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Spatial Distribution of the Taxonomic Diversity of Phytoplankton and Bioindication of the Shallow Protected Lake Borovoe in the Burabay National Natural Park, Northern Kazakhstan

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Abstract: The Burabay National Natural Park unites six lakes located among the steppe landscape, with Lake Borovoe being the most visited among them. The phytoplankton of the protected Lake Borovoe was examined in the summer season of 2019, at eight stations, which were defined for the first time as the monitoring sites on the lake surface. Altogether, 72 algae and cyanobacteria species from seven taxonomic phyla were found in the Lake Borovoe phytoplankton during the study period. The most species-rich were three phyla: diatoms, green algae, and cyanobacteria. The average phytoplankton abundance was 3012.6 cells L^{-1}, and biomass was 2383.41 mg L^{-1}. The ecological status of the lake in 2019 was assessed based on the species richness, abundance, biomass, and calculated indices of organic pollution and toxic impact. The statistical mapping, calculated community similarity, correlation, and Redundancy Analysis (RDA) revealed zones affected by human impact. These were located in the lake shores and low-alkaline water with the saprobity index of 1.63–2.00. This is typical for naturally clean lakes, indicating the oligotrophic-to-mesotrophic status of the lake during the study period. The increase in cyanobacteria species in coastal communities can be associated with an increase in the biogenic load on the lake ecosystem in recent times. Therefore, our multivariate analysis allowed us to assess the ecological state of Lake Borovoe, which can be the result of the interaction of many external environmental factors, such as climatic conditions, long-term accumulation of organic substances, the intensity and duration of anthropogenic press, and internal lake processes such as the development of algae communities. The results suggest a tendency for the eutrophication of Lake Borovoe to increase because of pollution coming from the human impact zones on the lake shores.

Keywords: phytoplankton; species richness; abundance; biomass; bioindicators; statistics; ecological mapping; Lake Borovoe; Burabay National Natural Park; Kazakhstan

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1. Introduction

The shallow Lake Borovoe is located on the Schuchinsk-Borovsk resort area in Northern Kazakhstan as a part of the territory of the National Natural Park "Burabay" [1]. International Union for Conservation of Nature and Natural Resources, IUCN [2], classified the Burabay wetlands as Category II—a national park that can be managed in a way that may contribute to local economies through promoting to educational and recreational tourism on a scale that will not reduce the effectiveness of conservation efforts. Lake Borovoe is not only the site most visited by tourists; it is also occupied by a few balneological resorts. The enrichment of the lake water with nutrients has been going on since the foundation of the first resort 100 years ago [3]. Increased anthropogenic pressure on

the lake is causing serious problems in regard to the water quality. High abundances of phytoplankton and zooplankton in the lake in the last decades have been documented, along with the blooming of Cyanobacteria [4–6].

Phytoplankton and zooplankton communities in Lake Borovoe demonstrate high heterogeneity, but the species richness has not been regularly studied. Nevertheless, research into the algae in Lake Borovoe was started in 1947 by N. Voronikhin [7–9], and it continued sporadically up until 2013; only a few species were mentioned in the previous reports [6,10–15]. The monitoring of the protected waterbodies has started revealing the species richness of its communities. All monitoring programs usually included the research of biodiversity and quantitative variables of the biological part of ecosystem, as well as the definition of major environmental variables [16,17]. Assessing the water quality of the protected waterbody is also an important task to identify the main sources of its pollution [18,19]. Floristic studies in aquatic systems are very important because the flora are environmental indicators that can be used to infer the environmental impacts on the natural, climatic, and economic conditions of the Burabay National Natural Park, as was revealed during the hydrochemical and hydrobiological study of five other lakes in the park territory [20]. Studies of algae are of special interest since the formation of their floras occurs under conditions of water flowing from the catchment basin and thus represents an accumulative result of natural and anthropogenic conditions throughout the entire catchment area over many years. So, the first step for the monitoring program is the screening of major chemical and biological variables on the net of sampling stations on the lake surface. Despite the occasional hydrochemical and hydrobiological studies of Lake Borovoe, a comprehensive assessment of its ecological status has not been performed yet.

Statistical data mapping is an effective tool for solving this application problem [21,22]. The effectiveness of this method in monitoring studies of water bodies in Kazakhstan has been shown previously [23,24]. The mapping of environmental and biological variables helps to reveal human impact zones in aquatic objects, as well as the ecosystem damage by them.

The purpose of this work was to study the species composition, abundance, and biomass of phytoplankton in Lake Borovoe in the protected area of the Burabay National Natural Park. We hypothesized that the distribution of algae indicators over the surface of the lake and the comparison of it to environmental variables, using statistical methods can, for the first time for Northern Kazakhstan, show the zones and main factors of human impact on the shallow lake.

2. Materials and Methods

2.1. Description of Study Site

Lake Borovoe is located at an altitude of 315.0 m above sea level. Borovoe is separated from the nearby lakes by ridges 400–900 m high (Figure 1a). It has an almost circular shape. The maximum length of the lake is about 4 km, with a width of 3.27 km. It is a shallow lake with a maximum depth of about 5 m. Two bays are placed in the western part (Figure 1b). The catchment area is 164.0 km^2. The east coast is sandy, sloping. The banks are overgrown with pine and birch. The Sary-Bulak River is inputted into the lake. The lake is fed by this small river, temporary streams, and precipitation. Only one small river, Kyrkyruek, flows from the lake. Sediments are represented by black silts. The coastal zone and northwestern bays are overgrown with *Potamogeton lucens* L. Macrophyte overgrowth is no more than 35–40% of the lake's surface and shoreline. The bottom is overgrown with Charophyta algae, except for the central part of the lake [25]. The position of Northern Kazakhstan in the depths of the mainland causes a sharp continental climate. Its characteristic features are a long cold winter with strong winds and snowstorms, and a short but hot summer [20,26]. Average long-term temperatures of the coldest month of January are about −17.6 °C to −18.5 °C, with a minimum of −45.0 °C. In July, the air temperature reaches an average of +19.0 °C to +19.5 °C, with an absolute maximum of +41.0 °C. The average annual precipitation varies from 290–295 to 425–435 mm. The snow cover lasts for about 5 months,

from November to March. The Lake Borovoe area has been a resort of national importance since 1920. The lake received conservation status in 2000 when the Burabay National Natural Park was created. The Borovoye village is located on the eastern shore of the lake, with numerous rest houses and balneological resorts. The two largest resorts are located on the southeast and northwest shores of the lake.

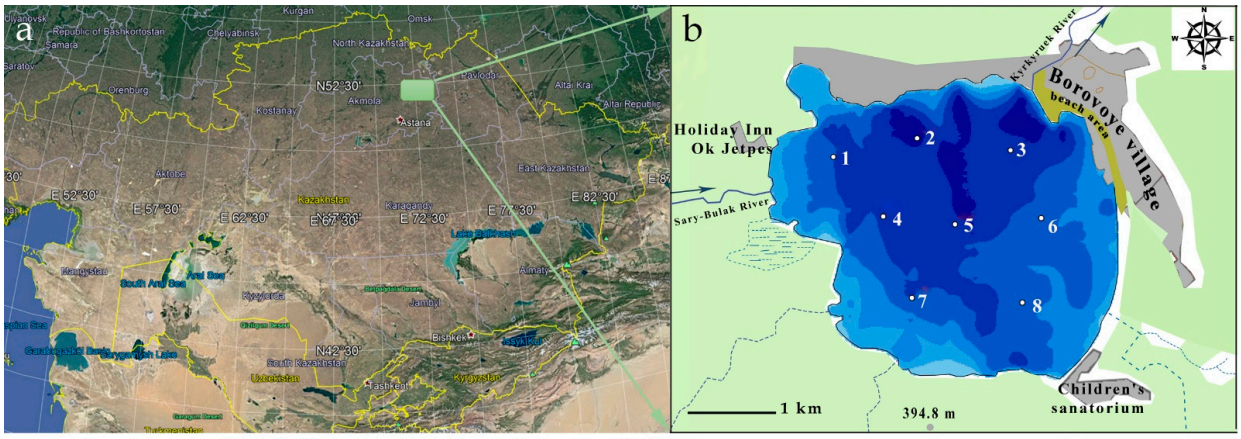

Figure 1. Map of study site on Lake Borovoe, Northern Kazakhstan, in July of 2019. Position of Lake Borovoe in Kazakhstan (**a**). Position of the phytoplankton sampling stations 1–8 on the lake surface (**b**). Map creating in ESRI ArcGIS 10.8. USA program on the base of our measurements of GIS coordinates and the lake depth on each sampling station.

2.2. Sampling and Laboratory Analysis

The Lake Borovoe was examined in the summer season (29 July of 2019). It was the first trip with sampling and measurements that covered the entire lake's surface as a screening stage for preliminary assessment for the purpose of monitoring. A total of eight sampling stations have been identified for the first time as monitoring sites on the surface of the lake. Coordinate referencing of the stations was performed by Garmin eTrex GPS-navigator. The temperature, Total Dissolved Solids (TDS), and pH values of the surface layers of water were measured in parallel with sampling with HANNA HI 9813-0, and N-NO_3 with HANNA HI 93728 (HANNA Instruments, Vensokit, RI, USA), with three repetitions. The transparency of the water was measured by using a Secchi disk.

