Przegląd Geologiczny, vol. 73, no. 2, 2025; doi: http://dx.doi.org/10.7306/2025.16

Bioindicators as a tool for reconstructing climate change

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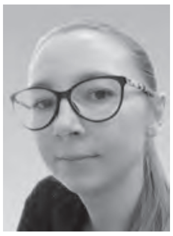

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Abstract. High-resolution multi-indicator analyses, combined with absolute age dating, allow us to track the variability of individual indicators over time. Using the example of analyses applied to Pleistocene deposits from the Lipowo 1 site profile, the scope and potential of three selected bioindicators, pollen, Cladocera and Chironomidae, are discussed with reference to the Late Glacial Scandinavian Ice Sheet (16.513 cal BP). Four cold and four warm climate oscillations of different durations were identified using these proxies: the Older Dryas deterioration of climatic conditions and two short-term coolings within the Allerød Interstadial, separated by warm periods in the Bølling and Allerød.

Keywords: *climate changes, last glacial period, indicators of the biotic environment, sensitivity to environmental conditions*

INTRODUCTION

The risks of human impact on climate change are regularly evaluated by the Intergovernmental Panel on Climate Change (IPCC), established under the United Nations. The climate models used for this are developed based on data including meteorological, dendrochronological, ice core and coral measurements. However, these models need to be validated by reconstructing climate changes that occurred earlier in the planet's history.

One source of difficulty is the fact that the resolution of geological climate data is significantly lower than that of instrumental meteorological data, which only goes back a few decades. For example, the average rate of sedimentation is ~3 cm per 1,000 years in continuous profiles of deep-sea sediments, 40–50 cm per 1,000 years in lake sediment profiles, 4 m in Antarctic ice, and 25 m in Greenland ice (Blunier, Brook, 2001; Marsz, 2009). Studies suggest that since the emergence of modern humans, over 200,000 years ago, the climate has undergone cyclic periods of warming (e.g., the Bronze Age, Roman period, and Middle Ages) and cooling (Bond events, including the Iron Age, the Dark Ages, and the Little Ice Age; Mayewski *et al.*, 2004; Kawamura *et al.*, 2007). The period of the retreat of the last Scandinavian Ice Sheet (SIS), marking the end of the last glaciation and the beginning of the Holocene warming, is particularly interesting for comparative studies.

The most detailed record of climate and environmental changes is preserved in the sediments of closed water basins (Mirosław-Grabowska *et al.*, 2020). Lake and peat bog ecosystems provide valuable opportunities to study palaeogeographical and climatic changes. The deposits accumulated after the ice cover melted recorded environmental and climatic changes, such as the lithology of lake deposits, changes in vegetation (both terrestrial and aquatic), and variations in lake conditions (trophic status, primary production, zooplankton development, and water temperature and level). By analysing botanical and faunal data, we can identify biological indicators of how the environment responded to changing climates.

Lakes are natural archives, where over thousands of years there accumulated, within the sediments, various remains of which are evidence of changes in the environment. The functioning of a lakes is a short-term phenomenon on a geological time scale. They are subject to gradual evolution that usually ends in disappearance. The reconstruction of the ecological and biological past of lakes is possible, *inter alia*, thanks to the remains of organisms preserved in their sediments with bioindicative properties.

Pollen analysis has been used in palaeoecological studies since the early 20th century, due to the production of large numbers of pollen grains and spores by plants which are well-mixed in the atmosphere (pollen rain) and present in abundance in organic-rich deposits (Birks, Birks, 1980). Palynomorphs so preserved can be determined at various taxonomic levels. By studying variations in the percentage composition of pollen spectra in successive stratigraphic layers, we obtain a record of changes in the vegetation cover through time and space either under the influence of natural conditions (climate) or under the influence of human activity.

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The habitat preferences of individual taxa allow us to read information about the conditions prevailing at the time of accumulation of the sediment in which the microfossils were preserved.

Cladocera (water fleas) belong to the small crustaceans, being one of the basic elements of the lacustrine zooplankton (Kajak, 2001). Cladocera as a component of zooplankton live in all aquatic and semi-aquatic environments. For this reason, changes in the Cladocera population and species composition clearly document the evolution of lakes as a consequence of the dynamics of hydrological processes, which were particularly significant during the end of the glacial period and during other significant climate changes. Climate changes also affect other processes occurring in the lake, which are reflected in the change of Cladocera taxa, e.g., changes in trophic level, pH, water depth and, consequently, the development or disappearance of stratyfication zones in the lake (Tolotti *et al.*, 2016). The high suitability of this group of organisms for the purposes of limnological as well as palaeolimnological studies results from their stable ecological requirements and the preservation potential of their chitinous carapaces, which can be identified to species level after extraction from lake deposits (Szeroczyńska, 1985). The small size of cladocerans (<1 mm), their aptitude to produce ephippia (dry-season eggs) which may be transported by birds to colonize new waterbodies, and ability to reproduce by parthenogenesis, caused the Cladocera to be much more expansive and mobile than larger aquatic animals. Thus, their response to changes of environment may be faster and more pronounced than in the case of larger organisms (Frey, 1986). Analysis of the subfossil content of Cladocera in lake deposits also shows great utility in reconstructing environmental conditions in the Late Glacial and Early Holocene due to rapid thermal and hydrological changes that were reflected in changes in species composition (Szeroczyńska, Zawisza, 2007; Pawłowski, 2012).

The Chironomidae are one of the leading proxies in palaeoclimatological and palaeolimnological studies. In Europe, they are mostly used for the mean July air temperature, as well as lake trophic state and depth reconstructions (Luoto, 2011; Kotrys *et al.*, 2020). Besides quantitative reconstructions, they can reveal qualitative processes in lake habitats such as paludification, macrophyte vegetation, overbank episodes in river valleys, and human impact (Płóciennik *et al.*, 2020). The high potential of Chironomidae as palaeobioindicators comes from their ecological character: they are widely distributed, taxonomically and ecologically diverse, usually are abundant in stagnant waters, have short life cycles (so there is no delay in response even to short-lived climatic oscillations), and are sensitive to environmental changes. The taxonomy of their subfossils and laboratory techniques used for subfossil processing and identification are well-defined (Brooks *et al.*, 2007; Bitušík *et al.*, 2024). Recent studies show that molecular identification of midge seda DNA can substantially increase their potential in reconstructing past environments (Blattner *et al.*, 2024).

The Chironomidae have been used for palaeoecological research in Poland since analysis of their remains in diluvial deposits of Starunia (Lengersdorf, 1934). Subsequently, Czeczuga *et al.* (1979), and Halkiewicz (2008) analysed their subfossils in Wigry Lake and Łęczyńsko-Włodwaskie Lakeland deposits, and following the study of Lamentowicz *et al.* (2009) the Chironomidae become frequently used as a Quaternary palaeoecological proxy. Other than Kołaczek *et al.* (2017, 2018), Pleskot *et al.* (2019, 2020, 2022) and de Mendosa *et al.* (2024), all this research was conducted in central Poland. In the Suwałki region, there were no wider studies of the Chironomidae in Late Glacial and Holocene stratigraphy.

High-resolution multi-indicator analyses, combined with absolute age dating, allow to track the variability of individual indicators over time. Analyses of the palaeolake deposits in the Lipowo 1 site profile enable discussion of the scope and potential of certain bioindicators.

Study of the Lipowo 1 succession involved biological indicators within multiproxy analyses to reconstruct environmental changes in the lake ecosystem, such as the mollusc, zooplankton and vegetation development, trophic state, water temperature and water level.

LOCATION OUTLINE

The Lipowo 1 site is located in the central part of the East Suwałki Lakeland, NE Poland (Fig. 1A). The section is situated on a hill elongated NNE–SSW on a hummocky moraine plateau. The hill is ~0.8 km long, 0.4 km wide, and its height is 225.0 m a.s.l. The section contains three units, L1-L3 (Fig. 1B, C). but only unit L-2 was analysed in detail and subdivided into six subunits (from L2a to L2-f). This unit reaches 1.5 m in thickness (Fig. 1C, D). Subunit L-2a, 5 cm thick, consists of sand passing gradually into peat. Above it is subunit L-2b, 29 cm of clayey gyttja and peat, overlain by subunit L-2c, 50 cm of clayey and calcareous gyttja with molluscs, passing gradually into massive peat. Subunit L-2d, 40 cm thick, is composed of clayey to calcareous gyttja with horizontal lamination. Subunit L-2e, 5–15 cm thick, consists of fine sand with horizontal and ripple-cross lamination. In the upper part of the subunit, a layer of sandy peat with plant remnants was observed. The upper subunit L-2f is slightly laminated clayey gyttja with a thickness of 22 cm. These deposits were subjected to lithological, geochemical, palynological and faunal analyses, and dated by the radiocarbon (^{14}C) and optically stimulated luminescence (OSL) methods.

