Article

Diversity of Diatom Algae in the Lena Delta Nature Reserve and the Adjacent Territory in the Specific Ecological Factors of the Arctic

Sophia Barinova [1,*], Viktor Gabyshev [2] and Sergey Genkal [3]

[1] Institute of Evolution, University of Haifa, Mount Carmel, 199 Abba Khoushi Ave., Haifa 3498838, Israel; sophia@evo.haifa.ac.il (S.B.)
[2] Institute for Biological Problems of Cryolithozone Siberian Branch of Russian Academy of Science (IBPC SB RAS), 677980, Yakutsk, Russia, Lenin av., 41; v.a.gabyshev@yandex.ru (V.G.)
[3] Papanin Institute for Biology of Inland Waters Russian Academy of Sciences (IBIW RAS), Borok, Nekouz District, Yaroslavl Region, 152742, Russia; genkal47@mail.ru (S.G.)
* Correspondence: sophia@evo.haifa.ac.il; Tel.: +972-508024968

Abstract: For the water bodies of the Lena Delta Nature Reserve, 413 taxa were known. In 14 small tundra reservoirs in its vicinity, we identified 385 taxa, which in the compilatory list made up a significant diversity (666 taxa including definitions to the genus level) of diatoms. Thus, the species composition of diatoms in the reserve and adjacent territories was replenished by 278 species. The predominance of species of the genera *Pinnularia* (57) and *Eunotia* (51) at the family and generic levels was revealed. Index of intraspecific variability Ssp./Sp. for the lakes of the reserve was 1.11, and for the lakes of the Tiksi region 1.14, which is typical for high-latitude and high-mountain communities. The number of rare or endangered species varied in different lakes within 1-10, totaling 42 species for the entire study area. Bioindication has shown that potentially threatened species prefer moderate temperatures, slightly acidic or neutral environments free from organic pollution. A comparative analysis of the species composition of diatoms in the vicinity of the Lena Delta and other northern water bodies of Yakutia and the Arctic Islands showed that the species composition of each lake in the Arctic is strictly individual. The indicator characteristics show a certain response of the species composition of diatoms to changes in salinity, pH, and organic pollution. A number of regularities in the spatial distribution of diatoms in the study area were found in connection with the physicochemical parameters of their habitat, height above sea level, and relation to a particular catchment basin. Statistical mapping of indicators of community and habitat diversity revealed a strong reaction to point one-time pollution and made it possible to assume the influence of summer northeast winds on the species composition. We suggest that the high diversity inherent in the diatom lakes of the Tiksi coastal zone, which can even be replenished in further studies, can be considered as a property of coastal biota inherent in ecotones. Since it is in the coastal Tiksi region that a surge in the number of species is observed, this region can be considered not only an ecotone, but also a hotspot of diatom diversity. The results of the study are important for developing the basis for monitoring biodiversity under the conditions of anthropogenic and climatic changes in the Arctic.

Keywords: diatoms; diversity; ecology; floristic; comparative floristics; climate; Red List; threatened species; bioindicators; statistical mapping

---

1. Introduction

The diatom algae of Bacillariophyta Karsten are a common group of colonial or single-celled organisms characterized by an exogenous siliceous shell. The study of the ecology and species diversity of diatoms in the Arctic is of particular importance in connection with the phenomena of global climate change.

The diatoms study of the Eurasian high Arctic aquatic ecosystems stays in the initial stage but even now represented results on Eurasian northern coast of Arctic Ocean [1,2], the islands of the Arctic Ocean [3-6], Chukotka [7-9], and the continental part of Yakutia [10-11].

Our studies of aquatic communities in Northern Yakutia were carried out to assess the impact of climatic and anthropogenic factors on them [12-18].

The water bodies of the Lena Delta Nature Reserve and adjacent territories are located beyond the Arctic Circle in the zone of continuous occurrence of permafrost soils. Algological studies of this area, including the lower reaches of the Lena River, its delta, the vast water area of the Laptev Sea, tundra reservoirs of the spurs of the Kharaulakh Range and the New Siberian Islands, were started almost 100 years ago. The latest summary, including all currently available information on the algoflora of the delta region was published as a database on the GBIF.org portal [19]. In accordance with it, the diatom flora of the Lena Delta Nature Reserve and close to it coastal area includes information on 413 taxa below the genus rank. Research in the area adjacent to the reserve is currently ongoing due to the potential for industrial development of the coastal territory and shelf [18].

Previously, it was shown that the species composition and diversity of diatoms in Arctic water bodies is influenced by several regional features: the area of the reservoir, the direction of the prevailing winds, water temperature, salinity, and pH [1, 18, 20]. However, identification of species in the category of the Red Book of the Arctic region [21, 6] has not been done so far. Figure 1 shows that the region of the Arctic coast near the Lena River Delta needed to be studied more. As a basis for this study, we chose the data on the species composition of diatoms of the Lena Delta Nature Reserve and the adjacent territory (green dots) hereinafter referred to as “delta region” [19] and a recent survey of 14 water bodies in the vicinity of Tiksi settlement (blue dots) hereinafter referred to as “Tiksi region” [18]. Unfortunately, there is very little data available on the habitat for water bodies in the “delta region” but the environmental data for the “Tiksi region” was sufficient [18].

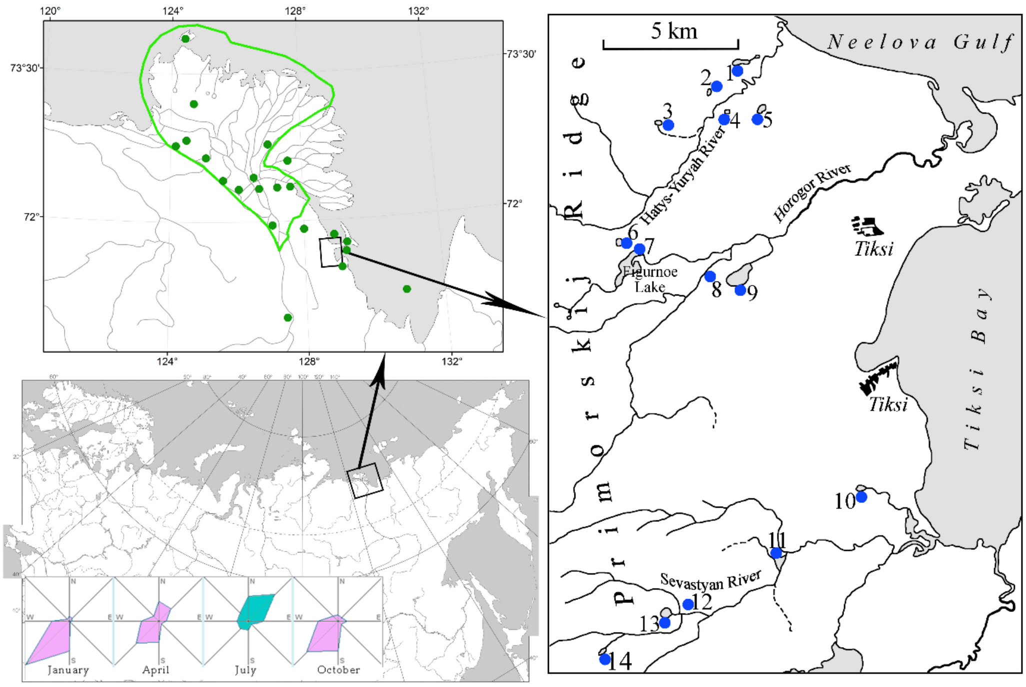

Figure 1. Investigated waterbodies in the Lena Delta Nature Reserve (green outline) and the adjacent territory (green dots, “delta region”) and a recent survey of waterbodies (blue dots, “Tiksi region”) with the wind rose seasonality.

Our hypothesis is that, by studying the relationship of biodiversity and indicator properties of diatoms with sufficiently studied environmental indicators in the adjacent

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 May 2023 doi:10.20944/preprints202305.1932.v1

territory, we can extrapolate these relationships to the diversity of the entire studied flora of diatoms in the coastal zone, including the reserve. So, we collected diatom samples to enrich study biodiversity in this area of the Arctic coast and defined environmental variables of its habitats.

The purpose of this study was to compile a general list of diatoms of the Lena Delta Nature Reserve and the adjacent territory, characterize the diversity and species richness, conduct an ecological and geographical analysis, identify environmental factors that affect the diversity of this group of aquatic organisms in the studied water bodies and identify potentially threatened species worthy of inclusion in the Red Book of the Arctic region.

2. Materials and Methods

2.1. Description of study area

The study area is located north of the Arctic Circle on the coast of the Laptev Sea of the Arctic Ocean and includes the Lena River Delta and reservoirs on the eastern spur of the Kharaulakh Range of the Verkhoyansk Mountain system. The maximum height reaches 400 m above sea level. The underlying rocks are mainly shales, sandstones, limestones, as well as effusive rocks that were formed because of removal by the Lena River or accumulated because of catastrophic outbursts of a glacier-dammed lake in the late Pleistocene-early Holocene [22-24]. The territory belongs to the tundra and mountain-tundra natural zones. The climate is polar maritime, the average annual air temperature is -9-11 °C [25], the average frost-free period is 45 days [26]. The depth of seasonal thawing of permafrost soils is 0.2–1.2 m [27]. The average annual precipitation reaches 212 mm, of which the bulk falls from June to August. The phenomena of a polar day in summer and a polar night in winter are characteristic. Strong winds are frequent, the warmest month of the year, July, is characterized by the lowest average hourly wind speed of the year, which is 15.5 km/h (Figure 1, wind roses). The delta and coastal areas are characterized by an abundance of small tundra reservoirs due to limited drainage due to the low thickness of the seasonally thawed permafrost layer [28]. Our work on the territory adjacent to the reserve was carried out on 14 different types of water bodies, which are shallow tundra lakes, small reservoirs, and a hollow in the swampy tundra (Table 1, Figures 1, 2).

