Acta Geologica Polonica, Vol. 73 (2023), No. 3, pp. 341–354
DOI: 10.24425/agp.2022.143601

Climate and vegetation changes recorded in the post Holsteinian lake deposits at Ossówka (eastern Poland)

KRZYSZTOF BIŃKA[1], MARCIN SZYMANEK[1] and JERZY NITYCHORUK[2,]

[1] *University of Warsaw, Faculty of Geology, Żwirki i Wigury 93, 02-089 Warszawa, Poland; e-mails: k.binka@uw.edu.pl; m.szymanek@uw.edu.pl*
[2] *John Paul II University of Applied Sciences in Biała Podlaska, Sidorska 95/97, 21-500 Biała Podlaska, Poland; e-mail: jerzy.nitychoruk@akademiabialska.pl*

ABSTRACT:

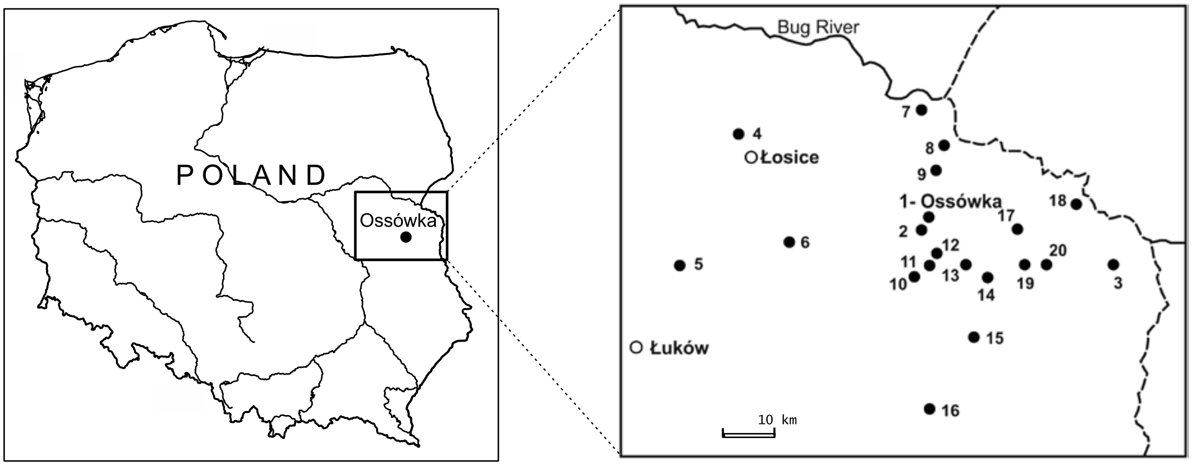
Bińka, K., Szymanek, M. and Nitychoruk, J. 2023. Climate and vegetation changes recorded in the post Holsteinian lake deposits at Ossówka (eastern Poland). *Acta Geologica Polonica*, **73** (3), 341–354. Warszawa.

Due to the long sedimentation period (about 70 000 years) and the unique quality of the lake deposits represented by very long, monotonous layers of lacustrine chalk, the sequence at Ossówka is exceptional. We conducted highly-resolved pollen and isotope analysis of the 27-m-long, upper part of the sequence of the lake sediments covering the final stage of the Holsteinian and the early phases of the Saalian Complex (Marine Isotope Stages (MIS) 11–10). In the pollen profile three main forest interstadials (L PAZ O-3, O-5, O-7) and the intervening steppe – tundra stadials (L PAZ O-2, O-4, O-6, O-8) as well as numerous units of lower rank were identified. Interstadials were characterized mainly by the presence of well-established pine forest. Stadials in turn, represented steppe – tundra vegetation with very pronounced continental influences. Also, three clearly established phases of forest fires starting at the beginning of interstadials and gradually disappearing are interesting feature of the sequence. Fires of that scale are very rarely noted in the palynological spectra. The examined sequence is characterized by the high dynamics of changes in the post interglacial part of the profile. It provides, coupled with clear features of the Holsteinian succession and its duration, a reliable correlation with other terrestrial and marine archives.

Key words: Pollen analysis; Lake deposits; Saalian; Holsteinian.

INTRODUCTION

Among the results of glaciations on land are numerous kettle holes filled with peat, or lacustrine deposits, marking former interglacial lakelands. One of them, dating from the Holsteinian has been identified in eastern Poland and many of its paleolakes have been the subject of palynological studies (Krupiński and Nitychoruk 1991; Krupiński 1995; Bińka and Nitychoruk 1995, 1996; Szymanek *et al.* 2016). Among the examined ones, the most interesting is the long sequence found at Ossówka, near Biała Podlaska (Text-fig. 1), investigated by means of pollen analysis (Krupiński 1995). The lake deposits occupy a large area of about 1.5 km^2. They represent deep water sediments up to 55 m thick starting in the final Elsterian, throughout the Holsteinian Interglacial (Mazovian Interglacial) and ending in the early Saalian. Krupiński (1995) in the Ossówka profile recognized the basic units of the Holsteinian and a following sequence of stadials and interstadials. This latter interval is particularly interesting due to the occurrence of long-lasting sedimentation without stratigraphical hiatuses, the unique nature of deposits, as well as the sequence giving the opportunity of its correlation with equivalents in the marine records. Later studies focused on the preliminary evidence of the forest fires at Ossówka against the back-



Text-fig. 1. Location of the Ossówka site and the sites of the Holsteinian Interglacial and/or the early Saalian Glaciation (1 – Ossówka, 2 – Hrud, 3 – Małaszewicze Małe, 4 – Zakrze, 5 – Maciejowice, 6 – Zasiadki, 7 – Borsuki, 8 – Pawłów Nowy, 9 – Romanów, 10 – Biała Podlaska, 11 – Grabanów, 12 – Wilczyn, 13 – Kaliłów, 14 – Woskrzenice, 15 – Ortel Królewski, 16 – Rossosz, 17 – Lipnica, 20 – Lachówka Mała).

ground of the fire dynamics noted in the palynological sequences (Bińka and Nitychoruk 2013) and the nature of the Younger Holsteinian Oscillation (YHO) registered in the hornbeam zone (Nitychoruk *et al.* 2018). In a similar manner to the Older Holsteinian Oscillation (OHO) this event is a short term and deep rebuilding of the forest communities and is well documented in the Holsteinian pollen and isotope records in Europe (Koutsodendris *et al.* 2010, 2013).

The aim of this paper is to give a detailed study of the paleoenvironmental changes in the post interglacial part of the profile from Ossówka collected in 1996 (Ossówka 1/96), especially by means of pollen analysis with the support of isotope data. This core has proved to be longer than that investigated by Krupiński (1995) offering the prospect of more detailed and complete sedimentary and pollen records.

