BOREAL ENVIRONMENT RESEARCH 4: 229–238 ISSN 1239-6095
Helsinki 30 September 1999

Trophic gradients and associated changes in the plankton community in two bays of Lake Ladoga

Juha Karjalainen[1)], Minna Rahkola[1)], Anna-Liisa Holopainen[1)], Timo Huttula[2)], Juha Jurvelius[3)], Markku Viljanen[1)], Valentin Avinski[4)], Galina Letanskaya[4)] and Irena Telesh[5)]

[1)] *Karelian Institute, University of Joensuu, P.O. Box 111, FIN- 80101 Joensuu, Finland*
[2)] *Pirkanmaa Regional Environment Centre, P.O. Box 297, FIN-33101 Tampere, Finland*
[3)] *Finnish Game and Fisheries Research Institute, FIN-58175 Enonkoski, Finland*
[4)] *Institute of Limnology, Russian Academy of Sciences, Sevastyanov Street 9, 196199, St. Petersburg, Russia*
[5)] *Zoological Institute, Russian Academy of Sciences, Universitetskaya 1, 199034, St. Petersburg, Russia*

Karjalainen, J., Rahkola, M., Holopainen, A.-L., Huttula, T., Jurvelius, J., Viljanen, M., Avinski, V., Letanskaya, G. & Telesh. I. 1999. Trophic gradients and associated changes in the plankton community in two bays of Lake Ladoga. *Boreal Env. Res.* 4: 229–238. ISSN 1239-6095.

Simultaneous analyses of water quality parameters, and the composition of phytoplankton, crustacean and rotifer assemblages were done at two sampling areas in Lake Ladoga: the Sortavala Archipelago (August 1994 and 1995) and the Bay of Volkhov (August 1994). The samples were taken at stations located at different distances from the main nutrient-loading points in both areas. The plankton communities in the two study areas differed due to differing hydrological conditions and also with respect to the waste water influence. The effect of nutrient loading on the plankton community is evident along the Bay of Sortavala. However, wind-induced currents from the pelagic zone to the bay also affect the structure of the plankton community. In the Bay of Volkhov, high discharge and turbidity as well as the waste waters appear to decrease phyto- and zooplankton biomasses in comparison to those in the Bay of Sortavala.

Introduction

The abundance and biomass of both phytoplankton and zooplankton are largely regulated by the resource base and tend to increase with trophic state of the lake (McCauley and Kalff 1981, Canfield and Jones 1996). In general, phytoplankton abundance correlates positively with nutrient concentrations (Dillon and Rigler 1974, Mazumder 1994, Zhang and Prepas 1996) and zooplankton abundance with phytoplankton abundance (Fasham 1978, McCauley and Kalff 1981, Pace 1986, Canfield and Jones 1996). From the human and economic points of view, increased nutrient loads and eutrophication often lead to ecosystem deterioration. In eutrophicated lake areas, less valuable fish, e.g. cyprinids, dominate, toxic blue-green algae are common and the littoral zones are often covered by dense mats of filamentous algae or other vegetation; effects that are detrimental to fish and fishing, tourism and various leisure activities.

This study is part of the joint Russian-Finnish research programme for evaluating the human impact on the ecosystem of Lake Ladoga (Simola *et al.* 1996). Earlier results concerning the plankton communities of Lake Ladoga have indicated that in the littoral zone the processes of eutrophication are more clearly evident than in the pelagic zone (Petrova 1987, Andronikova 1996). Based on the pelagic phytoplankton (Holopainen *et al.* 1996) and zooplankton communities (Andronikova 1996), Lake Ladoga might be classified as mesotrophic, but eutrophic areas exist in the northern archipelago of the lake and in areas influenced by the large inflowing rivers (Holopainen *et al.* 1996). Eutrophication has also affected the fish populations, notably those that spawn in autumn (Kudersky *et al.* 1996).

In this study, our aims were: (1) to measure the trophic gradient sustained by the nutrient loadings from human activities in two bays of Lake Ladoga, (2) to analyse the effect of nutrient gradient on phytoplankton and zooplankton assemblages, and (3) to determine the zone of influence of nutrient loading on plankton by using information on water currents.

Study area

Lake Ladoga is a large (17 891 km^2; 837 km^3), open and deep lake with a mean depth of 46.8 m and a maximum depth of 230 m (Sorokin *et al.* 1996). The 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, of which 75% is located in Russia and 25% in Finland.

Both the study areas, the Sortavala Archipelago and the Bay of Volkhov (Fig. 1), receive large loads of waste waters. Waste water from human settlements dominate in the areas close to the town of Sortavala, while in the Bay of Volkhov, the chemical industry and agriculture together with human settlements are the most important sources of polluted water (Raspletina *et al.* 1987). In the Bay of Volkhov, the water is also turbid (3.5 FTU (Formazine turbidity units)) and the phosphorus load (2 000–3 000 t a^{-1}, Drabkova *et al.* 1996) brought by the Volkhov river is much higher than in the Sortavala area.

Material and methods

In August 1994 and 1995 (in the Bay of Volkhov only in 1994), water quality and phytoplankton samples were taken from the water column of 0–10 m, zooplankton samples were sampled from the whole water column (0–10 m, 10–20 m and 20 m–bottom) and fish density was estimated by echosoundings. At sites with total depth of water < 10 m, samples were taken from surface to bottom. In the Sortavala Archipelago and in the Bay of Volkhov there were 8 and 13 sampling stations, respectively, located at various distances from the main nutrient-loading point (Fig. 1). All samples were gathered during the daytime. Water quality was analysed according to the methods of the National Board of Waters and the Environment (1981).

