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Effects of nutrient load on species composition and productivity of phytoplankton in Lake Ladoga

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As part of the joint Russian-Finnish evaluation of human impact on Lake Ladoga, we studied the phytoplankton species composition, biomass, chlorophyll *a* content and primary production in the lake in order to estimate the state of eutrophication. Samples were collected from 9–31 sampling stations in August 1992–95. In the surface water, the phytoplankton biomass varied from 0.3 to 6.6 g m^{-3} fresh weight, chlorophyll *a* from 1.7 to 18.6 mg m^{-3} and the primary productivity of phytoplankton from 33 to 471 mg C m^{-3} d^{-1}. The biomass was lowest close to the western shore and highest in the Sortavala Bay. Blue-green and green algae were abundant inshore and small cryptophyceans (*Rhodomonas lacustris*, *Cryptomonas* spp.) offshore. In the most nutrient-rich parts of Lake Ladoga (Volkhov, Sortavala and Svir bays) the phytoplankton communities were dominated mainly by blue-greens and cryptomonads. Areas close to the Vuoksa and Burnaya rivers were dominated by diatoms (*Diatoma tenuis*, *Asterionella formosa*, *Tabellaria fenestrata*, *Aulacoseira italica, A. granulata, Melosira varians, Fragilaria crotonensis, Stephanodiscus binderanus and Synedra actinastroides).* In the 1970s and 1980s eutrophication was seen not only as changes in species composition of phytoplankton but also as growing biomass and algal primary productivity. The maximum mean total phosphorus content (26 mg m^{-3}) was attained during the late 1970s when the mean biomass of algae was six times and the maximum values 20 times those in the 1960s. In the 1990s the tendency has been towards decreasing phosphorus content (1992–95 mean 18 mg m^{-3}), but the changes in phytoplankton productivity between years were connected mainly with temperature. On the basis of phytoplankton biomass, chlorophyll *a* content and primary production, Lake Ladoga can presently be classified as a mesotrophic lake. The most eutrophicated areas are found in the northern archipelago and in areas influenced by large rivers.

Introduction

Loading from various industries, agriculture and settlement change the lake ecosystems by increasing the nutrient content or harmful compounds in the lake water. This directly affects the hydrobiological development of the lake. Changes can be seen in algal biomass and species composition, chlorophyll *a* content and primary productivity (Dillon and Rigler 1974, Willén 1992). The phytoplankton species composition, in particular, seems to be very sensitive to waste water loading (Stoermer 1988, Holopainen *et al*. 1996, Karjalainen *et al*. 1996).

Since the beginning of the 1960s, Lake Ladoga has eutrophied, and changes can be seen especially in some loaded bays and littoral areas of the lake. Algal densities, especially those of blue-greens, have increased in these areas in particular. Due to wind induced currents, some harmful blooms of blue-green algae have also been found in the pelagic areas. Values of primary productivity and chlorophyll *a* content indicate clear changes in the lake since 1973.

The plankton communities of Lake Ladoga have been studied intensively during this century. Balakhontsev (1909) was one of the first to study the structure of the phytoplankton community of Lake Ladoga in the beginning of the 1900s. Since 1975 the phytoplankton of Lake Ladoga and its productivity have been studied by Petrova (1987), Letanskaya *et al*. (1987), Petrova *et al*. (1992), Letanskaya and Hindák (1992), Holopainen *et al*. (1992), Holopainen *et al*. (1996), Letanskaya and Protopova (1996), and Rahkola *et al*. (1994). The changes in phytoplankton are reflected on other trophic levels of the ecosystem, indicating serious changes in water quality, especially in polluted areas (Raspletina 1992, Holopainen *et al*. 1966). The aim of this research is to evaluate the present state of Lake Ladoga as revealed by phytoplankton biomass, species composition and productivity. This study is part of the joint multidisciplinary Russian-Finnish evaluation of human impact on Lake Ladoga.

Study area

Lake Ladoga is a large (area 17 891 km^2, volume 837 km^3), open and deep lake with a mean depth of 47 m and a maximum depth of 230 m (Sorokin *et al*. 1996). The residence time of the water is 12.3 years. The total river discharge to the lake is about 71 $km^3\ a^{-1}$ (68–80 $km^3\ a^{-1}$, Kirillova 1987). The catchment area of Lake Ladoga is 258 800 km^2, 75% of which is located in Russia and 25% in Finland. The largest rivers draining to Lake Ladoga are the Volkhov, the Syas, the Svir and the Burnaya (Vuoksa), which together bring the main load to this lake. The total phosphorus load (from natural, nonpoint and point sources) brought by those rivers is 4 400 t a^{-1} (Raspletina *et al*. 1987, Drabkova *et al*. 1996, Lozovik *et al*. 1997).

Low water temperatures, a short growing season and ice cover in winter are typical features affecting the ecosystem of Lake Ladoga. Ice formation starts in mid-November but the lake freezes over completely only during cold winters (Tikhomirov 1982). The ice normally begins to break up in April. From mid-July to mid-August the depth of epilimnion is about 10 metres; in south the layer is somewhat deeper and in north a little less.

