Modern pollen spectra of the Teletskoye Lake shore: early results

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The article presents for the first time the results of an analysis of modern pollen spectra of the Teletskoye Lake shore sampled using 12 Tauber traps installed in various characteristic forest and meadow communities. Landscape descriptions have been performed for each sampling point, which increases the reliability of the interpretation of pollen spectra. Spectra are presented as a percentage of pollen from 27 identified taxa with a significant predominance of conifers, which are widespread in the composition of vegetation. Herb pollen is more diverse in the spectra compared to tree pollen but contributes less to their formation. The pollen of early flowering species is not represented in the spectra due to the late dates of trap installation. Based on the analysis, indicator taxa (*Betula* sect. *Betula*, *Pinus sylvestris*, *Larix*) marking the differentiation of natural conditions in the latitudinal and meridional parts of Lake Teletskoye were revealed mainly according to humidity regime.

Acta Biologica Sibirica 10: 89–105 (2024) doi: 10.5281/zenodo.10863443

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Academic editor: A. Matsyura | Received 26 February 2024 | Accepted 11 March 2024 | Published 26 March 2024

http://zoobank.org/48B862AC-807F-4089-8584-8258D5FAA92E

Citation: Kuryatnikova NA, Biryukov RYu, Zolotov DV, Malygina NS, Chernykh DV (2024) Modern pollen spectra of the Teletskoye Lake shore: early results. Acta Biologica Sibirica 10: 89–105. https://doi.org/10.5281/zenodo.10863443

Keywords

Altai Mountains, pollen, pollen monitoring, North-Eastern Altai, Lake Teletskoye

Introduction

The relationship between modern pollen spectra and vegetation is the basis for reconstructions of past vegetation and climate from fossil pollen spectra, since it can provide indispensable data for the interpretation of the latter (Seppä and Bennett 2003). To date, numerous studies have been carried out to establish the relationship of modern pollen spectra with modern climate and vegetation (Wright et al. 1967; Gaillard et al. 1992; Sugita 1994; Cour et al. 1999; Davis 2000; Shen et al. 2006; Ma et al. 2008; Zhao and Herzschuh 2009; Zhao et al. 2009; Herzschuh et al. 2010; Lu et al. 2011; Fall 2012; Zheng et al. 2013; Tian et al. 2014; Ge et al. 2017; Guo et al. 2020; Lin et al. 2023). Most research is based on the study of surface pollen spectra obtained from soils or moss cushions, which accumulate the spectrum for 2–5 years. However, more reliable data are obtained using Tauber traps, which reflect modern annual spectra with a clear time reference. The use of Tauber traps in studies of modern pollen spectra was initiated as part of the Pollen Monitoring Programme, PMP (Hicks et al. 1996). To date, there is a detailed overview of the data obtained using Tauber traps for Europe and Turkey (Pardoe et al. 2010). Similar studies were also carried out in the New World, China, Africa (Levetin et al. 2000; Gosling et al. 2003; Xu et al. 2009), and Russia (Nosova et al. 2015a, 2015b, 2019, 2020). Most of this research is focused on plain areas, where natural conditions remain homogeneous over a considerable distance.

The study of modern pollen spectra of mountain regions compared to plain ones is complicated by a number of factors. Climatic and altitudinal factors determine the distribution of vegetation and regulate pollen productivity, and numerous local winds play an important role in the spatial distribution of pollen. The established patterns demonstrate nonlinear relationships between pollen spectra and vegetation composition (Pidek et al. 2013; Iglesias et al. 2017; Zhang et al. 2018). To date, there have been several studies of modern pollen spectra from moss cushions, soil, and peat deposits in various mountain regions of Europe (Cañellas-Boltà et al. 2009), South America (Niemann et al. 2010), Caucasus, Tibet, China (Lu et al. 2008; Herzschuh et al. 2010; Wei et al. 2011; Xu et al. 2016; Zhang et al. 2018), and the Himalayas (Bera 2000; Ranhotra and Bhattacharyya 2013; Ghosh et al. 2017). However, research of pollen spectra in mountain regions using Tauber traps is rare (Gerasimidis et al. 2006; Vallé et al. 2019).