Each phytoplankton sample consisted of ten lifts with a Limnos-type sampler. The collective sample of ca. 70 l was mixed in a vial and subsampled with a glass bottle (Holopainen *et al.* 1996). Water temperature and Secchi depth were measured at each station.

Zooplankton samples were taken with a Limnos tube sampler, a plankton pump and net (Juday net with a 120 µm mesh, mouth diameter 25 cm, total length 120 cm) (Rahkola *et al.* 1994). A composite sample taken with the plankton pump or the tube sampler (6.8 litres) included 10 or 20 lifts from the 0–5 m, 5–10, 10–20 m and 20 m–bottom depth zones. The number of vertical samples was dependent on the total depth of the sampling station. The samples were concentrated with a 50 µm net and preserved in 70% ethanol and

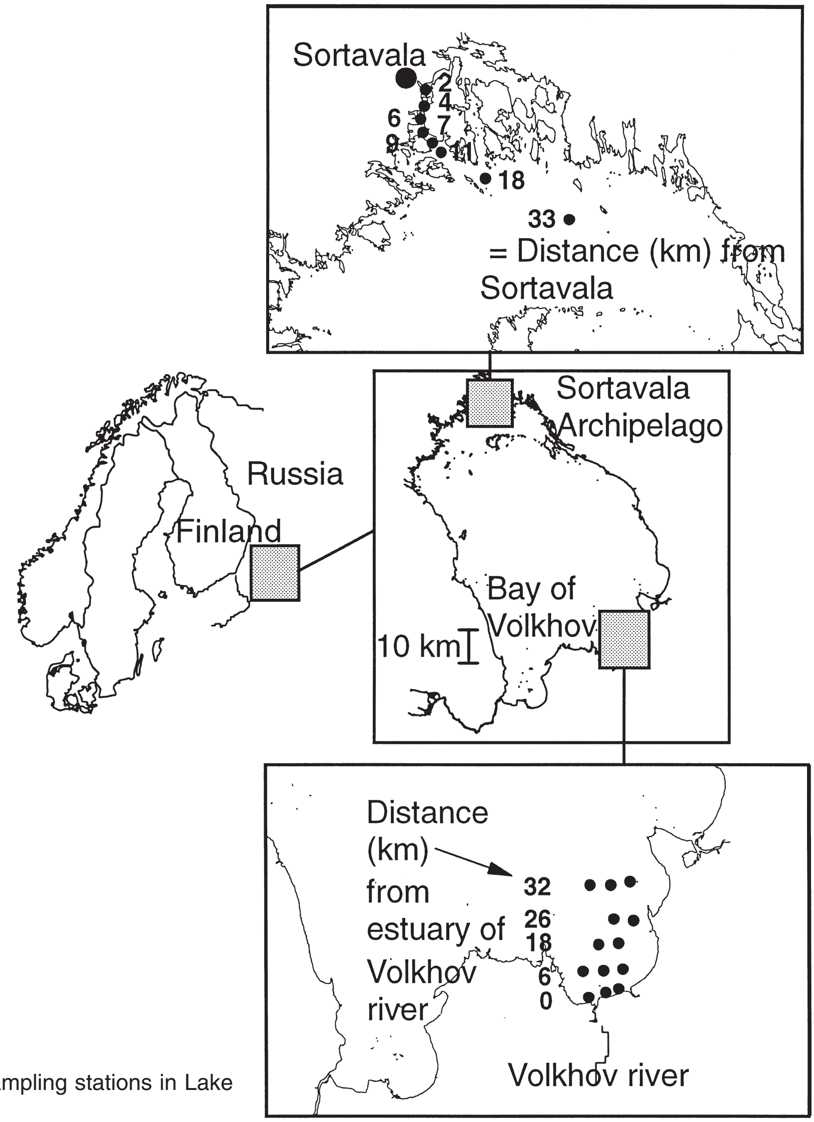

Fig. 1. Study areas and sampling stations in Lake Ladoga.

later in the laboratory in formaldehyde. Rotifer samples were taken by a plankton sampler from the 0–10 m layer at each sampling station: 68 l of water was filtered through a 50 µm mesh plankton net and the samples were preserved in 4% formaldehyde. The counting procedures were previously described in detail by Karjalainen *et al.* (1996). Individual body masses of rotifers (wet weight) were calculated from average body lengths with the formulae of Ruttner-Kolisko (1977) and converted to carbon values according to the factor Carbon mass = Fresh mass × 0.05527 (data from Dumont *et al.* 1975 and Salonen *et al.* 1976). The individual carbon masses of crustaceans were based on our own measurements made in 1995. Phytoplankton biomass was converted to carbon mass according to the conversion factor 0.14 mgC mm^{-3} ww of Olsen *et al.* (1983).

In 1995, the total density of fish in the whole water column of the sampling sites in the Sortavala Archipelago was measured with a Simrad EY-M single-beam (70 kHz, 11°) echosounder. The echosurveys were conducted simultaneously with the water and plankton sampling with a small (4 m) boat that cruised for about 15 minutes at a speed of 3 m s^{-1} in each sampling site between 3 p.m.

