Estonian Journal of Ecology, 2008, **57**, 3, 214–228 doi: 10.3176/eco.2008.3.04

The pelagic food web in forest lakes affected by alkaline mining waste in NW Russia

Ismo J. Holopainen[a✉], Anna-Liisa Holopainen[a], Eeva Huitu[b], Minna Rahkola-Sorsa[a], and Priit Zingel[c]

[a] Faculty of Biosciences, University of Joensuu, P.O. Box 111, FI-80101 Joensuu, Finland
[b] Lammi Biological Station, University of Helsinki, FI-16900 Lammi, Finland
[c] Estonian University of Life Sciences, Kreutzwaldi 64, 51014 Tartu, Estonia

✉ Corresponding author, Ismo.Holopainen@joensuu.fi

Received 15 May 2008

Abstract. The wastewaters of an iron mining company in NW Russia have changed the water quality in some forest lakes to be hard with a high pH, in contrast to the soft water and low pH in natural lakes. Two impacted lakes and a reference lake were sampled once in early August in three successive years for water quality, plankton communities, and fish. The concentrations of potassium, lithium, and sulphate were high in the impacted lakes. Total phosphorus was low (~10 µg L^{-1}) in all lakes. The primary producers' biomass and chlorophyll *a* content in the impacted lakes were high because of high densities of autotrophic picocyanobacteria (*Synechococcus* spp.). All planktonic communities showed a changed taxa composition and lower species richness. Zooplankton was predominantly Rotatoria in all the lakes. In the impacted lakes, Cladocera was represented by *Bosmina*, and Copepoda by small cyclopoids. The most obvious substance to be harmful to some planktonic species was potassium. The high pH and high mineral content of the water obviously lower both the toxicity and the bioavailability of heavy metals in the impacted lakes.

Key words: alkaline mining waste, picocyanobacteria, *Synechococcus*, phytoplankton, Ciliata, zooplankton.

INTRODUCTION

Industrial wastewaters often have harmful effects on recipient lakes. For example, acidic mine drainage with a low pH and high metal contents often causes serious ecological damage (e.g. Niinioja et al., 2003). Since 1984 the JSC Karelsky Okatysh mining company in the Kostomuksha area (64°43′ N, 30°58′ E) in Karelia, NW Russia, has extracted and processed magnetite ore into iron pellets (7.6 million tonnes in 2004). The company affects the environment by air pollution (SO_2 and dust) and alkaline wastewater emissions. Since 1994 wastewaters (approx. 10–20 million m^3 y^{-1}; Lozovik et al., 2001) from a dammed basin and from open mining pits (2–3 million m^3 y^{-1}) have been allowed to flow a distance of 75 km through a number of small lakes and the Kenti River to the larger lake Middle Kuito. Waste flow represents approximately 8% of the mean discharge of 8.21 m^3 s^{-1} (Kukharev et al., 1995) at the river outlet. Data on water quality and biota in this water course have been given e.g. in Virtanen & Markkanen (2000), Lozovik et al. (2001), and Kalinkina et al. (2003). Preliminary results on the food web are given e.g. in Holopainen et al. (2003b).

This paper analyses the structure of the planktonic food web in two lakes impacted by wastewaters in comparison to a reference lake. The fish faunas are similar but the catch-per-unit-effort is two-fold higher in the impacted lakes, while the water chemistry and plankton communities are drastically changed, suggesting that food chain characteristics underpin this apparently successful fish life.

STUDY SITE, MATERIAL, AND METHODS

Lakes Poppalijärvi (1.7 km^2, ca. 4 km downstream from the waste basin) and Kento (27.1 km^2, ca. 20 km downstream) are oligotrophic and mesohumic (Secchi depth 2–3 m) forest lakes impacted only by the mining waters (Table 1). A partly isolated basin of the larger Lake Upper Kuito, flowing like the impacted lakes into Lake Middle Kuito, was used as a reference area; it is only slightly affected by the local village, Vuokkiniemi, which has approximately 500 inhabitants. The climate is continental with relatively warm summers but cold winters: all the lakes are ice- and snow-covered for some 200 days each year.

