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Late-Holocene vegetation and fire history in Western Putorana Plateau (subarctic Siberia, Russia)

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Abstract

We present a reconstruction of vegetation dynamics and fire history from the western part of the Putorana Plateau during the Late-Holocene. The study area is located in the remote and poorly investigated region of Central Siberia, which represents an important area for understanding climate and environmental changes in the Russian Subarctic. Pollen and macroscopic charcoal data from three closely located lakes along an altitudinal transect in the Khantaika River basin show no major changes in vegetation in the study area during the last 3.9 ka BP. However, a detailed analysis of the data reveals an extension of forest coverage in lake catchments at about 3.1 ka BP followed by a gradual degradation of woodlands, and an expansion of shrubs and tundra vegetation at around 2.7–2.5 ka BP. Fire activity was relatively high between 3.0 and 2.0 ka BP compared to all but the most modern part of the record, while macroscopic charcoal accumulation reaches a maximum in the most recent surface sediments. This suggests an increase in the frequency and area of fires in the region since the end of the 19th century, which has no analog during the Late-Holocene.

Keywords

Central Siberia, lacustrine sediment, lakes, macroscopic charcoal, paleoenvironment reconstruction, pollen

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Introduction

Climate warming in recent decades has been accompanied by melting permafrost and increased fire frequencies in Arctic and Subarctic regions (IPCC, 2019), creating increased interest in understanding past environmental changes as a way to better understand modern processes and help predict future ecosystem dynamics. One of the most important tools for reconstructing these past environmental conditions is the use of paleolimnological studies (Biskaborn et al., 2016; CAPE Project Members, 2001), since lakes provide a unique "natural archive" for aquatic ecosystem dynamics and vegetation, climate, and fire history in their catchments.

The extensive area of polar Siberia is poorly investigated, mainly due to its remote location, limited transport networks, and severe climate. Previous paleoenvironmental studies in the region have been focused on the Taimyr peninsula (Andreev and Klimanov, 2000; Andreev et al., 2003, 2004), the northern Siberian lowlands, the Lena River delta area, and islands of the Laptev Sea (Andreev et al., 2009, 2011; Biskaborn et al., 2013; Herzschuh et al., 2013; Opel et al., 2017; Rudenko et al., 2020; Wetterich et al., 2008) and the northeastern extremity of Eurasia (Lozhkin and Anderson, 2013; Lozhkin et al., 2019; Murton et al., 2017; Wennrich et al., 2016). In the inner regions of Northern Siberia, studies of Holocene vegetation dynamics, climate, and lake ecosystems have mainly been undertaken in Yakutia (Klemm et al., 2013, 2016; Müller et al., 2009; Nazarova et al., 2013).

The present study is focused on the Late-Holocene vegetation and fire history of the western part of the Putorana Plateau (subarctic central Siberia), based on lake sediment records previously collected and studied by Self et al. (2015) to reconstruct summer temperatures from chironomid remains. The nearest detailed vegetation and climatic reconstructions for northwestern Putorana Plateau were previously obtained by Andreev et al. (2004), from a Late Glacial and Holocene pollen record from Lama Lake, 130 km to the northwest. Lama Lake is much larger (460 km^2)

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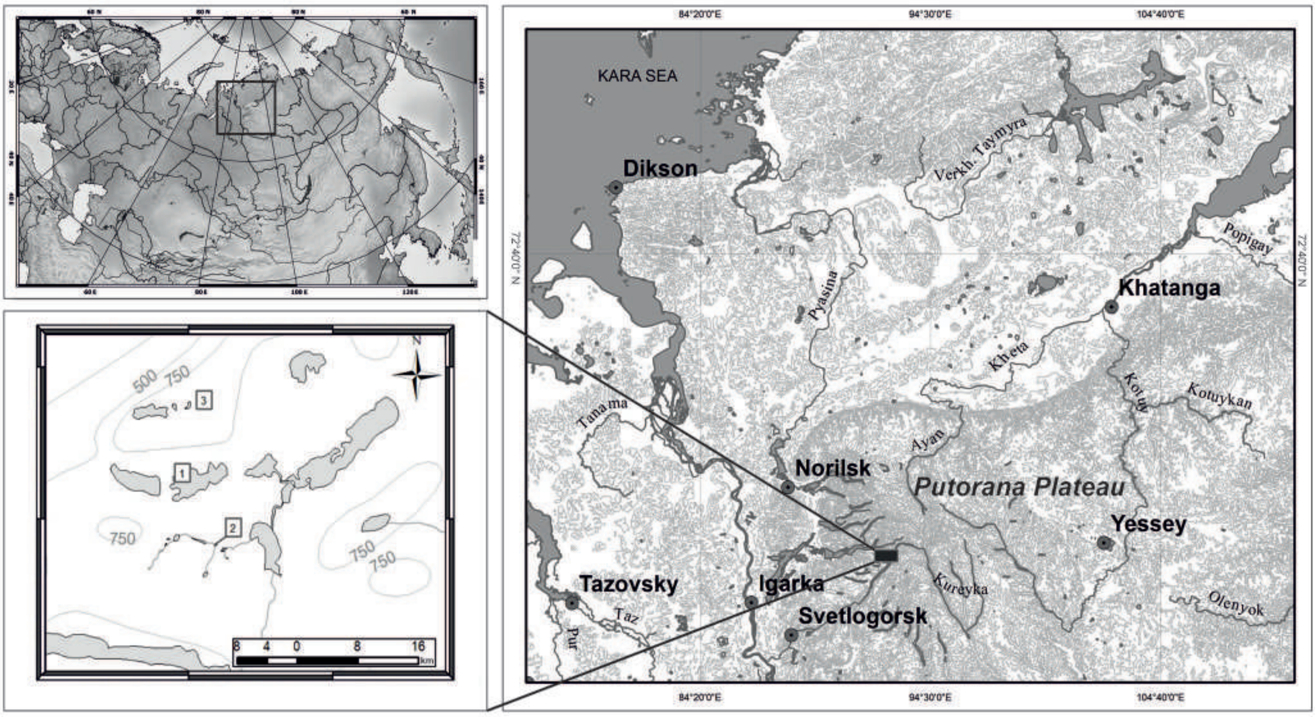

