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ЛАНДШАФТНО-КЛИМАТИЧЕСКИЕ ИЗМЕНЕНИЯ В ПРЕБОРЕАЛЕ НА СЕВЕРО-ЗАПАДЕ ЕВРОПЕЙСКОЙ ЧАСТИ РОССИИ

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Сравнение результатов комплексного изучения осадков озера Селигер с высоким разрешением по времени с опубликованными данными по пяти озерам, расположенным на сопредельных территориях, включая радиоуглеродное датирование, седиментологические и палеоботанические исследования, позволяет реконструировать изменения продуктивности озер и состава растительности в ответ на кратковременные климатические колебания в позднеледниковье и раннем голоцене. Проведенный анализ показал, что озерное осадконакопление на всех рассмотренных участках началось в интерстадиале аллерёд, 13–14.5 калиброванных тыс. л. н., когда ель, береза и сосна начали распространяться на северо-западе европейской части России, образуя участки редколесий. Существенное похолодание в позднем дриасе вызвало быстрое сокращение лесных сообществ и расширение тундрово-степной растительности при сохранении небольших групп деревьев в защищенных местообитаниях. Состав озерных отложений всюду изменялся сходным образом: от терригенных осадков в позднеледниковье до преимущественно органических (гиттии) в раннем голоцене. Быстрое потепление при переходе от позднеледниковья к голоцену привело к распространению лесов, образованных березой, а затем и сосной. Кратковременное похолодание 11.4–11.2 тыс. л. н., совпадающее по времени с пребореальной осцилляцией – похолоданием, установленным по данным изучения ледяных кернов из Гренландии, – наиболее ярко проявилось в снижении доли органического вещества в озерных осадках. Оно также прервало или замедлило процесс распространения березовых и сосновых лесов и вызвало новое увеличение роли открытых травянистых сообществ в растительном покрове. Влияние этого похолодания на развитие растительности и озерные экосистемы на северо-западе европейской части России проявилось несколько слабее, чем в Западной и Центральной Европе. В начале позднего пребореала вновь произошел быстрый переход к более теплому и влажному климату, вызвавший расселение березовых и сосновых лесов. Дальнейшее потепление в течение бореала привело к внедрению широколиственных пород в лесные сообщества и к снижению ландшафтной роли березняков. К этому времени некоторые озера были заполнены осадками, и озерное осадконакопление сменилось торфообразованием.

Ключевые слова: озерные отложения, быстрые изменения климата, ранний голоцен, пребореальная осцилляция

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1. INTRODUCTION

Paleogeographic data revealed that the warming at the transition of the global climate system from the final cold stage of the last glaciation (the Younger Dryas) to the modern interglacial (the Holocene) developed at the highest rate achieved under natural conditions and was interrupted by several short-term cooling episodes. These climatic shifts were dated by counting annual ice layers in cores from the Greenland Ice Sheet (Rasmussen et al., 2006). The amplitude of warming at the lower boundary of the Holocene, 11750 calibrated years BP (cal yr BP), is estimated at 10 ± 4°C over a period of ≤50 years (Grachev, Severinghaus, 2005). The first pronounced cooling of the Holocene – the so-called Preboreal Oscillation (PBO) – interrupted the early Preboreal warming approximately 300 years later and reached its peak at about 11.4 cal kyr BP. The cooling ended about 11.2 cal kyr BP by a new rapid warming when over several decades the air temperature in Greenland increased by 4 ± 1.5°C (Kobashi et al., 2008).

A cool event coeval with the PBO as observed in the Greenland ice-core records, that followed the rapid warming at the transition from the Late Glacial to the Holocene, can also be clearly seen in the high-resolution data from the multi-proxy studies of lacustrine deposits in the northwestern and central Europe. Thus, in The Netherlands, during the initial warm phase of the Preboreal (11530–11500 cal yr BP), birch woodlands replaced the tundra-steppe herbaceous-shrub communities typical for the Younger Dryas (van der Plicht et al., 2004; Bos et al., 2007). A prominent cooling recorded around 11430–11350 cal yr BP interrupted the afforestation process and brought about a new expansion of open grassland vegetation. After this dry continental phase, at the beginning of the late Preboreal (11270–11210 cal yr BP), a new shift to a more humid climate occurred, when the birch forests expanded again (van der Plicht et al., 2004; Bos et al., 2007). Well-preserved long sequences of annually laminated central European lacustrine sediments also testify to the presence of a short-term cooling in the early Preboreal. An increase in the thickness of varves in Lake Meerfelder Maar record in Germany and more negative δ18O values in the sediments of Lake Gościąż in Poland coincide with the PBO in time and indicate a cooling by approximately 3°C compare to the beginning of the Preboreal (Brauer et al., 1999).

The end of the PBO corresponds to the boundary between the early and late Preboreal. At the beginning of the late Preboreal, there was a new shift towards warming in the north of Europe, and a new stage in the spread of forest vegetation began, including the resettlement of pine. Thus, after 11.2 cal kyr BP, an increase in the content of organic matter in lake sediments in the central part of Latvia was registered. That may be explained by a decrease in the input of mineral particles into sediments under more forested conditions (Puusepp, Kangur, 2010). About 10.7 cal kyr BP dense pine forests developed in the southern part of the Baltic Sea basin (Bos et al., 2007). In general, in the Late Preboreal relatively warm and humid climatic conditions prevailed (Bos et al., 2007).

