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ORIGINAL ARTICLE

Phytoplankton dynamic and bioindication in the Kondopoga Bay, Lake Onego (Northern Russia)

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ABSTRACT

*On the basis of our collected material and historical information we assess phytoplankton dynamics in Kondopoga Bay, the Lake Onego in 1993-2011. The summer communities from continuously studied sampling stations contain 100 species belonging to eight divisions: Bacillariophyta, 40; Chlorophyta, 25; Cyanobacteria, 13; Chrysophyta, 12; Euglenophyta, 2; Dinophyta, 4; Cryptophyta, 3; and Xanthophyta, 1. Sample richness varied between 16 and 54 species, with a negative overall trend during the study period, but increases in Cyanobacteria and Dinophyta. Bioindication analysis shows that water acidification slowly rising from 1993 to 2011 with organic pollution (Index saprobity S) and the number of species with heterotrophic ability. In 1990s, the total abundance and biomass were on average 1.5 times higher than in 2000-2011, having similar fluctuation ranges (Pearson 0.74), with peaks in 1996 and 2006. At the same time, species richness decreased, showing a depletion of algal communities. Two critically impacted periods are revealed with the Shannon index in 1996 and 2007 and on the basis of the Aquatic Ecosystem State Index (WESI) calculation in 1995 and 2007, related to Kondopoga industrial wastewater influx enriched in nutrients and other contaminants. As a whole, the WESI was extremely high, reflecting a high self-purification capacity in respect to phosphate concentration in the bay. The canonical corresponded analysis (CCA) shows two different sets of taxa, those stimulated by temperature and nitric nitrogen (*Anabaena scheremetievii *Elenkin,* Dolichospermum lemmermannii *(Ricter) P. Wacklin, L. Hoffmann & J. Komárek, and* Aulacoseira alpigena *(Grunow) Krammer), and sensitive autotroph species inhabiting cool to temperate clear waters (*Aulacoseira distans *(Ehrenberg) Simonsen,* Ankistrodesmus fusiformis *Corda ex Korshikov,* Mucidosphaerium pulchellum *(H.C. Wood) C. Bock, Proschold & Krienitz). The comparative statistics with GRAPS program revealed two cores of species richness in years 1996 and 2011 that included most of species. The long-term dynamics of relative cell volume shows that phytoplankton communities were enriched with small-celled species, such as Cyanobacteria (*Microcystis aeruginosa *(Kützing) Kützing) and Cryptophyta (*Cryptomonas *sp. and* Katablepharis ovalis *Skuja) in the period between 1998 and 2006. Pearson correlation for Shannon index and relative cell biovolume is negative (-0.79), showing high stability of species rich communities under environmental impacts. Two periods of dinoflagellate blooms (1998, 2007) followed the peaks of total abundance and biomass (1996, 2006). Such correlation makes the Kondopoga Bay ecosystem comparable to those of large lakes in spite of a heavier anthropogenic impact from Kondopoga pulp and paper mill wastewater.*

Key words: phytoplankton, great lake, ecosystem, diversity, productivity, temporal dynamic.

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INTRODUCTION

The main characteristics of the North European region include the low range of altitudes and sharp seasonality of climate. The latitudinal distribution plays a major role in patterning plant species richness. Ecosystems of the large lakes in the region absorb the regional air and surface water pollution as well as enhancing the regional self-purification processes. Therefore, it is important to study the biotic responses to the long-term dynamics of environmental variables in the great northern lakes. Phytoplankton diversity of the Lake Ladoga (Petrova, 1968; Genkal and Trifonova, 2009; Petrova *et al*., 2010), the largest lake in the region, has received more attention in regional studies; the Lake Onego, next in the water area, is less studied though having a long history of research (Petrova, 1971, 1975, 1990; Visljanskaya, 1990, 1999; Chekryzheva, 2008a, 2008b, 2012a, 2012b).

The Lake Ladoga rates as mesotrophic, whereas the Lake Onego is oligotrophic; correspondingly, its ecosystem is more sensitive to environmental impact. At this stage, we focused on phytoplankton diversity responses to environmental impacts in the most polluted Kondopoga Bay of the Lake Onego ecosystem that was formed under strong climatic as well as various anthropogenic impacts. In the process of natural eutrophication of the lake ecosystem structural adjustments and functional characteristics of phytoplankton are regulated mainly by two factors: temperature and nutrient concentration. Anthropogenic eutrophication of deep lakes like the Lake Onego affects nutrient concentration in the first place; the thermal

regime remains essentially unchanged, except on account of seasonal fluctuations regulating algal growth in respect to the level of nutrient supply (Petrova, 1990). The fluctuations of the phytoplankton biomass show seasonal peaks in spring, autumn, and summer, associated with the main feature of the large lakes: the complexity of their thermal structure.

In order to reveal the long-term tendencies of the lake ecosystem development, we selected the summer season samples representing the most prominent peak of plankton biomass (Bilous *et al*., 2013) of the most anthropogenically impacted Kondopoga Bay. While the phytoplankton study of the Lake Onego has long story, the data on Kondopoga Bay have been never published. The aim of current research was ecological analysis of algal species preferences with help of bioindication and statistics during last twenty years. Methods used to reveal environmental impacts with the help of ecological indicators are the community structure fluctuation analysis, bio-indication of major impacting factors, calculations of integral density-diversity indices, and statistical approaches, linking structural and functional aspects of lacustrine communities with environmental fluctuations (Heywood, 2004).

METHODS

Study area

The Lake Onego is one of the largest and most northerly dimictic lakes in the world with the climatic defined thermal radiation mode and low biological productivity. The lake has an average depth of 30 m (maximum 120 m), volume of water weight 291 km^3, and the major water turnover period about 13.6 years. The lake water has a low mineral content (39-46 mg L^{-1}) and a low concentration of nutrients, the transparency of 4-5 m, and euphotic zone about 9-12 m. The water quality is high, and its trophic status is oligotrophic, with phosphate load 0.10 g m^2 per year (Filatov, 2010; Sabylina *et al*., 2012).

The Kondopoga Bay is located in the northwestern part of the Lake Onego in Northern Russia (Fig. 1), about 62° 10' N, 34° 18' E. This area has a lowland landscape and represents a part of the large lake which is elevated by 33 m above sea level (asl). Soils are composed of sands, silt, peat, and pebble, overgrown with lichens and lichen-moss communities, which are replaced in the coastal area of the lake by sedges and grasses. Mean annual temperature measured by thermometer in parallel with sampling in August is less than 16°C (Sabylina, 1999). For 6-6.5 months, from December to May, the lake is covered with ice. In spring (May-June) and autumn (October) a thermocline is formed with an epilimnion thickness about 20 m (Kukharev and Lukin, 2008; Filatov, 2010). The studied part of the lake is mostly of thermokarst origin; the lake surface is about 223 km^2, mean depth 10-50 m and 110 m in the deepest part, fairly insulated from the main body of Lake Onego. It is periodically diluted by smelt waters during spring and autumn seasons. Sediments of the lake are diverse, varying from sand and gravel to peat. Water is slightly yellow or colorless with pH 6.5-7.5, and total dissolved solids about 39-46 mg L^{-1}. Aquatic macrophyte vegetation is developed along the shore line for over 1.26 km^2 (up to 2% of littoral zone).

The water chemistry of the bay is governed by the inflow of the Suna River, as well as the industrial and municipal wastewater. For a long time, since 1929, the bay has been under the impact from the Kondopoga's pulp and paper mill wastewater and air pollution (Sabylina *et al*., 2012). Even with remediation of the bay waters, it is still subject to pollution and eutrophication impacts (Timakova *et al*., 2011; Sabylina *et al*., 2012). The bay is narrow, and an intermittent circulation of water masses due to wind currents, especially in the summer, provides for removal of sporadic pollution substances from the Kondopoga Bay to the pelagic area of the lake (Boyarinov and Rudnev, 1990). Water flow stirred by winds promotes removal of waste water (with north-west winds), or their

Fig. 1. Location of the studied site in the Kondopoga Bay of the Lake Onego with sampling points as white (sporadically) and black (continuously) triangles. Black rectangles are sampling stations with continuous monitoring during 1993-2011.

blocking (with south-east winds). Thus, with blocking of sewage in the apical part of the bay, as well as in calm weather, the concentration of certain chemicals in the narrow north-western part of the bay is higher than in the middle and the widest south-eastern parts of it (Sabylina and Ryzhakov, 2007).