Altai is a large mountain system on the territory of Russia, Mongolia, China and Kazakhstan, which stretches from north to south for more than 1200 km and rises up to 4500 m above sea level (Hwang et al. 2008). The Altai Mountains act as a climatic and natural boundary between the influence of the Pacific and Atlantic oceans, and they also serve as the border between the Boreal and Tethyan (Ancient Mediterranean) Subkingdoms of the Holarctic Kingdom, Holarctis (Takhtajan 1986). There are also relict plant species and communities in the Altai Mountains, which is very relevant for palaeoecological and palaeoclimatic studies.

A significant part of the Altai Mountains including Lake Teletskoye (one of the largest freshwater lakes in Altai in terms of area and depth) is a UNESCO World Heritage Site “Golden Mountains of Altai” and is included in the WWF’s Global 200 list of virgin or little changed ecoregions of the world that boast exceptional levels of biodiversity (90% of the Earth’s biodiversity) (Report… 1998). Lake Teletskoye and its water protection zone are part of the Altaiskiy State Nature Biosphere Reserve, whose main mission is to preserve biological diversity. Therefore, the Teletskoye Lake shore is a unique object where it is possible to fully study modern pollen spectra with minimal impact of anthropogenic pressure, which is necessary for more accurate and detailed paleoreconstructions of climate and vegetation.

Materials and methods

The material for the study was data on pollen spectra obtained in the frame of pol- len monitoring at the Teletskoye Lake shore during the growing season of 2021. According to physical-geographical regionalization, Lake Teletskoye belongs to the North-Eastern Altai province (Chernykh and Samoilova 2011), and by geobotanical regionalization to the Northern Altai subprovince (Kuminova 1960), where the Priteletsky mountain-taiga okrug and within it the Priteletsky mountain-forest region are distinguished. There is a chern taiga here, which is replaced by a fir-cedar mountain taiga above and by forest-steppe belt on the light slopes to the lake. The lake level is located at an altitude of 434 m asl. It has a channel-like shape and is divided into northern latitudinal and southern meridional parts, which differ in morphometric characteristics, structure of the bottom, shores, as well as climatic, ice-thermal, wind-wave, and other features of the regime (Selegey and Selegey 1978). The natural conditions of the Teletskoye Lake shore change from northwest to southeast. In this direction, the climate becomes drier and more continental; the fir that dominates among conifers in the northwest is gradually mixed with larch. Cedar or Siberian pine (*Pinus sibirica*) is found everywhere as a subdominant or admixture to other tree species on the shore and the nearest slopes to the lake. It is most abundant on rocks and bedrock outcrops along mountain tops.

In the Teletskoye Lake shore, Tauber traps were used that meet the requirements of the PMP (Hicks et al. 1996) and allow one to evaluate the qualitative patterns of pollen spectra formation. The traps were installed at a level of 1.5 m above the ground in the immediate vicinity of the Teletskoye lake depression, taking into account the diversity of landscape conditions (Fig. 1). In total, they were installed at 12 points with a landscape characteristic given in Table 1. The traps were installed in early May (13.05.2021) and removed after the end of the growing season (24–26.09.2021). At the time of installation, the flowering of a number of species had begun, but some widespread ones (aspen, willow, rhododendron, etc.) had already ended, leading to incomplete coverage of the total annual pollen spectrum for the study area.

Figure 1. *Study area and location of pollen trap installation points.*

After the traps, all collected material was transferred to prepared containers and mechanically cleaned from large particles (leaves, insects, etc.) with the following addition of formaldehyde to prevent the decomposition of organic matter. The prepared residues were processed according to standard procedures (Hicks et al. 1996; Nosova 2020). Microscopic analysis was performed using an Axio Lab.A1 microscope and a Nageotte chamber at 400× magnification. All samples were examined using perpendicular longitudinal transects. To identify species, atlases (Kupriyanova and Aleshina 1972, 1978; Karpovich et al. 2013), international databases (Palynological database 2023), and reference pollen samples prepared based on the results of the field work were used. Statistical calculations were performed in Excel, and diagramming was performed using the C2 program. The sum of all identified pollen grains was taken as 100%.