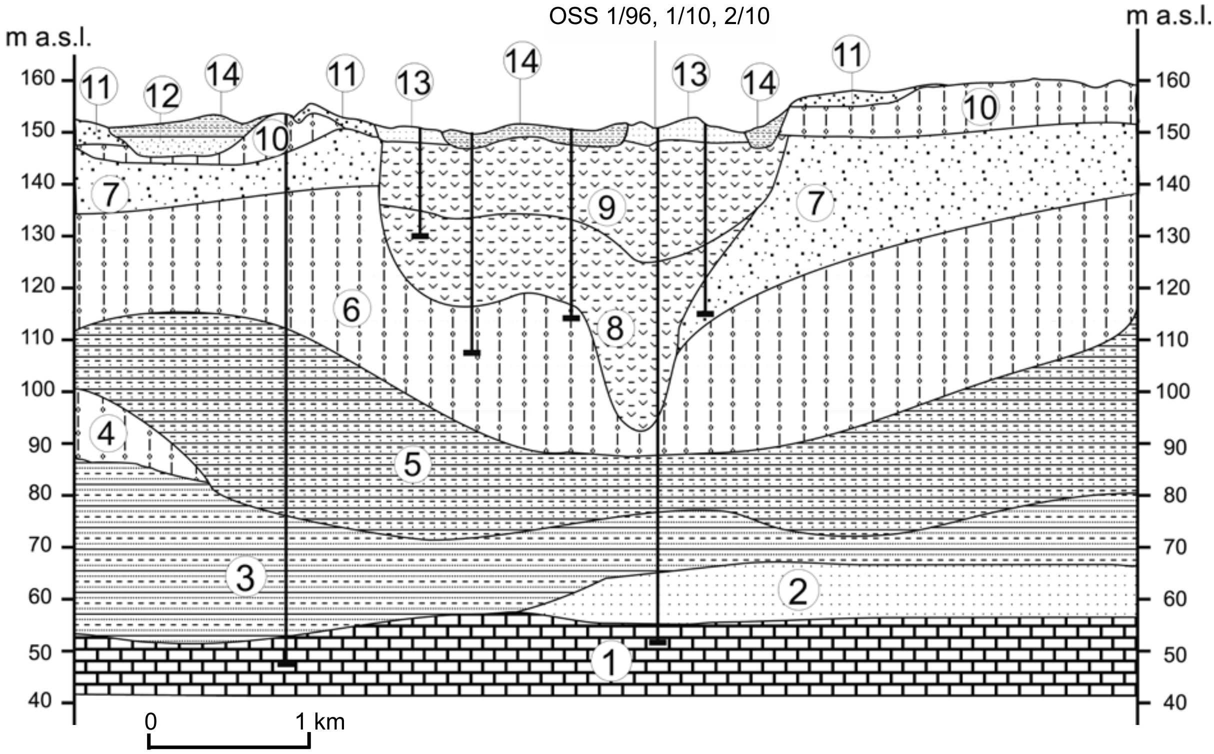
MATERIALS AND METHODS

Drillings at Ossówka were performed in 1996 and 2010 in central part of the fossil lake (Nitychoruk *et al.* 2018) (Text-fig. 2). The cores are characterized by similar thicknesses of deposits (55 m), representing a monotonous sequence of calcareous sediments, partly layered. We decided to sample the first core – Ossówka 1/96. It provides a complete isotope and palynological record for the Ossówka sequence. The investigation based on the drillings from 2010 focused only on the short-term climatic and vegetation changes during the YHO (cf. Nitychoruk *et al.* 2018).

Samples for pollen analysis were collected at 10 cm intervals. They were processed following the standard palynological procedure, including KOH, HF treatment and Erdtman's acetolysis. Depending on the frequency, about 1000 pollen grains were counted in each interstadial sample versus 500 counted in the stadials and 200–300 in the top two-meter-long part of the core. The percentage of pollen types was estimated based on the sum of all counted pollen grains (arboreal and non-arboreal pollen – AP, NAP) excluding aquatics and spores. The proportion of AP and NAP was assessed to trace the general trends in the evolution of the vegetation. Pollen concentrations were calculated using *Lycopodium* tablets added to each sample of the measured volume during laboratory procedures and the total numbers of spores and pollen types in all pollen slides were estimated (Stockmarr 1971). A pollen diagram was produced using Tilia and Tilia Graph software. Local pollen assemblage zones were identified using CONISS cluster analysis.

The chronology of the Holsteinian and the early Saalian was based on the correlation of the Ossówka pollen data with the marine records presented by Bińka and Marks (2018).

Isotope analysis was based on the Ossówka 1/96 core and covered the late Holsteinian Interglacial and the post-interglacial period (Nitychoruk 2000; Nitychoruk *et al.* 2005, 2006). Oxygen and carbon isotope ratios were correlated with the pollen diagram presented in this study and used to determine paleoenvironmental changes in the late-interglacial and the post-interglacial period. Basic isotope samples were taken at every 0.5 m and locally were



Text-fig. 2. Geological cross-section of lake deposits at the Ossówka site (after Nitychoruk *et al.* 2018 – slightly modified). Cretaceous–Maastrichtian: 1 – chalk. Palaeogene: 2 – glauconitic sands. Dorst: 3 – sands with silt and clay. Cromerian Complex (Glacial C): 4 – glacial till. Elsterian Glaciation: 5 – silts, clays and sands; 6 – glacial till; 7 – gravelly sand. Holsteinian Interglacial: 8 – carbonate gyttja and lacustrine chalk. Saalian Glaciation (initial part): 9 – carbonate gyttja and lacustrine chalk; 10 – glacial till; 11 – gravelly sands; 12 – sands with gravels. Saalian Glaciation: 13 – sands, gravels and silts. Holocene: 14 – sands, silts and peaty silts.

condensed to 0.1–0.4 m intervals (Nitychoruk 2000; Nitychoruk *et al*. 2005). The analyses were conducted using the classical McCrea method. The results were presented as δ values relative to the V-PDB standard (Nitychoruk 2000; Nitychoruk *et al*. 2005). The isotope horizons distinguished in this study were based on isotope curves and supported by statistical clustering analyses in the PAST program (Hammer *et al*. 2001).

RESULTS

Pollen analysis

Eight local pollen zones, representing four stadials and three interstadials and a few subzones were distinguished in the examined sequence (Text-figs 3, 4). Pollen is very well preserved throughout the profile. High frequency characterized boreal periods, falling to low values in the treeless phases, especially in the uppermost part of the sequence (Text-fig. 4).