Table 1. Sampling station parameters and its geographical coordinates of recent survey of waterbodies in "Tiksi region" (blue dots according to Figure 1)

No of station	Lake name	Water temperature	Altitude, m	North	East
1	Lake 1	16.7	25	71°44'44"	128°43'12"
2	Lake 2	15.1	66	71°44'12"	128°41'37"
3	Lake 3	15.0	109	71°43'31"	128°38'31"
4	Lake 4	20.4	38	71°43'48"	128°42'35"
5	Lake 5	20.6	-4	71°43'45"	128°44'36"
6	Lake 6	16.1	76	71°41'10"	128°36'50"
7	Lake 7	14.5	76	71°40'52"	128°37'11"
8	Lake-puddle 8	10.1	55	71°40'26"	128°41'21"
9	Lake 9	15.1	54	71°40'10"	128°43'27"
10	Lake 10	13.3	52	71°35'56"	128°51'70"
11	Lake 11	14.0	38	71°34'33"	128°45'51"
12	Swampy lake 12	-	105	71°33'36"	128°40'26"
13	Lake 13	14.6	85	71°33'17"	128°38'51"

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 May 2023 doi:10.20944/preprints202305.1932.v1

14	Lake 14	14.7	154	71°32'34"	128°34'57"

Figure 2. Natural landscape of investigated waterbodies in the Lena Delta Nature Reserve and the adjacent area. (a) Arctic tundra with small waterbodies; (b) phytoplankton sampling.

2.2. Sampling

Phytoplankton sampling on 14 waterbodies of the adjacent territory was carried out between 3 and 7 July 2021. When taking plankton samples, Apstein's plankton net (SEFAR NITEX fabric, mesh diameter 15 μm) was used. One sample from lake 10 was taken by washing off the biofilm from the surface of a submerged rock using a brush. Fixation with 4% neutral formaldehyde solution was carried out immediately after collection. The temperature of water and the morphometric parameters of each lake were determined during the collection of phytoplankton. Coordinates and altitude of the stations were defined by Garmin eTrex GPS-navigator (Table 1). Water samples of 1 L were collected from each lake for chemical analysis. All samples were transported to the determination in the Institute of Problem of the North, Yakutsk.

2.3. Diatom analysis

Cleaning of diatom shells from organic matter was carried out by burning in 30% hydrogen peroxide with 6-hour heat treatment in a thermostat at 85°C [29]. Diatoms in prepared permanent preparations were examined using a JSM-6510 LV (JEOL Ltd.; Tokyo, Japan) scanning electron microscope.

Handbooks and individual articles were used for the diatom species determinations [30-46, 9, 47-51]. The modern species names were adopted using algaebase.org [52]. Rare and endangered species are marked based on data on the distribution of well-studied diatoms in Central Europe [53] in comparison with IUCN [54] (The International Union for Conservation of Nature) criteria (Table 2). Bioindicator analysis was performed according [55] with species-specific ecological preferences of revealed [56-57]. Statistical maps were constructed as the network analysis in JASP (significant only) on the botnet package in R Statistica package of [58]. The BioDiversity Pro 2.0 program was used for similarity calculation [59].

Table 2. Threat categories for diatom species in the waterbodies of the Lena Delta Nature Reserve and the adjacent area

IUCN Category	IUCN Code	No of Red List Category	Red List Category	Number of species
EXTINCT	EX	1	Extinct or Lost	2
CRITICALLY ENDANGERED	CR	2, 3	Threatened with Extinction, Highly Threatened	40

ENDANGERED	EN	4, 5	Threatened, Threat of Unknown Extent	112
VULNERABLE	VU	6	Extremely Rare	16
NEAR THREATENED	NT	7	Near Threatened	28
LEAST CONCERN	LC	9	Not Threatened	198
DATA DEFICIENT	DD	8	Data Deficient	43
NOT EVALUATED	NE	0, 10	Not established	194

3. Results

3.1. Taxonomical and floristic analysis of diatoms

A significant diversity (385 taxa, Appendix A Figure A1 and Appendix A Figure A2) of diatoms was found for 14 small tundra shallow lakes in "Tiksi region" [18], which, together with the identified previously diatom species in the Nature Reserve itself of the "delta region" [19], makes up a general floristic list of 666 taxa (including definitions to the genus level) (Appendix A Table A1). Thus, the species composition of diatoms in the reserve and adjacent protected areas was replenished by 278 species.

For the diatom flora of the habitats of this Arctic coast, a wide range of generic richness of 123 genera was revealed, including from 1 to 57 species (Figure 3a) with a predominance of species of the *Pinnularia* (57) and *Eunotia* (51) genera (Figure 3b).

Among the first 10 Families out of 47, the Naviculaceae Family with 65 species moves in first place, while Pinnulariaceae and Eunotiaceae move to 2nd and 5th place, respectively (Figure 3c). Floristic data were checked by us for completeness of knowledge by constructing a Willis curve comparing the number of species in genera [60].

Figure 3d shows that the distribution of the number of species over the number of genera is a smooth enough line, almost coinciding with the trend line. This is evidence that the diatom flora of the Lena Delta Nature Reserve and the adjacent area is sufficiently studied to allow a systematic and ecological analysis of its species composition. However, irregularities on the distribution line indicate that the list of species has not yet been exhausted and will be replenished with further research.

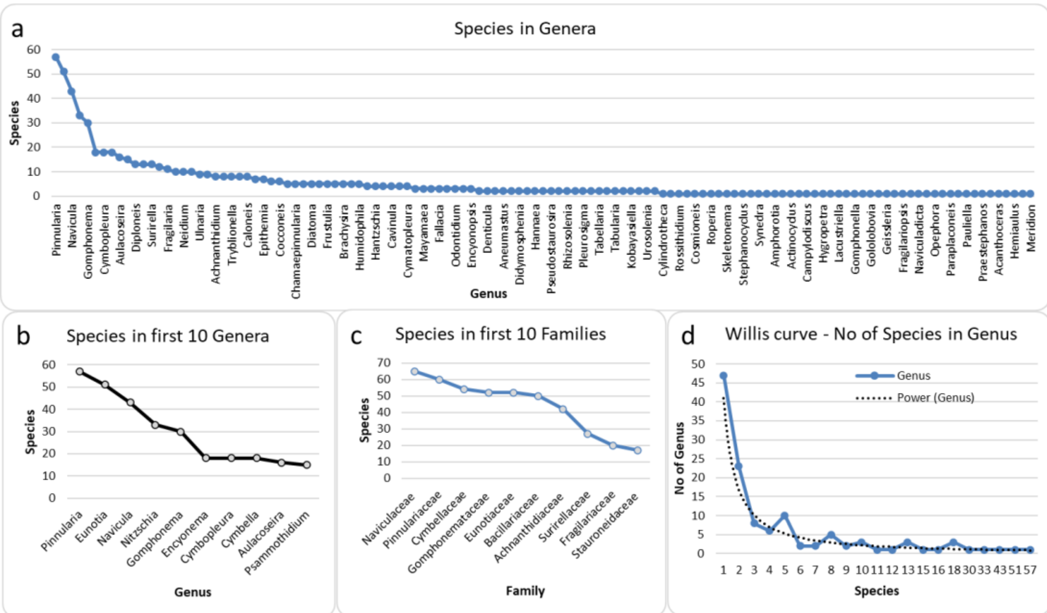

Figure 3. Distribution of diatom species over 123 genera (a), ten richest genera (b), ten richest families (c), and Willis's curve (c) in the Lena Delta Nature Reserve and the adjacent area

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 May 2023 doi:10.20944/preprints202305.1932.v1

Floristic properties may be characteristic of the region under study. For this purpose, the Index of intraspecific variability was calculated for the floristic composition of lakes in the Tiksi region. The index was defined as the quotient of the total number of identified taxa with a rank below the genus divided by the number of species [61]. Index Ssp./Sp. for the entire Lena Delta Nature Reserve and the adjacent area, which includes the "Tiksi region" and "delta region", was 1.11, and for the study area of the "Tiksi region", the index was 1.14, typical for high-latitude and high-altitude communities (Table 3). The number of diatom species per area of the reserve and the "Tiksi region" differed markedly, amounting to 0.05 and 2.14 species per area, respectively.

Table 3. Floristic parameters of the entire Lena Delta Nature Reserve and the adjacent area as the "Delta region", and the "Tiksi region".