Considerable spatial variation in water quality is characteristic of Lake Ladoga. In 1987–1989 the mean summer concentration of phosphorus in the water was 20–21 mg m^{-3} in the pelagic zone (deeper than 15 m) and 32 mg m^{-3} in the littoral zone (Raspletina 1992). During the August 1993 expedition, the mean total phosphorus concentration of the surface water varied from 15 to 28 mg m^{-3} and the mean total nitrogen concentration from 593 mg m^{-3} to 670 mg m^{-3} (Niinioja *et al*. 1996). The highest nitrogen (N_{tot} max. 810 mg m^{-3}) and phosphorus (P_{tot} 61 mg m^{-3}) concentrations were measured in the south-eastern part of the lake. In addition to the high nutrient concentrations, the water is also turbid (3.5 FTU; Formazine turbidity units) in this area. The point-source load of phosphorus (610 t a^{-1}) brought by the Volkhov River is 87% of the total incoming load (Lozovik *et al*. 1997). High phosphorus concentrations were also measured close to the town of Sortavala (26 mg m^{-3} at 1 m depth). The lowest nutrient concentrations (P_{tot} 12 mg m^{-3}) were always observed in the pelagic areas of western Ladoga. The effects of water currents caused by wind are very important for explaining the patterns in the water quality of Lake Ladoga (Beletsky 1996). In 1993–95 the transparency (Secchi depth) of the water was highest (max. 3.4 m) in the deeper northern pelagic areas and lowest in the loaded shallow areas in the bays of Sortavala and Volkhov (< 1.4 m). Colour of the water varied from 25 to 90 g Pt m^{-3} in 1993–95 and the highest values were measured in southern part of the lake (Niinioja *et al*. 1997). The difference between the mean temperature values of the warmest and coldest year was 3.2 °C (Table 1).

The pulp and paper industry, the chemical industry and agriculture, together with human settlements and air pollution, are the most important sources of nutrients, phenollignosulfate, heavy metals and organic matter (Raspletina *et al*. 1987). Pulp and paper industry effluents are important in the north, close to Pitkäranta and Läskelä (the latter mill closed since 1989), in the south (Syas River) and in the west coast (effluents of Svetogorsk). The areas close to the Volkhov River are exposed to effluents from the chemical industry. The load from human settlement dominates in the areas adjacent to the town of Sortavala.

Material and methods

In August, in each of the years 1992–1995, phytoplankton samples were collected from Lake Ladoga. The number of sampling stations varied from 9 to 31 in the different years (Fig. 1). The stations were situated both in the archipelago and in the pelagic areas of Lake Ladoga. The topmost surface layer (0–1 m) was chosen to represent horizontal differences. The water depth at the sampling stations varied between 7 and 230 metres. Samples for the study of vertical variation of phytoplankton and chlorophyll *a* in the archipelago and in the pelagic areas were taken from seven sampling stations in 1994 (Stations 13, 16, 17, 19, 33, 306) at 1, 2, 3, 4, 5, 8, 10, 15 and 20 metres depth. All phytoplankton samples consisted of five lifts with a Limnos-type sampler. The combined sample of ca.15 litre was mixed in a vial and subsampled with a glass bottle. Samples for chlorophyll *a* and primary production were taken from the same vial. Phytoplankton samples have been fixed with formalin in Russia but during the joint studies Lugol's solution was used to ensure better state of preservation. The methods used for phytoplankton identification, biomass calculation and chlorophyll *a* analysis are given in detail in Holopainen *et al.* (1996).

Primary production measurements were made with an oxygen method on board a research vessel (24 h incubation of 100 ml light and dark bottles in aquarium in the daylight). The Winkler titration was used in the oxygen determination. The gross production results were expressed as organic carbon content (Vinberg 1960). Primary production was calculated per square metre according to Bulion (1994). The determination of trophic state of Lake Ladoga was based on the classification of Likens (1975), and Forsberg and Ryding (1980).

Chlorophyll fluorescence was measured with a Turner Designs model 10 automatic continuous-flow fluorometer, which was furnished with the recommended exitation and emission filters for chlorophyll analysis (for details, *see* Viljanen *et al.* 1999). The effect of humic substances on fluorescence was corrected by subtracting the corresponding background fluorescence from the filtrate.

Water temperature and Secchi depth were measured at each station, and samples for water quality were taken at three depths: at 1 metre, at the depth half-way down the water column, and close to the bottom.

Table 1. Phytoplankton biomass, chlorophyll *a* and primary production at 1 m depth in the pelagic zone of Lake Ladoga in August 1992–1995.

Year	Biomass g m^{-3}				Chlorophyll *a* mg m^{-3}				Primary production mg C m^{-3} d^{-1}				Water temperature °C			
	$\bar{x}$	range	*n*	SE	$\bar{x}$	range	*n*	SE	$\bar{x}$	range	*n*	SE	$\bar{x}$	range	*n*	SE
1992	1.9	0.9–4.1	9	0.3	8.6	3.6–18.6	9	1.6	222	90–455	8	50	16.6	14.9–18.8	9	0.4
1993	1.4	0.4–6.6	19	0.3	4.9	1.7–15.8	19	0.7	163	81–240	10	16	16.1	13.7–17.8	17	0.3
1994	1.6	0.4–3.4	31	0.1	7.8	2.3–14.9	32	0.5	244	66–471	21	23	19.9	16.7–22.6	31	0.2
1995	1.6	0.3–5.3	20	0.3	6.1	1.9–14.0	20	0.8	202	33–471	20	26	17.4	15.2–20.3	20	0.3