METHODS DESCRIPTION

Environmental changes reflect climatic factors such as temperature, sunlight, and precipitation. The range of biological analyses used to reconstruct environmental changes in the ancient lake basin of Lipowo 1 included palynological studies (pollen and plant macrofossils), zooplankton and benthic organisms studies (cladocerans, chironomids, diatoms). The most information was provided by those that appeared throughout the profile.

POLLEN ANALYSIS

Decomposition of palynomorphs and other organic remains in these deposits was prevented by anoxic conditions, the best biogenic archives forming in water bodies like lakes and peat bogs.

The 41 samples for pollen anylysis from the Lipowo 1 site were prepared following the standard procedure by using heavy liquid and the modified Erdtman's acetolysis (Moore *et al.*, 1991; Rychel *et al.*, 2022). Depending on the frequency, 100 to 500 pollen grains were counted (Berglund, Ralska-Jasiewiczowa, 1986). The results are shown in a pollen percentage diagram that includes total curves

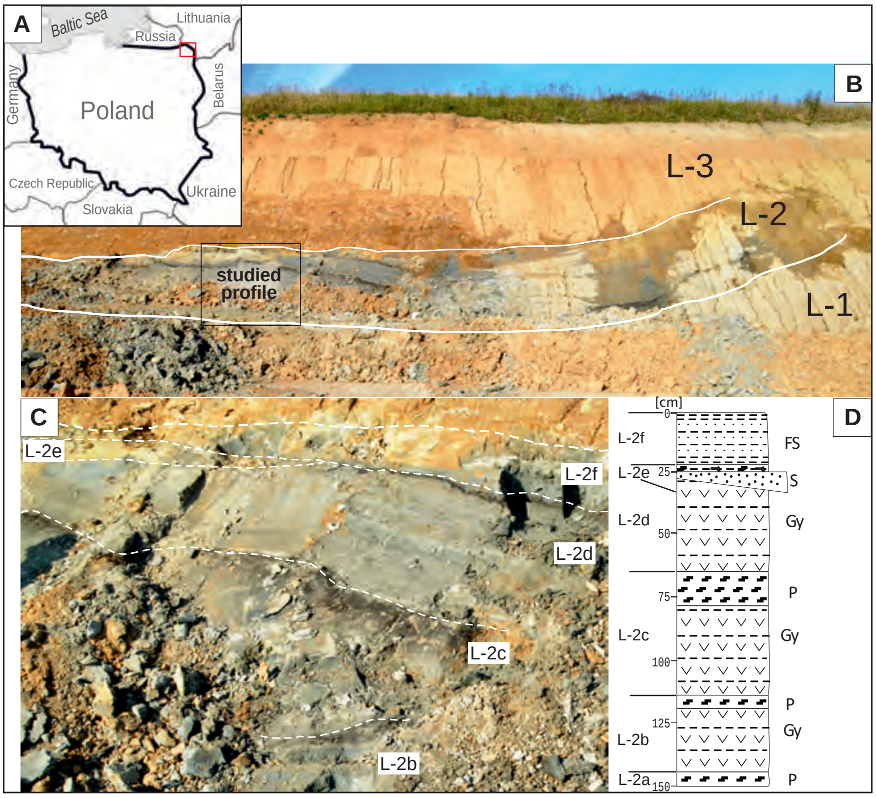

Fig. 1. A – location of the Lipowo 1 site; **B** – panoramic view of the three main sedimentary units; **C** – the profile studied; **D** – lithological log of the depositional succession of Unit L-2; symbols the lithofacies code by Miall (1977, 1985) with modified by Zieliński, Pisarska-Jamroży (2012)

and selected taxa. The Late Glacial indicators total curve (LGT) contains the most important plant taxa characteristic of late glacial plant communities: *Juniperus, Hippophaë rhamnoides, Betula nana*-type, *Dryas octopetala, Helianthemum,* Saxifragaceae, *Artemisia,* Chenopodiaceae.

CLADOCERA ANALYSIS

In the Lipowo 1 profile, 30 lacustrine samples from unit L-2 were analysed for Cladocera remains, from core depths of 0.01–1.50 m. 1 cm^3 samples were prepared according to a standard procedure (Frey, 1986; Rychel *et al.*, 2022). All Cladocera remains from each slide were counted (head shield, shell, postabdomen, postabdominal claws, antennules and others). Identification and ecological interpretation of the Cladocera remains were carried out according to: Goulden (1964), Szeroczyńska (1985), Hofmann (1986, 2000), Korhola (1990), Duigan (1992), Flössner (2000), Szeroczyńska, Sarmaja-Korjonen (2007) and Rybak, Błędzki (2010). The results of quantitative and qualitative analyses were summarized in a diagram showing grouping of species according to ecological requirements (lake zone – littoral, open water, trophic level, temperature). The classification of Cladocera was prepared based on the publications by Flössner (1964), Whiteside (1970), Hofmann (1987), Whiteside, Swindoll (1988), Korhola (1990) and Korhola, Rautio (2001).

CHIRONOMIDAE ANALYSIS

At least 40–50 head capsules are required for reliable palaeotemperature reconstruction (Quinlan, Smol, 2001). As Chironomidae head capsules are abundant in lake gyttjas, <5 cm^3 of the sediment is usually enough for analysis to obtain tens or even hundreds of specimens. The mean July air temperature was reconstructed from Lipowo 1 using the Swiss-Norwegian-Polish Training Set (Kotrys *et al.*, 2020).

AGE DATING

The numerical age of the deposits was obtained by radiocarbon and luminescence dating.

^{14}C analysis was performed on three samples of macroremains (MKL-A5352, MKL-A5353, MKL-A5354) using accelerator mass spectrometry (AMS) and one bulk sample (MKL-5074) by the liquid scintillation counting (LSC) method. All samples were dated in the Radiocarbon Laboratory in Kraków and were calibrated in OxCal ver. 4.4 software (Bronk Ramsey, 2009) using the IntCal20 calibration curve (Reimer *et al.*, 2020).

Analysis for OSL dating was performed on two samples of fine-grained laminated sands. All laboratory procedures were performed at the Luminescence Dating Laboratory, Silesian Technical University in Gliwice.

RESULTS

Pollen succession at the Lipowo 1 site

During the Late Glacial period, an open landscape dominated with vegetation communities represented mainly by herbaceous and shrubby plants with a small proportion of woody species. However, even then, there were periodic changes in the temperature and humidity that affected the vegetation cover. During the Oldest Dryas period, most of the area was overgrown by steppe communities with Poaceae and *Artemisia*, with sparse tundra in moist habitats with Cyperaceae, *Betula nana* and *Salix* (Fig. 2). The vegetation cover in the Lipowo 1 lake vicinity represents a classic community for the Oldest Dryas in Poland (Ralska-Jasiewiczowa *et al.*, 2004). This cold period was followed by an climatic warming in the Bølling. The plant communities gradually transformed from steppe-tundra to forest-tundra. The proportion of pine and then birch trees increased. However, most of the area was covered by peatland vegetation with Cyperaceae, *Sphagnum* and low shrubs. This warm period was followed by a short-lived cooling termed the Older Dryas. Climatic factors more conducive to the presence of pioneer trees appeared again in the Allerød. Warmer conditions resulted in the gradual appearance of sparse pine-birch forests. However, the openness of the landscape still favoured light-demanding species and allowed the presence of juniper bushes (*Juniperus*), and the abundant presence of sea buckthorn (*Hippophaë rhamnoides)* in the landscape.