Table 1. Some physical and chemical characteristics of the lakes studied. The chemical analyses refer to surface water in August 2000–2002

Characteristic	Impacted lakes in Kenti-River system						Reference lake		
	Poppalijärvi			Kento			Upper Kuito		
	2000	2001	2002	2000	2001	2002	2000	2001	2002
Oxygen saturation, % (surface/bottom)	107/95	94/91	109/14	97/74	96/85	100/30	115/95	90/94	104/77
pH	8.3	8.0	8.0	7.7	7.7	8.0	6.8	6.7	6.6
Conductivity, mS/m	39.1	39.4	39.0	4.9	14.0	14.5	2.5	2.4	2.8
Colour, mg Pt L^{-1}	35	40	40	40	40	35	40	50	40
Total phosphorus, µg L^{-1}	6	9	7	8	8	8	14	11	9
Total nitrogen, µg L^{-1}	3888	4038	4192	797	697	724	263	–	273
SO_4^{2-}, mg L^{-1}	82.0*	–	–	20.6*	–	–	2.2*	–	–
Na^+, mg L^{-1}	6.2	6.4	6.2	2.8	2.6	2.7	1.2	0.8	1.3
K^+, mg L^{-1}	60	60	51	20	20	17	0.5	0.4	0.6
Li^+, µg L^{-1}	20	–	20	7	–	4	0.2	–	0
Ca^{2+}, mg L^{-1}	21	23	21	7.9	8.4	8.7	1.9	1.9	2.1
Mg^{2+}, mg L^{-1}	8.3	7.7	8.0	3.1	3.2	3.1	0.8	0.6	0.9

* Data from Lozovik et al. (2001).
– No data.

All the three lakes were sampled once in early August in three successive years (2000–2002) for water chemistry, phytoplankton, zoobenthos, and fish. In 2001–2002, bacteria, zooplankton, and Ciliata were also sampled. Samples for water quality were taken with a Ruttner-type tube sampler and analysed according to Finnish standard methods (SFS Standards) in the experienced water laboratory of the Karelian Institute at the University of Joensuu.

For bacteria, phytoplankton, and Ciliata, a sample of approximately 10 L of surface water (0–1 m) was subsampled (100 mL) and fixed with acidic Lugol solution (see e.g. Pomroy, 1984; Wetzel & Likens, 2000). The hypolimnion (9–12 m, 1 m from bottom) was also sampled in 2002. Species composition and biomass (volumes) of phytoplankton and Ciliata were determined by inverted microscopy using the sedimentation chamber technique (Utermöhl, 1958). The conversion factor from cell volumes to carbon was 1 μg C L^{-1} = 0.11 μm^{-3} L^{-1} biovolume for phytoplankton (Wetzel & Likens, 2000) and 190 fg C μm^{-3} for Ciliata (Putt & Stoecker, 1989). Before the bacteria were stained with 0.20 μm filtered acriflavine solution (Bergström et al., 1986), the samples were clarified with thiosulphate crystals. Two replicate 1 mL samples were filtered on black Poretics polycarbonate filters (pore size 0.22 μm) and the bacteria were counted with an epifluorescence microscope (Olympus IX 50) at 1500 × magnification from 5–10 random fields (5901 μm^2) in each sample (for variation see Table 2). A video camera and the analySIS 3.0 Image analysing program (Soft Imaging System GmbH, Münster) were used to determine bacterial densities and the sizes and volumes of the bacteria counted. The number of bacteria counted ranged between 636 and 836 per sample. The conversion factor from bacterial cell volumes to carbon was 360 fg C μm^{-3} (Tulonen, 1993).

For transmission electron microscopy (TEM), 100 mL of prefiltered (10 μm) water was filtered through 0.45 μm membrane filters, which were fixed in glutaraldehyde. Two-millilitre samples of the material rinsed from the filters were then centrifuged for 5 min at 3000 ×*g*. Planktonic material at the bottom of the tubes was fixed for 24 h in 1.5 mL 2% glutaraldehyde in 0.1 M sodium cacodylate buffer. The tubes were centrifuged again for 5 min at 3000 ×*g* and postfixed for 3 h in 1% OsO_4 in 0.1 M sodium cacodylate buffer. After dehydration, the plankton

Table 2. Bacterial (including autotrophic picoplankton) biomass (μg C L^{-1}) in the surface water of the lakes studied in 2001 and 2002. A and B are two replicates from a combined water sample. The coefficient of variation (CV in %) is given for each set of sub-samples counted (N = 5–10). The mean values for impacted lakes differ from the reference lake ($P < 0.05$ ANOVA) but the differences between years are not significant