Despite numerous palynological studies of the Holocene sediments conducted in the European territory of Russia (Khotinski et al., 1991; Elina et al., 1995; Subetto et al., 2002; Novik et al., 2010; Novenko et al., 2014 and many others), the sections with Preboreal deposits studied in sufficient detail with good chronological control are still absent there, although the layers of this time interval can be distinguished on numerous pollen diagrams. This paper presents sedimentological and palynological data obtained from a sediment core taken from Lake Seliger (Konstantinov et al., 2021), where a new series of radiocarbon AMS-dates provides an opportunity to define position of the Preboreal interval and to investigate short-term vegetation and climate changes within it. We compared these data with earlier published evidence from five sites with the Late Glacial – early Holocene lake sediments, where the Preboreal interval can be distinguished with confidence. These sites are situated in the northwestern part of East Europe within the distance of 100–500 km from Lake Seliger: Lake Terebenskoye (Wohlfarth et al., 2007), Lake Dolgoye (Kremenetski et al., 2000), Moshkarnoye mire (Filimonova, 1995), Lake Sudoble (Bogdel et al., 1983; Novik et al., 2010), and Lake Nakri (Amon et al., 2012). We present a synthesis of these investigations and new studies of Lake Seliger deposits, to examine vegetation response to the climate oscillations during the Late Glacial and early Holocene period ca. 14000–9000 cal yr BP with special attention to the Preboreal interval and PBO.

2. STUDY AREA

Lake Seliger (57°17'N, 33°04'E, 205 m a.s.l.) is located on the Valdai Highlands, in the marginal zone of the last (Late Valdaian/Late Weichselian) glaciation (fig. 1). The landscape in the drainage basin of the lake combines glacial and glaciofluvial landforms and deposits. Lake Seliger with a total area of about 260 km^2 has a complex shape and consists of a chain of lakes and bays, interconnected by short channels. Long and narrow Selizharovskii bay forms the southernmost part of Lake Seliger.

The climate of the region is temperate and moderately continental, with the mean January and July temperatures –8.6°C and +17.5°C, respectively. The mean annual temperature is +4.5°C, annual precipitation amounts to 687 mm (Ostashkov weather station: http://meteo.ru/data). The lake area falls within the southern taiga zone (coniferous forest with minor inclusion of broadleaved trees) (Rastitel'nost'..., 1980). For hilly watersheds, spruce forests with participation of such broadleaved species as *Tilia cordata, Quercus robur,* and *Ulmus glabra* are typical; on sandy deposits, pine forests grow. Widespread birch (*Betula pendula, B. pubescens*), aspen (*Populus tremula*) and grey alder (*Alnus incana*) communities alternate with mires of various types in the paludified depressions.

3. MATERIALS AND METHODS

Lake coring was conducted from the lake ice in the southern part of the Selizharovskii bay, using a modified Livingstone piston corer (Konstantinov et al., 2021). The depth at the coring site SP-2 is 3.65 m. The core was extruded, wrapped in the field, transported, and subsampled in the Laboratory of Environmental Paleoarchives of the Institute of Geography of RAS.

The chronology of the SP-2 section is based on AMS radiocarbon dates of total organic carbon (TOC) and plant remains. Radiocarbon dating was performed in the Centre of Collective Usage "Laboratory of radiocarbon dating and electronic microscopy" of the Institute of Geography of RAS (Moscow, Russia). Calibration of ^{14}C dates was carried out in the OxCal 4.4 software package (Bronk Ramsey, 2009) based on the IntCal20 calibration curve (Reimer et al., 2020). Five new ^{14}C dates obtained in addition to two dates published in (Konstantinov et al., 2021) allowed improving the time resolution for the lower part of the

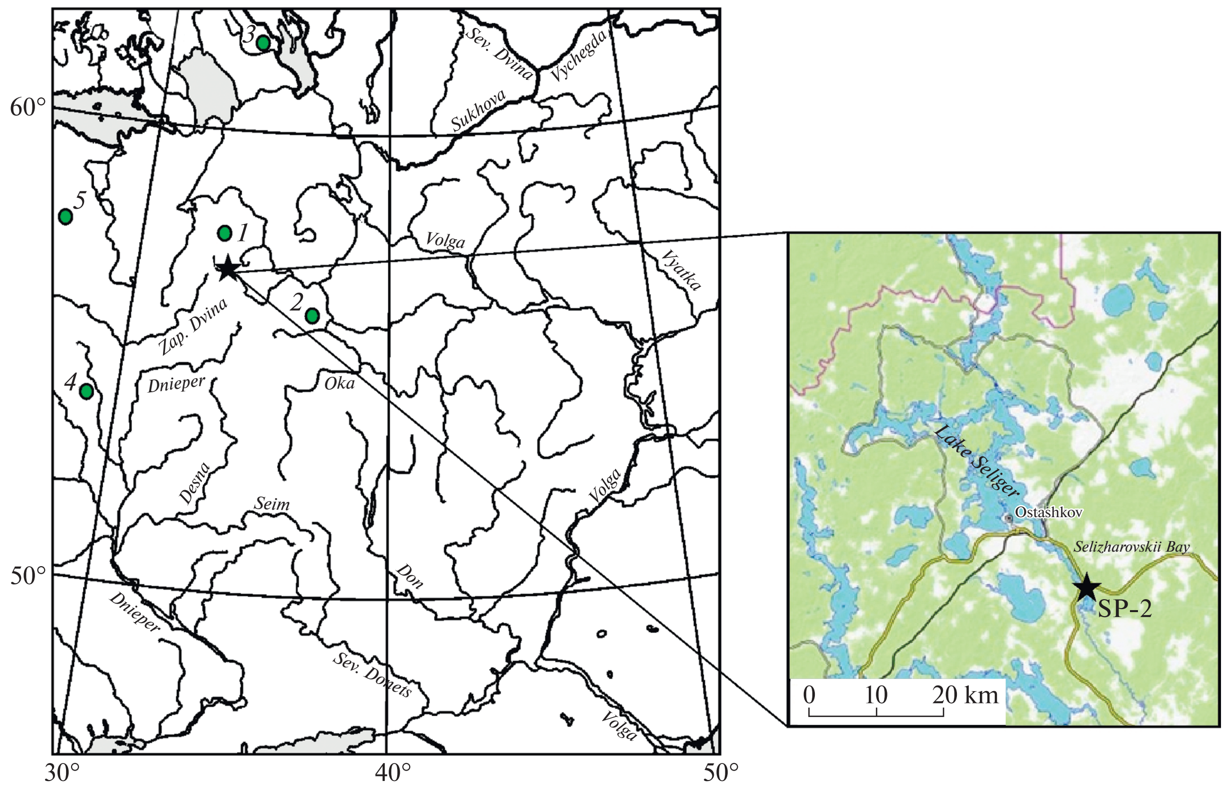

Fig. 1. Location of the study site (marked by an asterisk) and reference sites:
1 – Lake Terebenskoye (Wohlfarth et al., 2007); *2* – Lake Dolgoye (Kremenetski et al., 2000); *3* – Moshkarnoye mire (Filimonova, 1995); *4* – Lake Sudoble (Novik et al., 2010; Bogdel et al., 1983); *5* – Lake Nakri (Amon et al., 2012).

