

Vegetation and Climate in the North of the Minusinsk Basin in the Late Holocene: A Record from Shira Lake Resolved by Decade

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Received June 3, 2024; revised June 15, 2024; accepted June 18, 2024

Abstract—The results of studying the bottom sediments of meromictic Shira Lake, located in the northern part of the Minusinsk Basin, are presented. The sediments are represented by varves, annual layered series, which make it possible to reconstruct the history of the regional natural environment with a high resolution. The age model is based on seven ¹⁴C dates. The proposed new palynological record from the upper part of the Shira-2021-II-1 core extends the previous record by 530 years, providing the reconstruction of the regional natural environment for the past 2980 calibrated years with an average resolution of 21 years. The reconstructions show a humid regional climate 2980–2650 BP, with the climate of the basin itself being more arid, providing the existence of steppe and meadow–steppe assemblages around Shira Lake for the past 2980 years. The trend of changes in the *Artemisia*/Chenopodiaceae pollen ratio, considered as an indicator of available moisture for plants, suggests a slight increase in the moisture level in the Minusinsk Basin in 2980–70 BP and a noticeable decrease in the past 70 years. However, the increase was interrupted by short-term intervals of increased climate aridization. The reconstructions have shown that changes in vegetation around Shira Lake in the Late Holocene were mainly caused by large-scale circulation processes that changed the regional moisture balance. The steppe assemblages were the most sensitive to moisture changes on a decadal scale. Like the previous pollen record, the new one does not have clear pollen indicators of anthropogenic influence on vegetation. Only a noticeable increase in the birch pollen content in the past 50 years may indicate planting of greenery around the resort areas.

Keywords: southern part of Western Siberia, pollen, charcoal particles, Late Holocene, moisture variations, decadal temporal resolution, anthropogenic impact

DOI: 10.1134/S1028334X2460316X

INTRODUCTION

Lake sediments have proven themselves valuable geological archives that store long-term records of changes in the natural environment on various spatial scales, as well as information on interactions of human with the surrounding landscape [1, 2]. However, the contribution of these archives to the reconstruction of vegetation and climate history, as well as to the regional climate models, is often limited by coarse temporal resolution. In this context, the bottom sediments of Shira Lake, located in the northern part of the Minusinsk Basin, are recognized as a valuable archive of Holocene natural–climatic changes due to having varves, annually laminated sediment sequences

[3], which allows making reconstructions of the natural environment with a seasonal–decadal resolution. The results of studying the current state of the lake biota and ecosystem have been published in many sources [4–6]. However, not enough attention was given to paleolimnological reconstructions using the bottom sediments from Shira Lake. For example, based on the results of X-ray fluorescence analysis of sediments from the LS09 core of the year 2009, a correlation was established between the content of several trace elements and centennial variations in the natural environment in the past 2450 years [3]. Later on, the first pollen record with an average resolution of 22 years was obtained from the sediments of this core [7].

The new proposed palynological record from the upper part of the Shira-2021-II-1 core turned out to be 530 years older than the previous one, which made it possible to reconstruct the history of the environment of Khakassia for the past 2980 years with an average resolution of 21 years.

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Table 1. Results of AMS ^{14}C dating of sediments in the Shira-2021-II-1 core

Depth in the core, cm	Material dated	Laboratory number	^{14}C -age, yr BP	Calibrated values with respect to RE	Median age (cal. BP)
19.5	Bulk sediments	Poz-156319	545 ± 30	187	240
39.5	OOU	Poz-156305	1395 ± 35	1037	820
59.5	OOU	Poz-156306	1550 ± 30	1192	1100
79.5	OOU	Poz-156307	2185 ± 30	1827	1650
99.5	OOU	Poz-156308	2425 ± 30	2067	2000
119.5	OOU	Poz-156309	2845 ± 35	2487	2490
139.5	OOU	Poz-156310	3185 ± 35	2827	2900