Lake	2001				2002			
	Biom A	CV	Biom B	CV	Biom A	CV	Biom B	CV
Poppalijärvi	87.1	19	93.9	26	64.2	20	69.0	33
Kento	92.6	31	76.5	22	44.0	26	48.2	34
Upper Kuito	19.1	36	9.0	29	19.3	25	25.3	15

samples were embedded in Epon. For transmission electron microscopy (TEM), ultrathin sections were cut with a diamond knife, stained with uranyl acetate and lead citrate, and examined with a Zeiss 900 electron microscope.

Zooplankton was sampled by a tube-sampler (Limnos, 6.8 L) from both littoral (0.5–2.5 m) and pelagic (0–5 m and 5–10 m separately) zones. At each of the three depths, ten lifts (68 L) were combined to form a sample, which was sieved through a plankton net (48 µm) and fixed with ethanol in the field and formaldehyde in the laboratory. The invertebrates were counted with an inverted microscope after sub-sampling. From a stirred sample of 250 mL, at least three quantitative sub-samples (total 60–170 mL) were pipetted into a counting chamber. The counts were converted to biomass using average carbon values for appropriate size classes of each taxon (Salonen et al., 1976; Rahkola et al., 1998).

A stratified random sampling of fish from three habitats (bottom inshore, bottom offshore, and surface) in each lake was carried out using nine multimesh gillnets (mesh sizes 10, 12, 15, 20, 25, 30, 35, 45, and 55 mm from knot to knot in each 1.5 × 30 m net; each mesh panel 1.5 × 3 m; Kurkilahti & Rask, 1996; Holopainen et al., 2003b).

RESULTS

All three 8–13 m deep basins sampled were unstratified in early August 2000 and 2001. In August 2002 the two impacted (smaller) lakes were stratified. For the water quality of the lakes see Table 1.

Similar densities ($1.8–2.8 \times 10^6$ cells mL^{-1}) of bacteria were found in the surface waters of all the lakes. In the hypolimnion (9–12 m) both the densities and cell volumes were similar to those in the surface waters of Lake Poppalijärvi, whereas in the two other lakes both the size and density were lower close to the bottom. A large rod-shaped cyanobacterium (tentatively identified as *Synechococcus* spp.) predominated in the two impacted lakes. The TEM micrographs of this cell (approx. 1.0 μm^3 or 0.7 × 2.7 µm) show e.g. a four-layered cell wall (Fig. 1). The bacteria in the impacted lakes were much larger than those in the reference lake (Fig. 2), and because their densities were approximately the same, their biomass was also much higher (Table 2).

In a routine count, the total biomass of (nano)phytoplankton ranged between 16 and 78 mg C m^{-3} in all lakes and years, the values being higher in the reference lake in 2000 and 2001 (Table 3). Cyanophyceae, Cryptophyceae, and Chlorophyceae were characteristic of Lake Poppalijärvi, and Chrysophyceae and Cryptophyceae of Lake Kento, but Diatomophyceae and Dinophyceae of the reference lake (Fig. 3). In Lake Poppalijärvi, *Cryptomonas* spp. and *Synedra* spp. were predominant in the biomass. In 2000, however, the biomass of blue-greens (mainly *Planktothrix agardhii* (Gomont) Anagnostidis and Komárek, 1988) was high. In Lake Kento, small Cryptophyceae flagellates together with the chrysophytes *Pseudopedinella* spp. and *Uroglena* sp. were abundant. In the reference lake

