



Holocene history of the lake and forest island ecosystem at and around Lake Seliger, Valdai Hills (East European Plain, Russia)

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Abstract

Here, we present a palaeoecological study from the Valdai Hills to examine the Holocene dynamics of forest and lake ecosystems as apparent from the isolated Lake Chernoye, which developed on an island within the greater Lake Seliger middle of the East European Plain, Russia. Palaeobotanical (plant macrofossils and pollen), geochemical and quartz grains analyses, complemented with radiocarbon dating, were carried out on a 370-cm-long sediment core. Our study involves a period between ca. 11,000 and 2100 cal. yr BP, with four main results: (1) The development of Lake Chernoye began in ca. 11,000 cal. yr BP, after the melting of buried dead-ice blocks intensified by the Early Holocene warming. As pioneer plants, *Chara* sp., *Isöetes* and *C. demersum*, appeared in the water with a high Ca and Mg content. High values of *Pinus*, *Artemisia*, *Betula nana* and Chenopodiaceae pollen may indicate the remains of cold flora that have occurred in the Younger Drays in this region. (2) Between 8000 and 6500 cal. yr BP, water level decreased as apparent from a sediment hiatus. This may be connected with the Holocene thermal maximum and final melting of the buried dead-ice block. Lower water level at that time is documented by the spreading of *Najas marina*, *N. flexilis* and *Potamogeton pusillus*, which are all submerged plants growing in eutrophic shallow water. Significant changes in the forest ecosystem also took place in this time frame: an increase of *Quercus*, *Corylus* and *Alnus* was accompanied by a decrease of *Pinus*. (3) A decrease in deciduous tree pollen (*Ulmus*, *Quercus*, *Tilia*) and an increase in coniferous tree pollen (*Picea* and *Pinus*) at ca. 4200 cal. yr BP and ca. 2700 cal. yr BP are associated with the climate cooling documented by multiproxy records in many sites in Europe. (4) Location of the lake on the isolated island did not lead to different vegetation pattern development, since this latter is similar to the other sites in the East European Plain.

Keywords Lake sediments · Valdai Hills · Plant macrofossils · Pollen · Plant succession · Palaeoecology · Macrophyte · Climate change · Vegetation dynamics · Grain microtexture

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Introduction

A complex post-glacial history in Central Russia is recorded by a combination of periods that were strongly influenced by changing climatic conditions. At first, stagnant ice and permafrost were widespread in North-western and Central Russia during the Late Glacial and the Early Holocene periods. Later, warmer air temperatures triggered permafrost degradation, resulting in sub-surface drainage of the lakes, recorded as asynchronous sedimentary hiatuses in its sediments (Wohlfarth et al. 2007). During the Holocene, the northern part of Central Europe (above 47°N) experienced a significantly slower temperature increase in comparison to its southern counterpart (below 50°N) (Feurdean et al. 2014). The Early and Middle Holocene was relatively cool and dry, followed by warming during the Holocene thermal optimum. This latter period is marked in the Central European Russia (54–58°N) between ca. 8600 and 6900 cal. yr BP. Human impact occurred later and is registered as two events at ca. 4200–3700 and ca. 1400–1000 cal. yr BP as a result of forest clearance at that time (Tarasov et al. 2019).

In general, key forest-forming trees such as birch, pine, and spruce migrated from Southeast Russia to the west, and later spread to the northeast and northwest, paralleling the direction of ice retreat, with *B. pubescens* immigrating first, followed by *P. sylvestris* and *Picea abies*. The first *P. abies* and *B. pubescens* macrofossils around Lake Terebenskoye in the Valdai Hills appeared at ca. 11,200 cal. yr BP (Wohlfarth et al. 2007). Pollen data from Lake Terebenskoye suggests an occurrence of *Picea* at 11,200–11,820 cal. yr BP (T. Sapelko, unpublished data). Mixed broad-leaved coniferous forests were widespread in the Rostov-Jaroslavl' area between 8200 and 6100 cal. yr BP and developed into dense, species-rich forests between 6100 and 2500 cal. yr BP, thus marking the warmest interval (Wohlfarth et al. 2006). Around Lake Terebenskoye in the Valdai Hills (T. Sapelko, unpublished data) and in the Upper Volga region (Borisova 2019), the first broad-leaved trees appeared around 10,300–10,670 cal. yr BP.

Former geomorphological studies revealed that the relief of Central Russia was formed during the Weichselian/Valdian and the Saale/Moscow Glacial periods, mainly during their degradation and under neotectonic conditions that both formed a variety of landscape types (Markov 1977; Velichko et al. 1997). Two of them are especially interesting and refer to the vast and low-located East European Plain and the prominent Valdai Hills. The Hills extend to nearly 600 km in length, have a maximum elevation of 346 m a.s.l., and have a north-east–northwest extension (Astakhov et al. 2016), and thus

preserves an important palaeogeographical record for the region. Affected by several older glaciations and the last glaciation, the Hills are considered a well-preserved ice marginal belt of the Scandinavian ice sheet (Rinterknecht et al. 2018), with multiple fronts (Gorlach et al. 2017; Kalm 2012). Numerous chronologies from sediments north of the Valdai Hills were obtained and established between 17,000 yr and 18,000 yr BP (i.e. Mangerud et al. 2008). The latest cosmogenic surface exposure dating positioned the timing of the last local glacial limit at $20,100 \pm 400$ yr BP (Rinterknecht et al. 2018). At this time, several proglacial lakes were formed along the ice margin (Gorlach et al. 2017). After this, deglaciation took place no earlier than 19,100 cal. yr BP and by 13,300 cal. yr BP (Lasberg and Kalm 2013), and further resulted in lake drainage (Rinterknecht et al. 2018). Lake Seliger is traditionally considered a relict lake (Kvasov 1975) that remained after degradation of a huge proglacial lake, where sand, mud and gyttja alternate (Konstantinov et al. 2018). This latter combination of sediments is a response of the aquatic and terrestrial ecosystems to the Holocene climate fluctuations.

Here, we present a palaeoecological study from the Valdai Hills to examine the Holocene (a time span between 11,700 and 2100 cal. yr BP) dynamics of lake and forest ecosystems developed on the island of Lake Seliger. This is the first multiproxy Holocene data on the lake deposits in this region. The Holocene palaeoenvironmental development of the East European Plain in Northern Eurasia has been intensively studied in Russia since the 1950s, but mostly published in Russian and without any reliable chronology (Neustadt 1957, Neustadt et al. 1965; Sukachev 1968; Khotinsky 1977). Late post-glacial deposits from various archives were studied, but until now, mostly peat deposits have been used for reconstruction of climate and vegetation changes (Aleshinskaya et al. 1992; Tarasov et al. 1996, 2019; Kremenetski et al. 2000; Davydova et al. 2001; Gunova et al. 2001; Wohlfarth et al. 2006, 2007; Borisova 2019). However, in recent years, new studies re-examining old sites have begun to appear in publications (Borisova 2019; Tarasov et al. 2019). Nevertheless, a knowledge gap still exists, and our new and multiproxy study aims to close this gap.

This study examines Lake Chernoye, located in the Khachin Island of Lake Seliger. Studies on small lakes provide not only the history of the lake itself along with the island in which it is located, but also the regional changes of the Lake Seliger basin. During the Late Glacial Period, Lake Seliger was a part of the larger Lake Tverskoye (Kvasov 1975), with a water level of ca. 140–145 m a.s.l. during the Late Glacial Period followed by its later drop. At its highest level, the lake occupies the entire lowlands with a flow threshold east of the modern watershed. Due to the shallow

depths of Lake Tverskoye varved clay, usually present in Late Glacial lakes, did not accumulate here.

The main aims of our study are: (1) to reconstruct the small lake ecosystem that developed on the island of the bigger lake, (2) to assess forest vegetation response to Holocene climate change at Khachin Island and in the catchment of the Lake Seliger basin, and (3) to compare the development of the isolated lake and forest ecosystems with general patterns of vegetation shifts in the region.

Study site

Lake Chernoye ($57^{\circ} 17,039' N$; $33^{\circ} 02,765' E$) is located at an elevation of 213 m a.s.l. in the middle East European Plain. The lake is situated in the biggest island, Khachin Island, within the Lake Seliger system (Fig. 1). Lake Chernoye covers an area of 10,136 m² with a maximum depth of 15.2 m (Naumenko et al. 2014).

The climate of the study region is temperate continental, mild and humid. According to the weather station in Ostashkov near Lake Seliger ($57^{\circ} 11' N$; $33^{\circ} 10' E$; 214 m a.s.l.), the average annual temperature is +4 °C (mean July temperature of 17 °C). The average annual precipitation is about 600 mm and most of it falls in the summer. The prevailing winds are in a west and southwest direction. The territory of the district is located in the subzone of the southern taiga. Sod-podzolic soils are mostly widespread. Forests with a dominance of evergreen coniferous trees (spruce and pine) dominate the natural vegetation cover. Among deciduous tree species, *Betula*, *A. incana*, *A. glutinosa*, and *Populus tremula* are common, but *Quercus*, *Ulmus*, *Tilia*, *Acer*,

and *Fraxinus* also occur in the region. Common and waterlogged meadows are also widespread. The most predominant types of meadow grasses include Poaceae, Cyperaceae, Fabaceae, etc.