Sampling and laboratory studies

We used the previously collected material (1999, 2005-2008, 2011) and historical data provided by the Northern Water Problems Institute, Karelian Research Centre, Russian Academy of Science (1993-1998) on abundance and biomass of summer phytoplankton of the Kondopoga bay from three major sampling stations (black triangles) with continuous monitoring (Fig. 1). Water samples for chemistry and phytoplankton analyses (1 L) were collected in parallel with sampling from the same stations (Fig. 1) in the epilimnion, 0.5 m below the water surface of the pelagic zone in July-August, 1993-2011. Samples were taken with a bathometer, filtered with membrane filters of 0.95-1.02 μm and fixed with 3% lugol-formaldehyde fixator solution. Species definition and counting were performed in the Nageotte chamber of 0.02 mL. The biovolume of each species was calculated on the basis of the geometric cell volumes (Morduhay-Boltovskiy, 1975; Fedorov, 1979). Nutrients concentration data (Pmin, Ptot, N-NH_4, N-NO_2, N-NO_3, Norg, Ntot, Si, Fetot), were taken from the database of The Laboratory of Hydrochemistry and Hydrobiology of Northern Water Problems Institute (Sabylina, 1999; Sabylina and Ryzhakov, 2007; Sabylina *et al*., 2010). For taxonomic identification, a series of monographic studies have been used (Zabelina *et al*., 1951; Hollerbach *et al*., 1953; Kiselev, 1954; Matvienko, 1954; Popova, 1955; Dedusenko-Schegoleva *et al*., 1959; Dedusenko-Schegoleva and Hollerbach, 1962; Palamar-Mordvintseva, 1982; Korshikov, 1953; Kosinskaya, 1960; Matviyenko and Litvinenko, 1977; Starmach, 1985; Komárek and Anagnostidis, 1986; Anagnostidis and Komárek, 1988; Krammer and Lange-Bertalot, 1986, 1988, 1991a, 1991b).

Bio-indication and indices calculation

Our ecological analysis has revealed a grouping of freshwater algae indicators in respect to pH, salinity and saprobity and the other habitat conditions (Barinova *et al*., 2006). Each group was separately assessed for its bio-indication significance. The species that predictably responded to environmental variables can be used as bio-indicators of the aquatic ecosystem's response to eutrophication, pH levels (acidifications), salinity, and organic pollutants. Saprobic Index (S) was calculated after Sládeček (1973, 1986) for the algal community on the basis of the species-specific saprobity level (Barinova *et al*., 2006) and the relative abundance of each species in the community as:

$$S = \sum_{i=1}^{n}(s_i.a_i) \Big/ \sum_{i=1}^{n}(a_i) \qquad \text{(eq. 1)}$$

where: S is the Saprobity Index of algal community; s_i is the species-specific saprobity index; a_i is the species abundance.

The Saprobic Index S indicates the saprobic zone and has been adapted for classes of water quality based on the ecological classification widely used in European and Asian countries (Barinova *et al*., 2006; Romanenko *et al*., 1990; Whitton *et al*., 1991; European Commission, 2000).

The calculated integral index of aquatic ecosystem sustainability (Aquatic Ecosystem State Index, WESI) is based on the water-quality classes (Barinova *et al*., 2006, 2010a,b; Barinova, 2011; Barinova and Krassilov, 2012; Barinova and Sivaci, 2013) reflecting self-purification capacities for each of the sampling stations. If WESI is equal to or larger than 1, the photosynthetic level is positively correlated with the level of nitrate concentration. The WESI is less than 1 attests to photosynthesis being suppressed, presumably owing to a toxic, light intensity or other disturbance (Barinova, 2011; Barinova *et al*., 2006, 2010b; Saks *et al*., 1976).

For environmental variables, we applied the 5-Class System adapted to water-quality evaluation based on more than 30 parameters (Sladecek, 1973; Barinova *et al*., 2006).

The Shannon's diversity index (Odum, 1969) was calculated as:

$$\bar{H} = -\sum_{i=1}^{s}\frac{n_i}{N}\log_2\frac{n_i}{N} \qquad \text{(eq. 2)}$$

where: N is the total cells (individuals) number, l; s is the species number; n_i is the individuals number of every species; $\bar{H}$ is the Shannon diversity index. The mean phytoplankton community cell size was estimated from the ratio between total biovolume and total abundance (according to Pugnetti *et al*., 2004). Statistical methods of comparative floristic analysis (Novakovsky, 2004) were used for calculating similarity of algal communities in the sampling stations.

Statistical analysis

Structural diversity was calculated using statistical methods recommended by Heywood (2004) for floristic and taxonomic studies. At the same time, the statistical significance of variables was assessed using Pearson correlation method. Statistical analysis of relationships between species diversity of algal communities and their environmental variables were studied by canonical correspondence analysis (CCA) with CANOCO for Windows 4.5 package (Ter Braak and Šmilauer, 2002).

Statistical significance of each variable was assessed using the Monte Carlo unrestricted permutation test involving 999 permutations (Ter Braak, 1990). Variables of greatest correlation values have been included in analysis. For CCA analysis we choose species with abundance values from 4% to 25% (maximal).

RESULTS

Species richness and bio-indication

In the bathometric phytoplankton of the Kondopoga Bay of Lake Onego in the summer period, there are 100 taxa below the rank of genus, belonging to eight divisions: Bacillariophyta, 40; Chlorophyta, 25; Cyanobacteria, 13; Chrysophyta, 12; Euglenophyta, 2; Dinophyta, 4; Cryptophyta, 3; and Xanthophyta, 1 (Tab. 1). With large for oligotrophic lakes species richness, phytoplankton was dominated by diatoms in all seasons of the year. The most abundant of them are the cool temperate species of spring and autumn communities (*Aulacoseira islandica*, *A. italica* var. *italica*, and *A. alpigena)*, as well as the summer temperate species (*Tabellaria fenestrata*, *Asterionella formosa*, and *Fragilaria crotonensis*).

Species richness in the summer planktonic communities varied between 54 in 1993 and 16 in 2007 and had a negative linear trend (R^2=0.69) during the study period, with increases in Cyanobacteria and flagellate species, such as dinophytes (Tab. 1; Figs. 2a; 3b). Bio-indication analysis on the basis of the species list (Tab. 1) suggests that water acidification is slowly increasing during the study period with removal of alkalibiontes from the communities (Fig. 2b). Organic pollution slightly increased with winnowing of saproxenes (Fig. 2c) and the rise of diatom species with ability to heterotrophic type of nutrition in unfavorable environment (Saks *et al*., 1976) such as *Nitzschia acicularis*