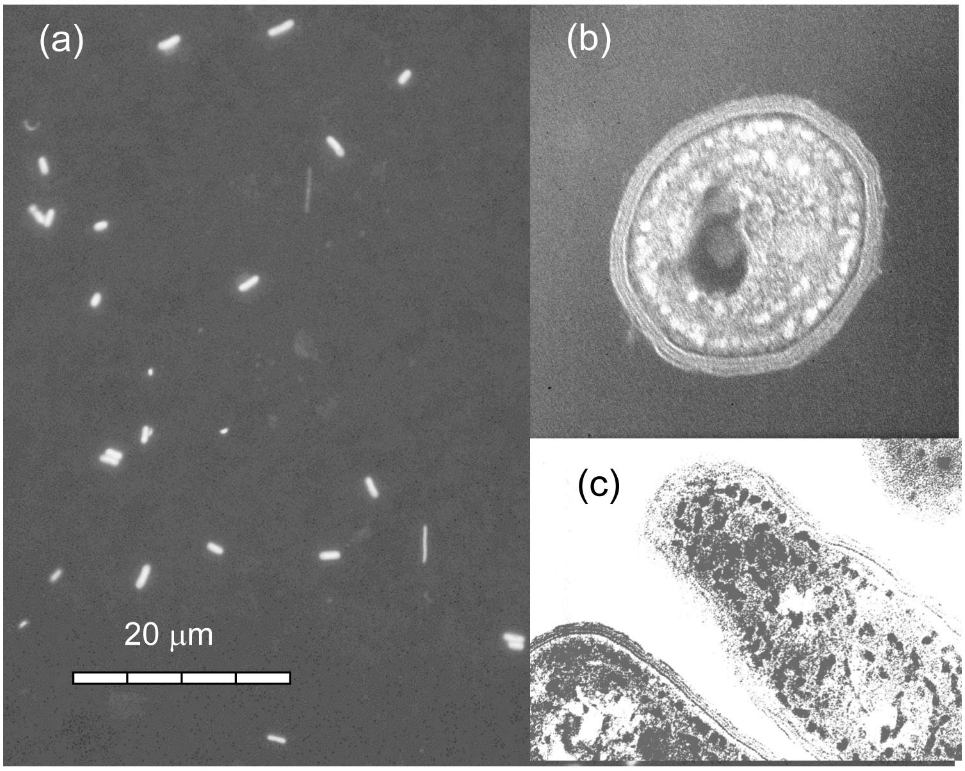

Fig. 1. Photomicrographs of the picocyanobacteria in Lake Poppalijärvi in 2001: (a) a view in epifluorescence microscope, (b) cross-section of one cell (diameter 0.7 µm, TEM photo), (c) longitudinal sections of cells with a length of ca. 2.7 µm (TEM photo).

the total number of taxa was higher (Table 3), and the most abundant were the blue-green *Merismopedia warmingiana* Lagerheim, the Cryptophyceae flagellates, and the diatom *Rhizosolenia longiseta* Zacharias. In 2001 and 2002, heterotrophic and potentially mixotrophic algae (Cryptophyceae, Dinophyceae, Chrysophyceae, Euglenophyceae, Choano- and Zooflagellata, unidentified heterotrophic flagellates) attained the lowest relative biomass (42–43% of total phytoplankton) in the reference lake Upper Kuito, where their absolute biomass was 34–95% of those in the impacted lakes.

In 2001 the ciliate community in the surface water of Lake Poppalijärvi was dominated by Oligotrichida (*Pelagostrombidium* sp. formed 50% of the biomass), but in 2002 by Peritrichia (*Vorticella* sp.) and Scuticociliatida (Fig. 4). All the groups present consisted mainly of small species. In Lake Kento Oligotrichida (*Rimostrombidium* spp. and *Limnostrombidium* sp.), Prostomatida (*Coleps* sp.), and Hypotrichia (*Stichotricha aculeata* Wrzesnioski, 1884) were predominant. The high ciliate biomass in the surface water of the reference lake, Upper Kuito (Table 3), was clearly dominated by *Rimostrombidium* spp. and *Limnostrombidium* sp. In the hypolimnion of Lake Poppalijärvi, 54% of the biomass