Pollen zones

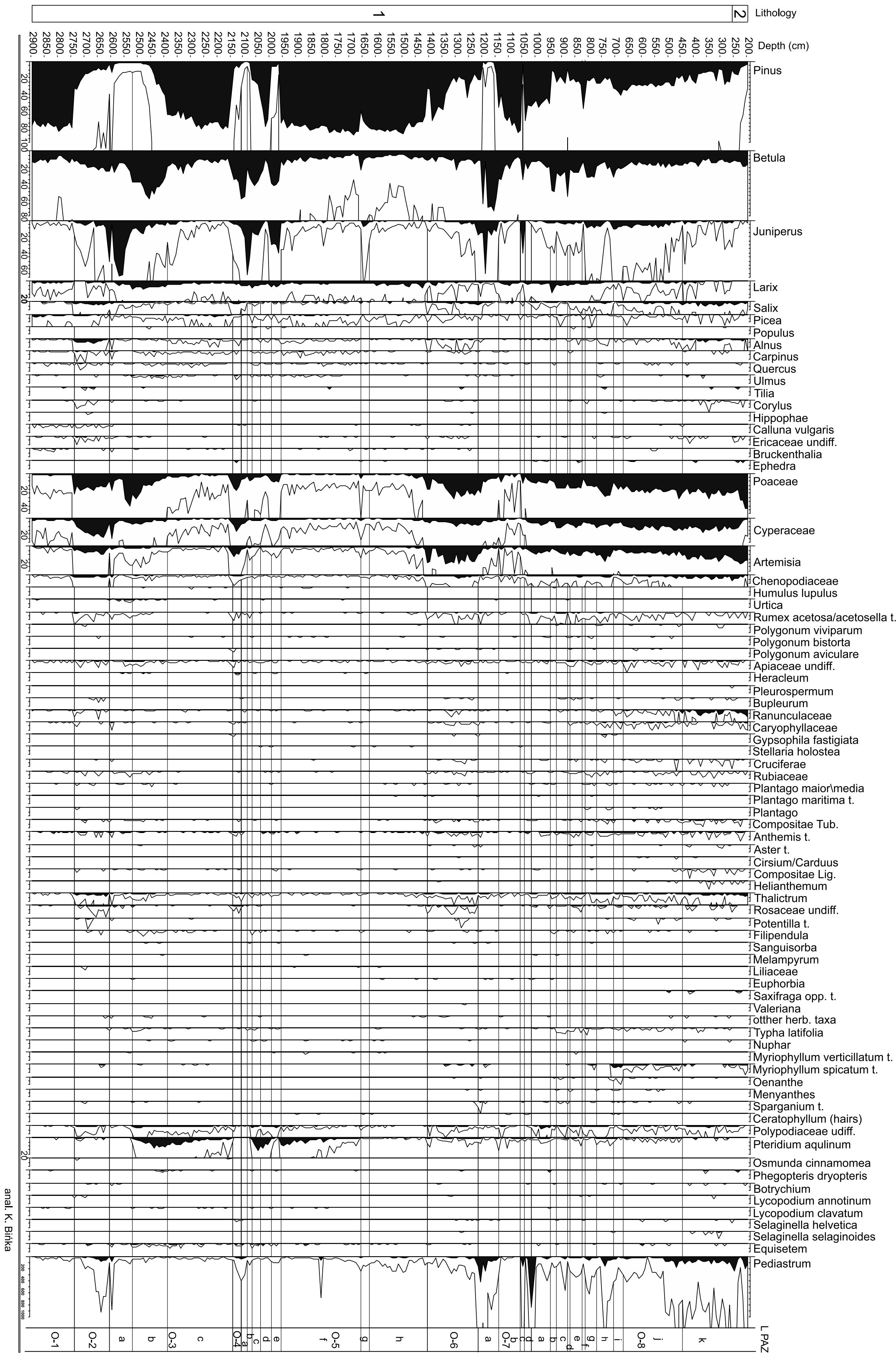
L PAZ O-1 (28.9–27.4 m).

Clear dominance of *Pinus sylvestris* pollen. Percentages of herbs – mostly Poaceae and Cyperaceae – do not differ from that noted in the closed coniferous forests. The transition to the post-interglacial phases is abrupt, but without stratigraphical gap. Terminal interglacial zone dominated by boreal pine forest with small admixture of *Betula*, *Larix* and *Picea*.

Saalian Glaciation (MIS 11b–11a; MIS 10)

L PAZ O-2 (27.3–26.1 m, 392 ka – 389 ka BP). Stadial 1.

Decrease in pollen frequency and the presence of secondary pollen characterize the first Saalian zone. AP – a small proportion of constantly declining *Pinus* pollen with simultaneous inconspicuous increase in *Betula* (including *B. nana*), *Juniperus* and *Salix*. NAP – Poaceae, Cyperaceae and *Artemisia* (PCA) pollen reach a high level. Lower values, however quite sig-



Text-fig. 3. Pollen diagram of the lake deposits at the Ossówka site. Lithological column: 1 – calcareous gyttja, 2 – clayey silt.

nificant, show also Chenopodiaceae, *Thalictrum* and other herbaceous plants rich in taxa.

Plant communities are typical of dry steppe (with rare tundra element) with scattered patches of trees and shrubs – with willow and dwarf birch in moist habitats and with juniper and larch in dry ones.

L PAZ O-3 (26.0–21.5 m, 389 ka – 385 ka BP). Interstadial 1.

a – 26.0–25.1 m. Abrupt expansion of shrub communities marks the beginning of the first Saalian interstadial. Initial subzone with higher pollen frequency, interrupted by short return to stadial conditions of the previous zone (at a depth of 25.9 m) is characterized by significant rise in *Juniperus*, constant increase in *Larix* up to 4% and decrease in NAP.

Plant communities – dry steppe dominated by shrubby vegetation with juniper and patches of larch.

b – 25.2–23.9 m. Next step towards rebuilding of boreal pine forest – the rise of *Betula* pollen, its culmination and gradual replacing by *Pinus*, culmination of *Larix* and continuous decline of *Juniperus*. NAP – high values of Poaceae as well as somewhat higher percentages of Cyperaceae, *Artemisia* and herbs in the first half of the subzone. A major increase in *Pteridium*, spores of which form a high curve.

Plant communities – forest-steppe with grasses in the lower part of the zone, with birch, larch and juniper and finally pine.

c – 23.8–21.5 m. Zone dominated by *Pinus sylvestris*, percentages of which rise towards the top, with the simultaneous decline of *Larix*, *Juniper* and *Betula*. Frequency of NAP low. *Pteridium* shows gradual decrease towards the end of the zone.

Plant communities – constant shift towards closed, scots pine forest. Gradual decrease in bracken marks the decline in wildfires.

L PAZ O-4 (21.4–21.1 m, 385 ka – 382 ka BP), Stadial 2.

Short-lived treeless phase with very low pollen concentration and maximum value of NAP – mostly Poaceae, Cyperaceae, *Artemisia* and other herbaceous plants.

Plant communities – dry steppe with shrubs of willow, juniper and rare patches of larch. Dwarf birch is also present in this zone. In the whole zone very numerous, unidentified, rounded cysts are present.

L PAZ O-5 (21.0–14.1 m, 382 ka – 375 ka BP), Interstadial 2.

a – 21.0–20.9 m. Renewed increase in pollen concentration. Culmination of pollen of *Betula* as well as rise in *Juniperus* and *Larix*. Higher NAP is still present – mainly PCA – however with lower values than in the stadial 2.