Phytoplankton samples were taken from the surface water layers about 0–0.5 m into 1 L plastic containers [27], fixed in 3% neutral formaldehyde, and transported to the lab in an icebox. The sedimentary method was used to process phytoplankton samples, with the final volume of the concentrated sample being 5–10 mL [28,29]. Fixed phytoplankton samples were also studied in the lab in three repetitions, from wet and permanent slides [30], under light microscopes A Nikon ECLIPSE E200 (Nikon Instruments Inc., Melville, NY, USA) was used, with a magnification of ×100–×2000. Cells' abundance was calculated in the Nageotte counting chamber (Hausser Scientific, Horsham, PA, USA). Wet biomass was calculated from the volume of the cell in mg L^{-1}. Species identification was performed by using standard methods with relevant guides to the species identifications [31–36]. Modern taxonomy was adopted with [37].

The Shannon Diversity Index [38] was calculated with the Primer 6 program, using the following Formula (1):

$$H = -\sum_{i=1}^{n} p_i \times log2\ p_i \quad (1)$$

where H is the Shannon Index (bits/ind.), p_i is the share of the i-th species in the total abundance, $log2$ is the logarithm to base 2, n is the number of species in the sample, and $\sum$ is the sum of values for the sample.

Index saprobity S was calculated for each algal community, according to V. Sládeček [39], as a function of the number of saprobic species and their relative abundances (2):

$$S = \sum_{i=1}^{n}(s_i h_i) / \sum_{i=1}^{n}(h_i) \quad (2)$$

where S is the index of saprobity for algal community (unitless), s is species-specific saprobity index [40,41], and h is the cell density of each species, n is the number of species in the sample, and $\sum$ is the sum of values for the sample.

Bioindicator analysis was performed with species-specific ecological preferences of planktonic algae found at each sampling station [40–42] for revealing influencing external factors such as temperature, salinity, pH, oxygen conditions, organic pollution level, and trophic status of a water body.

Statistical maps [22] that reflect the probability of mapped variable distribution over the lake surface were built in the Statistica 12.0 Software based on the GPS coordinates of sampling points for each measured biological and chemical variable. Cluster analysis of the Bray–Curtis similarity of phytoplankton communities was carried out by using the Biodiversity-Pro program. A correlation analysis of the revealed data was carried out by using the JASP 0.16.4.0 program [43]. A heat map was constructed in the ExStatR program [44]. The linear ordination method *Redundancy Detrended Analysis* (RDA) was processed in the CANOCO 4.5 program in order to recognize the species–environment relationships [45].

3. Results

3.1. Environmental Characteristics of the Lake Borovoe

The lake was shallow, as can be seen in Appendix Table A1 and Figure 2c. During the study period, the temperature of the surface water reached 22.0–22.86 °C (Appendix Table A1) and was lowest in the central part of the lake (Figure 2b). The water was fresh, with a TDS of about 200 mg L^{-1}, and highest ionic content was found in the central part of the lake (Figure 2a). The water was slightly alkaline, with a pH of about 8.3 and transparency of about 0.5–0.8 m (Figure 2d). So, major environmental variables can demonstrate the uniform condition in two parts of the Lake Borovoe surface—northwestern and southeastern parts—as represented in the maps in Figure 2a,b. The distribution of TDS and water temperature was controversial (R = –0.93, p = 0.001), especially in the central part with no correlations with the depth (p = 0.53) (Figure 2c). The water transparency was not correlated with temperature (p = 0.39), but visually, we can see a similar distribution near the wetlands of Station 3 and Borovoe village (Figure 2b,d).

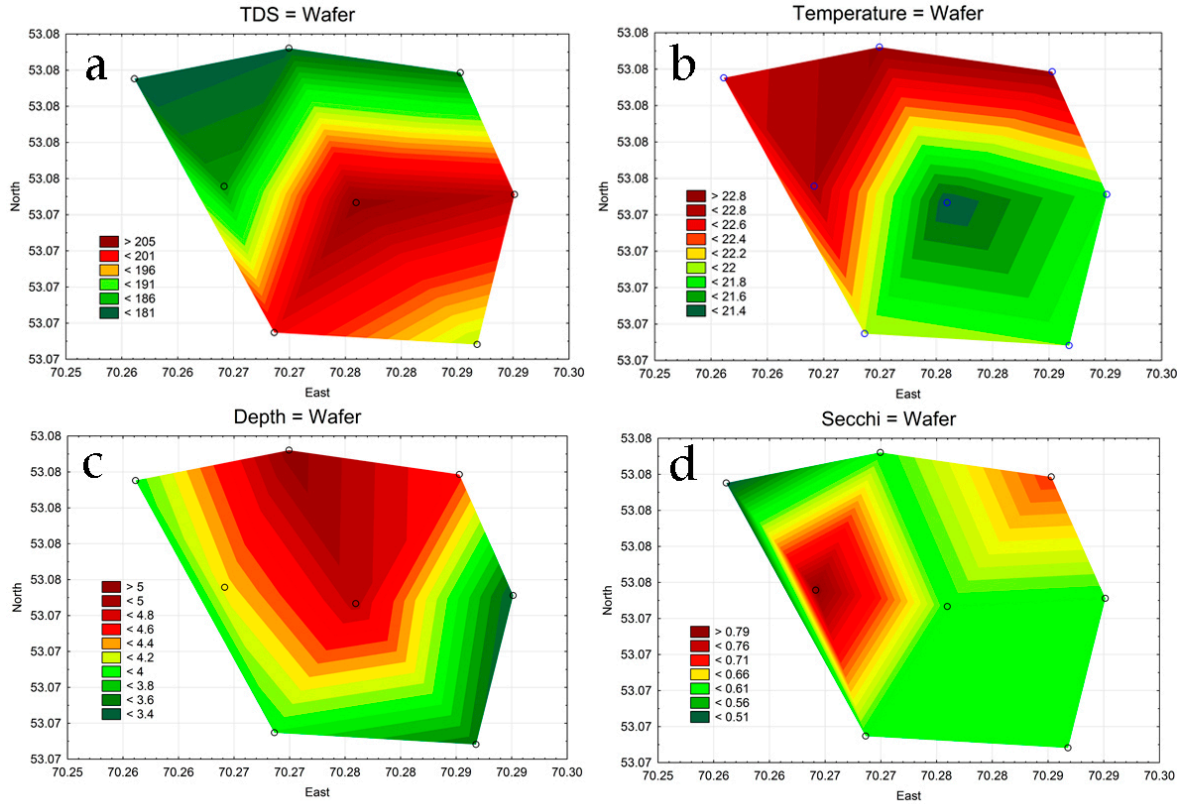

Figure 2. Distribution of major environmental variables in the sampling stations of Lake Borovoe's surface, 2019. TDS (**a**), water temperature (**b**), lake depth (**c**), and transparency by Secchi disk (**d**).

3.2. Phytoplankton in the Lake Borovoe

Altogether, 72 algae and cyanobacteria taxa from seven taxonomic phyla were found in Lake Borovoe during the sampling period (Appendix Table A2). The diatom species was the richest, with 29 taxa, followed green algae, with 18, and cyanobacteria, with 15 taxa (Table 1). Species richness at sampling stations varies within a small range, from 21 to 29 taxa (Table 1). The lowermost species number was in Station 4, where water transparency was maximal (Figure 2d).

Table 1. Species richness of phytoplanktonic algae and cyanobacteria in Lake Borovoe, summer 2019.

Phylum	1	2	3	4	5	6	7	8	Percent
Bacillariophyta	7	11	8	10	9	11	9	7	40
Chlorophyta	7	6	7	2	8	8	8	10	25
Cyanobacteria	8	4	7	5	5	7	6	5	21
Euglenozoa	0	0	1	1	2	0	1	1	3
Miozoa	1	2	3	1	1	1	2	3	7
Ochrophyta	1	1	1	1	1	1	1	1	1
Charophyta	2	1	1	1	1	1	1	1	3
Total	26	25	28	21	27	29	28	28	100

The Bray–Curtis similarity analysis divided the species richness into two clusters, the first of which included the three most species-rich phyla–diatoms, green algae, and cyanobacteria (Figure 3); the second cluster included four other phyla, which contained a small number of species (Table 1).