Рис. 1. Положение исследованного разреза (отмечено звездочкой) и разрезов, использованных для сравнения: *1* – оз. Теребенское (Wohlfarth et al., 2007); *2* – оз. Долгое (Kremenetski et al., 2000); *3* – болото Мошкарное (Filimonova, 1995); *4* – оз. Судобле (Novik et al., 2010; Bogdel et al., 1983); *5* – оз. Накри (Amon et al., 2012).

section including the Late Glacial and the early Holocene sediments.

The loss on ignition (LOI) analysis at 550°C, used to estimate the content of organic matter in lake sediments, followed the procedure described in (Heiri et al., 2001).

Separation with heavy liquid (2.25 g cm^{-3}) was used for pollen extraction from sediments. 500–600 pollen grains per sample were counted in order to ensure a statistically significant sample size. Calculation of pollen percentages was based on the total terrestrial pollen and spores sum – arboreal pollen (AP) plus non-arboreal pollen (NAP) plus spores. In addition, percentages of the main arboreal taxa were calculated based on the AP sum. Local pollen assemblage zones were identified by the analysis of statistical similarity of the AP composition by CONISS software program from TILIA special software package. Pretreated *Lycopodium* spores were added to each subsample of 1 cm^3 to calculate pollen concentrations and subsequently pollen accumulation rate (PAR) values, expressed as pollen grains cm^{-2} yr^{-1} (Stockmarr, 1971).

4. RESULTS

4.1. The data on the Late Glacial–early Holocene interval in sediment sequence from Lake Seliger (core SP-2)

4.1.1. Stratigraphy and radiocarbon dating. The following core stratigraphy was observed in the field and laboratory (Konstantinov et al., 2021):

0–270 cm – green-brown gyttja;

270–350 cm – dark brown gyttja;

350–460 cm – grey carbonate gyttja;

460–500 cm – fine and medium-grained sand.

Seven AMS radiocarbon dates were obtained from bulk organic sediment and plant remains from core SP-2 (table 1).

Six of them were used to compile a depth-age model for the lower part of the section (fig. 2). The new ^{14}C dates obtained made it possible to determine the position of the boundaries of the Blytt-Sernander climate-stratigraphic intervals in the SP-2 sediment sequence more accurately. An average sedimentation rate calculated for the Late Glacial – early Holocene interval using the calibrated chronology is 0.56 mm yr^{-1}.

Table 1. Results of radiocarbon dating of sediments from core SP-2
Таблица 1. Результаты радиоуглеродного датирования осадков из разреза SP-2

Laboratory code $IGAN_{AMS}$	Sampling depth, cm	Material	Radiocarbon date, ^{14}C yr BP (±1σ)	Calibrated age, cal yr BP (±1σ) IntCal 20
8148	63–65	TOC	6580 ± 25	7480 ± 40
8149	140–142	TOC	7670 ± 25	8455 ± 40
8150	219–221	TOC	8650 ± 30	9605 ± 45
8151	269–271	TOC	9205 ± 30	10 360 ± 65
6181	320–325	TOC	9510 ± 30	10 850 ± 130*
8152	373–375	TOC	10 475 ± 30	12 500 ± 120
6182	442	Plant remains	11 960 ± 35	13 810 ± 70*

* – ^{14}C dates published earlier in Konstantinov et al., 2021.

It varies through the core, from 0.4 mm yr in the Allerød and Younger Dryas, to 0.9 mm per year in the Preboreal, and about 0.5 mm yr^{-1} in the Boreal interval.

LOI analysis showed that at the beginning of the Allerød organic contents of the sediments increased rapidly from 2–3% to 10–15%, remained at this level for about one thousand years and continued to increase during the Younger Dryas to about 25% (Konstantinov et al., 2021). The main increase in the organic content of the sediment (from 25% to 50%) coincides with the Late Glacial – Holocene boundary. Up the section, LOI decreases by 5–7% and then increases once again reaching the maximum values for the entire section (over 60%). In the layer corresponding to the early Boreal, LOI remains at about 55% and gradually decreases to 40% during the late Boreal.

4.1.2. Pollen analysis. The pollen stratigraphy of the SP-2 core extends back to approximately 14 cal kyr BP and provides evidence of vegetation and climate histo-