Plant communities – expansion of forest-steppe with patches of birch, larch and juniper.

b – 20.8–20.7 m. Rapid increase in *Juniperus* with the admixture of *Betula* and *Larix*. NAP significantly lower than in subzone a. Vegetation type – short-lived interval of shrubland with juniper and patches of birch and larch.

c – 20.6–20.4 m. *Betula* and low percentages of *Pinus*, *Juniperus* and *Larix* as well as herbaceous taxa marks renewed expansion of forest-steppe. Sharp increase in *Pteridium*, high percentages of which are indicative of large-scale fires (Bińka and Nitychoruk 2013).

d – 20.3–20.0 m. Rapid increase in *Pinus sylvestris* up to 75% with contemporaneous decrease in *Betula*, *Larix*, *Juniper* and non-arboreal taxa (including gradual decrease in *Pteridium*). Plant communities – scots pine forest with larch.

e – 19.9–19.6 m. Firm increase in *Betula* and *Juniperus* pollen and to a lesser extent *Larix*. Non-arboreal pollen – mostly Poaceae and Cyperaceae also show higher values. Plant communities – forest-steppe with grasslands, shrubs and patches of birch and larch.

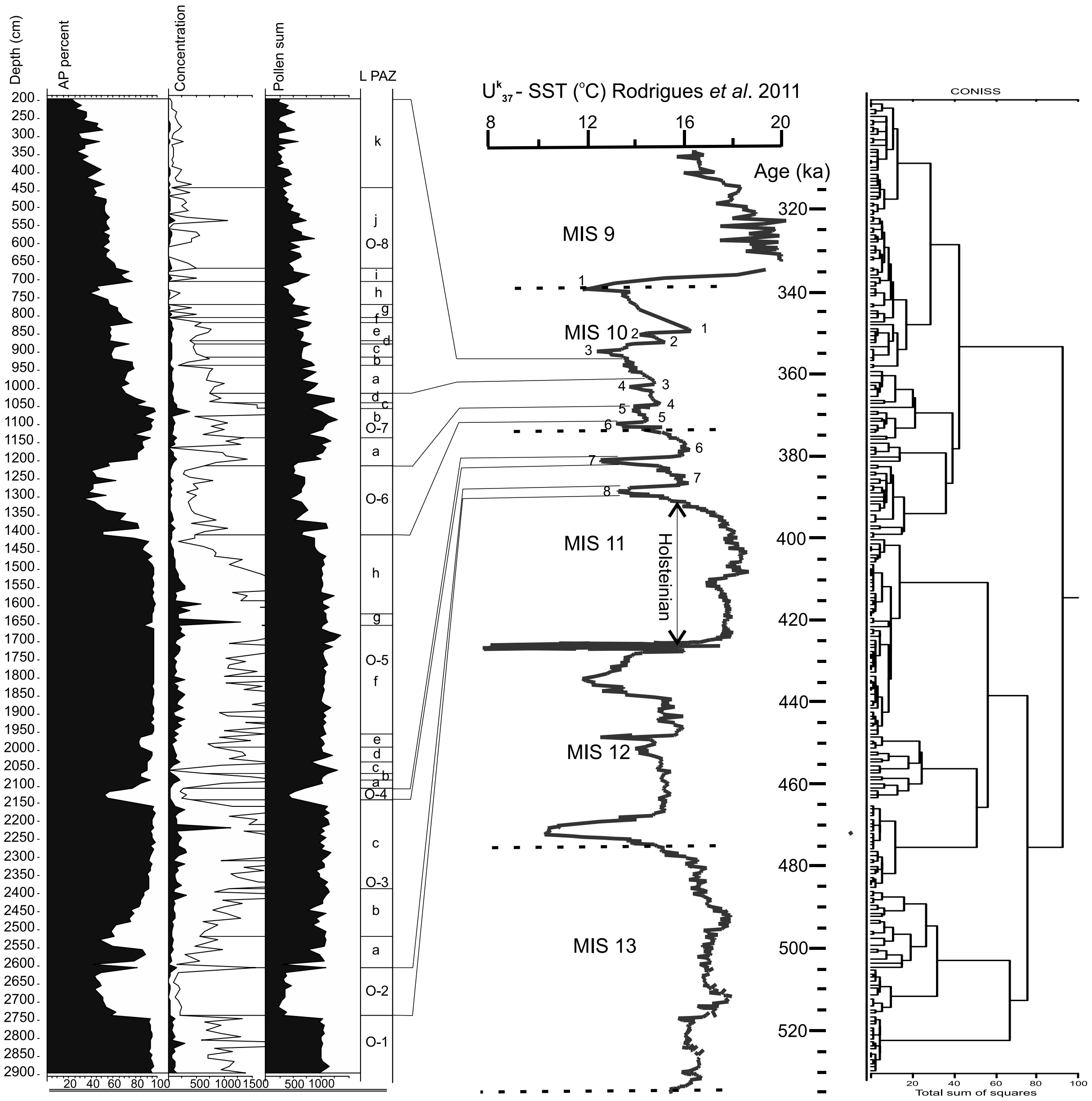
f – 19.5–16.6 m. The subzone is very similar to the O-3 – c and O-5 – d ones. Absolute dominance of *Pinus sylvestris* with simultaneous decline of *Betula*, *Juniperus* and *Larix*. The low values of NAP are typical of closed forest. Plant communities – scots pine forest with small admixture of larch. Gradual decline of natural fires (decrease in bracken).

g – 16.5–16.3 m. The subzone is not homogenous – at a depth of 16.5 m a small increase in *Betula* and NAP is replaced by slight rise in *Juniperus* in the two successive samples. Vegetation – pine forest with post fire succession of birch, juniper and grasses. Short term forest fire, however without expansion of bracken.

h – 16.2–14.1 m. This subzone in its main features closely resembles the f subzone dominated by *Pinus* pollen. The only difference is the higher content of *Larix* and almost total absence of *Pteridium*. However, towards the end of the zone the proportion of PCA as well as of other herbaceous plants, rich in taxa, begins to rise. Plant communities – scots pine forest with larch.

L PAZ O-6 (14.0–12.2 m, 375 ka – 370 ka BP), Stadial 3.

Pollen concentration and AP frequencies low. The last are represented by *Pinus* pollen and partly *Betula* (probably long transported) as well as scarce shrubs (*Betula nana*, small increase in *Juniperus* and *Salix* from the half of the subzone). NAP very high