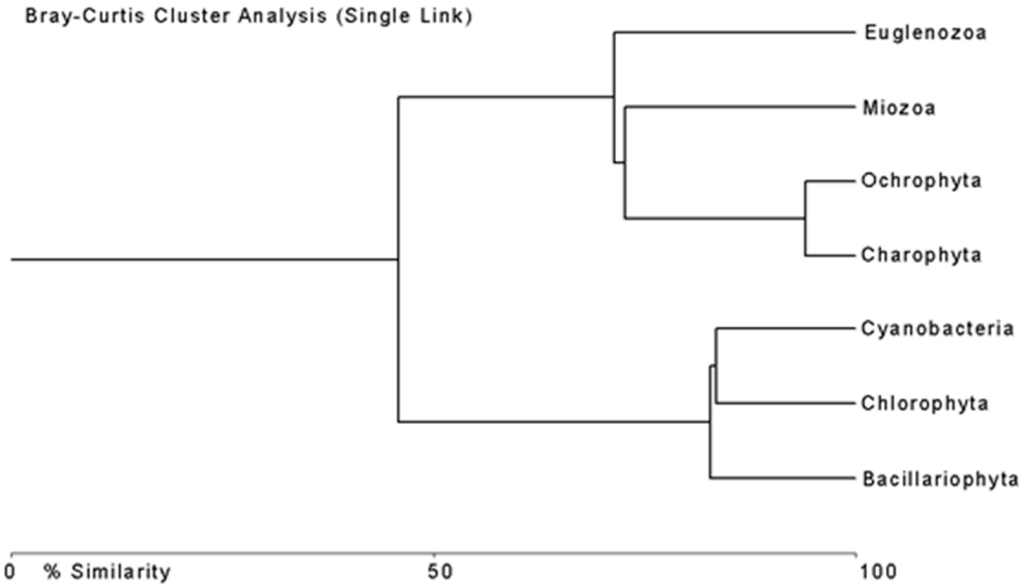

Figure 3. Cluster dendrogram of phytoplankton community species richness in the Lake Borovoe, 2019.

Phytoplankton species occupy the first level of the food pyramid and depend on the concentration of essential nutrients such as nitrate and phosphate. Thus, phytoplankton species are rich where nutrients can be available. We tried to reveal the relationship between phytoplankton species richness in sampling stations by using statistical methods to reveal some homogeneity of the lake environment. Figure 4 shows a graph of JASP analysis of the correlation of phytoplankton species number at sampling stations. At a similarity level of more than 50%, the graph divides the phytoplankton species richness into three groups. The most similar communities are at Stations 1, 2, and 6 (Group 1); 3 and 7 (Group 2); and 4, 5, and 8 (Group 3).

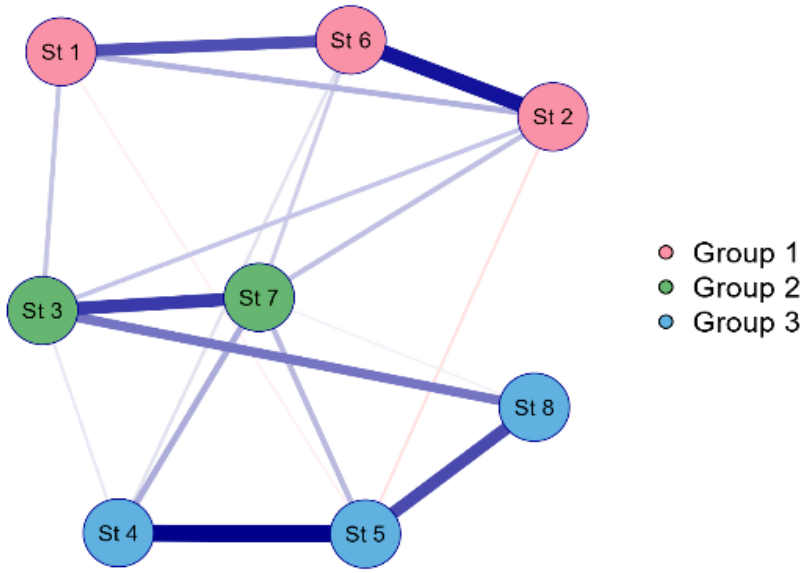

Figure 4. JASP correlation plot of the phytoplankton species richness in Lake Borovoe, 2019. Bold line shows largest similarity on type of analysis, "Huge" correlation > 0.5.

The averages of the parameter values (Table 2) were calculated to indicate the differences in the stations grouped in Figure 4. Group 1 includes Stations 1, 3, and 6, where, compared to other groups, there is less depth, transparency, TDS, and biomass, but higher

water warming, which indicates not only the high ecosystem activity work of the lake, but also greater stress for phytoplankton, when the WESI index decreases. The second group of stations (Stations 3 and 7) is characterized by a higher abundance of phytoplankton, mainly at Station 7. Both stations are located near actively visited or populated lake shores. Group 3 consists of three stations (Stations 4, 5, and 8) that are deeper, transparent, cool, mineralized, and alkaline, where there are fewer nitrates, and the WESI index was higher. The stations of Group 3 are located closer to the middle of the lake and are the most remote from anthropogenic influence.

Table 2. Distribution of averaged environmental and biological variables of phytoplankton over groups of stations in Figure 4.

Station Group	1	2	3
Depth, m	4.13	4.22	4.21
Secchi, m	0.57	0.65	0.67
T, °C	22.44	22.43	22.00
pH	8.17	8.17	8.24
TDS, mg L^{-1}	188.47	191.80	194.43
N-NO3, mg L^{-1}	0.56	0.58	0.04
Index S	1.81	1.89	1.81
Index WESI	1.11	1.17	3.33
Abundance, cells L^{-1}	2516.5	4603.7	2448.0
Biomass mg L^{-1}	2087.4	3237.2	2110.2
Shannon Index	0.751	0.530	0.738

Therefore, to understand the importance of species dynamics at the phylum level, we constructed statistical maps for each taxa distribution in the sampling stations. Figure 5a shows that the total number of species was minimal at Station 4, which had the highest water transparency and temperature, as well as lower TDS values (Appendix Table A1). Figure 5b shows that the total number of phytoplankton species was determined by the number of green algae species that take a part of its composition. The distribution of diatoms is inversely relative to the distribution of green algae (Figure 5c). Cyanobacteria are most represented offshore, where the water temperature and anthropogenic load were higher, and the TDS was lower (Figure 5d). Euglenoids were mainly in the central part (Figure 5e), but charophyte planktonic species were concentrated in the northwestern bay of the lake (Figure 5f).

Spatial maps of phytoplankton abundance and biomass show an opposite distribution (Figure 6a,b). The abundance of phytoplankton was greatest where an influx of nitrates was found (Figure 6c). At the same time, the distribution of the WESI index (Figure 6d), which shows stress zones for algae, outlines the entire coast, including the points of nitrate inflow, as vulnerable, and the middle of the lake as the most preferable.