Materials and methods

Coring and sampling

A manual Russian corer with a diameter of 5 cm and length of 1 m was used for drilling. Overlapping sediment sequence was transported to the laboratory, described, and sub-sampled for detailed palaeoecological studies using pollen, plant macrofossils combined with quartz grains, loss on ignition and metals analyses. The sampling interval in the lake sediments sequence was 2 cm at the bottom and 5 cm at the top of the sequence.

Morphometric model

The data for the morphometric model of Lake Chernoye was obtained during a field trip, when echo-sounding depth measurements were carried out. To measure depth, a Lowrance echo sounder with a GPS coordinate system was used (determining the depth at an accuracy of up to 0.1 m, coordinates up to 5 m). To obtain all these, an inflatable boat in calm weather was used for 1–2 days. Digital models of depth and slope distribution were created with help from precise survey by echo sounding (Naumenko et al. 2014). Spatial resolution of the models is 10 m.



Fig. 1 Location map with the last glacial limit (LGM after Svendsen et al. 2004) (1), study area, where red cross marks the location of Lake Chernoye on Khachin Island (2) and details on Lake Chernoye:

bottom depths (in m) (a) with slopes (in °) (b) (3). 1—Karelian Isthmus; 2—Lake Terebenskoye. Hatching shows the Valdai Hills

Chronology

Six accelerator mass spectrometry (AMS) radiocarbon dates measured on selected terrestrial plants at the Poznań Radiocarbon Laboratory were used to generate the age–depth (Table 1). Calibration of the radiocarbon dates and construction of the age–depth were performed with OxCal 4.1 software (Bronk Ramsey 2009) and the IntCal13 curve (Reimer et al. 2013), applying a P_Sequence function with a k parameter of 1 cm⁻¹ and 1-cm resolution. The most distinct changes in deposit composition, which might be a signal of changes in the sedimentation accumulation rate, were introduced using the boundary command (Fig. 3). The modelled age is expressed as calibrated calendar years before present (cal. yr BP) where present equals 1950 AD.

Pollen analysis

Sub-samples of 2 cm³ for each 2 cm horizon were prepared for pollen analysis using a standard procedure (Gričuk 1940; Berglund and Ralska-Jasiewiczowa 1986) that includes heavy liquid separation (CdI₂ + KI). 400–800 pollen grains were counted for most samples, except for the bottom sandy layer, where low pollen concentrations (about 100 pollen grains) were counted. Pollen identification was based on a proposal by Kuprianova and Alyoshina (1972), Moore et al. (1991), and by comparison with pollen reference slides at the Institute of Limnology Russian Academy of Sciences (RAS) in St. Petersburg. The results were plotted in diagrams using TILIA, TILIA GRAPH and TGView programs (Grimm 1991, 2007). The total pollen sum was calculated as the sum of tree, shrub, herb pollen and spores.

Plant macrofossil analysis

Plant macrofossils were analysed at 1-cm intervals in contiguous samples of approximately 10–12 cm³, totalling 335 samples. Samples were washed and sieved under warm

tap water using 0.20-mm mesh screens. Initially, the entire sample was analysed with a stereoscopic microscope. In this way, the percentage of individual fossils of vascular plants and brown mosses were obtained. Fossil carpological remains and vegetative fragments (leaves, rootlets, epidermis) were identified using identification keys (Smith 2004; Velichkevich and Zastawniak 2006, 2008) and were compared with recent collection materials. The numbers of seeds, fruits, needles, bud scales and leaves were counted separately. Macroscopic charcoal pieces were also counted during plant macrofossils analysis, and their presence in the sediment provides information of past fire occurrence (Mooney and Tinner 2011; Robin et al. 2013).

Quartz grain analysis

Sand quartz grains were visually detected in the samples taken from a depth of 700–705 cm, 792–796 cm and 807–809.5 cm (six samples altogether; Table 2), and these samples were subjected to a quartz grain inspection. This inspection allows us to define grain surface and its three-dimensionality, and such a combination of both grain rounding and the type of its surface may be offered by Cailleux (1942) method, further modified by Mycielska-Dowgiało and Woronko (2004). Prior to the analysis, a portion of sediment was treated by 10% HCl to remove any carbonates, washed thoroughly with distilled water to remove any excess and dried at room temperature. Seven grain groups were selected: (1) well rounded with a whole matte surface; (2) partially rounded, matte only on the most convex part of the grains; (3) well rounded and shiny; (4) partially rounded and shiny; (5) fresh, with sharp edges and corners; (6) broken with at least 30% of the original grain surface affected, and (7) with intensively weathered surface. Approximately, 100–125 quartz grains from a 0.2–0.355 mm fraction were randomly selected into one of the seven groups under binocular microscopy. Normally, coarser sand fractions

Table 1 Radiocarbon dates of sediment sequence from the Lake Chernoye of the Khachin Island, Lake Seliger, Valdai Hills

Depth (cm)	Material	Nr. Lab	C14 date	Age cal yr BP (95.4%)
462.5	Fruit scales and fruits of <i>Betula pubescens</i> , needles and bud scales of <i>Pinus sylvestris</i> , needles and bud scales of <i>Picea abies</i>	Poz-86189	2485 ± 30 BP	2725–2437
562.5	Needles and bud scales of <i>Pinus sylvestris</i> , fruits scales and fruits of <i>Betula pubescens</i> , bud scale of <i>Alnus glutinosa</i>	Poz-86190	3145 ± 30 BP	3447–3258
687.5	Needle and bud scales of <i>Pinus sylvestris</i> , fruits scales and fruits of <i>Betula</i>	Poz-91705	5650 ± 40 BP	6505–6314
705.5	fruits scales and fruits of <i>Betula pubescens</i> , needles and wing of seed of <i>Pinus sylvestris</i>	Poz-86191	7040 ± 35 BP	7948–7795
725	Needle, seed and bud scales of <i>Pinus sylvestris</i>	Poz-91706	7620 ± 40 BP	8518–8365
801.5	fruits scales and fruits of <i>Betula pubescens</i> , fruit of <i>Schoenoplectus lacustris</i>	Poz-86192	9530 ± 50 BP	11,091–10,685

Table 2 Data on quartz grain analysis of the 0.2–0.355 mm fraction

Sample depth, m	Grain sum	Types of grains (%)						
		Well rounded with whole matt surface	Partially rounded matt	Well rounded shiny	Partially rounded shiny	Fresh, with sharp edges and corners	Broken	Weathered
7.00–7.01	105	0	21	1	35	24	19	0
7.03–7.05	108	7	22	0	19	34	17	1
7.02–7.03	114	3	32	0	27	31	7	0
7.94–7.96	110	3	31	1	32	23	11	0
7.92–7.94	121	7	19	0	42	27	4	0
8.07–8.095	125	3	43	2	25	22	5	0

(0.5–1.0 mm) are considered in the analysis. However, in this study, a finer fraction was chosen for grain observation due to its abundance and lack of coarser material.

Loss on ignition

The content of organic material and terrigenous matter was determined by a loss-on-ignition (LOI) survey. To ascertain the LOI, sediments covering a 2–5 cm interval were dried at 105 °C for 24 h and combusted at 500 °C (4 h) to calculate organic matter, carbonate and mineral compounds, respectively (Heiri et al, 2001).

Geochemical investigations

The total content of major elements (Si, Al, Fe, Ca, Mg) in weight percentages and trace elements (Mn, Ni, Co, Cr, Cu, Pb) in mg/kg were determined by atomic optical emission spectrophotometry (AOES) in the laboratory of the Institute of Limnology RAS, St. Petersburg, Russia.

Results

Morphometry, lithostratigraphy and chronology

The Lake Chernoye depression has a regular shape and forms a conical shape. Its southeastern part reveals a maximum slope inclination of up to 28°, whereas the northern part is gentler ca. 16°–18°. The central part of the depression has the least inclined slope (6°) with an average value of about 18° (Fig. 1).

The core excavated at sampling point 3 generally consists of two parts (Fig. 2). The bottom part (8.05–8.15 m depth) of the section consists of light grey silty clay, brown gyttja sand and dark brown organic layers. The upper part (4.45–8.05 m) is represented by brown and dark brown gyttja with plant macrofossils and sandy gyttja at the bottom. The borders between the units are distinct. At the base of the section,

light grey sand appears. A sandy organic layer with wood fragments (bark, small branches) appears between depths 7.02–7.05 m.