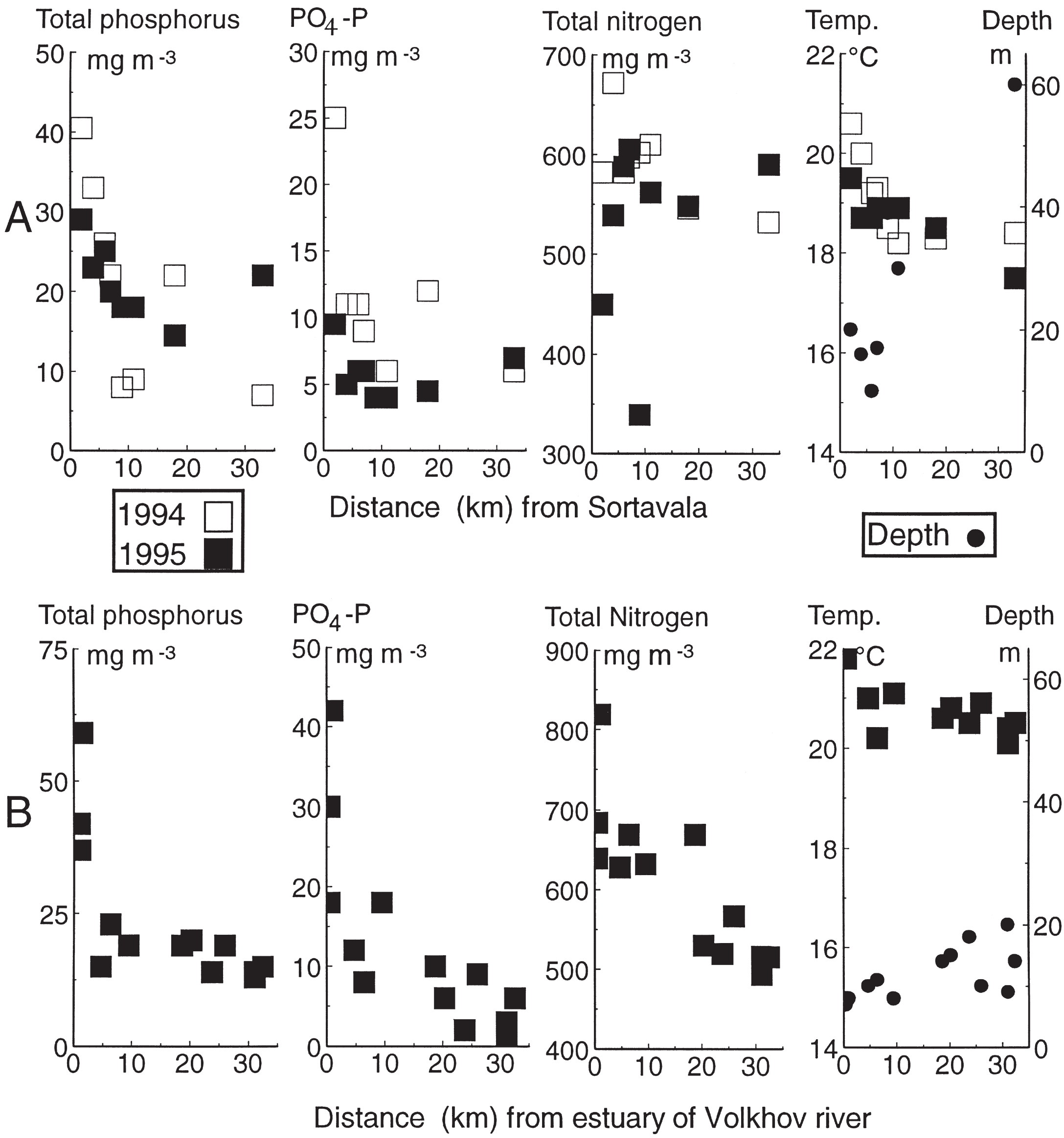

Fig. 2. Total phosphorus, phosphate phosphorus and total nitrogen concentrations at the sampling stations of the Sortavala Archipelago (A) and the Bay of Volkhov (B) in 1994 and 1995. Water temperature and total depth of the water (solid circles) are also given.

and 7 p.m. A more detailed description of the sounder and echocounting system is given by Lindem (1983), Bayona (1984) and Jurvelius (1991).

A numerical finite element flow model (Podsetchine *et al*. 1995, and unpublished data of V. Podsetchine and T. Huttula) was used for modelling the steady-state patterns of water flow under different wind conditions.

Relationships between the distance of the sampling stations from the main loading point and the different variables of plankton and nutrient concentrations were analysed by Spearman nonparametric correlation analysis. The data from three one-day sampling surveys are presented: two sets of data from the Sortavala Archipelago and one from the Bay of Volkhov.

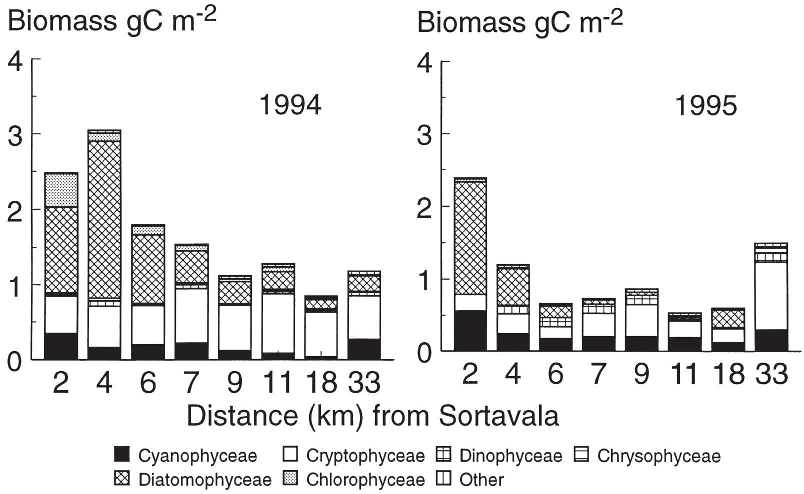

Fig. 3. Biomass of phytoplankton at the sampling stations of the Sortavala Archipelago in August 1994 and 1995.