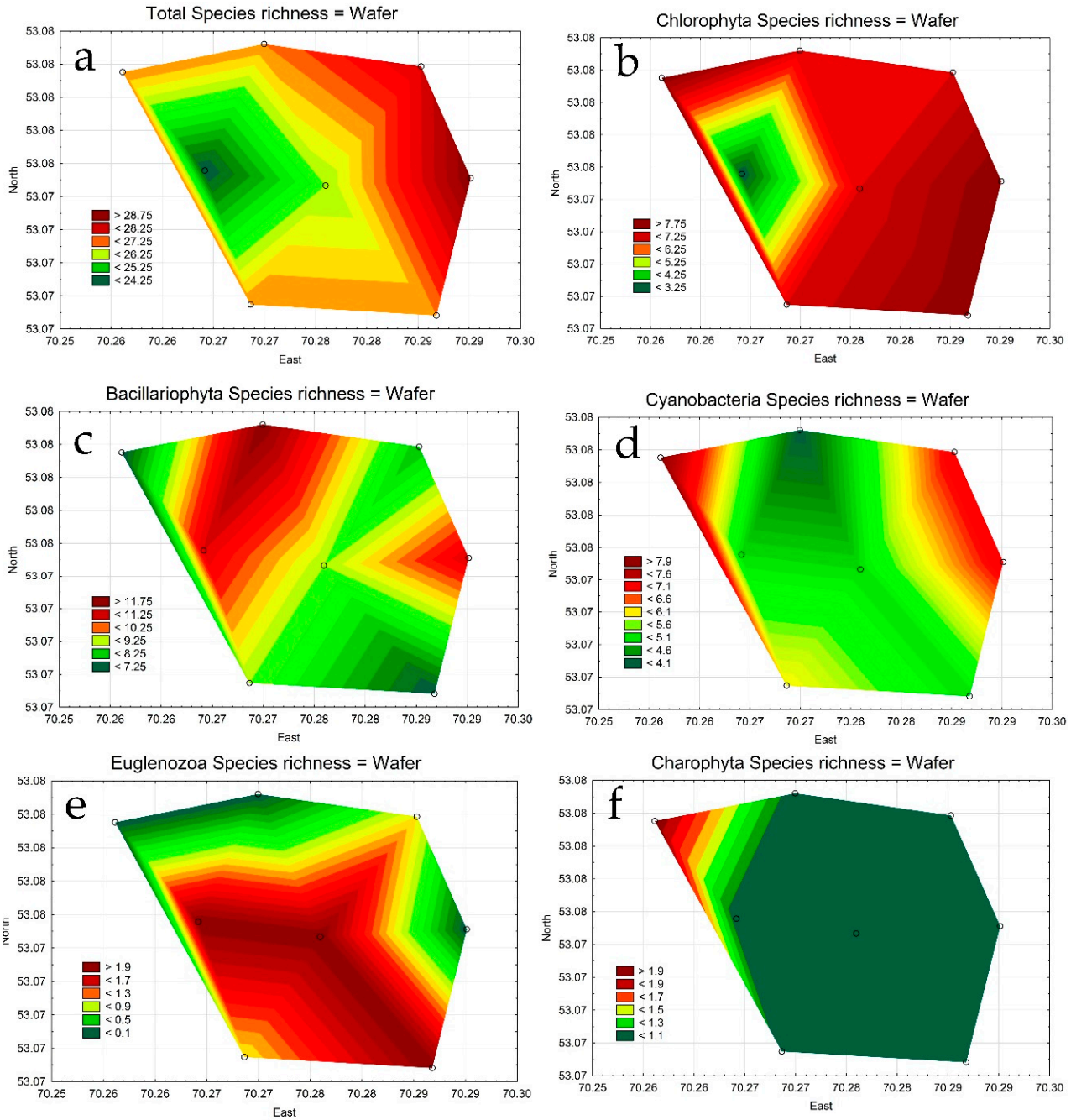

Figure 5. Statistical maps of distribution of phyla species richness in phytoplankton communities on the sampling stations of the Lake Borovoe surface, 2019. Total species richness (**a**), Chlorophyta (**b**), Bacillariophyta (**c**), Cyanobacteria (**d**), Euglenozoa (**e**), and Charophyta (**f**).

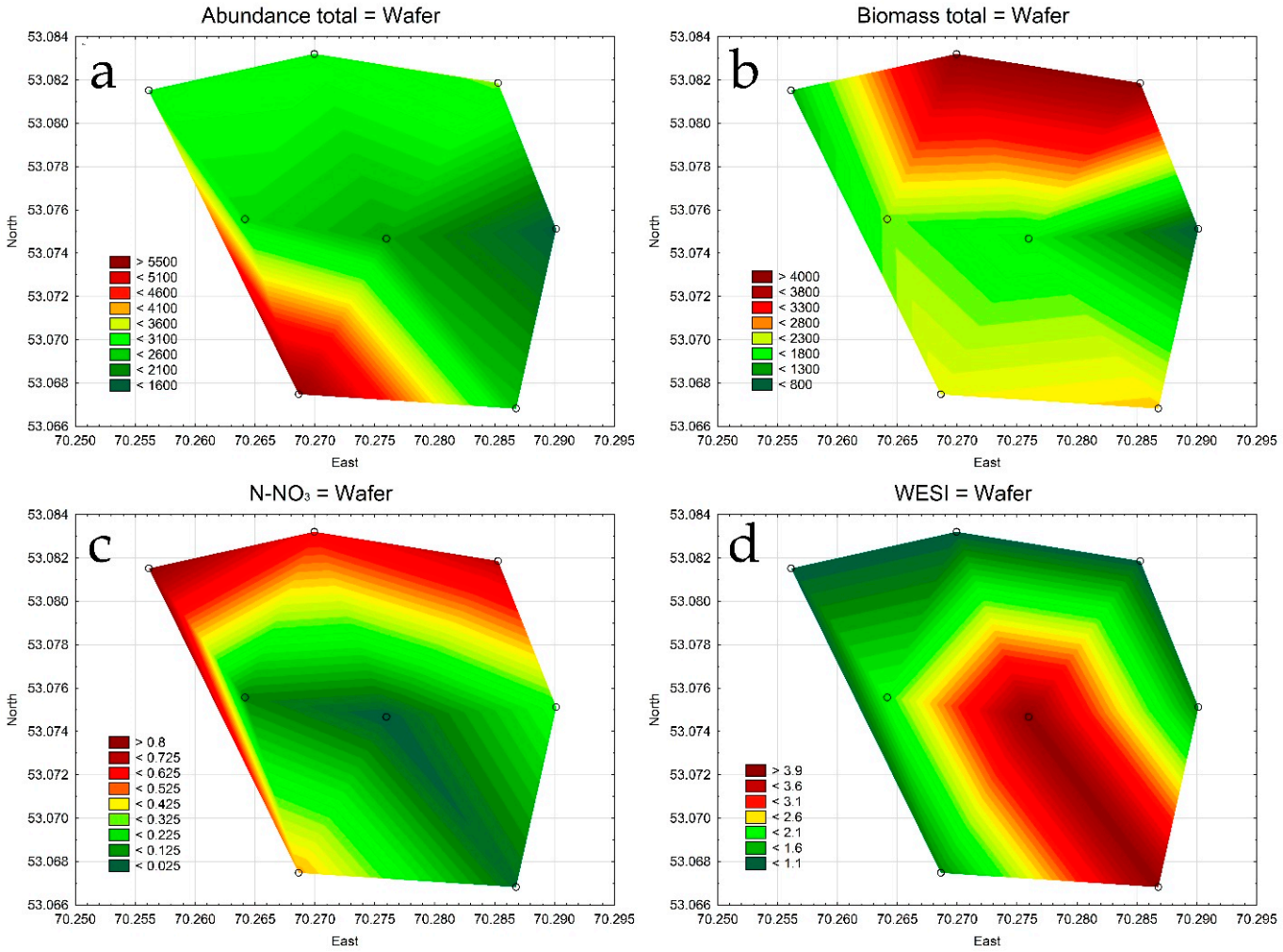

Figure 6. Maps of the surface phytoplankton abundance (**a**), biomass (**b**), nitrates (**c**), and WESI index (**d**) in Lake Borovoe, summer 2019.

3.3. Phytoplankton Indicators of Water Quality

The bioindication results on the basis of phytoplankton species' ecological preferences (Appendix Table A2) are represented in Appendix Table A3 and visualized in Figure 7. Even though the indicator values for stations represent a mosaic, it is possible to single out the main characteristic groups: Bacillariophyta and Chlorophyta species, planktonic and plankto-benthic inhabitants, and middle oxygenated water indicators of Class 3 of water quality.