Figure 1. Location of the study area. Numbers indicate studied lakes: 1 – GYXO, 2 – PONE, 3 – PTHE.

than the lakes investigated by Self et al. (2015), and at a lower altitude of only 53 m above sea level (a.s.l.). Several other studies of lake sediments have been carried out in the southern part of the Taimyr Peninsula, adjacent to the Putorana Plateau (Andreev et al., 2003; Bolshiyanov and Pavlov, 2019; Kind and Leonov 1982; Syrykh et al., 2017). However, the western part of the Putorana Plateau has remained largely unexplored. The area is very important for understanding the history of environmental changes in the Russian Subarctic, representing one of the largest nature reserves and UNESCO World Heritage sites in Russia, and being relatively untouched by human activity.

Recent climate change has affected wildfire regimes in Arctic and Subarctic regions (IPCC, 2019). Fires have a great impact on permafrost, forest, and tundra ecosystems (Kirdyanov et al., 2020), and have a significant influence on human livelihoods. Studies of Holocene fire history in polar regions has mainly been focused on northern Canada and Alaska (Gajewski et al., 2021; Vachula et al., 2020). A few studies have been undertaken in the permafrost zone of Siberia (Heim et al., 2021), but we are aware of no previous paleofire records from the Putorana Plateau region.

In this paper, we present new pollen and macroscopic charcoal data from three closely located lakes at different altitudes in the western part of the Putorana Plateau. Field work, coring, and sampling in these lakes was carried out by a research group from the University College London (UCL) and Natural History Museum in 2006, as part of a project dedicated to studying the ecology of chironomid communities and creating a transfer function for paleoclimate reconstruction (Self et al., 2015). The chronology of the lake sediment cores is based on AMS radiocarbon dating, together with ^{137}Cs/^{210}Pb dating of the uppermost sediments. Initial work on the cores was restricted to chironomid analysis before storage at UCL in a sediment cold room. In 2019, the remaining sediment was transferred to Lomonosov Moscow State University for further analysis. Our objectives are (i) to reconstruct vegetation changes and fire frequencies during the last 4000 years, and (ii) to reveal the influence of climate change on vegetation dynamics and fire regimes, by comparing our results with previous climate reconstructions in the study area and additional paleoecological data from north-central Siberia.

Study area

The Putorana Plateau is a rugged mountain range with an average elevation of 500–1500 m a.s.l., located in the northwest corner of the Central Siberian Plateau (Figure 1). The topography of the western part of the Putorana Plateau is a combination of flattened peaks, stepped slopes, and deep valleys with rivers and lake basins (Yanchenko et al., 2010). The bedrock is Triassic igneous basalts of the Siberian Traps.

The study area is characterized by Siberian subarctic climate (Alisov, 1956) and located within the region of continuous permafrost. According to observations at the Dudinka weather station, located 200 km to the west at an elevation of 20 m (period of observation 1970–2012), the mean annual temperature is −9°C. The winter is long and severe, and the mean temperature of the coldest month (January) is −34°C. The summer is short, but relatively warm, with a mean July temperature of 12°C. The western part of the Putorana Plateau is influenced by Atlantic air masses, and the mean annual precipitation reaches 540 mm.

The vegetation cover of the Putorana Plateau is dominated by sub-arctic larch forests (*Larix gmelinii, Larix sibirica*) that are replaced by open *Larix* woodland and shrubs on mountain slopes (*Duschekia fruticosa, Betula nana, B tortuosa, B. cajander*: Shahgedanova et al., 2002). Mixed woodlands of *Larix gmelinii, L. sibirica, Picea obovata*, and *Betula tortuosa* are common in the lower mountain belt (Malyshev, 1976). Tundra occupies areas above the upper timberline in the elevation range of 400–600 m a.s.l. Soil cover is poorly developed and forms a thin layer of organic material near the surface.

The studied lakes are located along an altitudinal transect in the Khantaika River basin of western Putorana Plateau. The first sediment core was taken from Glukhoe Lake (code-named GYXO), which is a relatively large lake (230 Ha) located in a wetland complex at relatively low altitudes on the valley floor at lower altitudes within a valley floor – wetlands complex (068°09′54″N, 092°10′23″E, altitude 569 m a.s.l.). The second lake (code-named PONE) is a small unnamed lake (0.9 Ha), situated within the undulating topography of a hanging valley, between two mountains at mid-altitudes close to the tree line (068°08′33″N 092°12′11″E, alt. 596 m a.s.l.), located 3 km southeast of GYXO. The third lake,

Table 1. Results of radiocarbon dating of samples from the sediment core from lakes GYXO and PTHE.