Name of trap	Coordinates	Landscape characteristics	Number of pollen grains
Artybash	51°47′58.65″N87°16′33.48″E	The upper part of the eastern slope of the small watercourse valley cut into the lake terrace. Cedar-pine-birch tallgrass forest.	381
Samysh	51°45′48.91″N87°21′57.43″E	The lower part of the declivous northern slope located 1 km northwest of the Samysh River mouth. Birch-cedar-fir fern-tallgrass forest.	475
Baygazan	51°45′32.69″N87°25′56.25″E	The gentle terraced plume of the southern slope. Aspen-birch with the participation of fir and cedar shrubby fern-tallgrass forest.	385
Ydyp	51°44′9.02″N87°34′48.98″E	The gentle northern slope. Cedar-birch-fir shrubby horsetail-grass-forb forest.	504
Yaylyu_1	51°46′17.33″N87°36′15.70″E	The surface of the lake terrace slightly inclined to the south. Degraded forb-grass meadow.	392
Yaylyu_2	51°47′9.32″N87°35′51.08″E	The surface near the watershed. Birch-fir fern-tallgrass forest.	386
Kamga	51°47′56.68″N87°42′27.35″E	The alluvial cone of a small w atercourse.Fir-cedar-parvifoliate shrubby fern-tallgrass forest.	413
Kokshi	51°34′40.90″N87°41′9.00″E	The alluvial cone of the river. Mixed (birch, pine, cedar) rhododendron bilberry-grass-forb forest.	398
B. Chili	51°28′53.58″N87°42′1.34″E	The alluvial cone of the river. Cedar-pine-birch shrubby forest.	558
Bele	51°24′36.99″N87°47′44.09″E	The terraced declivous slope of southwest exposure. Larch-birch shrub-forb-grass forest.	479
Kyga_1	51°21′40.70″N87°50′27.00″E	The alluvial cone of a small watercourse. Degraded forb-grass meadow.	413
Kyga_2	51°21′0.22″N 87°50′42.49″E	The extended mouth part of the river valley. Pine-cedar-willow-birch horsetail-forb forest.	410

Table 1. *Location of pollen traps, description of landscape conditions, and the number of determined pollen grains*

Result

During the microscopic analysis of the samples, the pollen of 27 taxa was identified, including all the basic forest-forming species of the study area (Fig. 1). The main role in the formation of the pollen spectra of Teletskoye Lake shore belongs to the conifers, namely the pine family (Pinaceae), which includes cedar or Siberian pine (*Pinus sibirica*), fir (*Abies*), common pine (*Pinus sylvestris*), spruce (*Picea*) and larch (*Larix*). Herb pollen is more diverse than tree pollen. It should also be noted that due to the late installation dates of the traps (13.05.2021), the spectra did not include a significant number of early flowering plants that are widespread along the shores of Lake Teletskoye. Therefore, the pollen of rhododendron (*Rhododendron*), aspen (*Populus tremula*), and willow (*Salix*) was not determined in the samples analyzed. The beginning of plant pollination depends on the weather conditions, among which temperature is the main factor (Table 2). In general, it is not the temperature at a certain point in time that is important, but the sum of effective temperatures is greater than +5°C (Nekrasova 1983). According to the calculated sum of effective temperatures for the Artybash weather station (RIHMI-WDC 2023), the dates of beginning pollination were established for the main coniferous forest-forming species of the Teletskoye Lake shore regarding the sampling period. The data obtained allow us to assess the extent of coverage the main pollen season in the study area.