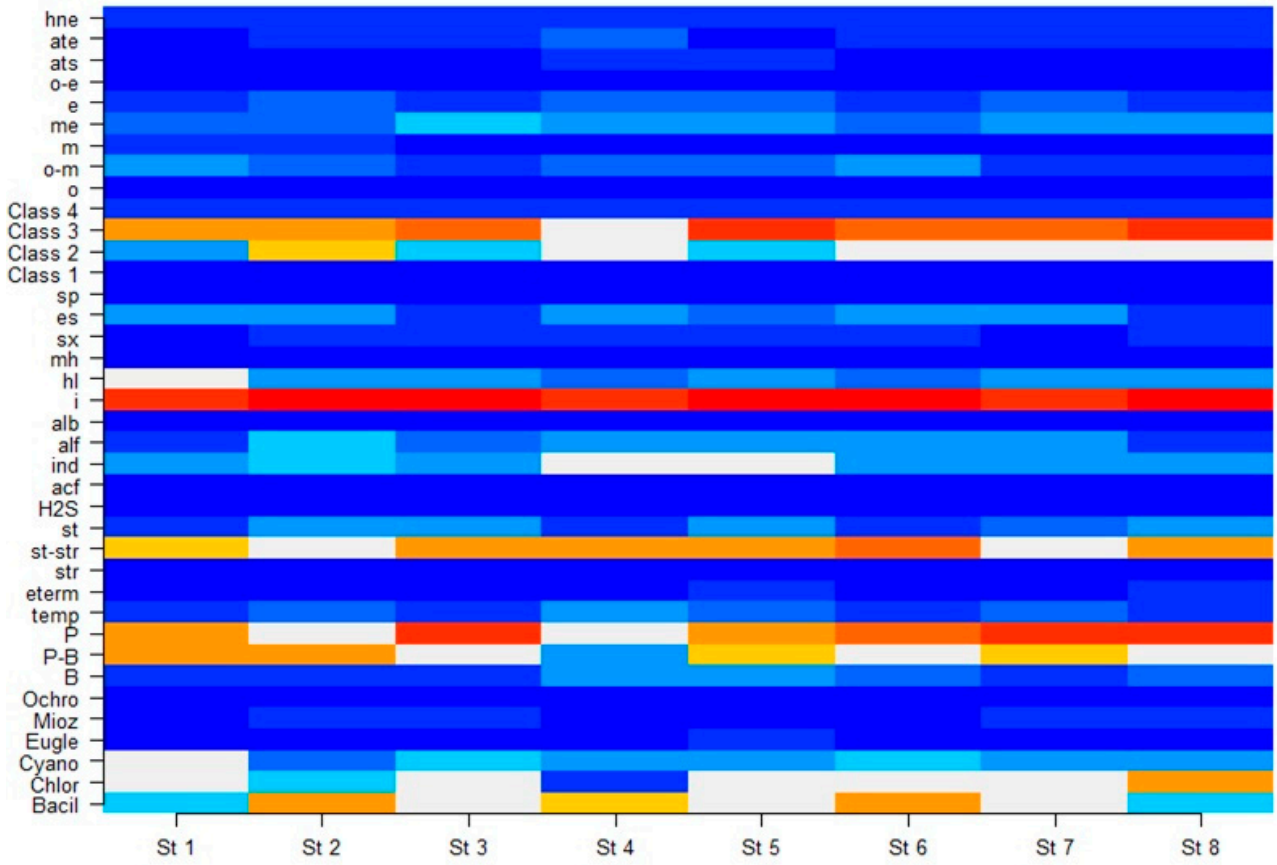

Figure 7. Heat map for distribution of indicators in phytoplankton communities over the sampling stations at Lake Borovoe, 2019. Abbreviations: Bacil, Bacillariophyta; Chlor, Chlorophyta; Cyano, Cyanobacteria; Eugle, Euglenozoa; Mioz, Miozoa; Ochro, Ochrophyta; B, benthic; P-B, plankto-benthic; P, planktonic; temp, inhabitants of temperate-temperature waters; eterm, eurythermic; str, streaming well-oxygenated waters inhabitants; st-str, inhabitants of standing to streaming middle-oxygenated waters; st, inhabitants of standing low-oxygenated waters; H_2S, sulfides anoxia indicators; acf, acidophilic; ind, pH indifferent; alf, alkaliphilic; alb, alkalibiontes; i, chlorides indifferent; hl, halophiles; mh, mesohalobes; sx, saproxenes; es, eurysaprobes; sp, saprophiles; Classes 1–4 of water-quality indicators according to Index S; o, oligotraphentes; o-m, oligo-mesotraphentes; m, mesotraphentes; me, meso-eutraphentes; e, eutraphentes; o-e, oligotraphentes to eutraphentes; ats, autotrophes-inhabited low-nitric-nitrogen waters; ate, autotrophes-inhabited high-nitric-nitrogen waters; hne, facultative-heterotrophes-inhabited low organically enriched waters. In the *x*-axis are station numbers, and in the *y*-axis are the same abbreviations as in Appendix Table A3. The color of the cells varies from white to blue and then to red, according to the proportion of the number in the entire distribution.

An RDA triplot was constructed on the base of environmental data (Appendix Table A1) and species richness in phyla (Table 1). Figure 8 shows that nitrate-nitrogen-stimulated Charophyta and Cyanobacteria grow in the waters of Stations 1 and 8 with less transparency (Figure 2d) and depth (Figure 2c). Diatom, green algae, and euglenoids were diverse in Stations 5, 6, and 7, where there was the highest TDS (Figure 2a) and total species richness (Figure 5a,b). Miozoa species (*Ceratium hirundinella*) were richest in Stations 2 and 3, which had highest temperature (Figure 2b) and lowest TDS (Figure 2a).

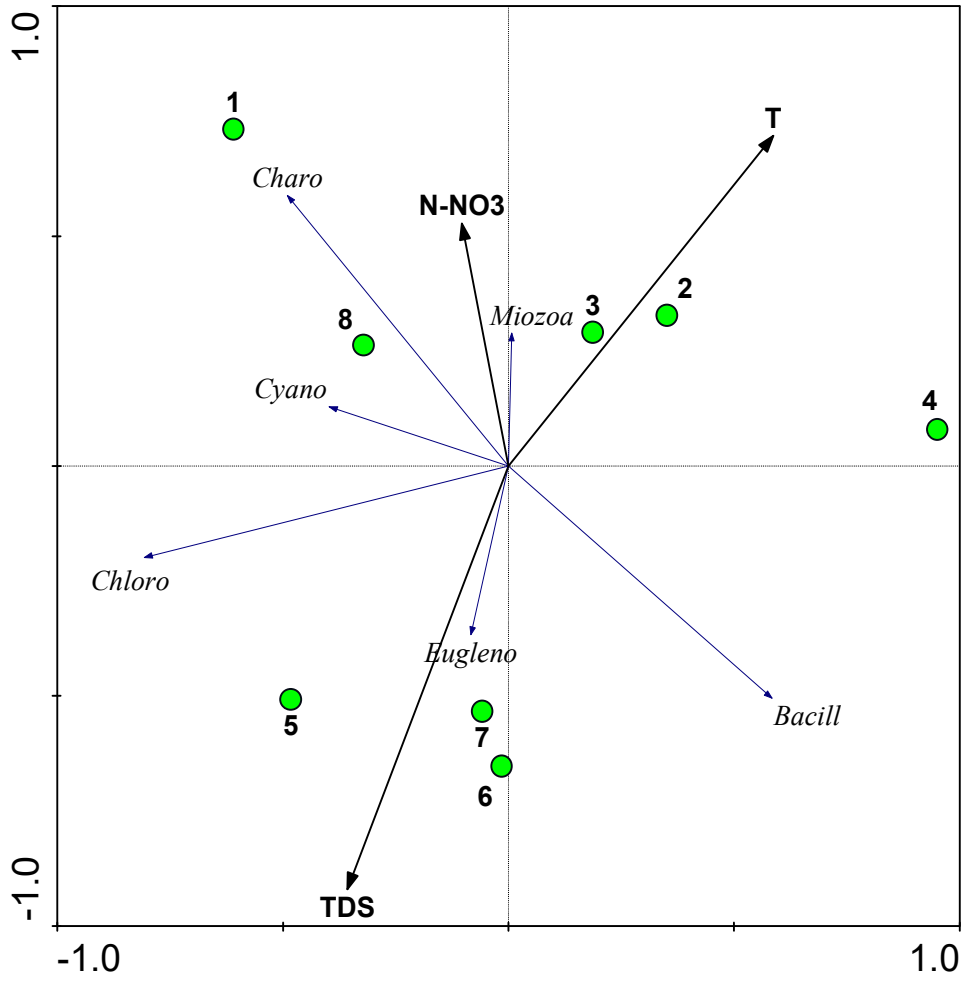

Figure 8. RDA plot of the relationships between environmental variables: temperature, nitrates-nitrogen concentration, TDS, depth, and species richness in phyla of phytoplankton in the Lake Borovoe, 2019. Monte Carlo test summary for 945 permutations: eigenvalue = 0.421; *p*-value = 0.136.

4. Discussion

Northern Kazakhstan abounds in shallow lakes, most of which are objects of WWF protection, as they are located on the migratory routes of birds [46]. Therefore, it is especially important not only to identify the diversity of organisms at protected sites, but also to determine the main influencing anthropogenic or natural factors. Algae, as the first level of the trophic pyramid, are the first to respond to changes in the lake's ecosystem, with the most noticeable impact on the example of phytoplankton [47]. Phytoplankton in the lakes of Northern Kazakhstan, including Lake Borovoe, has been studied sporadically [6–15]. In connection with the projects of the WWF on the status of protection, we undertook a large-scale study of phytoplankton during 1999–2000 in 34 North Kazakhstan lakes that have a conservation status or are under preparation [48]; with the help of bioindication and statistical analysis, it was possible to identify the main factor affecting the diversity of communities in the lakes of this region, i.e., salinity [49]. A subsequent comparison with lakes of similar size in the semi-arid climate zone in the Eastern Mediterranean not only confirmed the conclusion made, but also expanded the understanding of the importance of using bioindication to identify the main factors affecting phytoplankton [48]. The mentioned studies on protected lakes have shown that salinity is a regional natural factor related to climate. Our studies at Lake Borovoe also revealed a close inverse relationship between temperature and TDS ($p = 0.001$). A study of phytoplankton in the nearby Lake Zerenda showed that, for lakes whose shores are visited by tourists, the anthropogenic

factor is the influx of nitrates [50]. At the same time, nitrates in all the studied lakes of Northern Kazakhstan turned out to be a factor stimulating the diversity of algae, and in Lake Borovoe, also its abundance and biomass. Thus, saprobity indices were higher where nitrate concentrations were higher [48]. Lake Borovoe, where the saprobity indices were in the range of 1.52–2.00, is comparable with freshwater lakes in terms of this indicator and the number of species in the community.

Our calculations of the index toxicity WESI were comparable with its values in the lakes of Northern Kazakhstan for those lakes where salinity (TDS) was higher, which indicates a long history of evaporation and a small inflow of surface water, that is, the natural state of the lakes [48]. For Lake Borovoe, the WESI index was higher (better condition) in the center of the lake, away from coastal pollution, where TDS is higher and water temperature is lower. This distribution shows that the phytoplankton of the lake was affected by organic pollution coming from the shore zone, which does not reach the center of the lake. Therefore, the lake retains sufficient self-purification capacity.