Laboratory code	Depth, cm	Radiocarbon date ^{14}C yr BP (1σ)	Calibrated age range, 95% confidence interval (probability)
GYXO Lake			
SUERC-51090	11.75–12.00	1527 ± 35	1316–1322 (0.012) 1345–1478 (0.859) 1481–1517 (0.129)
SUERC-51091	19.00–19.25	2488 ± 35	377–2380 (0.003) 2426–2724 (0.997)
SUERC-51092	26.25–26.50	2311 ± 35	2157–2244 (0.254) 2300–2366 (0.734) 2392–2405 (0.012)
Beta-312807	31.75–32.50	3210 ± 30	3371–3466 (0.991) 3475–3479 (0.009)
PTHE Lake			
SUERC-51098	16.50–16.75	2293 ± 40	2155–2262 (0.464) 2298–2357 (0.536)
SUERC-51099	25.00–25.50	2663 ± 40	2737–2851 (1.000)
SUERC-51100	33.00–33.50	3556 ± 40	3701–3704 (0.072) 3716–3803 (0.296) 3812–3932 (0.631)

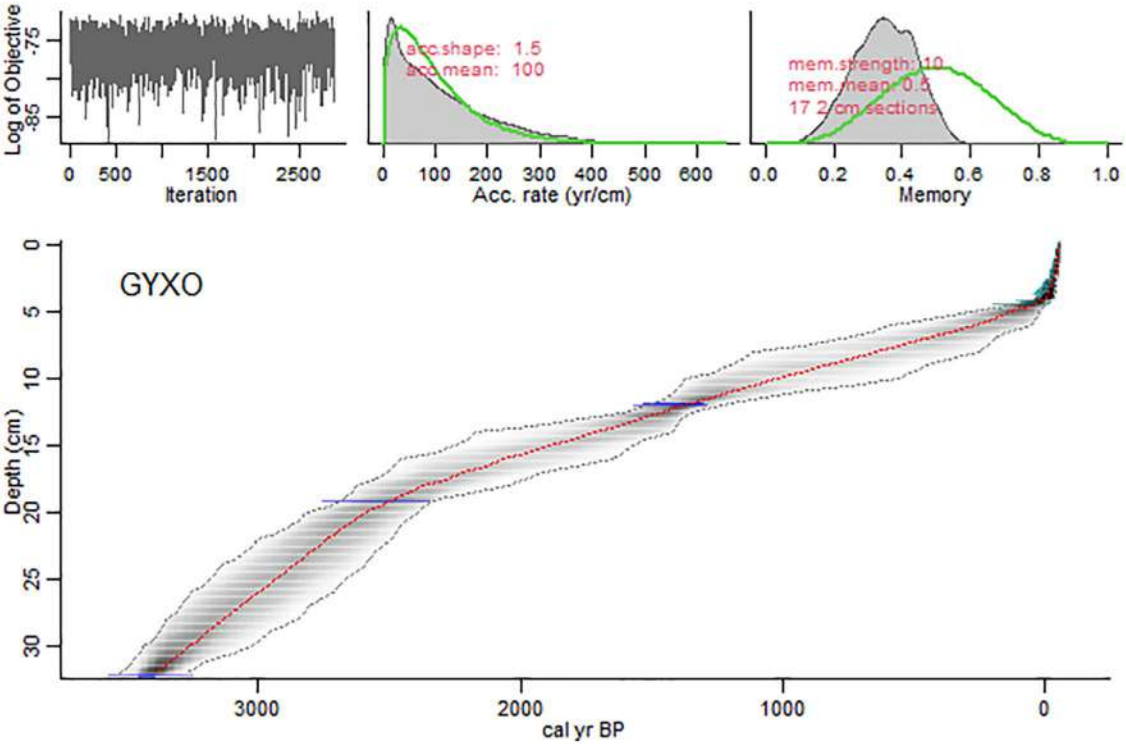

Figure 2. Ade-depth model of sediments in GYXO Lake.

unnamed (code-named PTHE, 068°12′12″N, 092°10′44″E), was the highest altitude lake in the present study, situated in a small rocky hollow (6.8 Ha) at an elevation of 805 m a.s.l. and 5 km to the north of GYXO. The vegetation around GYXO and PONE consists of scattered *Larix sibirica* and *L. gmelinii*, with an understorey of *Duschekia fruticosa* and *Betula nana* (Self et al., 2015). *Salix* thickets occur in wetter areas. PTHE was surrounded by sparse vegetation, including prostrate willows and lichens.

Materials and methods

Sediment cores were obtained from the deepest point of each lake in July 2006, using a 70-mm diameter HON-Kajak corer (Renberg, 1991) with a 0.5-m Perspex coring tube (Self et al., 2015).

According to Self (2010), the sediment core from PTHE included loose algal material (0–2 cm), a layer of sediment, graded gradually from gyttja (2–10 cm) to gray clay (10–35 cm). The core from PONE included loose organic-rich sediment (0–2 cm), brown gyttja (2–10 cm), and gray clay (10–28 cm). The sediment core from GYXO was composed of homogeneous gyttja (Self et al., 2015).

Three AMS radiocarbon dates were obtained from each core. Radiocarbon dating of the bulk sediment samples was performed in the NERC Radiocarbon Facility (Environment) and SUERC AMS Laboratory (allocation number 1746.1013), while an additional sample from the base of the GYXO core (31.75–32.00 cm) was analyzed by Beta-Analytical, USA (Self et al., 2015). The top 4–8 cm of each core was also dated with ^{137}Cs/^{210}Pb analysis. The ^{14}C dates were calibrated using the program Calib 8.2, and the calibration dataset Intcal20 (Reimer et al., 2020). All calculations were done at 2σ level (Table 1). We used the Bacon age-modelling software (Blaauw and Christen, 2011) to construct an age-depth model for sediment cores PTHE and GYXO, based on all ^{210}Pb and ^{14}C dates (Figures 2 and 3).