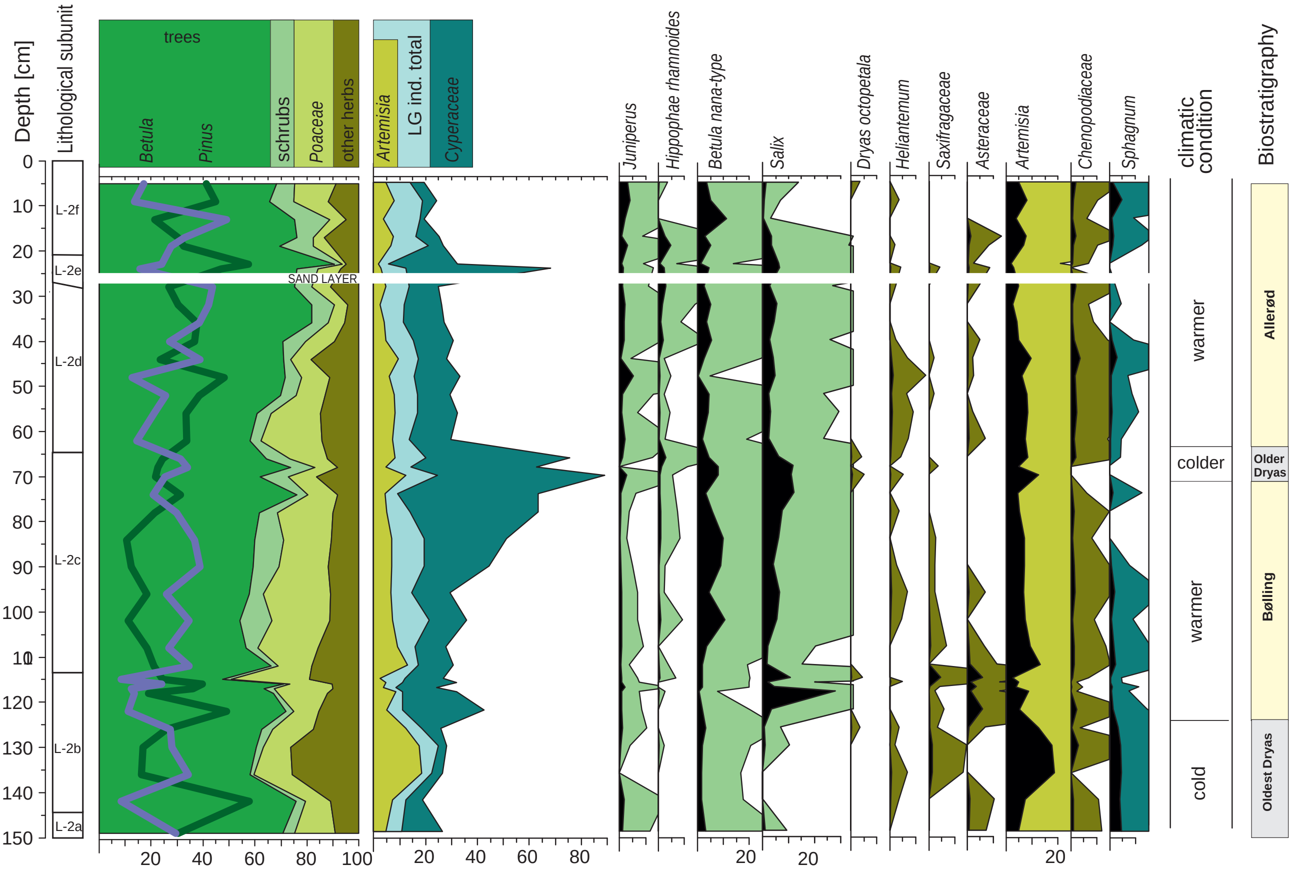

Fig. 2. Pollen synthetic diagram from Lipowo 1 palaeolake with selected indicator taxa

Cladocera succession in the Lipowo 1 site

In NE Poland, in lakes examined for their Cladocera content from the Late Glacial period in cold periods (Oldest and Older Dryas), the species recorded were limited to 3–5 taxa, mainly cold-tolerant, and the frequency of individuals was low (Zawisza, Szeroczyńska, 2007). The situation was similar in Lake Lipowo 1.

During the Bølling period, the conditions were more favourable to a wider group of Cladocera species. The species present mainly related to the macrophyte zone, and were dominant in clear, low productivity/low trophic level water (Fig. 3), common in ponds and bogs (Whiteside, 1970). A slight increase in water level indicates the presences of a species from the open water zone, *Bosmina longirostris*. At 117–130 cm depth, a large proportion of ephippia was recorded, which may indicate environmental stress and increased production of resing eggs (Sarmaja-Korjonen, 2003). In the Middle Bølling conditions improved and eight Cladocera species occurred. The presence of two species from open water [*Ceriodaphnia* sp., *Bosmina (Eubosmina) longispina*] may suggest a higher water level. A significant increase in the frequency of two species, *Chydorus sphaericus* and *Bosmina longirostris*, may also suggest an increase in productivity and a higher trophic level (Nevalainen *et al.*, 2013).

In the second warm period of the Late Glacial – Allerød, nine species were identified in the lake. The peak of this interval was marked by ubiquitous *Chydorus sphaericus*. This phase was the only one in which the cladoceran species, *Monospilus dispar*, which has higher thermal requirements, was recorded. *Monospilus dispar*, together with the overall improvement in cladoceran frequency, indicates an increase in water temperature. The presence of species with higher trophic requirements – *Bosmina longirostris* and *Chydorus sphaericus* – together with *Monospilus* sp. (Adamska, Mikulski, 1969) may indicate a meso/eutrophic condition in the lake. At a depth of ~44 cm, there is recorded a brief decline in the frequency of almost all Cladocera species, which may indicate a deterioration of living conditions and a cool climate oscillation. At the end of the Allerød, all species living in the lake gradually withdrew. The first ones to disappear were *Alona quadrangularis*, small *Alona* and *Alonella nana*, which may also be related to the disappearance of the macrophyte zone. The last withdrawals are the cold-resistant *Acroperus harpae* and *Chydorus sphaericus*, the abundance of which was initially still quite high (Rychel *et al.*, 2022). Above 11 cm there are no cladoceran remains in the sediment.

Chironomid succession in the Lipowo 1 site

Late Glacial clastic deposits often include higher concentrations of midge head capsules. The low Chironomidae abundance can result from oxygen deficiencies or paludification (Brooks *et al.*, 2007).

The Lipowo 1 Chironomidae communities are dominated by cool temperate taxa typical of Late Glacial sites across Europe (Płóciennik *et al.*, 2011; Tóth *et al.*, 2022; Engels *et al.*, 2024), such as *Corynocera ambigua* that was abundant from the Oldest to the Older Dryas, and disappeared in the Allerød (Fig. 4). This taxon was widespread across Europe in the Late Glacial, especially in the Younger Dryas. It is tolerant of large fluctuations in the environment that are unfavorable