Forest-forming tree species	Sum of effective	Average date of pollination beginning (Nekrasova 1983)	Date of pollination beginning in 2021 (RIHMI-WDC 2023)
Betula pendula	47.5	No data	May 7
Picea sibirica	131	May 22	May 24
Abies sibirica	133–151	June 5	May 25–26
Pinus sylvestris	196.3	June 5	June 1
Pinus sylvestris	313.5	June 19	June 14

Table 2. *Average dates of pollination beginning and the necessary sums of effective temperatures for the main forest-forming tree species*

The analyzed pollen spectra are dominated by cedar pollen (*Pinus sibirica*) found in samples from all points and its share in the spectra ranged from 39 to 71%. Although cedar is a widespread species in North-Eastern Altai, it is most common in the upper altitudinal stripe of the forest belt and the lower altitudinal stripe of the subalpine belt. In places where traps were installed, only individual trees or small groups represent it. Cedar pollination is observed when the sum of effective temperatures reaches 313.5°C (Table 2) that was noted in the study area on June 14 (RIHMI-WDC 2023). In addition, the researcher of the Altaiskiy State Nature Biosphere Reserve R.I. Vorobyov pointed out “dry fog” in the Yaylyu village on June 14, 2021. It is a phenomenon in which clouds of pollen are observed due to massive pollination of cedar on Teletskoye Lake shore. Among all conifers, cedar requires the highest sum of effective temperatures for pollination that, it would seem, should lead to the shortest duration of the pollen period. However, cedar has the longest pollen period among conifers, which is explained by its tolerance to shade and complex structure of tree stands. All this leads to asynchronous development of generative organs both in different trees and within the same branch (Nekrasova 1983). The mass distribution of cedar in the upper altitudinal belts, the extended pollen period, and high pollen productivity (up to 3 kg per tree in forest ranges (Golovko 2004) are reflected as high proportions in the pollen spectra. Crown density at the sampling sites should have reduced the proportion of cedar in the spectra, and on the contrary, higher proportion should have been observed in open areas. It has been revealed (Dimbleby 1961) that under the forest canopy the participation of pollen brought by the wind from remote areas is significantly less than in open habitats due to the filtering effect of the crowns. However, the smallest proportion of cedar (39%) was detected in the sample taken at the Yaylyu_1 key point, where the Tauber trap was installed on a meteorological site with anthropogenically disturbed vegetation and complete absence of trees. In general, the smallest proportion of cedar in the pollen spectra is observed in those points where gently sloping banks with sparse or absent forest cover are most pronounced, and slopes covered by forests with the participation of cedar are located at a considerable distance that reduces the flow of local pollen into traps.

On the Teletskoye Lake shore, where Tauber traps were installed, forests with the participation or dominance of Siberian fir (*Abies sibirica*) are widespread. Therefore, fir is mentioned in the names of communities in 4 of 12 analyzed points (Table 1) and forms the basis of forest stands in 3 points. Despite such a widespread distribution of fir, its share in the spectrum ranged from 2 to 9 %. The discrepancy between shares of fir in the vegetation composition and pollen spectrum can be explained by its pollen period in the study area and the low pollen productivity. According to the meteorological data analysis (RIHMI-WDC 2023), mass fir pollination during the observation period began on May 24, when the sum of effective temperatures reached 131°C (Table 2). However, thunderstorms were observed in the fir pollen period that contributed to the washing out of pollen grains from the air. In addition, the latter are the heaviest among conifers – the weight of one pollen grain reaches 251 ng (Nekrasova 1983). Fir is characterized by low pollen productivity, which is only 350–450 g for one free-standing adult tree, and in forest ranges this value is even less. The combination of the above factors affected the small proportions of fir in pollen spectra.

Common pine (*Pinus sylvestris*) pollen was present in some samples and its proportion ranged from 1 to 8 %. As an accompanying tree species, pine is found everywhere, but does not rise high into the mountains. The spatial distribution of common pine pollen shows that in most cases it was determined in samples taken in the southern meridional part of the Teletskoye Lake shore (Fig. 2). Presumably, this distribution is natural and reflects a decrease in the humidity level of the lake shore from the latitudinal to the meridional part, and their difference can reach one third (Selegey and Selegey 1978), which is confirmed by reanalysis data (ECMWF 2023) for the observation period. Thus, pine is present in the names of 3 out of 5 communities on the meridional part of the lake shore. It should also be noted that pine is widespread along the terraces of the Biya River flowing from Lake Teletskoye and its pollen could be massively transported from there to the latitudinal part of the lake shore, but this is probably prevented by local wind roses. Longer observations are required to confirm this assumption.