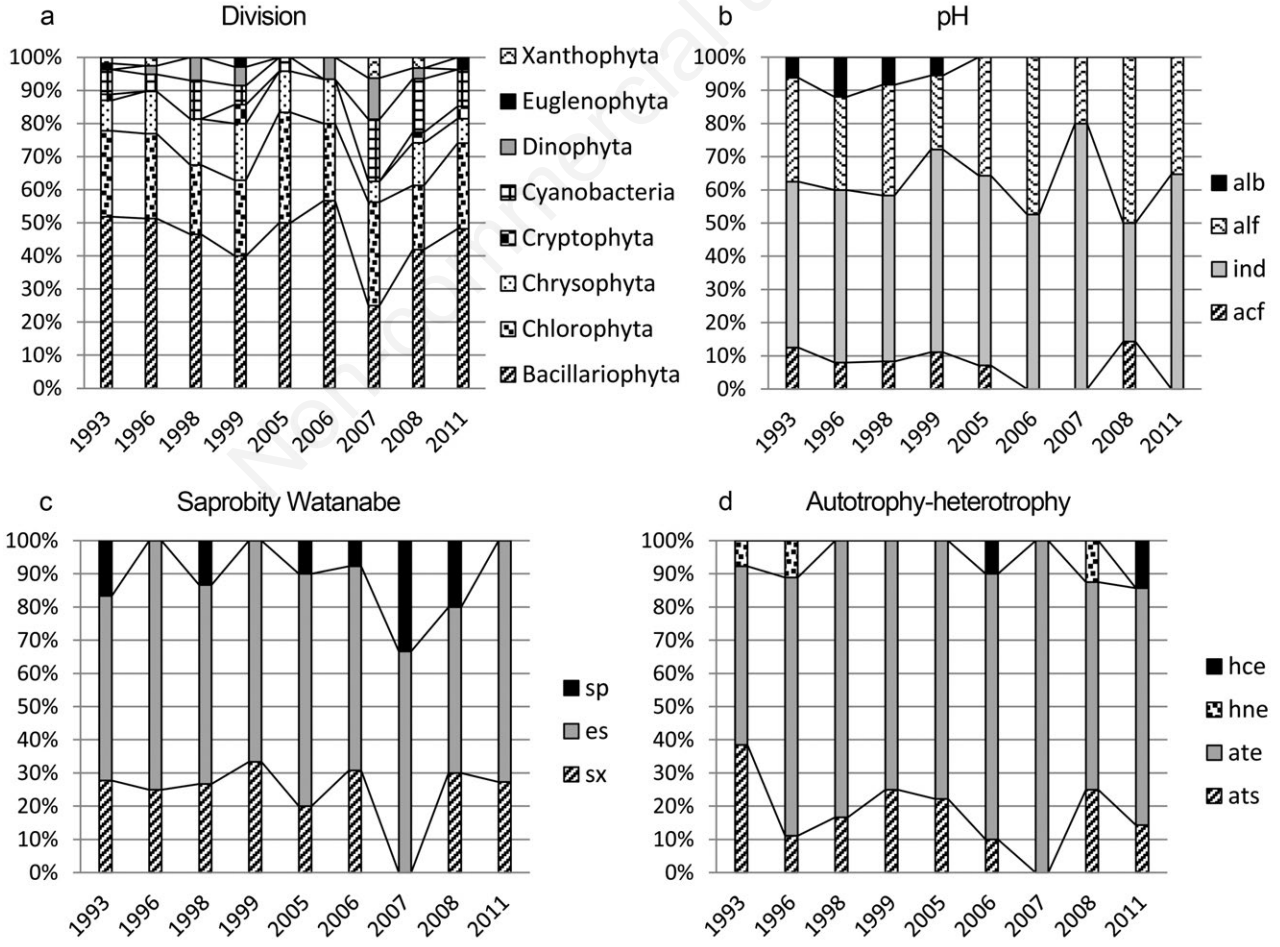

Fig. 2. Dynamics (1993-2011) of phytoplankton divisional species richness (a), bio-indication of pH (b), organic pollution (c), and nutrition type (d) in the Kondopoga Bay of the Lake Onego. Abbreviation of ecological groups are given in Tab. 1.

and *Cyclotella meneghiniana* (Van Dam *et al*., 1994) in the last year's communities (Fig. 2d).

Chemical and phytoplankton variables

Chemical variables concentrations, in particular the phosphates (Pmin) in the bay water (Tab. 2) are increased during the study period and correspond to transition from oligotrophic (0 to 7.6 mkg P L^{-1}) to a mesotrophic (18.7 mkg P L^{-1}) state of the lake ecosystem (Carlson and Simpson, 1996). Tab. 2 shows increasing in water temperature during study period. It can be seen that in 2005-2011 the water temperature in the bay was on average (17.1°C) higher than the long-term averages (16.8°C), and also, on average, higher than in the 1990s (16.3°C). As can be seen in Tab. 3, mean value of abundance and biomass were rather low, fluctuating between 177-5858 cells per liter in 2007 and 2006, respectively, and 0.336-5.872 mg L^{-1} in 2011 and 1996, respectively, which correspond to oligotrophic state of the Kondopoga Bay. The major productive elements as phosphates and nitrates were not so high in the studied site and corresponded to the of water quality Class I-II according to Sládeček's, (1973) classification (Barinova *et al*., 2006). Fig. 3 shows that diatoms were most abundant in the bay communities over the studied period with fluctuation of their abundance and biomass. Only in 1998 and 2007 this group contained less than 50% of total cell numbers. During 1996-2005 and 2008-2011, the planktonic communities were enriched by abundant Chlorophyta, with a peak of abundance in 2005. The planktonic Cyanobacteria species actively developed with the rises of cell abundance in 1993, 1998, and 2007, whereas the Dinophyta bloomed in summer period of 1998. The tendency of ecosystem diversity fluctuation shows an increase of phytoplankton abundance and biomass in 2004 to 2011, approaching the the values for 1993, the starting year of our analysis. In the biomass fluctuation we can see that diatoms also represent more than 50% of the total, excluding 1998 and 2007. Two periods can be revealed: 1998-2006 and 2007-2011 in which communities were dominated by dinoflagellates and green algae, resulting in the reduction of diatoms.

Total abundance and biomass fluctuated (Fig. 4a) with similar tendencies over the studied period showing peaks in 1996 and 2006. Pearson correlation index is 0.74 with P value of 0.006. Species richness decreased during the studied period from 54 to 21 species with a minimum of 16 species in 2007 (Fig. 4b), a considerable depletion of algal communities. But structural parameters such as the Shannon index show only a periodical impact on phytoplankton community, with lower values in 1996 and 2007 coinciding with the peaks of cell abundance values. Species richness and Shannon index show conformable fluctuation in 1993-1998 and 2006-2011, but opposite sign fluctuations in 1999-2005. Both assessments revealed two years in which the Kondopoga Bay phytoplankton communities were impacted with the input of wastewater rich in nutrients and other contaminants that came from the Kondopoga industry works.

Indices calculation

The Aquatic Ecosystem State Index WESI calculated on the basis of the Saprobity index S and concentration of major productive variables, nitrates and phosphates (Fig. 5) shows high amplitude fluctuation during the study

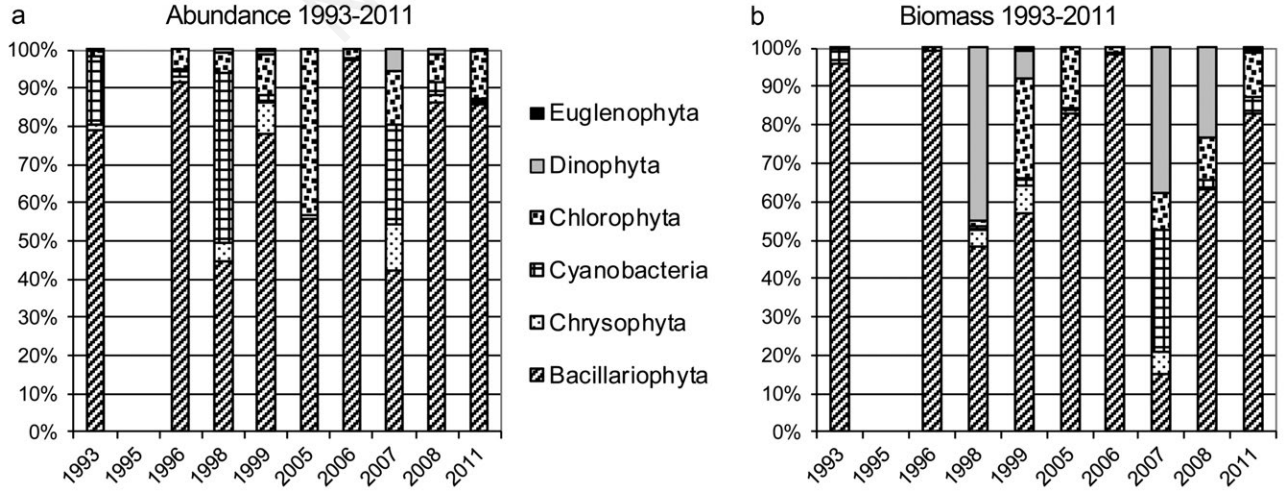

Fig. 3. Dynamics (1993-2011) of phytoplankton abundance and biomass over taxonomic Divisions in the Kondopoga Bay of the Lake Onego.

Tab. 1. Diversity and ecological preferences (Barinova *et al.*, 2006) of phytoplankton species in summer communities of the Kondopoga Bay of the Onego Lake in 1993-2011.