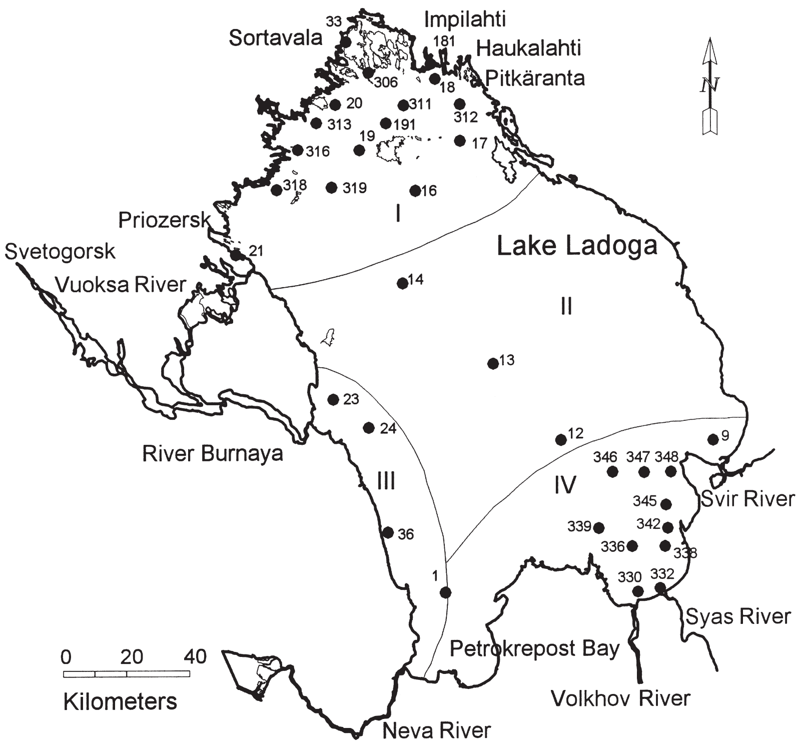

Fig. 1. Sampling stations and pelagic zones in Lake Ladoga: northern (I), central (II), western (III) and southern (IV).

Results

Horizontal variation of phytoplankton biomass.

In 1992–95, the phytoplankton biomass of the surface water (1 metre) varied from 0.3 to 6.6 g m^{-3} fresh weight in the pelagic area of Lake Ladoga (Table 1, Figs. 2 and 3). In 1993 (Holopainen *et al.* 1996) and 1994 (Fig. 2) the biomass was lowest at the western shore, but in 1995 in the central pelagic zone. During the same period, chlorophyll *a* concentration ranged from 1.7 to 18.6 mg m^{-3} and primary productivity of the phytoplankton from 33 to 471 mg C m^{-3} d^{-1}. Both productivity and the chlorophyll *a* values together with the biomass of phytoplankton were smallest in 1993, when the mean temperature of the water was lowest. Differences in the mean values between the years 1992–95 were small (Table 1). The maximum phytoplankton biomass was always measured in a separate bay close to the town of Sortavala in the northern part of Lake Ladoga (Station 33). The highest chlorophyll concentration (20.1 mg m^{-3}) and phytoplankton productivity (816 mg C m^{-3} d^{-1}) values were measured in 1993–95 in the same bay (Table 2).

In the central pelagic zone the variation in phytoplankton biomass was small in 1993–95 (Figs. 2 and 3, Holopainen *et al.* 1996). In the depth of 0–10 m the mean phytoplankton biomass was 0.9 g m^{-3} (Table 3). The smallest phosphorus contents of water in a 20-year period were also measured during this time (Table 3). The data for chlorophyll *a* (4.9–8.6 mg m^{-3}) and for primary productivity (163–244 mg m^{-3} d^{-1}, Table 1) suggest stabile conditions in the pelagic area in the beginning of 1990.

In the pelagic zone both the biomass and chlorophyll *a* attained high values at the same stations, resulting in a significant correlation between them ($r = 0.77$, $p < 0.001$, $n = 97$). The correlation between primary productivity and chlorophyll *a* also gave a significant value ($r = 0.72$, $p < 0.001$, $n = 59$). A positive correlation was found between total phosphorus and chlorophyll *a* content ($r = 0.28$, $p < 0.05$, $n = 72$) and also between total phosphorus and primary productivity (mg m^{-3} d^{-1}) ($r = 0.50$, $p < 0.001$, $n = 57$). The primary productivity and chlorophyll *a* values were always highest in the loaded turbid areas close to Sortavala