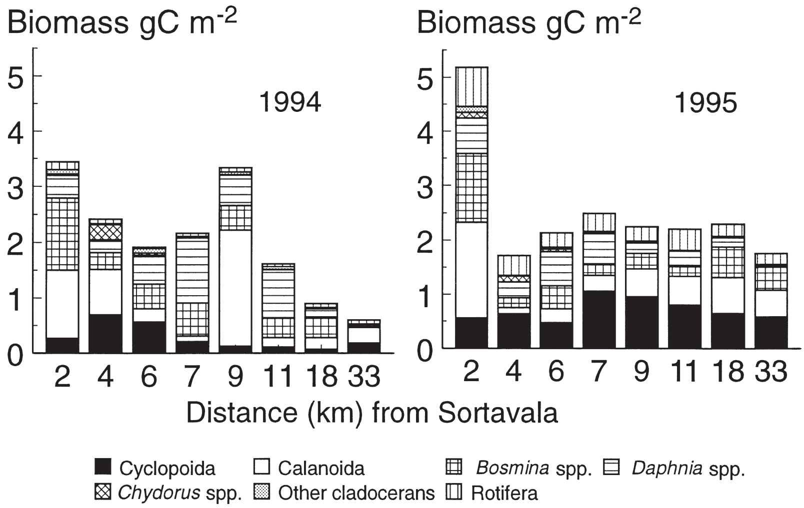

Fig. 4. Biomass of zooplankton at the sampling stations of the Sortavala Archipelago in August 1994 and 1995.

Results

Clear trophic gradients were observed in the water quality and the biological variables in both study areas; nutrient concentrations decreased with increasing distance from the main loading points (Fig. 2). In 1994 in the Sortavala Archipelago, total phosphorus (r_s = Spearman correlation coefficient = –0.874 , $p < 0.05$), phosphate phosphorus concentrations ($r_s = –0.518, p < 0.05$), water temperature ($r_s = –0.881, p < 0.05$) and total phytoplankton biomass ($r_s = –0.857, p < 0.05$) as well as total zooplankton biomass ($r_s = –0.833, p < 0.05$) were negatively correlated with the distance of the sampling station ($n = 8$) from the town of Sortavala (Figs. 3 and 4). In 1995, total phosphorus concentrations ($r_s = –0.731, p < 0.05$) decreased from Sortavala to the pelagic stations, whereas the pattern was statistically not significant for total phytoplankton ($r_s = –0.381, p > 0.05$) or zooplankton ($r_s = –0.333, p > 0.05$) biomasses. However, at the station located near Sortavala (2 km) the phytoplankton and zooplankton biomasses were much higher than at the other stations. The distance from the nutrient-loading point (Sortavala) did not explain the variation in total nitrogen ($r_s =$ –0.431, $p > 0.05$ in 1994 and $r_s = 0.357, p > 0.05$ in 1995), nor NO_2-NO_3 concentrations ($r_s = 0.321$,

$p > 0.05$ in 1994 and $r_s = 0.695$, $p > 0.05$ in 1995). Total depth ($r_s = 0.762$, $p < 0.05$) and visibility (Secchi depth, $r_s = 0.964$, $p < 0.05$) of the water at the sampling stations increased from the site near Sortavala to that in the pelagic zone.

The highest density of fish (9 300 fish ha^{-1}) was observed near Sortavala and the lowest density (3 300 fish ha^{-1}) at the farthest sampling station. The total fish density decreased in relation to the distance from the main loading point in 1995 ($r_s = –0.785$, $p < 0.05$; no samples in 1994). The most fish were observed in the epilimnion, and the depth at which the densities were highest is given in Table 1.

Diatoms (*Diatoma tenuis* Agardh, *Aulacoseira* spp., *Fragilaria* spp.) and Cryptophyceae species: (*Rhodomonas lacustris* Pascher et Ruttner, *Katablepharis ovalis* Skuja, *Cryptomonas* spp.) made up the major part of the phytoplankton biomass in the bay of Sortavala. In 1994 and 1995, diatoms ($r_s = –0.952$, $p < 0.05$) and chlorophyceans ($r_s = –0.952$, $p < 0.05$) decreased along the trophic gradient. The biomass of only one zooplankton species, *Chydorus sphaericus* (O.F. Müller), correlated negatively with distance from the main loading point ($r_s = –0.928$, $p < 0.05$). The biomasses of the other phytoplankton (Chrysophyceae, Conjugatophyceae Cryptophyceae, Cyanophyceae, Dinophyceae, Tribophyceae) and zooplankton (*Bosmina* spp., calanoids, cyclopoids, *Daphnia* spp., other cladocerans, rotifers) taxa were independent of the distance from Sortavala. In the Sortavala Archipelago, the dominant species at all stations were *Conochilus unicornis* Rousselet, *Keratella cochlearis* Gosse, phytophagous *Polyarthra* spp., and *Trichocerca* spp. (mainly *T. cylindrica* Imhof and *T. capucina* Wierz).