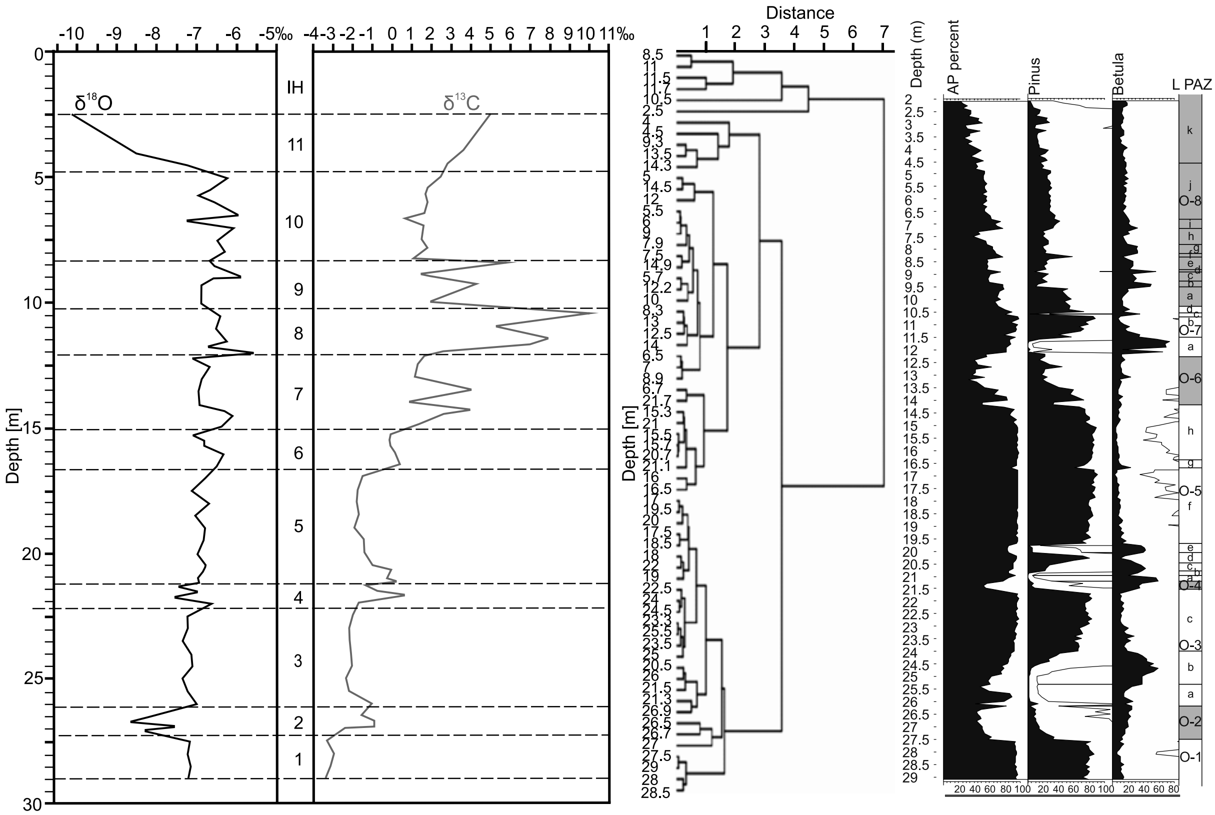
Text-fig. 4. Simplified pollen diagram of the lake deposits at the Ossówka site and corresponding stadials and interstadials in marine deposits according to Rodrigues *et al.* (2011).

– especially abundant are Poaceae and *Artemisia*, with the percentages even higher than in the zone O-2 and O-4 and to a lesser extent Chenopodiaceae, Cyperaceae and numerous herbaceous taxa. The only exception is a recovery phase between 13.8–13.6 m, with a higher pollen concentration and rising *Pinus* pollen for a short while, indicating improvement of climatic conditions. Plant communities – sagebrush steppe.

L PAZ O-7, (12.1–10.2 m, 370 ka – 362 ka BP), Interstadial 3.

a – 12.1–11.4 m. Decrease in NAP and the simultaneous rise in pollen of *Betula* (tree birches) and *Juniperus*. Plant communities – forest-steppe with patches of birches and shrubs with episodic return of more open landscape.

b – 11.3–10.5 m. Rising predominance of *Pinus sylvestris* at the expense of declining *Betula* and



Text-fig. 5. Oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) isotopes in the final part of the Holsteinian Interglacial (L PAZ O-1) and the initial part of the Saalian Glaciation (L PAZ O-2–O-8) at Ossówka 1/96 core (based on Nitychoruk *et al.* 2005) with the fragment of pollen diagram. IH – isotope horizons. Stadials in gray.

non-arboreal pollen. *Larix* more abundant than in previous subzone. Plant communities – scots pine forest. Temporary and small-scale cooling at a depth of 11.25 m.

c – 10.4 m. Dominance of pollen of *Juniperus* and *Betula* (tree birches). NAP present, however at lower levels – mostly Poaceae and *Artemisia*. Plant communities – forest-steppe with patches of birch, shrubs and grasses.

d – 10.3–10.2 m. Return to the conditions from the b subzone. Scots pine forest.

L PAZ O-8 (10.1–1.9 m, 362.5 ka – 358 ka BP), Stadial 4.

a – 10.1–9.4 m. Pollen concentration low. Spectra are dominated by long transported pollen of *Pinus sylvestris* t. and to a lesser extent by *Betula* with admixture of *Juniperus* and *Salix*. Abundant non-arboreal pollen consists of PCA and numerous pollen types of herbaceous taxa. Treeless phase – steppe with rare patches of larch and towards the end of the subzone – juniper.

b – 9.3–9.2 m. Increase in pollen concentration as well as *Betula* and *Larix* frequencies. NAP at lower levels than in the subzone a. Plant communities – forest-steppe ecotone with patches of larch and birch.

c – 9.1–8.8 m. Decrease in pollen concentration. Arboreal pollen (AP) dominated by *Pinus* (*P. cembra* t. found sparingly) and *Betula* (tree birches) – both most probably long transported – and *Larix* and *Juniperus*. NAP abundant – PCA and numerous herbaceous pollen. Plant communities – dry steppe.

d – 8.7 m. Rise in pollen concentration. AP dominated by *Betula* (tree birches). Higher NAP present, but it is at lower values than in the subzone c. Plant communities – steppe with patches of tree birches and larch as well as juniper.

e – 8.6–8.2 m. Lower pollen concentration with predominance of PCA and herbaceous taxa. AP is represented only by *Larix* and *Juniperus* pollen. Plant communities – dry steppe with rare patches of juniper and larch.

f – 8.1 m. Increase in *Pinus sylvestris* pollen, slightly higher pollen concentration and somewhat lower NAP characterizes the subzone. Plant community – dry sagebrush steppe. Forest-steppe zone with pine moved closer to investigated site.

g – 8.0–7.7 m. Pollen concentration like in previous zone. AP formed by higher percentages of *Betula* and *Juniperus*. Small increase in NAP. Sagebrush steppe with patches of birch and juniper.

h – 7.6–7.1 m. Dominance of herbaceous plants – significant increase in NAP (PCA and numerous pollen types). Treeless phase – steppe with *B. nana* on damper places.

i – 7.0–6.7 m. Rise in pollen frequency as well as small increase in AP dominated by *Pinus* (*P. cembra* t. present), *Betula* and *Juniperus* and decrease in NAP – first of all PCA. Mosaic of sagebrush steppe with patches of birch and juniper.

j – 6.6 m – 4.5 m. Pollen concentration and AP level low. AP consists of *Pinus sylvestris* t., *P. cembra* t., *Betula* and *Juniperus* and it declines at the end of the subzone. Rise in PCA marks dominance of steppe vegetation with patches of juniper.

In the sequence, since the subzone b of L PAZ O-8 open water and lake shore plants such as *Menyanthes trifoliata*, *Myriophyllum spicatum*, *M. verticillatum*, *Sparganium* t., and *Typha latifolia* occurred regularly. This might indicate that the marginal areas of the lake grew progressively shallower.

k – 4.4–1.9 m. This carbonate free subzone is characterized by completely treeless vegetation and low pollen concentration. Arboreal pollen (AP) frequencies as well as production of organic matter are very low. Sagebrush steppe with *Salix* dominated by PCA and other herbaceous taxa.