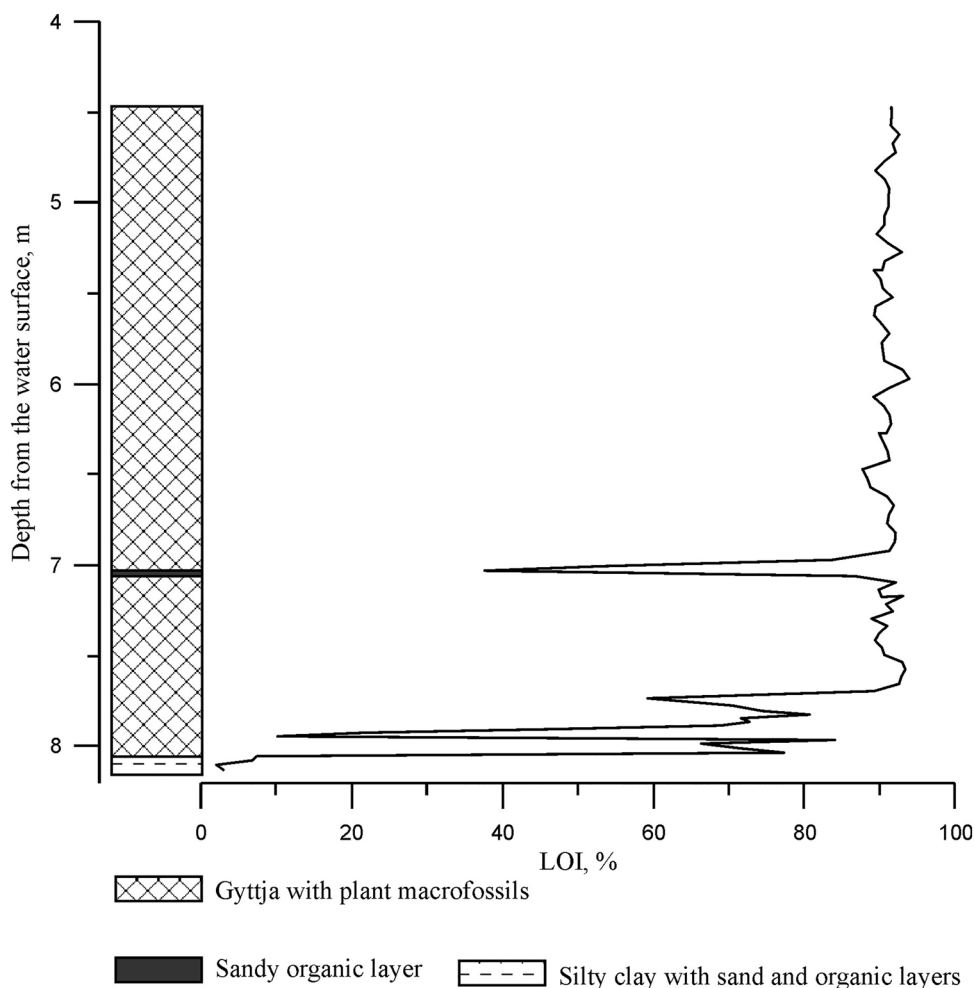
Based on the depth–age model (Fig. 3), accumulation of organic sediments began at ca. 11,100 cal. yr BP. The bottom part of the studied deposits accumulated between 11,100 and 10,800 cal. yr BP at depths 815–805 cm, and consists of light grey silty clay, brown gyttja sand and dark brown organic layers. Above this layer, and between 10,800 and 2100 cal. yr BP at depth 805–445 cm, brown and dark brown gyttja with plant detritus was deposited. Sediments at a depth of 705–702 cm were dated back at ca. 7000 cal. yr BP.

Palaeobotanical results

Trees, shrubs and selected terrestrial plant succession

Six zones in trees, shrubs and selected herbs plants development were visually delimited in the pollen and macrofossil diagram (Fig. 4). Zone CL-tr-1 (11,100–10,800 cal. yr BP) is characterised by high abundances of *Picea*, *Pinus*, *Artemisia*, *Chenopodiaceae*, and *Asteraceae* pollen. One *P. abies* needle and *B. section albae* macrofossils in this zone were also found. In zone CL-tr-2 (10,800–9600 cal. yr BP), the highest abundance of *Betula* pollen (up to 60%) and macrofossils (fruits and fruit scales) were recorded. High abundances of *B. nana* and *Poaceae* pollen were also recorded. In zone CL-tr-2 (9600–6700 cal. yr BP), an increase in deciduous trees such as *Ulmus* (the highest value in the entire period), *Tilia*, *Quercus* and *Alnus*, as well as high abundances of *Pinus* and *Betula* (ca. 50%) took place. Zone CL-tr-4 (6700–4200 cal. yr BP) is dominated by deciduous trees such as *Quercus*, *Tilia*, and *Alnus*, and is also characterised by an increased presence of *Picea* (up to 20%). Numerous *Picea abies* and *P. sylvestris* macroremains were also recorded. In zone CL-tr-5 (4200–2700 cal. yr BP), *Picea*, *Pinus*, *Betula* and *A. glutinosa* pollen were dominant. A constant presence of *P. sylvestris* macrofossils and *Cerealia* pollen in this zone were also documented. Zone CL-tr-6

Fig. 2 Sediment lithology and LOI (%) of Lake Chernoye



(2700–2100 cal. yr BP) is characterised by high abundances of coniferous trees and low abundances of deciduous trees. An increase in *B. nana* pollen (up to 6%) and a peak of *A. incana* pollen also took place in this zone.

Local wetland plants succession

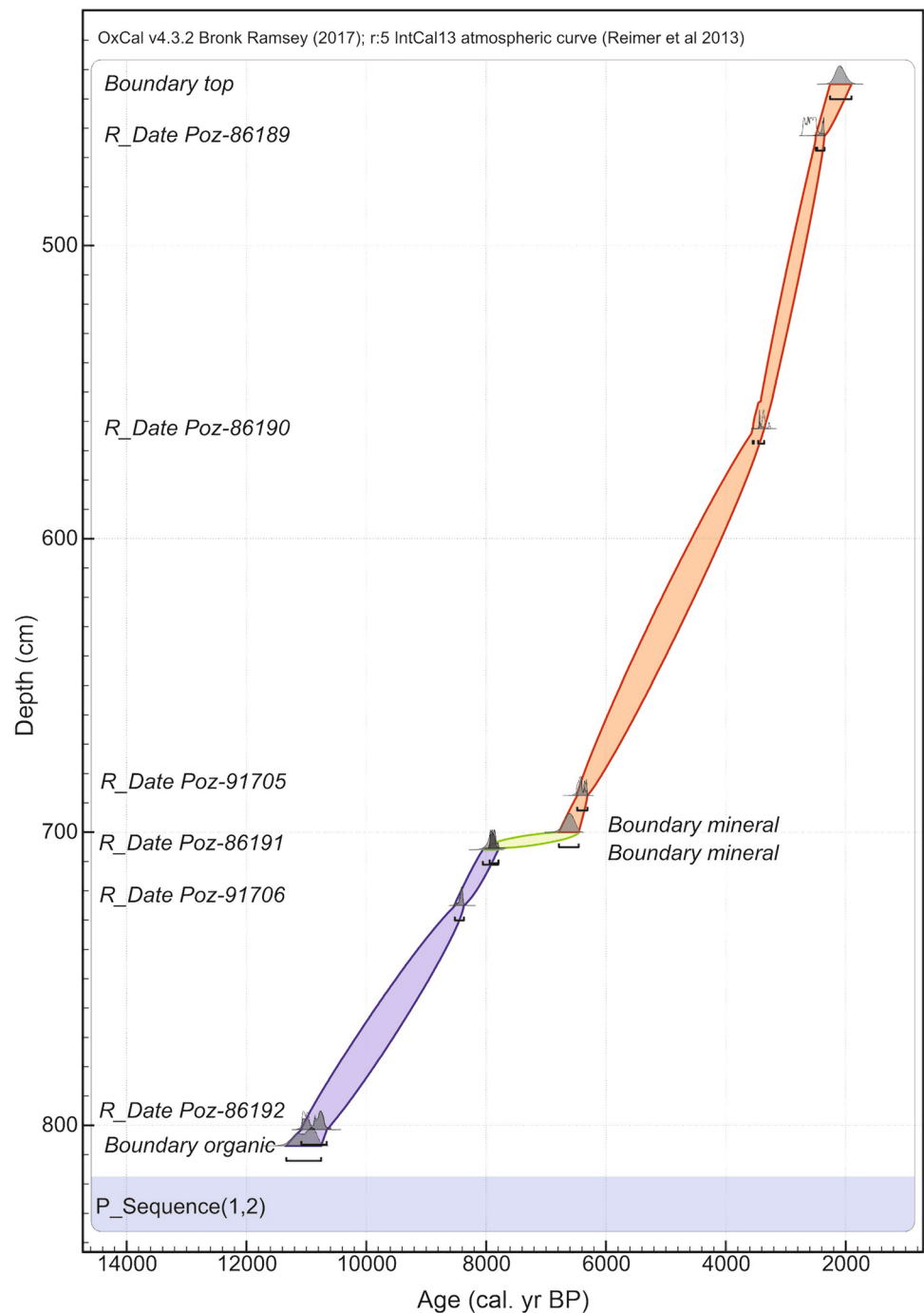
Five zones in the local vegetation development were visually delimited in the pollen and macrofossil diagram (Fig. 5). Zone CL-lo-1 (11,100–9700 cal. yr BP) representing a shallow lake with aquatic submerged plants such as *Chara* sp., *Myriophyllum spicatum*, *C. submersum* and *P. perfolitum*. High values of rush plant pollen such as *Carex*, *Equisetum*, and *Sparganium*, as well as the presence of plant macrofossils such as *Schoenoplectus lacustris* and *Carex pseudocyperus* were also documented. One macrocharcoal piece in this zone was found. Zone CL-lo-2 (9700–8500 cal. yr BP) is characterised by the abundant presence of *Isöetes* microspores, Polypodiaceae spores, *Alisma* pollen and *Pediastrum*. *Nymphaea* cf. *candida*, *P.* cf. *lucens* and *Menyanthes trifoliata* macroremains were also recorded. In