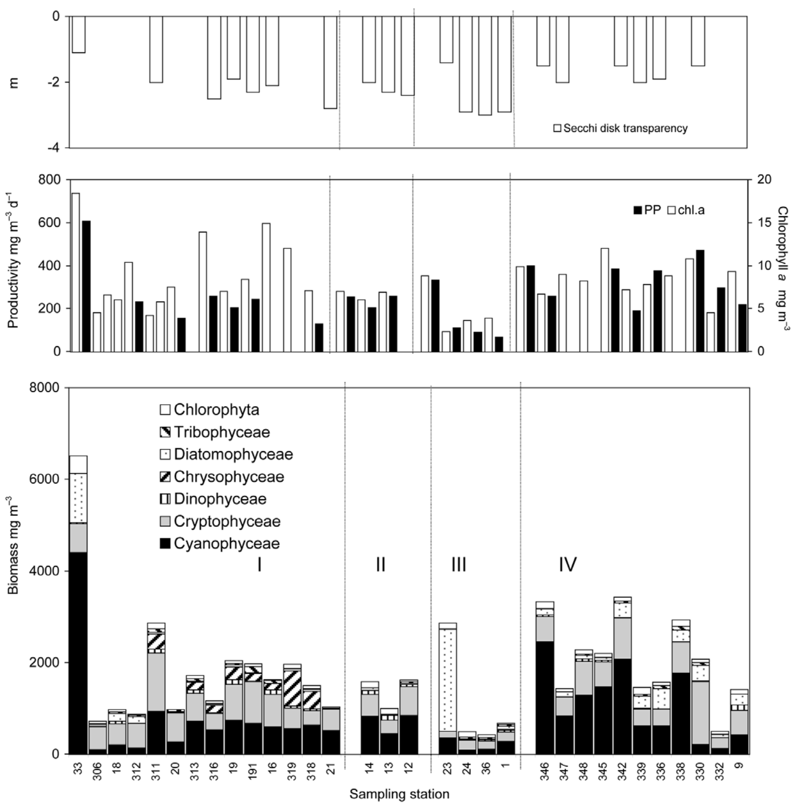

Fig. 2. Phytoplankton biomass and species composition, chlorophyll *a* content, primary production (0–1 m) and Secchi depth in Lake Ladoga in 1994. Pelagic zones as in Fig. 1: northern (I), central (II), western (III) and southern (IV).

and the Burnaya River and in the Volkhov Bay. (Figs. 2 and 3), which could be seen as a negative correlation between transparency and chlorophyll *a* ($r = -0.53$, $p < 0.001$, $n = 79$), and also between transparency and primary productivity (expressed as mg m^{-2} d^{-1}) ($r = -0.28$, $p < 0.05$, $n = 59$).

Horizontal distribution of phytoplankton species composition.

In 1992–95 the structure of the phytoplankton community was dominated by Cyanophyceae and Cryptophyceae in the summer period (Figs. 2 and 3). The dominant species of blue-greens were: *Aphanizomenon flos-aquae* (L.) Ralfs, *Woronichinia naegeliana* (Ung.) Lemm., *Anabaena spiroides* Kleb., *A. circinalis* Rabenh. and *A. lemmermannii* P. Richter, and cryptophyceans *Cryptomonas* spp. and *Rhodomonas lacustris* Pasch. & Ruttn. Diatoms were scarce in summer phytoplankton, except for those areas influenced by rivers rich in diatoms. The dominant species close to the Vuoksa River were *Diatoma tenuis* (Lyngb.) Ag., *Asterionella formosa* Hass., *Tabellaria fenestrata* (Lyngb.) Kütz. and *Aulacoseira italica* (Ehr.) Kütz. (50% of total biomass). In the areas influenced by the Burnaya River, diatoms dominated every year comprising up to 80% of the total biomass. The main species were *Aulacoseira italica* (Ehr.) Simons., *A. granulata* (Ehr.) Simons., *Melosira varians* Ag., *Fragilaria crotonensis* Kitt. and *Synedra actinastroides* Lemm. In the Volkhov Bay *Stephanodiscus binderanus* (Kütz.) Krieger and *Stephanodiscus hantzschii* Grun. were numerous among the diatoms (30% of the total biomass).

Horizontal variation in the phytoplankton species composition was seen especially in the relative abundances of species indicating eutrophy and oligotrophy. In the loaded southern areas the number of eutrophy indicating species (Sládeček 1986, Tikkanen 1986) was 26–36 (total number of species 52–68), in the central pelagic zone their numbers were 15–24 (total 33–47), in the western areas 11–26 (total 25–56) and in the northern pelagic zone 15–28 (total 30–36). Close to the

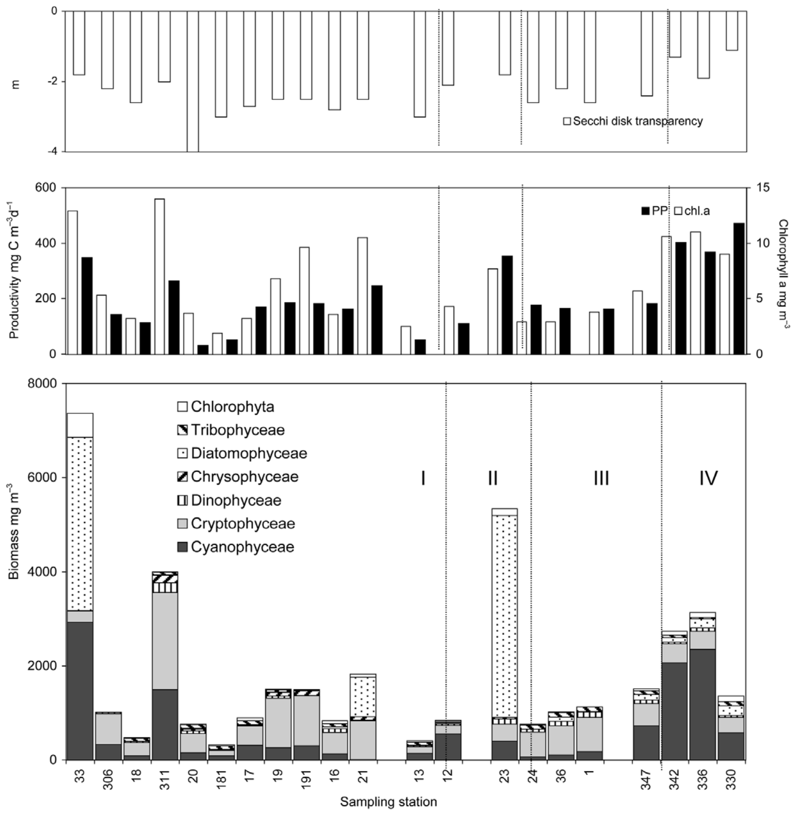

Fig. 3. Phytoplankton biomass and species composition, chlorophyll *a* content, primary production (0–1 m) and Secchi depth in 1995 in Lake Ladoga. Pelagic zones as in Fig. 1: northern (I), central (II), western (III) and southern (IV).