MODERN NATURAL CONDITIONS IN THE NORTHERN PART OF THE MINUSINSK BASIN

The drainless, meromictic, saline Shira Lake is located in the Khakasskii State Nature Reserve. The surface area of the lake is 36 km², with a maximum water depth of ~25 m. The lake is fed by the Son River. The other water sources are ground waters and atmospheric precipitation [3]. The hydrological balance of the lake is variable [5]. The climate of the steppe zone where Shira Lake is located is harsh continental and arid. The average temperature in July is +18°C; in January, –19°C, with an average annual precipitation of 300 mm [5]. The lake is covered with ice from late November to May. The snow cover height ranges from 0 to 30 mm. In the northern Minusinsk Basin, the vegetation is dominated by steppe and forest–steppe. The foothills are covered with light coniferous forests of Siberian larch *Larix sibirica* and, to a lesser extent, Scots pine *Pinus sylvestris*. Forests of birch (*Betula*), pine, Siberian spruce (*Picea obovata*), Siberian fir (*Abies sibirica*), and Siberian pine (*Pinus sibirica*) form the mountain–taiga belt of ridges around the basin [8]. Near Shira Lake, meadow–steppe associations prevail with dominant (*Poaceae*), legume (*Fabaceae*), (*Asteraceae*), (*Rosaceae*), and (*Artemisia*). Larch, white birch, poplar (*Populus*), pine, Siberian Elm (*Ulmus pumila*), and Willow (*Salix*) grow along the shores. Shira Lake is also an important recreational object.

MATERIALS AND METHODS

In 2021, a borehole was drilled in the deepest part of the lake (25.3 m) using the UWITEC drilling equipment, which exposed the full section of the bottom sediments; the undisturbed core was sampled. By now, the upper 144-cm portion of the sediment section from the Shira-2021-II-1 borehole has been studied by the palynological method. The age model is based on the results of ^{14}C dating using accelerator mass spectrometry AMS (Table 1). Linear regression was used to evaluate the reservoir effect (RE) by the ^{14}C dates in stratigraphic order using the “interception method”

[9]. The value of 358 yr BP at the intersection point of the axes was taken as the RE value. The age corrected for this value was calibrated using the IntCal20 curve [10]. The age of each centimeter of sediments in the core was estimated by the method of interpolation between two adjacent dates taking into account the average sedimentation rate between them.

For the palynological analysis, each centimeter of sediments was sampled. The percentage of pollen taxa was calculated based on the sum of terrestrial pollen taken as 100%. The pollen slides were used to count charcoal microparticles larger than 100 μm, which were regarded as indicators of subregional/local fires [11]. The number of charcoal particles was calculated as their influx (pcs/cm²/yr) by multiplying the charcoal concentration by the sedimentation rate (cm/yr). A spore–pollen diagram was constructed in the Tilia/TiliaGraph/TGView program [12]. Local pollen subzones (SH-d–a) were identified based on CONISS stratigraphically constrained cluster analysis [12]. The lithological composition of the sediments was described by examining smear slides in three replicates. The ratio of *Artemisia* and Chenopodiaceae pollen (A/Ch) was used as an indicator of the effective moisture at the regional level [2].

RESULTS AND DISCUSSION

The age model shows that the sediments in the Shira-2021-II-1 core were formed in the past 2980 years and are represented by alternating multi-colored strata with thin layering (Fig. 1). The clay fraction is the dominant in the sediments. The proportion of sand and silts increases in the upper five centimeters (Fig. 2).

The CONISS dendrogram shows a similar composition of pollen spectra on the assumption that the record represents a single pollen zone that can be divided into subzones (Fig. 1). Subzone descriptions contain the average values of all indicators.

SH-d (144–126 cm, 2980–2650 BP), 63% of tree pollen and 33.5% of herb pollen. The maximum contents are recorded for pollen of *Abies* (4.3%), Chenopodiaceae (3%), and *Artemisia* (20%), and the minimum contents,