The spatial distribution of phytoplankton suggests that the lake water is influenced by pollution of the communal services of the Borovoye village and two resorts (Figure 1). The main contribution of the village is associated not only with wastewater discharges but also with surface runoff from the beach area along all east coasts. As can be seen from Figures 2d and 5, in the eastern and southeastern parts of the water surface, the signs of eutrophication of the lake can be recognized. Here, the high species richness of phytoplankton due to Chlorophyta taxa was recorded, as well as minimum values of water transparency and maximal value of TDS show that phytoplankton communities are formed under the conditions of a constant influx of fresh nutrients. As is known, the number of phytoplankton species decreases with an increase in their abundance and biomass [16], which we observe on spatial statistical maps for Lake Borovoe.

The spatial distribution of phytoplankton and environmental parameters in the lakes of Northern Kazakhstan were studied for the first time on Lake Borovoe. However, for more southerly lakes, this method has been applied with effective results. For a fairly large regional lake Balkhash, the zones of influence of both climatic (salinity) and anthropogenic (organic pollution) factors were clearly shown, using statistical mapping [51]. The phytoplankton of smaller lakes in Kazakhstan revealed the anthropogenic factor of organic pollution coming with the tourist flow to the lakes of the Kolsay cascade [52] or with runoff from fields and inflow to the Shardara reservoir [53]. Thus, statistical mapping, statistical methods, and bioindication can serve together as effective tools for identifying factors and zones of natural and anthropogenic impact in this region.

According to the results of the analysis of the main environmental variables in the summer of 2019 (Table 1), the water of Lake Borovoe can be assessed as fresh and low alkaline, corresponding to the level of clean, slightly polluted waters of Classes 2 and 3 of water quality [39]. This may be due to historically low nutrient content [4,6], even during the period of fish mortality in 1974 [3]. It is known that the best period for studying phytoplankton is the middle of summer, as in our case, when all processes in the lake give the maximum diversity and biomass of plankton communities [52–54]. The total species richness of phytoplankton in Lake Borovoe is currently determined mainly by the number of Chlorophyta species. This and phytoplankton abundance and biomass are typical for naturally clean lakes and may indicate the oligotrophic status of the lake during the study period. At the same time, the increase in cyanobacteria species in coastal communities may be associated with an increase in the biogenic load on the lake ecosystem in recent times [1]. The analysis shows that pollutants entering the lake water are associated with villages and resort areas located on the coast. However, they are utilized by algae almost completely, which can be seen in the distribution of pollution indices, showing cleaner water in the middle of the lake.

The phytoplankton is a part of total autotrophic organisms that, together with macrophytes, settled the lake and therefore can use only part of the total value of nutrient inflow to the lake. Since the IUCN protected Charophyte species [55] grow in the coastal area, it is

important to monitor water quality and the state of their populations during monitoring, since the disappearance of charophytes will indicate the loss of a protected object in the IUCN system. The Lake Borovoe shores are inhabited by five species of *Chara*, *Nitellopsis obtusa*, and *Nitella flexilis* [25]. There is a unique diversity of charophytes in this one lake. Therefore, the role of macrophytes and charophytes in the trophic condition of the lake is very important. The anthropogenic load may be one of the reasons for the eutrophication of Lake Borovoe, leading to degradation of the macrophyte communities. The Lake Fund monitoring showed that macrophytes occupied 65–80% of the bottom surface in 1964–2002 [3], while their density had decreased to approximately 30–35% by 2019. Therefore, a decrease in the role of macrophytes consuming nutrients [56] has created favorable conditions for planktonic algae [19] and caused changes in the trophic conditions of the lake.

The differences in environmental and biological variables distribution were revealed with the help of statistical mapping, even in the case of low amplitude of variables [21], as in Lake Borovoe. The preliminary hydrochemical and hydrobiological assessment of the lakes of the Shchuchinsko-Borovsk resort zone [20] confirm that this approach can be recommended in the monitoring of different protected lakes' sustainability.

5. Conclusions

Our study showed that the ecological state of Lake Borovoe can be the result of the interaction of many environmental factors, such as climatic conditions, long-term accumulation of organic matter, the intensity and duration of anthropogenic pressure, as well as intralake processes, such as the development of a community of macrophytes, algae, and invertebrates. An assessment of the phytoplankton communities showed a trend towards an increase in eutrophication of the lake, as revealed during statistical mapping, because of organic pollution from populated and resort areas. The assessment of water quality by the bioindication of plankton species revealed weakly alkaline and slightly organically polluted water of Classes 2 and 3. With the help of indications and statistics, the salinity was determined as a climatic factor and organic pollution as an anthropogenic factor affecting the ecosystem of Lake Borovoe. Thus, the indication of phytoplankton and environmental parameters in Lake Borovoe reflect the state of the lake as oligotrophic with a transition to the mesotrophic stage, subject to organic pollution in the coastal part, but coping with anthropogenic impact.

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Appendix A

Table A1. Averaged environmental variables with standard deviation and coordinates of sampling stations on the Lake Borovoe, 2019.

Station	1	2	3	4	5	6	7	8	Average
North	53.08152	53.08321	53.08186	53.07557	53.07467	53.07512	53.06748	53.06682	
East	70.25613	70.26995	70.28529	70.26416	70.27596	70.29014	70.26864	70.28679	
Depth, m	3.92 ± 0.06	5.06 ± 0.05	4.55 ± 0.06	4.25 ± 0.06	4.85 ± 0.04	3.4 ± 0.02	3.89 ± 0.04	3.53 ± 0.02	4.18
Secchi, m	0.5 ± 0.09	0.6 ± 0.09	0.7 ± 0.08	0.8 ± 0.06	0.6 ± 0.05	0.6 ± 0.05	0.6 ± 0.05	0.6 ± 0.06	0.63
T °C	22.61 ± 0.6	22.92 ± 0.5	22.86 ± 0.6	22.8 ± 0.6	21.3 ± 0.5	21.8 ± 0.5	22 ± 0.3	21.9 ± 0.5	22.27
pH	8.17 ± 0.01	8.16 ± 0.01	8.18 ± 0.02	8.16 ± 0.02	8.43 ± 0.01	8.19 ± 0.01	8.16 ± 0.01	8.12 ± 0.01	8.20
TDS, mg L^{-1}	180 ± 11.51	180.8 ± 11.2	182.2 ± 10.8	183.8 ± 9.58	207.8 ± 11.0	204.6 ± 10.0	201.4 ± 9.56	191.7 ± 9.12	191.5
N-NO_3, mg L^{-1}	0.816 ± 0.32	0.599 ± 0.12	0.700 ± 0.24	0.090 ± 0.01	0.000 ± 0.0	0.272 ± 0.02	0.466 ± 0.10	0.039 ± 0.01	0.373
Index S	1.82 ± 0.18	1.98 ± 0.15	1.77 ± 0.17	1.94 ± 0.18	1.99 ± 0.16	1.63 ± 0.13	2.00 ± 0.20	1.52 ± 0.11	1.83
Index WESI	1.00	1.00	1.00	2.00	4.00	1.33	1.33	4.00	1.96
Abundance, cells L^{-1}	2982.9 ± 193.3	3026.5 ± 220.7	3238.9 ± 245.9	2642.7 ± 222.8	2226.9 ± 137.9	1540.2 ± 80.1	5968.4 ± 575.0	2474.3 ± 141.5	3012.6
Biomass mg L^{-1}	1403.2 ± 78.4	4086.6 ± 270.0	4087.5 ± 215.0	2044.2 ± 95.6	1732.5 ± 101.6	772.5 ± 38.8	2386.8 ± 129.9	2554 ± 149.0	2383.4
Shannon Index	0.753 ± 0.17	0.614 ± 0.15	0.659 ± 0.14	0.552 ± 0.11	0.797 ± 0.17	0.885 ± 0.18	0.401 ± 0.10	0.864 ± 0.16	0.691

Table A2. Diversity of algae and cyanobacteria on the sampling stations (1–8) of the Lake Borovoe, 2019. Abbreviations: **Hab**, substrate preferences: B, benthic; P-B, plankto-benthic; and P, planktonic. **T**, temperature indicators: temp, inhabitants of temperate-temperature waters; and eterm, eurythermic. **Oxy**, Dissolved oxygen and water mobility indicators: str, inhabitants of streaming well-oxygenated waters; st-str, inhabitants of standing to streaming middle-oxygenated waters; st, inhabitants of standing low-oxygenated waters; H_2S, sulfides anoxia indicators. **pH**, water acidity indicators: acf, acidophilic; ind, pH indifferent; alf, alkaliphilic; alb, alkalibiontes. **Sal**, salinity indicators: i, chlorides indifferent; hl, halophiles; mh, mesohalobes; oh, broad spectrum oligohalobes. **D**, Watanabe diatom indicators for organic pollution: sx, saproxenes; es, eurysaprobes; sp, saprophiles. **Sap**, saprobity indicator categories with species-specific index S: b-a, 2.4–beta-alpha-mesosaprobiont; b-o, 1.6–beta-oligosaprobiont; o, 1.0–oligosaprobiont; o-a, 1.8–oligo-alpha-mesosaprobiont; o-b, 1.4–oligo-beta-mesosaprobiont; o-x, 0.6–oligo-xenosaprobiont; x, 0.0–xenosaprobiont; x-b, 0.8–xeno-beta-mesosaprobiont; x-o, 0.4–xeno-oligosaprobiont. **Index S**, species-specific index saprobity S. **Tro**, trophic-state indicators: o, oligotraphentes; o-m, oligo-mesotraphentes; m, mesotraphentes; me, meso-eutraphentes; e, eutraphentes; o-e, oligotraphentes to eutraphentes. **Aut-Het**, indicators of autotrophy-heterotrophy nutrition type: ats, autotrophes-inhabited low-nitric-nitrogen waters; ate, autotrophes-inhabited high-nitric-nitrogen waters; hne, facultative-heterotrophes-inhabited low organically enriched waters; "-", no data.