Burnaya and Svir rivers, the number of species indicating eutrophy was highest (35–47) as was also the total number of species (48–81) observed. In 1992–95, the number of species indicating oligotrophy varied between 9 and 14 in the whole lake.

In the 1990s some obvious horizontal differences were found in the biomass of phytoplankton, in the chlorophyll *a* content as well as in the primary productivity of algae (Table 4). Variation in species composition was also found in the lake during that time (Holopainen *et al.* 1996). According to phytoplankton community structure and productivity, the pelagic area of Lake Ladoga could be divided into four separate areas: northern (I), central (II), western (III) and southern (IV) pelagic area (Figs. 1–3, Tables 4 and 5).

Table 2. Phytoplankton biomass, chlorophyll *a* and primary productivity of phytoplankton at 1 m depth in the Sortavala Bay in the northern archipelago of the Lake Ladoga (Station 33).

Date	Biomass g m^{-3}	Chlorophyll *a* mg m^{-3}	Primary productivity mg C m^{-3} d^{-1}
04.VIII.1986	–	15.9	1 053
15.VI.1987	–	20.2	720
18.VII.1990	–	20.2	606
11.VIII.1993	6.4	20.1	816
10.VIII.1994	6.5	18.4	606
04.VIII.1995	3.1	12.9	384

In the northern part (I) *Cryptomonas* species (55% of the mean total biomass in the years 1992–95) were more abundant than blue-greens (27%; Table 5). The northern part (I) can be further divided into three subareas. In the north-eastern subarea cryptomonads were more abundant (47%–69% of the total biomass) than blue-greens (14%–28% of the total biomass). Typical blue-greens were various *Anabaena* species. In the north-western subarea the relationship between these groups was similar, whereas in the central subarea the amounts of cryptophyceans and cyanophyceans were equal (ca. 50% each); the blue-green *Aphanizomenon flos-aquae* was more abundant than other blue-green species. In addition, *Uroglena* sp. (Chrysophyceae) was found occasionally in 1994.

In the central part of the pelagic area (II), the mean biomasses of both cryptomonads and blue-greens were about the same (both 40%–45%) in 1992–95 (Table 5). Of the blue-greens, *Aphanizomenon flos-aquae* was the dominant species. In areas towards the Volkhov Bay, the amounts of *Microcystis*, *Anabaena* and *Gomphosphaeria* species increased. The blue-greens were exceptionally abundant (50% of the total biomass) in the central pelagic zone during 1994–95, when the temperature of the water was highest (Table 1).

In the western pelagic area (III) low phytoplankton biomass, chlorophyll *a* content and primary productivity values were always measured. The community structure of the phytoplankton there resembled that of the central pelagic zone. Cyanophytes (mean 18% of the total biomass in 1992–95), which were common in other parts of the lake, were not as abundant here. The amount of diatoms (21%) were higher than in other areas (Table 5). The chrysophyte *Dinobryon* was numerous only in the Petrokrepost Bay. The blue-green *Coelosphaerium kuetzingianum* (Näg.) was also common in that bay.

In the southern (IV), most shallow and most loaded part of pelagic Lake Ladoga, cyanophytes always dominated and cryptomonads were not as abundant (Table 5). The numbers of green algae were higher than in other areas of the lake, but

Table 3. Mean values for phytoplankton biomass, chlorophyll *a*, primary production and total phosphorus (n > 100 for each given period) in the pelagic zone of Lake Ladoga during the summer period of 1960 to 1995.

Period	Biomass (g m^{-3})			Chl. *a* (mg m^{-3})	Productivity mg C m^{-2} d^{-1}	Phosphorus mg m^{-3}	Reference
	0–1 m	0–10 m	0–10 m max.				
1960–1962	–	0.1	0.4	–	–	~10	Petrova (1987)
1973–1974	2.1	–	–	4.6	360	8–20	Pyrina & Trifonova (1979)
1976–1980	–	0.6	8.2	8.0[a)]	509	26	Petrova *et al.* (1992)
1981–1983	–	–	–	6.8[a)]	317	23	Petrova *et al.* (1992)
1987–1989	–	–	–	6.0[a)]	590	21	Petrova *et al.* (1992)
1990	1.7	–	–	6.3	–	20	Kovalenko (1997), Lepistö(1997)
1992–1995	1.6	0.9[b)]	1.7[b)]	6.8	429	18	

[a)] calculated with the formulas of Dillon and Rigler (1974)
[b)] mean 1993–95

Table 4. Phytoplankton biomass, chlorophyll *a* and primary production in the different pelagic zones (cf. Fig. 1) of Lake Ladoga. Averages for the sampling stations and for the years 1992–1995 are given.

Pelagic zone	Biomass g m^{-3}			Chl. *a* mg m^{-3}			Primary production mg C m^{-3} d^{-1}			Primary production mg C m^{-2} d^{-1} [(a]		
	$\bar{x}$	SE	n	$\bar{x}$	SE	n	$\bar{x}$	SE	n	$\bar{x}$	SE	n
I	1.37	0.15	29	6.9	0.7	30	173	2	19	419	3	10
II	1.25	0.16	10	5.6	0.8	10	171	20	9	434	44	9
III	1.39	0.38	13	4.2	0.6	13	157	30	11	361	38	11
IV	2.03	0.24	27	8.3	0.7	27	301	26	20	464	30	20

[a)] calculated according to Bulion (1994) their biomass was not significantly higher (3%–11% of the total biomass). The abundant green algae included *Scenedesmus, Pediastum*, *Monoraphidium* and *Dictyosphaerium* species. The diversity of phytoplankton was highest in this area. The dominant blue-green was *Aphanizomenon flos-aquae,* but close to the shore line the biomass of *Microcystis* spp. and *Woronichinia naegeliana* increased.