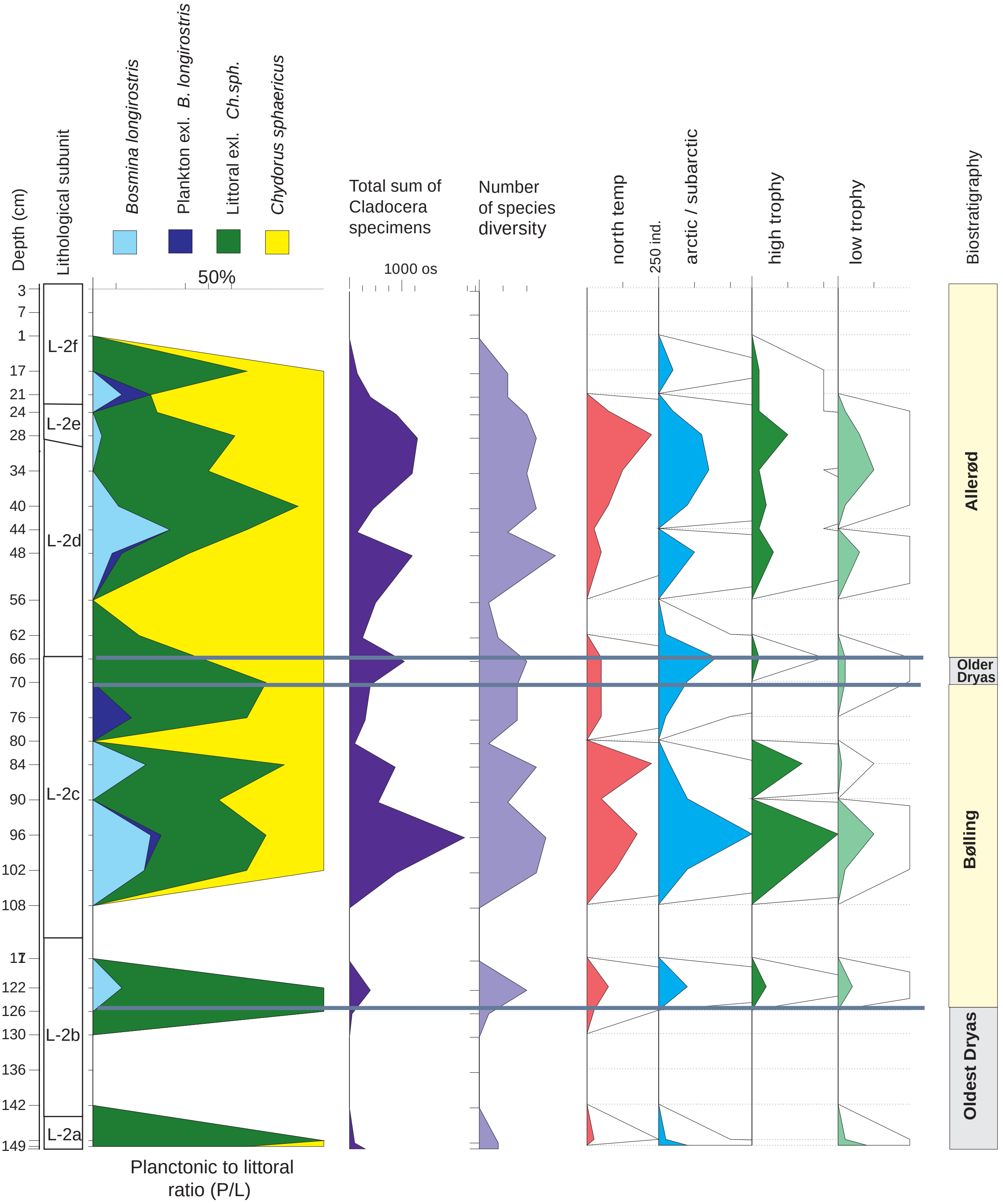

Fig. 3. Ecological preference of Cladocera species from the Lipowo 1 site. P/L – Planktonic (P) to littoral (L) ratio: P: *Bosmina longirostris* (light blue), *Bosmina (E) longispina*, *Ceriodaphnia* sp. (blue); L: remaining species (green) *Chydorus sphaericus*; north temperature: *Alona quadrangularis*, Small *Alona* (Hofmann, 2000)(red); arctic/subarctic: *Acroperus harpae*, *Alona affinis*, *Alonella nana* (blue); high trophy: *Bosmina longirostris*, *Alona affinis*, *Alona quadrangularis* (green); low trophy: *Alonella nana*, *Bosmina longispina*, *Monospilus dispar* (light green)

for other taxa. It tolerates a wide range of temperatures (Halkiewicz, 2008; Lapellegerie *et al.*, 2024), having in Swiss-Norwegian-Polish Training Set (SNP TS) a relatively temperate climatic optimum but currently it is still much more abundant in cold regions like Scandinavia and is generally restricted to the boreal-arctic zone. It appears infrequently in the warm temperate lowland regions of Europe, including Pomerania and Masuria in Poland but is rarely abundant (Kotrys *et al.*, 2020). The *Microtendipes pedellus*-type and *Chironomus anthracinus*-type are also indicators of cool climate conditions though more mild than those with *Corynocera ambigua* (Brooks *et al.*, 2007). During the Bølling-Allerød interstadial