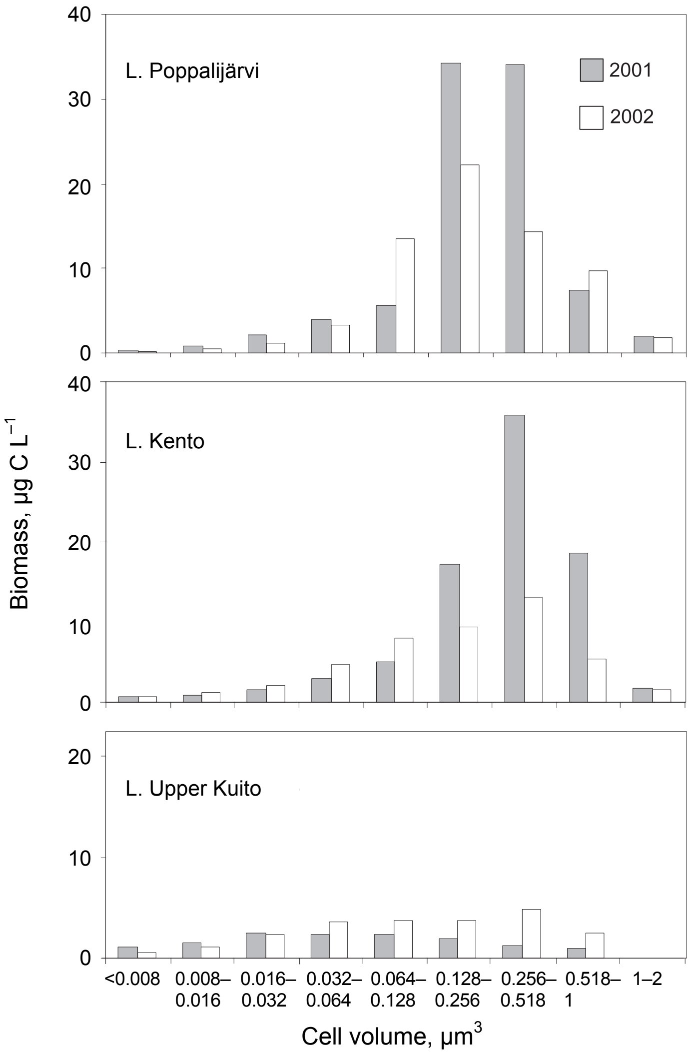

Fig. 2. The size-specific biomass of bacteria and picoplankton in the three lakes in 2001 and 2002.

consisted of Scuticociliatida; in Lake Kento Oligotrichida and Prostomatida were again predominant, and in Lake Upper Kuito *Rimostrombidium* spp. and *Mesodinium* sp. (Gymnostomatea) dominated.

The taxa richness of Rotatoria per sample increased downstream from Lake Poppalijärvi (6–10 taxa) to Lake Upper Kuito (9–15 taxa). Similarly, the numbers of Cladocera and Copepoda taxa were higher (6–8 and 4–5 taxa, respectively) in the reference lake than in the other two lakes (2–7 and 1–4, respectively). No differences were found among habitats (shore, surface, bottom) in any lake. The total biomass of zooplankton in all areas was lowest in the most impacted

Table 3. Some biological characteristics in the lakes studied. The zooplanktivorous fish include roach, whitefish, bleak, and vendace. All fish values and those of crustacean zooplankton represent mean biomass over the three habitats sampled

Characteristic	Impacted lakes in Kenti-River system						Reference lake		
	Poppalijärvi			Kento			Upper Kuito		
	2000	2001	2002	2000	2001	2002	2000	2001	2002
Phytoplankton biomass, μg C L^{-1}	22.0	30.8	29.0	16.3	27.5	28.9	78.1	40.7	21.7
Phytoplankton, taxa per sample	18	27	23	23	23	25	41	37	38
Chlorophyll *a*, μg L^{-1}	7.2	7.4	6.4	5.2	7.3	3.4	3.2	3.7	1.6
Ciliata**,** No. of taxa (surface/bottom)	–	9	5/12	–	11	11/10	–	17	11/7
Ciliata, density, cells mL^{-1}	–	6.2	5.2	–	8.9	10.9	–	21.7	7.1
Ciliata, biomass, μg C L^{-1} (surface/bottom)	–	11.6	1.7/7.8	–	11.7	9.1/3.2	–	25.5	3.4/1.9
Zooplankton biomass, μg C L^{-1}, shore 0–2 m	–	4.1	2.6	–	33.6	6.4	–	32.5	42.7
Zooplankton biomass, μg C L^{-1}, 5–10 m	–	6.5	14.3	–	36.6	14.3	–	37.1	21.5
Zooplankton biomass, μg C L^{-1}, 0–5 m	–	12.4	9.5	–	47.0	12.0	–	30.0	16.3
Planktonic crustacean biomass, μg C L^{-1}	–	3.6	4.9	–	9.4	4.8	–	15.2	11.9
Daphnia biomass, μg C L^{-1}, 0–5 m	–	0.2	0.1	–	2.2	0	–	9.5	3.8
Bosmina biomass, μg C L^{-1}, 0–5 m	–	0.1	3.1	–	3.4	4.6	–	0.8	0.7
Fish, CPUE, g net^{-1} day^{-1}	1697	1123	1359	1197	2111	1861	874	498	504
Zooplanktivorous fish, g net^{-1} day^{-1}	956	583	386	658	771	674	537	282	381

– No data.

