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Article

Short-Term Climatic Oscillations in the Central Region of the East-European Plain at the Beginning of the Holocene Based on Palynological Studies of Lacustrine Deposits

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Abstract: The Preboreal (11.75–10.70 ka BP) is still the least paleogeographically studied time interval in the central part of the East European Plain. High-resolution multi-proxy studies of lacustrine sediments at the Seltso site located in the Desna River floodplain (Dnieper River basin) were conducted. Radiocarbon dating, loss-on-ignition determination, sedimentological and palynological studies and identification of Non-Pollen Palynomorphs in lacustrine sediments allow us to reconstruct changes in vegetation caused by rapid warming at the Younger Dryas–Holocene boundary, short-term climatic fluctuations within the Preboreal and subsequent resumption of warming. Initial Preboreal warming reached its maximum at about 11.5 ka BP when a relatively dry continental climate existed. Between 11.4 and 11.2 ka BP, a short-term cooling corresponding to the Preboreal Oscillation in Greenland occurred, as indicated by a significant reduction of woody vegetation and expansion of open plant communities. In the Late Preboreal, approximately 11.2–10.7 ka BP, warming resumed, which was accompanied by a decrease in the climate continentality. Comparison with high-resolution lithological and palynological data from eight reliably dated sections of the central East European Plain indicates that in northwestern and central Europe, the impact of the Preboreal Oscillation cooling on the vegetation and the lake ecosystems' development was probably somewhat stronger.

Keywords: lacustrine sediments; pollen analysis; rapid climate changes; Preboreal Oscillation; Early Holocene

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1. Introduction

Studies of changes in the isotopic composition of ice from GRIP, GISP2 and NGRIP cores from the Greenland Ice Sheet ([1–3] and references therein) showed that after a series of contrasting climatic phases of the Late Glacial, around 11.75 ka BP, extremely rapid warming occurred, indicating the transition to the Holocene. This warming reached 10 ± 4 °C over a period of about 50 years [4], after which there was a relative stabilization of climatic conditions in the Holocene. According to the European Blytt–Sernander biostratigraphic scale, this boundary corresponds to the transition from the Younger Dryas to the Preboreal, when the most profound transformation of vegetation cover and landscape systems took place. This rapid warming continued into the warm initial phase of the Early Preboreal, lasting about 300 years, after which a 200-year-long cooling event occurred in Greenland (the so-called Preboreal Oscillation—PBO) [1]. This cold episode was followed by new warming when the air temperature in Greenland increased by 4 ± 1.5 °C within several decades [5].

Multi-proxy studies of the lacustrine sediment cores indicate a cooling corresponding to the PBO in various regions of northwest and central Europe, although the weak response of ecosystem components to this climatic event combined with its short duration makes it difficult to detect its traces [6]. The combined lacustrine, tree-ring and glacial records imply that the PBO was characterized by cool and humid conditions [6]. Palynological data for The Netherlands indicate that tundra-steppe grass-shrub communities, characteristic of the

Younger Dryas, were replaced by birch woodlands in the initial warm phase of the Preboreal at ~11.5 calibrated ka BP [7,8]. Between 11.43 and 11.35 ka BP, a dry continental phase with a noticeable cooling interrupted forest expansion, causing a new extension of open plant communities [7,8]. At the beginning of the Late Preboreal (11.27–11.21 ka BP), climate humidity increased again, marked by an increase in the proportion of birch forests in the vegetation cover. At the end of the Late Preboreal, pine began to establish, and about 10.7 ka BP, pine forests became widespread in The Netherlands [8]. In general, in the Late Preboreal, the climate in northern Europe became relatively warm and humid [8]. The vegetation responses to PBO were also observed in pollen records from lake sediments in Switzerland [9–12].

High-resolution stable-isotope records of lake sediments in Central Europe showed close similarities to the Greenland stable-isotope record [13–15]. A short-term cooling in the Early Preboreal also manifested itself in a decreased thickness of the annual layers of sediments of Lake Meerfelder Maar in Germany [16,17]. A decrease in δ18O values in carbonate deposits of Lake Gościąż in central Poland, coinciding with the PBO, indicates a cooling of about 3 °C compared to the beginning of the Preboreal [16]. Chironomid analysis of the Lake Gościąż sediments also points to a decrease in temperature during the PBO [18]. Multi-proxy studies of sediments of Lake Jelonek, situated in northern Poland, suggest two phases of cooling during the PBO, as well as a considerable change in terrestrial plant communities, reflected in a replacement of birch woodlands by grass vegetation [19]. The multi-proxy data (pollen, diatoms, Cladocera and 14C) from the sediments of Lake Suchar Wielki in NE Poland indicate three short cold events during the Early Preboreal, with a drop in temperature and a decrease in humidity [20]. In southern Estonia, the cooling during the PBO was expressed in a slowdown in the productivity of Lake Nakri, a decrease in the proportion of arboreal pollen in the lake sediments, and a reduction in the Pollen Accumulation Rates (PARs) of *Pinus* and *Betula* [21]. In the Late Preboreal, the productivity of Lake Nakri and *Betula* PAR increased again. In the part of the section after the PBO, macrofossils of *Betula alba* were found, which indicates rapid warming. *Pinus* PAR also increased during the Late Preboreal and at the beginning of the Boreal, suggesting pine forest expansion in the area [21]. At the beginning of the Late Preboreal, an increase in the organic contents in lake sediments was also noted in the central part of Latvia. It can be explained by an increase in lake productivity and a decrease in the input of mineral particles into sediments under conditions of forest expansion [22].

Problems in the reconstruction of landscape-climatic changes at the transition from the Late Glacial to the Holocene are associated with active erosion processes that often prevented the accumulation of a continuous series of sediments, with the low content of organic matter in terrigenous deposits, insufficient for bulk radiocarbon dating and with the predominance of wind-pollinated trees that produce abundant pollen (birch and pine). Because of these difficulties, the Preboreal to this day remains the least studied interval in the mid-latitudinal part of the East European Plain despite numerous palynological studies of Holocene sediments conducted in the region [23–31]. N.A. Khotinsky [32] identified for the first time two stages within the Preboreal in European Russia—an early, warmer (the so-called Polovetskoe warming) and a later, colder stage (Pereslavl' cooling)—mainly based on changes in the pollen contents of shrub birches in the section of the Polovetsko–Kupanskoe mire. A high-resolution palynological study of this peat section [23] and a new series of 15 radiocarbon dates made it possible to improve the reconstruction of vegetation and climate changes during the Holocene. However, even in this new record, still only two samples corresponded to the Preboreal. We hope that the data obtained on the Seltso record with high time resolution for the Preboreal and its comparison with the results of studies of eight sections from the adjacent territory will allow us to fill this information gap to some extent.

The probable cause of the short-lived cooling that interrupted the warming process at the end of the Early Preboreal was a sudden release of meltwater from Lake Agassiz into the North Atlantic. Desalination of surface seawater led to a temporary suppression of the thermohaline circulation [33]. A similar mechanism is proposed for the development of other multi-centennial cooling events of the Early Holocene, the most pronounced of which is the 8.2 ka cold event. According to this hypothesis, melting of the remnants of the Laurentide Ice Sheet and a large influx of meltwater into the North Atlantic caused the freshening of sea surface water, which hindered oceanic convection and deep-water formation, reducing the heat advection from the ocean to the European continent [34,35].