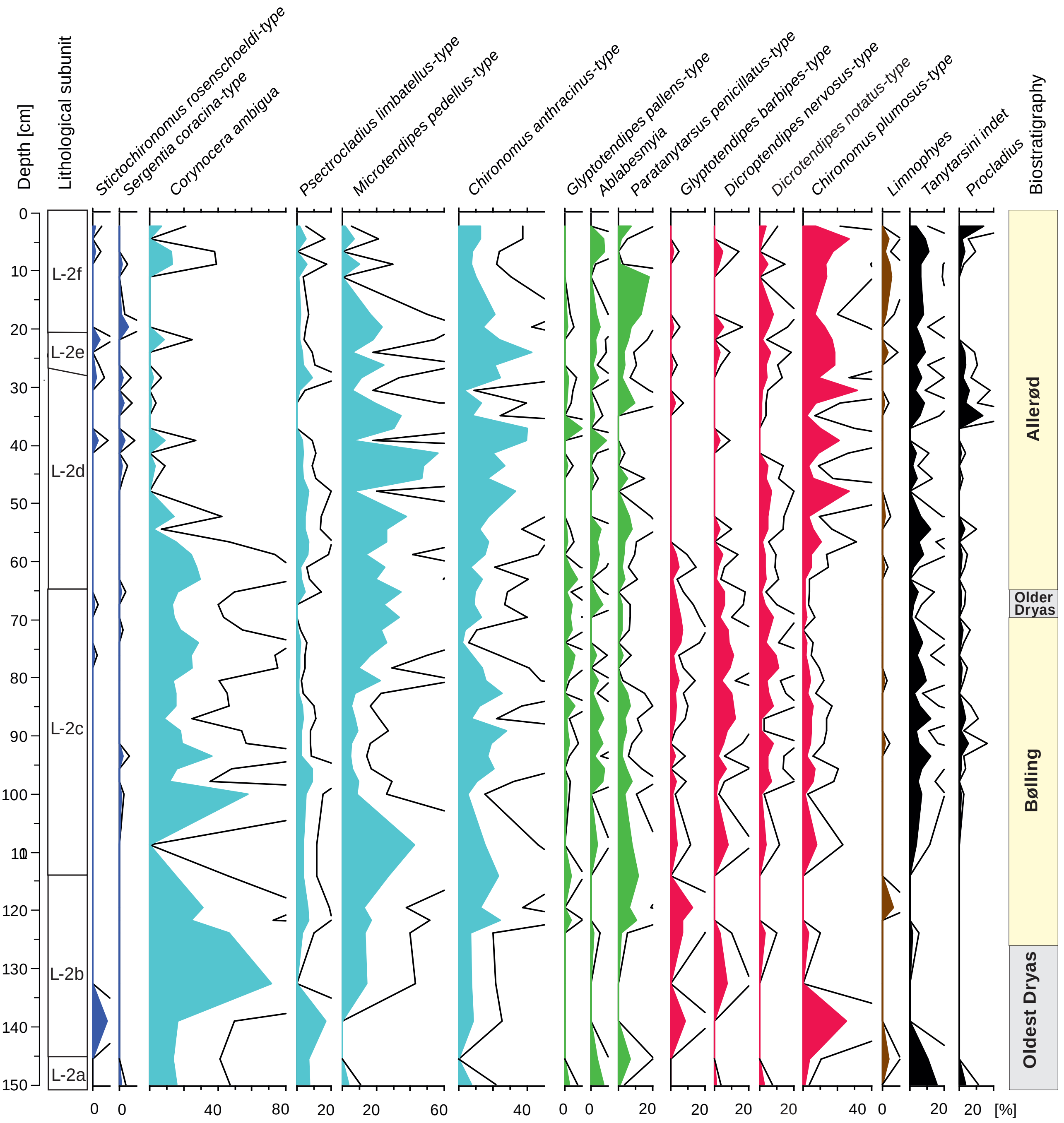

Fig. 4. Chironomidae synthetic diagram from Lipowo 1 site

there are also abundant phytophile and warm stenotherm taxa – *Glyptotendipes*, *Dicroptendipes* and *Chironomus plumosus*-type – which additionally indicate warm summer conditions that where eariler inferred in Eastern Europe from palaeobotanical proxy (Schenk *et al.*, 2020). Chironomidae-inferred mean July air temperatures are warmer later in the Bølling (late GI-1e) and were even warmer during the early to middle Allerød GI-1c2. Chironomid data suggest three cold oscillations (Figs. 4 and 5). The first is at the beginning of GI-1e when the temperature was still not much higher than during GS-2-1a. The second starts with a temperature decrease at Older Dryas (GI-1d) with the lowest temperature at early GI-1c3. The reconstruction is generally consistent with the Cladocera-inferred climatic conditions, but the maximum cooling is inferred for the Older Dryas (GI-1d). The third cold oscillation occurs, according to the chironomid data, in the middle Allerød (GI-1c1/GI-1b), a little later than suggested by pollen and Cladocera. Rychel *et al.* (2022) corroborate the warming at Lipowo 1 during GI-1e with the highest temperature at its final stage. The climate must have been still very continental as there are cold-adapted molluscs, plant communities are open, and warm stenothermic Cladocera are absent. Chironomids suggest cooling rather at GI-1c3, which corresponds approximately with Greenland ice core stratigraphy (Rasmussen *et al.*, 2014). The plant and Chironomidae communities reveal similarly the climate cooling at GI-1c1/GI-1b (Rychel *et al.*, 2022). The Chironomidae-inferred reconstruction from the Suwałki region corresponds well with climate history of northern Europe (Brooks, Langdon, 2014) but the cold oscillations do not overlap adequately with the Greenland ice core climate stra-

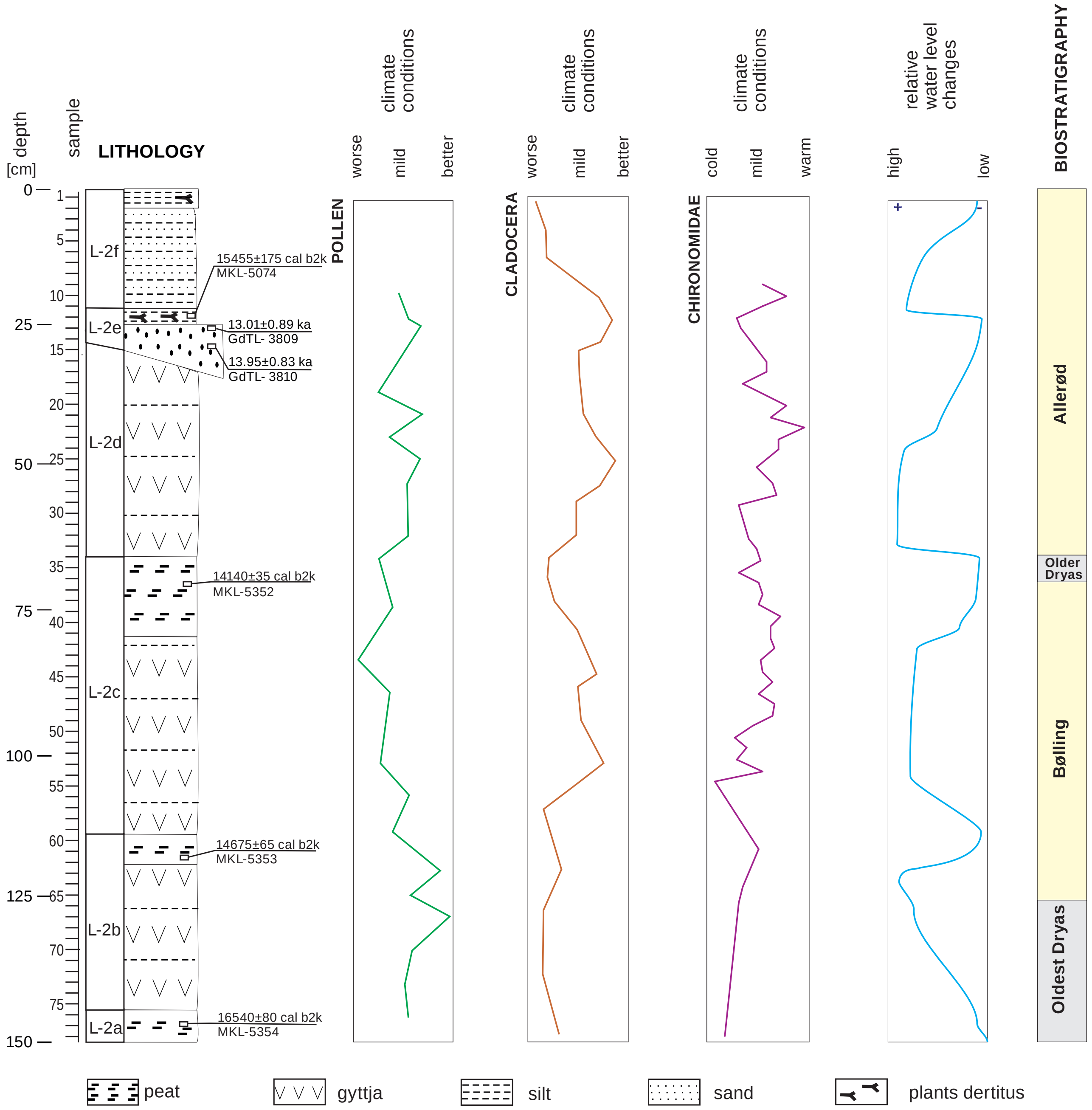

Fig. 5. An indicative compilation of the course of changes in the climatic conditions represented by the Lipowo 1 profile for selected bioindicators; the water level changes based on Cladocera

tigraphy (Rasmussen *et al.*, 2014). The cold episode revealed by all three proxies at GI-1c1/GI-1b can be identified as the Gerzensee Oscillation. Antczak-Orlewska *et al.* (2023) also recorded the Gerzensee Oscillation from the Luciąża River oxbow. The Older Dryas was weaker in eastern Europe, but it has been noted in the Peribaltic region for several decades (Šeirienė *et al.*, 2021; Druzhinina *et al.*, 2023). On the Polish Plain it is hard to detect in Chironomidae communities, but is often significant in pollen stratigraphy (i.e. Dzieduszyńska, Petera-Zganiacz, 2018). Generally, summer temperatures in central Poland were mild to warm during the Late Glacial, reaching similar levels to Holocene values (Kotrys *et al.*, 2020; Forysiak *et al.*, 2023). Lipowo 1, situated in the young postglacial region, experienced stronger temperature fluctuations and winter-summer contrast. The Chironomidae-inferred July temperature reconstruction follows the general pattern of European climate, and is consistent with the other proxies analysed at Lipowo 1 (Pollen, Cladocera, diatoms). However, detailed analysis of the assemblages suggests that other factors, like the trophic state, may interfere with temperature influence in the trends in species composition of the communities.

Age model of the Lipowo 1 site

The results of numerical age dating obtained are in stratigraphical order, except for sample MKL-5074, where the calibrated age (15,406 ±175 cal a BP) is overestimated (Fig. 5). All of the age data served as the basis for the determination of the age of the Lipowo 1 succession deposits, where the deposition started about 16,490 ±80 cal a BP and lasted at least to 13.01 ±0.89 ka BP (GdTL-3809).

SUMMARY

Bioindicators provide much information about the environment e.g. changes in water depth and temperature (Fig. 5). This allows reconstruction of changes in climatic conditions in the past, comparisons with other areas, and tracking of changes beyond the local level.

Plants have varied requirements and their occurrence depends on a combination of factors such as temperature, insolation, access to water, soil fertility. A combination of these factors influences the type of vegetation in a given area under any given climatic conditions. Palynological analysis of sediments collected from Lipowo 1 allowed reconstruction of the vegetation cover from the Oldest Dryas time to the Late Allerød (Fig. 2). A characteristic feature of the Lipowo 1 diagram is the occurrence of taxa typical of cool floras, e.g., *Juniperus*, *Betula nana t.*, *Hippophae rhamnoides*. Changes in vegetation showed that during the Late Vistulian the climate was strongly fluctuating. There were warm periods in which pioneer trees could spread (Fig. 5). Areas with loose forest cover were mainly formed by pioneer trees such as birch which are characterized primarily by rapid growth, high expansivity, and a wide tolerance as regards climate (Berndt, 1979).