zone CL-lo-3 (8500–6600 cal. yr BP), spreading of *Chara* sp., *N. marina*, *N. flexilis*, and *P. pusillus* took place. Two macrocharcoal pieces were also found. In zone CL-lo-4 (6600–3300 cal. yr BP), *Myriophyllum* sp., *Potamogeton* sp. and *Nuphar* sp. pollen were common. The first leaves of *Sphagnum* mosses were found here. In zone CL-lo-5 (3300–2100 cal. yr BP), *P. pusillus* reappeared and *Carex lasiocarpa* and *Sphagnum teres* appeared for the first time. *Myriophyllum* sp. pollen disappeared in this zone.

Mineral and geochemical analysis

No clear grain group prevalence can be seen in the investigated part of the profile, but rather three groups of quartz grains contribute roughly equally in all investigated samples (Table 2). These are: (1) the partially rounded grains with a shiny surface (19–42%), (2) fresh grains with sharp edges (22–34%), and (3) partially rounded grains with a matte surface (19–43%). These are followed by broken grains (7–19%) and well-rounded grains with a matte surface (0–7%). The remaining types of grains were either absent

Fig. 3 Age–depth model of the lake sediments profile in Lake Chernoye. Colours refer to main stages of the sediment accumulation



or minor. Importantly, almost half of the investigated grains in the lowermost part of the profile (807–809.5 cm) have a matte surface, followed by an instant interlayer where shiny grains prevail.

The LOI results show stable high organic content for most of the core (ca. 90%) and large fluctuations in the bottom section. Minimum LOI values (2–7%) are marked ca. 11,000 cal. yr BP for non-organic deposits (Fig. 6). Further up, there is a sharp increase in the LOI values to 76% ca. 10,800 fluctuations with a range 10–83% between

10,700 and 9800 cal. yr BP. From ca. 9800 cal. yr BP (depth of 776 cm) to 2100 cal. yr BP, LOI values are 88–92%. The exception is the sandy peat layer accumulated between 7500/7000 cal. yr BP (depth 705–700 cm), where LOI values decreased to 37%. In zone CL-ge-1 (11,100–9600 cal. yr BP), the majority of elements had elevated concentrations. Zone CL-ge-2 (9600–8000 cal. yr BP) is characterised by constant low values of elements such as Si, Al, Mn, Fe, Pb. In CL-ge-3 zone (8000–6600 cal. yr BP), elements such as Si, Al, Ni, Cr, Pb and Co peaked. In zone

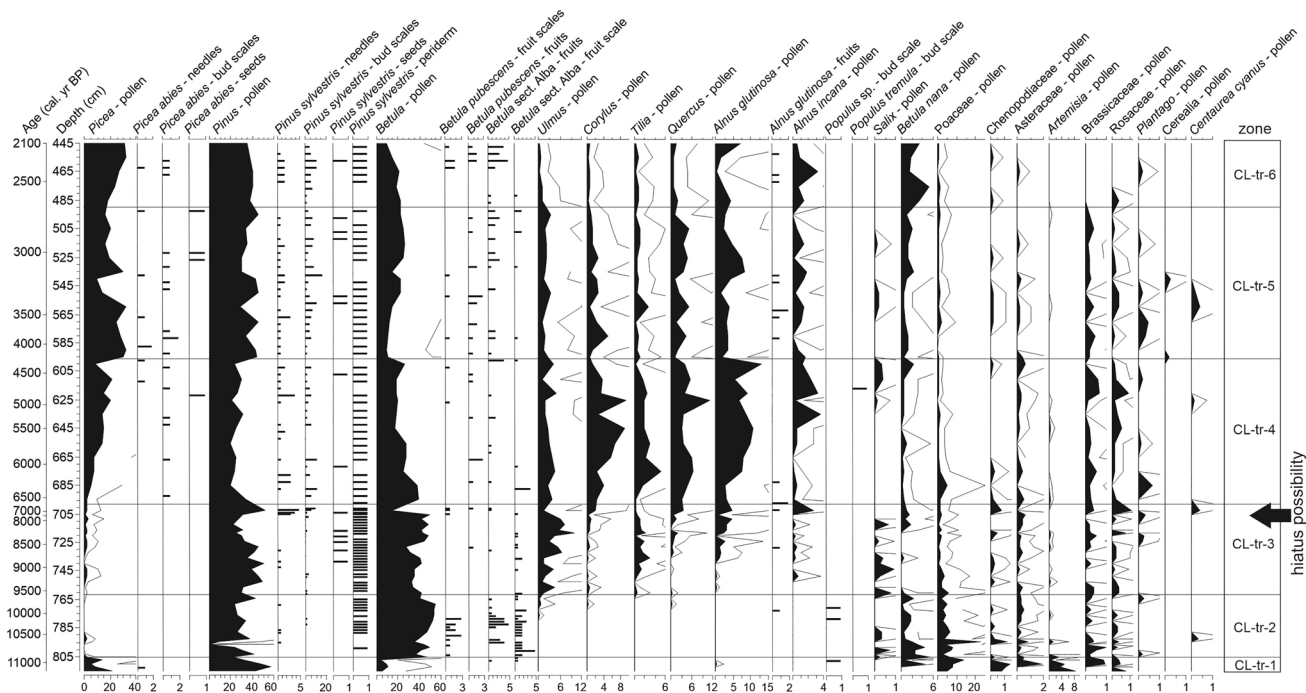


Fig. 4 Pollen and plant diagram presenting local and regional vegetation (mainly trees) changes of Lake Chernoye. Pollen percentages are shown in black, five times exaggeration in grey. Plant macrofossils

are given in counted numbers. CL-tr-1–6 refer to six zones that mark the development of trees, shrubs and selected herbs between 11,100 cal. yr BP and 2100 cal. yr BP

CL-ge-4 (6600–2100 cal. yr BP), elements such as Ca, Mn and Cu had unstable values; elements such as Si, Al, Mg, Ni, Cr and Pb had low and nearly constant values. At ca. 5700 cal. yr BP, Fe, Cr and Pb values peaked.

Discussion

Palaeobotanical, geochemical and quartz grains data obtained from a sediment log of Lake Chernoye along with radiocarbon dating allow us to determine the local and regional vegetation history and island lake development in the Holocene. This is discussed in the following sections (Fig. 7).

Forest development

Picea abies is the main forest species in the region, and appeared at ca. 11,000 cal. yr BP on the island as apparent from the macroremains and pollen study. Between ca. 10,400 and 9700 cal. yr BP, *Betula* pollen dominates the forest. At ca. 9500, the climate must have warmed, as the population of *B. nana* declined and was replaced by *Ulmus*, which was one of the first deciduous trees in the region. Its Early Holocene spreading is synchronised with other data from Central and Eastern Europe (Feurdean et al. 2014). The period between ca. 9600 and

6700 cal. yr BP was dominated by a pine and birch forest, with small percentages of *Ulmus*, *Tilia*, *Quercus* and *Corylus*. With gradually improving climate conditions and a possible increase of groundwater at ca. 9000 cal. yr BP, swamp forests of black alder (*A. glutinosa*) developed around the lake. Increasing humidity might have also contributed to the spread of grey alder (*A. incana*). In the Upper Volga region, an increase in *A. glutinosa* and *A. incana* was observed in sediments deposited at about 9000–4700 cal. yr BP (Borisova 2019). In the Rostov-Jaroslavl' area, mixed deciduous–coniferous forests were common between 8200 and 6100 cal. yr BP and became dense and species rich between 6100 and 2500 cal. yr BP (Wohlfarth et al. 2006). *P. abies* most likely re-appeared on the studied island at ca. 6500 cal. yr BP, because macroremain (bud scale) was recorded at that time. Starting from this time, the role of spruces gradually increased; it might have been one of the most important trees next to *Pinus* in the forest that occupied the island (Fig. 3). Climate cooling, noted in Scandinavia and the Baltic countries from ca. 4500 cal. yr BP (e.g. Heikkilä and Seppä 2003; Seppä and Poska 2004), is clearly observed in our study at ca. 4300 cal. yr BP through a decline of deciduous trees and a spread of *Picea*. This regional cooling signal is supported by changes in the main forest components in many sites in Eastern and Central Europe (Seppä and