Variable	"Delta region"	"Tiksi region"
Square, km^2	14300	180
Species with intraspecies	666	385
Taxa without sp.	631	356
Species only	569	337
Sp./Area	**0.05**	**2.14**
Ssp./Sp.	**1.11**	**1.14**

Figure 4 makes it possible to compare the distribution of the studied lakes in the "delta region" and a group of 14 lakes in the "Tiksi region". Both studied areas have a significant number of the investigated lakes evenly distributed over the territory, the altitude of which is within 0-140 m a.s.l. and the number of species in individual lakes varies in a wider range on the territory of the reserve than on the territory of Tiksi. That is, environmental properties are similar, and differences are observed in the number of species in lakes. In this regard, it should be noted that the lakes in the delta were visited repeatedly over several years, while 14 lakes in the "Tiksi region" were examined only once.

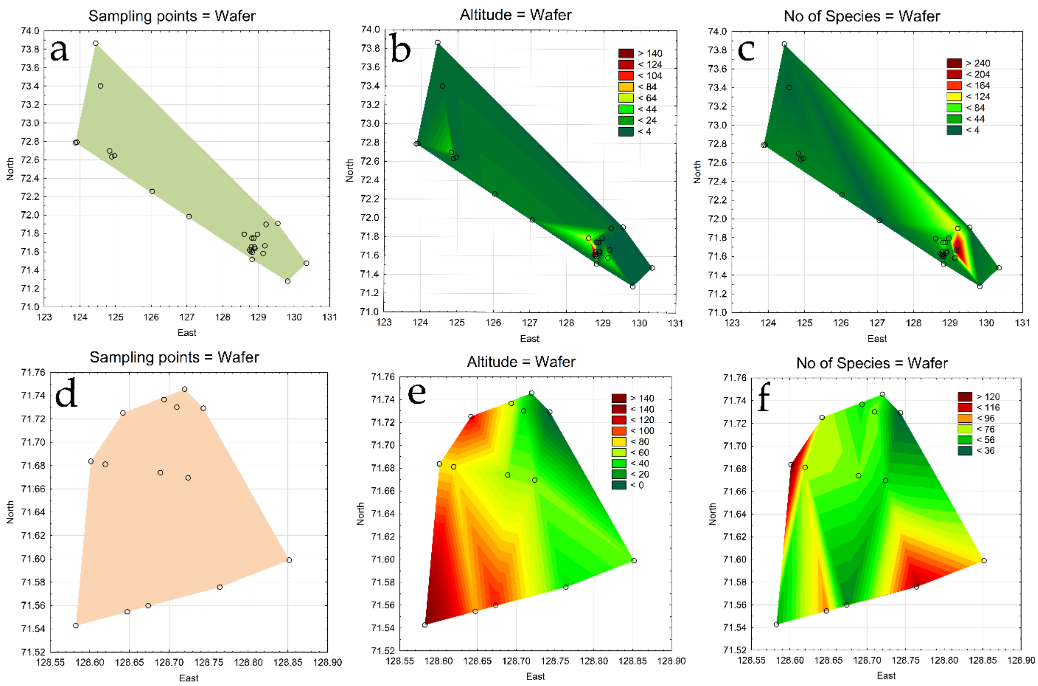

Figure 4. Distribution of the studied lakes in the territory of the "delta region" (a) and a group of 14 lakes in the "Tiksi region" (d), altitude (b and e) and the number of diatom species (c and f).

We also tried to find a relationship between the morphometry of the studied lakes and the diatom species richness. Table 4 presents the calculation data for the number of

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 May 2023 doi:10.20944/preprints202305.1932.v1

species per lake area, which shows that the species richness was the highest in lake 6, however, the Sp./Area index has the highest value for lake 4. The calculation of correlations of this index with the morphometric parameters of a group of lakes showed a significant correlation (p-value = 0.04), which is -0.502 for Sp./Area and Coastline length.

Table 4. Distribution of the diatom species richness of the "Tiksi region" lakes over the lake surface

No of station	Lake name	Lake surface area, km²	Coastline length, m	No of Species	Sp./Area
1	Lake 1	0.075	1618.42	66	881.601
2	Lake 2	0.038	894.56	62	1635.603
3	Lake 3	0.031	763.29	76	2460.437
4	Lake 4	0.008	359.76	72	8891.117
5	Lake 5	0.067	1188.51	33	493.171
6	Lake 6	0.042	902.78	137	3252.128
7	Lake 7	0.586	5716.74	75	128.074
8	Lake-puddle 8	-	-	69	-
9	Lake 9	0.486	3167.26	59	121.281
10	Lake 10	0.077	1153.85	85	1101.333
11	Lake 11	0.124	1800.36	117	946.742
12	Swampy lake 12	-	-	43	-
13	Lake 13	0.158	1639.88	96	609.365
14	Lake 14	0.023	712.85	50	2175.773

3.2. Bioindicators and ecological preferences of diatoms

Ecological preferences of revealed species in "Tiksi region" and "delta region" are presented in Appendix A Table A2. Distribution of the indicator numbers in ecological categories can be seen in Figure 5. Benthic and planktonic-benthic inhabitants prevail (Figure 5a). Temperate temperature species and indicators of middle oxygenated waters were strongly prevailed (Figure 5b, c). Indicators of low salinity group of indifferents (i) prevail in the studied area on the seacoast (Figure 5d). Indicators of water pH distribution show prevalence of groups of alkaliphiles and neutral waters (Figure 5e). Organic pollution indicators according to Watanabe demonstrated clear waters with sx and es groups in Figure 5f. Water quality was defined with relation of species-specific index saprobity S to 1-5 class. Figure 5g shows the prevailing of organically unpolluted water indicators of class 2 and 3. Between nutrition type indicators the autotrophs (ats and ate) strongly prevail (Figure 5h). Trophic state indicators distribution was irregular with two peaks in oligotrophic and eutrophic groups (ot and e) that reflected the impact to aquatic ecosystems, which increased some the lakes in trophicity (Figure 5i). Detailed distribution of species indicators over ecological categories is represented in Appendix A Table A3.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 May 2023 doi:10.20944/preprints202305.1932.v1