Stable isotope analysis

Altogether eleven isotope horizons IH were distinguished. IH 1 (29–27.5 m) correlates with the late Holsteinian Interglacial (L PAZ O-1). It is characterized by rather uniform $\delta^{18}O$ values of about -7.2‰ and $\delta^{13}C$ values in the range of -3.4 – -3‰ (Text-fig. 5). A distinct decrease in $\delta^{18}O$ to minimum value of -8.6‰ is noted in the beginning of Saalian Glaciation (IH 2; 27–26.5 m; L PAZ O-2). By contrast, $\delta^{13}C$ increases up to -0.9‰ (Text-fig. 5).

In IH 3 (26–22.5 m) a distinct rise in $\delta^{18}O$ (up to -7.1‰) is noted, whereas carbon isotope ratios decrease significantly to -2.4‰. Higher in this level both isotope curves show rather minor fluctuations. IH 3 corresponds with the lower and the middle part of the L PAZ O-3 (Interstadial 1) (Text-fig. 5).

IH 4 (22–21.3 m) is characterised by several oscillations in $\delta^{18}O$ (from -7.5 to -6.6‰) and significant increase in $\delta^{13}C$ (reaching 0.6‰). It covers both the upper part of L PAZ O-3 (Interstadial 1) and the beginning of L PAZ O-4 (Stadial 2) marked by a drop in oxygen and carbon isotope ratios (Text-fig. 5).

In IH 5 (21.1–17 m) $\delta^{18}O$ fluctuates slightly in the range of -7.1 – -6.7‰. The $\delta^{13}C$ values increase significantly to 0.15‰ in the beginning of this horizon and then gradually decrease to -1.9‰ (Text-fig. 5). IH 6 (16.5–15.3 m) is characterized by almost synchronous increase and then decrease of isotope ratios. These changes followed by a rapid increase in $\delta^{18}O$ and $\delta^{13}C$ in the beginning of IH 7 (14.9–12 m) correspond with L PAZ O-5 (Interstadial 2), whereas the following samples in IH 7 are correlated with L PAZ O-6 (Stadial 3). The last sample in IH 7 with the rise in oxygen and carbon isotope ratios (up to -5.6‰ and up to 2.6‰, respectively) may correspond with L PAZ O-7 (Interstadial 3), which is fully covered by IH 8 (11.7–10.5 m). In this level two distinct maxima of $\delta^{13}C$ occur (7.8 and 10‰). The $\delta^{18}O$ values show minor oscillations.

High variability of carbon isotope ratios (the range of 1.5–5.8‰) continues in IH 9 (10–8.5 m). In IH 10 (8.3–5 m) they decrease to 0.7‰. Oxygen isotope ratios fluctuate between -7.2 and -5.9‰ (Text-fig. 5). IH 11 in the upper part of the sequence (4–2.5 m) is characterized by a distinct drop in oxygen and an increase in carbon isotope ratios. Changes noted in IH 9-11 represent L PAZ O-8 (Stadial 4) distinguished by the pollen spectra (Text-fig. 5).

DISCUSSION

There is no doubt that the analyzed sequence represents the final stage of the Holsteinian and the series of following stadials and interstadials (Bińka and Marks 2018). Four clear post interglacial cold oscillations (L PAZ O-2, O-4, O-6 and O-8) and three interstadial ones as well as numerous minor changes of lower rank are noted at Ossówka. A similar pattern of the three interstadials can be traced in the marine isotope records (Voelker *et al*. 2010; Rodrigues *et al*. 2011; Candy *et al*. 2014) and also in palynological sequences noted in marine deposits (e.g. near the west coast of Portugal – Desprat *et al*. 2005). However, the alkenone-based temperature reconstructions of marine deposits, which show even subtle oscillations, have proved to be of great value (Voelker *et al*. 2010; Rodrigues *et al*. 2011). Even in the case of pollen sequences as remote as those from Central Europe, the precise correlation of interglacials together with accompanying stadials and interstadials has become possible (Bińka and Marks 2018), e.g.

in the Holsteinian – the early Saalian and also in the bioptimal Ferdinandovian Interglacial. In the case of the first one, at Ossówka, the alkenone curve shows exactly the same changes as those observed at that time in the Podlasie region with 3 interstadials as well as intra interglacial cooling (OHO) (Text-figs 3, 4). A similar pattern of 3 interstadials is visible, in the corresponding period as distant as the EPICA DOME C site, in the sequences of deuterium and CH_4 (EPICA 2004; Jouzel *et al*. 2007). Alkenone-based correlation of terrestrial and marine sequences has also allowed the determination of the duration of the post interglacial deposits registered at Ossówka. They are estimated at about 37 000 years and the length of the whole sequence at 70 000 respectively (Bińka and Marks 2018).

In Europe, continental records of the early Saalian are rare and usually there are breaks in sedimentation. In the best of them – the Praclaux sequence – only three cold periods of relatively similar duration to these at Ossówka are registered – two short ones (Chacomac, Coucouron) and a long interval (Bargette) (Reille *at al*. 2000). Other profiles, e.g. at Schöningen in Germany (Urban *et al*. 1991) also noted the presence of three interstadials however poorly developed. In southern Europe numerous interstadials are registered in the early Saalian sequences in Lake Ohrid (Kousis *et al*. 2018) and at Tenaghi Philippon (Ardenghi *et al.* 2019).

Both pollen and isotope records indicate paleoenvironmental changes in the late interglacial and post-interglacial period at Ossówka. Pollen zones and isotope horizons appear quite congruent, especially in the late interglacial, the early Saalian and interstadial 3, where IH strictly corresponds with L PAZ (Text-fig. 5). The higher number of IH within separate stadials and interstadials presumably results from changing conditions, which are not reflected in the pollen spectra. It may result from the slower reaction of the plant cover to climatic changes (cf. Nitychoruk 2000; Nitychoruk *et al*. 2005).

In general a trend toward more negative $\delta^{18}O$ values indicates a cooling phase, whereas a trend towards more positive ones a warming phase. The drop in the oxygen isotope curve during IH 2, 4 and 7 (L PAZ O-2, O-4, O-6; Stadials 1, 2 and 3) corresponds with a distinct decrease in *Pinus* pollen and expansion of the steppe-tundra communities. Positive excursions in $\delta^{18}O$ values (IH 3, 5, 6 and 8) co-occur with increased frequency of tree pollen and the development of forest-steppe and scots pine forest (L PAZ O-3, O-5, O-7; Interstadials 1, 2 and 3) (Text-fig. 5).

Based on the pollen data from eastern Poland the cooling phases were characterized by the stronger influence of continental climate with warmer summers and cooler winters. The precipitation and consequently the water level of the lakes were lower at that time (Nitychoruk 2000; Nitychoruk *et al*. 2005).

The $\delta^{13}C$ curve shows a reverse trend in comparison to that of the $\delta^{18}O$ curve. High $\delta^{13}C$ values are probably associated with reduced vegetation and the lake shallowing, especially well expressed in the upper part of the sequence (Nitychoruk 2000; Nitychoruk *et al*. 2005).