In the Bay of Volkhov ($n = 13$), concentrations of total phosphorus ($r_s = –0.785$, $p < 0.05$), phosphate phosphorus ($r_s = –0.833$, $p < 0.05$) and total nitrogen ($r_s = –0.863$, $p < 0.05$) as well as water temperature ($r_s = –0.742$, $p < 0.05$) correlated negatively with distance of the sampling station from the estuary of the Volkhov river (Fig. 2). The distance from the nutrient-loading point did not explain the variation in NO_2-NO_3 concentrations ($r_s = –0.138$, $p > 0.05$). In the same way as in Sortavala Archipelago, total depth ($r_s = 0.667$, $p < 0.05$) and visibility (Secchi depth, $r_s = 0.532$, $p < 0.05$) of water at the sampling stations increased from the estuary of the Volkhov river to the pelagic zone.

In the Bay of Volkhov, total biomass of phytoplankton ($r_s = –0.262$, $p > 0.05$) and zooplankton was independent ($r_s = 0.226$, $p > 0.05$) of the distance from the main nutrient loading point (Fig. 5). Furthermore, the phytoplankton biomass at the stations near the estuary of the Volkhov river was lower than expected on the basis of nutrient concentrations. If the observed total phosphorus concentrations in the estuary of the Volkhov river had been used, the total phytoplankton biomass (PHB) — total phosphorus (TOTP) regression for the Sortavala Archipelago ($PHB = 0.4489 \times TOTP^{0.4713}$, $r^2 = 0.816$, $n = 8$, $p > 0.01$) — would have resulted in phytoplankton biomasses that were 2–3 times higher than the observed values.

Cryptophyceaean species (*Rhodomonas lacustris, Cryptomonas* spp.) and blue-green algae (*Aphanizomenon flos-aquae* (Linné) Ralfs, *Woronichinia naegeliana* (Unger) Elenkin, *Microcystis reinboldii* (Richter) Forti) comprised the major part of phytoplankton biomass in the

Table 1. Depth of the water layer with the highest fish density ("maximum layer"), density of fish in this layer and total density of fish (individuals ha^{-1}) at the different sampling stations in the Sortavala Archipelago, Lake Ladoga.

Distance from Sortavala (km)	Depth of maximum layer (m)	Fish density in maximum layer (ind. ha^{-1})	Total fish density (ind. ha^{-1})
2	4–10	4 110	6 600
4	4–11	9 300	9 300
6	6–18	4 700	5 700
7	6–15	7 900	7 900
9	8–17	3 400	4 300
11	7–19	3 100	3 700
18	13–22	2 100	3 300

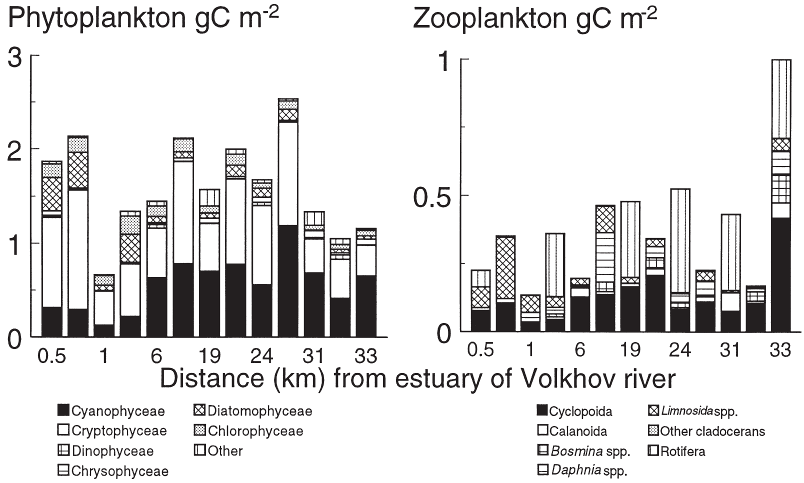

Fig. 5. Biomass of phytoplankton and zooplankton at the sampling stations of the Bay of Volkhov in August 1994.

Bay of Volkhov. Despite the fact that the biomass of total phytoplankton was independent of the distance, diatoms (r_s = –0.686, p < 0.05) and chlorophyceans (r_s = –0.821, p < 0.05) decreased and blue-greens (r_s = 0.543, p < 0.05) increased significantly from the estuary to the pelagic zone. Among zooplankton, the biomass of *Limnosida frontosa* Sars (r_s = –0.928, p < 0.05) correlated negatively and the biomass of calanoids (r_s = 0.675, p < 0.05) positively with distance from the main loading point. The biomasses of other phytoplankton and zooplankton taxa were independent of distance from the estuary of the Volkhov river.

Discussion

The nutrient concentrations decreased along the expected gradient from the waste-water loading point in the bays of Sortavala and Volkhov to the pelagic zone. The trophic gradient could be assumed to be sustained by nutrient loadings from human activities. The properties of the gradient, e.g. the extent of the zone of influence and the stability of the gradient, is regulated by the morphometry and hydrological conditions of the receiving water area, and the intensity and quality of the nutrient loading (Huttula *et al.* 1996). In addition, the composition of the plankton food webs may regulate the final response of the water ecosystems to nutrient loading (Sager and Richman 1991, Elser and Goldman 1991, Karjalainen *et al.* 1996).

In the Bay of Sortavala, the difference in the distribution of the plankton biomass and nutrient gradient between the years 1994 and 1995 was due to the wind-induced water currents, which regulated the area of influence of the nutrient loading. Easterly and southeasterly winds dominated in 1994 during and before the sampling period, and wind-induced currents in Sortavala Bay flowed from the town of Sortavala to the south according to the model of Podsetchine *et al.* (1995) and Huttula *et al.* (1996) (Fig. 6). The effects of trophic gradient on plankton could be observed at the stations located within about 7–9 km from the town. In 1995, westerly, southwesterly and southerly winds induced currents which flowed in the opposite direction bringing water from the pelagic zone to the bay, and changed the structure of the plankton community in the bay towards that of the pelagic community. As was shown recently, so far, anthropogenic eutrophication and pollution of Lake Ladoga seem not to have affected the macrophyte-associated zooplankton communities (Kurashov *et al.* 1996). In fact, the coastal areas of Lake Ladoga are affected by human activities, but the periodical exchange of water between the coastal areas and the large body of water in the middle of the pelagic zone (Beletsky 1996, Leonov *et al.* 1996) decrease the potential problems caused by the local waste water loadings.