In Lake Lipowo 1, during warmer periods only cold-tolerant Cladocera species were present: arctic, subarctic and north temperate groups (Fig. 3; Hofmann, 2000; except for the depth of 48 cm, where remains of the stenothermic *Monospilus dispar* were found). A similar species composition, i.e. a lack of species with higher thermal requirements, was found in Poland in the Late Glacial in mountain lakes and in Lake Wigry (Zawisza, Szeroczyńska, 2007). It is likely that in this area, during the entire Late Glacial, the climate was continental, it was relatively severe, and prolonged seasonal ice cover on the lakes limited life within them (Szaroczyńska, Zawisza, 2007). A very similar species composition was also found in the lake at Kråkenes, western Norway (Duigan, Birks, 2000) during this period. In addition to thermal conditions, the species composition was also influenced by it being a shallow lake dominated by littoral species of the Chydoridae: *Alonas* and *Chydorus sphaericus*.

More information about thermal conditions is provided by the Chironomidae. During the last glacial termination, summer temperature fluctuations were the main drivers of deglaciation, permafrost thawing, and biocenoses development. The temperature increase conditioned the trophic state of the lakes and their primary productivity, and the colonization of the post-glacial landscape by mime midges (Płóciennik *et al.*, 2011). This is because midges are essential for regional and local environmental reconstruction and freshwater biodiversity estimates. Chironomidae were used mainly for climate reconstruction in the studies presented here (Figs. 4 and 5), this helps to test the hypothesis of a much earlier deglaciation in north eastern Poland than was previously supposed.

Plant, invertebrate and algal bioindicators are sensitive with a wide range of conditions and serve broad applications in palaeoecology. This helps to identify regional scale changes (e.g., mega-floods in the Suwałki Lakeland: Weckwert *et al.*, 2020) or test the hypothesis of much earlier deglaciation in north eastern Poland (Rychel *et al.*, 2022) and the extent of the continental climate in Europe during the Late Glacial SIS.

Presented the results show that environmental changes in the past have occurred for thousands of years in a complex way, shaping biocenoses in the lakes and their catchment. Global warming at the end of the Vistulian was the primary driver of aquatic and terrestrial ecosystems. Multi-proxy palaeolimnological studies shed light on the current climate's influence on ecological processes in periglacial landscapes. We hope that understanding the mechanisms of climate change in the geological past will help us better appreciate the context of the climatic problems of today's world.

Acknowledgements. The publication fee was financed by the Ministry of Science and Higher Education.

We would like to thank the anonymous reviewers for their constructive and helpful comments.

REFERENCES

ADAMSKA A., MIKULSKI J.S. 1969 – Cladocera remains in the superficial sediments of lakes as a typologic indicator. Z. Naukowe UMK 25. Prace Stacji Limnologicznej w Iławie, 5: 41–48.

ANTCZAK-ORLEWSKA O., OKUPNY D., PAWŁOWSKI D., KOTRYS B., KRĄPIEC M., LUOTO T.P., PEYRON O., PŁÓCIENNIK M., STACHOWICZ-RYBKA R., WACNIK A., SZMAŃDA J.B., SZYCHOWSKA-KRĄPIEC E., KITTEL P. 2023 – The environmental history of the oxbow in the Luciąża River valley – study on the specific microclimatic during Allerød and Younger Dryas in central Poland. Quaternary International, 644–645: 178–195; https://doi.org/10.1016/j.quaint.2021.08.011

BERGLUND B.E., RALSKA-JASIEWICZOWA M. 1986 – Pollen analysis. [In:] Berglund B.E. (ed.), Handbook of Holocene Palaeoecology and Palaohydrology. J. Wiley and Sons Ltd. Chichester – New York: 455483

BIRKS H.J.B., BIRKS H.H. 1980 – Quaternary Palaeoecology. The Blackburn Press, Caldwell.

BITUŠÍK P., HAMERLÍK L., CHAMUTIOVÁ T. 2024 – Subfossil Chironomidae of the Western and Eastern Carpathians. An identification guide to larval remains from lake sediments. Brill.

BLATTNER L.A., LAPELLEGERIE P., COURTNEY-MUSTAPHI C., HEIRI O. 2024 – Sediment core DNA-metabarcoding and chitinous remain identification: integrating complementary methods to characterise Chironomidae biodiversity in lake sediment archives. Molecular Ecology Resources, e14035; https://doi.org/10.1111/1755-0998.14035

BERNDT J. 1979 – Betula 7. Państwowe Wydawnictwo Naukowe.

BRONK RAMSEY C. 2009 – Bayesian analysis of radiocarbon dates. Radiocarbon, 51: 337–360; https://doi.org/10.1017/ S0033822200033865

BLUNIER T., BROOK E. 2001 – Timing of millennial-scale climate change in Antarctica and Greenland during the last glacial period. Science, 291: 109–112; https://doi.org/10.1126/science.291.5501.109

BROOKS S.J., LANGDON P.G. 2014 – Summer temperature gradients in northwest Europe during the Late Glacial to early Holocene transition (15–8 ka BP) inferred from chironomid assemblages. Quaternary International, 341: 80–90.

BROOKS S.J., HEIRI O., LANGDON P.G. 2007 – The identification and use of palaearctic Chironomidae larvae in palaeoecology. Quaternary Research Association, London.

CZECZUGA B., KOSSACKA W., NIEDŹWIEDZKI E. 1979 – Ecological changes in Wigry Lake in the postglacial period. Part III. Investigations of the Chironomidae stratigraphy. Polskie Archiwum Hydrobiologii, 26: 351–369.

DRUZHININA O., RUDINSKAYA A., FILIPPOVA K., LAZUKOVA L., LAVROVA N., ZHAROV A., SKHODNOV I., BURKO A., VAN DEN BERGHE K. 2023 – The Bølling–Allerød transition in the Eastern Baltic: environmental responses to climate change. Biology, 12 (6): 821; https://doi.org/10.3390/biology12060821

DUIGAN C.A., BIRKS H.H. 2000 – The late-glacial and early-Holocene palaeoecology of cladoceran microfossil assemblages at Kråkenes, western Norway, with a quantitative reconstruction of temperature changes. Journal of Paleolimnology, 23, 6776.

DZIEDUSZYŃSKA D.A., PETERA-ZGANIACZ J. 2018 – Small-scale geologic evidence for Vistulian decline cooling periods: case studies from the Łódź Region (Central Poland). Bulletin of the Geological Society of Finland, 90: 209–222; https://doi.org/10.17741/bgsf/90.2.006

DUIGAN C.A. 1992 – The ecology and distribution of the littoral freshwater Chydoridae (Branchiopoda, Anomopoda) of Ireland with taxonomic comments on some species. Hydrobiology, 241: 1–70.

ENGELS S., LANE C.S., HOEK W.Z., BANESCHI I., BOUWMAN A., BROGAN E., BRONK RAMSEY C., COLLINS J., DE BRUIJN R., HALIUC A., HEIRI O., HUBAY K., JONES G., JONES V., LAUG A., MERKT J., MUSCHITIELLO F., MÜLLER M., PETERS T., PETERSE F., PUESCHEL A., STAFF R.A., TER SCHURE A., TURNER F., VAN DEN BOS V. 2024 – Wagner-Cremer, Biodiversity responses to Late glacial climate change in the subdecadally-resolved record of Lake Hämelsee (Germany), Quaternary Science Reviews. 331: 108634; https://doi.org/10.1016/j.quascirev.2024.108634

FLÖSSNER D. 1964 – Zur Cladocerenfauna des Stechlinsee-Gebietes. II. Ökologische Untersuchungen über die litoralen Arten. Limnologica (Berlin), 2 (1): 35100.

FLÖSSNER D. 2000 – Die Haplopoda und Cladocera (ohne Bosminidae) Mitteleuropas. Backhuys Publishers: Leiden.

FREY D.G. 1986 – Cladocera analysis. [In:] Berglund B.E. (ed.). Handbook of Holocene Palaeoecology and Palaeohydrology Wiley, Chichester, 667–692.