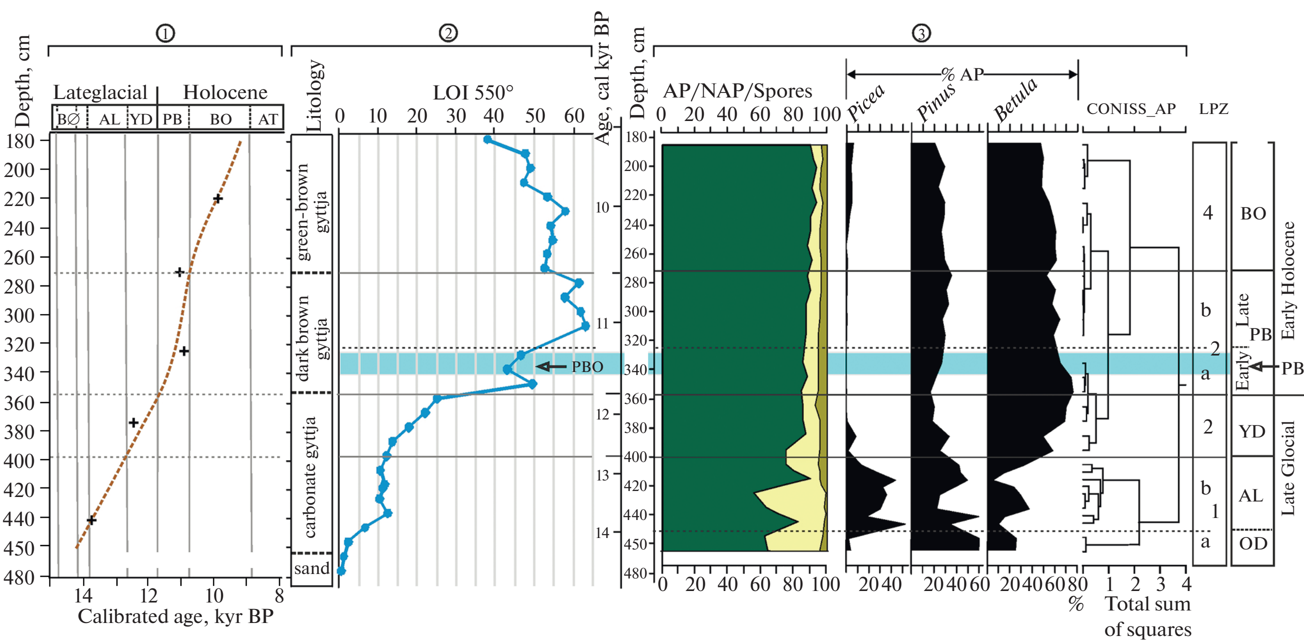

Fig. 2. The main results obtained for SP-2 core from Lake Seliger:
1 – sedimentation rates as estimated from radiocarbon dates; 2 – sediment properties (adapted from Konstantinov et al., 2021); 3 – general composition of the pollen spectra and pollen contents of selected tree species. Biostratigraphy: OD – Older Dryas, AL – Allerød, YD – Younger Dryas, PB – Preboreal, BO – Boreal, PBO – Preboreal Oscillation.

Рис. 2. Основные результаты, полученные по разрезу отложений оз. Селигер SP-2:
1 – скорости осадконакопления, реконструированные по ^{14}C-датировкам; 2 – изменения состава осадков (по Konstantinov et al., 2021); 3 – общий состав пыльцевых спектров и содержания пыльцы основных пород деревьев. Биостратиграфия: OD – средний дриас, AL – аллерёд, YD – поздний дриас, PB – пребореал, BO – бореал, PBO – пребореальная осцилляция.

ry of the Late Glacial, beginning from the Older Dryas cooling, and the entire Holocene. In this article, we will discuss the results of pollen analysis obtained on the Preboreal interval of the section, in comparison with the data on the Late Glacial and Boreal, which were only in a small part published in our previous paper (Konstantinov et al., 2021). In the pollen sequence under consideration, four local pollen zones (LPZ) are distinguished (fig. 2).

In LPZ 1 (464–400 cm; from about 14.5 cal kyr BP extrapolated to 12.7 cal kyr BP), the NAP make up to 40–50% of pollen spectra, *Artemisia* and Cyperaceae pollen being the most abundant of the group. In the lowermost part of the zone corresponding to the Older Dryas (LPZ 1a), tree pollen consists almost entirely of *Betula* and *Pinus*. In PAZ 1b, correlated to the Allerød interstadial, *Picea*, *Pinus* and *Betula* dominate the AP group. Pollen percentages and accumulation rates of *Picea* are at their maximum for the diagram: 30–45% of AP and up to 9000 grains cm^{-2} yr^{-1}. First *Betula* sect. *Albae* and then *Pinus* pollen contents increase in the upper part of the zone (up to 40–50% of AP and up to 10×10^3 grains cm^{-2} yr^{-1}), while *Picea* percentages and PAR decrease rapidly.

In LPZ 2 (400–355 cm; 12.7–11.7 cal kyr BP), correlated to the Younger Dryas cold stage, pollen percentages and accumulation rates of *Picea* further decline. *Pinus* pollen percentages decrease from 40% to 15% of AP, although PAR remain at the same level as in LPZ 1. *Betula* percentage and accumulation rates increase steeply to 70% of AP and 30×10^3 grains cm^{-2} yr^{-1}, respectively. AP content increases up to 85% of pollen and spores sum. Herb pollen percentages decline to 10–20%, but NAP accumulation rates are close to those in LPZ 1.

LPZ 3 (355–270 cm; 11.7–10.7 cal kyr BP) generally corresponds to the Preboreal epoch of the Holocene. In subzone 3a, percentages of *Betula* pollen reach their maximum for the diagram: 75% of AP. PAR of tree birch continues to increase and reaches the maximum at about 100×10^3 grains cm^{-2} yr^{-1} in subzone 3b, despite a decrease of *Betula* percentages by 20%, with a corresponding increase in the share of *Pinus* pollen in pollen spectra. *Pinus* also has its highest PAR in subzone 3b (up to 50×10^3 grains cm^{-2} yr^{-1}). *Picea* pollen in LPZ 3 is rare. NAP percentages continue to decline, although accumulation rates of Poaceae, Cyperaceae, and *Artemisia* increase considerably by the beginning of the late Preboreal (LPZ 3b).

In LPZ 4 (270–180 cm; 10.7–9.0 cal kyr BP), pollen percentages and PARs of birch and pine are similar to those in LPZ 3b, and continuous deposition of spruce pollen resumes. PAR of *Picea* reaches $6–7 \times \times 10^3$ grains cm^{-2} yr^{-1} in the upper part of LPZ 4. Accumulation rates for Poaceae, Cyperaceae, Chenopodiaceae and *Artemisia* remain at the same level as in LPZ 3b, although NAP percentages in PAZ 4 are at a minimum for the diagram (5–7% of spectra).