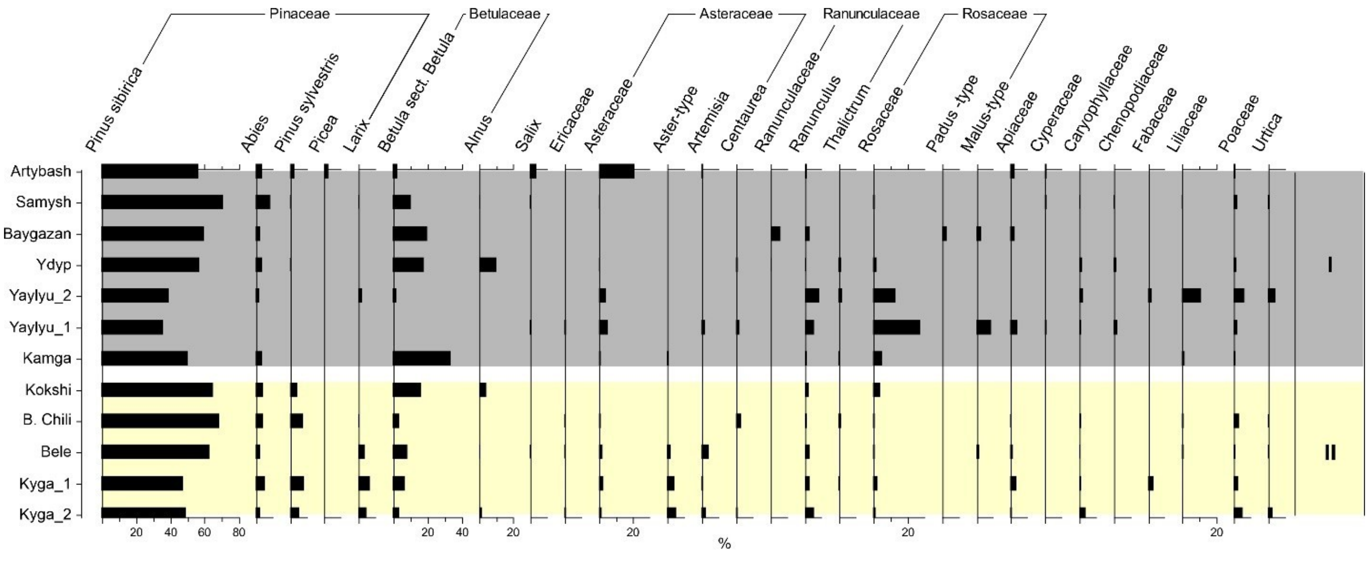

Figure 2. *Percentage of pollen in Tauber traps. I – northern latitudinal part of Teletskoye Lake shore; II – southern meridional part.*

Spruce pollen (*Picea*) was revealed only in one Artybash sample and accounted for 3% of the spectrum. However, the vegetation composition of the Artybash point environs contained fewer spruce trees than at the places of other traps installation located in river valleys. This discrepancy may be related to the location of the traps. In Artybash, a Tauber trap was installed directly under the spruce tree, where up to 90% of the produced pollen settles (Golovko 2004). In addition, microstrobiles where pollen is formed were found in the primary sample that led to an increase of spruce pollen share in the spectrum. At other points, spruce trees were not observed in the immediate vicinity of the trap installation sites, and the transfer of its pollen in woodlands is difficult due to the density of the crown and large weight of pollen grains – 93 ng (Golovko 2004).