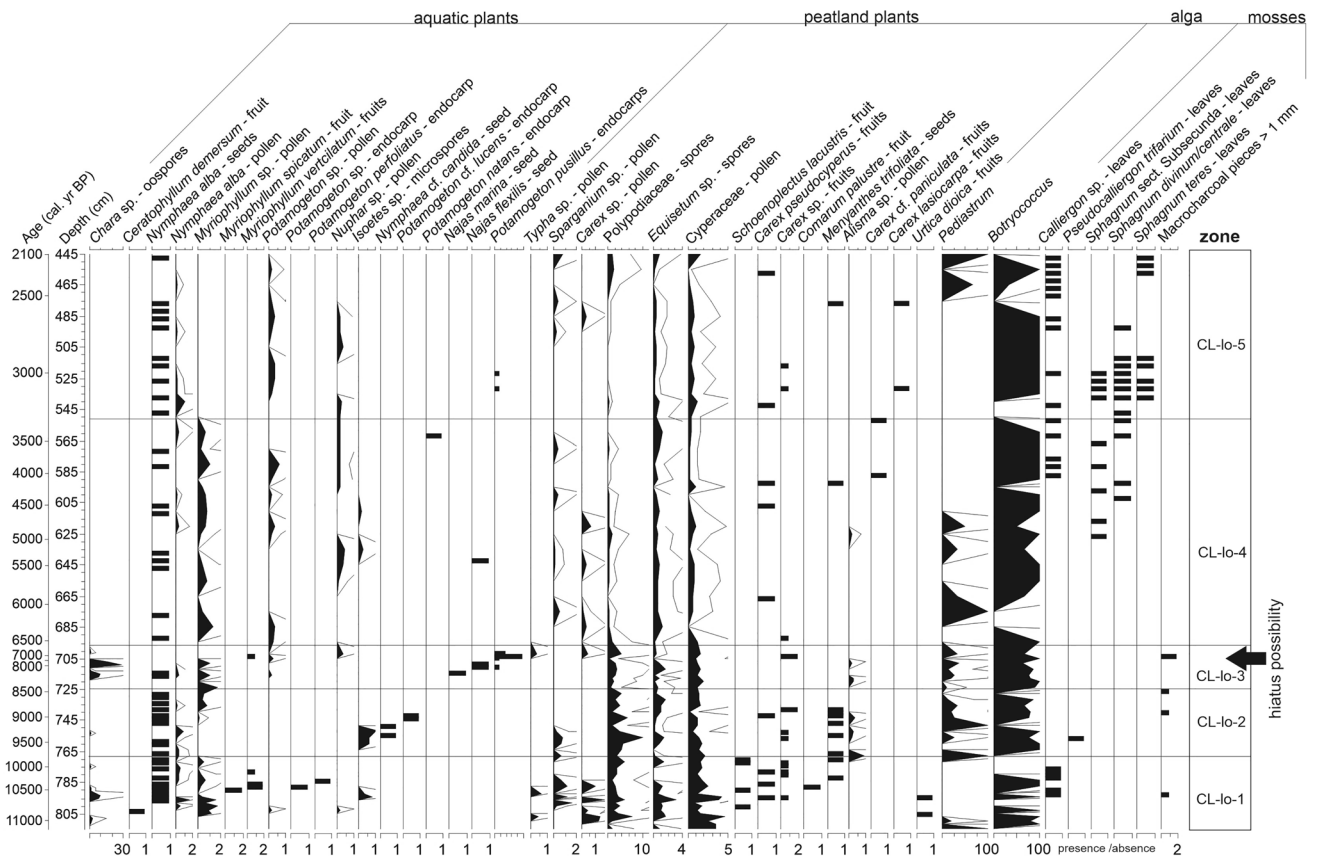


Fig. 5 Pollen and plant diagram, presenting local and regional vegetation changes of Lake Chernoye. Pollen percentages are shown in black, five times exaggeration in grey. Plant macrofossils are given

in counted numbers. The CL-lo-1–5 refer to five zones that mark an occurrence of local wetland plants between 11,100 cal. yr BP and 2100 cal. yr BP

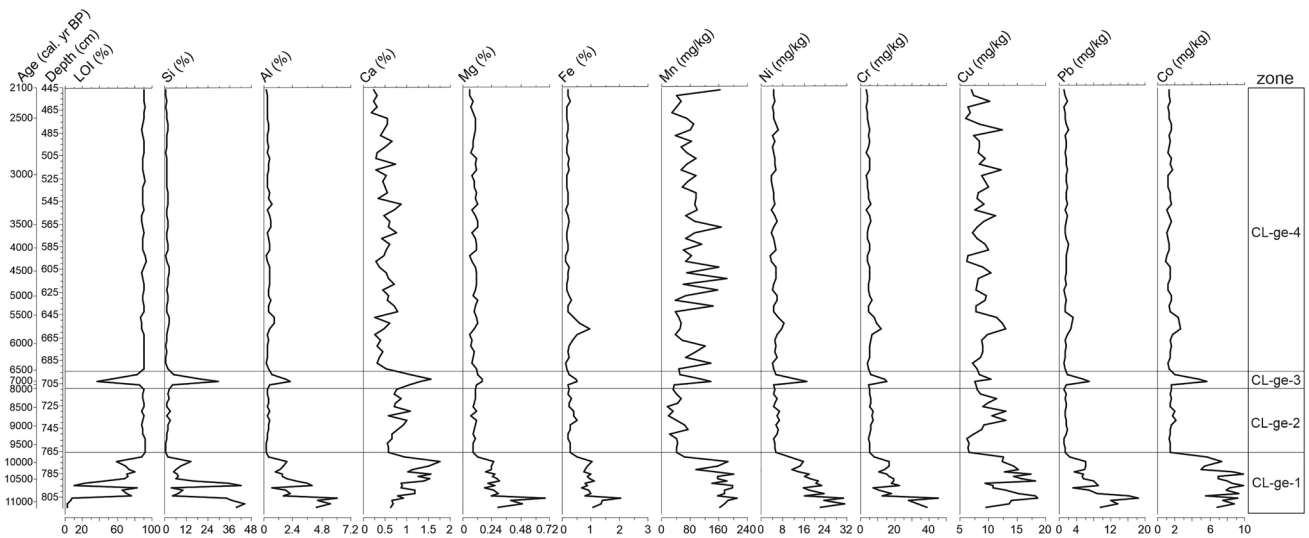


Fig. 6 Changes in the LOI and metals of Lake Chernoye. CL-ge-1–4 refer to four zones with LOI and major element fluctuations

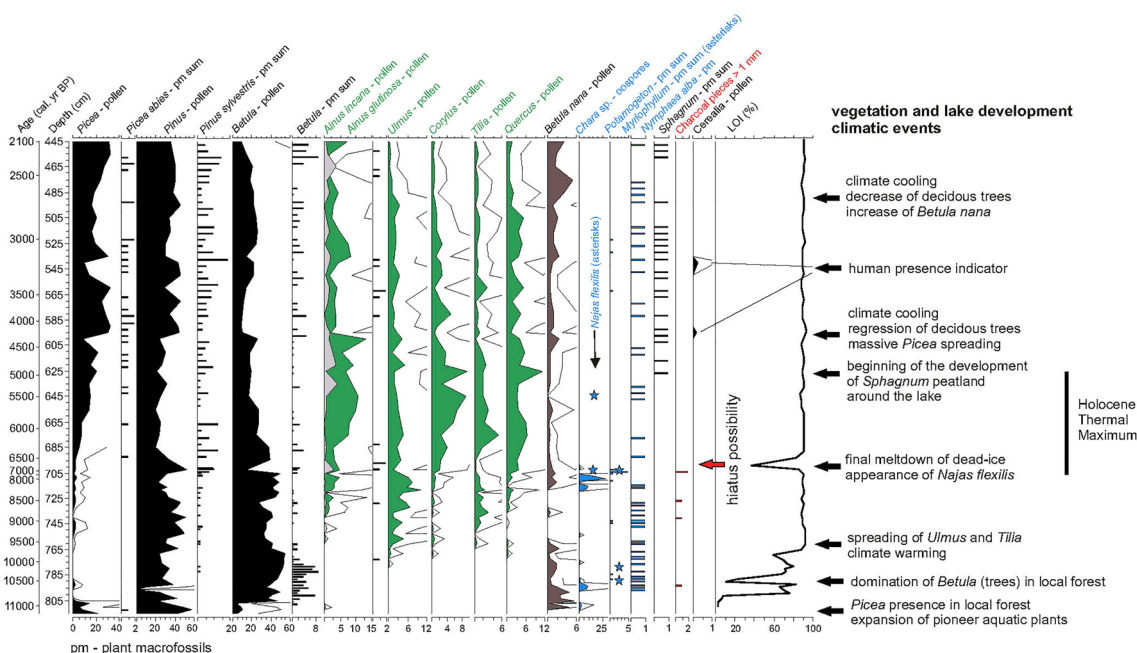


Fig. 7 Comparison of chosen taxa from two botanical data sets: plant macrofossils and pollen, and LOI presenting vegetation and lake development with marked main climatic events

Poska 2004; Gaidamavičius et al. 2011; Gałka et al. 2014; Stivrins et al. 2014).