No	Species	Code	1993	1996	1998	1999	2005	2006	2007	2008	2011	Hab	T	Reo	D	S	Hal	pH	Aut-Het	Tro
	Cyanobacteria																			
1	*Anabaena scheremetievii* Elenkin	ANASCH	0	0	0	0	0	0	1	1	0	P	-	-	-	-	i	-	-	-
2	*Aphanizomenon flos-aquae* Ralfs ex Bornet & Flahault	APHFLA	0	0	0	1	0	0	0	1	1	P	-	-	-	b	hl	-	-	-
3	*Chroococcus dispersus* (Keissler) Lemmermann	CHRDIS	1	0	0	0	0	0	0	0	1	P	-	st	-	b-o	-	-	-	-
4	*Coelosphaerium kuetzingianum* Nägeli	COEKUT	1	1	1	0	0	0	0	0	0	P	-	-	-	b-o	i	-	-	-
5	*Dolichospermum lemmermannii* (Ricter) P. Wacklin, L. Hoffmann & J. Komárek	DOLLE	0	0	0	1	1	0	1	1	1	P	-	-	-	b	i	-	-	-
6	*Limnothrix planctonica* (Woloszynska) Meffert	LIMPLA	0	1	1	0	0	0	0	0	0	P	-	-	-	o-b	i	-	-	-
7	*Merismopedia tenuissima* Lemmermann	MERTEN	0	0	0	0	0	0	0	1	0	P-B	-	-	-	b-a	hl	-	-	-
8	*Microcystis aeruginosa* (Kützing) Kützing	MICAER	0	0	1	0	0	0	0	0	0	P	-	-	-	o-a	hl	-	-	-
9	*Oscillatoria tenuis* C. Agardh ex Gomont	OSCTEN	1	0	0	0	0	0	0	0	0	P-B	-	st-str	-	b-a	hl	-	-	-
10	*Planktolyngbya limnetica* (Lemmermann) J. Komárková-Legnerová & G. Cronberg	PLALIM	1	0	0	0	0	0	0	0	0	P-B	-	st-str	-	o-b	hl	-	-	-
11	*Planktothrix agardhii* (Gomont) Anagnostidis & Komárek	PLAAGA	0	0	1	0	0	0	1	1	0	P-B	-	st	-	b-o	hl	-	-	-
12	*Pseudanabaena endophytica* (Elenkin & Hollerbach) Anagnostidis	PSEEND	0	0	1	0	0	0	0	0	0	Ep	-	-	-	-	i	-	-	-
13	*Woronichinia naegeliana* (Unger) Elenkin	WORNA	0	0	0	0	0	0	0	0	0	P	-	st	-	o-b	-	-	-	-
	Bacillariophyta																			
14	*Amphora ovalis* var. *gracilis* (Ehrenberg) van Heurck	AMPOL	0	0	1	0	0	0	0	0	0	B	-	-	sx	a-b	i	alf	-	-
15	*Asterionella formosa* Hassall var. *formosa*	ASTFOR	1	1	1	1	1	1	0	1	1	P	-	st-str	sx	o	i	alf	ate	me
16	*Asterionella formosa* var. *gracillima* (Hanztsch) Grunow	ASTFOG	1	1	1	1	0	0	0	1	0	P	-	-	es	x	i	acf	-	-
17	*Aulacoseira alpigena* (Grunow) Krammer	AULALP	1	0	1	0	0	1	1	0	0	P-B	cool	-	sp	-	i	alf	-	-
18	*Aulacoseira ambigua* (Grunow) Simonsen	AULAM	1	0	0	0	0	0	0	0	0	P	-	st-str	sp	a-b	i	alf	ate	e
19	*Aulacoseira distans* (Ehrenberg) Simonsen	AULDIS	1	0	0	0	1	0	0	1	0	P-B	cool	str	sp	x-o	i	acf	ats	ot
20	*Aulacoseira islandica* (O.Müller) Simonsen	AULISL	1	1	1	1	1	1	0	1	1	P	cool	st-str	es	o-x	i	neu	ate	o-e
21	*Aulacoseira italica* (Ehrenberg) Simonsen var. *italica*	AULITA	1	1	1	1	1	1	1	1	1	P-B	cool	st-str	es	o-a	i	neu	ate	me
22	*Aulacoseira italica* var. *tenuissima* (Grunow) Simonsen	AULITT	1	1	1	1	1	1	1	0	0	P	cool	st-str	es	b	i	neu	ate	me
23	*Cocconeis pediculus* Ehrenberg	COCPED	0	0	0	1	0	0	0	1	0	B	-	st-str	sx	o-a	i	alf	ate	e
24	*Cyclotella comta* (Ehrenberg) Kützing var. *comta*	CYCCO	1	1	1	1	1	1	0	1	1	P	-	st	sx	b-o	i	alf	-	-
25	*Cyclotella comta* var. *oligactis* (Ehrenberg) Grunow	CYCOO	1	1	1	0	0	1	0	1	0	P	-	-	-	-	i	alf	-	-

To be continued on next page

Tab. 1. Continued from previous page.

No	Species	Code	1993	1996	1998	1999	2005	2006	2007	2008	2011	Hab	T	Reo	D	S	Hal	pH	Aut-Het	Tro
26	*Cyclotella meneghiniana* Kützing	CYCME	0	0	0	0	0	0	0	1	0	P-B	temp	st	sp	o-a	hl	alf	hne	e
27	*Cyclotella operculata* (C. Agardh) Brébisson	CYCOPE	1	0	0	0	0	0	0	0	0	P	-	st	-	o	i	ind	-	-
28	*Cyclotella planctonica* Brunnthaler	CYCPLA	0	1	1	1	1	1	1	1	1	P	-	-	-	-	i	ind	-	-
29	*Cyclotella schroeteri* Lemmermann	CYCSCH	1	0	1	0	0	0	0	0	0	P	-	-	-	b-a	i	ind	-	-
30	*Diatoma elongata* (Lyngbye) C. Agardh	DIAELO	1	1	1	1	0	1	0	0	1	P-B	-	-	sx	o-b	hl	ind	-	-
31	*Diatoma vulgaris* Bory de Saint-Vincent	DIAVUL	1	1	0	0	0	1	0	0	0	P-B	-	st-str	sx	b-a	i	ind	ate	me
32	*Discostella stelligera* (Cleve & Grunow) Houk & Klee	DISSTE	1	1	0	1	0	1	0	0	1	P-B	-	st	es	x	i	ind	-	-
33	*Eunotia bilunaris* (Ehrenberg) Schaarschmidt	EUBBIL	1	0	0	0	0	0	0	0	0	B	-	st	-	o	hb	acf	-	-
34	*Eunotia sibirica* Ehrenberg	EUNSIB	1	0	0	0	0	0	0	0	0	B	-	-	-	-	i	-	-	-
35	*Fragilaria bidens* Heiberg	FRABID	1	0	0	0	0	0	0	0	0	P-B	-	str	-	b	i	alf	ats	e
36	*Fragilaria capucina* Desmazières	FRACAP	0	0	1	0	1	0	0	0	1	B	-	-	es	o	i	neu	-	m
37	*Fragilaria capucina* subsp. *rumpens* (Kützing) Lange-Bertalot	FRACAR	0	0	1	0	0	0	0	0	0	B	-	-	es	o	i	alf	-	-
38	*Fragilaria crotonensis* Kitton	FRACRO	1	1	1	0	1	1	0	1	1	P	-	st	es	a-b	hl	alf	ate	m
39	*Fragilaria radians* (Kützing) D.M. Williams & Round	FRARAD	1	0	0	0	0	0	0	0	0	B	-	-	sx	o	i	alf	-	-
40	*Fragilaria tenera* (W. Smith) Lange-Bertalot	FRATEN	1	1	0	0	0	0	0	0	0	B	-	-	-	o	i	-	-	-
41	*Navicula rhynchocephala* Kützing	NAVRH	0	0	0	0	1	0	0	0	0	B	-	-	-	b	hl	alf	ate	o-e
42	*Nitzschia acicularis* (Kützing) W. Smith	NITACI	0	0	0	0	0	1	0	0	1	P-B	temp	-	es	o-b	i	alf	hce	e
43	*Nitzschia sigmoidea* (Nitzsch) W. Smith	NITSIG	0	0	0	0	0	1	0	0	0	P-B	-	st-str	-	o	i	alf	ate	e
44	*Puncticulata bodanica* (Eulenstein ex Grunow) H. Håkansson	PUNBOD	1	0	0	0	0	0	0	0	0	P	-	st	-	x	i	ind	ats	ot
45	*Rhizosolenia longiseta* O. Zacharias	RHILON	1	0	1	1	0	0	0	0	0	P	-	str	-	x-o	i	acf	ats	me
46	*Stephanodiscus astraea* (Ehrenberg) Grunow	STEAST	1	1	0	0	0	0	0	0	0	P	temp	st	es	b	i	alb	-	-
47	*Stephanodiscus hantzschii* Grunow	STEHAN	1	1	0	0	0	0	0	0	0	P	temp	st	es	a-b	i	alf	hne	he
48	*Stephanodiscus minutulus* (Kützing) Cleve & Möller	STEMIN	1	1	1	0	0	0	0	0	0	P	temp	-	es	o	i	alb	-	-
49	*Synedra acus* Kützing	SYNACU	0	1	1	1	0	0	0	0	0	P	-	st-str	es	b	i	alb	-	-
50	*Synedra berolinensis* Lemmermann	SYNBER	0	0	1	0	0	0	0	0	0	P	-	-	sp	o-a	i	ind	-	-
51	*Tabellaria fenestrata* (Lyngbye) Kützing	TAFEN	1	1	0	1	1	1	0	1	1	P-B	-	st-str	es	x	hb	neu	ats	o-m
52	*Tabellaria flocculosa* (Roth) Kützing	TAFLO	1	1	1	0	0	1	0	1	1	P-B	-	-	-	o-a	hb	alf	-	-
53	*Ulnaria ulna* (Nitzsch) P. Compère	ULNULN	0	1	0	1	1	1	0	0	1	P-B	temp	st-str	es	b-o	i	alf	ate	o-e
	Chrysophyta																			
54	*Chrysococcus cordiformis* Naumann	CHRCOR	0	0	0	1	1	0	0	1	0	-	-	-	-	o-b	-	-	-	-
55	*Chrysococcus rufescens* Klebs	CHRRUF	0	0	0	0	1	1	0	1	1	P	-	-	-	o-b	hb	-	-	-
56	*Dinobryon bavaricum* Imhof	DINBAV	1	1	1	1	0	1	0	0	0	P	-	-	-	o	i	-	-	-