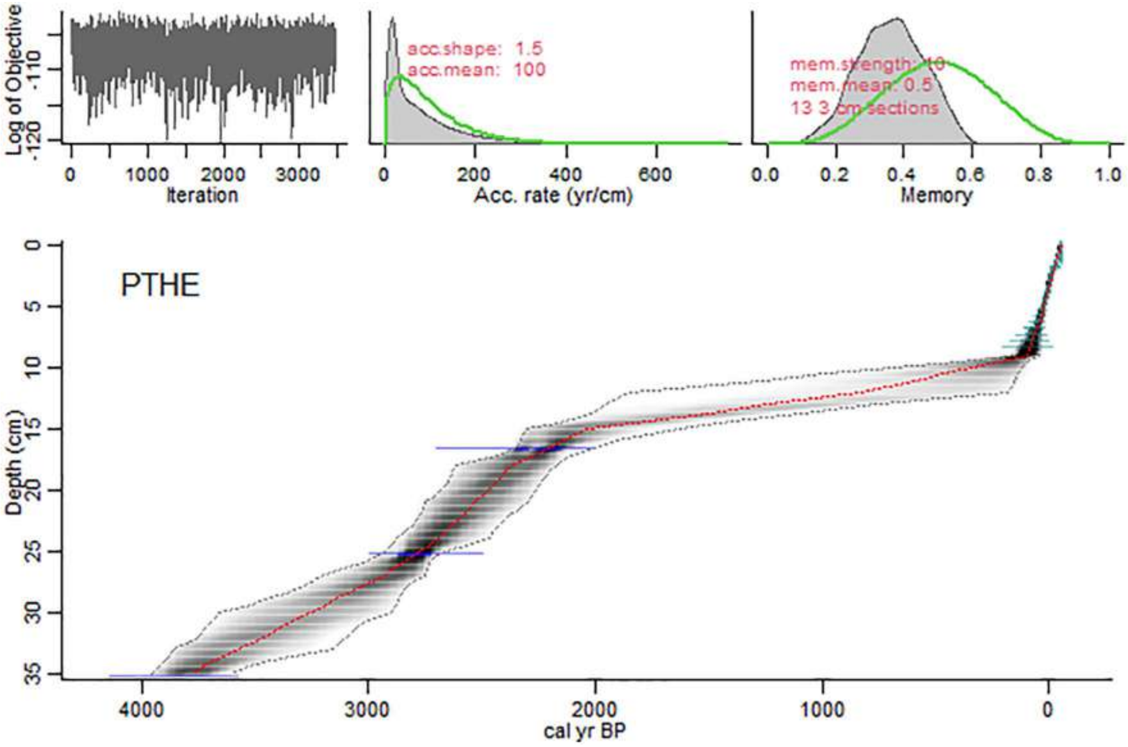

Figure 3. Ade-depth model of sediments in PTHE Lake.

According to Self et al. (2015), radiocarbon dates from the sediment core PONE revealed an age inversion, suggesting that the basal section of the core had been disturbed or contaminated, and was therefore unsuitable for time-dependent comparisons. We did not use these radiocarbon dates in the present study and focused on the uppermost 7.5 cm of this core, which accumulated during the last 140 years.

The sampling interval for pollen analysis was every 3 cm in each core. Each pollen sample (1 cm^3) was prepared following Moore et al. (1991). The samples were heated for 10 min in 10% KOH to remove humic material, then silicates were removed using HF (Bennett and Willis, 2002), followed by fine-sieving through a 10 µm mesh with 10% $Na_4P_2O_7$. The last stage of the sample treatment was an acetolysis in a water bath for 5 min, to dissolve cellulose. Pollen was identified using a Zeiss Axio Lab A1 microscope at 400 magnification following Reille (1992) and Beug (2004). More than 500 terrestrial pollen grains were counted in each sample. Calculation of pollen percentages was based on the terrestrial pollen sum – arboreal pollen (AP) plus non-arboreal pollen (NAP) without aquatic plants, spores, and non-pollen palynomorphs. Pollen diagrams were constructed using Tilia 2.0.2 and TGView software (Grimm, 1990). Pollen assemblage zones were defined by constrained incremental sum of squares cluster analysis (Grimm, 1987), using the CONISS application in the Tilia 2.0.2 program.

Samples for macroscopic charcoal analysis were taken continuously in 1 cm intervals from sediment cores GYXO and PTHE. The method of sample preparation (Mooney and Tinner, 2011) included bleaching of the sample with a volume of 1 cm^3 in 10% NaOCl solution for 24 h, sieving through 125 µm mesh and then counting all charcoal particles under a stereomicroscope at 40-fold magnification.

Data processing of macro-charcoal concentration was carried out using CharAnalysis software (Higuera et al., 2007). To determine fire events and fire frequency, the following parameters were used: CHAR – charcoal accumulation rate (pieces cm^{-2} yr^{-1}); C_{int} – CHAR of interpolated record; C_{back} – low-frequency trend in C_{int}; and C_{peak} – high-frequency trends in C_{int}. We used 60 years to interpolate the record. The charcoal peaks were defined as a ratio ($C_{peak} = C_{int}/C_{back}$). These peaks were separated from background charcoal (C_{back}) using the LOWESS smoothing method. A 500-year window was applied to smooth the record, in order to estimate C_{back}. The threshold values were set at the 95th percentile of a Gaussian mixture model, within a time window of 2400 years for GYXO, and 1500 years for PTHE.

Results

According to radiocarbon dating, the sediment cores of GYXO and PTHE accumulated during the last 3.9 and 3.0 ka BP respectively. Dating uncertainties in the lower part of the PONE core only allow us to discuss the last 140 years with confidence.

Pollen analysis

Despite differences in altitude, lake size, and local vegetation, the composition of pollen assemblages from the lacustrine sediments of three lakes are very similar (Figures 4–6). Pollen assemblages are characterized by a high proportion of arboreal pollen (50–60%), composed mainly of shrub species. The arboreal pollen (AP) is dominated by *Betula nana*-type and *Duschekia fruticosa* (40–50%). Tree pollen (10–20%) is represented mainly by *Betula alba*-type with a small proportion of *Pinus, Larix, Alnus sp.*, and *Picea.* The over-representation of *Betula* pollen in samples of larch taiga compared to their relatively low proportion in the plant cover is a typical feature for northern Siberia (Niemeyer et al., 2015). The proportion of *Larix* varies from 0.2 to 2.5% in the sediments of both GYXO and PONE, and does not exceed 1% in sediments of PTHE. These proportions are close to the representation of *Larix* pollen in surface samples from sediment cores in treeless areas or open woodlands in northern Siberia (Niemeyer et al., 2015). The pollen of *Alnus* sp., *Pinus*, and *Abies* has most likely been transported by wind from the southwestern part of the Putorana plateau. The occurrence of broadleaved *Tilia* and *Ulmus* pollen in the upper part of the sediment core PONE is noteworthy. The finding of thermophilic plants in pollen assemblages from the