The share of larch pollen (*Larix*) in the samples varied from 1 to 7% that generally corresponds to its relatively low role in the composition of tree stands on the Lake Teletskoye shore. The larch is reflected in the name of only one of all the communities considered where it also does not dominate. Low shares in the spectrum are also associated with late trap installation, because larch pollination occurs between the end of April – beginning of May and lasts 5 to 7 days (Nekrasova 1983; ASNBR 2023). Most of all *Larix* pollen was revealed along samples taken in the meridional part of the Teletskoye Lake shore where larch is more abundant compared to the latitudinal part, which also reflects the humidity regime. Furthermore, larch is one of the main forest-forming species in the Chulyshman river basin, from where local winds can also bring pollen to the meridional part of the Teletskoye Lake shore. The discrepancy between the participation of *Larix* pollen in the spectra and its role in plant communities has been repeatedly noted by palynologists studying the history of larch forests and changes in vegetation in the regions where they grow (Novenko et al. 2021).

There are several species of tree birch (ASNBR 2023) in the study area and the pollen is morphologically difficult to distinguish. Therefore, it was assigned to the section *Betula* sect. *Betula*. The share of birch pollen varies from 2 to 34% (Kamga). The insignificant percentage of birch pollen can be explained by later dates of traps installation. The mass flowering of birch in Western Siberia lasts 7–10 days and begins at a sum of effective temperatures of 47.5°C (Nekrasova 1983). However, birch is a very polymorphic species that leads to an extended pollen period of up to 16–18 days when simultaneously flower 3–5% of birch trees in forest stand (Nekrasova 1983). According to the analysis of meteorological data in the study area, the sum of effective temperatures favorable for the beginning of birch pollination reached 07.05.2021 (Table 2), but traps were installed only on 13.05.2021 that did not allow covering the entire pollen period and especially its peak, which reflected in small shares in the spectra. The maximum share of tree birch pollen (34%) was revealed in a sample from the Kamga key point located in the latitudinal part of the shore. According to aeropalynological observations that were carried out on 14 May 2021 at this point using an unmanned aerial vehicle at an altitude of 1000 m, the maximum concentrations of birch pollen grains among all the study points were determined. The presence of pollen at a given height indicates distant (regional) transfer, which is confirmed by the calculated backward air masses trajectory (Fig. 3). According to this trajectory, air masses formed over more northern territories including the plains of Altai Krai, where the birch pollen concentrations in the air were very high and reached more than 1000 units/m3 based on data from the joint project of SILAM and Pollen Club (Pollen Club 2023).

Therefore, such a significant contribution of birch pollen in the spectrum of the Kamga sample taken using the Tauber trap can be greatly overestimated relative to the contribution of birch in the vegetation composition of sampling point. The share of tree birch pollen (*Betula* sect. *Betula*) decreased noticeably in samples taken in the meridional part of the shore with a minimum contribution of 4% in the Kyga_2 sample. In general, the decrease in the percentage of pollen is associated with a decrease in the role of birch in forest stands when moving from north to south and reflects a reduction in humidity in this direction.

Pollen of alder (*Alnus*) and willow (*Salix*) revealed in the samples in small amounts that varied 1–10% for alder and 1–4% for willow. The only representative of the genus *Alnus*s. l. in the Teletskoye Lake basin and the Republic of Altai is a shrubby alder (*Duschekia fruticosa* (Rupr.) Pouzar), which occurs sporadically in suitable ecotopes and does not form large thickets. This explains the uneven distribution of its pollen. In contrast, willow is a widespread species on the lake shore. However, such a small amount of pollen is associated with the late dates of traps installation (mid-May) after the main period of its pollination, which begins in the second half of April.

Herb pollen is more diverse than tree pollen and generally reflects the vegetation composition of the sampling sites. The Asteraceae family has a share of 2–22% in pollen spectra. It includes pollen grains identified only as the family, *Aster*-type, genera wormwood (*Artemisia*) and cornflower (*Centaurea*). Maximum values (22%) were identified in the Artybash sample that is explained by the local characteristics of the sampling point located in an anthropogenically disturbed place with cultural vegetation. Most of all representatives of this family were revealed in samples taken in the meridional part of the shore, where pollen transfer by valley winds (“verkhovka”) from the Chulyshman river valley with steppe vegetation is very likely. Furthermore, wormwood is a typical representative of synanthropic vegetation, which is reflected in the spectra of the Artybash and Yailyu_1 points (2% each) located in anthropogenically disturbed areas.