Considering today's anthropogenic warming, investigations of short-term cooling events of the Early Holocene, such as the PBO, are important as a possible scenario for the development of cooling caused by rapid warming.

2. Materials and Methods

The studied site is located on the high floodplain of the Desna River (a tributary of the Dnieper River) near the town of Seltso in Bryansk region (53°20′48″ N; 34°6′30″ E, 150 m a.s.l.) (Figure 1). The area is located on the southern margin of the Smolensk–Moscow Upland. Within the sublatitudinal stretch of the Desna River valley from Seltso to Bryansk, the high southern bank is composed of the Lower Cretaceous sediments overlain by Middle Pleistocene glaciofluvial sands and silts and Late Pleistocene loess-like deposits. Gently undulating elevated plains, weakly or medium-dissected, with heights of 180–220 m a.s.l. predominate the area. The highest elevation of the watershed near the section is 288 m a.s.l. The lower northern bank of the Desna River valley is an alluvial plain with a complex of river terraces, with absolute heights of 140–180 m. The climate of the region is humid continental. Winters are relatively mild and snowy, while summers are warm. The average long-term annual temperature in the north of the Bryansk region is +4.8 °C. Average air temperatures are −8.5 °C in January and 18.0 °C in July. The annual amount of atmospheric precipitation is 550–600 mm, while the minimum amount of precipitation falls in February–March and the maximum falls in July. The average height of the snow cover is about 40 cm [36]. The territory lies in the zone of mixed broadleaved-coniferous subtaiga (hemiboreal) forests. The main forest-forming species are pine (*Pinus sylvestris*), birch (*Betula pubescens* and *B. verrucosa*) and aspen (*Populus tremula*). Spruce (*Picea abies*), oak (*Quercus robur*), linden (*Tilia cordata*) and black alder (*Alnus glutinosa*) are less common. Floodplain and upland meadows and grass-sedge swamps are widespread [37].

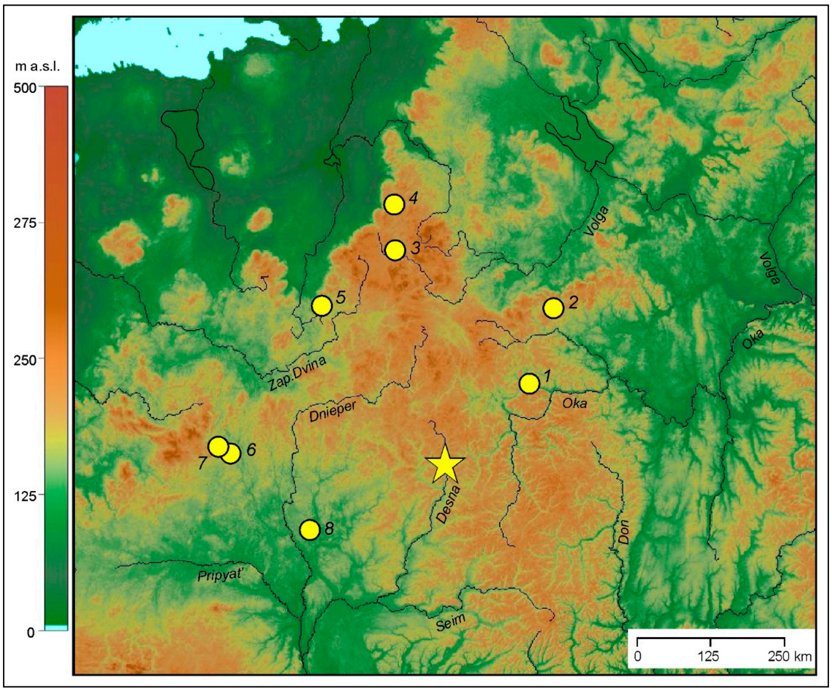

Figure 1. Key section Seltso (marked with an asterisk) and sites used for comparison: 1—Protva River, core PR-10 [38,39]; 2—Lake Dolgoye [25,40]; 3—Lake Seliger, core SP-2 [40,41]; 4—Lake Terebenskoye [42]; 5—Zmeinoe Mire [43]; 6—Lake Sudoble [44,45]; 7—Lake Velikoye [46]; 8—Lake Staroje [47].

Coring was carried out in the rear part of the high floodplain massif at the edge of the bend of the large paleochannel of the Desna River (Figure 2). The borehole penetrated lacustrine–palustrine deposits about 350 cm thick, which filled the oxbow depression. The cores were extruded and wrapped in the field and subsampled at the Institute of Geography of the Russian Academy of Sciences.

Figure 2. Location of the coring site 16713 on the higher level of the Desna River floodplain near Seltso town (marked by an asterisk).

A series of seven 14C AMS dates obtained at the Center for Collective Use "Laboratory of Radiocarbon Dating and Electron Microscopy" of the Institute of Geography RAS and at the Center for Isotope Research of the University of Georgia (USA) made it possible to develop a sedimentation model for this section. Radiocarbon ages were calibrated using the OxCal v.4.4.2 software [48] and IntCal20 database [49] (Table 1). The calibrated chronology is used throughout this paper.

To estimate the content of organic matter in the sediments, loss on ignition (LOI) analysis at 550 °C was performed following the procedure described in [50].

Pollen analysis was conducted on 36 samples obtained from a depth of 340–201 cm. Pollen and spores were extracted from the sediment following the Grichuk [51] method of using a heavy liquid with a density of 2.25 g cm^{-3} and acetolysis using propionic anhydride and concentrated sulfuric acid [52]. Pollen slides were studied using a light microscope with a magnification of 400×. As a result, 400–600 pollen grains and spores per sample were counted. Each pollen slide was subsequently scanned to search for rare palynomorphs.

Table 1. Radiocarbon dates of sediments from the Seltso site, core 16713.

Lab. No		Depth (cm)	Material	14C BP ($\pm 1\sigma$)	Calibrated Age (cal a BP)	
IGRAN	UGAMS				from ($+1\sigma$)	to (-1σ)
5984		25	Bulk sample	580 ± 20	625	545
5985		75	Bulk sample	1450 ± 25	1350	1305
5986		130	Bulk sample	5490 ± 30	6310	6220
5670	30223	175	Bulk sample	8945 ± 30	10,195	9960
5669	30222	230	Bulk sample	9670 ± 30	11,185	10,895
5408	29028	275	Bulk sample	9730 ± 30	11,215	11,160
5409	29029	308	Peat	9970 ± 30	11,600	11,270

Identification of pollen and spores was carried out in accordance with [53–55] and the reference collection of modern pollen of the Institute of Geography of the Russian Academy of Sciences.

Relative frequencies of pollen were calculated based on the total terrestrial pollen sum, which included the pollen of trees and shrubs (Arboreal Pollen—AP) and herbaceous plants (Non-Arboreal Pollen—NAP). Percentage values of the pollen of aquatic plants and spores were also calculated based on the total terrestrial pollen sum. The pollen diagram was constructed using the Tilia (version 2.6.1) and TiliaGraph programs [56]. Zonation of the diagram was established using the CONISS program for stratigraphically constrained cluster analysis [57]. The local pollen assemblage zones were then correlated to the European biostratigraphic Blytt–Sernander zones, slightly modified for northern Eurasia by Khotinsky [32]. Pollen analysis was carried out at intervals of 3 to 5 cm in the lower, most informative part of the section in order to achieve a high temporal resolution. In addition to pollen and spores, we identified other microfossils of plant origin found in the same pollen slides (conifer stomata, leaf hairs of hornwort, fern sporangia) that aided in the reconstruction of local plant communities in more detail, using [58,59].