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Tab. 1. Continued from previous page.

No	Species	Code	1993	1996	1998	1999	2005	2006	2007	2008	2011	Hab	T	Reo	D	S	Hal	pH	Aut-Het	Tro
57	*Dinobryon cylindricum* O.E. Imhof	DINCYL	1	0	1	1	0	0	0	0	0	P	-	-	-	o-b	i	-	-	-
58	*Dinobryon divergens* O.E. Imhof	DINDIV	1	1	1	1	0	1	0	0	1	P	-	st-str	-	o-a	i	ind	-	-
59	*Dinobryon sertularia* Ehrenberg	DINSER	1	1	0	0	0	0	0	0	0	P	-	-	-	o-a	i	-	-	-
60	*Dinobryon sociale* (Ehrenberg) Ehrenberg	DINSOC	1	0	1	0	0	0	0	0	0	P	-	-	-	b	i	-	-	-
61	*Kephyrion cupuliforme* Conrad	KEPCUP	0	0	0	0	0	1	0	1	0	-	-	-	-	-	-	-	-	-
62	*Mallomonas akrokomos* Ruttner	MALAK	0	0	1	1	1	0	0	1	0	P	-	-	-	o	i	-	-	-
63	*Mallomonas caudata* Iwanoff	MALCA	0	0	0	1	0	0	0	0	0	P	-	-	-	o	i	-	-	-
64	*Mallomonas coronata* Bolochonzew	MALCO	0	1	1	0	0	0	0	0	0	P	-	-	-	-	i	-	-	-
65	*Stenokalyx inconstans* Schmidle	STEINC	0	1	0	0	0	0	0	0	0	-	-	-	-	-	-	-	-	-
	Xanthophyta																			
66	*Tribonema affine* (Kützing) G.S. West	TRIAFF	1	1	0	0	0	0	1	1	0	B	-	-	-	-	hb	-	-	-
	Euglenophyta																			
67	*Lepocinclis acus* (O.F. Müller) Marin & Melkonian in Marin *et al.*	LEPACU	0	0	0	1	0	0	0	0	0	P	eterm	st	-	b	i	ind	-	-
68	*Trachelomonas volvocina* (Ehrenberg) Ehrenberg	TRAVOL	1	0	0	0	0	0	0	0	1	B	eterm	st-str	-	b	i	ind	-	-
	Cryptophyta																			
69	*Cryptomonas ovata* Ehrenberg	CRYOV	1	0	0	0	0	0	0	0	0	P	-	st-str	-	b-a	hl	-	-	-
70	*Cryptomonas* sp.	CRYPTO	0	0	0	1	0	0	1	1	1	-	-	-	-	-	-	-	-	-
71	*Katablepharis ovalis* Skuja	KATOV	0	0	0	1	0	0	0	0	0	-	-	-	-	a	-	-	-	-
	Dinophyta																			
72	*Ceratium hirundinella* (O.F. Müller) Dujardin	CERHIR	0	0	1	1	0	0	1	1	0	P	-	st-str	-	o	i	-	-	-
73	*Gymnodinium* sp.	GYMNO	0	0	1	1	0	0	0	0	0	-	-	-	-	-	-	-	-	-
74	*Peridiniopsis thompsonii* (Thompson) Bourrelly	PERTHO	0	0	0	0	0	1	1	0	0	P	-	-	-	-	-	-	-	-
75	*Peridinium aciculiferum* Lemmermann	PERACI	0	1	1	0	0	1	0	0	0	-	-	-	-	o-b	-	-	-	-
	Chlorophyta																			
76	*Actinastrum hantzschii* Lagerheim	ACTHA	1	0	0	1	0	0	0	0	0	P-B	-	st-str	-	b	i	-	-	-
77	*Ankistrodesmus fusiformis* Corda ex Korshikov	ANKFUS	0	0	0	0	1	0	0	0	0	P-B	-	st-str	-	b-o	i	-	-	-
78	*Chlorophyta* spp.	CHLORO	0	0	0	0	0	1	1	0	0	-	-	-	-	-	-	-	-	-
79	*Crucigenia quadrata* Morren	CRUQU	0	1	0	0	0	0	0	0	0	P-B	-	st-str	-	b-o	i	acf	-	-
80	*Crucigenia tetrapedia* (Kirchner) Kuntze	CRUTET	1	1	1	1	0	0	0	1	1	P-B	-	st-str	-	o-a	i	ind	-	-
81	*Desmidium swartzii* C. Agardh ex Ralfs	DESSWA	0	0	0	0	1	0	0	0	0	-	-	-	-	o	i	-	-	-
82	*Desmodesmus quadricaudatus* (Turpin) Hegewald	DESQUA	1	0	1	1	1	1	1	0	0	P	-	-	-	b	i	ind	-	-
83	*Elakatothrix genevensis* (Reverdin) Hindák	ELAGEN	1	0	0	0	0	0	0	0	0	P-B	-	st-str	-	o-a	-	-	-	-
84	*Eudorina elegans* Ehrenberg	EUDELE	0	0	0	1	0	0	0	0	1	P	-	st-str	-	b	i	-	-	-

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Tab. 1. Continued from previous page.