FORYSIAK J., OKUPNY D., OBREMSKA M., ANTCZAK-ORLEWSKA O., PŁÓCIENNIK M., PAWŁOWSKI D., BARADYN D., KOTRYS B., LUOTO T.P., NEVALAINEN L., BORÓWKA R.K. 2023 – Changes in habitat conditions in a Late Glacial fluviogenic lake in response to climatic fluctuations (Warta River valley, central Poland). Geological Quarterly, 67: 1; http://dx.doi.org/10.7306/gq.1672

GOULDEN C.E. 1964 – The history of the cladoceran fauna of Esthwaite Water (England) and its limnological significance. Archiv für Hydrobiologie, 60: 1–53.

HALKIEWICZ A. 2008 – *Corynocera ambigua* (Insecta, Diptera) subfossils occurrence in recent sediments of four shallow Polesie lakes. Annales Universitatis Maria Curie-Skłodowska Sectio C, 63: 31–36.

HOFMANN W. 1986 – Developmental history of the Grosser Plöner See and the Schöhsee (north Germany): cladoceran analysis, with special reference to eutrophication. Archiv für Hydrobiologie Supplements, 74: 259–287.

HOFMANN W. 1987 – Cladocera in space and time: analysis of lake sediments. Hydrobiologia, 145, 315321.

HOFMANN W. 2000 – Response of the chydorid faunas to rapid climatic changes in four alpine lakes at different altitudes. Palaeogeography, Palaeoclimatology, Palaeoecology, 159: 281–292.

KAJAK Z. 2001 – Hydrobiologia-limnologia: ekosystemy wód śródlądowych. Wydawnictwo Naukowe PWN, Warszawa.

KAWAMURA K., PARRENIN F., LISIECKI L., UEMURA R., VIMEUX F., SEVERINGHAUS J.P., HUTTERLI M.A., NAKAZAWA T., AOKI S., JOUZEL J., RAYMO M.E., MATSUMOTO K., NAKATA H., MOTOYAMA H., FUJITA S., GOTO-AZUMA K., FUJII Y., WATANABE O. 2007 – Northern Hemisphere forcing of climatic cycles in Antarctica over the past 360,000 years. Nature, 448: 912–916; https://doi.org/10.1038/nature06015

KOŁACZEK P., MARGIELEWSKI W., GAŁKA M., APOLINARSKA K., PŁÓCIENNIK M., GĄSIOROWSKI M., BUCZEK K., KARPIŃSKA-KOŁACZEK M. 2017 – Five centuries of the Early Holocene forest development and its interactions with palaeoecosystem of small landslide lake in the Beskid Makowski Mountains (Western Carpathians, Poland) – high resolution multi-proxy study. Review of Palaeobotany and Palynology, 244: 113–127; https://doi.org/10.1016/j.revpalbo.2017.05.002

KOŁACZEK P., PŁÓCIENNIK M., GAŁKA M., APOLINARSKA K., TOSIK K., GĄSIOROWSKI M., BROOKS S.J., KARPIŃSKA-KOŁACZEK M. 2018 – Persist or take advantage of global warming: A development of Early Holocene riparian forest and oxbow lake ecosystems in Central Europe. Quaternary Science Reviews, 200: 191–211; https://doi.org/10.1016/j.quascirev.2018.09.031

KORHOLA A. 1990 – Paleolimnology and hydroseral development of the Kotasuo Bog, Southern Finland, with special reference to the Cladocera. Annales Academiæ Scientiarum Fennicæ, 155: 5–40.

KORHOLA A., RAUTIO M. 2001 – Cladocera and other bra-chiopod crustaceans. [In:] Smol J.P., Birks H.J.B., Last W.M (eds.), Tracking Environmental Change Using Lake Sediments 4: Zoological Indicators. Kluwer Academic Publishers, Dordrecht, The Netherlands: 5–41

KOTRYS B., PŁÓCIENNIK M., SYDOR P., BROOKS S. 2020 – Expanding the Swiss-Norwegian chironomid training set with Polish data. Boreas, 49: 89–107; https://doi.org/10. 1111/ bor. 12406.

LAPELLEGERIE P., MILLET L., RIUS D., DUPRAT-OUALID F., LUOTO T., HEIRI O. 2024 – Chironomid-inferred summer temperature during the Last Glacial Maximum in the Southern Black Forest, Central Europe. Quaternary Science Reviews, 345; https://doi.org/10.1016/j.quascirev.2024. 109016

LAMENTOWICZ M., BALWIERZ Z., FORYSIAK J., PŁÓCIENNIK M., KITTEL P., KLOSS M., TWARDY J., ŻUREK S., PAWLYTA J. 2009 – Multiproxy study of anthropogenic and climatic changes in the last two millennia from a small mire in central Poland. Hydrobiologia, 631: 213–230; https://doi.org/10.1007/978-90-481-3387-1_13

LENGERSDORF F. 1934 – Dwuskrzydłe z warstw dyluwjalnych Staruni (in Polish). Starunia, Polska Akademia Umiejętności, 4: 1–8.

LUOTO T.P. 2011 – The relationship between water quality and chironomid distribution in Finland – a new assemblage-based tool for assessments of long-term nutrient dynamics. Ecological Indicators, 1: 255–262; https://doi.org/10.1016/j.ecolind.2010.05.002

MARSZ A. 2009 – Klimat Arktyki w późnym glacjale i holocenie (in Polish). Problemy Klimatologii Polarnej, 19: 33–79.

MAYEWSKI P.A., ROHLING E.E., STAGER J.C., KARLEN W., MAASCH K.A., MEEKER L.D., MEYERSON E.A., GASSE F., VAN KREVELD S., HOLMGREN K., LEE-THORP J., ROSQVIST G., RACK F., STAUBWASSER M., SCHNEIDER R.R., STEIG E.J. 2004 – Holocene climate variability. Quaternary Research, 62 (3), 243255; https://doi.org/10.1016/j.yqres.2004.07.001

MENDOZA G., KOTRYS B., PŁÓCIENNIK M., SYDOR P., OKUPNY D. 2024 – Common chironomids drive the biodiversity – temperature relationship during the Younger Dryas Holocene transition in a southern Baltic coastal lake. Hydrobiologia, 851: 503–525; https://doi. org/10.1007/s10750-023-05337-w

MIROSŁAW-GRABOWSKA J., OBREMSKA M., ZAWISZA E., STAŃCZAK J., SŁOWIŃSKI M., MULCZYK A. 2020 – Biological and geochemical indicators of climatic oscillations during the Last Glacial Termination, the Kaniewo palaeolake (Central Poland). Ecological Indicators, 114: 106301; https://doi.org/10.1016/j.ecolind.2020.106301

MIALL A.D. 1977 – A review of the braided river environment. Earth-Science Reviews, 13: 1–62.

MIALL A.D. 1985 – Architectural-element analysis: a new method of facies analysis applied to fluvial deposits. Earth-Science Reviews, 22: 261–308

MOORE P.D., WEBB J.A., COLLINSON M.E. 1991 – Pollen analysis. Blackwell Scientific Publications, Oxford.

NEVALAINEN L., LUOTO T.P., KULTTI S., SARMAJA-KORJONEN K. 2013 – Spatio- temporal distribution of sedimentary Cladocera (Crustacea: Branchiopoda) in relation to climate. Journal of Biogeography, 40: 1548–1559; https://doi.org/10.1111/jbi.12101

PAWŁOWSKI D. 2012 – Younger Dryas Cladocera assemblages from two valley mires in central Poland and their potential significance for climate reconstructions. Geologos, 18: 237–249; https://doi:10.2478/v10118-012-0012-2

PŁÓCIENNIK M., PAWŁOWSKI D., VILIZZI L., ANTCZAK-ORLEWSKA O. 2020 – From oxbow to mire: Chironomidae and Cladocera as habitat palaeoindicators. Hydrobiologia, 847: 3257–3275; https://doi.org/10.1007/s10750-020-04327-6

PŁÓCIENNIK M., SELF A., BIRKS H.J.B., BROOKS S.J. 2011 – Chironomidae (Insecta: Diptera) succession in Żabieniec bog and its palaeolake (central Poland) through the Late Weichselian and Holocene. Palaeogeography Palaeoclimatology Palaeoecology, 307: 150–167; https://doi.org/10.1016/j.palaeo.2011.05.010

PLESKOT K., TÓTH M., APOLINARSKA K. 2019 – Distribution of subfossil chironomids (Diptera, Chironomidae) along a water depth gradient in the shallow Lake Spore, northern Poland. Journal of Limnology, 78: 336–347; https://doi.org/10.4081/jlimnol.2019.1916

PLESKOT K., APOLINARSKA K., KOŁACZEK P., SUCHORA M., FOJUTOWSKI M., JONIAK T., KOTRYS B., KRAMKOWSKI M., SŁOWIŃSKI M., WOŹNIAK M., LAMENTOWICZ M. 2020 – Searching for the 4.2 ka climate event at Lake Spore, Poland. Catena, 191, 104565; https://doi.org/10.1016/j.catena.2020.104565

PLESKOT K., APOLINARSKA K., CWYNAR L., KOTRYS B., LAMENTOWICZ M. 2022 – The late-Holocene relationship between peatland water table depth and summer temperature in northern Poland. Palaeogeography, Palaeoclimatology, Palaeoecology, 586, 110758; https://doi.org/10.1016/j.palaeo.2021.110758

QUINLAN R., SMOL J.P. 2001 – Setting minimum head capsule abundance and taxa deletion criteria in chironomid-based inference models. Journal of Paleolimnology, 26: 327–342.