4.2. Previously published data on the Late Glacial-early Holocene sediment sequences chosen for comparison

4.2.1. Lake Terebenskoye is located on the Valdai Highland (58°08′N, 32°59′E, 153 m a.s.l.), about 100 km north of Lake Seliger. AMS ^{14}C dating and lithological, geochemical and plant macrofossil analyses for the 5 m sediment sequence from Lake Terebenskoye suggest that sedimentation started there about 14 cal kyr BP (Wohlfarth et al., 2007). Total carbon content (TC) is very low in the layer of silty clay accumulated during the Late Glacial and increases to 8% at the top of this layer, which corresponds to the Younger Dryas/Holocene transition according to the age-depth curve. TC drops again and remains low (1–3%) during the early Preboreal. It rises sharply around 11.3 cal kyr BP and remains at the level of 5–7% during the late Preboreal, when silty clay gyttja accumulates in the lake. In the Boreal, a gradual rise in TC up to 10–12% is registered; fine detritus gyttja accumulated in the lake (Wohlfarth et al., 2007).

Plant macrofossils found in the lowermost part of the Lake Terebenskoye sediment sequence (13.8–12.5 cal kyr BP) are of *Betula nana* and *Dryas octopetala*, which is consistent with low TC values indicating a low productivity lake. 14C-dated macrofossils indicate the time since which spruce, pine, and birch participate in the local vegetation on the Valdai Highlands. *Picea abies* needles and seeds from the Terebenskoye sequence are dated to approximately 12 cal kyr BP. The first *Pinus sylvestris* remains occur there at about 11.4 cal kyr BP and *Betula pubescens* remains first appear in the sediment sequence at 11.2 cal kyr BP (Wohlfarth et al., 2007).

4.2.2. Lake Dolgoye (56°04′N, 37°20′E, 201 m a.s.l.) is located on the Klin-Dmitrov Ridge, about 270 km to the east-south-east from Lake Seliger. The lower layer of lake deposits 305 cm thick consists of clayey silt with gradually increasing organic content in the upper 50 cm (Kremenetski et al., 2000). It is overlain by gyttja ~500 cm thick. AMS ^{14}C date obtained at the base of the sediment sequence indicates that accumulation in the lake started around 14.5 cal kyr BP. Unfortunately, the other 11 ^{14}C dates were obtained from organic deposits in the upper part of the section, above the Boreal/Atlantic boundary (Kremenetski et al., 2000). Therefore, we compiled the depth-age model for the lower part of the section by interpolation between two available ^{14}C dates, based on the assumption of a constant accumulation rate of lacustrine silts supported by pollen stratigraphy.

LOI analysis (Kremenetski et al., 2000) showed low and relatively stable contents of organic matter (7–10%) in the layer of clayey silt, with a slight rise at the very beginning of the Holocene (up to 15%) and a small decline in the interval comparable in time to the PBO. The rapid increase of LOI from 10% to 50–60% coincides in time with the Boreal. Similar phases of changes are expressed more clearly in the AP/NAP ratio in the pollen spectra. During the transition from the Late Glacial to the Holocene, percentages of AP increase to 55% of the terrestrial pollen sum Σ. They decrease to 30% with the onset of the PBO, increase again to 40% in the late Preboreal and sharply increase in the Boreal (up to 80–90% of Σ). These changes are also reflected in the pollen ratios of the main tree species (*Picea*, *Pinus*, and *Betula*). Birch pollen accounts for up to 70–90% of AP in most samples from the Late Glacial–early Holocene interval. The share of spruce and pine pollen sharply increases at the very beginning of the Preboreal and decreases just as sharply in the PBO interval. A new maximum of *Pinus* pollen (up to 30–40% of AP) corresponds to the Boreal, while *Picea* pollen in this layer is rare.

In the Allerød, PAR of *Picea* in the Lake Dolgoye sediment sequence does not exceed 1000 grains cm^{-2} yr^{-1}. However, findings of spruce stomata in the same layer confirm its presence at the site. Preboreal and Boreal sediments are characterized by extremely low PAR of *Picea*. PAR of *Pinus* show a slight rise in the Allerød layers and a more significant increase (up to 600 grains cm^{-2} yr^{-1}) at the lower boundary of the Holocene. Only in the middle part of the Boreal, *Pinus* PAR va-lues exceed the “local presence limit” of 500 grains cm^{-2} yr^{-1} (Seppä, Hicks , 2006) and continue to rise rapidly in the late Boreal (up to 8–11 × × 10^3 grains cm^{-2} yr^{-1}). Changes in *Betula* PAR are similar to those described for *Pinus* pollen, although the contents of birch pollen are generally higher. The main difference is the rise of *Betula* PAR to the pre-PBO level of over 1000 grains cm^{-2} yr^{-1} indicating local presence of *Betula* and development of open birch forests, according to (Seppä, Hicks, 2006), already in the late Preboreal.

4.2.3. Moshkarnoye mire (62°15′N, 34°00′E, 50 m a.s.l.) is situated in the Lake Onega basin, about 500 km north of Lake Seliger. According to (Filimonova, 1995), the sediment sequence ~15 m thick includes 7 m of lake clay overlain by 4 m of clayey gyttja and 4.5 m of peat. Nine ^{14}C dates were obtained for bulk peat and gyttja samples from the upper 8 m of the sediment core. Calibration of these dates and extrapolation of resulting age-depth curve into the lower part of the section, assuming a steady accumulation rate of the lacustrine clay, indicates that the deposition in the lake began at least as early as 13.2 cal kyr BP, at the end of the Allerød. Pollen stratigraphy confirms positions of the boundaries between the main stages of the Late Glacial and early Holocene, drawn based on the sedimentation model. According to the model, Preboreal deposits in this section are unusually thick – about 3 m.

The AP content is up to 60% of the terrestrial pollen sum in the Allerød; it decreases to 15–20% in the Younger Dryas and increases to 35% in the early Preboreal. In the depth interval corresponding to the PBO, AP decrease to 20% and rise again in the late Preboreal to ~50%. The increase of AP continues in the Boreal, reaching 90% of spectra by its end (Filimonova, 1995). In the lower part of the sediment sequence, pollen of *Betula* sect. *Albae* is the most abundant (60–70% of AP). *Pinus* pollen contents increase from 10–15% in the Late Glacial to 50% in the early Boreal and reach their maximum (>90% of AP) in the late Boreal. *Picea* pollen is rare; it forms a continuous curve only at the base of the section, in the layers corresponding to the late Allerød and beginning of the Younger Dryas. *Betula* sect. *Nanae* pollen curve culminates in the Younger Dryas (~35%), and then gradually decline to disappear at the middle of the Boreal. In the interval corresponding to the PBO, the pollen diagram shows a decrease of *Pinus* pollen by 8–10% and a small increase of *Juniperus* pollen, which form a continuous curve in the Late Glacial part of the section and very seldom occur in its Holocene part (Filimonova, 1995).