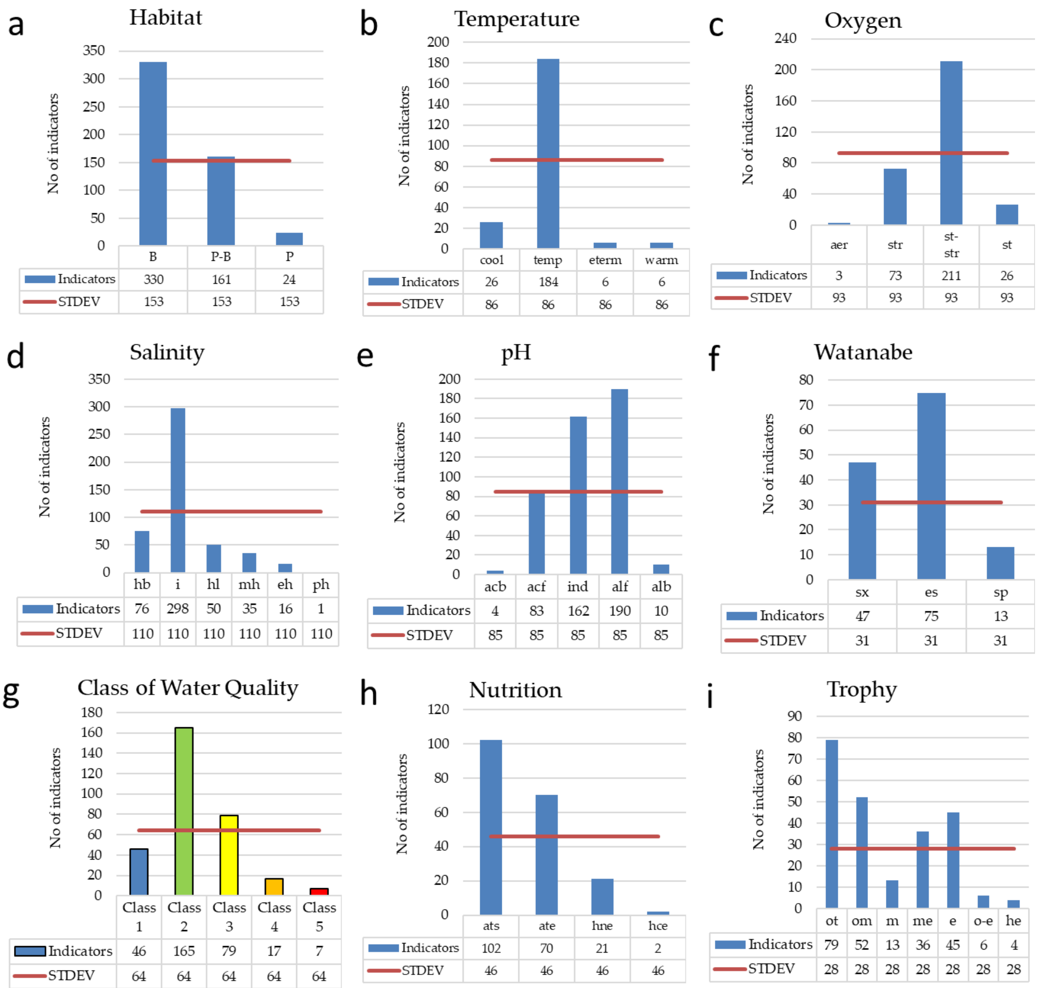

Figure 5. Distribution of species-indicators of the waterbodies in the entire Lena Delta Nature Reserve and the adjacent areas over ecological groups. The ecological groups order on the axis x follow to the related environmental indicator increasing. **(a)** Habitat (P – planktonic, P-B – plankto-benthic, B – benthic). **(b)** Temperature preferences (cool – cool-water, temp – temperate, eterm – eurythermic, warm – warm-water). **(c)** Oxygen and streaming (st – standing water, str – streaming water, st-str – low streaming water, aer – aerophiles). **(d)** Salinity ecological groups according to Hustedt (1938–1939) [62] (hb – oligohalobes-halophobes, i – oligohalobes-indifferent, hl – halophiles; mh – mesohalobes, eh – euhalobes, ph – polyhalobes). **(e)** pH preferences groups (pH) according to Hustedt (1957) [63] (alb – alkalibiontes; alf – alkaliphiles, ind – indifferent; acf – acidophiles; acb – acidobiontes). **(f)** Organic pollution indicators according to Watanabe et al. (1986) [64]: sx – saproxenes; es – eurysaprobes; sp – saprophiles. **(g)** Class 1-5 of organic pollution indicators according to species-specific Index saprobity of Sládeček, 1986 [65]. **(h)** Nutrition type as nitrogen uptake metabolism (Van Dam et al., 1994) [66]: ats – nitrogen-autotrophic taxa, tolerating very small concentrations of organically bound nitrogen; ate – nitrogen-autotrophic taxa, tolerating elevated concentrations of organically bound nitrogen; hne – facultative nitrogen-heterotrophic taxa, needing periodically elevated concentrations of organically bound nitrogen; hce – obligate nitrogen-heterotrophic taxa, needing continuously elevated concentrations of organically bound nitrogen. **(i)** Trophic state indicators (Van Dam et al., 1994) [66]: (ot – oligotraphentic; om – oligomesotraphentic; m – mesotraphentic; me – mesoeutraphentic; e – eutraphentic; he – hypereutraphentic; o-e – oligo- to eutraphentic (hypereutraphentic)).

3.3. Species in Threat Categories

Appendix A Table A1 shows that the number of diatom species in the entire Lena Delta Nature Reserve and the adjacent areas is extremely high, which forces us to analyze the degree of their endemism and rarity, as well as the threat of extinction. Unfortunately, there is no mention of endangered diatom species in the Protected Areas of Russia [6]. Therefore, we used Germany's most developed red data book diatom species resource [53]

 doi:10.20944/preprints202305.1932.v1

as a basis for identifying potentially threatened species in the Lena Delta Nature Reserve and the adjacent areas (Table 2).

Distribution of the revealed species over threat categories can be seen in Figure 6. Analysis of the revealed species composition of diatoms in relation to Threatened species categories of the highest three threat levels 1-3 from Extinct or Lost to Highly Threatened showed that 42 species can be classified as such (Table 5) found on the Lena Delta Nature Reserve and the adjacent areas.

The most of them are species of the genus *Psammothidium* (6), and three species each from the genera *Brachysira* and *Navicula*. Among the list of species there are both newly described (*Boreozonacola hustedtii*) taxa without studied ecology and distribution, and widespread species (*Neidium iridis*). We have summarized the known ecological preferences (Appendix A Table A2) of these endangered species in Table 5 and found that they inhabit waters of moderate temperature (temp), well supplied with oxygen (str), low salinity (ind), neutral waters, weakly saturated with organic substances (es, o). These species are characterized by an autotrophic type of nutrition (ats) and living in communities of oligotrophic water bodies (ot). It follows that clean, fresh, pH-neutral, and unpolluted water communities are under threat.

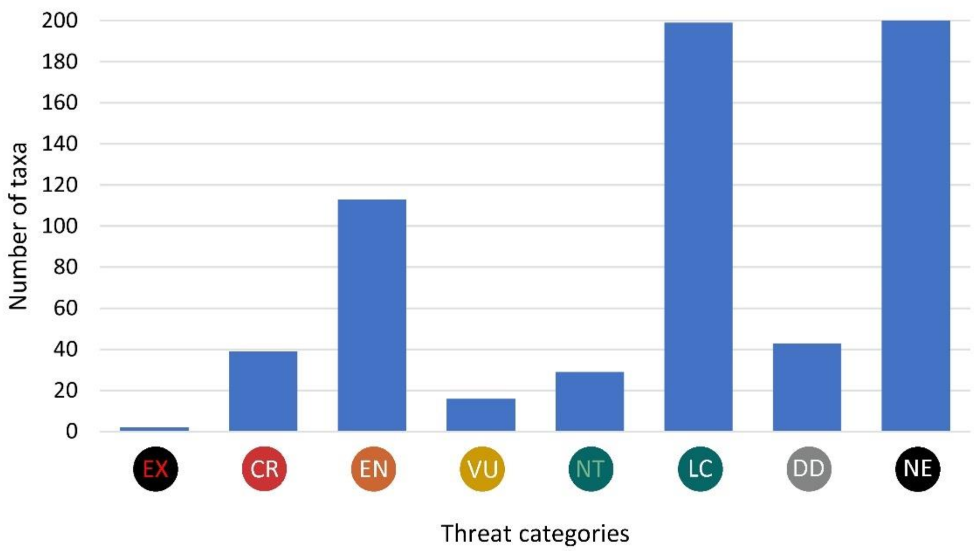

Figure 6. Distribution of the number of diatom species in the flora of water bodies of the Lena Delta Nature Reserve and adjacent territories by IUCN threat categories. The order of the IUCN categories on the x-axis corresponds to threat reduction.

Table 5. Ecological preferences of Species in IUCN Threat Categories (Red Data List) of the Lena Delta Nature Reserve and adjacent areas.

Species in Threat Categories	Hab	T	Oxy	Sal	pH	D	Index S	Sap	Aut-Het	Tro
EXTINCT (Extinct or Lost)										
Cymbopleura designata (Krammer) Bahls	B	temp	st-str	i	alf	-	1.8	o-a	ats	m
Encyonema latens (Krasske) D.G.Mann	B	-	-	-	-	-	1.0	o	ats	ot
CRITICALLY ENDANGERED (Threatened with Extinction)										
Eunotia elegans Østrup	P-B	-	st-str	hb	acf	-	0.2	x	ats	ot

 doi:10.20944/preprints202305.1932.v1

Eunotia faba Ehrenberg	B	temp	st-str	-	alf	-	-	o	ats	ot
Frustulia krammeri Lange-Bertalot & Metzeltin	B	-	-	-	acf	-	-	-	-	e
Navigeia thingvallae (Østrup) Bukhtiyarova	B	-	-	-	-	-	-	-	-	-
Tetracyclus glans (Ehrenberg) F.W.Mills	P-B	temp	-	i	acf	-	1.0	x-o	-	ot
CRITICALLY ENDANGERED (Highly Threatened)										
Boreozonacola hustedtii Lange-Bertalot, Kulikovskiy & Witkowski	-	-	-	-	-	-	-	-	-	-
Brachysira calcicola Lange-Bertalot	B	-	-	-	-	-	1.0	o	-	-
Brachysira procera Lange-Bertalot & Gerd Moser	B	-	-	-	acf	-	-	-	-	-
Brachysira styriaca (Grunow) R.Ross	B	temp	-	i	ind	es	1.0	o	-	ot
Cymbella affinis Kützing	B	temp	st-str	i	alf	sx	1.1	b	ats	e
Cymbella carassius Skvortzov	-	-	-	-	-	-	-	-	-	-
Cymbellafalsa diluviana (Krasske) Lange-Bertalot & Metzeltin	B	-	-	i	alf	-	1.0	o	-	ot
Cymbopleura tynnii (Krammer) Krammer	B	-	-	-	-	-	-	-	-	-
Diploneis ovalis (Hilse) Cleve	B	-	st-str	i	alf	-	0.9	x-b	ate	m
Eucocconeis alpestris (Brun) Lange-Bertalot	B	temp	str	hb	ind	-	-	-	-	-
Eucocconeis austriaca (Hustedt) Lange-Bertalot	B	-	-	i	alf	-	0.2	x	ats	ot
Eucocconeis flexella (Kützing) F.Meister	B	temp	str	mh	ind	-	-	-	-	-
Eunotia bigibba Kützing	B	-	str	i	acf	-	0.4	x-o	-	ot
Eunotia flexuosa (Brébisson ex Kützing) Kützing	B	temp	st-str	i	acf	-	0.4	x-o	-	-
Eunotia praerupta Ehrenberg	P-B	cool	st-str	hb	acf	-	0.3	x	-	-
Eunotia triodon Ehrenberg	B	temp	-	hb	acf	-	1.0	o	-	ot
Gomphonema helveticum Brun	B	-	-	i	ind	-	-	-	-	-
Gomphonema lagerheimii A.Cleve	B	-	str	hb	acf	-	-	-	-	m
Gomphonema ventricosum W.Gregory	B	cool	str	i	ind	-	1.0	o	-	-
Iconella curvula (W.Smith) Ruck & Nakov	B	-	str	hb	acf	-	2.0	b	-	me