No	Species	Code	1993	1996	1998	1999	2005	2006	2007	2008	2011	Hab	T	Reo	D	S	Hal	pH	Aut-Het	Tro
85	*Koliella longiseta* (Vischer) Hindák	KOLLON	1	1	1	1	0	1	0	0	0	P	-	st	-	b	i	-	-	-
86	*Koliella spiculiformis* (Vischer) Hindák	KOLSPI	1	1	1	0	0	0	0	0	0	-	-	-	-	o-a	-	-	-	-
87	*Microglena monadina* Ehrenberg	MICMO	0	0	0	1	1	1	1	1	1	P	-	-	-	b	i	-	-	-
88	*Monoraphidium arcuatum* (Korshikov) Hindák	MONAR	1	1	1	0	0	0	0	0	0	P	-	-	-	-	i	-	-	-
89	*Monoraphidium contortum* (Thuret) Komárková-Legnerová	MONCO	1	1	1	0	0	1	0	1	1	P-B	-	st-str	-	b	i	-	-	-
90	*Monoraphidium mirabile* (West & G.S. West) Pankow	MONMI	1	0	0	0	0	1	0	0	0	P-B	-	st	-	b-a	oh	-	-	-
91	*Mucidosphaerium pulchellum* (H.C. Wood) C. Bock, Proschold & Krienitz	MUCPU	1	1	0	0	1	0	0	0	0	P-B	-	st-str	-	b	i	ind	-	-
92	*Oocystis lacustris* Chodat	OOCLAC	0	0	0	1	0	0	0	1	0	P-B	-	st-str	-	b-o	hl	-	-	-
93	*Oocystis submarina* Lagerheim	OOCSUB	1	0	0	0	0	0	0	0	0	P-B	-	st	-	-	i	-	-	-
94	*Phacotus angustus* A. Pascher	PHAAN	0	0	0	0	0	0	1	1	0	-	-	-	-	-	-	-	-	-
95	*Planctococcus sphaerocystiformis* Korshikov	PLASPH	0	0	1	1	1	1	1	1	1	P	-	st	-	-	-	-	-	-
96	*Quadrigula closterioides* (Bohlin) Printz	QUACL	0	0	0	0	1	0	0	0	0	-	-	-	-	o-b	-	-	-	-
97	*Scenedesmus ecornis* (Ehrenberg) Chodat	SCEECO	1	1	1	0	0	0	0	0	1	P	-	-	-	o-b	i	-	-	-
98	*Sphaerocystis schroeteri* Chodat	SPHSCH	1	1	1	0	0	0	0	0	1	P	-	-	-	b-o	i	ind	-	-
99	*Staurastrum paradoxum* Meyen ex Ralfs	STAPAR	0	0	0	0	1	0	0	0	0	P	-	st	-	-	i	-	-	-
100	*Stauridium tetras* (Ehrenberg) E. Hegewald	STATET	0	1	0	0	0	0	0	0	0	P-B	-	st-str	-	o-a	i	ind	-	-

Hab, ecological types: B, benthic; P-B, planktic-benthic; Ep, epiphytes; P, planktonic. T, temperature: cool, cool-water; temp, temperate; eterm, eurythermic. Reo, streaming and oxygenation: st, standing water; str, stream; st-str, standing-streaming. D, saprobity (Watanabe et al.*, 1986): es, eurysaprob; sx, saproxen; sp, saprophil. Sap, saprobity (Sládeček, 1986): o, oligosaprob; o-b, oligo-beta-mesosaprob; b, beta-mesosaprob; b-o, beta-oligomesosaprob; b-a, beta-alpha-mesosaprob; a, alpha-mesosaprob; a-b, alpha-beta-mesosaprob; x, xenosaprob; x-o, xeno-oligosaprob; o-x, oligo-xenosaprob; x-b, xeno-beta-mesosaprob; o-a, oligo-alpha-mesosaprob. Sal, halobity (Hustedt, 1938-1939): i, oligohalobious-indifferent; hl, oligohalobious-halophilous; hb, oligohalobious-halophobous. pH, acidity (Hustedt, 1957): ind, indifferent; alf, alkaliphil; acf, acidophil; alb, alkalibiont. Het, nitrogen uptake metabolism (Van Dam* et al.*, 1994): ats, nitrogen-autotrophic taxa, tolerating very small concentrations of organically bound nitrogen; ate, nitrogen-autotrophic taxa, tolerating elevated concentrations of organically bound nitrogen; hne, facultatively nitrogen-heterotrophic taxa, needing periodically elevated concentrations of organically bound nitrogen; hce, obligately nitrogen-heterotrophic taxa, needing continuously elevated concentrations of organically bound nitrogen. Tro, trophic state (Van Dam* et al.*, 1994): ot, oligotraphentic; o-m, oligo-mesotraphentic; m, mesotraphentic; me, meso-eutraphentic; e, eutraphentic; he, hypereutraphentic; o-e, oligo- to eutraphentic (hypereutraphentic).*

period. Even in the most polluted Kondopoga Bay, the WESI remained above normal (=1), attesting to an extremely high self-purification capacity during the entire study period. The value of index calculated on the basis of phosphate concentration is larger than for the nitrate index, which can be related to a lower concentration of the usable for photosynthesis phosphates than nitrates. However, two critical periods in 1995 and 2007 can be seen in Fig. 5, with WESI lows in both phosphates and nitrates.

Species-environment relationships

Calculation of regression coefficients in CCA shows significant positive relationships between species richness and Norg (0.697), and negative relationships of Saprobity Index S and water temperature (-0.667), ammonia (-0.694), and silica (-0.725). In turn, the chemical variables are dependent on each other as nitric nitrogen concentration and temperature (0.707), or nitric nitrogen and Norg (-0.725), as well as iron and temperature (0.904). For accomplishing CCA analysis we choose 18 abundant species and five chemical variables (N-NO_3, T, N-NH_4, Si, and Norg). Planktonic community response to environmental impact (Fig. 6) reveals two different sets of environmental variables; the first includes temperature and nitric nitrogen, the second

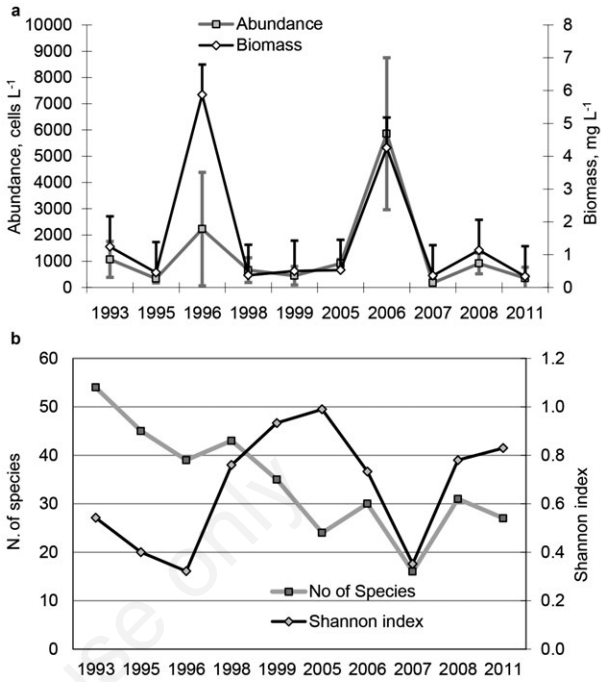

Fig. 4. Dynamics (1993-2011) (with standard deviation) of phytoplankton abundance and biomass (a), species richness and Shannon index (b), in the Kondopoga bay of the Lake Onego.

Tab. 2. Mean values of environmental variables (mg L^{-1}) in the Kondopoga Bay of the Onego Lake.

Year	T (°C)	Pmin	TSS	Ptot	N-NH_4	N-NO_2	N-NO_3	Norg	Ntot	Si	Fetot
1993	15.6	0.0013	0.009	0.03	0.05	0.002	0.12	0.52	0.73	0.33	0.05
1996	15.6	0.0030	0.014	0.04	0.05	0.001	0.07	0.55	0.68	0.36	0.09
1998	18.2	0.0013	0.008	0.02	0.06	0.002	0.14	0.48	0.69	0.53	0.18
1999	16.0	0.0027	0.000	0.03	0.05	0.001	0.11	0.42	0.59	0.22	0.11
2005	17.2	0.0000	0.000	0.02	0.04	0.002	0.24	0.17	0.45	0.35	0.14
2006	16.0	0.0001	0.000	0.02	0.03	0.001	0.17	0.41	0.61	0.06	0.10
2007	19.9	0.0062	0.000	0.04	0.04	0.000	0.27	0.33	0.65	0.66	0.18
2008	16.6	0.0076	0.000	0.03	0.05	0.002	0.12	0.31	0.48	0.68	0.10
2011	16.0	0.0187	0.000	0.04	0.06	0.000	0.09	0.49	0.65	0.60	0.10

Pmin, mineral phosphorous; TSS, total suspended solids; Ptot, total phosphorous; Norg, organic nitrogen; Ntot, total nitrogen; Si, silica; Fetot, total iron.

Tab. 3. Dynamics of mean biological variables of phytoplankton assemblages in the Kondopoga Bay of the Onego Lake.