Taxa	1	2	3	4	5	6	7	8	Hab	T	Oxy	pH	Sal	D	Sap	Index S	Tro	Aut-Het
Cyanobacteria																		
Anabaena contorta Bachmann	0	0	0	0	0	1	0	0	P	-	st-str	-	-	-	-	-	-	-
Anagnostidinema amphibium (C. Agardh ex Gomont) Strunecký, Bohunická, J.R. Johansen and J. Komárek	1	0	0	0	0	0	0	0	P-B, S	-	st-str, H_2S	-	hl	-	a-o	2.6	m	-
Anathece clathrata (West and G.S. West) Komárek, Kastovsky and Jezberová	1	1	1	1	1	1	1	1	P	-	-	-	hl	-	o-a	1.8	me	-
Aphanocapsa holsatica (Lemmermann) G. Cronberg and Komárek	0	0	1	0	0	0	0	0	P	-	-	-	i	-	o-b	1.4	me	-

Table A2. *Cont.*

Taxa	1	2	3	4	5	6	7	8	Hab	T	Oxy	pH	Sal	D	Sap	Index S	Tro	Aut-Het
Cyanobacteria																		
Aphanocapsa incerta (Lemmermann) G. Cronberg and Komárek	0	0	0	0	0	1	1	0	P-B	-	-	-	i	-	b	2.2	me	-
Aphanocapsa planctonica (G.M. Smith) Komárek and Anagnostidis	1	1	1	0	0	1	0	0	P	-	-	-	i	-	-	-	o	-
Chroococcus minimus (Keissler) Lemmermann	1	0	0	0	0	0	0	0	P-B	-	-	-	hl	-	-	-	o-m	-
Chroococcus minutus (Kützing) Nägeli	0	0	0	1	1	0	0	0	P-B	-	-	ind	i	-	o-a	1.8	o-m	-
Merismopedia tenuissima Lemmermann	1	0	0	0	0	0	0	0	P-B	-	-	-	hl	-	b-a	2.4	e	-
Microcystis aeruginosa (Kützing) Kützing	1	1	1	1	1	1	1	1	P	-	-	-	hl	-	b	2.1	e	-
Planktolyngbya contorta (Lemmermann) Anagnostidis and Komárek	0	0	1	0	0	0	0	0	P	-	-	-	-	-	o-a	1.8	me	-
Planktolyngbya limnetica (Lemmermann) Komárková-Legnerová and Cronberg	1	1	0	1	0	0	0	0	P-B, S	-	st-str	-	hl	-	o-b	1.5	e	-
Radiocystis geminata Skuja	1	0	1	0	1	0	1	1	P	-	-	-	-	-	-	-	me	-
Rhabdoderma lineare Schmidle and Lauterborn	0	0	0	0	0	1	1	1	P	-	-	-	-	-	b	2.2	-	-
Snowella atomus Komárek and Hindák	0	0	1	1	1	1	1	1	P	-	-	-	-	-	-	-	me	-
Bacillariophyta																		
Achnanthidium minutissimum (Kützing) Czarnecki	0	0	0	0	0	1	0	0	P-B	eterm	st-str	ind	i	es	x-b	0.95	o-e	ate
Amphora ovalis (Kützing) Kützing	0	0	0	1	0	0	0	0	B	temp	st-str	alf	i	sx	o-b	1.5	me	ate
Aulacoseira granulata (Ehrenberg) Simonsen	1	1	0	1	0	0	0	0	P-B	temp	st-str	ind	i	es	b	2	me	ate
Caloneis bacillum (Grunow) Cleve	0	0	0	1	1	0	0	0	B	temp	st-str	ind	i	es	o	1.3	me	ats
Cyclotella meneghiniana Kützing	0	1	1	0	1	0	1	0	P-B	temp	st	alf	hl	sp	a-o	2.8	e	hne
Cymbella cistula (Ehrenberg) O. Kirchner	0	0	0	0	1	0	0	0	B	-	st-str	alf	i	sx	o	1.2	e	ats
Cymbella helvetica Kützing	0	0	0	0	0	1	0	0	B	-	str	ind	i	-	o-x	0.6	o-m	-
Diatoma vulgaris Bory	0	0	1	0	0	0	0	0	P-B	-	st-str	ind	i	sx	b	2.2	me	ate
Discostella stelligera (Cleve and Grunow) Houk and Klee	1	1	1	1	1	1	1	1	P	-	-	ind	i	-	o-b	1.4	o-m	-
Epithemia adnata (Kützing) Brébisson	0	0	0	0	0	0	0	1	B	temp	st	alb	i	sx	o	1.2	me	ats
Eunotia arcus Ehrenberg	0	0	0	1	0	0	0	0	B	-	st-str	acf	i	-	x-o	0.5	ot	ats
Fragilaria capucina Desmazières	0	1	0	0	0	0	0	0	P-B	-	-	ind	i	es	b-o	1.6	m	-
Fragilaria radians (Kützing) D.M.Williams and Round	1	1	1	1	1	1	1	1	P-B	-	st-str	alf	i	sx	b-o	1.7	o-m	-
Gomphonella olivacea (Hornemann) Rabenhorst	0	1	1	1	1	1	1	1	B	-	st-str	alf	i	es	o-b	1.45	e	ate

Table A2. *Cont.*

Taxa	1	2	3	4	5	6	7	8	Hab	T	Oxy	pH	Sal	D	Sap	Index S	Tro	Aut-Het
Bacillariophyta																		
Gomphonema acuminatum Ehrenberg	1	0	0	0	0	0	0	0	B	-	st	ind	i	es	o-b	1.4	o-m	ats
Eunotia arcus Ehrenberg	0	0	0	1	0	0	0	0	B	-	st-str	acf	i	-	x-o	0.5	ot	ats
Fragilaria capucina Desmazières	0	1	0	0	0	0	0	0	P-B	-	-	ind	i	es	b-o	1.6	m	-
Fragilaria radians (Kützing) D.M. Williams and Round	1	1	1	1	1	1	1	1	P-B	-	st-str	alf	i	sx	b-o	1.7	o-m	-
Gomphonella olivacea (Hornemann) Rabenhorst	0	1	1	1	1	1	1	1	B	-	st-str	alf	i	es	o-b	1.45	e	ate
Gomphonema acuminatum Ehrenberg	1	0	0	0	0	0	0	0	B	-	st	ind	i	es	o-b	1.4	o-m	ats
Gomphonema gracile Ehrenberg	0	1	0	0	0	0	0	0	B	temp	st	alf	i	es	x-b	0.8	m	ats
Gyrosigma strigilis (W. Smith) J.W. Griffin and Henfrey	0	0	1	0	0	0	0	0	B	-	-	-	mh	-	-	-	-	-
Halamphora veneta (Kützing) Levkov	0	0	0	1	0	1	0	0	B	-	st-str	alf	i	es	a-o	2.6	e	ate
Lindavia comta (Kützing) Nakov, Gullory, Julius, Theriot, and Alverson	0	1	0	0	0	1	0	0	P	-	st	alf	i	sx	o	1.2	o-m	-
Melosira varians C.Agardh	1	1	1	1	1	1	1	1	P-B	temp	st-str	ind	hl	es	b	2.1	me	hne
Pauliella taeniata (Grunow) Round and Basson	0	0	0	0	1	0	1	0	B	-	-	alf	mh	-	b	2.0	-	-
Pinnularia viridis (Nitzsch) Ehrenberg	0	0	0	0	0	0	1	0	P-B	temp	st-str	ind	i	es	x	0.3	o-e	ate
Sellaphora pupula (Kützing) Mereschkovsky	0	0	0	0	0	0	0	1	B	eterm	st	ind	hl	sx	o-a	1.9	me	ate
Staurosira leptostauron (Ehrenberg) Kulikovskiy and Genkal	0	0	0	0	0	1	0	0		-	-	-	-	-	-	1.1	-	-
Stephanodiscus hantzschii Grunow	1	0	1	1	1	1	1	1	P	temp	st	alf	i	es	a-o	2.7	o-m	hne
Surirella elegans Ehrenberg	0	1	0	0	0	0	0	0	P-B	-	str	alf	i	-	o	1	me	-
Ulnaria acus (Kützing) Aboal	1	0	0	0	0	1	0	0	P-B	-	st-str	alf	i	es	o-a	1.85	o-m	-
Ulnaria amphirhynchus (Ehrenberg) Compère and Bukhtiyarova	0	1	0	0	0	0	0	0	P-B	-	-	alf	i	es	b	2	o-m	-
Ulnaria capitata (Ehrenberg) Compère	0	0	0	0	0	0	1	0	P-B	-	st-str	alf	i	es	o-b	1.5	e	ats
Euglenozoa																		
Lepocinclis ovum (Ehrenberg) Lemmermann	0	0	0	1	1	0	1	1	P	eterm	st	ind	i	-	b-a	2.4	-	-
Trachelomonas hispida (Perty) F.Stein	0	0	1	0	1	0	0	0	P-B	eterm	st-str	-	i	-	b	2.2	-	-
Miozoa																		
Ceratium hirundinella (O.F. Müller) Dujardin	1	1	1	0	1	1	1	1	P	-	st-str	-	i	-	o	1.3	-	-
Gymnodinium variabile E.C. Herdman	0	0	0	0	0	0	1	0	P	-	-	-	-	-	o-b	1.5	-	-
Naiadinium polonicum (Woloszynska) Carty	0	1	1	1	0	0	0	1	P	-	st	-	-	-	o	1.3	-	-