Kobayasiella subtilissima (Cleve) Lange-Bertalot	B	temp	st-str	i	acb	-	1.6	b-o	ats	me
Mayamaea disjuncta (Hustedt) J.Y. Li & Y.Z.Qi	B	-	str	i	ind	sp	3.0	a	ate	he
Navicula angusta Grunow	B	-	st-str	i	ind	-	1.0	o	-	-
Navicula gottlandica Grunow	P-B	-	-	hl	alf	es	2.5	b-a	ate	e
Navicula mediocostata E.Reichardt	B	-	-	oh	alf	es	3.0	a	ate	e
Navicula notha J.H.Wallace	B	-	str	i	acf	-	-	-	-	-
Neidium iridis (Ehrenberg) Cleve var. iridis	B	temp	st-str	hb	ind	-	-	-	-	-
Nitzschia frigida Grunow	-	-	-	-	-	-	-	-	-	-
Placoneis opportuna (Hustedt) Chudaev & Gololobova	B	-	-	-	-	es	-	-	-	-
Psammothidium kryophilum (J.B.Petersen) E.Reichardt	P-B	-	str	i	ind	sx	0.5	x-o	ats	ot
Psammothidium levanderi (Hustedt) Bukhtiyarova & Round	B	temp	str	i	ind	sx	2.0	b	ats	om
Psammothidium rechtense (Leclercq) Lange-Bertalot	B	-	str	hb	alf	-	1.0	o	ats	ot
Psammothidium rossii (Hustedt) Bukhtiyarova & Round	B	-	str	hb	ind	-	1.0	o	ats	ot
Psammothidium scoticum (R.J.Flower & V.J.Jones) Bukhtiyarova & Round	B	temp	-	-	-	-	-	-	-	-
Psammothidium ventrale (Krasske) Bukhtiyarova & Round	B	-	str	hb	acf	-	2.0	b	ats	om

Note: "-", not found. Abbreviations: Habitat (Hab) (P-B – plankto-benthic, B – benthic); temperature (T) preferences (cool – cool-water, temp – temperate, eterm – eurythermic, warm – warm-water); oxygenation and streaming (Oxy) (str – streaming water, st-str – low streaming water); pH preferences groups (pH) according to Hustedt (1957) [63] (alb – alkalibiontes; alf – alkaliphiles, ind – indifferent; acf – acidophiles; salinity ecological groups (Sal) according to Hustedt (1938–1939) [62] (hb – oligohalobes-halophobes, i – oligohalobes-indifferent, hl – halophiles; mh – mesohalobes, oh – oligohalobes of wide spectrum with optimum as indifferent); Index S, species-specific index saprobity according to Sládeček, 1986 [65]; self-purification zone with index of saprobity (Sap) (x/0.0 – xenosaprobe; x-o/0.4 – xeno-oligosaprobe; x-b/0.8 – xeno-betamesosaprobe; o/1.0 – oligosaprobe; b-o/1.6 – beta-oligosaprobe; o-a/1.8 – oligo-alphamesosaprobe; b/2.0 – betamesosaprobe; a/3.0 – alphamesosaprobe; organic pollution indicators according to Watanabe et al. (1986) [64] (D): sx – saproxenes; es – eurysaprobes; sp – saprophiles; nitrogen uptake metabolism (Aut-Het) (Van Dam et al., 1994) [66]: ats – nitrogen-autotrophic taxa, tolerating very small concentrations of organically bound nitrogen; ate – nitrogen-autotrophic taxa, tolerating elevated concentrations of organically bound nitrogen; Trophic state indicators (Tro) (Van Dam et al., 1994) [66]: (ot – oligotraphentic; om – oligomesotraphentic; m – mesotraphentic; me – mesoeutraphentic; e – eutraphentic; he – hypereutraphentic).

3.4. Comparative floristic

We can see the sufficient role of climatic, morphometric, and other environmental variables to the high latitude lakes community composition because of this calculation. Therefore, we decided to compare diatom community composition in morphometrically similar lakes which were located at the north of Eurasia. Altogether 40 lakes including

Tiksi 14 lakes were taken for similarity of diatom community calculation: Yakutia 9 lakes (Y) Aalaah, Kurelah, Sullah, Dyiere, Ynah, Nal Tungulu, Large and Small Tungulu, Abalah, Nidzhili [10]; Bolshezemelskaya Tundra lakes (BZ) Vanutkiny, Kharbeyskiye, Korotaikha, Vorkuta, Usa, Kara [2]; Tiksi (T), species from "Tiksi region" 14 lakes [18] (Appendix A Table A1). Bray-Curtis calculation of diatom species composition similarity of the lakes above the Arctic circle latitude of Russia show strong separation of each group of the lakes. Figure 7 demonstrates three clusters that marked for North Yakutia (1), Bolshezemelskaya Tundra (2) and Tiksi 14 lakes from current research (3).

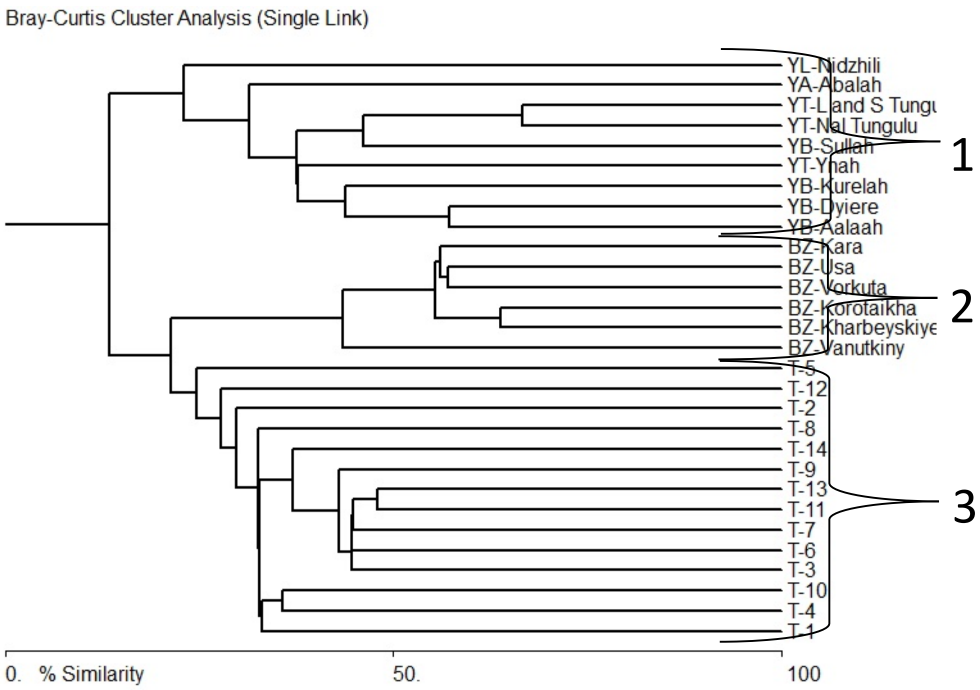

Figure 7. Bray-Curtis cluster analysis of diatom list similarity of the Arctic lakes over Arctic circle in Eurasia. Cluster 1, Yakutia 9 lakes (Y): Aalaah, Kurelah, Sullah, Dyiere, Ynah, Nal Tungulu, L. and S. Tungulu, Abalah, Nidzhili [10]. Cluster 2, Bolshezemelskaya Tundra lakes (BZ) Vanutkiny, Kharbeyskiye, Korotaikha, Vorkuta, Usa, Kara [2]. Cluster 3, Tiksi (T), species from 14 lakes [18] (Appendix A Table A1).

We have expanded the list of diatom floras for the next step of comparison that including: Arctic Chukotka from Amguema basin lakes Ervynaygytgyn, Matachingagytgyn, Ekitiki [7,8], Bolshezemelskaya Tundra lakes Vanutkiny, Kharbeyskiye, Korotaikha, Vorkuta, Usa, Kara [2], Svalbard, Hornsund fiord 10 lakes [5], Yakutia 9 lakes Aalaah, Kurelah, Sullah, Dyiere, Ynah, Nal Tungulu, Large and Small Tungulu, Abalah, and Nidzhili [10].

Comparison with the JASP program represented results of calculation in Figure 8. Can be seen that species composition of each group of the lakes is strongly separated from each other. This high individuality of species composition can be result of influence of geographical position of the lakes group and its climatic features.

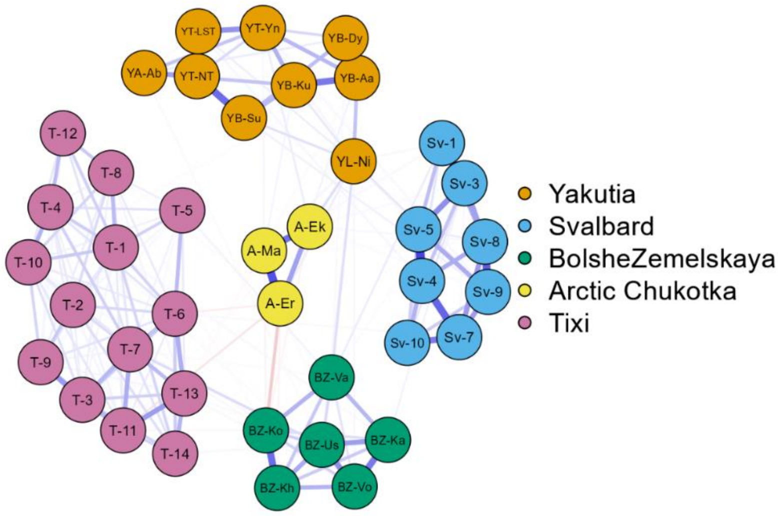

Figure 8. JASP Network plot of diatom species composition correlation for the small Arctic lakes, *p*< 0.5. Tiksi (T), species from the Tiksi region 14 lakes [18]. Arctic Chukotka, species from Amguema basin lakes: Ervynaygytgyn, Matachingagytgyn, Ekitiki [7,8]. Bolshezemelskaya Tundra lakes (BZ) Vanutkiny, Kharbeyskiye, Korotaikha, Vorkuta, Usa, Kara [2]. Svalbard (Sv), Hornsund fiord 8 lakes [5]. Yakutia (Y) 9 lakes: Aalaah, Kurelah, Sullah, Dyiere, Ynah, Nal Tungulu, Large and Small Tungulu, Abalah, Nidzhili [10].