Figure 3. *Backward air masses trajectory on 14.05.2021 (Air Resources Laboratory 2023).*

The Crowfoot family (Ranunculaceae) in the pollen spectra are represented by the genera *Ranunculus* and *Thalictrum*, as well as pollen grains identified only as the family. Their share varies from 1 to 9%, which is related to the abundance of the crowfoot family in meadow and forest tallgrasses and forbs of the meadows and forests. Therefore, the increase in family share is quite naturally associated with an increase in areas occupied by forest and meadow vegetation and reflects the characteristics of local landscapes and not the distant transfer.

The Goosefoot family (Chenopodiaceae) in the spectra had an expectedly low share (1 to 2%) according to its role in landscapes with a maximum in the Yaylyu_1 sample that may be due to anthropogenic disturbance of the sampling site.

The Rose family (Rosaceae) dominated in samples from the northern latitudinal part of the lake shore. The maximum share was revealed in Yailyu_1 where pollen grains belonging to the Malus-type (apple-type) were also identified, which may be due to the presence of apple orchards in the immediate vicinity of the sampling point. A similar situation is observed for the Baigazan and Bele samples where in addition to Malus-type pollen the Padus-type was also revealed whose representatives are also present in the gardens.

Pollen from the bluegrass family (Poaceae) or graminoids was determined in the spectra of most samples with variations ranging from 1 to 7%. The contribution of graminoids pollen in the spectrum increased significantly in samples taken in the meridional part of the lake shore, which may be associated with transfer by valley winds.

The remaining herbs (Apiaceae, Cyperaceae, Caryophyllaceae, Fabaceae, Liliaceae, Urticaceae) were represented in small quantities and reflected the local pollen spectra of the lake shore sites and adjacent territories.

The analysis of pollen spectra in observation points confirmed the differentiation of natural conditions in the latitudinal and meridional parts of Lake Teletskoye (Selegey and Selegey 1978). The most striking indicators of differentiation were pollen of tree birch (*Betula* set. *Betula*), common pine (*Pinus sylvestris*), and larch (*Larix*), as well as meadow-steppe forbs (Asteraceae).

All identified taxa are primarily indicators of the humidity that decreases from the latitudinal to the meridional part. It is confirmed by the participation of the identified taxa in the vegetation composition of the sampling points. Thus, the participation of *Betula* sect. *Betula* in the forest stand decreases from north to south, and the participation of *Larix*, on the contrary, increases in the meridional part. *Pinus sylvestris* is only represented in sampling points located in the meridional part of the lake coast, which is confirmed by landscape descriptions (Table 1). Pollen from Asteraceae also predominates at points on the meridional part of the lake coast, where there is less moisture compared to the latitudinal part (Fig. 4).