3. Results

3.1. Stratigraphy and Radiocarbon Dating of Sediment Sequence from Seltso

The deposits at the Seltso site are characterized by gyttja, sandy at the base between 350–335 cm, clayey in the middle part (310–275 cm) and peaty in the upper part (275–215 cm). The gyttja is overlain by eutrophic peat (Figure 3).

The age–depth model (Table 1) shows that the layer of sandy gyttja at the base of the Seltso section accumulated at the end of the Younger Dryas (Figure 3). The thickness of the Preboreal sediments, represented by gyttja, is 120 cm. Formation of peat began at the site at the beginning of the Boreal. The time resolution for the analyses performed is 20–25 years for the Early Preboreal and 25–35 years for the Late Preboreal.

The average sedimentation rate for the gyttja is about 1 mm a^{-1} for the Early Holocene. It varies throughout the core, from 1.3 mm a^{-1} in the Early Preboreal to 0.8 mm a^{-1} at the end of the Preboreal—Early Boreal interval. LOI analysis shows that the organic contents of the sediments increased from 20% to 35–40% in the Early Preboreal and decreased to 20% at a depth of 310 cm, corresponding to the beginning of the Preboreal Oscillation. Higher in the section in the gyttja layers, LOI increases with slight fluctuations and reaches 80% in the Early Boreal peat layer.

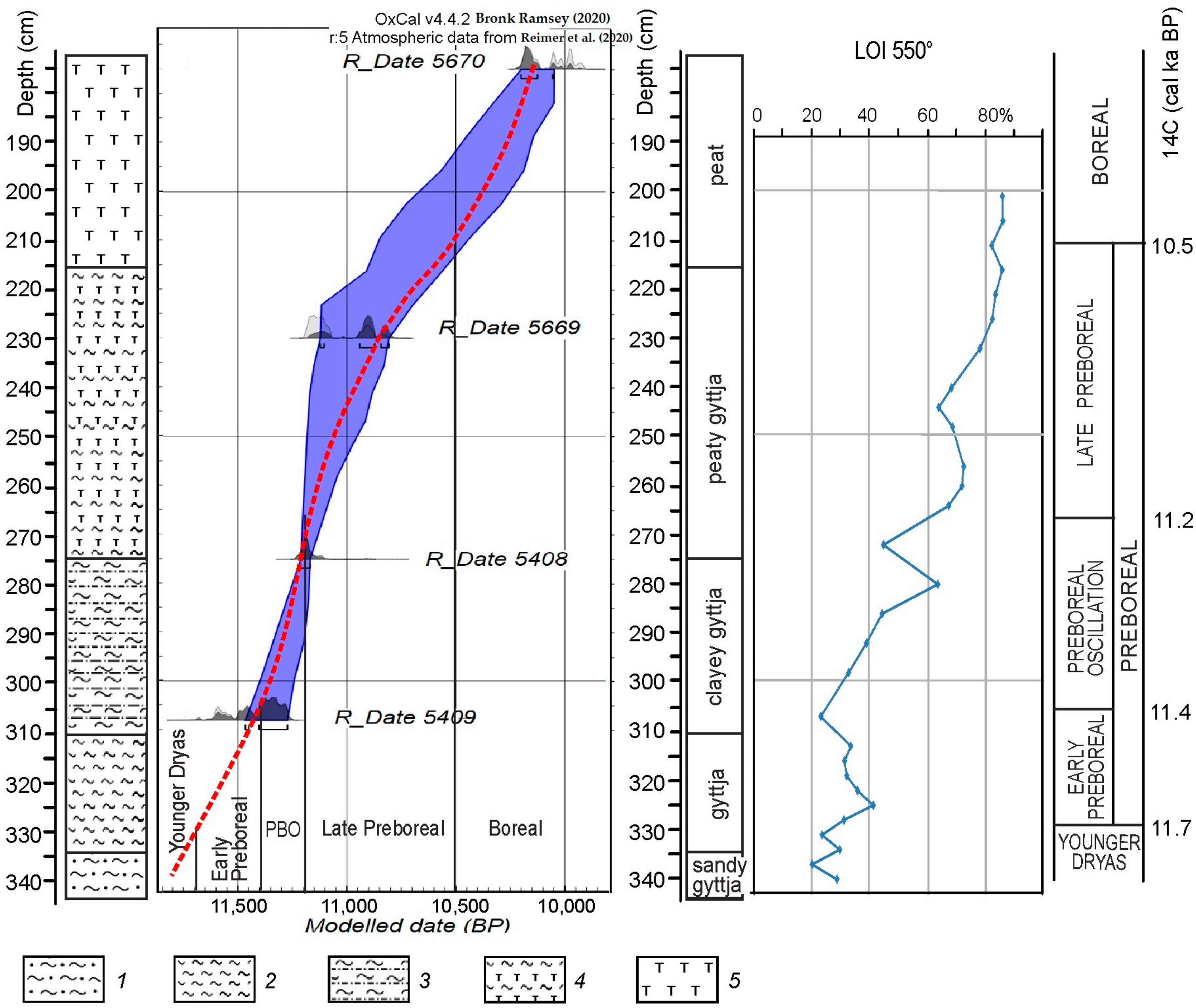

Figure 3. The age–depth model and the main properties of the Early Holocene sediments from the Seltso site. Lithology: 1—sandy gyttja, 2—gyttja, 3—clayey gyttja, 4—peaty gyttja, 5—peat; LOI—loss on ignition. The age-depth model is compiled using the OxCal v.4.4.2 software [48] and IntCal20 database [49].

3.2. Pollen Analysis

The Seltso core is dominated by AP, which makes up 55–85% of the total pollen of terrestrial plants Σ, represented mainly by *Pinus sylvestris* (up to 60–70%) and *Betula* sect. *Albae* (up to 40–50%). Pollen of herbs and dwarf shrubs (NAP) accounts for 15–40%. Within this group, Cyperaceae (up to 20%), Poaceae (up to 10%) and *Artemisia* (up to 10%) predominate. The abundance of fern spores (Polypodiaceae) varies widely throughout the core. In the diagram, five local pollen zones (LPZs) are distinguished (Figure 4).

In LPZ 1 (sandy gyttja, 340–332 cm; 12.7–11.7 ka BP), correlated to the Younger Dryas cold stage, the NAP makes up 30–35% of pollen spectra. Cyperaceae (up to 20%), *Artemisia* and Poaceae (5–10%) dominate the NAP group. *Pinus sylvestris* (35–55%), *Betula* (10–20%) and *Salix* (up to 15%) dominate the AP group. Pollen grains of *Picea*, *Pinus sibirica* and *Juniperus* occur in this layer. The percentage of Polypodiaceae spores decreases from 80% to 10%, while spores of *Equisetum* and *Riccia* are scarce.