4. Discussion

The subject of our study was the flora of diatoms found in the lakes of the "Tiksi region" in the vicinity of Tiksi settlement and the delta on the territory of the "delta region" of the Lena Delta Nature Reserve. The general list was compiled from our studies of the "delta region" [19] including 413 taxa and 385 taxa of the "Tiksi region", [18] and amounted to 666 taxa of diatoms (including definitions to the genus level), 278 of which were enriched the regional flora. The floristic analysis was carried out after constructing the Willis curve, which turned out to be quite smooth and close to the trend line, which indicates that the list of diatoms is sufficiently complete for an adequate flora of the analysis region. Willis's curve was not so smooth that allows us to assume that the list of species has not yet been exhausted and will be replenished with further research. Index of intraspecific variability Ssp./Sp. for the lakes of the "delta region" was 1.11, and for the lakes of the "Tiksi region" was 1.14, which is typical for high-latitude and high-mountain communities.

We calculated the Index Sp./Area as number of diatom species per whole studied area that was for the "delta region" 0.05 but for the "Tiksi region"2.14 that show differences between biodiversity of both studied areas and confirm that coastal zone can be the hotspot of the Arctic diatoms as was revealed for Arctic chrysophytes [67]. It also confirms the idea that the most important factor for diatom species richness can be the lake morphometry [68]. Thus, the geographic factor turned out to be significant for the formation of diatom communities in the Arctic floras, in addition to this, the association with individual river runoff basins on the coast, elevated habitats, as well as the influence of such climatic factors as summer northeast winds on the species composition was previously revealed [18].

The Arctic deltas are responsible for nutrient transport to the sea, which varies by delta and season, and it is estimated that the Lena Delta retains about 15% of the input load, the largest in the Arctic Ocean [69]. At the same time, the deposition of nitrates by the tundra landscape in the spring and their subsequent accumulation in lakes and wetlands adjacent to river channels contributes to the enrichment of lake water with a nutrient base [69]. This makes the water of the Lena River a source of nutrients [17, 70] on the one

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 May 2023 doi:10.20944/preprints202305.1932.v1

hand, but on the other hand, stimulates the diversity of algae, as has been shown in the lakes of the Tiksi coastal region [18]. Despite this, the current diatom flora shows clean, organically uncontaminated waters, although there is a diversity burst response to a one-time nutrient point impact in the Tiksi area.

Whole flora bioindicators analysis shows that the diatoms identified in the "delta region" and the coastal "Tiksi region" were mainly benthic autotrophs, preferring temperate, middle oxygenated, low saline, low alkalic clear water class 2 and characterize two trophic type of waterbodies - oligotrophic and eutrophic.

The high individuality of diatom communities was revealed both for the entire Lena Delta and its adjacent areas, and in a comparative analysis with the lacustrine floras of Yakutia and the High Arctic of Eurasia. For the first time for the Arctic regions of Eurasia, a preliminary analysis of the threat of diatom species was carried out and 42 species of the IUCN categories were identified. These rare or threatened species prefer moderate temperatures, slightly acidic or neutral environments free from organic pollution. Thus, the lake communities in clean, fresh, pH-neutral, and unpolluted waters in the coastal zone of the Arctic Ocean with the highest diversity are the most vulnerable.

As a result of comparing the properties of the natural environment of the "delta region" and the coastal zone of the "Tiksi region", our hypothesis is confirmed about the possibility of extrapolating the patterns identified for the territory of Tiksi to the diversity of the entire studied flora of diatoms because the conditions were similar, but differences were significant in the diatom species content of the lakes. The species richness in the Tiksi coastal lakes was higher than in the delta lakes even though the lakes in the delta were sampled many times over several years, and 14 lakes in the "Tiksi region" were surveyed only once. This allows us to suggest that the high diversity inherent in the diatom lakes of the Tiksi coastal zone, which can even be replenished in further studies, can be considered as a property of coastal biota inherent in ecotones. Since it is in the coastal region of Tiksi that a surge in the number of species is observed, this region can be considered not only an ecotone, but also a hotspot of diatom diversity. Ecotones are border areas of different landscapes where there is a marked increase in the diversity of organisms [71]. Until now, the landscapes of the coast of the Arctic Ocean have not been considered as ecotones for diatom communities. But for the diversity of algae, this term was used, for example, for communities of river habitats [72]. The diversity of diatoms in the coastal area of the "Tiksi region" may be due to several factors. As known, studies of diatoms in a scanning electron microscope give a higher percentage of certain species [73].

We have formed a hypothesis about the introduction of species from temperate latitudes into Arctic waters under the conditions of global climate change [20].

Then the record level of species diversity of these hydrobionts and the change in the structure of their communities reflect the beginning of manifestations of climate warming. On the other hand, there is an opinion that the similarity between the algal communities of the northern and temperate regions may be more apparent than real [74]. This is confirmed by the sharp predominance of species of the genera *Pinnularia* and *Eunotia*, not only in our studied lakes, but also in a comparative analysis with other Arctic floras. Moreover, the further north the flora, the more saturated with species are these two genera. This may be one of the decisive signs for assessing the impact of climate change on the aquatic communities of the Arctic.

Therefore, we revealed the important role of climatic, morphometric, and other environmental variables related with geographical position of the waterbody in forming the diatom community composition in the high latitude lakes. The results of the study are important for developing the basis for monitoring the biodiversity of non-impact, ecologically sensitive territories, and climate change in the future. Their relevance for assessing the consequences of local anthropogenic impact is high.

Supplementary Materials: Not applicable.

Author Contributions: Conceptualization, S.B. and V.G.; methodology, S.B. and V.G.; software, S.B.; validation, S.B., V.G., S.G.; formal analysis, V.G., S.G.; investigation, V.G.; resources, V.G.; data curation, S.G. and V.G.; writing—original draft preparation, S.B. and V.G.; writing—review and editing, S.B., V.G., S.G.; visualization, S.B.; supervision, V.G.; project administration, V.G.; funding acquisition, V.G. All authors have read and agreed to the published version of the manuscript.

Funding: The research was carried out within the state assignment of the Ministry of Science and Higher Education of the Russian Federation (theme No. FWRS-2021-0023, reg. No. AAAA-A21-121012190038-0), (theme No. 121051100099-5).