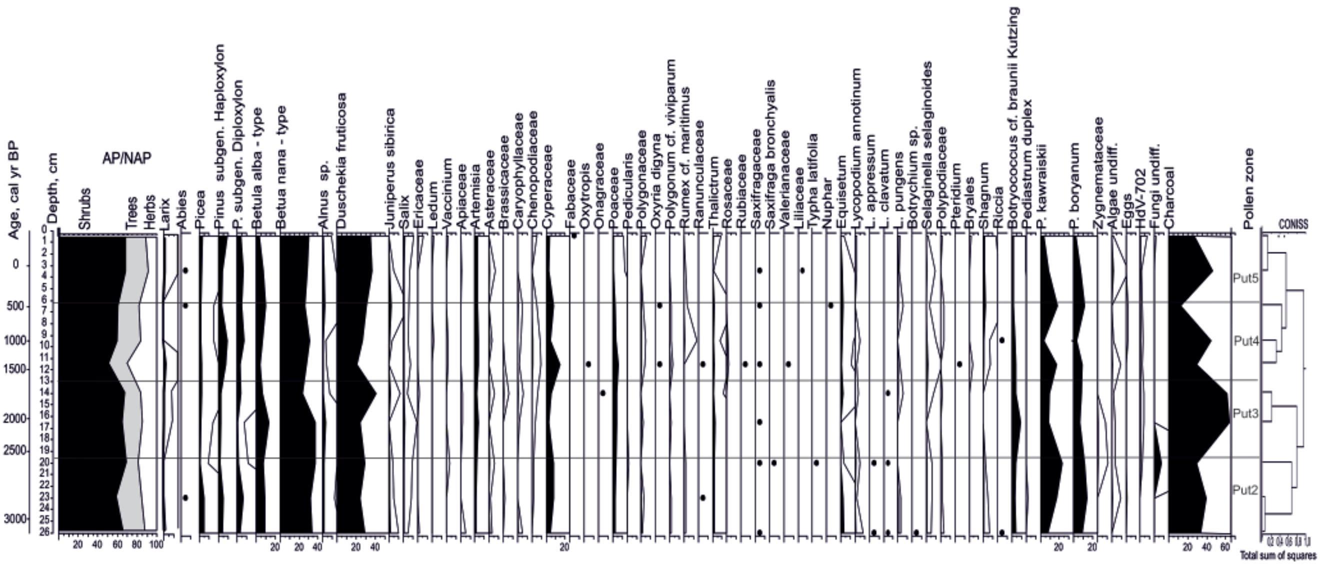

Figure 4. Pollen diagram of the sediment core from GYXO Lake (pollen sum: AP + NAP; additional curves represent ×10 exaggeration of base curves; black dots represent the presence of taxa <1%).

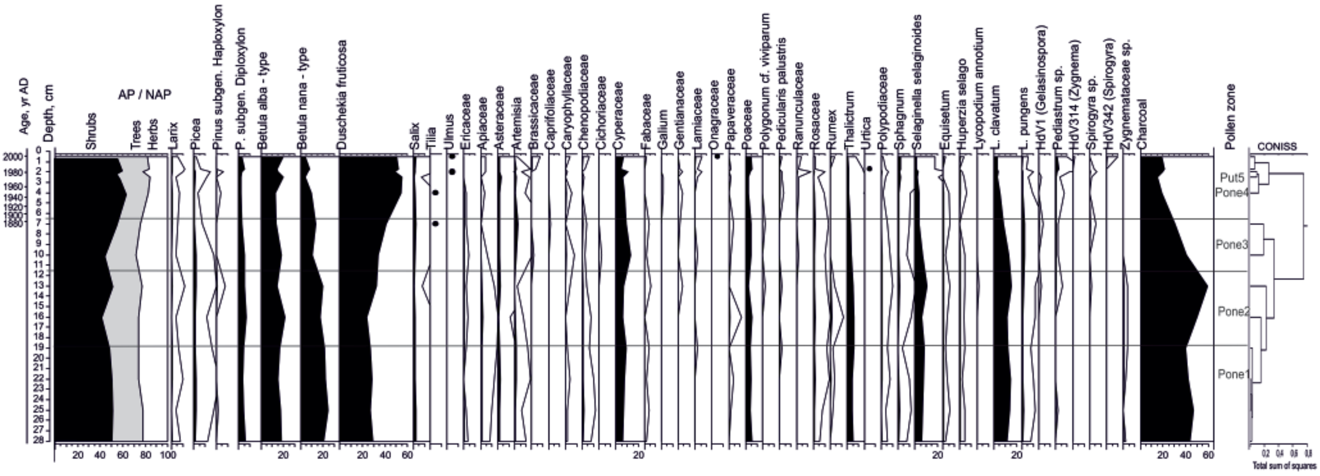

Figure 5. Pollen diagram of the sediment core from PONE Lake (pollen sum: AP + NAP; additional curves represent ×10 exaggeration of base curves; black dots represent the presence of taxa <1%).