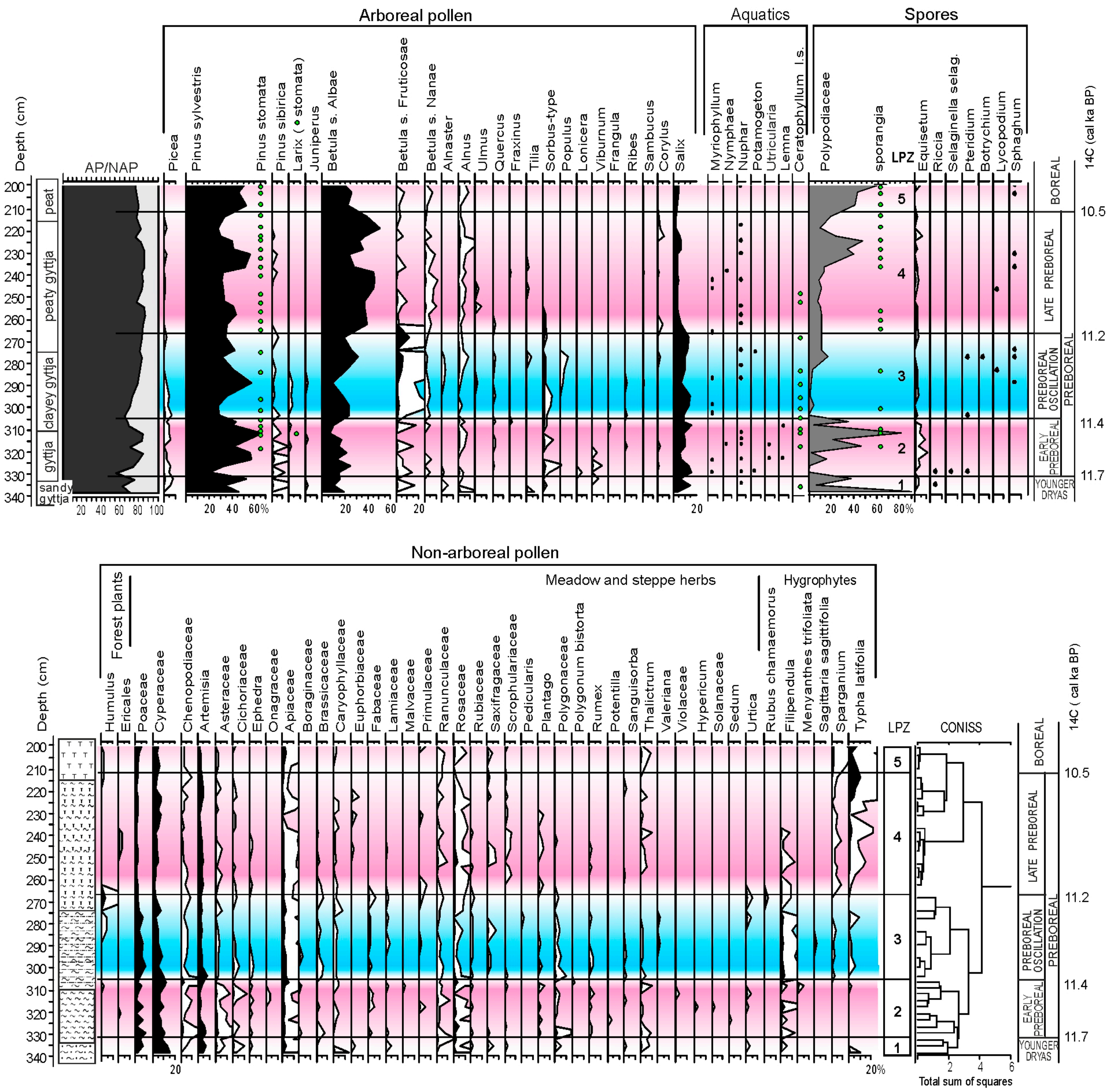

Figure 4. Pollen diagram for the lower part of core 16573 at Seltso. Exaggeration curves are with 5-fold magnification. *Ceratophyllum* l.s.—leaf spines of *Ceratophyllum*.

LPZ 2 (gyttja, 332–307 cm; 11.7–11.4 ka BP) corresponds to the Early Preboreal. AP content increases from 55% to 85%, mainly due to an increase in *Pinus* pollen from 20% to 60%. Pine stomata are found in the upper part of LPZ 2. *Larix* pollen is registered in the upper part of LPZ 2, and larch stomata are registered in one sample. *Betula* pollen remains at the same level as in LPZ 1, pollen of *B.* sect. *Nanae* and *Fruticosae* occur in minor quantities. *Salix* percentages vary from 15% to 8–10%. Rare pollen grains of mesophilous shrubs, such as *Viburnum*, *Frangula*, *Lonicera*, *Sorbus*-type and *Alnus*, are registered. At the base of LPZ 2, the pollen of Cyperaceae, Poaceae and *Artemisia* are the most abundant herbaceous plants (up to 10–15%); their contents noticeably decrease up the section. The pollen of meadow forbs is very diverse (up to 15 families represented in each sample), as well as that of aquatic plants (*Myriophyllum*, *Nuphar*, *Utricularia*, etc.). The abundance of Polypodiaceae spores increases sharply in the upper part of LPZ 2, reaching 80% of the total pollen sum Σ. In the lower part of LPZ 2, rare spores of *Selaginella selaginoides*, *Pteridium aquilinum* and *Riccia* were found. *Equisetum* spores occur in all samples in this zone.

At the base of LPZ 3 (clayey gyttja, 307–267 cm, 11.4–11.2 ka BP), the NAP percentages increase up to 35%, mainly due to Poaceae, *Artemisia* and forbs (Apiaceae, Polygonaceae, Brassicaceae and many others). *Ephedra* pollen occurs in the lower part of LPZ 3. The composition of AP is close to that described for LPZ 2. However, *Pinus* pollen decreases from 60% to 30% in the first half of LPZ 3 and then increases again. *Betula* contents reach 25–30%. Fern spores' abundances in LPZ 3 drop substantially. The aquatic plants' diversity is lower than that in LPZ 2; pollen of coastal aquatic plants and inhabitants of waterlogged soils, such as *Sagittaria sagittifolia*, *Typha latifolia*, *Sparganium* and *Filipendula ulmaria*, occur in this layer. The diversity of spores slightly increases in the upper part of the zone, where *Botrychium*, *Lycopodium*, *Pteridium* and *Sphagnum* appear.

LPZ 4 (267–212 cm; 11.2–10.5 ka BP) corresponds to the layer of peaty gyttja characterized by the highest AP content (up to 85%) for the Preboreal. The *Betula* pollen content increases to 40–50% in the upper part of the zone. The abundance of *Pinus* pollen increases from 30% to 50%. Pollen of *Picea* and *Pinus sibirica* are occasionally found only in the lower part of LPZ 3; pollen of *Larix* and *Juniperus* are absent. *Betula* sect. *Fruticosae* and *Salix* pollen are more abundant in the lower part of LPZ 4, where *Sorbus*-type and *Humulus lupulus* pollen also occur. NAP percentages are at a minimum (10–15%) in spite of a great diversity of herbaceous taxa. In the lower part of the zone, rare pollen grains of *Ephedra* are registered. Of the species growing on wet soil and along the lake shores, *Filipendula*, *Sparganium* and *Typha latifolia* occurred. Pollen contents of *Typha latifolia* increase at the top of the zone, reaching 10%. Of the aquatic plants, only *Nuphar* pollen occurs in the upper part of the zone.