Table A2. *Cont.*

Taxa	1	2	3	4	5	6	7	8	Hab	T	Oxy	pH	Sal	D	Sap	Index S	Tro	Aut-Het
Miozoa																		
Peridinium bipes F. Stein	0	0	0	0	0	0	0	1	P	-	st-str	-	oh	-	o	1.3	-	-
Peridinium cinctum (O.F. Müller) Ehrenberg	0	0	1	0	0	0	0	0	P-B	-	st-str	-	i	-	b-o	1.6	-	-
Ochrophyta																		
Dinobryon divergens O.E. Imhof	1	1	1	1	1	1	1	1	P	-	st-str	ind	i	-	o-b	1.45	-	-
Chlorophyta																		
Binuclearia lauterbornii (Schmidle) Proschkina-Lavrenko	1	0	0	0	0	0	0	0	-	-	-	-	-	-	o-a	1.8	-	
Chlorella vulgaris Beyerinck [Beijerinck]	1	1	1	0	1	1	1	1	P-B, pb,S	-	-	-	hl	-	a	3.1	-	
Desmodesmus brasiliensis (Bohlin) E.Hegewald	0	0	0	0	1	1	1	1	P-B	-	st-str	-	-	-	b	2	-	
Monoraphidium contortum (Thuret) Komárková-Legnerová	1	0	1	0	0	0	0	0	P-B	-	st-str	-	i	-	b	2.2	-	
Monoraphidium convolutum (Corda) Komárková-Legnerová	0	0	0	0	0	1	0	1	P-B	-	st-str	-	-	-	b	2.3	-	
Monoraphidium minutum (Nägeli) Komárková-Legnerová	0	0	0	0	0	0	0	1	P-B	-	st-str	-	i	-	b-a	2.5	-	
Mucidosphaerium pulchellum (H.C. Wood) C.Bock, Proschold and Krienitz	0	0	0	0	1	0	0	0	P-B	-	st-str	ind	i	-	b	2.3	-	
Myrmecia irregularis (J.B. Petersen) Ettl and Gärtner	1	0	1	0	1	1	1	1	P	-	-	-	oh	-	-	-	-	
Neglectella solitaria (Wittrock) Stenclová and Kastovsky	0	0	1	0	1	0	0	0	P	-	st	ind	i	-	b-o	1.7	-	
Oocystis borgei J.W. Snow	0	1	0	0	0	0	0	0	P-B	-	st-str	ind	i	-	o-a	1.9	-	
Oocystis pusilla Hansgirg	0	0	0	0	0	0	1	1	P	-	-	-	oh	-	o-b	1.4	-	
Pseudodidymocystis planctonica (Korshikov) E.Hegewald and Deason	0	1	0	0	0	1	1	0	-	-	-	-	-	-	o-a	1.8	-	
Scenedesmus quadricauda (Turpin) Brébisson	1	1	0	1	1	1	1	1	P	-	-	ind	i	-	b	2.1	-	
Schroederia setigera (Schröder) Lemmermann	1	0	0	0	0	0	0	0	P	-	st-str	-	i	-	b-o	1.7	-	
Tetradesmus obliquus (Turpin) M.J.Wynne	0	1	1	0	1	0	1	1	P-B, S	-	st	-	i	-	b-a	2.4	-	
Tetraëdron minimum (A. Braun) Hansgirg	1	1	1	1	0	1	1	1	P-B	-	st-str	-	i	-	b	2.1	-	
Tetraëdron minutissimum Korshikov	0	0	1	0	1	0	0	1	P-B	-	st-str	-	i	-	b	2.1	-	
Tetrastrum staurogeniiforme (Schröder) Lemmermann	0	0	0	0	0	1	0	0	P-B	-	st-str	-	i	-	b	2.2	-	
Charophyta																		
Cosmarium baileyi Wolle	1	1	1	1	1	1	1	1	B	-	-	-	-	-	o	1.2	-	-
Cosmarium undulatum Corda ex Ralfs	1	0	0	0	0	0	0	0	P-B	-	-	acf	i	-	-	-	m	-

Table A3. Distribution of species richness in phyla, total species number in community, and ecological properties of bioindicators for sampling stations on Lake Borovoe, 2019. Abbreviations: B, benthic; P-B, plankto-benthic; P, planktonic; temp, inhabitants of temperate-temperature waters; eterm, eurythermic; str, inhabitants of streaming well-oxygenated waters; st-str, inhabitants of standing to streaming middle-oxygenated waters; st, inhabitants of standing low oxygenated waters; H2S, sulfides anoxia indicators; acf, acidophilic; ind, pH-indifferent; alf, alkaliphilic; alb, alkalibiontes; i, chlorides indifferents; hl, halophiles; mh, mesohalobes; sx, saproxenes; es, eurysaprobes; sp, saprophiles; Classes 1–4 of water-quality indicators according to Index S; o, oligotraphentes; o-m, oligo-mesotraphentes; m, mesotraphentes; me, meso-eutraphentes; e, eutraphentes; o-e, oligotraphentes to eutraphentes; ats, autotrophes-inhabited low-nitric-nitrogen waters; ate, autotrophes-inhabited high-nitric-nitrogen waters; hne, facultative-heterotrophes-inhabited low organically enriched waters.

Station	1	2	3	4	5	6	7	8
Species richness in phyla								
Bacillariophyta	7	11	8	10	9	11	9	7
Chlorophyta	7	6	7	2	8	8	8	10
Charophyta	2	1	1	1	1	1	1	1
Cyanobacteria	8	4	7	5	5	7	6	5
Euglenozoa	0	0	1	1	2	0	1	1
Miozoa	1	2	3	1	1	1	2	3
Ochrophyta	1	1	1	1	1	1	1	1
Total Species number	26	25	28	21	27	29	28	28
Substrate								
B	2	3	3	6	5	4	3	4
P-B	12	12	9	6	10	9	10	9
P	11	9	14	9	12	13	14	15
Temperature								
temp	3	4	3	5	4	2	4	3
eterm	0	0	1	1	2	1	1	2
Water moving and oxygenation								
str	0	1	0	0	0	1	0	0
st-str	10	9	11	11	11	13	9	11
st	2	5	5	3	5	2	4	6
H_2S	1	0	0	0	0	0	0	0
pH								
acf	1	0	0	1	0	0	0	0
ind	6	7	5	8	9	6	6	6
alf	3	7	4	5	6	6	6	3
alb	0	0	0	0	0	0	0	1
Salinity								
i	15	16	17	14	17	17	15	16
hl	8	6	5	4	5	4	5	5
mh	0	0	1	0	1	0	1	0
Watanabe								
sx	1	2	2	2	2	2	1	3
es	5	6	3	6	4	6	5	3
sp	0	1	1	0	1	0	1	0
Class of water quality based on species-specific index saprobity S								
Class 1	0	0	0	1	0	0	1	0
Class 2	6	10	7	8	7	9	8	9
Class 3	12	12	13	9	14	13	13	14
Class 4	3	2	2	3	3	3	3	2

Table A3. *Cont.*

Station	1	2	3	4	5	6	7	8
Trophic state								
o	1	1	1	1	0	1	0	0
o-m	6	4	3	4	4	6	3	3
m	2	2	0	0	0	0	0	0
me	4	4	7	6	5	4	5	6
e	3	4	3	4	4	3	4	2
o-e	0	0	0	0	0	1	1	0
Autotrophy–heterotrophy								
ats	1	1	0	2	2	0	1	1
ate	1	2	2	4	1	3	2	2
hne	2	2	3	2	3	2	3	2

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