RALSKA-JASIEWICZOWA M., LATAŁOWA M., WASYLIKOWA K., TOBOLSKI K., MADEYSKA E., WRIGHT H.E., TURNER C. (eds.) 2004 – Late Glacial and Holocene history of vegetation in Poland based on isopollen maps. Szafer Institute of Botany, Polish Academy of Sciences: Kraków: 47–68, 119–145, 253–261, 305–308.

RASMUSSEN S.O., BIGLER M., BLOCKLEY S.P., BLUNIER T., BUCHARDT S.L., CLAUSEN H.B., CVIJANOVIC I., DAHL-JENSEN D., JOHNSEN S.J., FISCHER H., GKINIS V., GUILLEVIC M., HOEK W.Z., LOWE J.J., PEDRO J.B., POPP T., SEIERSTAD I.K., STEFFENSEN J.P., SVENSSON A.M., VALLELONGA P., VINTHER B.M., WALKER M.J.C., WHEATLEY J.J., WINSTRUP M. 2014 – A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy. Quaternary Science Reviews, 106: 14–28; https://doi.org/10.1016/j.quascirev.2014. 09.007

REIMER P.J., AUSTIN WEN BARD E., BAYLISS A., BLACKWELL P.G., BRONK RAMSEY C., BUTZIN M., CHENG H., EDWARDS R.L., FRIEDRICH M., GROOTES P.M., GUILDERSON T.P., HAJDAS I., HEATON T.J., HOGG A.G., HUGHEN K.A., KROMER B., MANNING S.W., MUSCHELER R., PALMER J.G., PEARSON C., VAN

DER PLICHT J., REIMER R.W., RICHARDS D.A., SCOTT E.M., SOUTHON J.R., TURNEY C.S.M., WACKER L., ADOLPHI F., BÜNTGEN U., CAPANO M., FAHRNI S.M., FOGTMANN-SCHULZ A., FRIEDRICH R., KÖHLER P., KUDSK S., MIYAKE F., OLSEN J., REINIG F., SAKAMOTO M., SOOKDEO A., TALAM S. 2020 – The IntCal20 northern hemisphere radiocarbon age calibration curve (0–55 cal kBP). Radiocarbon, 62 (4): 725–757; https://doi.org/10.1017/RDC. 2020.41

RYBAK J.I., BŁĘDZKI L.A. 2010 – Słodkowodne skorupiaki planktonowe: klucz do oznaczania gatunków (in Polish). Wydawnictwa Uniwersytetu Warszawskiego.

RYCHEL J., SOKOŁOWSKI R.J., SIERADZ D., HRYNOWIECKA A., MIROSŁAW-GRABOWSKA J., SIENKIEWICZ E., NISKA M., SZYMANEK M., ZBUCKI Ł., CIOŁKO U., ROGÓŻ-MATYSZCZAK A. 2022 – Late Pleniglacial–Late Glacial climate oscillations detected in the organic lacustrine succession at the Lipowo site, north-eastern Poland. Journal of Quaternary Science, 38 (2): 186–207; https://doi.org/10.1002/jqs.3477

SARMAJA-KORJONEN K. 2003 – Chydoid ephippia as indicators of environmental change biostratigraphical evidence from two lakes in southern Finland. The Holocene, 13 (5): 691–700.

SCHENK F., BENNIKE O., VÄLIRANTA M., AVERY R., BJÖRCK S., WOHLFARTH B. 2020 – Floral evidence for high summer temperatures in southern Scandinavia during 15–11 cal ka BP. Quaternary Science Reviews 233, 106243; https://doi.org/10.1016/j.quascirev.2020.106243

RASMUSSEN S.O., BIGLER M., BLOCKLEY S.P., BLUNIER T., BUCHARDT S.L., CLAUSEN H.B., CVIJANOVIC I., DAHL-JENSEN D., JOHNSEN S.J., FISCHER H., GKINIS V., GUILLEVIC M., HOEK W.Z., LOWE J.J., PEDRO J.B., POPP T., SEIERSTAD I.K., STEFFENSEN J.P., SVENSSON A.M., VALLELONGA P., VINTHER B.M., WALKER M.J.C., WHEATLEY J.J., WINSTRUP M. 2014 – A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the Intimate event stratigraphy, Quaternary Science Reviews, 106: 14–28; https://doi.org/10.1016/j.quascirev.2014.09.007

SZEROCZYŃSKA K. 1985 – Cladocera as ecologic indicator in late Quaternary lacustrine sediments in Northern Poland. Acta Palaeontologica Polonica, 30: 3–69.

SZEROCZYŃSKA K., SARMAJA-KORJONEN K. 2007 – Atlas of subfossil Cladocera from central and northern Europe. Friends of Lower Vistula. Society, Gruczno: 1–84.

SZEROCZYŃSKA K., ZAWISZA E. 2007 – Paleolimnologia–historia rozwoju jezior w Polsce w świetle badań fauny wioślarek (in Polish). Studia Limnologica et Telmatologica, 1 (1): 51–60.

ŠEIRIENĖ V., GASTEVIČIENĖ N., LUOTO T.P., GEDMINIENĖ L., STANČIKAITĖ M. 2021 – The Late glacial and early Holocene climate variability and vegetation dynamics derived from chironomid and pollen records of Lieporiai palaeolake, North Lithuania. Quaternary International 605–606: 55–64; https://doi.org/10.1016/j.quaint.2020.12.017

TOLOTTI M., MILAN M., KSZEROCZYNSKA K. 2016 – Subfossil Cladocera as a powerful tool for paleoecological reconstruction. Advances in Oceanography and Limnology, 7: 125–130.

TÓTH M., HEIRI O., VINCZE I., BRAUN M., SZABÓ Z., MAGYARI E.K. 2022 – Limnological changes and chironomid-inferred summer air temperature from the Late Pleniglacial to the Early Holocene in the East Carpathians. Quaternary Research, 105, 151165; https://doi.org/10.1017/qua.2021.36

WECKWERT P., WYSOTA W., PIOTROWSKI J.A., KRAWIEC A. 2020 – Pleistocene glacial megaflood landform system in NE Poland. [In:] Weckwerth P., Kalińska E., Wysota W., (eds.), Glacial Megaflood, Landform and Sediments in NE Poland. UMK Toruń.

WHITESIDE M.C. 1970 – Danish chydorid Cladocera: modern ecology and core studies. Ecological Monographs, 40: 79–118.

WHITESIDE M.C., SWINDOLL M.R. 1988 – Guidelines and limitations to cladoceran palaeoecological interpretations. Palaeogeography, Palaeoclimatology, Palaeoecology, 62: 405–412.

ZIELIŃSKI T., PISARSKA-JAMROŻY M. 2012 – Which features of deposits should be included in a code and which not? Przegląd Geologiczny 60: 387–397.

ZAWISZA E., SZEROCZYŃSKA K. 2007 – The development history of Wigry Lake as shown by subfossil Cladocera. Geochronometria, 27: 67–74; https://DOI.10.2478/v10003-007-0021-2

The work was received by the editorial office on 17.12.2024
Accepted for printing on 27.01.2025

Etna – the biggest volcano in Europe is still smouldering and producing further portions of lava. Photo by S. Wołkowicz