In LPZ 5 (peat, 212–200 cm, 11.2–10.5 ka BP), the percentage of AP slightly decreases to 80%, mainly due to *Betula* decline by 20–25%. *Pinus* pollen percentage once again reaches about 60%. The composition of pollen spectra is much poorer compared to LPZ 4. Except for pine and birch, only rare pollen grains of mesophilous shrubs, *B.* sect. *Nanae*, *Fruticosae* and *Alnus* are registered. The diversity of the NAP group is significantly reduced. Pollen of Cyperaceae and Poaceae and other families, including many moisture-loving species (e.g., Apiaceae, Ranunculaceae and Rosaceae), predominates. The percentages of Polypodiaceae spores increase again to 40–60%.

4. Discussion

4.1. Interpretation of the Seltso Record

The Seltso record, covering the Late Glacial–Holocene transition and Preboreal, reflects several climatic phases that can be detected from lithostratigraphic and palynological data. The substantial rise in the organic contents of the sediments in the Early Preboreal compared to the Younger Dryas reflects rapid warming and increasing lake productivity. The LOI curve shows a clear decrease corresponding to the beginning of the PBO. The resumption of warming in the Late Preboreal is indicated by a new rise of organic contents of gyttja, reaching ~80% at the transition to peat accumulation at the beginning of the Boreal.

The pollen record from Seltso suggests that at the end of the Younger Dryas, the periglacial forest-steppe vegetation with complex mosaic structure typical of the East-European Plain during the cold stage existed at the site. Forest communities formed mainly of birch with pine and spruce had a limited distribution among open vegetation, similar to the present cold, dry steppes. In the woods of that time, *Pinus sibirica* occurred, which indicates more continental climatic conditions compared to the present in the region.

In the Early Preboreal, the vegetation cover of the area around the oxbow lake remained similar to that at the end of the Younger Dryas. The abundance and diversity of herbaceous plants and the simultaneous presence of xerophytes and microthermal taxa point to the limited role of forests in vegetation cover close to the periglacial forest-steppe. Nevertheless, the role of forest communities, primarily pine woodlands, increased in response to rapid warming. The local presence of pine is proved by findings of its stomata, which are most abundant in the sediments formed at the end of the Early Preboreal. Besides pine and birch, such continental-climate trees as *Pinus sibirica* and *Larix* occurred in the woods. Relatively high summer temperatures at this time interval are indicated by changes in the composition of aquatic vegetation: while *Myriophyllum* and *Nuphar* appeared in the lake already at the very beginning of the Preboreal, more thermophilous water lily (*Nymphaea*) also settled there about 11.5 ka BP.

Palynological data for the PBO time interval imply that tree vegetation experienced a short setback after its expansion in the Early Preboreal. A sharp decrease in arboreal pollen, especially in pine pollen contents, indicates an abrupt cooling followed by a slower warming accompanied by a decrease in the continentality of the climate. *Pinus* stomata are extremely rare in the layer corresponding to the PBO, which indicates a reduced participation of pine on the lake shores. During the cooling, *Pinus sibirica*, *Larix* and *Picea* occurred in the woodlands. The diversity of herbs, including *Sanguisorba*, *Thalictrum*, *Polygonum bistorta* and *Valeriana*, in this interval indicates a sufficiently warm summer for the development of species-rich meadow communities. In the initial phase of the cooling, only the hardy aquatic species, such as *Myriophyllum* and *Ceratophyllum*, remained at the site, and in its later part, *Nuphar* reappeared in the lake. A somewhat milder and more humid climate in the late part of the PBO is indicated by the spread of mesophilous trees and shrubs—*Betula* sect. *Fruticosae*, *Alnus*, *Populus* and *Salix* spp., a new stage of fern settlement and the appearance of *Lycopodium* and *Sphagnum* in the ground cover.

In the Late Preboreal, changes in pollen composition reflect a new advance of birch and pine forests at Seltso caused by renewed warming. The proportion of open herbaceous communities in the vegetation cover declined significantly. In the vicinity of the coring location, pine and birch forests, possibly with minor participation of such broad-leaved taxa as *Ulmus*, *Quercus*, *Tilia* and *Corylus*, occurred. Changes in the composition of aquatic and coastal vegetation and a new sharp increase in Polypodiaceae indicate rapid terrestrialization during the Late Preboreal. A new sharp increase in the content of fern spores marks the development of a rich fen at the beginning of the Boreal.

4.2. Short-Term Changes in Central East European Plain at the Turn of the Late Glacial and Holocene According to the Studies of Key Sections

The results obtained for Seltso were compared with published multi-proxy high-resolution investigations of lacustrine and palustrine deposits at eight key sites from the adjacent territory (Figure 1, Table 2). Currently, all these sites are situated within the zone of mixed broadleaved-coniferous (hemiboreal) forest [37].

Table 2. Previously published data on locations with lithologically and palynologically studied sediments of the Late Glacial and the Holocene.

Site Number	Site Name	Latitude, N	Longtitude, E	Altitude (m a.s.l.)	Data Sources	Number of 14C Dates
1	Protva River, core PR-10	55°12′09″	36°29′33″	137	[38,39] + non-published pollen data	8
2	Lake Dolgoye	56°04′02″	37°20′00″	201	[25,40]	8
3	Lake Seliger, core SP-2	57°02′21″	33°18′13″	205	[40,41]	7
4	Lake Terebenskoye	58°08′	32°59′	153	[42]	6
5	Zmeinoe Mire	56°16′53″	31°15′36″	165	[43]	22
6	Lake Sudoble	54°03′	28°24′	165	[44,45]	8
7	Lake Velikoye	54°09′37″	28°08′56″	164	[46]	4
8	Lake Staroje	52°51′	30°58′	130.5	[47]	4

4.2.1. Changes in the Composition of Lacustrine Sediments

The accumulation of lacustrine sediments occurred both in Seltso and in all the sections mentioned above during the Late Glacial and Preboreal. Sedimentation models based on 14C dating made it possible to determine the boundaries of the main climatic phases in the sections. Particular attention is paid to the Younger Dryas–Holocene transition, the Preboreal and the time interval corresponding to the PBO. In all sections, the composition of lake sediments changed from predominantly mineral in the Late Glacial to gyttja with a high content of organic matter and, in some cases, carbonates in the Early Holocene. The nature of changes in the composition of sediments and the time of this transition vary considerably from site to site.