Year	N. of species	Shannon index	Index S	Abundance, cells L^{-1}	Biomass, mg L^{-1}	Relative cell volume, mg $cells^{-1}$
1993	54	0.542	1.752	1070.9	1.242	0.0012
1995	45	0.400	1.703	340.0	0.458	0.0013
1996	39	0.322	1.840	2227.7	5.872	0.0026
1998	43	0.760	1.563	662.0	0.375	0.0006
1999	35	0.933	1.773	449.0	0.504	0.0011
2005	24	0.990	1.830	915.0	0.531	0.0006
2006	30	0.733	1.940	5858.6	4.258	0.0007
2007	16	0.352	1.625	177.5	0.364	0.0020
2008	31	0.780	1.717	916.0	1.137	0.0012
2011	27	0.830	1.720	355.0	0.336	0.0009

Norg, and N-NH_4. The first set variables are manifest in the abundance of the temperature and nitrogen indicators *Anabaena scheremetievii* and *Dolichospermum lemmermannii* (Cyanobacteria), and *Aulacoseira alpigena* from diatoms (marked in the upper right circle). The second set variables are relevant to species sensitive to ammonia and Norg, marked in the upper left circle, in particular the diatoms *Aulacoseira distans* (cool oligotrophic water, xeno-oligosaprobiont) and greens *Ankistrodesmus fusiformis* (beta-oligosaprobiont) and *Mucidosphaerium pulchellum* (beta-mesosaprobiont) which are known as autotrophic species inhabiting cool to temperate clear waters (Tab. 1; Barinova *et al*., 2006).

Comparative statistics

With the help of the GRAPHS Program, a statistical comparison of species richness revealed that all algal diversity of the studied years can be divided into three major clusters with a similarity level of 50% (Fig. 7). The first cluster of similarity tree includes species sampled in 1993, 1996, and 1998; the second in 1999, 2005, 2006, and 2011, and the third in 2007 and 2008. The calculation of species overlap shows a high level of similarity of sampling year phytoplankton, with fluctuation between 46% and 64%. The dendrite reveals two cores of species richness, in years 1996 and 2011, respectively.

DISCUSSION

The analysis of long time series of air and water temperature at various lakes of the world showed recent warming trends (Ministry of the Environment and Statistics, 2010; George, 2010; Nazarova, 2012). This can lead to transformation of distribution and increase in phytoplankton productivity (Jeppesen *et al.*, 2009). In the Kondopoga Bay, mean phosphates concentration remain low (Tab. 2) with increasing tendency that correspond to transition from oligotrophic (0 to 7.6 mkg P L^{-1}) in 1993-2008 to a mesotrophic (18.7 mkg P L^{-1}) state in 2011 of the lake ecosystem (Carlson and Simpson, 1996) in controversy to Sabylina *et al*. (2012) conclusion about of the oligotrophic state over all studied periods. In the same time, significant changes were detected in the total nitrogen, including the perennial concentration of its mineral forms consumed by phytoplankton for the entire study period.

The total taxonomic diversity for all sampling stations in the open water period comprises 228 taxa below the rank of genus, belonging to eight divisions: Bacillariophyta, 97 (43%); Chlorophyta, 57 (25%); Cyanobacteria, 17 (7%); Chrysophyta, 29 (13%); Euglenophyta, 12 (5%); Dinophyta, 6 (3%); Cryptophyta, 7 (3%); Xanthophyta, 3 (1%); (Chekryzheva, 2008). The most representatives diversity and abundance data are obtained for three major monitoring stations where we have continuous counting results for the entire period (Tab. 1, Fig. 1). The divisional distribution is like in the total flora, with slight increase in Cyanobacteria.

The cryptophyta algae are observed in plankton of the bay since the mid-1990s, with maximal concentration in the apical north-western part of the bay in August 1999.

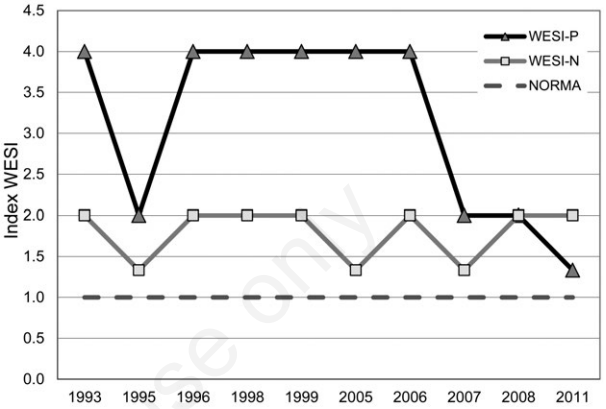

Fig. 5. Dynamics (1993-2011) of the aquatic ecosystem state index WESI calculated on the basis of the Saprobity index S and concentration of N-NO_3 and P-PO_4 in the Kondopoga Bay of the Lake Onego. Index WESI=1 marked as NORMA.

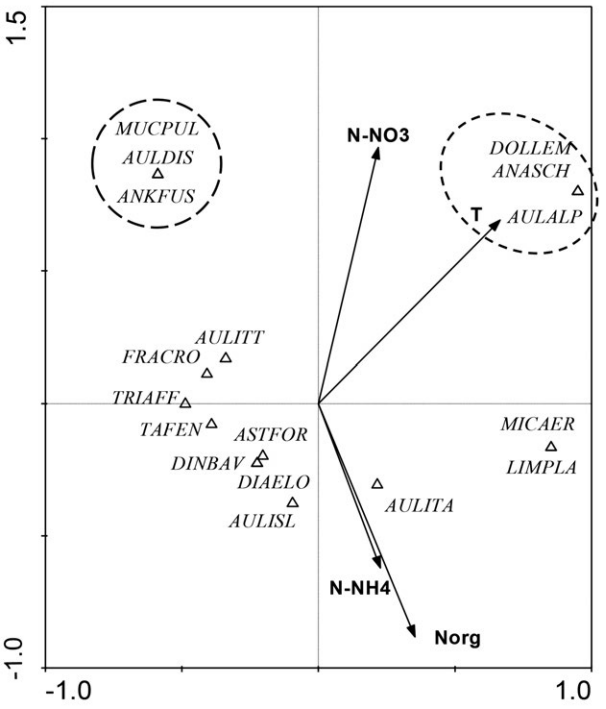

Fig. 6. Biplot of canonical corresponded analysis (CCA) for phytoplankton communities and environmental variables in the Kondopoga Bay of the Lake Onego. Abbreviated species names are given in Tab. 1. Monte Carlo test: eigenvalue=0.804, P=0.05.

As in the other large regional lakes, the ratios of species numbers of taxonomic divisions have not changed significantly in the process of anthropogenic eutrophication. At the same time, a characteristic feature of eutrophication is an increase in blue-green algae and green chlorococcalean (Tab. 1) in abundance and biomass (Tab. 3). Cryptophyta algae exhibit ecological features such as a high growth rate, mobility, ability to mixotrophic nutrition as well as osmo- and fagotrophy (Stewart and Wetzel, 1986; Olrik, 1998). Cyanobacteria that display adaptability to high concentrations of organic nitrogen and ammonia are joined by cryptophytes in showing the ability of heterotrophic nutrition (Trifonova, 1990; Blomqvist *et al*., 1994; Rücker *et al*., 1997; Havens *et al*., 1998). Lately, the increasing role of diatoms in phytoplankton communities is accompanied by the increasing ability of heterotroph nutrition (Van Dam *et al*., 1994) in this group also (Figs. 3 and 4a). Together with heterotrophic Cyanobacteria such as *Oscillatoria* members (Trifonova, 1990) they contribute to the number of indicator species for organic pollution (Fig. 2 a-d). In calm weather algal blooms caused by the massive development of blue-green algae such as *Oscillatoria tenuis*, *Anabaena scheremetievii*, *Woronichinia naegeliana*, as well as green algae, *Eudorina elegans*, *Sphaerocystis schroeteri* and *Mucidosphaerium pulchellum,* were observed. It means that a number of diatom species is replaced by green algae and cyanobacteria, well adapted to temperate waters. Diatoms, such as *Aulacoseira*, have an adaptive optimum in low-temperature ranges (Barinova *et al*., 2006: 12 taxa are low temperature indicators from 15 taxa of *Aulacoseira* with known temperature preferences). Therefore, it can be concluded that at temperature and organic pollution are the major factors of the diversity forming process in planktonic communities of the Kondopoga Bay.