4.2.4. Lake Sudoble (54°03′N, 28°24′E; 165 m a.s.l.) is situated in the Dnieper River basin in the central part of Belorussia, approximately 450 km to the southwest from Lake Seliger. The thickness of the sediment core is 9 m (Bogdel et al., 1983). At the base of the core, a thin layer of peat of the Allerød age overlies glaciofluvial sands. It is covered by sandy gyttja accumulated during the late Allerød, Younger Dryas and Preboreal. Starting from the Boreal, >7 m of detritus gyttja accumulated at the site. Eight calibrated ^{14}C dates based on TOC (Novik et al., 2010) make it possible to build a depth-age model and to determine positions of the Preboreal interval and PBO in the sediment sequence and on the pollen diagram.

Arboreal pollen contents reach 80–90% of the terrestrial pollen sum in the Allerød and 65–80% in the Younger Dryas. *Pinus* pollen dominate in the entire Late Glacial part of the sequence, reaching 75–85% of AP, while *Betula* pollen make up 20–30% of AP (Bogdel et al., 1983). Pollen percentages of *Picea* slowly increase from zero to 10% during the Late Glacial, rise to 15% at the Holocene boundary and remain at 12–13% of AP during the Preboreal. In the Boreal, spruce pollen occurs rarely. The warming at the lower boundary of the Holocene is marked by a sharp increase in the share of *Betula* pollen (up to 40% of the AP). At the depth corresponding to the PBO, its content decrease due to an increase in the proportion of *Pinus* pollen. It rises again in the late Preboreal and reaches a maximum for the entire section (~70%) at the beginning of the Boreal. In the late Boreal, birch/pine pollen ratio is close to 50/50 (Bogdel et al., 1983).

4.2.5. Lake Nakri (57°54′N, 26°16′E, 48.5 m a.s.l.) is situated in the Baltic area, in southern Estonia, in approximately 420 km to the west-north-west of Lake Seliger. The sediment thickness from Lake Nakri includes ~4 m of silt, sandy at the bottom and increasingly clayey at the top, near the Late Glacial–Holocene boundary, with an interlayer of silt with organic matter corresponding to the Allerød (Amon et al., 2012). These mineral deposits are overlain by gyttja

3 m thick. The age-depth model of sedimentation is based on nine AMS ^{14}C dates.

The LOI measurements indicate a very rapid rise in organic matter content from 5% to 30% during the early Preboreal. At the very beginning of the Preboreal, LOI rises more slowly, so that it first reaches the level of the end of the Allerød before the PBO. Then a rapid rise begins with a slowing down corresponding to the PBO (Amon et al., 2012).

The data from Lake Nakri include high-resolution pollen and plant macrofossil records (Amon et al., 2012). In the layer corresponding to the Older Dryas and early Allerød, AP/NAP ratio is 40/60. Tree *Betula* and *Pinus* each make up about 20% of the total terrestrial pollen sum, shrubs *Betula nana*, *Salix*, and *Juniperus* are present. *Betula* PAR is <500 grains cm^{-2} yr^{-1}. The reconstructed vegetation type for this time interval is treeless tundra. In the later part of the Allerød, AP dominate pollen spectra (up to 80%); *Betula* and *Pinus* reach over 30%, *Betula nana* and *Juniperus* expand. *Betula* PAR increase to 4700 grains cm^{-2} yr^{-1} and *Pinus* PAR rise to 2400 grains cm^{-2} yr^{-1}, indicating spread of forest-tundra with birch and scattered pine. A single stoma of pine was found at a depth corresponding to 13 250 cal yr BP, where the PAR of *Pinus* is about 2000 grains cm^{-2} yr^{-1}. This finding confirms the local presence of pine. In layers corresponding to the Younger Dryas, AP/NAP ratio is approximately 50/50. Tree *Betula* and *Pinus* pollen are less than 20% each; *Betula nana* and *Juniperus* pollen contents reach their maxima. PAR of *Betula* is less than 1000 grains cm^{-2} yr^{-1}. For the Younger Dryas cooling, treeless tundra vegetation is reconstructed at the site (Amon et al., 2012).

In the interval corresponding to the early Holocene as a whole, AP dominates the pollen spectra (up to 90%). Tree *Betula* reaches 80% of the total terrestrial pollen sum, pollen of shrubs and NAP decline drastically. Macrofossils of *Betula nana* and macrospores of *Selaginella selaginoides* found below the boundary between the Late Glacial and Holocene are not registered in the Preboreal. In the early Preboreal, PARs of *Pinus* and *Betula* remain approximately at the same level as in the Younger Dryas – somewhat below the "forest level" for birch (about 1000 grains cm^{-2} yr^{-1}) and the "local presence level" for pine, >500 grains cm^{-2} yr^{-1} (Seppä, Hicks, 2006). However, already in the late Preboreal and at the beginning of the Boreal, *Betula* PAR exceeds 20×10^3 grains cm^{-2} yr^{-1}. Macrofossils of *Betula alba* are found in the section immediately after the PBO, indicating a rapid warming. *Pinus* PAR also increases during the late Preboreal and at the beginning of the Boreal reaches about 4×10^3 grains cm^{-2} yr^{-1} suggesting forest expansion (Amon et al., 2012).