Smaller lakes that existed at the sites of Seltso, Protva and Zmeinoe were filled in with sediments by the end of the Early Holocene, and grass-sedge swamps formed at the sites. In the Seltso core, at the boundary of the Younger Dryas and the Preboreal, sandy gyttja is overlain by a typical gyttja, with a 15–20% increase in LOI, which reflects an increase in the productivity of the lake and a decrease in erosion activity in its catchment area under the influence of climate warming. In the interval corresponding to the cooling of the PBO, the proportion of clay in the sediments increased, and the LOI again decreased to the level of the Younger Dryas (20–30%), then gradually rose and reached about 50% by the beginning of the Late Preboreal. With the warming, which resumed in the Late Preboreal, the content of organic matter in the sediments increased even more. By the beginning of the Boreal, the oxbow lake at the Seltso site was completely overgrown, and the accumulation of peaty gyttja was replaced by peat formation. At the Protva site, lake clays formed in the Early Preboreal differ from deposits of the Younger Dryas in abundant inclusions of mollusk shells, which probably reflects increasing lake productivity under the influence of warming. In this section, lake loams with a lower content of organic matter and without inclusions of shells correspond to the PBO cooling [39]. These deposits complete the process of terrestrialization, and at the beginning of the Late Preboreal, accumulation of sedge peat begins at the site of the former oxbow lake. In the lake that existed in the Late Glacial in place of Zmeinoe Mire, lacustrine deposits include sandy silt formed during the earlier part of the Younger Dryas and gyttja formed during the late part of the Younger Dryas and Preboreal with a relatively steady sedimentation rate [43]. In the Early Boreal, a layer of peat with interlayers of gyttja was deposited, followed by peat formation, which continued at the site during the entire Holocene.

In larger and/or deeper lakes, lacustrine sedimentation continues to the present day. In the Lake Dolgoye sediment sequence [25,40], the transition from the Younger Dryas to the Preboreal is marked by a change in the color of lacustrine sediments from gray to brownish-gray and brown, which reflects the increase in organic matter in the sediment. Clayey silts formed during the Younger Dryas show low organic matter content (7–10%) with a slight rise up to 15% in the Early Preboreal and a decline to 10% in the PBO and the Late Preboreal. A rapid rise of LOI from 10% to 50–55% occurred during the Early Boreal when typical gyttja accumulated in the lake. In Lake Seliger [40,41], the transition from mineral sediments to carbonate gyttja, where LOI rapidly increases from 25% to 50%, coincides with the Late Glacial–Holocene boundary. Up the section, organic contents drop by 5–7% and then increase once again in the Late Preboreal, reaching 60–65%. LOI reaches ca. 55% in the layer corresponding to the Early Boreal [40,41]. In Lake Terebenskoye [42], the layer of silty clay accumulated during the Late Glacial is characterized by a very low content of Total Carbon (TC). At the top of this layer, corresponding to the transition from the Younger Dryas to the Holocene, TC increases to 8%. During the Early Preboreal, TC decreases to 1–3%. In the Late Preboreal, ~11.3 ka BP, when silty clayey gyttja accumulates in the lake, TC content increases sharply and remains at the level of 5–7%. In the Boreal, when fine detritus gyttja accumulated, TC rose gradually to 10–12%. In Lake Sudoble [44,45], sandy gyttja accumulated in the Younger Dryas and the Early Preboreal. Detritus gyttja with higher organic contents formed there in the Late Preboreal. In Lake Velikoye [46], a layer of light grey sandy gyttja accumulated during the Younger Dryas. A transition to greyish-blue gyttja in this core corresponds to the Late Glacial–Holocene boundary. Such a gyttja formed in this lake during the entire Early Holocene. In Lake Staroje [47], the proportion of the non-carbonate mineral fraction in the sediments drops from 80–85% in the Younger Dryas to 20% at the beginning of the Holocene when the content of carbonates sharply rises from 10% to 70%. After a short-term decrease of about 15% within the Early Preboreal, which possibly coincides with the cooling of the PBO, it increases to 80% in the Late Preboreal. LOI remains at ~10% during the Preboreal and increases to 20–25% in the Boreal.

Thus, in the time interval corresponding to the PBO, at most sections, a decrease in the content of organic matter and/or carbonates in sediments is evidence of a decrease in lake productivity.

4.2.2. Changes in Vegetation and Climate

A comparison of palaeoecological data from the sections of lake sediments discussed above makes it possible to trace the main changes in the composition of flora and vegetation that occurred under the influence of climatic fluctuations.

Late Glacial

In all records, the increase in AP confirmed by PAR data and findings of stomata of coniferous trees shows that during the Allerød, the most cold-resistant and hardy tree species grew in the region. Tree birch and Scots pine were the main species forming open woods. The proportion of spruce in forest communities was slightly higher in the more northern areas—Protva, Seliger, Dolgoye, Zmeinoe and Sudoble. The local presence of spruce near lakes Seliger and Dolgoye is evidenced by high percentages and PARs of *Picea* and findings of spruce stomata [25,40]. At Lake Velikoye, the PARs of *Pinus* exceed the limit, indicating the local presence of pine [60] both in the Allerød and in the Younger Dryas layers [46]. In the sediments of Lake Staroje, *Pinus* stomata occur sporadically in the Allerød layers [47]. In general, palynological data show that the Allerød Interstadial in this region was characterized by patchy vegetation with alternating periglacial steppe and sparse boreal forest communities. Apart from birch, pine and spruce, these forests included tree species with modern ranges, including the northeastern part of the East European Plain and Siberia—*Abies*, *Larix* and *Pinus sibirica*. Meadow communities and thickets of shrubs were also widespread. Overall, the vegetation cover still had a relatively open and patchy character typical of the periglacial forest steppe.

In the layers accumulated in the Younger Dryas, a considerable decrease in the contents of AP is registered in all considered pollen records. This indicates that the contribution of forest communities to regional vegetation dropped again during this colder and dryer stage. In the Seliger and Dolgoe sections, at the beginning of the Younger Dryas, the PARs of spruce, pine and birch decreased quite sharply [40]. This reduction in PARs reflects a decline in the abundance of the main arboreal taxa and their pollen productivity under the influence of rapid cooling [40]. The absence of *Pinus* stomata in the layer corresponding to the earlier part of the Younger Dryas in the sediments of Lake Staroje [47] and a sharp drop in the *Pinus* pollen percentages at Lake Velikoye [46] indicate a decline of the pine communities around the lakes in response to the cooling.

The so-called "lower maximum of spruce" (*Picea* pollen peak with contents up to 50–60% of AP), which is clearly seen in pollen records from the central East European Plain, was originally correlated by M.I. Neishtadt with the Allerød Interstadial [32,61]. Subsequently, the comparison of palynological and geochronological data on lacustrine sediments has shown that the lower maximum of spruce covers not only the Allerød but also the Younger Dryas and, in some cases, almost completely corresponds to the Younger Dryas. This is especially noticeable in the sections located in the southwest of the study area, where sandy deposits are widespread, in particular at the sites Sudoble [44,45], Velikoye [46] and Staroje [47]. In the latter paper, the authors [47] noted a simultaneous increase in *Artemisia* and *Picea* pollen contents in the Younger Dryas interval of the Lake Staroje pollen record and suggested that it may be connected with re-established permafrost and increasing intensity of erosional processes. We also believe that during the Younger Dryas, relatively favorable conditions for the spread of spruce with its shallow root system may have been associated with a reduction in the thickness of the seasonally thawed layer, which maintained higher humidity in the upper soil layer. In Lake Staroje, besides pollen, *Picea* stomata were found in the sediments of the Younger Dryas age [47]. The earliest *Picea* macrofossils found in the Terebenskoye section are also dated to the end of the Younger Dryas [42].