The first traces of *Cerealia* pollen were found approximately 4200 cal. yr BP. The presence of *Cerealia*, *Plantago lanceolata* and *Centaurea cyanus* pollen (Fig. 4) suggests that the open spaces in Khachin Island were used as fields or pastures. A ca. 2800–2600 cal. yr BP decline of *Ulmus*, *Quercus*, and *Corylus* responds to the 2.8 ka cool event (cf. Wanner et al. 2011).

Our data clearly correspond with other palaeobotanical date of this type in the East European Plain, and therefore our island case seems to not record specific isolated conditions, but rather contribute to a general regional tree succession pattern.

Lake ecosystem development in the western part of the boreal zone

Our study area is located in relative proximity to the LGM ice sheet limit (Svendsen et al. 2004), which deglaciated asynchronously and is dated back in this area to 20,000–19,000 yr BP (Hughes et al. 2016). The studied lake basin formed about 11,000 cal. yr BP, possibly due to melting of stagnant glacier ice. The great lake depth combined with its small area may indicate this along with a general geological situation. The high water level at the studied lake correlated with the Late Glacial and Early Holocene periods and was most likely the result of melting of most of the dead-ice blocks. At this time, variations in Ca correlate well

with the Si elements in the lake sediment. This indicates that calcite is of siliciclastic origin (Pleskot et al. 2018).

Several Late Glacial ice marginal formations, termed as the Veps, Krestsy, Luga and Neva, along with intervening interstadial sediments, have been identified in the area between the Valdai Hills and the Karelian Isthmus (Subetto et al. 2002). During the recession of the ice sheet, blocks of dead ice remained in the ground. Later, ice-block preservation in the landscape depended on various aspects, such as air temperature, hydrology and geomorphological conditions (Stivrins et al. 2017). Thermokarst processes were extensive throughout Central and the Northern Europe, and also in Northwest Russia due to the Last Glacial deglaciation over these areas (Subetto et al. 2002; Stančikaite et al. 2009; Stivrins et al. 2017; Gałka et al. 2019). Climatic conditions at 11,100–10,800 cal. yr BP were cold according to our pollen data. Open landscapes with Poaceae, *Artemisia*, Chenopodiaceae and Cyperaceae were widespread around the lake at this time. Heavy metal distribution in the sediment core points to a high amount of elements in the lake formation and clearly reveals that lake conditions were relatively stable during the Holocene. The sharp decline in LOI in the bottom part of the core is not associated with a change in lithology, as depressions of organic matter were short term and visible layers in the lithological sequence were not represented.

A distinct increase of partially rounded, matte grains is observed in the bottom part of the sediment profile, where almost half of the investigated grains showed a matte outline. These matte grains carry an entirely matte surface,

including in grain depressions. This clearly demonstrates that grains were mobilised under colder climate conditions and the sediment underwent long-term aeolian abrasion. The material of aeolian qualities was deposited slightly after 11,091–10,685 cal. yr BP, likely representing Early Holocene aeolian activity as known throughout Western and Central Europe (Kolstrup 2007; Vandenberghe et al. 2013; Zieliński et al. 2015) and in the neighbouring Baltic States (Kalińska et al. 2019, 2020a). Aeolian grains are also not a surprise in lake sediment record, since it has been observed in numerous lake profiles (Kalińska-Nartiša et al. 2018; Kalińska-Nartiša and Gałka 2018). In such cases, transportation is rather short and comes from adjacent aeolian sources. In this study, shiny quartz grains, which, in general, are known as a typical record of fluvial action (Kalińska et al. 2020b), also dominate in lacustrine deposition at ca. 11,000 cal. yr BP, which corresponds well with a high stand water in the lake in the end of the Late Glacial.

After 10,800 cal. yr BP, the climate became warmer. The area of boreal forest with *Pinus* and *Betula* development increased (Fig. 7). At ca. 10,700 cal. yr BP, one of the first documented aquatic plants that occurred in the studied lake was *C. demersum*, which is an indicator of warmer conditions, and its presence suggests that temperatures in July oscillated between approximately 15 °C (Litt 1994) or even 18 °C (Mai 1985). However, *C. demersum* appeared in Northeast Europe earlier than recorded in our study. Its occurrence was documented before 11,000 cal. yr BP in Lake Kojle, Northeast Poland (Gałka et al. 2015). In addition, in the Kaliska Basin, Northeast Poland, *C. demersum* fruits were documented in sandy gyttja deposits, dated to ca. 9700 cal. yr BP (Stachowicz-Rybka and Obidowicz 2013). The later presence of *C. demersum* fruits in gyttja accumulated similarly atop of the peat layer, which was dated back to ca. 8000 cal. yr BP in sediment cores of Lake Kikuru, Western Latvia (Stivrins et al. 2017). In our study, *Typha* pollen and *Carex pseudocyperus* occurred at ca. 10,500 cal. yr BP, which are typical species for the Early Holocene, indicating warming climate. The presence of these species in the sediment suggests that the mean minimum July temperature reached 13–16 °C, depending on the particular *Typha* species (Kolstrup 1979).

The area of the lake was probably larger than it is currently. At ca. 9500–8500 cal. yr BP, the presence of *Isoetes* and *Nymphaea* cf. *candidata* indicate oligotrophic conditions in the lake. The gradual lowering of the water level, the formation of a shoreline close to the coring site and evidence for a hiatus between 8500 and 7500 cal. yr BP show that the level of the lake decreased considerably and remained low for a longer time. During this period, there was a sharp decrease in organic matter and an increase in the supply of mineral precipitation, according to the peaks of the all elements studied (Fig. 6). Combined with the number of

broken quartz grains, the investigated grain mineral matter resembles glacial-driven conditions. Under ice conditions, either fracturing or abrasion occurred (Whalley and Langway 1980), thus producing either highly angular or partially abraded grains (Hart 2006), which can be found in numerous glacial-origin sediments (Immonen 2013; Mahaney and Kalm 1995; Vos et al. 2014). In our study, these two types of grains dominate. However, the number of fresh and broken grains increased in the 7.03–7.05 m sediment sample. Assuming the sediment deposition at 7950–7800 cal. yr BP, quartz grains of this glacial suite cannot mark a glaciation, but must originate, for example, from the adjacent moraine sources, being delivered to the lacustrine system, and further resulting into lake shallowing. A similar mechanism is known from lacustrine deposition, for example in Northeast Poland (Kalińska-Nartiša and Gałka 2018).

The warm period at about 6900–5000 cal. yr BP could be linked to the Holocene thermal maximum (Fig. 7), which, in Northwest Europe and Russia, was characterised by warm and dry conditions (Birks and Seppä 2010; Borisova 2019, respectively), and is marked by a reduced groundwater and lake level along with increased peat decomposition in peatlands in numerous sites during this period (Wohlfarth et al. 2007; Gałka et al. 2014; Stivrins et al. 2017). Similarly, the final meltdown of dead ice was at the Holocene thermal maximum (8500–7400 cal. yr BP) in Western Latvia, Eastern Baltic (Stivrins et al. 2017). Abiotic and biotic processes following the ice-block meltdown suggest abrupt development of thermokarst from 8500 to 7400 cal. yr BP. The Holocene thermal maximum in the Western Dvina River region started ca. 8600–6900 cal. yr BP and ended some centuries earlier ca. 8100–5600 cal. yr BP (Tarasov et al. 2019) than suggested for the neighboring Baltic region.

The decreased water level favoured the re-appearance of *Chara* and allowed development of submerged plant communities with *N. flexilis*, *N. marina* and *P. pusillus*. *N. flexilis* seeds are especially common and are noted in Eurasia and North America in Early and Middle Holocene sediments, but the presence of this species is usually short term in comparison to other submerged macrophytes (cf. Swinehart and Parker 2000; Gałka et al. 2012). From ca. 5000 cal. yr BP, leaves from *Sphagnum* mosses (*S. sect. subsecunda*, *S. medium/divinum* and later *S. teres*) and *Carex lasiocarpa* fruits were recorded in the sediments that suggest gradual development of floating mats around the lake.