Vertical distribution of phytoplankton biomass and species composition.

In Lake Ladoga the phytoplankton biomass was greatest in the surface water above a depth of 5 m (Fig. 4). At the Sampling stations 17 and 19 (region I), the fluorometer values were significantly high down to a depth of 10 metres, indicating photosynthetic activity also in deeper layers (Fig. 5). The phytoplankton biomass maxima could be found either in the very surface water or deeper (at 3–4 m), depending on the station. The algal densities were highest at a depth of 4 m at Stations 13 and 17. These maxima were due mainly to large numbers of cryptophyceans (*Rhodomonas lacustris*). At Station 13 the blue-greens were also most abundant at this depth. The dominant species were *Aphanizomenon flos-aquae*, *Anabaena circinalis* Rabenh. and *A. spiroides* Kleb. Small surface maxima were found at Stations 16 and 306 in the northern archipelago. At Station 306, cryptophyceans dominated (70% of the total biomass). Here *Rhodomonas lacustris* was numerically the most abundant species. At Station 16, cryptophyceans made up 34% of the total biomass.

Table 5. Relative proportions of the main phytoplankton groups (%) of the total phytoplankton biomass in 1992–1995 in the different pelagic zones of Lake Ladoga. Pelagic zones (Fig. 1): I = northern; II = central; III = western and IV = southern.

Group	Zone			
	I	II	III	IV
Cyanophyceae	27	40	18	54
Cryptophyceae	55	45	44	21
Dinophyceae	3	4	4	3
Chrysophyceae	4	1	1	1
Diatomophyceae	5	3	21	11
Tribophyceae	5	4	7	3
Chlorophyta	1	3	5	7

At Stations 16 (in the central pelagic zone) and 19 (in the pelagic zone north of Valaam), the phytoplankton biomass was composed of chrysophycean flagellates in addition to cryptophyceans. The biomass of chrysophyceans was high at the deepest station 19 (35% of the total biomass), dominant species being *Uroglena* sp. Station 13 (region II), which is situated in the middle of the lake, deviates from the others due to the smaller total biomass and relatively great abundance of blue-greens (34%–41% of the total biomass at a depth of 0–5 metres).

The greatest biomass was always found in the Sortavala Bay. The biomass values in the surface water were three times greater than in the pelagic zone. Most algae were concentrated in the uppermost 4 m. Variation in species composition in the trophogenic layer was small. Diatoms formed the dominant group in terms of biomass (*Fragilaria crotonensis*, *Diatoma tenuis*, *Cyclotella* spp., *Stephanodiscus hantzchii* and *Aulacoseira* spp.). The blue-greens made up only 15% of the total biomass, the dominant species being *Anabaena planctonica* (Brunnthaler), *Pseudanabaena* spp. and *Anabaena* spp. (Fig. 4).

Discussion

At the time of Balakhontsev's (1909) studies in the early 1900s, the phytoplankton of Lake Ladoga was dominated by diatoms in all seasons. In summer the dominant species were *Tabellaria fenestrata*, *Asterionella formosa* var. *gracillima* Hantz., and *Attheya zachariasi* Brun. Co-dominants included the blue-greens *Aphanizomenon flos-aquae*, *Woronichinia naegeliana*, *Anabaena spiroides* and *A. lemmermannii*. *Sphaerocystis schroeteri* Chod. and *Tribonema (Conferva) depauperatum* (Wille) Bal. were also common during that time. However, the numbers of blue-greens were low in all parts of Lake Ladoga. Right to the 1960s the phytoplankton communities remained almost the same. The trophic state of the lake at that time is difficult to assess because the phytoplankton samples were qualitative (net samples), and no