Both phytoplankton and zooplankton density and biomass are usually positively related to lake trophy (Pace 1986, Sager and Richman 1991). In our study areas, the nutrient gradient regulated the phytoplankton biomass and species composition. The biomass of diatoms was strongly related to the total phosphorus concentrations when wind

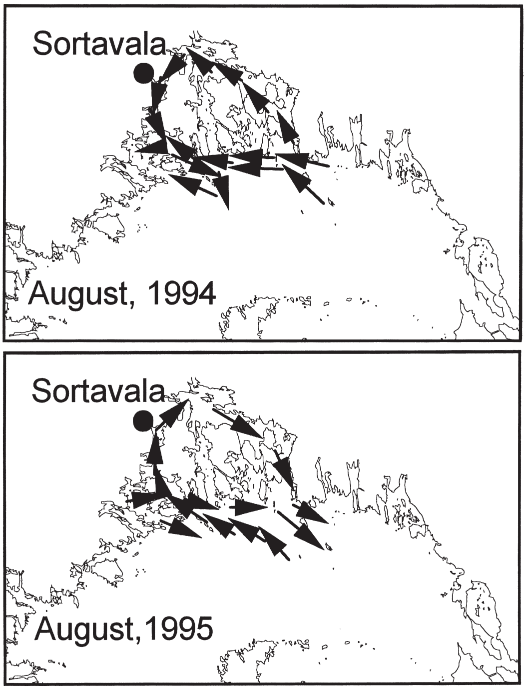

Fig. 6. Water currents in the Sortavala Archipelago in August 1994 and 1995 according to the simulations model of Podsetchine *et al.* (1995). Prevailing winds registered at the airport of Lappeenranta during the 5-day period were western to south-western in 1994, and south-eastern to eastern in 1995.

conditions let the nutrient-rich water flow from Sortavala to the south along the bay. The fish density decreased from Sortavala to the pelagic zone, and the highest densities of fish were observed in the epilimnion where the primary production occurs in humic and brownish water lakes (Huovinen *et al.* 1992). Thus, the fish populations also seem to be regulated by the nutrient gradient and the feeding conditions. Among zooplankton in our study areas, the abundance of only two species (*Chydorus sphaericus* and *Limnosida frontosa*) correlated with the observed nutrient gradient. Flössner (1972) noticed that *C. sphaericus* lives in oligotrophic lakes near the bottom or in the littoral zone and its distribution is probably affected by the water depth. On the other hand, Viljanen and Karjalainen (1993) observed that *C. sphaericus* was as common in the pelagic zone of Lake Pyhäselkä (Finland) as in the littoral zone and the densities of *Limnosida* were higher in the pelagic zone than in the littoral zone. Although the effect of nutrient gradient seems to be significant, also the temperature gradient and the effect of the water depth influence the composition of plankton. These three components together shape the trophic gradient and, thus, plankton community in the form which we observed it.

Copepods, especially calanoids, are the dominant crustaceans in the communities of the pelagic zone of large lakes (Sager and Richman 1991, Carter *et al.* 1995, Andronikova 1996) and under meso-oligotrophic conditions (Sager and Richman 1991, Elser and Goldman 1991, Maier 1996). An increase in the abundance of calanoids could be also observed in our data, although our sampling stations were not located in the middle of the pelagic zone of Lake Ladoga where copepods make up over 70% of the zooplankton biomass (Andronikova 1996) and cryptophyceans are the dominant phytoplankton species (Holopainen *et al.* 1996). This clear discrepancy between inshore and pelagic communities is commonly found in several large lakes (Johannsson *et al.* 1991, Carter *et al.* 1995).

In the Bay of Volkhov, the water temperature and nutrient concentrations were higher but the phytoplankton biomasses lower than in the Bay of Sortavala. The species composition of phytoplankton differed between the study areas: in the Bay of Volkhov, cryptophyceans and blue-greens dominated and in the Bay of Sortavala, diatoms and cryptophyceans dominated. The Volkhov river transports high concentrations of dissolved substances to the estuary, and the visibility of water in the Bay of Volkhov is lower than in our northern study area. Algae that are capable of heterotrophic metabolism, such as cryptophyceans, thrive under such conditions (Haffner *et al.* 1980). Dirnberger and Threlkeld (1986) noted that during the period of flooding of the Red River (USA), most zooplankton populations declined due to the increased inflow to the river and to turbidity. The Volkhov river, however, is also loaded by chemical industry; and in the Bay of Volkhov contamination e.g. by heavy metals and chloro-organic compounds has been observed in the water and sediments (Frumin *et al.* 1996, Vorobieva *et al.* 1996). Inhibition of plankton growth and decreased survival caused by these toxicants (Moore and Ramamoorthy 1984, Walsh and Merrill 1984, Whitton 1984) may be one factor which lowers the biomass of phytoplankton in the Bay of Volkhov. The inflow of the Volkhov river turns east in the generally prevailing wind conditions, and the effect of inflowing water is greatest near the eastern coastal areas of the Bay of Volkhov (V. Podsetchine and T. Huttula, unpublished results).