5. DISCUSSION

5.1. Sedimentation history. During the Late Glacial and early Holocene, in all the sections discussed above lacustrine sediments accumulated. From sedimentation models based on ^{14}C dating, the boundaries of the main climatic phases were determined in the sections, with special attention to the Preboreal and to the time interval corresponding to PBO. The analysis of ^{14}C and lithological data shows that sedimentation in all these sections began at 13–14.5 cal kyr BP. The composition of lacustrine deposits changed everywhere in a similar way – from predominantly mineral deposits in the Late Glacial to those with high organic contents (gyttja) in the early Holocene. Nevertheless, both the time of the transition to the accumulation of gyttja and the nature of changes in the sediments' composition vary considerably from place to place.

In the Lake Seliger sediments, the transition from carbonate gyttja with LOI 10–15% to typical gyttja with LOI >50% corresponds to the beginning of the Holocene (Konstantinov et al., 2021). At the Lake Nakri site, the transition from lacustrine silt to gyttja also roughly corresponds to the Late Glacial–Holocene boundary: during the early Preboreal, LOI increases there from 5% to ~30% (Amon et al., 2012). In Lake Terebenskoye, where organic contents are generally low, the transition from silty clay to clayey gyttja corresponds to the beginning of the late Preboreal, and accumulation of detritus gyttja begins in the Boreal (Wohlfarth et al., 2007). In the sediments of Lake Dolgoye, clayey silt gives way to gyttja accumulation at the boundary between the Preboreal and Boreal, and at the beginning of the Boreal, the organic content in the sediment rapidly rises from 10% to 50% (Kremenetski et al., 2000). In the Sudoble section, sandy gyttja accumulated until the Boreal when formation of detrital gyttja began (Bogdel et al., 1983). In the lake that existed in the Late Glacial in place of the modern Moshkarnoye mire, mineral clays accumulated till the middle of the Boreal (~9500 cal yr BP); they are overlain by a gyttja with a thin (~20 cm) clayey interlayer at the base (Filimonova, 1995).

Changes in LOI of the sediments of lakes Seliger, Dolgoye, Nakri, and Terebenskoye show traces of a short-term cooling corresponding to PBO. Thus, in the Seliger section, after a sharp increase at the transition to the Holocene, a decrease in LOI by 5–7% coincides with the PBO time interval. At the beginning of the late Preboreal, this brief drop is succeeded by a new increase in LOI to 60–65%. In the Dolgoye section, a 7% decrease in LOI also corresponds to PBO. However, the organic contents in this section remained at this low level throughout the entire Preboreal, and only at the beginning of the Boreal did the rise of LOI resume. A similar temporal structure is shown by the carbon content changes in the sediments of Lake Terebenskoye (Wohlfarth et al., 2007). In Lake Nakri, the PBO time interval is marked by a slowdown in the increase of LOI at a level of about 20%. We assume that these changes reflect a temporary reduction in the productivity of lakes caused by a short-term cooling corresponding to PBO. A rapid warming at the beginning of the late Preboreal brought about a new increase in the productivity of lake ecosystems.

5.2. Vegetation history. Changes in the AP/NAP proportion in the lake sediments generally reflect the role of trees in the composition of vegetation at the studied sites during the period ca. 14–9 cal kyr BP. It increased during the Allerød interstadial warming and decreased again in the Younger Dryas cold stage. In all the considered sections, the main species in the AP group are *Betula* and *Pinus*, as well as *Picea* in the sections Seliger, Dolgoye, and to a lesser extent Sudoble. The role of such wind-pollinated trees with high pollen productivity, as pine and birch, in local vegetation is difficult to assess only by the percentages of their pollen in the spectra. To improve our reconstruction, we used for the purpose additional information from PAR calculations, dated tree macrofossils, and stomata of the coniferous trees found in the studied lake sediments.

In the Allerød, PARs of *Pinus* and *Betula* in the Seliger, Dolgoye, and Nakri sections exceeded the values indicating their local presence according to (Seppä, Hicks, 2006). Tree *Betula* macrofossils and a single *Pinus* stoma were found in the Nakri section in a layer with an age of 13–13.5 cal kyr BP (Amon et al., 2012). Thus, both birch and pine took part in the vegetation at these sites already in the Allerød, forming the forest-tundra or open forest communities. The ratio of pine and birch in such communities probably depended from local features, in particular, from the spread of sandy soils. The participation of *Picea* in local vegetation was definitely established for the Seliger and Dolgoye sites, where, in addition to a high proportion of spruce pollen in the spectra (up to 30–40% of AP), *Picea* PARs form a distinct peak in the Allerød, reaching 9000 and 1000 grains cm^{-2} yr^{-1}, respectively. Moreover, *Picea* stomata were found in the same layer in the Dolgoye section. It is difficult to prove the presence of spruce in the Allerød at the other sites, since *Picea* pollen occur there in very small quantities.

In response to the cooling at the beginning of the Younger Dryas, the PAR of spruce, pine, and birch in the Seliger and Dolgoye sections, as well as the PARs of pine and birch in the Nakri section, decreased quite sharply, reflecting a decline of forest communities. Warming at the Late Glacial/Holocene boundary led to a new increase in the tree pollen accumulation. It is also indicated by a significant shift in the AP/NAP ratio towards tree pollen domination. In the Dolgoye section, pollen of spruce and pine reached 30% of AP each in the early Preboreal. At the same time, *Pinus* PAR in the sections Seliger and Dolgoye exceeds the value of the Allerød. A rapid increase in *Betula* PAR in the Seliger section begins already ~13 cal kyr BP, proceeds steadily during the Younger Dryas, and reaches a peak at the beginning of the late Preboreal, while in the Dolgoye section a sharp rise in *Betula* PAR occurs later, in the Boreal. In the Terebenskoye section, the earliest dated finds of *Picea* macrofossils date back to the end of the Younger Dryas, and those of tree birch – to the beginning of the Preboreal (Wohlfarth et al., 2007), which also confirms the increased participation of these species in the local vegetation in response to the warming at the Late Glacial/Holocene transition. The onset of the Boreal was characterised by the introduction of broadleaved species into forest communities and a decrease in the landscape role of birch forests indicating further warming and some amelioration of climate continentality.