Conclusions

The results of our study showed:

1. At ca. 11,000 cal. yr BP, development of Lake Chernoye began after the melting of buried dead-ice blocks,

- which was intensified by the Early Holocene warming. As pioneer plants, *Chara* sp., *Isöetes* and *C. demersum* appeared in the water with high Ca and Mg content. High values of *Pinus*, *Artemisia*, *B. nana* and Chenopodiaceae pollen may indicate remains of cold flora that occurred in the Younger Drays in this region.
- Between 8000 and 6500 cal. yr BP, the water level decreased, as apparent from a sediment hiatus. This may have been related to the Holocene thermal maximum and final melting of the buried dead-ice block. Lower water level at that time is documented by the spreading of *N. marina*, *N. flexilis* and *P. pusillus*, which are all submerged plants growing in eutrophic shallow water. Significant changes in the forest ecosystem at that time also took place. An increase in *Quercus*, *Corylus* and *Alnus* was accompanied by a decrease in *Pinus*.
 - Ca. 4200 cal. yr BP and ca. 2700 cal. yr BP are associated with climate cooling, documented by multiproxy records in many sites in Europe. A decrease in deciduous tree pollen (*Ulmus*, *Quercus*, *Tilia*) and increase in coniferous tree pollen (*Picea* and *Pinus*) mark this cooling period.
 - At ca. 4200 cal yr BP, climate deterioration was marked by the contemporaneous appearance of cereal pollen.
 - Location of the lake on the isolated island did not lead to differ in the vegetation pattern development, since this latter is similar to the other sites in the East European Plain.
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- ## References
- Aleshinskaya ZV, Gunova VS, Leflat ON (1992) History of Lakes in the centre of the Russian plain. In: The history of the lakes. History of the lakes of the East European Plain. St. Petersburg, pp 168–182
- Astakhov V, Shkatova V, Zastrozhnov A, Chuyko M (2016) Glaciomorphological map of the Russian federation. *Quat Int* 420:4–14. <https://doi.org/10.1016/j.quaint.2015.09.024>
- Berglund BE, Ralska-Jasiewiczowa M (1986) Pollen analysis and pollen diagrams 455–484. In: Berglund BE (ed) Handbook of holocene palaeoecology and palaeohydrology. Wiley, Chichester, pp 455–484
- Birks HJB, Seppä H (2010) Late-Quaternary palaeoclimatic research in Fennoscandia: a historical review. *Boreas* 39:655–673. <https://doi.org/10.1111/j.1502-3885.2010.00160.x>
- Borisova O (2019) Environmental and climatic conditions of human occupation in the central East European Plain during the Middle Holocene: reconstruction from palaeofloristic data. *Quat Int* 516:42–57. <https://doi.org/10.1016/j.quaint.2018.05.025>
- Bronk Ramsey C (2009) Bayesian analysis of radiocarbon dates. *Radiocarbon* 51:337–360. https://doi.org/10.2458/azu_js_rc.v51i1.3494
- Cailleux A (1942) Les actions éoliennes périglaciaires en Europe
- Davydova NN, Subetto DA, Khomutova VI, Sapelko TV (2001) Late Pleistocene-Holocene paleolimnology of three northwestern Russian lakes. *J Paleolimnol* 26:37–51
- Feurdean A, Perşoiu A, Tanţău I et al (2014) Climate variability and associated vegetation response throughout Central and Eastern Europe (CEE) between 60 and 8ka. *Quat Sci Rev* 106:206–224. <https://doi.org/10.1016/j.quascirev.2014.06.003>
- Gaidamavičius A, Stančikaitė M, Kisieliėnė D et al (2011) Post-glacial vegetation and environment of the Labanoras Region, East Lithuania: implications for regional history. *Geol Qual* 55:63–69
- Gałka M, Sypniewski J, Apolinaraska K (2019) Early Holocene succession of vegetation and molluscs in Lake Jaczno, East-Central Europe. *Quat Int* 524:31–39
- Gałka M, Tobolski K, Bubak I (2015) Late Glacial and Early Holocene lake level fluctuations in NE Poland tracked by macro-fossil, pollen and diatom records. *Quat Int* 388:23–38. <https://doi.org/10.1016/j.quaint.2014.03.009>
- Gałka M, Tobolski K, Kofacek P (2012) The Holocene decline of slender naiad (*Najas flexilis* (Willd.) Rostk. & W.L.E. Schmidt) in NE Poland in the light of new palaeobotanical data. *Acta Palaeobot* 52:127–138
- Gałka M, Tobolski K, Zawisza E, Goslar T (2014) Postglacial history of vegetation, human activity and lake-level changes at Jezioro Linówek in northeast Poland, based on multi-proxy data. *Veg Hist Archaeobot* 23:123–152. <https://doi.org/10.1007/s00334-013-0401-7>
- Gorlach A, Hang T, Kalm V (2017) GIS-based reconstruction of Late Weichselian proglacial lakes in northwestern Russia and Belarus. *Boreas* 46:486–502. <https://doi.org/10.1111/bor.12223>
- Grichuk VP (1940) Method of treatment of the sediments poor in organic remains for the pollen analysis. *Probl Phys Geogr* 8:53–58
- Grimm E (1991) *Tilia* 1.12, *Tilia* Graph 1.18.
- Grimm EC (2007) *Tilia* Version 1.0.1
- Gunova VS, Tarasov PE, Uspenskaya ON, et al (2001) Holocene evolution of the Trostenskoe Lake and adjacent area. *Vestnik-Moskovskogo Univ Ser 5 Geogr* 1:61–67
- Hart JK (2006) An investigation of subglacial processes at the micro-scale from Briksdalsbreen, Norway. *Sedimentology* 53:125–146. <https://doi.org/10.1111/j.1365-3091.2005.00758.x>
- Heikkilä M, Seppä H (2003) A 11,000 yr palaeotemperature reconstruction from the southern boreal zone in Finland. *Quat Sci Rev* 22:541–554. [https://doi.org/10.1016/S0277-3791\(02\)00189-0](https://doi.org/10.1016/S0277-3791(02)00189-0)
- Heiri O, Lotter AF, Lemcke G (2001) Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *J Paleolimnol* 25:101–110
- Hughes ALC, Gyllencreutz R, Lohne ØS et al (2016) The last Eurasian ice sheets - a chronological database and time-slice reconstruction, DATED-1. *Boreas* 45:1–45. <https://doi.org/10.1111/bor.12142>
- Immonen N (2013) Surface microtextures of ice-rafted quartz grains revealing glacial ice in the Cenozoic Arctic. *Palaeogeogr Palaeoclimatol Palaeoecol* 374:293–302. <https://doi.org/10.1016/j.palaeo.2013.02.003>
- Kalińska-Nartiša E, Gałka M (2018) Sand in Early Holocene lake sediment: a microscopic study from Lake Jaczno. *Est J Earth Sci* 67:122–132. <https://doi.org/10.3176/earth.2018.09>
- Kalińska-Nartiša E, Stivrins N, Grudzinska I (2018) Quartz grains reveal sedimentary palaeoenvironment and past storm events: a case study from eastern Baltic. *Estuar Coast Shelf Sci* 200:359–370. <https://doi.org/10.1016/j.ecss.2017.11.027>
- Kalińska E, Hang T, Jöeleht A et al (2019) Macro- and micro-scale study and chronology of Late Weichselian aeolian sediments