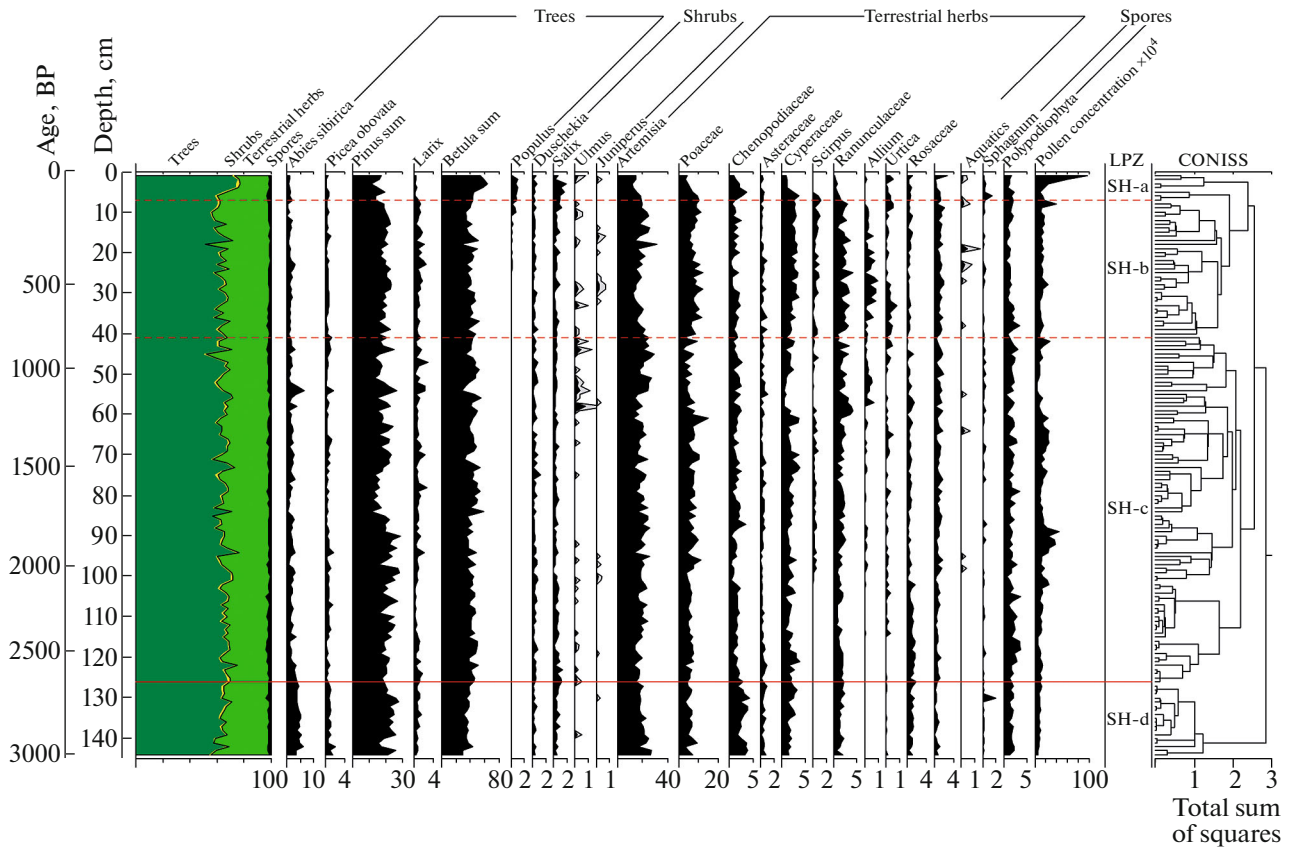


Fig. 1. Spore–pollen diagram of sediments in the Shira-2021-II-1 core presented relative to the depth and age of the sediments.

for pollen of *Betula* (36%) and *Larix* (0.8%). The pollen concentration was 85000 grains/cm², and the influx of charcoal microparticles was 400 pcs/cm²/yr.

SH-c (126–42 cm, 2650–880 BP), the abundance of tree species and herb pollen almost did not change (64.7% and 32.4%, respectively), while the abundance of *Abies* pollen decreased to 1.9% and *Betula* pollen increased to 42%. The pollen concentration was 146 000 grains/cm², and the influx of charcoal was 890 pcs/cm²/yr.

SH-b (42–6 cm, 880–70 BP), the abundance of tree species and herb pollen was 62% and 35%, respectively. *Larix* pollen amounted to 1.5%. The spectra characterized by the increasing abundance of pollen from Poaceae, Cyperaceae, meadow-steppe herbs, and the appearance of *Populus* pollen. The pollen concentration was 142000 grains/cm², and the influx of charcoal microparticles decreased to 490 pcs/cm²/yr.

SH-a (7–1 cm, recent 70 years), the proportion of tree pollen reached maximum values (72.5%), while herb pollen reached the minimum (23%). The pollen values increased to 58% and 0.7% for *Betula* and *Populus*, respectively, within the group of tree species. The average pollen concentration reached the maximum of

496 000 grains/cm³, and so did the influx of charcoal, 900 pcs/cm²/yr.

The pollen record we obtained at the temporal resolution has only one similar record in the Minusinsk Basin [7], extending it by 530 years.

The reconstructions imply the development of *Artemisia*–Poaceae–meadow–steppe assemblages on the plains of the northern Minusinsk Basin and larch on the hilltops in the continental and insufficiently humid climate of the basin 2980–2650 BP, which is supported by the low A/Ch values (on average, 7) (Fig. 2). However, the increased abundance of fir and spruce pollen enables us to reconstruct more humid conditions in the mountains surrounding the basin, which corresponds to the humid and cool climate of the Altai–Sayan region during 3000–2300 BP [13, 14]. Importantly, at 2980–2750 BP the lake accumulated “whitish” silts poor in organic matter, which are typical of the intervals of the holomictic state of the lake system and a low water level. The latter could have happened when the deeply frozen rocks blocked the groundwater influx, which led to the fall in the level of Shira Lake [3]. The colder climate was likely to contribute to reduced evaporation/increased moisture and the occurrence of favorable conditions for dark coniferous tree species in the mountains.