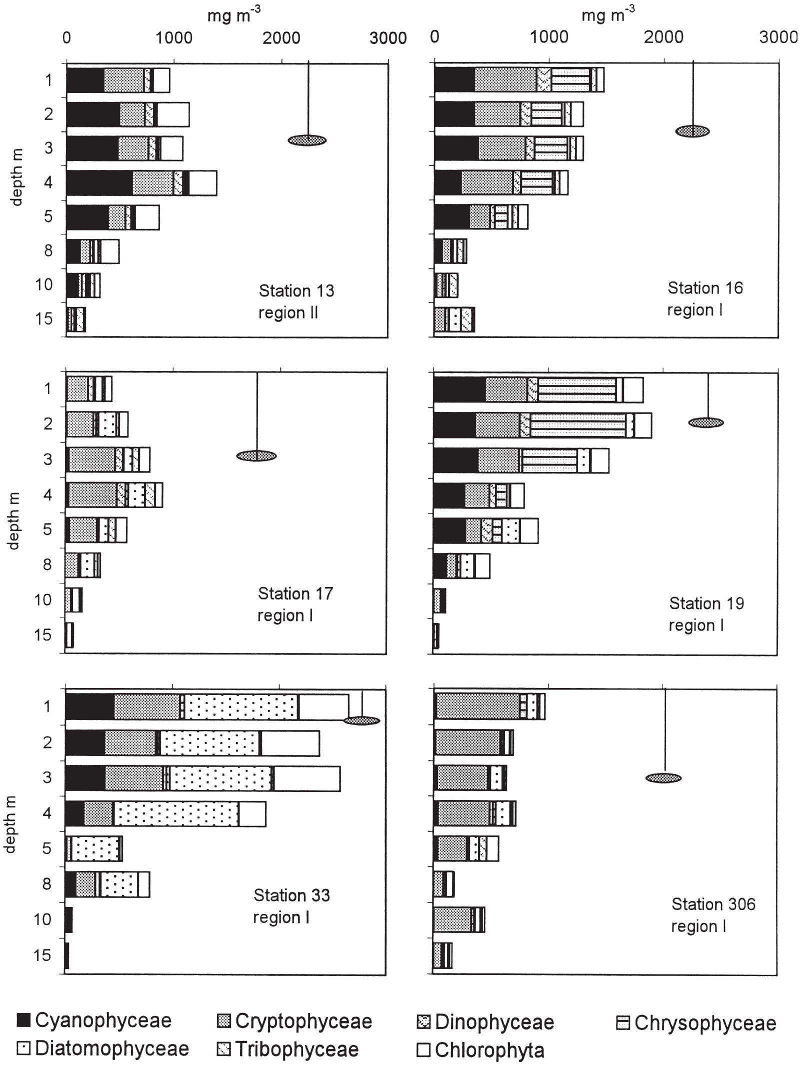

Fig. 4. Vertical distribution of phytoplankton biomass and species composition in Lake Ladoga in 1994 at the Sampling stations 16, 17, 19, 33, 201 and 13. Secchi depth is indicated with a line and ellipse.

data on nutrient contents are available. According to Witting (1929), the Secchi depth of the water was 6 m in the area close to the Vuoksa River and 5.5 m in the central pelagic zone in August at the end of the 19th century. On this basis, the lake could be classified as an oligotrophic lake at that time (Forsberg and Ryding 1980).

In the middle of the 1970s, the amount of blue-green algae increased in summer as a response to an increased nutrient load. The dominant species were *Aphanizomenon flos-aquae, Microcystis aeruginosa* (Kütz emend. Elenk.) and *M. reinboldii* (Petrova 1987). Changes in phytoplankton appeared first in the shallow southern part of the lake and in the bays of the northern part or in the areas of maximum phosphorus load (regions IV and I). Later on, changes could be seen all over the lake (Petrova 1987). *Tribonema affine* West also played an important role in Lake Ladoga during that period (Petrova 1987). The number of diatoms was not significant in summer plankton. Cryptomonadas were not found, probably because they were destroyed in storage with formalin. However, they were reported to occur in the Neva Bay in the middle of the 1980s (Alimov *et al.* 1993). In the 1970s and 1980s signs of eutrophication were seen not only in phytoplankton species composition but also in the growing biomass and in algal primary productivity (Table 3). The maximum mean total phosphorus content (26 mg m^{-3},

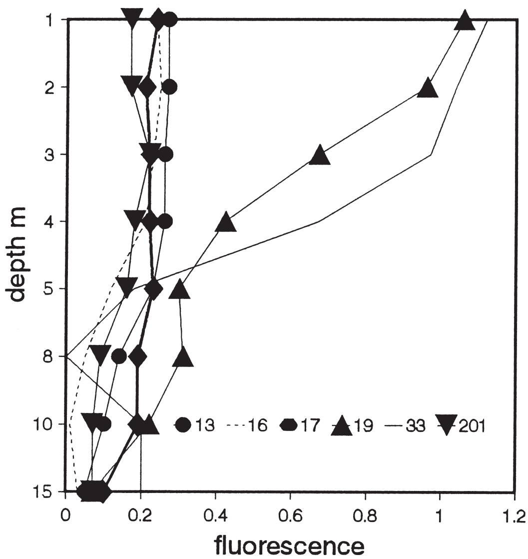

Fig. 5. Vertical distribution of the fluorometer readings in Lake Ladoga in 1994 at Sampling stations 16, 17, 19, 33, 201 and 13.

$n > 100$) was measured during the late 1970s when the mean biomass of algae was six times and maximum values 20 times those of the 1960s (Petrova 1982). The primary productivity of algae also increased two-fold. The eutrophication process was obvious during the 1970s–1980s, and the pelagic zone of Lake Ladoga could be classified as mesotrophic.

In the recent decades the change in species composition of the phytoplankton and the dominance of blue-greens in the summer period was caused by the enrichment of water by nutrients (Petrova 1987, Letanskaya *et al.* 1987, Petrova *et al.* 1992, Holopainen *et al.* 1996). During the last two decades of investigations of Lake Ladoga, no obvious changes in trophic status are evident as regards chlorophyll *a* and primary production, but a tendency towards decreasing phosphorus content has been observed in the 1990's. Our results showed only small changes between years; these were related mainly to temperature. The high water temperature and calm conditions in 1994 explains the higher levels of cyanophyceans, particularly in the central pelagic zone and in the northern archipelago of Lake Ladoga. The effect of the water temperature could also be seen in the mean primary productivity of algae.