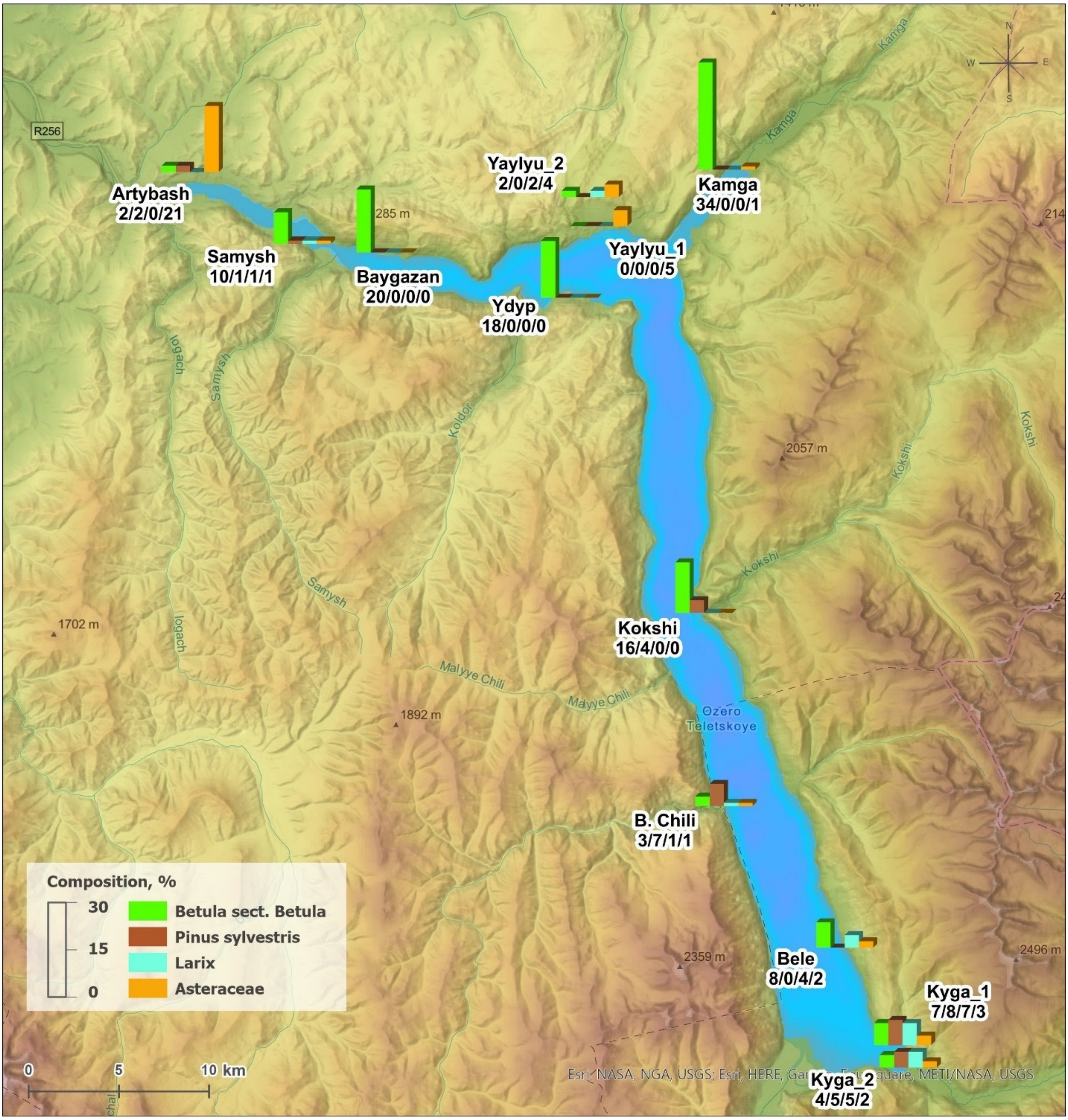

Figure 4. *Spatial distribution of the pollen share of indicator taxa in samples: Betula sect. Betula (first column), Pinus sylvestris (second column), Larix (third column) and Asteraceae (fourth column).*

Conclusion

Analysis of the composition of pollen spectra obtained using Tauber traps installed on the Teletskoye Lake shore allowed us to draw the following conclusions.

The general pollen spectrum represented by 27 taxa fairly adequately reflects the participation of the identified taxa in the composition of the vegetation. However, the absence of widespread early flowering species in the spectrum is due to the late installation of Tauber traps.

To analyze the annual pollen spectrum, traps should be installed in anthropogenically undisturbed sites long before pollination began and removed after its completion.

Based on the presence and percentage in the local spectra of pollen of tree birch (*Betula* set. *Betula*), common pine (*Pinus sylvestris*), larch (*Larix*), and meadowsteppe forbs (Asteraceae), these taxa are proposed to be indicators for differentiating the natural conditions of latitudinal and meridional parts of the Teletskoye Lake shore (Fig. 4).

Acknowledgements

Sampling and microscopic analysis was supported by RSF Grant No. 21-17-00135, while the analysis of synoptic conditions as well as composition and distribution of vegetation was carried out in the framework of State Assignment of IWEP SB RAS No. FUFZ-2021-0007.

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