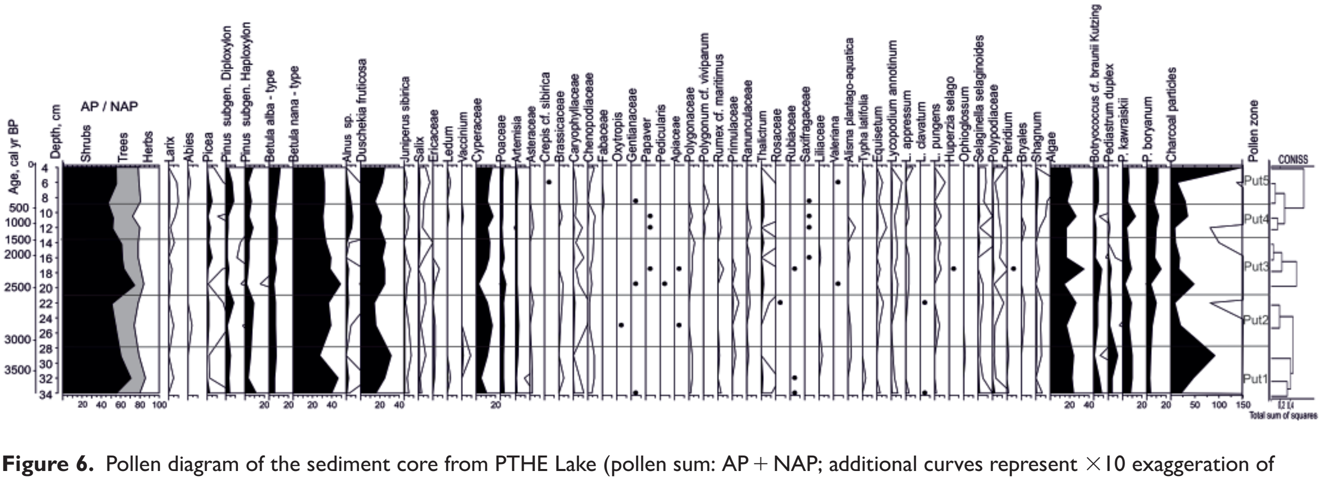

Figure 6. Pollen diagram of the sediment core from PTHE Lake (pollen sum: AP + NAP; additional curves represent ×10 exaggeration of base curves; black dots represent the presence of taxa <1%).

region is not uncommon, as rare pollen grains of broadleaved trees transferred from remote regions were also registered in the Talikit and Tonel lakes of the northern Putorana Plateau, and several lakes in Taimyr Peninsula (Bolshiyanov and Pavlov, 2019).

The amount of non-arboreal pollen (NAP) in the three cores varies from 15 to 25%, with a predominance of Cyperaceae, Poaceae and *Thalictrum* (7–10%). *Artemisia*, Apiaceae, Asteraceae, Rosaceae, Fabaceae, Onagraceae, Ranunculaceae, and Ericaceae are also present. Among spores, *Selaginella selaginoides, Huperzia selago*, and *Equisetum* sp. are relatively abundant, and *Lycopodium annotinum, L. clavatum*, Polypodiaceae, and *Sphagnum* occur in small quantities. Algae is plentiful in pollen assemblages from PTHE and GYXO, represented by *Pediastrum duplex, P. kawraiskii, P. boryanum, P. simplex, Botryococcus braunii,* and *Zygnemataceae*. Non-pollen palynomorphs (NPP) were recorded in the PONE sediment core. Among them the most important was *Gelasinospora* (HdV-1), which becomes common from a depth of 9 cm.

The proportion of the main pollen taxa and age boundaries of the pollen zones in PTHE and GYXO are remarkably similar, so we assigned a common system of regional pollen assemblage zones (PAZs: Put1–5). As we supposed that the lower part of the PONE core had been disturbed, we did not include the pollen zones identified in PONE as part of the regional PAZs. Nevertheless, we divided the pollen diagram from PONE into 4 local PAZs (PONE 1–4), and found that the depths and characteristics of the zones were close to those identified in the PTHE and GYXO cores.

PAZ Put-1 is represented only in the PHTE core (34–28 cm, 3.9–3.1 ka BP). Pollen assemblages are characterized by high proportion of tundra shrubs, such as *Betula nana* (30–40%) and *Duschekia fruticosa* (20–30%); algae were relatively abundant, and microcharcoal occured in high amounts.

PAZ Put-2 (PTHE: 28–21 cm, GYXO: 20–26 cm, 3.1–2.5 ka BP, LPAZ PONE-1, 28–19 cm). Pollen assemblages in this zone are marked by relatively high proportions of tree pollen in all sediment cores, and a rise of Cyperaceae and a decline of charcoal in pollen assemblages from PHTE. The pollen value of *Picea* and *Pinus* in GYXO, PTHE, and PONE reached 5–7% and amount of *Betula alba*-type was about 10%. In PTHE share of *Larix* and *Abies* slightly rose.

PAZ Put-3 (PTHE: 21–14 cm, GYXO: 20–13 cm, 2.5–1.5 ka BP, LPAZ PONE-2, 19–12 cm). The proportion of tree pollen decreased in this zone, while the pollen of shrubs (*Betula nana, Duschekia fruticosa*) and microscopic charcoal become more abundant.

PAZ Put-4 (PTHE: 14–9 cm, GYXO: 13–7 cm, 1.5–0.2 ka BP, LPAZ PONE-3, 12–7 cm. The upper boundary of this zone corresponds to the date AD 1880 according to the age-depth model from PONE and PTHE based on 137Cs/210Pb analysis). Pollen assemblages demonstrated an increase of *Larix* and *Pinus* pollen at the beginning of this zone. Pollen assemblages from GYXO are characterized by a higher diversity of herbs and an increase of *Selaginella selaginoides* spore values, indicating the presence of treeless habitats like meadows or shrub plant communities.

PAZ Put-5 (PTHE: 9–0 cm, GYXO: 7–0 cm, PONE: 7–0 cm, AD 1880 – present). During this period, pollen spectra show an increase in AP percentages and a rise of *Larix, Pinus, Betula*, and *Picea*. A noticeable increase in *Duschekia fruticosa* pollen abundance (up to 60%) occurred in PONE and GYXO. A distinct peak of *Picea, Larix*, and *Pinus* (subgen. *Haploxylon*) occurred in the 1970s and 1980s in the pollen sequences from PONE.