- in Estonia, north-eastern European Sand Belt. *Int J Earth Sci* 108:2021–2035. <https://doi.org/10.1007/s00531-019-01746-2>
- Kalińska E, Alexanderson H, Krievāns M (2020a) The Raunis section central Latvia revisited first luminescence results and reevaluation of a key Baltic States stratigraphic site.pdf. *Geogr Ann Ser A Phys Geogr*. <https://doi.org/10.1080/04353676.2020a.1813982>
- Kalińska E, Kot R, Krievāns M (2020b) Adding another piece to North-Easterne European Aeolian Sand Belt puzzles: a sedimentary age case study of Pērtupe site, Eastern Latvia. *Baltica* 33:46–57. <https://doi.org/10.5200/baltica.2020.1.5>
- Khotinsky NA (1977) *Holocene of Northern Eurasia*. Nauka, Moscow
- Kolstrup E (2007) Lateglacial older and younger coversand in north-west Europe: chronology and relation to climate and vegetation. *Boreas* 36:65–75. <https://doi.org/10.1080/03009480600827280>
- Kolstrup E (1979) Herbs as July temperature indicators for parts of the Pleniglacial and the Lateglacial in The Netherlands. *Geol En Mijnbouw/netherlands J Geosci* 59:377–380
- Konstantinov E, Panin A, Karpukhina N, Zakharov A (2018) History of Lake Seliger (Valdai Upland, Russia): new data. In: Subetto DA, Shelekhova TS, Slukovskii ZI, Druzhinina OA (eds) *Lateglacial-Interglacial transition: glaciectonic, seismoactivity, catastrophic hydrographic and landscape changes*. Excursion guide and Abstracts of INQUA Peribaltic Working Group Meeting and Excursion (International Scientific Conference and School for. Karelian Research Centre of Russian Academy of Science, Petrozavodsk, pp 78–79
- Kremenetski KV, Borisova OK, Zelikson EM (2000) The Late Glacial and Holocene history of vegetation in the Moscow region. *Palynology* 34:S67–S74
- Kuprianova LA, Alyoshina LA (1972) *Pollen and spores of plants from the Flora of European Part of the USSR*. Nauka, Leningrad
- Kvasov DD (1975) *The late Quaternary history of large lakes and inland seas of Eastern Europe*. Leningrad
- Lasberg K, Kalm V (2013) Chronology of Late Weichselian glaciation in the western part of the East European Plain. *Boreas* 42:995–1007. <https://doi.org/10.1111/bor.12016>
- Litt T (1994) *Paläoökologie, paläobotanik und stratigraphie des Jungquartärs im nordmitteleuropäischen Tiefland*. Diss. Bot. 227
- Mahaney WC, Kalm V (1995) Pleistocene and Holocene glacier thicknesses, transport histories and dynamics inferred from SEM microtextures on quartz particles. *Boreas* 24:293–304. <https://doi.org/10.1111/j.1502-3885.1995.tb00781.x>
- Mai DH (1985) Development of the water plant and Swamp Associations of Europe from the Cretaceous to the Quaternary. *Flora* 176:449–511
- Mangerud J, Gosse J, Matiouchkov A, Dolvik T (2008) Glaciers in the Polar Urals, Russia, were not much larger during the Last Global Glacial Maximum than today. *Quat Sci Rev* 27:1047–1057. <https://doi.org/10.1016/j.quascirev.2008.01.015>
- Markov KK (1977) *Sections of glacial deposits in the Central Russian Plain*. Moscow University Press, Moscow
- Mooney SD, Tinner W (2011) The analysis of charcoal in peat and organic sediments. *Mires and Peats* 7:1–18
- Moore PD, Webb JA, Collison ME (1991) *Pollen analysis*. Blackwell scientific publications
- Mycielska-Dowgiało E, Woronko B (2004) The degree of aeolization of Quaternary deposits in Poland as a tool for stratigraphic interpretation. *Sediment Geol* 168:149–163
- Naumenko MA, Guzivaty VV, Sapelko TV (2014) Digital morphometric models of small lakes. *Proc Russ State Hydrometeorol Univ* 34:26–34
- Neustadt MI (1957) *History of forests and paleogeography of SSSR during Holocene*. Academy of Sciences of the USSR
- Neustadt MI, Fedorova RV, Khotinsky NA et al (1965) *Osechenskoye peatbogs (Kalinin region)*. In: Neustadt MI (ed) *Upper pleistocene and holocene paleogeography and chronology in the light of radio-carbon dating*. Nauka, Moscow, pp 81–86
- Pleskot K, Tjallingii R, Makohonienko M et al (2018) Holocene paleohydrological reconstruction of Lake Strzeszyńskie (western Poland) and its implications for the central European climatic transition zone. *J Paleolimnol* 59:443–459. <https://doi.org/10.1007/s10933-017-9999-2>
- Reimer PJ, Bard E, Bayliss A et al (2013) Intcal13 and Marine13 radio-carbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55:1869–1887
- Rinterknecht V, Hang T, Gorchach A et al (2018) The Last Glacial Maximum extent of the Scandinavian Ice Sheet in the Valdai Heights, western Russia: evidence from cosmogenic surface exposure dating using ¹⁰Be. *Quat Sci Rev* 200:106–113. <https://doi.org/10.1016/j.quascirev.2018.09.032>
- Robin V, Knapp H, Bork H, Nelle O (2013) Complementary use of pedoanthracology and peat macro-charcoal analysis for fire history assessment: illustration from Central Germany. *Quat Int* 289:78–87. <https://doi.org/10.1016/j.quaint.2012.03.031>
- Seppä H, Poska A (2004) Holocene annual mean temperature changes in Estonia and their relationship to solar insolation and atmospheric circulation patterns. *Quat Res* 61:22–31. <https://doi.org/10.1016/j.yqres.2003.08.005>
- Smith AJE (2004) *The Moss Flora of Britain and Ireland*, 2nd edn. Cambridge University Press, Cambridge
- Stachowicz-Rybka R, Obidowicz A (2013) The development and genesis of a small thaw lake filling the Skaliska Basin during the Late Glacial and Holocene. *Acta Palaeobot* 53:69–91
- Stančikaite M, Daugnora L, Hjelle K, Hufthammer AK (2009) The environment of the Neolithic archaeological sites in Šventoji, Western Lithuania. *Quat Int* 207:117–129. <https://doi.org/10.1016/j.quaint.2009.01.012>
- Stivrins N, Kalnina L, Veski S, Zeimule S (2014) Local and regional Holocene vegetation dynamics at two sites in eastern Latvia. *Boreal Environ Res* 19:310–322
- Stivrins N, Liiv M, Heinsalu A et al (2017) The final meltdown of dead-ice at the Holocene Thermal Maximum (8500–7400 cal. yr BP) in western Latvia, eastern Baltic. *Holocene* 27:1146–1157. <https://doi.org/10.1177/09596836166683255>
- Subetto DA, Wohlfarth B, Davydova NN et al (2002) Climate and environment on the Karelian Isthmus, Northwestern Russia, 13000–9000 cal. yrs BP. *Boreas* 31:1–19. <https://doi.org/10.1111/j.1502-3885.2002.tb01051.x>
- Sukachev VN (1968) On vegetation of periglacial zones of the central parts of the Russian Plain. In: Neustadt MI (ed) *History of development of biogeosoenos cover of the Central Parts of the Russian Plain USSR during the Anthropogen*. Nauka, Moscow, pp 5–21
- Svensden JI, Alexanderson H, Astakhov VI et al (2004) Late Quaternary ice sheet history of northern Eurasia. *Quat Sci Rev* 23:1229–1271. <https://doi.org/10.1016/j.quascirev.2003.12.008>
- Tarasov PE, Pushenko MY, Harrison SP, et al (1996) *Lake Status Record from the Former Soviet Union and Mongolia: Documentation of the Second Version of the Database*. Boulder, Colorado, USA
- Tarasov PE, Savelieva LA, Long T, Leipe C (2019) Postglacial vegetation and climate history and traces of early human impact and agriculture in the present-day cool mixed forest zone of European Russia. *Quat Int* 516:21–41. <https://doi.org/10.1016/j.quaint.2018.02.029>
- Vandenberghe DAG, Derese C, Kasse C, Van den Haute P (2013) Late Weichselian (fluvio-)aeolian sediments and Holocene drift-sands of the classic type locality in Twente (E Netherlands): a high-resolution dating study using optically stimulated luminescence. *Quat Sci Rev* 68:96–113. <https://doi.org/10.1016/j.quascirev.2013.02.009>

- Velichkevich FU, Zastawniak E (2006) Atlas of the pleistocene vascular plant macrofossils of central and Eastern Europe. Part 1: pteridophytes and Monocotylendons. Instytut Botaniki im. W. Szafera, Polska Akademia Nauk, Kraków
- Velichkevich FU, Zastawniak E (2008) Atlas of the pleistocene vascular plant macrofossils of central and Eastern Europe. Part 2: Pteridophytes and Monocotylendons. Instytut Botaniki im. W. Szafera, Polska Akademia Nauk, Kraków
- Velichko AA, Kononov YM, Faustova MA (1997) The last glaciation of earth: size and volume of ice-sheets. *Quat Int* 41(42):43–51
- Vos K, Vandenberghe N, Elsen J (2014) Surface textural analysis of quartz grains by scanning electron microscopy (SEM): from sample preparation to environmental interpretation. *Earth-Science Rev* 128:93–104. <https://doi.org/10.1016/j.earscirev.2013.10.013>
- Wanner H, Solomina O, Grosjean M et al (2011) Structure and origin of Holocene cold events. *Quat Sci Rev* 30:3109–3123. <https://doi.org/10.1016/j.quascirev.2011.07.010>
- Whalley WB, Langway CC (1980) A scanning electron microscope examination of subglacial quartz grains from camp century core, Greenland—a preliminary study. *J Glaciol* 25:125–132. <https://doi.org/10.3189/s0022143000010340>
- Wohlfarth B, Lacourse T, Bennike O et al (2007) Climatic and environmental changes in north-western Russia between 15,000 and 8000 cal yr BP: a review. *Quat Sci Rev* 26:1871–1883. <https://doi.org/10.1016/j.quascirev.2007.04.005>
- Wohlfarth B, Tarasov P, Bennike O et al (2006) Late glacial and Holocene palaeoenvironmental changes in the Rostov-Yaroslavl' area, West Central Russia. *J Paleolimnol* 35:543–569. <https://doi.org/10.1007/s10933-005-3240-4>
- Zieliński P, Sokołowski RJ, Woronko B et al (2015) The depositional conditions of the fluvio-aeolian succession during the last climate minimum based on the examples from Poland and NW Ukraine. *Quat Int* 386:30–41. <https://doi.org/10.1016/j.quaint.2014.08.013>