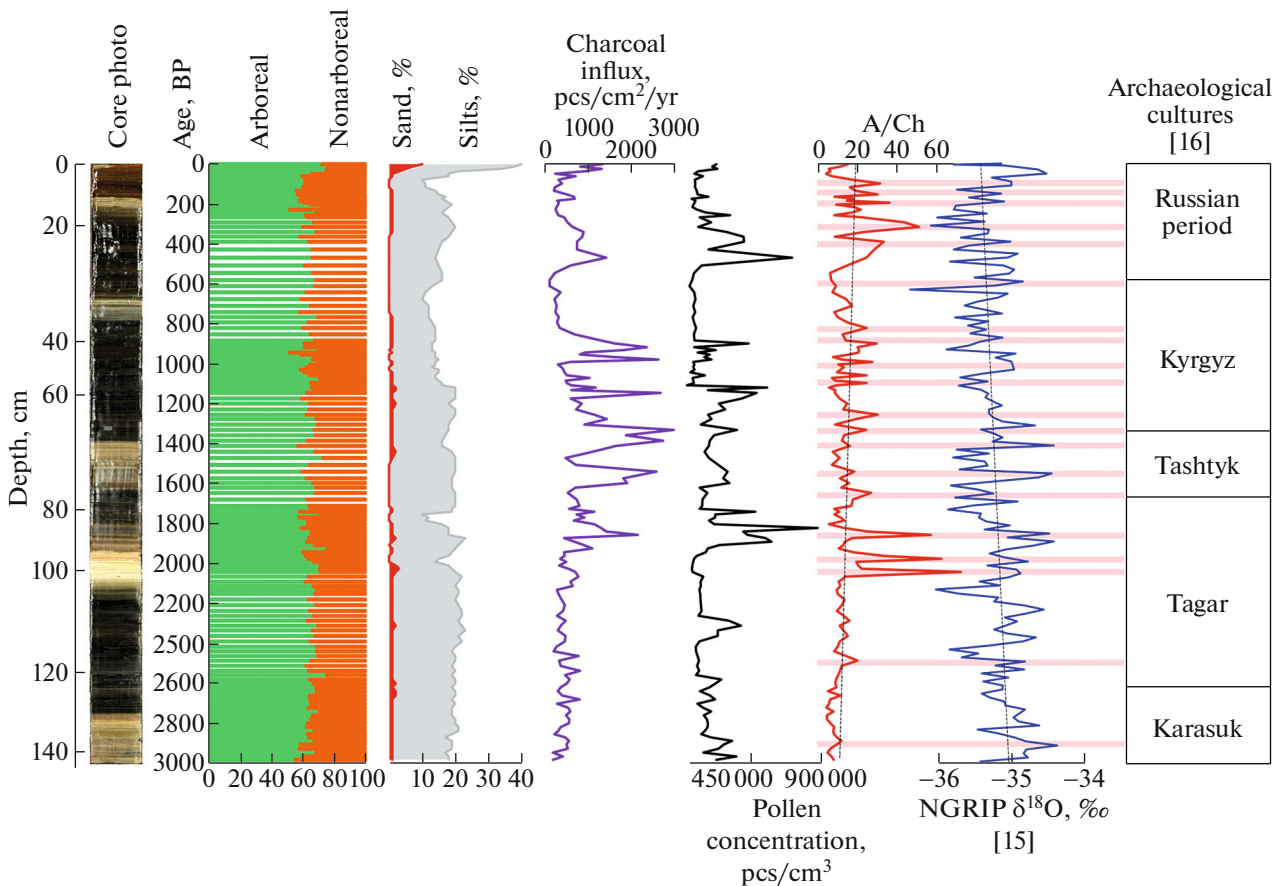


Fig. 2. Photo of the core and summary plot of selected indicators of changes in the natural environment in the basin of Shira Lake over the past 2980 years: pollen of arboreal and nonarboreal plants; content of coarse particles in the sediment from the Shira-2021-II-1 core; charcoal particle influx reflecting local fires; pollen concentration; A/Ch pollen ratio as an indicator of changes in available moisture for plants; NGRIP oxygen isotope record from the Greenland ice core [15] as an indicator of the North Atlantic climate over the past 2980 years; pink rectangles designating peaks in the A/Ch curve, corresponding to peaks in the NGRIP curve (low temperatures).