Macro-charcoal analysis

Macroscopic charcoal analysis of the GYXO sediment core shows that C_{int} varied from 0 to 0.22 pieces cm^{-2} yr^{-1} (Figure 7). In the time interval from 3.0 to 2.5 ka BP, C_{back} amounted to 0.02–0.07 pieces cm^{-2} yr^{-1}. Three peaks of CHAR were determined during this time period, indicating three fire events. Charcoal input declined notably between 2.5 and 0.25 ka BP. No charcoal particles were recorded in sediments with the exception of samples formed in intervals 1.7–1.9, 1.0–1.35, and 0.50–0.25 ka BP, where C_{int} was about 0.25 pieces cm^{-2} yr^{-1}. The last 250 years was characterized by a sharp increase in the charcoal accumulation rate. C_{int} and C_{back} increased to 0.31 and 0.22 respectively, and achieved their highest values of the entire sediment core. One fire event was identified.

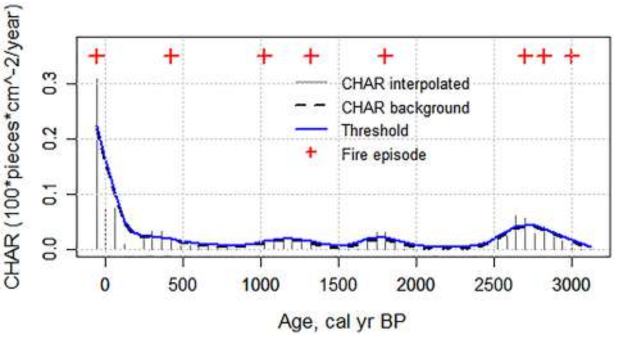

Figure 7. Macroscopic charcoal accumulation rate in sediments of GYXO Lake.

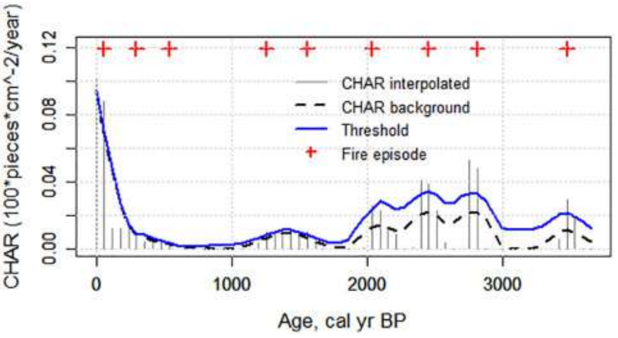

Figure 8. Macroscopic charcoal accumulation rate in sediments of PTHE Lake.

Macro-charcoal analysis of the PTHE sediment core revealed that C_{back} ranged from 0 to 0.1 pieces cm^{-2} yr^{-1} (Figure 8). Between 3.9 and 3.0 ka BP, C_{back} ranged from 0.01 to 0.02 pieces cm^{-2} yr^{-1} with a peak at 3.4–3.6 ka BP, corresponding to a fire event. In the period from 3.0 to 2.0 ka BP, C_{back}, and C_{int} increased to 0.04 and 0.05 pieces cm^{-2} yr^{-1} respectively. Three fire events were determined at 2.8, 2.4, and 2.0 ka BP. Accumulation of macroscopic charcoal declined between 2.0 and 1.1 ka BP, with C_{back} decreasing to 0–0.01 pieces cm^{-2} yr^{-1}. Two fire events in the interval 1.6–1.3 ka BP were identified. During the next period, from 1.1 to 0.5 ka BP, macroscopic charcoal accumulation in the lake ceased. Since about 0.5 ka BP, charcoal accumulation gradually increased. A sharp rise of charcoal input occurred during the last 170 years, as C_{back} grew from 0.01 to 0.1 pieces cm^{-2} yr^{-1} and reached the maximum value over the whole study period.

Discussion

The results show no remarkable changes in the vegetation of the study area since 3.9 ka BP, in agreement with the results of detailed vegetation and climate reconstructions from pollen records located at the Lama Lake, some 130 km north-west of the study area (Andreev et al., 2004). According to these data, the role of forests in the low altitudinal vegetation belt gradually decreased after ca. 5.2 ka BP, and at ca. 2.5 ka BP, vegetation patterns became similar to modern environments. Although the pollen assemblages from the studied sediment cores appear to be largely unchanging, a detailed analysis of the obtained pollen and macrocharcoal data allowed us to determine the impact of climate change on vegetation and fire activity in the study area.

The obtained results show that during the period from 3.9 to 3.1 ka BP, the vegetation cover in the lower mountain belt of the study area was represented by woodlands formed by larch, spruce, and birch, which were replaced by shrub and tundra communities along mountain slopes. Changes in the composition of pollen assemblages at about 3.1 ka BP (PAZ Put-2) indicate a climate warming and extension of forest coverage at low and middle altitudes of the study area. Since *Larix* has low pollen productivity and its pollen is poorly preserved in sediments (Klemm et al., 2013; Niemeyer et al., 2015), even small increases in *Larix* pollen could indicate that larch became more abundant in the vegetation. An increase of *Picea* in pollen assemblages suggests a higher proportion of spruce in woodlands. *Picea* today occurs sporadically in the study area in low altitude forests that lie at the boundary of its natural geographical range (Malyshev, 1976) and its pollen is rare. Pollen of *Pinus* and *Abies* was apparently wind transported from a taiga region of Western Siberia, and the increase in their proportions in assemblages might indicate a strengthening of the westerly transfer of air masses. Chironomid-based July temperature reconstructions from PTHE and GYXO (Self et al., 2015) suggest that a warmer and more maritime climate existed around 3.4–3.2 ka BP than at present. Climate warming inferred from pollen data appears to lag behind inferences from chironomid assemblages, possibly due to the inertia of vegetation change in comparison with insects. Pollen based temperature reconstructions in records from the Levinson-Lessing Lake in the northern Taimyr Peninsula also indicate a positive July temperature anomaly at about 3.0 ka BP (Andreev et al., 2003).