At present the numbers of diatoms in summer plankton are small, but diatoms are typical of areas influenced by the large rivers. In areas close to the Vuoksa (region I) and Burnaya (region II) outflows the diatoms dominated (Holopainen *et al.* 1996). Diatoms are good competitors in areas of high nutrient and silica content; the turbulence and the temperature of the water also seem to be important to these algae (Reynolds 1984, Willén 1991). In those areas the temperature of the water is comparable to that in the pelagic zone (Niinioja *et al.* 1997) and thus it does not explain the richness in the above-mentioned areas. According to Petrova (1987), the abundance of diatoms in the pelagic zone of Lake Ladoga increases only after stormy weather. In 1976–79, no differences in silica content in the lake were found between spring and summer: mean 0.37 g m^{-3} in spring and 0.33 g m^{-3} in summer (Raspletina 1982). At the end of the 1980s (0.1–0.2 g m^{-3}, Raspletina, unpublished data) and in 1990 the silica content (0.1–0.3 g m^{-3}, Niinioja *et al.* 1997) decreased in summer and it is now probably limiting for the growth of some diatom species in summertime (Willén 1991).

Many of the diatoms identified are typical of mesotrophic or eutrophic lakes *(Aulacoseira granulata*, *Diatoma tenuis, Fragilaria crotonensis, Synedra actinastroides)*. Palaeolimnological results confirm that these species dominate in heavily polluted areas near pulp and paper mills in Lakes Onega, Ladoga and Saimaa (Davydova 1990, Simola *et al.* 1992, Davydova *et al.* 1993). In the Sortavala Bay, which is loaded mainly by municipal sewage effluents, the dominant diatoms were *Fragilaria crotonensis*, *Diatoma tenuis, Stephanodiscus hantzschii and Cyclotella* spp. Close to the pulp industry, pennate diatoms seem to be more common than in areas loaded by human settlement, where the small centrics were the most abundant. *Stephanodiscus binderanus*, *S. hantzschii* and *Cyclotella meneghiana* Kütz are typical of the Volkhov Bay. *Stephanodiscus binderanus* is commonly found in areas where phosphorus content is high but silica content low (Willén 1991), and, in general, *Stephanodiscus* species have been thought to have high phosphorus requirements (Reynolds 1984), which might explain their limited distribution in Lake Ladoga as well.

Considerable spatial variation was seen in the phytoplankton composition and biomass in Lake

Ladoga. According to Rahkola *et al*. (1997), movements of algae or vertical currents can cause vertical differences in Lake Ladoga; during the dark period, the biomass of cryptophyceans was higher in deeper water (5–10 m) and during daytime the maximum was in the surface 0–5 m. Because Station 17 was sampled during early morning (9 h), the maximum biomass was found in deeper water (4 m). Other stations were sampled during midday or at noon. This maximum was due mainly to large numbers of cryptophyceans (*Rhodomonas lacustris),* which as mobile algae are able to find optimal light conditions and nutrient contents.

The phytoplankton communities in the most nutrient-rich parts of Lake Ladoga, Volkhov and Svir bays and areas close to the Sortavala Bay, have many features in common (Holopainen *et al*. 1996). Blue-greens and greens are typical of these communities. Especially among the green algae, many species indicate eutrophy; for example a great abundance of *Scenedesmus* species is a sign of strong eutrophication (Rosén 1981). *Anabaena circinalis*, *Microcystis aeruginosa, M. wesenbergii* (Kom.) Starmach*, M. viridis* (A. Braun) Lemm.*,* typical blue-greens that indicate eutrophy, were also present in these areas of Lake Ladoga. In the loaded southern areas and close to the Burnaya and Svir rivers the number of eutrophy-indicating species was highest, whereas in the central pelagic zone, in the western areas of the lake and in the northern pelagic zone the number of these species was smaller. Blue-greens dominate in the loaded bays and in areas where the nitrogen: phosphorus ratio is low. The mean nitrogen: phosphorus ratio varied from 19 to 23 at the shore line and from 26 to 39 in the pelagic zone (Niinioja *et al*. 1997), which is comparable to that of large Canadian lakes (Hecky *et al*. 1993). Especially in areas close to the Volkhov (N:P ratio 12) and the Sortavala Bay (N:P ratio 13), the nutrient ratios indicated eutrophic conditions, which favours the development of nitrogen fixing blue-greens and suppresses the growth of other groups.

According to phytoplankton biomass, chlorophyll *a* content and primary productivity, the pelagic zone of Lake Ladoga can be classified as a mesotrophic area. In addition, some eutrophied areas are to be found in the archipelago, for example, in areas close to Sortavala. Natural eutrophication of some bays in this archipelago with restricted water exchange (Impilahti, Haukkalahti) have previously been reported by Letanskaya and Hindák (1992). Areas near the Burnaya River are also classified as eutrophic. Phytoplankton biomass in the Svir and Volkhov bays was unexpectedly low compared to the amount of nutrients (Holopainen *et al*. 1996, Niinioja *et al*. 1966). According to Niinioja *et al*. (1966), heavy metal concentrations were generally low in the Volkhov Bay, but aluminium concentrations were high. It is also possible that toxic effects of other xenobiotics could decrease the biomass in these areas. The main physical factors affecting phytoplankton are turbulence, unstable chemical environment and low transparency, which partly explain the low phytoplankton biomass of that area.

The results of this study support previous observations on the water quality and the state of Lake Ladoga. Only minor changes are expected in the trophic state of the lake in the 1990s. Although the pelagic zone, in particular, has been stable throughout the span of this study, effective control of the anthropogenic load in future is also important in that area. Severe eutrophication, as indicated by increased nutrient levels, high algal biomass and high abundance of blue-greens, is obvious in isolated bays and in areas influenced by large rivers. Effective control of water pollution of those areas, especially in the Volkhov Bay, should be implemented in a way that will sustain the high value of Lake Ladoga as a natural resource.

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