In summary, the plankton communities of the Sortavala Archipelago and the Bay of Volkhov were found to differ, due to differences in the location and hydrological conditions of the study area but also due to differences in the content of waste waters discharging into the two bays. The effect of nutrient loading on the plankton community can be observed along the Bay of Sortavala, but wind-induced currents may bring water from the pelagic zone to the bay and change the structure of the plankton community. Finally, in the Bay of Volkhov, high discharge, high turbidity and the effects of waste waters seem to affect the phytoplankton and zooplankton biomasses in the estuary.

Acknowledgements: This study was financed by the Academy of Finland, the Finnish Ministry of the Environment, the University of Joensuu and the Russian Academy of Sciences. The simplified maps of flow fields were drawn according to the original, unpublished data of Dr. T. Huttula and Dr. V. Podsetchine, Regional Environmental Agency of Pirkanmaa, Finland. The English was checked by Ph.D. Joann von Weissenberg.

References

Andronikova I. 1996. Zooplankton characteristics in monitoring of Lake Ladoga. *Hydrobiologia* 322: 173–179.

Bayona J.D.R. 1984. Comparison of acoustics survey systems for use in developing countries. In: Mitson R.B. (ed.), *Acoustic systems for the assessment of fisheries*. Rome. FAO Fish. Circ. 778: 1–19.

Beletsky D.V. 1996. Numerical modelling of large-scale circulation in Lakes Onega and Ladoga. *Hydrobiologia* 322: 75–80.

Canfield T.J. & Jones J.R. 1996. Zooplankton abundance, biomass, and size-distribution in selected midwestern waterbodies and relation with trophic state. *J. Freshw. Ecol.* 11: 171–181.

Carter J.C.H., Taylor W.D. & Tudorancea C. 1995. A horizontal gradient in zooplankton community structure, and its implications for the relationships among mesozooplankton, microzooplankton, and phytoplankton. *Arch. Hydrobiol.* 133: 197–222.

Dillon P.J. & Rigler F.H. 1974. The phosphorus-chlorophyll relationships in lakes. *Limnol. Oceanogr.* 19: 767–773.

Dirnberger J. & Threlkeld S. 1986. Advective effects of a reservoir flood on zooplankton abundance and dispersion. *Freshw. Biol.* 16: 387–396.

Drabkova V.G., Rumyantsev V.A., Sergeeva L.V. & Slepukhina T.D. 1996. Ecological problems of Lake Ladoga: causes and solutions. *Hydrobiologia* 322: 1–7.

Dumont H.J., van de Velde I. & Dumont S. 1975. The dry weight estimate of biomass in a selection of Cladocera, Copepoda and Rotifera from the plankton, periphyton and benthos of continental waters. *Oecologia* 19: 75–97.

Elser J.J. & Goldman C.R. 1991. Zooplankton effects on phytoplankton in lakes of contrasting trophic status. *Limnol. Oceanogr.* 36: 64–90.

Fasham M. 1978. The statistical and mathematical analysis of plankton patchiness. *Oceanogr. Mar. Biol. Ann. Rev.* 16: 43–79.

Flössner D. 1972. *Krebstiere: Branchiopoda & Branchiura*. Die Tierwelt Deutschlands 60: 1–501.

Frumin G.T., Chernykh O.A., Krylenkova N.L. & Scherbak V.A. 1996. Lake Ladoga: chemical pollution and biochemical self-purification. *Hydrobiologia* 322: 143–147.

Haffner G.D., Harris G.P. & Jarai M.K. 1980. Physical variability and phytoplankton communities. III Vertical structure in phytoplankton populations. *Arch. Hydrobiol.* 89: 363–381.

Holopainen A.-L., Huttunen P., Letanskaya G. & Protopopova E. V. 1996. The trophic state of Lake Ladoga as indicated by late summer phytoplankton. *Hydrobiologia* 322: 9–16.

Huttula T., Koponen J., Lehtinen K., Wahlgren A. & Niinioja R. 1996. Water currents and spreading of river load in Lake Pyhäselkä, Saimaa, Finland. *Hydrobiologia* 322: 117–124.

Huovinen P., Holopainen A.-L. & Huttunen P. 1992. Spatial variation of community respiration and primary productivity in two large lakes. *Verh. Internat. Verein. Limnol.* 25: 552–556.

Johannsson O.E., Mills E.L. & O'Gorman R. 1991. Changes in the nearshore and offshore zooplankton communities in Lake Ontario: 1981–88. *Can. J. Fish. Aquat. Sci.* 48: 1546–1557.

Jurvelius J. 1991. Distribution and density of pelagic fish stocks, especially vendace (*Coregonus albula* (L.)), monitored by hydroacoustics in shallow and deep southern boreal lakes. *Finnish Fish. Res.* 12: 2–19.

Karjalainen J., Holopainen A.-L. & Huttunen P. 1996. Spatial patterns and relationships between phytoplankton, zooplankton and water quality in the Saimaa lake system, Finland. *Hydrobiologia*. 322: 267–276.

Karjalainen J., Rahkola M., Viljanen M., Andronikova I. N. & Avinskii V. A. 1996. Comparison of methods used in zooplankton sampling and counting in the joint Russian–Finnish evaluation of the trophic state of Lake Ladoga. *Hydrobiologia*. 322: 249–253.

Kirillova V.A. [Кириллова В.А.] 1987. Vodnyi pritok [Water currents]. In: Petrov N. A. & Raspletina G. A. (eds.), [*Present state of Lake Ladoga ecosystem*]. Nauka, Leningrad, pp. 23–27. [In Russian].