In the IH 11 very low $\delta^{18}O$ and high $\delta^{13}C$ values co-occur, being connected with distinct cooling and lake shallowing (Text-fig. 5). These reflect the most severe climatic conditions during the glacial cooling phase and the ice sheet advance (Nitychoruk 2000; Nitychoruk *et al*. 2005) which induced both sedimentation and floristic changes. In the lake sedimentation changed from calcareous gyttja to clayey silts whereas the landscape was dominated by sagebrush steppe.

The tree/shrub genera occurring at Ossówka

The main feature of the above succession is a series of vegetation shifts from boreal forests to treeless landscapes, often with transitional phases presented in more detail. A modern equivalent of this stadial – interstadial flora can be found in northern Eurasia in the boreal zone or in the tundra as well as in mountainous areas of southern Siberia, where different types of boreal forest, steppe/tundra vegetation and their ecotones occur (Chytrý *et al*. 2008). The last area seems to be a better analogue of inferred fossil communities, not only for its latitudinal position (similar to that at Ossówka) and some climatic parameters – higher summer temperatures and longer growing season than in northern Eurasia. Valuable to our consideration is that in southern Siberia several studies of surface pollen-vegetation relationship for the main types of communities with identified climatic data have been performed by Pelánková *et al*. (2008) and Pelánková and Chytrý (2009). In some cases, they have shown a discrepancy between pollen rain and actual vegetation, both in the local and the regional scale.

Tree birch (*Betula*), scots pine (*Pinus sylvestris* type), larch (*Larix*) juniper (*Juniperus*) and PCA are the key genera of tree/shrub/herbaceous plants characteristic of this post interglacial succession in the investigated area, where repeatedly continuous boreal forest gives way to forest-steppe and finally tundra/steppe vegetation. At Ossówka, *Betula pendula* is probably responsible for the subsequent maxima of birch pollen. In Poland, in the Pleistocene sequences, a rapid increase in birch and its expansion into treeless areas marks the beginning of the interglacial or interstadial zone due to the profound amelioration of climate e.g. at the beginning of Allerød and Preboreal (Ralska-Jasiewiczowa *et al.* 2004 and many others), and in the initial zone of the Eemian, in the Vistulian and the Holsteinian e.g. at nearby sites (Granoszewski 2003; Bińka and Nitychoruk 1996, 2003; Szymanek *et al.* 2016). Macroremains of *Betula pendula* or/and *Betula pubescens* were also found when semi open landscapes prevailed (Wasylikowa 1964; Mamakowa 1989). The last pattern suggests some similarity to northern Fennoscandia, where *B. pubescens* ssp. *tortuosa* forms a narrow belt of treeline and it rarely occurs in the tundra. In turn, in northeastern Siberia *Betula pendula* occurs near the treeline as an admixture of *Larix*. However under more continental climates e.g. in southern Siberia, *Betula pendula* is noted e.g. in pine-birch forests in the post fire succession or it forms individual patches in the steppe. At Ossówka, we can observe birch in such post fire or patchy communities.

Pinus sylvestris – the second dominant tree – formed at Ossówka long-term pure stands in warm interstadials. A close analogue for this community in southern Siberia is dry pine forest with admixture of *Larix* and *B. pendula* (climate parameters -19ºC to -29ºC and 14ºC to 16ºC, precipitation 500–800 mm, Chytry *et al.* 2008). In turn, the summer temperatures and precipitation for the scots pine forest of northern Finland are lower than the above (present pine isoline +12.2ºC, precipitation 400 mm – Kultti *et al.* 2006), whereas winter temperatures at this line are higher – -14 ºC to -16 ºC. On the pollen diagram almost all percentages of the *Pinus* curve represents *Pinus sylvestris*.

Juniperus – The pollen of this light-demanding shrub shows repeated pronounced peaks marking at Ossówka expansion of shrub communities. Sometimes they formed almost pure stands (L PAZ O-3a) or patches in the steppe. More often juniper occurred with birch in open forest representing the first post-stadial zone (L PAZ O-5a–c, O-7a). Usually this massive expansion preceded the appearance of more closed forest. In this area, a similar pattern in the Vistulian sequence is noted at the nearby site at Czaple (Bińka and Nitychoruk 2011). Fires clearly restricted this occurrence in the investigated area.

Larix – (surely *L. decidua* s.l.) Pollen of larch at Ossówka is noted in all phases, with higher percentages (to 10%) in birch and/or juniper zones (L PAZ O-3a, b, O-5a–c, O-8b–d) or with pine (L PAZ O-5h, O-7b, O-8a, f). This tree in north-eastern Russia forms the tree line zone with the tundra.

In turn, in southern Siberia, larch forms nearly pure stands (“larch dry forest’’) occurring within a temperature range between -29ºC to -36ºC and from +11ºC to +16ºC and with precipitation from 230 mm to 450 mm (Pelánková and Chytrý 2009) or it is noted as an admixture of birch/pine forest or as patches in steppe vegetation. Larch is a drought-resistant plant and it is characterized by high values of the continentality index with very low winter temperatures. Unfortunately, the correspondence between the level of its surface pollen spectra and its abundance in diverse communities is rather poor (op. cit.) and does not reflect its role in the local flora. Also the occurrence of even abundant macroremains of *Larix* does not translate into an increase in its pollen in deposits, as we can see e.g. in the Vistulian sequences in this area (Granoszewski 2003; Kalińska-Nartiša *et al.* 2016). Hence the interpretation of larch maxima can lead to serious errors. At Ossówka the temperatures and precipitation for zones with higher representation of larch were probably somewhat higher than those for dry larch forest.

Picea – pollen of spruce is noted in small quantity – more often in the lower part of the sequence. In Siberia *Picea* forms taiga forest. However in the so called subtaiga the occurrence of spruce is limited only to areas near rivers (Nazimova *et al.* 2009). In southern Siberia low percentages of spruce pollen are noted in pollen rain throughout the region, however without its presence in the local flora (Pelánková and Chytrý 2009).

Pinus cembra s.l. – pollen is poorly represented. Only in pollen zone O-8 (subzones g, i, j) it is noted more abundantly apart from scots pine, however by a decidedly low AP. According to Pelánková *et al.* (2008) and Pelánková and Chytrý (2009) because of over representation of its pollen, only more than 60% of AP proves the presence of this tree in the local vegetation. It is believed that *P. cembra* t. is a tree adapted to low summer and winter temperatures and somewhat higher precipitation.

The above trees form four main plant communities (with rare tundra elements) in the analyzed sequence:

- dry steppe with or without scattered patches of trees and shrubs.
- dry steppe with higher admixture of shrubby vegetation with juniper and patches of larch.
- forest-steppe with grasslands, juniper shrubs and patches of birch and larch with or without bracken
- scots pine forest with small admixture of larch.

At Ossówka, the fresh moraine landscape, with numerous depressions filled by interglacial basins, had a great influence on the vegetation cover. In the early Saalian most of the lakes disappeared. However they might constitute potential refugial areas, providing access to moisture for trees. This promoted, even in dry periods, a mosaic of habitats and plant communities.

Similarly as in southern Siberia, the level of precipitation or more strikingly the moisture availability was the main climatic factor influencing vegetation at Ossówka. Stadials were dominated by steppe vegetation and forest-steppe with patches of larch marking periods with lower precipitation whereas the pine forest of the interstadials needed a more humid climate.