Institutional Review Board Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: This work was partly supported by the Israeli Ministry of Aliyah and Integration.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Barinova, S.; Stenina, A. Diatom diversity and ecological variables in the Arctic lakes of the Kostyanoi Nos Cape (Nenetsky Natural Reserve, Russian North). *Plant Biosystems - An International Journal Dealing with all Aspects of Plant Biology* **2013**, *147*(2), pp. 397-410. DOI: 10.1080/11263504.2012.749956.
2. Stenina, A.S. *Diatoms (Bacillariophyta) in the lakes of the east of the Bolshezemelskaya tundra;* Institute of Biology, Komi Scientific Center, Ural Branch, Russian Academy of Sciences: Syktyvkar, Russia, 2009; 176 p. (In Russian).
3. Kharitonov, V.G. Diatoms of the benthos of water bodies of Wrangel Island. *News of taxonomy of lower plants* **1981**, *18*, pp. 33–39.
4. Pinseel, E.; Van de Vijver, B.; Kavan, J.; Verleyen, E.; Kopalová, K. Diversity, ecology and community structure of the freshwater littoral diatom flora from Petuniabukta (Spitsbergen). *Polar Biol* **2017**, *40*, pp. 533–551. DOI: 10.1007/s00300-016-1976-0.
5. Picińska-Fałtynowicz, J. Freshwater benthic diatoms from the south-western part of the Hornsund fiord area, SW Spitsbergen. *Polar Research* **1988**, *6*(1), pp. 19-34. DOI: 10.3402/polar.v6i1.6843.
6. Protected Areas of Russia. Red Books. Red Book of the Republic of Sakha (Yakutia). Developer FGBU "AARI", Laboratory of geoinformation technologies. Available online: http://www.oopt.aari.ru/rbdata/75/plant.
7. Kharitonov, V.G. Diatom algae of fresh water bodies. In *Ecology of the Basin of the r. Amguema;* Russian acad. Sciences, Far Eastern Department, Institute of Biological Problems of the North. Publisher: Vladivostok, Russia, 1993, pp. 47–81. (In Russian).
8. Kharitonov, V.G. Diatoms (Bacillariophyseae) in the Sediments of Three Mountain, Oligotrophic Lakes in the Amguema River Basin (Chukotka). *Siberian Ecological Journal* **2010**, *4*, pp. 609-622.
9. Kharitonov, V.G.; Genkal, S.I. *Diatoms of Lake Elgygytgyn and its environs (Chukotka)*. Publisher: NESC FEB RAS: Magadan, Russia, 2012; pp. 1-402. (In Russian).
10. Kopyrina, L.; Pshennikova, E.; Barinova, S. Diversity and ecological characteristic of algae and cyanobacteria of thermokarst lakes in Yakutia (northeastern Russia). *Oceanological and Hydrobiological Studies* **2020**, *49*(2), pp. 99-122. DOI: 10.1515/ohs-2020-0010.
11. Kopyrina L.; Pshennikova E.; Barinova S. Diversity and Ecology of Non-Diatom Algae in a Swampy Mountain Lake of the Suntar-Khayat Ridge (Republic Sakha, Yakutia, Russia). *Transylvanian Review of Systematical and Ecological Research* **2022**, *24*(1), pp. 17-34. DOI: 10.2478/trser-2022-0002.
12. Barinova, S.; Gabyshev, V.; Gabysheva, O. Climate impact of freshwater biodiversity: general patterns in extreme environments of North-Eastern Siberia (Russia). *British Journal of Environment and Climate Change* **2014**, *4*(4), pp. 423-443. DOI: 10.9734/BJECC/2014/9530.
13. Barinova, S.; Gabyshev, V.; Boboev, M.; Kukhaleishvili, L.; Bilous, O. Algal Indication of Climatic Gradients, American Journal of Environmental Protection. *Special Issue: Applied Ecology: Problems, Innovations* **2015**, *4*(3-1), pp. 72-77. DOI: 10.11648/j.ajep.s.2015040301.22.
14. Gabyshev, V.; Ivanova, A.; Gabysheva, O. Long-term survey of algae of the Lena Delta Wildlife Reserve including data on chemistry of waters. Institute for Biological Problems of Cryolithozone SB RAS. *Sampling event dataset* **2021,** *Version 1.2*. DOI: 10.21072/mbj.2021.06.3.02.
15. Barinova S.S.; Gabyshev V.A.; Ivanova A.P.; Gabysheva O.I. Bioindication of the water salinity dynamics by the microalgae communities in the Lena River Delta, Laptev Sea, Russian Arctic. *Marine Biological Journal* **2021**, *6*(3), pp. 15–28. DOI: 10.21072/mbj.2021.06.3.02.
16. Gabysheva, O.I.; Gabyshev, V.A.; Barinova, S. Influence of the Active Layer Thickness of Permafrost in Eastern Siberia on the River Discharge of Nutrients into the Arctic Ocean. *Water*, **2022**, *14(1)*, pp. 84. DOI: 10.3390/w14010084.
17. Gabyshev, V.; Barinova, S.; Ivanova, A.; Gabysheva, O.; Curtean-Bănăduc, A. The Indicator Role of Algae in Assessing the Organic Pollution in the Lena River Delta, the Russian Arctic. *Front. Environ. Sci.* **2022**, *10*, pp. 921819. DOI: 10.3389/fenvs.2022.921819.
18. Barinova, S.; Gabyshev, V.; Genkal, S.; Gabysheva, O. Diatoms of Small Water Bodies as Bioindicators in the Assessment of Climatic and Anthropogenic Impacts on the Coast of Tiksi Bay, Russian Arctic. *Water* **2023**, *15*, pp. 1533. DOI: 10.3390/w15081533

19. Gabyshev, V.; Ivanova, A.; Gabysheva, O. Long-term survey of algae of the Lena Delta Wildlife Reserve including data on chemistry of waters. Institute for Biological Problems of Cryolithozone SB RAS. *Sampling event dataset* **2021,** *Version 1.2*. DOI: 10.21072/mbj.2021.06.3.02.
20. Bessudova, A.; Gabyshev, V.; Firsova, A.; Gabysheva, O.; Bukin, Y.; Likhoshway, Y. Diversity variation of silica-scaled chrysophytes related to differences in physicochemical variables in estuaries of rivers in an Arctic watershed. *Sustainability* **2021**, *13*, pp. 13768. DOI: 10.3390/su132413768.
21. Komulainen, S.F. Freshwater algae in red data books: state-of-the-art and problems. *Transactions of Karelian Research Centre of Russian Academy of Science. Biogeography, Petrozavodsk* **2009**, *1*, pp. 57-61.
22. Gvozdetsky, N.A.; Mikhailov, N.I. *Physical Geography of the USSR: Asian part*, 3rd ed.; Mysl': Moscow, Russia, 1978; 512 p. (In Russian).
23. Grosswald, M.G.; Spektor, V.B. Glacial landforms of the Tiksi region (western coast of the Buor-Khaya Bay, Northern Yakutia). *Geomorfologiya (Geomorphology RAS)* **1993**, pp. 72–82.
24. Spektor, V.B.; Shestakova, A.A.; Torgovkin, Y.I. New genetic types of landforms and deposits of the coastal part of the western sector of the Laptev Sea and the Lena River Delta. *Arctic and Subarctic Natural Resources* **2021**, *26*(2), pp. 81–93. DOI 10.31242/2618-9712-2021-26-2-5.
25. Konstantinov, P.Y.; Tregubov, O.D.; Zhang, M.; Li G. Permafrost temperature dynamics over the last 30 years in certain regions of the Eastern sector of the Russian Arcric. *International journal of applied sciences and technologies «Integral»* **2022**, pp. 260–267. DOI: 10.55186/02357801.2022.7111.
26. Reference book on the climate of the USSR. Issue. 24: Yakut ASSR. Part 2: Temperature of air and soil / Yakutsk hydrometeorological observatory. Publisher: Gidrometeoizdat: Leningrad, USSR, **1966**; pp. 1-398.
27. Fedorov, A.N.; Botulu, T.A.; Varlamov. S.P. *Permafrost landscapes of Yakutia (explanatory note to the permafrost-landscape map of the Yakut ASSR, scale 1:2500000)*. GUGK: Novosibirsk, Russia, 1989; 170 p. (In Russian).
28. Kirillov, A.F.; Chernyshev, I.A. Annotated listing of pisciforms and fishes of marine and fresh waters of Yakutia. *Bulletin of Yakutsk State University* **2006**, *3*(4), pp. 5–13.
29. Balonov, I.M. Preparation of diatoms and golden algae for electron microscopy. *In: Methods for the study of biogeocenoses of inland waterbodies.* Moscow: Nauka, USSR, 1975, pp. 87–89. (In Russian).
30. Lange-Bertalot, H.; Moser, G. Brachysira: Monographie der Gattung; wichtige indicator-species für das Gewässer-Monitoring und Naviculadicta nov. gen.; ein Lösungsvorschlag zu dem Problem Navicula sensu lato onhe Navicula sensu stricto. *Bibliotheca Diatomologica* **1994**, *29*, pp. 1–212.
31. Krammer, K. Die cymbelloiden Diatomeen. Teil 1. Allgemeines und Encyonema part. *Bibliotheca Diatomologica* **1997**, *36*, pp. 1–382.
32. Krammer, K. Die cymbelloiden Diatomeen. Teil 2. Encyonema part., Encyonopsis und Cymbellopsis. *Bibliotheca Diatomologica* **1997**, *7*, pp. 1–469.
33. Krammer, K. Pinnularia. In *Diatoms of Europe*; Lange-Bertalot, H., Eds.; Publisher: Ruggell, Liechtenstein, 2000; 1, pp. 1–703.
34. Krammer, K. Cymbella. In *Diatoms of Europe*; Lange-Bertalot, H., Eds.; Publisher: Ruggell, Liechtenstein, 2002; 3, pp. 1–584.
35. Krammer, K. Cymbopleura, Delicata, Navicymbula, Gomphocymbellopsis, Afrocymbella. In *Diatoms of Europe*; Lange-Bertalot, H., Eds.; Publisher: Ruggell, Liechtenstein, 2003; 4, pp. 1–530.
36. Krammer, K.; Lange-Bertalot, H. Bacillariophyceae. Teil 1. Naviculaceae. In *Die Süsswasserflora von Mitteleuropa*. Publisher: Stuttgart, Germany, 1986; bd 2/1, pp. 1–876.
37. Krammer, K.; Lange-Bertalot, H. Bacillariophyceae. Teil 2. Epithemiaceae, Bacillariaceae, Surirellaceae. In *Die Süsswasserflora von Mitteleuropa*; Publisher: Stuttgart, Germany, 1988; bd. 2/2, pp. 1–536.
38. Krammer, K.; Lange-Bertalot, H. Bacillariophyceae. Teil 3. Centrales, Fragilariaceae, Eunotiaceae. In *Die Süsswasserflora von Mitteleuropa*; H. Ettl, J., Gerloff, H., Eds.; Publisher: Stuttgart, Germany, 1991a; bd. 2/3, pp. 1–576.
39. Krammer, K.; Lange-Bertalot, H. Bacillariophyceae. Teil. 4. Achnanthaceae, Kritische Erganzungen zu Navicula (Lineolatae) und Gomphonema. In *Die Süsswasserflora von Mitteleuropa*; Gustav Fisher Verlag: Stuttgart, Germany, 1991b; bd. 2/4, pp. 1–437.
40. Lange-Bertalot, H.; Genkal, S.I. Diatoms of Siberia. I. *Iconographia Diatomologica* **1999**, *6*, pp. 7–272.
41. Reichardt, E. Zur revision der gattung Gomphonema. *Iconographia Diatomologica* **1999**, *8*, pp. 1–203.
42. Lange-Bertalot, H. Navicula sensu stricto, 10 genera separated from Navicula sensu lato Frustulia. In *Diatoms of Europe*; Lange-Bertalot, H., Eds.; A.R.G. Gantner Verlag K.-G.: Ruggell, Liechtenstein, 2001; 2, pp. 1–526.
43. Werum, M.; Lange-Bertalot, H. Diatoms in springs from Central Europe and elsewhere under the influence of hydrogeology and anthropogenic impacts. *Iconographia Diatomologica* **2004**, *13*, pp. 1-417.
44. Levkov, Z. Amphora sensu lato. In *Diatoms of Europe*; Lange-Bertalot, H., Eds.; A.R.G. Gantner Verlag K.-G.: Ruggell, Liechtenstein, 2009; 5, pp.1–916.
45. Genkal, S.I.; Bondarenko, N.A.; Shchur, L.A. *Diatoms of lakes in the south and north of Eastern Siberia*; Publisher OAO "Rybinsk Press House": Rybinsk, Russia, 2011; 72 p. (In Russian).
46. Lange-Bertalot, H.; Bak, M.; Witkowski, A. Eunotia and some related genera. In *Diatoms of Europe*; A.R.G. Gantner Verlag K.-G.: Ruggell, Liechtenstein, 2011; 6, pp. 1–747.
47. Levkov, Z.; Metzeltin, D.; Pavlov, A. Luticola, Luticolopsis. In *Diatoms of Europe*; Lange-Bertalot, H., Eds.; A.R.G. Gantner Verlag K.-G.: Ruggell, Liechtenstein, 2013; 7, pp. 1–697.
48. Levkov, Z.; Mitić-Kopanja, D.; Reichardt, E. The diatom genus Gomphonema from the Republik of Macedonia. In *Diatoms of Europe*; Lange-Bertalot, H., Eds.; A.R.G. Gantner Verlag K.-G.: Ruggell, Liechtenstein, 2016; 8, pp.1–552.