Kudersky L.K., Jurvelius J., Kaukoranta M., Tuunainen P. & Mäkinen K. 1996. Fishery of Lake Ladoga — past, present and future. *Hydrobiologia* 322: 57–64.

Kurashov E.A., Telesh I. V., Panov V.E., Usenko N.V. & Rychkova M.A. 1996. Invertebrate communities associated with macrophytes in Lake Ladoga: the effects of environmental factors. *Hydrobiologia* 322: 49–55.

Leonov A.V., Filatov N.N. & Titov V.S. 1996. The estimation of current state of Lake Ladoga using mathematical models. *Hydrobiologia* 322: 103–108.

Lindem T. 1983. Successes with conventional in situ determinations of fish target strength. In: Nakken O. & Venema S.C. (eds.), *Symposium on fisheries acoustics. Selected papers of the ICES/FAO Symposium on fisheries acoustics. Bergen, Norway, 21–24 June 1982.* Rome. FAO Fish. Rep. 300: 104–111.

Maier G. 1996. Copepod communities in lakes of varying trophic degree. *Arch. Hydrobiol.* 136: 455–465.

Mazumder A. 1994. Phosphorus-chlorophyll relationships under contrasting herbivore and thermal stratification: predictions and patterns. *Can. J. Fish. Aquat. Sci.* 51: 390–400.

McCauley E. & Kalff J. 1981. Empirical relationships between phytoplankton and zooplankton biomass in lakes. *Can. J. Fish. Aquat. Sci.* 38: 458–463.

Moore J.W. & Ramamoorthy S. 1984. *Heavy metals in natural waters*. Springer-Verlag. New York, Berlin, Heidelberg, Tokyo, 268 pp.

National Board of Waters and the Environment 1981. *Vesihallinnon analyysimenetelmät*. Publ. Nat. Board of Waters, Finland. Report 213: 1–136.

Olsen Y., Jensen A., Reinertsen H. & Rugstad K. 1983. Comparison of different algal carbon estimates by use of the Drop-model for nutrient limited growth. *J. Plankton Res.* 5: 43–51.

Pace M.L. 1986. An empirical analysis of zooplankton community size structure across lake trophic gradients. *Limnol. Oceanogr.* 31: 45–55.

Petrova N. 1987. The phytoplankton of Ladoga and Onega lakes and its recent successional changes. *Arch. Hydrobiol. Beih. Ergebn. Limnol.* 25: 11–18.

Podsetchine V., Huttula T. & Filatov N. 1995. Water exchange in the straits of northern Ladoga: results of field and numerical simulations. *Phys. Chem. Earth* 20: 207–213.

Rahkola, M., Karjalainen, J., & Viljanen, M. 1994. Evaluation of pumping system for zooplankton sampling. *J. Plankton Res.* 16: 905–910.

Raspletina G.F., Murashova E.B., Tregubova T.M., Kulish P.P. & Chernykh O.A. [Расплетина Г.Ф., Мурашова Е.Б., Трегубова Т.М., Кулиш П.П. & Черных О. А] 1987. Gidrokhimichetskaya kharakteristika pritokov [Hydrochemical characteristics of the inflowing waters]. In: Petrov N. A. & Raspletina G. A. (eds.), [*Present state of Lake Ladoga ecosystem*]. Nauka, Leningrad: 27–42. [In Russian].

Ruttner-Kolisko A. 1977. Suggestion for biomass calculation of planktonic rotifers. *Arch. Hydrobiol. Beih. Ergebn. Limnol.* 8: 71–76.

Sager P.E. & Richman S. 1991. Functional interaction of phytoplankton and zooplankton along the trophic gradient in Green Bay, Lake Michigan. *Can. J. Fish. Aquat. Sci.* 48: 116–122.

Salonen K., Sarvala J., Hakala I. & Viljanen M.-L. 1976. The relation of energy and organic carbon in aquatic invertebrates. *Limnol. Oceanogr.* 21: 724–730.

Simola H., Viljanen M., Slepukhina, T. & Murthy, R. (eds.) 1996. *Proceedings of the First International Lake Ladoga Symposium: Ecological Problems of Lake Ladoga.* Hydrobiologia 322/Developments in Hydrobiology 113, 328 pp.

Sorokin A.I., Naumenko M.A. & Veselova M.F. 1996. New morphometrical data of Lake Ladoga. *Hydrobiologia* 322: 65–67.

Vorobieva L.V., Selyuzhitskii G. V. & Chernova G. I. 1996. Ecologic and hygienic evaluation of Lake Ladoga as a source of drinking water. *Hydrobiologia* 322: 137–141.

Walsh G.E. & Merrill R.G. 1984. Algal bioassays of industrial and energy process effluents. In: Shubert L.E. (ed.), *Algae as ecological indicators*. Academic Press Ltd. London, pp. 329–360.

Whitton B.A. 1984. Algae as monitors of heavy metals in freshwaters. In: Shubert L.E. (ed.), *Algae as ecological indicators*. Academic Press Ltd. London, pp. 257–280.

Viljanen M. & Karjalainen J. 1993. Horizontal distribution of zooplankton in two large lakes in Eastern Finland. *Verh. Internat. Verein. Limnol.* 25: 548–551.

Zhang Y. & Prepas E.E. 1996. Regulation of the dominance of planktonic diatoms and cyanobacteria in four eutrophic hardwater lakes by nutrients, water column stability, and temperature. *Can. J. Fish. Aquat. Sci.* 53: 621–633.

Received 29 August 1996, accepted 1 September 1997