A good equivalent of the steppe and forest-steppe communities expanding in the subsequent phases at Ossówka can be found in Kazakhstan. Kazakh Steppe, stretching attitudinally east of Pontic one, with annual precipitation 200–400 mm (average 327 mm) and July temperatures ranging from +20ºC to +26ºC and from -12ºC to -19ºC in January respectively, is dominated by grasses and mugworts. North of this ecotone extends the belt of forest-steppe. It receives about 330 mm/year and the average temperatures are +19.7ºC in July and -17.5ºC in January (Karamysheva and Rachkovskaya 1973; Erdős *et al.* 2017; Rachkovskaya and Bragina, 2012).

It is difficult to estimate the climatic parameters of the interstadial pine forests. Their characteristics include a low level of herbaceous plants. Hence, the dry pine forests of western Siberia with open tree layer (Chytrý *et al.* 2008) are not a good modern analogue. Similar communities with pine in northern Finland occupy the regions having slightly oceanic to continental features of climate with July and January temperatures from more than +12.2ºC and from -11ºC to -12.5ºC and the annual precipitation about 400–500 mm (Kultti *et al.* 2006).

Fire evidence in the Ossówka sequence

At Ossówka, fires are an important factor influencing boreal vegetation. They may be inferred from the more abundant occurrence of the excellent indicator of fire regimes – spores of *Pteridium*. Fires may be induced by humans (the Holocene) but often appear naturally in the conifer interglacial phases (Bińka and Nitychoruk 2013). In Europe, as well as in Siberia, *Pteridium* is chiefly characteristic of semi-open forest landscape or of open ones, however with sufficient moisture (Ershova 2010).

Because spores of bracken need ash for germination, its generative phase in northern Europe (e.g. in Finland and adjacent areas of Russia) is limited by wet litter. This makes wildfire events rarer in this region, even during extremely dry summers (Oinonen 1967; Yaroshenko *et al.* 2001; Larjavaara *et al.* 2005). Hence, the potential analogue of the natural fires noted in Ossówka, also by some similarity of communities, we can seek e.g. in southern Siberia.

The magnitude of the suggested fires at Ossówka is of an exceptional nature. In the sequence, we can see three clear periods of substantial culmination of *Pteridium* after dominance of forest-steppe (or steppe with patches of trees) with larch, juniper and grasses (L PAZ O-3b and O-5c) as well as birch in the third cycle (L PAZ O-5f). The highest bracken content is observed when forest-steppe with birch, larch and declining juniper as well as pine dominates in the third cycle. It is not excluded that fires already started earlier, in each of the preceding phases, as is shown by the increase of larch percentages since that time. However *Pteridium* was probably not yet present because of insufficient moisture availability. *Larix* and to a lesser extent *Pinus sylvestris* are considered to be more fire resistant. In turn, as is apparent from observation of forest-steppe in southern Europe – juniper is not able to regenerate after fire (Ónodi *et al.* 2008). Thus, in these initial phases juniper, grasses and dry larch litter and finally pine were affected by fires. Its increase causes expansion of birch as well as bracken. Modern birch-pine forests in Siberia are considered as short term post fire communities, replaced by more fire-tolerant ones dominated by scots pine (Nazimova *et al.* 2009). *Betula pendula*, as the effects of fires of pine-larch forests in southern Siberia demonstrate, is present even 120 years after the initial invasion and then after 200–350 years of succession it is removed by pine and larch with the decline of fire events (Nazimova *et al.* 2009). At Ossówka, when fires declined, pine forests with their more closed canopy restricted the occurrence of *Pteridium* to the low level typical for areas with low forest fire events.

Why do fires become less frequent in the closed pine forest? It is interesting that e.g. in the Alaska region, in the narrow ecotone of forests and treeless areas with continental signature, fires are most frequent (Dissing and Verbyla 2003). At Ossówka, they probably declined, because the transitional zone moved away as a result of amelioration of climatic conditions.

Aquatic vegetation

In the investigated post interglacial interval, until the beginning of L PAZ O-8j, a lacustrine chalk without visible macrofossils accumulated. Only in the final subzone (L PAZ O-8k) did the content of mud and silt increase substantially. All these demonstrate that the lake was deepwater and probably with a rather narrow belt of marginal flora. For this reason local pollen flora is poorly represented in the profile. Pollen of water species [*Typha latifolia*, *Nuphar*, *Sparganium* t., *Ceratophyllum* (thorns), *Myriophyllum*, and *Menyanthes*] is noted rarely and these species are rather limited to warmer intervals. Therefore, it is hard to draw precise conclusions about any oscillation in the water level based on the pollen of these plants. The only exceptions are higher percentages of *Myriopyllum* (at a depth of 6.8 m) and *Batrachium* t. (3.0 and 3.5 m), however in the zone of low pollen concentration.

The curve of *Pediastrum* (mostly *P. boryanum* and *P. kawraiskyi*) in turn, because of the depth of the lake and climatic conditions is also low. Slightly higher percentages are noted in the stadials (the second half of L PAZ O-2, the end of L PAZ O-4, the start of L PAZ O-8) as well as in the somewhat warmer the juniper zones for example (L PAZ O-5a, O-7a and O-7c). It is not excluded that in these periods lowering of the water table and faster heating of surface water occurred. In part this is also purely a statistical effect – e.g. low concentration and at the same time higher percentages of microfossils. Among the plants mentioned above only the broadleaf cattail points to the temperate zone and MTWA not lower than 14°C (Iversen 1973; Ellenberg *et al*. 1991).

GENERAL CONCLUSIONS

1. The upper part of the profile from Ossówka analyzed by means of pollen analysis with the support of oxygen and carbon isotopes is the most complete picture of paleoenvironmental changes registered among European sequences.

The character of sedimentation – the long core of lacustrine chalk without stratigraphical gaps – was of crucial importance. A very detailed image of the changes recorded in the sequence reveals a series of stadials and interstadials as well as numerous oscillations of lower rank extending over the end of the Holsteinian and the early Saalian.

2. During the three main interstadials (L PAZ O-3, O-5 and O-7) well-established pine forest prevailed in the study area. During the stadials (L PAZ O-2, O-4, O-6 and O-8) a steppe-tundra vegetation with the very pronounced continental influences occurred.

3. In general, the cooling phases are indicated by more negative δ^{18}O values, whereas interstadials are recorded by more positive δ^{18}O values. An increase in δ^{13}C values is associated with the lake shallowing.

4. In the investigated sequence we noted three long-term fire cycles of a scale only exceptionally found in palynological spectra. In each of the cycles they gradually disappeared with the declining of the strong influence of continental climate.

5. The very high variability of the vegetational pattern in the post interglacial part of the profile enables the firm correlation of the Ossówka sequence with other terrestrial and marine records of that age.

Acknowledgements

We thank Dr A. Koutsodendris and two anonymous reviewers for their careful reading of our manuscript and very helpful comments and suggestions.

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Manuscript submitted: 22nd November 2022
Revised version accepted: 21st March 2023