Despite significant cooling, the summer in the Younger Dryas was relatively warm and dry, as indicated by high levels of *Artemisia* pollen and, to a lesser extent, of the Chenopodiaceae family. The highest species diversity of pollen from meadow and meadow-steppe forbs and the findings of pollen from relatively thermophilous aquatic plants in the sediments of this age (e.g., *Nuphar* pollen at Seltso and Protva sites, and *Typha latifolia* seeds at Velikoye site [46]) also point to the relatively high summer temperatures. As in the Allerød, the flora of the Younger Dryas included tree species that are now common in the areas with a more continental climate than the modern one in the region (e.g., *Pinus sibirica* and *Larix*). It also combined heliophytes (*Hippophae rhamnoides* and *Helianthemum*), cryophytes (*Selaginella selaginoides*, *Betula nana* and *Botrychium boreale*), and typical xerophytes (*Ephedra* and *Eurotia ceratoides*). Such extreme diversity of the Younger Dryas flora confirms the conclusion of V.P. Grichuk [62] that during the Younger Dryas, the last advance of the periglacial steppe vegetation occurred in the central region of the East European Plain.

Early Preboreal

An abrupt shift in the AP/NAP ratio towards the predominance of AP in all the compared records reflects afforestation of the area caused by rapid warming at the transition from the Late Glacial to the Holocene. In the Early Preboreal, pine (at Seltso, Protva, Dolgoye, Velikoye and Sudoble) and birch (at Seliger and Zmeinoe) still predominated among trees, although their actual participation in local vegetation is difficult to assess. Nevertheless, the earliest dated findings of *Betula* macrofossils in the Terebenskoye section coincide with the beginning of the Preboreal [42], which confirms the increasing role of tree birch in the woods near the lake. Numerous findings of *Pinus* stomata in the Early Preboreal layer of the Seltso section prove that pine grew at the site as early as 11.5 ka BP. *Pinus* stomata found in the Early Preboreal sediments of Lake Staroje [47] also point to a local presence of pine. At the Velikoye site, the earliest findings of *Pinus* macrofossils approximately correspond to the Late Glacial/Holocene boundary, and pine pollen influx shows a maximum in the Early Preboreal [46]. In general, spruce played a lesser role in the forest communities of the region in the Early Preboreal than pine and birch. Only in the Dolgoye record, *Picea* pollen makes up about 20%, and this peak coincides with the local maximum of *Pinus* pollen (~20%) [25]. In the Early Preboreal, such "continental climate" trees as *Pinus sibirica* and *Larix* still occurred in the regional woodlands. At the same time, forest communities became more diverse, thus indicating climate warming: mesophilous shrubs, such as *Viburnum*, *Frangula* and *Lonicera*, appeared in the forest understory, and *Alnus* and *Salix* species spread on wet grounds surrounding lakes and mires. Rare pollen grains of the broad-leaved trees (*Ulmus, Quercus, Tilia* and *Corylus*) found in the Early Preboreal sediments indicate an advance of these relatively thermophilous species into the region brought about by rapid warming. The findings of *Nymphaea* pollen at the Seltso and Protva sites and the presence of *Nymphaea* macrofossils in Lake Velikoye sediments at the very beginning of the Preboreal [32] suggest relatively high summer temperatures associated with the continental climate.

Despite significant warming, the composition of pollen spectra in the Early Preboreal still reflects the patchy pattern of the vegetation cover inherited from the cold stage of the Younger Dryas. In particular, the pollen diversity of meadow forbs with the participation of xerophytes and cryophytes indicates the preservation of vegetation communities close to the periglacial forest-steppe during this time interval.

Preboreal Oscillation

In most of the pollen diagrams, the PBO cooling is marked by a decrease in AP compared to the Early Preboreal. The ratio of pollen from the main tree species (*Betula*, *Pinus* and *Picea*) also changes significantly in this time interval: a sharp rise of the birch pollen curve is distinct in all the records. Thus, at the very beginning of the cooling, *Betula* pollen makes up 60–70% of the pollen sum in the sections Seliger, Sudoble and Staroje [41,44,47] and up to 80–90% in the sections Zmeinoe and Velikoye [43,46]. The rapid cooling, evidenced by a sharp decrease in the percentages of pine pollen, is confirmed by the rarity of *Pinus* stomata in the PBO layer in the Seltso record and by their absence in the same interval in the Velikoye record [46]. Moreover, in the Velikoye record, *Pinus* PARs decrease by 3–4 times compared to the level of the Early Preboreal, i.e., approximately to the level of the Younger Dryas. The PARs of *Betula*, on the contrary, increase during the PBO by about two times compared with the Early Preboreal [46]. In all the discussed sections, *Picea* pollen is rare during the PBO, and even in the Dolgoye section, where its percentages in the Early Preboreal are relatively high, spruce pollen is scarce in the PBO [25,40]. Rare pollen grains of relatively thermophilous broad-leaved species, which occurred in the Staroje section in the Early Preboreal, are absent in the layer corresponding to the PBO, except for a few pollen grains of *Ulmus* [47].

An increase in NAP, especially *Artemisia* and Poaceae, in the Seliger and Dolgoye sections and, to a lesser extent, in the Velikoye section, indicates an expansion of open herbaceous communities and, possibly, relatively dry summer conditions, especially at the beginning of the cooling. The expansion of open steppe-like vegetation and a decline of forest communities are emphasized by a large variety of pollen from meadow and steppe species, by findings of pollen from *Ephedra* and some heliophytes (e.g., *Hippophae rhamnoides* in the Seliger record). In the interval corresponding to the PBO in the Dolgoye and Seliger records, an increase in the PARs of Poaceae, *Artemisia* and other herbaceous plants is registered. Of the aquatic plants, only the least thermophilous species were present during the PBO, e.g., *Myriophyllum*, *Potamogeton* and *Ceratophyllum* at the Protva site.

Late Preboreal

An increase in AP up to 80–90% in all the records reflects a new stage of forest expansion in the Late Preboreal brought about by a resumption of warming. These woodlands were still mainly composed of birch and pine. In those sections where AP was high throughout the Early Preboreal and remained high or decreased slightly in the PBO, an even greater increase in the proportion of *Betula* pollen in the spectra is registered. The Seliger, Zmeinoe, Velikoye, Sudoble and Staroje records show that in the Late Preboreal birch was the main forest-forming species. In the Dolgoye section, where AP contents are generally quite low, there is a slight increase in AP compared to the PBO (from 30 to 45%), with *Betula* pollen reaching 90% of AP [25,40]. The predominance of birch in the Late Preboreal vegetation is confirmed by the findings of *Betula pubescens* macrofossils dated to 11.2 ka BP in the sediments of Lake Terebenskoye [42]. In the sediments of Lake Velikoye, fruits of *Betula* sect. *Albae* occurs during the entire Late Preboreal [46]. In the Protva section, the contents of pine and birch pollen in the Late Preboreal layer are 30–35% and 30–45%, respectively, while spruce pollen is rare. In the Sudoble section, at the same time interval, *Picea* pollen reaches 10%, although up the section, in the peat layer corresponding to the Boreal, it is absent [45]. At Lake Terebenskoye, the first *Pinus sylvestris* macrofossils are dated to about 11.4 ka BP [42]. Pine stomata were found in the Late Preboreal layers at the Seltso and Staroje sites [47]. Findings of pollen from more thermophilous trees and shrubs (*Ulmus, Quercus, Tilia, Fraxinus, Corylus, Sambucus* and *Viburnum*) in the Late Preboreal layers indicate an enrichment of forest communities caused by the warming that followed the short-term cooling of the PBO.