In the pollen diagrams of the sections discussed above, the Preboreal cold oscillation dated to around 11.4–11.2 cal kyr BP (Rasmussen et al., 2006) is reflected rather weakly. In most diagrams, this interval corresponds to a decrease in the proportion of AP in the spectra compared to the beginning of the Preboreal. In the Dolgoye section, there is a decrease in the PARs of the main trees, and in the Seliger section, an increase in the PARs of herbaceous plants, especially Poaceae and *Artemisia*, was also registered. In the Nakri and Moshkarnoye pollen sequences, the PBO corresponds to a small peak of *Juniperus* pollen, which is more characteristic of the Younger Dryas pollen spectra (Filimonova, 1995; Amon et al., 2012).

5.3. Comparison with PBO manifestations in northwestern and central Europe. In general, similar changes in the composition of sediments and pollen spectra are much more pronounced in the sedimentological and paleobotanical data from northwestern and central regions of Europe (Brauer et al., 1999; van der Plicht et al., 2004; Bos et al., 2007). For example, the LOI curve of the Lochem-Ampsen record in The Netherlands shows considerable shifts (Bos et al., 2007): by the end of the early Preboreal warming (the so-called Friesland Phase) LOI reaches 40% and then drops to about 10% at the beginning of the Rammelbeek Phase corresponding to the PBO in The Netherlands. During the late Preboreal, the LOI values increase once again to around 85% and later only minor oscillations are recorded (Bos et al., 2007). In the Lochem-Ampsen section, the pollen contents of *Betula* sect. *Albae* which make up 50–70% of the terrestrial pollen sum in the Younger Dryas and early Preboreal, decrease to 20–30% in the PBO interval. The proportion of upland herbs pollen (with the exception of Cyperaceae) in this cold interval is 2–3 times higher than in the end of the Younger Dryas and during the initial warm phase of the early Preboreal.

Similar changes in the composition of pollen spectra are also found in the Borchert section in The Netherlands, where the content of *Betula* sect. *Albae* pollen increases from 30% at the end of the Younger Dryas to 90% at the end of the Friesland warming, while in PBO it sharply decreases to 30–40% (van der Plicht et al., 2004). The content of *Pinus* pollen, which reaches 20–30% of the terrestrial pollen sum in the Younger Dryas, does not exceed 5% of the pollen spectra in the Early Preboreal (van der Plicht et al., 2004).

The short cooling corresponding to PBO is also clearly manifested in the varved lake sediment records, such as that of Meerfelder Maar in Germany, as well as in a negative excursion in the δ18O values in the lake carbonate record of Lake Gościąż in Poland (Brauer et al., 1999).

6. CONCLUSION

Detailed high-resolution multi-proxy studies of lake sediments, including AMS ^{14}C dating, lithology, LOI measurements, pollen analysis and identification of plant macrofossils, of Lake Seliger and five other lacustrine records used for comparison showed the main features of changes in the productivity of lakes and vegetation development in response to the short-term climatic oscillations during the Late Glacial and early Holocene.

The Allerød interstadial was the first warming episode when spruce, birch and pine spread in the northwest of European Russia and formed the forest-tundra or open woodlands. A substantial cooling in the Younger Dryas caused a rapid decline of forest communities and a re-advance of the tundra-steppe vegetation with scattered groups of trees in the most protected habitats.

Following the rapid climate warming at the Late Glacial/Holocene transition, woodlands formed by cold-resistant and light-loving pioneer species – birch and, somewhat later, pine – expanded again over the area. A short-term cooling in the PBO, around 11.4 cal kyr BP, most clearly manifested itself by a decrease in the proportion of organic matter in lake sediments. It also interrupted or slowed down the expansion of birch and pine forests and caused a new spread of open grassland vegetation. At the beginning of the late Preboreal, there was a new rapid shift to a warmer and more humid climate, and birch forests expanded again, followed later by pine. Further warming during the Boreal brought about the beginning of the introduction of broadleaved species into forest communities and a decrease in the landscape role of birch forests.

Our analysis showed that the first short-term cooling of the Holocene, corresponding to the PBO in the Greenland ice-core records, also manifested itself in the northwest of European Russia. However, the impact of this cooling on the vegetation development and lake ecosystems was probably weaker than in north-western and central Europe.

Landscape And Climate Changes in the Preboreal in the Northwestern European Russia

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High-resolution multi-proxy studies of lake sediments, including AMS ^{14}C dating, lithology, loss-on-ignition measurements, pollen analysis and identification of plant macrofossils, of Lake Seliger (57°17'N, 33°04'E) and five other lacustrine records from the adjacent areas used for comparison, make it possible to reconstruct the main changes in the productivity of lakes and vegetation development in response to the short-term climatic oscillations during the Late Glacial and early Holocene. The analysis showed that lacustrine sedimentation at all these sites began 13–14.5 cal kyr BP, in the Allerød Interstadial, when spruce, birch and pine began to spread in the northwest of European Russia forming the open woodlands. A substantial cooling in the Younger Dryas caused a rapid decline of forest communities and a re-advance of the tundra-steppe vegetation with scattered groups of trees in the protected habitats. The composition of lake sediments changed everywhere in a similar way – from predominantly mineral deposits in the Late Glacial to those with high organic contents (gyttja) in the early Holocene. Following the rapid warming at the Late Glacial/Holocene transition, woodlands formed by birch and, later, pine expanded again over the area. A short-term cooling 11.4–11.2 cal kyr BP, coeval with the Preboreal Oscillation observed in the Greenland ice-core records, most clearly manifested itself by a decrease in the proportion of organic matter in lake sediments. It also interrupted or slowed down the expansion of birch and pine forests and caused a new spread of open grassland vegetation. However, the impact of this cooling on the vegetation development and lake ecosystems in the northwest of European Russia was probably weaker than in western and central Europe. At the beginning of the late Preboreal, there was a new rapid shift to a warmer and more humid climate, when birch forests expanded again, followed later by pine. Further warming during the Boreal brought about the introduction of broadleaved tree species into forest communities and a decrease in the landscape role of birch forests. At this time, some lakes were filled, and lacustrine sedimentation was replaced by the formation of peat.

Keywords: lake sediments, rapid climate changes, early Holocene, Preboreal Oscillation

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