Later on, during 2650–880 BP, the role of meadow–steppe assemblages increased in the north of the Minusinsk Basin. The increased pollen concentrations imply higher pollen productivity of vegetation in the basin and/or a thicker vegetation cover than before. The proportion of dark coniferous tree species decreased, or their lower boundary rose in the mountains surrounding the basin. Larch, elm, and willow remained important elements of the local vegetation. The reconstructed changes in the vegetation composition at 2650–880 BP imply a continental, insufficiently humid climate of the region, which, however, was interrupted by short episodes of increased moisture, as indicated by the maximum A/Ch values at 2040, 1980, and 1850 BP. The layer of “whitish” silts, corresponding to cooling, was formed during 2090–1950 BP. Cooling might have led to reduced evaporation, providing sufficient moisture for meadow–steppe communities, as indicated by the A/Ch ratio increasing to 16 during 2650–880 BP.

In the period 880–70 BP, *Artemisia*–*Poaceae* steppes remained dominant. Starting from 120–100 BP, moist habitats that were favorable for poplar, sedges, and buttercups developed along the lake shores, which may evidence the expansion of the littoral/shallow water zone. The intense participation of *Poaceae* pollen (including cultivated ones) may reflect their involvement in the vegetation of the basin and/or the expansion of the littoral zone, where *Poaceae* (reeds) are currently abundant too. The average value of the A/Ch ratio during the period 880–50 BP reached 18, admitting even more favorable conditions of moisture for vegetation than before.

The increased role of birch in the past 50 years coincides in time with a similar event from the LS09 record, confirming the reliability of the age models of both records and their high temporal resolution. The spread of birch could have followed from the transformation of local landscapes due to the construction of resort zones around Shira Lake [7]. The sharply increased input of sand- to silt-sized particles into the

lake in the past 50 years could also have been caused by increased anthropogenic erosion along with active aeolian input.

The comparison of variations in the influx of charcoal microparticles in the Shira-2021-II-1 record (Fig. 2) with a sequence of the Bronze and Iron Age cultures [13] in Khakassia shows that the increased influx of charcoals occurred in the final period of the Tagar culture, the middle of the Tashtyk culture, the first half of the Kyrgyz culture, and the modern period. In addition, the past 50–40 years were characterized by a consistently high influx of charcoal particles into the bottom sediments, which is also confirmed by a sharp increase in the influx of charcoal particles into the lake during the modern period [6].

To understand the possible causes of the reconstructed changes in regional vegetation, a comparison was made between the A/Ch values as an indicator of plant-available moisture and the variations in air temperature in the North Atlantic (Fig. 2). The visual comparison of both curves shows that, over the past 2980 years, almost each A/Ch peak corresponds to the peak in the NGRIP oxygen isotope record from the Greenland ice core. This may indicate that the moisture conditions for vegetation in the north of the Minusinsk Basin reflect decadal variability in the North Atlantic temperature [7]. Uncertainty in the age models of the records dated by the different methods could be a reason why not all peaks in the two curves coincided.

CONCLUSIONS

Thus, the new palynological record from the Shira-2021-II-1 core turned out to be 530 years older than the previous one, which made it possible to reconstruct the history of vegetation, climate, and fire of the northern Minusinsk Basin over the past 2980 years with a unique average temporal resolution of 21 years. The reconstructions show the existence of a relatively humid regional climate during 2980–2650 BP. The climate of the basin itself remained quite arid, providing the existence of steppe and meadow–steppe assemblages around Shira Lake for the past 2980 years. The trend of changes in the A/Ch pollen ratio implies a slight increase in the moisture level of the Minusinsk Basin at 2980–70 BP and a noticeable decrease in the past 70 years. However, this increase was interrupted by short-term periods of climate aridization. The maximum influx of charcoal particles in the past 2980 years was recorded during the existence of the Tashtyk and Kyrgyz cultures, and in the modern period, but at the current stage of research it is hardly possible to determine whether it was caused only by the anthropogenic impact.

The reconstructions showed that the changes in vegetation around Shira Lake in the Late Holocene were mainly caused by large-scale circulation pro-

cesses that changed the heat and moisture balance in the region. Like the previous pollen record, the new one did not have clear pollen indicators of anthropogenic influence on vegetation. The noticeable increase in the birch pollen content for nearly the past 50 years may indicate trees planting around the resort areas.

ACKNOWLEDGMENTS

We are grateful to E.V. Kerber for work with the age model.

FUNDING

This work was supported by the Russian Science Foundation, grant no. 23-17-00067 (drilling, core sampling, and the palynological analysis) and conforms in part to a State Assignment of the Vinogradov Institute of Geochemistry, Siberian Branch, Russian Academy of Sciences, project no. 0284-2021-0003.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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Translated by L. Mukhortova

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