49. Kulikovskiy, M.S.; Glushchtnko, A.M.; Genkal, S.I.; Kuznetsova, I.V. *Identification book of diatoms from Russia*; Publisher: Filigran': Yaroslavl, Russia, 2016; 804 p. (In Russian).
50. Lange-Bertalot, H.; Hofmann, G.; Werum, M.; Cantonati, M. *Freshwater benthic diatoms of Central Europe*. Koeltz Botanical Books: Schmitten-Oberreifenberg, Germany, 2017; 942 p.
51. Beauger, A.; Allain, E.; Voldoire, O.; Blavignac, C.; Rossi, S.; Wetzel, C.; Ector, L. Gomphosphenia vallei (Bacillariophyta), a new diatom species from a stream in the "Réserve Naturelle Nationale de la Vallée de Chaudefour", Massif Central (France). *Phytotaxa* **2022**, *542(2)*, pp. 167-179. DOI: 10.11646/phytotaxa.542.2.4.
52. Guiry, M.D.; Guiry, G.M. AlgaeBase World-Wide Electronic Publication. National University of Ireland, Galway. Available online: http://www.algaebase.org (accessed on 24 June 2019).
53. Hofmann, G.; Lange-Bertalot, H.; Werum, M.; Klee, R. Rote Liste und Gesamtartenliste der limnischen Kieselalgen (Bacillariophyta) Deutschlands. In *Rote Liste der gefährdeten Tiere, Pflanzen und Pilze Deutschlands*; Band 7: Pflanzen. Bonn (Bundesamt für Naturschutz). Naturschutz und Biologische Vielfalt, **2018**, *70*(7), pp. 601–708.
54. IUCN. *IUCN Red List Categories and Criteria, Version 3.1*, 2nd ed.; IUCN: Gland, Switzerland; Cambridge, UK, 2012; p. 1-32.
55. Barinova, S. Essential and practical bioindication methods and systems for the water quality assessment. *Int. J. Environ. Sci. Nat. Resour.* **2017**, *2*, pp. 1–11. DOI: 10.19080/IJESNR.2017.02.555588.
56. Barinova, S.S.; Medvedeva, L.A.; Anissimova, O.V. *Diversity of Algal Indicators in Environmental Assessment*; Pilies Studio Publisher: Tel Aviv, Israel, 2006; 498 p. (In Russian).
57. Barinova, S.S.; Bilous, O.P.; Tsarenko, P.M. *Algal Indication of Water Bodies in Ukraine: Methods and Prospects*; Publishing House of Haifa University: Haifa, Kyiv, Israel, 2019; 367 p. (In Russian).
58. Love, J.; Selker, R.; Marsman, M.; Jamil, T.; Dropmann, D.; Verhagen, J.A.; Ly, A.; Gronau, F.Q.; Smira, M.; Epskamp, S. et al. JASP: Graphical statistical software for common statistical designs. *J. Stat. Softw.* **2019**, *88*, pp. 1–17. DOI: 10.18637/jss.v088.i02.
59. McAleece, N., Gage, J.D.G., Lambshead, P.J.D., Paterson, G.L.J. BioDiversity Professional statistics analysis software. Jointly developed by the Scottish Association for Marine Science and the Natural History Museum London, 1997.
60. Barinova, S. Systemic Criteria for the Analysis of Alpha- and Gamma-Diversity of Freshwater Algae. *Int. J. Environ. Sci. Nat. Res.* **2017**, *4(2)*, pp. 555633. DOI: 10.19080/IJESNR.2017.04.555633
61. Barinova, S. The effect of altitude on distribution of freshwater algae in continental Israel. *Current Topics in Plant Biology* **2011**, *12*, pp. 89-95.
62. Hustedt, F. Systematisch und Ökologische Untersuchungen über die Diatomeenflora von Java, Bali und Sumatra. *Archiv für Hydrobiologie, Suppl*. **1938–1939**, *15-16*, pp. 131–177, 393–506, 638–790, 1–155, 274–394.
63. Hustedt, F. Die Diatomeenflora des Flußsystems der Weser im Gebiet der Hansestadt Bremen. *Abhandlungen des Naturwissenschaftlichen Vereins zu Bremen* **1957**, *34*, pp. 181–440.
64. Watanabe T.; Asai K.; Houki A. Numerical estimation of organic pollution of flowing water by using the epilithic diatom assemblage – Diatom Assemblage Index (DAIpo). *Science of Total Environment* **1986**, *55*, pp. 209–218. DOI:10.1016/0048-9697(86)90180-4.
65. Sládeček, V. Diatoms as indicators of organic pollution. *Acta Hydrochimica et Hydrobiologica* **1986**, *14*, pp. 555–566.
66. Van Dam, H.; Mertens, A.; Sinkeldam, J. A coded checklist and ecological indicator values of freshwater diatoms from the Netherlands. *Netherlands Journal of Aquatic Ecology* **1994**, *28*(1), pp. 117–133. DOI: 10.1007/BF02334251.
67. Bessudova, A.; Gabyshev, V.; Bukin, Y.; Gabysheva, O.; Likhoshway, Y. V. Species richness of scaled Chrysophytes in arctic waters in the Tiksi Region (Yakutia, Russia). *Acta Biologica Sibirica* **2022**, *8*, pp. 431–459. DOI: 10.5281/zenodo.7710355.
68. Trifonova, I. Phytoplankton composition and biomass structure in relation to trophic gradient in some temperate and subarctic lakes of north-western Russia and the Prebaltic. *Hydrobiologia* **1998**, *369*, pp. 99–108. DOI: 10.1023/A:1017074615932.
69. Knights, D., Piliouras, A., Schwenk, J., Hariharan, J., & Russoniello, C. Seasonal and morphological controls on nitrate retention in Arctic deltas. *Geophysical Research Letters* **2023**, *50*, pp. 1-10. DOI: 10.1029/2022GL10220.
70. Gabyshev, V.A.; Tsarenko, P.M.; Ivanova, A.P. Diversity and Features of the Spatial Structure of Algal Communities of Water Bodies and Watercourses in the Lena River Estuary. *Inland Water Biol 12 (Suppl 1)* **2019**, pp. 1–9. DOI: 10.1134/S1995082919050067.
71. Odum, E.P. *Fundamentals of Ecology*. Third Edition, W.B. Saunders Co., Philadelphia, 1971; pp. 1-574.
72. Sharipova M. Yu. Algae of terraqueous ecotones of the Basu River Valley (South Ural, Russia). *International Journal on Algae* **2007**, *9*(2), pp.162-173. DOI: 10.1615/InterJAlgae.v9.i2.60.
73. Percopo, I.; Siano, R.; Cerino, F.; Sarno, D.; Zingone, A. Phytoplankton diversity during the spring bloom in the northwestern Mediterranean Sea. *Botanica Marina*, **2011**, *54*(3), pp. 1-25. DOI: 10.1515/BOT.2011.033.
74. Sheath, R.G.; Steinman, A.D. A checklist of freshwater algae of the Northwest Territories, Canada. *Can. J. Bot.* **1982**, *60*(10), pp. 1964-1997.