A quantitative comparison of phytoplankton in the study period 1993-2011 showed that the value of total abundance and biomass of phytoplankton of the lake in the 1990s was on average 1.5 times higher than in the years between 2000 and 2011 (Chekryzheva, 2012b). Their abundance in the 1990s averaged 766.0 thousand cells L^{-1} and from 2000-2011 reached to 490.0 thousand cells L^{-1}. The phytoplankton biomass over the same period averaged 0.66 g cm^{-3} and 0.44 g cm^{-3}. However, the quantitative development of phytoplankton for the two periods was not so distinct at a significance level of 0.05. Notably, the relative cell size reflects not only small-celled algal bloom periods but also the response of phytoplankton diversity to impact (Stolte, 1995; Negro *et al*., 2000; Alimov, 2001; Visljanskaya, 2007; Finkel *et al*., 2010; Zhang *et al*., 2012). Long-term dynamics of relative cell volume that we calculated for the entire study period (Fig. 4) shows that phytoplankton communities were enriched by small-celled species, such as Cyanobacteria (*Microcystis aeruginosa*, *Dolichospermum lemmermannii*), and cryptophytes (*Cryptomonas* sp. and *Katablepharis ovalis*), in the period between 1998 and 2006 when the total cell abundance and biomass were low (Tab. 3, Fig. 4a). Phytoplankton of this period contains a number of small-celled greens and Cryptophyta (*Cryptomonas* sp. and *Katablepharis ovalis*) as well as Cyanobacteria (*Microcystis aeruginosa*, *Dolichospermum lemmermannii*) (Tab. 3). In the same time, Shannon index of structural complexity is rather high (Tab. 3, Fig. 4b) and therefore reflect species rich communities that maintain a high level of stability under environmental impacts. Pearson correlation for Shannon and relative cell biovolume is negative -0.79 with p value of 0.002, which confirms that community was impacted during the blooms of small-celled algae as *Microcystis aeruginosa*. Remarkably, during two critical years, 1996 and 2007, a different relationship between the relative cell size and structural complexity was observed. As mentioned above (Tab. 3, Fig. 3), it was the

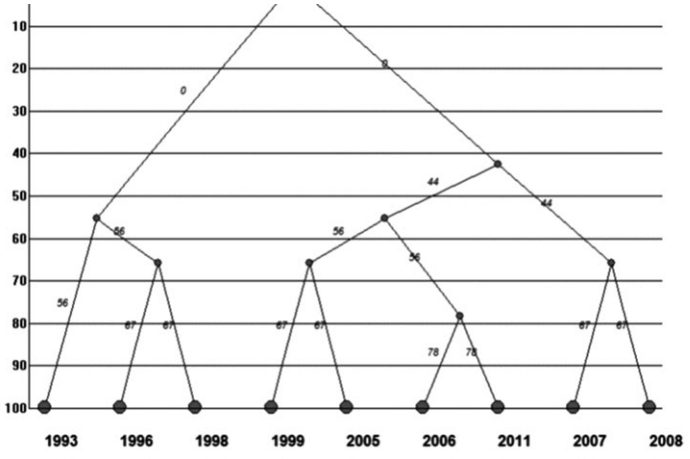

Fig. 7. Tree of similarity of the phytoplankton communities in the Kondopoga Bay of the Lake Onego calculated on the basis of Sørensen-Czekanowski indices. At the similarity level of 50% three clusters are cut off.

time of large-celled Dinophyta bloom involving *Ceratium hirundinella* and *Peridinium aciculiferum*. Therefore, Dinophyta co-exist with the other plankters at low densities, but disrupt the structure of plankton communities at blooms. Causation of Dinophyta blooms in large lakes has not been given the attention it deserves, but a few examples (Zohary *et al*., 1998; Grigorszky *et al*., 2003) point to the blooms enhancing instability under increasing temperature and organic impacts. Even small northern lakes show high buffer capacity under industrial pollution impact (Blais *et al*., 1999), and for the large lakes as Onego the delay can be more significant. On the other hand, periods of dinoflagellate blooms (1998, 2007) are strongly followed by peaks of total abundance and biomass (1996, 2006).

We tried to relate the anthropogenic impacts to self-purification capacities in the bay and extrapolate over the lake ecosystem as a whole. The saprobity indices reflect organic pollution that stimulate photosynthetic activity on the one hand, and species richness, on the other (Barinova, 2011), showing high self-purification capacities (Tab. 3). This conclusion is confirmed by WESI values which were more than 1.0 over the studied period, being relatively low in 1995 and 2007 (Fig. 5). It can be related to increases in nitrate and phosphate concentrations in these years, but with organic pollution (the Saprobity index S) concomitantly decreasing. To clarify the problem, we compare WESI with ecological information summarized in Tab. 3. While in critical years the Saprobity index S scarcely increased, the phosphate and nitrate concentrations levels are considerably elevated. This tendency can be seen in Fig. 5 during the last years (2007-2011) in respect to phosphates, which increased significantly. Therefore, the WESI conveys the increase in inorganic pollution during the last few years, at the same time attesting to self-purification capacities. Statistical analysis of species-environmental relationships with CCA (Fig. 6) of 18 abundant species and five most correlated chemical variables reveals increasing of abundance of the temperature and nitrogen indicators *Anabaena scheremetievii*, *Dolichospermum lemmermannii*, and *Aulacoseira alpigena*, as well as decreasing of sensitive to ammonia and Norg species *Aulacoseira distans*, *Ankistrodesmus fusiformis*, and *Mucidosphaerium pulchellum*.

We also analyzed regression coefficients for most significant pairs of variables. Our calculations shows significant positive relationships of species richness and Norg (0.697), and negative relationships of saprobity index S and water temperature (-0.667), ammonia (-0.694), and silica (-0.725). In turn, the chemical variables are dependent each other as nitric nitrogen and temperature (0.707), or nitric nitrogen and Norg (-0.725), as well as iron and temperature (0.904). The comparative species richness analysis (Novakovsky, 2004) has divided phytoplankton into years representing three different clusters (Fig. 7), related to fluctuations in species diversity and nutrients. Species richness overlap analysis shows a high level of similarity of studied communities with similarity cores in 1996 and 2011. It looks like a very important change of environmental situations (years 1998 and 2011) in which the planktonic communities of the Kondopoga bay were formed. We speculate that turnover might have been related to a 100-fold increase of total nitrogen, which comes from the Kondopoga treatment plants to the Kondopoga bay after 1998 (Sabylina, 1999; Sabylina *et al*., 2010; Rukhovets and Filatov, 2010; Kalinkina *et al*., 2012).

On the other hand, the long-term study of the great lakes ecosystem (Petrova *et al*., 2010) revealed a multiparametric stressors impact (Summers *et al*., 2012), which can be inflicted not only by water pollution but also by the air dust (Psenner, 1999) and acidification (Skjelkvåle *et al*., 2005), but mostly related to anthropogenic load. In deep lakes of the humid zone such as the Lake Ladoga (Petrova *et al*., 2010) and Lake Superior (Pourriot and Meybeck, 1995), the ecosystem trends toward the allochthonous, heterotrophic type even notwithstanding the absence of significant increase in anthropogenic load (Petrova *et al*., 2010). In the case of the Onego Lake, the eutrophication trend is associated not only with the nutrients increase (Timakova *et al*., 2011) but also with multiparametric stressors, which in our bio-indication result are manifest in the rise of species with heterotrophic nutrition ability (Saks *et al*., 1976).

CONCLUSIONS

Our results suggest that the Kondopoga Bay ecosystem has high self-purification ability in spite of its anthropogenic impact from the Kondopoga pulp and paper mill wastewater. Bio-indication shows a trend of slight acidification and eutrophication of the bay waters. Our results characterize the Kondopoga Bay as similar to ecosystems of large lakes, such as the Lake Ladoga, under low year-round insolation as well as having the highest water temperatures in summer. The anthropogenic eutrophication process is localized in deep bays like the Kondopoga Bay. Its morphometric features and thermodynamics contribute to slowing down of the eutrophication process, at the same time spreading it over the entire area of the Lake Onego. Temperature and nutrients emerge from this study as the major factors of the lake ecosystem dynamics.

Future investigations of phytoplankton in this great northern lake would allow for more exact estimate of pollution intensity and the impact of the Kondopoga Bay eutrophication confers to the whole great lake ecosystem.

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