzykowskie Lake's sediments during the Subboreal period (*ca.* 3,500 yr cal. BP – stage A). No direct evidence of settlement has been found around the Charzykowskie Lake. On the basis of archaeological data, it can be assumed that the traces of human presence date back to before Roman times. The pollen grains of *Rumex acetosa/acetosella*, *Plantago media/major* and *Plantago lanceolata,* as well as the single pollen grains of *Triticum*-type, suggest the initial human activity (stage B, from *ca*. 2,500 yr cal. BP). The lack of archaeological artifacts does not allow for a precise determination of the culture, but it seems that this human stage can be associated with the Wielbark culture (Miotk-Szpiganowicz 1992; Filbrandt-Czaja 2009) The first traces of agricultural activity noted from Cerealia pollen were dated to *ca.* 1,400–2,000 yr cal. BP – human stage C). This human activity started in the early Middle Ages (Woźny 2015). About 800 yr cal. BP permanent human settlement and agriculture, documented by occurrences of human indicator pollen grains, including cereals and ruderal plants, have been noticed in the vicinity of Charzykowskie Lake – stage D). This human stage developed in the Middle Ages.

Human activity has been only slightly recorded in the Cladocera and geochemical compositions of the lake sediments, probably due to the size and depth of the lake and its isolation from direct human activity. No direct correlation was also observed between higher phosphorous content and human presence. This may be related to the lack of settlement directly in the lake catchment area.

The isotopic record of about the last 6,000 years from Charzykowskie Lake is similar to the data from the nearby Skrzynka Lake. The narrow range of oxygen isotope values (*ca.* -8‰), assigned to the late Subatlantic chronozone "indicates the stability of the factors influencing the $\delta^{18}O$ of the lake water" (Apolinarska *et al.* 2012). The carbon isotope data reflect an analogous trend towards higher values observed from the Atlantic to the middle Subatlantic chronozones. During all these periods, Charzykowskie Lake was characterized by well-oxygenated water (based on the isotopic data) and carbonate-rich sedimentation, in contrast to the smaller Skrzynka Lake, where the decrease in oxygenation and in carbonate deposition occurred in the late Subatlantic period (Apolinarska *et al.* 2012).

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