The result of macroscopic charcoal analysis showed an increase in charcoal concentration in GYXO and PTHE at the time intervals 3.0–2.5 and 3.0–2.0 ka BP respectively. We suggest that higher summer temperatures possibly caused an occurrence of fire-hazardous weather conditions, which could lead to increased fire activity.

Climate cooling was recorded at about 2.7–2.5 ka BP in chironomid records from our studied lakes (Self et al., 2015), and also in a number of records in the circumpolar Arctic (Christiansen and Ljungqvist, 2017; MacDonald et al., 2000; PAGES 2k Consortium, 2013). This cooling may have led to the reduction of forest vegetation and expansion of tundra plant communities recorded in the study area (PAZ Put-3), as well as decreasing fire activity. A decline of summer temperature around 2.7–2.5 ka BP is also recorded in a tree-ring based paleoclimate reconstruction from the Yamal Peninsula (Hantemirov and Shiyatov, 2002), and in an analysis of *Larix* wood disturbances (Hantemirov et al., 2011). An increase in $K+$ deposition in the GISP2 ice core at 2.8–2.9 ka BP may indicate a change in the strength of the Siberian High (Mayewski et al., 2004), which would lead to an increase in climate continentality in Central Siberia.

During the period from 2.5 ka BP until the last 140 years, vegetation dynamics were characterized by a gradual reduction of woodland area and an expansion of hypoarctic shrubs (*Betula nana, Dushekia fruticosa, Salix*) and grasses. It is noteworthy that an increase in the spores of *Selaginella selaginoides* was recorded in pollen assemblages from GYXO, suggesting an increase in the area of treeless vegetation communities, in the form of wet meadows and shrub thickets.

The Little Ice Age (LIA) in the northwestern part of the Putorana Plateau has been identified between 520 and 90 years ago by pollen records and varve chronology of the sediment core from Lama Lake (Bolshiyanov et al., 2009). This is close to the time frame of the LIA at global scale, determined to lie between AD 1400 and 1850 (Mann et al., 2009; PAGES 2k Consortium, 2013). Pollen and macroscopic charcoal records from the studied lakes suggest that cold climatic conditions and rare fires occurred at this time. Charcoal accumulation was extremely low or ceased, indicating no fire activity in the lake catchments. According to dendrochronological data and reconstruction of fire regimes using fire scars on tree trunks, the LIA was characterized by a significant reduction of forest fire frequency in the permafrost zone of Central Siberia (Kharuk et al., 2011).

Notable changes in vegetation, climate, and fire regimes have occurred over the past two centuries. Detailed palynological analysis of the upper part of the PONE sediment core, combined with chronological control based on ^{137}Cs/^{210}Pb isotope dating, show an increase in the abundance of larch and spruce in forest communities between 1970 and 1980. Reconstruction of July temperature by chironomid data from the same sediment core, as well as meteorological observations (Self et al., 2015), indicate a climate warming during this time and more favorable conditions for tree growth.

The charcoal accumulation rate in surface sediments of the studied lakes increased to maximum values over the last 200 years, never before experienced during the entire Late-Holocene. Spores of *Gelasinospora* sp. (HdV-1) fungi – which are mainly carbonicolous and often grow on charred wood – and charcoal particles were common in PONE, providing additional independent evidence that fires occurred in the area adjacent to the lake and mountain slopes (Shumilovskikh et al., 2015; Van Geel, 1978). At the same time, pollen assemblages from PTHE demonstrate the highest peak in micro-charcoal values compared to other part of the sediment core, which reflects the high input of charcoal particles not only at the local, but also at the regional level. Dendrochronological studies in northern Siberia have shown that the fire frequency and the area of fires increased significantly in the 20th century (Kharuk et al., 2011; Kirdyanov et al., 2020), both due to climate changes and human impact.

Conclusions

The results of palynological and macrocharcoal analysis of sediment cores from three lakes in the western part of the Putorana Plateau have given us a unique possibility to examine the Late-Holocene palaeoenvironmental and climatic changes in this remote, poorly investigated region of Central Siberia. This region is a globally important bio-reserve and protected wilderness area, representing one of the few environments with a limited history of human impact. Therefore our study is ideal for understanding natural climatic processes and phenomena in Arctic and Subarctic regions. Our main conclusions are as follows: (1) Despite differences in catchment size, altitude, and local vegetation around the studied lakes (forest at GYXO and PONE, tundra at PTHE), the composition of pollen assemblages and the proportion of the main pollen taxa were remarkably similar in all lakes, indicating a large transfer of arboreal pollen from the lower mountain belts to the upper slopes. (2) Palynological data from the three studied lakes demonstrates that vegetation and environmental conditions in the western part of Putorana Plateau were similar to modern conditions over the last four thousand years. However, a detailed analysis of the obtained pollen and macroscopic charcoal records shows that climate warming at about 3.1 ka BP encouraged an increase in the proportion of forest coverage and a rise of fire activity across lake catchments. The subsequent climate cooling then led to a gradual degradation of woodlands and an expansion of shrubs and tundra vegetation, associated with a decrease in the number of fires and charcoal concentrations recorded in lake sediments. The most notable changes in vegetation occurred in the 20th century, as climate warming during the 1970s provided more favorable conditions for the growth of larch and spruce, causing an increase in their abundance in woodlands. (3) Macroscopic charcoal concentrations in lake surface sediments reached their maximum values of the entire study period over the last 200 years (since about 3.9 ka BP), which suggests a recent increase in the frequency and area of regional fires that has no analog during the Late-Holocene. The causes and extent of this enhanced fire activity require further detailed research.

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