By the beginning of the Boreal, the landscape role of birch forests had decreased throughout the region under consideration. In the forest communities of the Boreal, pine predominated, and the spread of broad-leaved species continued, which indicates further warming accompanied by some decrease in the continentality of climate.

4.3. Comparison with the PBO in Northwest and Central Europe

Based on lithological and paleobotanical data, similar changes in the composition of sediments and vegetation have been reconstructed in the northwestern regions of Europe [7,8,63]. Thus, considerable shifts in the organic contents of sediments are found in the Lochem–Ampsen record in The Netherlands [8]. At the end of the Early Preboreal warm Friesland Phase, LOI reached 40% [8]. At the beginning of the cold Rammelbeek Phase corresponding to the PBO LOI dropped to about 10% [8]. During the Late Preboreal, the LOI values reached 85% [8]. In the Younger Dryas and Early Preboreal, pollen of *Betula* sect. *Albae* make up 50–70% of the terrestrial pollen sum and decrease to 20–30% in the PBO in the Lochem–Ampsen section [8]. During this cooling, the proportion of pollen from upland herbs increases 2–3 times compared to the end of the Younger Dryas and the initial warming of the Early Preboreal [8]. Considerable changes in the pollen spectra are also registered in the Borchert section in The Netherlands [7,63]. In this section, the tree birch pollen content increases from 30% at the end of the Younger Dryas to 90% by the end of the Friesland warming and sharply decreases to 30–40% in response to the PBO cooling [7,63]. Pine pollen makes up 20–30% of the total terrestrial pollen in the Younger Dryas and does not exceed 5% of the spectra in the Early Preboreal [7,63].

At the site, *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 the PBO, it sharply decreases to 30–40%. *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 [7].

Based on high-resolution pollen analysis at five lakes situated at different altitudes in Switzerland, L. Wick [11] analyzed the response of plant communities to the Preboreal climatic oscillation. She came to the conclusion that the vegetation responses to climatic changes are more distinct near vegetation ecotones at medium and higher altitudes (lakes Leysin and Zeneggen) than in the lowlands (Lake Gerzensee) [11]. At two central alpine sites situated near the treeline, the Preboreal Oscillation was recorded as a strong depression in tree-pollen concentrations at around 9500 uncal. yr B.P., lasting about 150 yr [11].

In many pollen records from Poland, an increased percentage of *Betula* in the older part of the Early Preboreal is registered (e.g., [18–20,64]). These changes are usually interpreted as an indication of a temporary decline of pine and the spreading of birch forests as a reaction to the colder and wetter climatic events. Based on the high-resolution multi-proxy analyses of the sediments of Lake Suchar Wielki in NE Poland, Fiłoc et al. [20] concluded that after the warm beginning of the Holocene, three cold episodes, separated from each other by short warm intervals, occurred in the Early Preboreal, between 11.3 and 10.8 ka BP. The first of these coolings was registered at ~11.3–11.15 ka BP. However, at the same time as a rapid increase in the percentages of *Betula* pollen in Lake Suchar Wielki record, the total concentration of pollen, both of *Pinus sylvestris* and *Betula*, strongly decreased [20]. The authors suggest that the cold event more negatively affected pollen production of pine rather than birch, which is more resistant to low temperatures ([20], p. 14). Therefore, the peaks in birch pollen percentages, typical of the pollen records during the Preboreal cold events, are most likely explained by different degrees of reduction in the pollen productivity of birch and pine than by changes in the forested areas [20].

Kramkowski et al. [19] estimated mean July air temperatures (MJAT) in the Preboreal in northern Poland based on the changes in Chironomidae composition in sediments of Lake Jelonek. Two phases of cooling were reconstructed. The first phase, 11.45–11.3 ka BP, was cooler, with the MJAT below 16 °C, and the second phase, 11.3–11.15 ka BP, had an MJAT slightly above 16 °C. After that, the air temperature returned to the MJAT above 18 °C, which was characteristic of the previous warm interval. These air temperature fluctuations are comparable to those reconstructed in northwestern Europe [8].

Quantitative climatic reconstructions for the Preboreal interval in the northwest of the East European Plain were obtained by B. Wohlfarth et al. [42] based on the findings of spruce, pine, aspen and birch macrofossils in sediments of Lake Terebenskoye. The radiocarbon dating of the macrofossils showed that *Picea abies* grew on the Valdai Upland as early as 12 ka BP, *Pinus sylvestris* and *Populus tremula*—about 11.4 ka BP, and *Betula pubescens*—about 11.2 ka BP. The participation of these tree species in the forest communities on the Valdai Upland indicates that already in the Preboreal mean July temperatures in this region were 10–12 °C [42]. However, palynological data collected to date are still insufficient to reconstruct the decrease in temperature in the central region of the East European Plain during the PBO.

On the whole, the comparison of the above reconstructions of vegetation and climate suggests that the degree of manifestation of the PBO decreases with distance from the North Atlantic, as does the degree of manifestation of other short-term cooling events of the Holocene, in particular, 8.2 ka BP [65,66]. This similarity supports the hypothesis about the influence of thermohaline circulation disturbances on the development of sharp climatic fluctuations in the final stages of degradation of the last glaciation.

5. Conclusions

Pollen analyses and sediment studies carried out for the Seltso section with the high temporal resolution (20–25 years for the Early Preboreal and 25–35 years for the Late Preboreal) make it possible to trace changes in vegetation that occurred at the site at the beginning of the Holocene. Comparison of the data for the Seltso section with high-resolution lithostratigraphic and palynological data from eight reliably dated sections located in adjacent territories allows the reconstruction of short-term changes in vegetation and lake sedimentation in the central region of the East European Plain during the Preboreal. The similarity of the registered changes and their simultaneous manifestation in all sections considered gives grounds to conclude that their main cause was climatic fluctuations.

About 11.4 ka BP, a decrease in organic contents in lake sediments corresponding to the PBO occurred in the region. This cooling interrupted or slowed down the expansion of pine forests, while birch forests became more widespread and caused a new expansion of open herbaceous communities close to the periglacial steppe. In the Late Preboreal, 11.2–10.7 ka BP, the process of warming resumed, which led to a new expansion of pine and birch forest communities. With further warming in the Boreal, pine and mixed forests, with the participation of relatively thermophilous broad-leaved species, took a dominant position in the vegetation cover of the territory, while the landscape role of birch forests decreased. In the central region of the East European Plain, two phases were distinguished within the PBO time interval—a sharp cooling around 11.4 ka BP and a slightly warmer phase with lesser climate continentality.

The reconstructed multi-centennial climate changes in the Preboreal in the central region of the East European Plain correspond fairly well with those reported for other regions of Europe. However, the impact of the PBO cooling on the vegetation development in this region was weaker than in northwestern and central Europe. This eastward weakening of the signal is similar to the geographic pattern of the 8.2 ka BP cold event, which may indicate their similar causes. Spatial heterogeneity in the manifestation of PBO on the East European Plain requires further study.

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