Lake Poppalijärvi (Fig. 5). Rotatoria always formed a major part of the biomass (31–80%). The dominant species were *Brachionus angularis* (Gosse, 1851) and *Keratella cochlearis* (Gosse, 1851) in Lake Poppalijärvi and the genus *Keratella* in Lake Kento. The pelagic zone of Lake Upper Kuito was dominated by *Polyarthra* sp. and *Kellicottia longispina* Kellicott, 1870, and the littoral by *Synchaeta* spp. The biomass of Cladocera increased downstream and was dominated by *Bosmina longirostris* (O. F. Muller, 1785) in lakes Poppalijärvi and Kento, but by *Daphnia cristata* Sars, 1862 in Lake Upper Kuito. Despite their much lower numbers in Lake Poppalijärvi, *B. longirostris* appeared to be clearly (*t*-test $P < 0.001$) larger (length 329±77μm, mean±S.D., $n = 50$) than those in Lake Kento (239±37 μm) and to include more egg-bearing females (28/50 vs. 14/50).

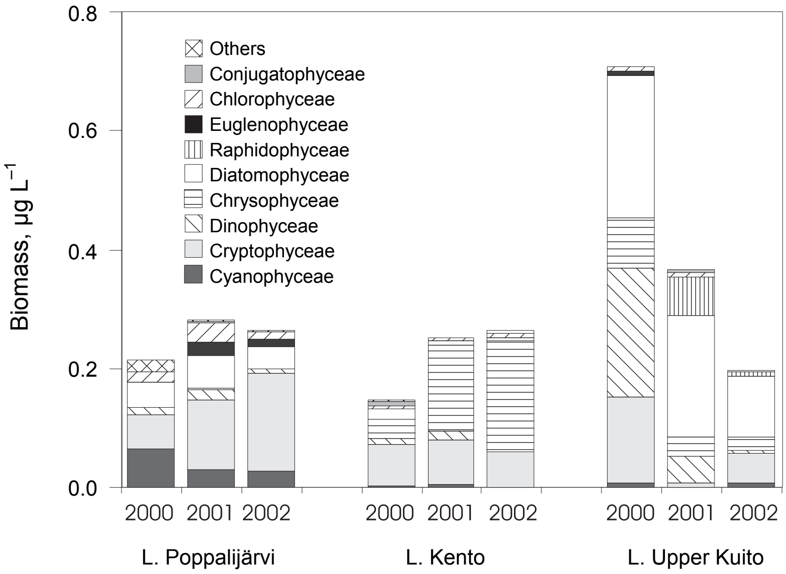

Fig. 3. Phytoplankton biomass (biovolume) and taxa composition in the three lakes in 2000–2002.

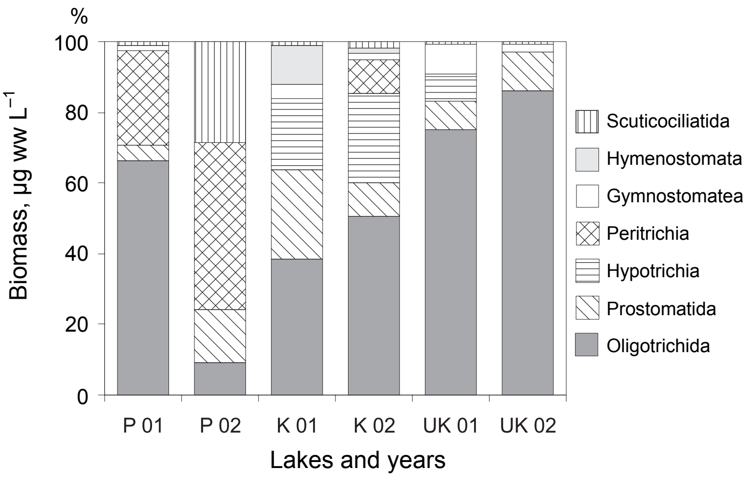

Fig. 4. The relative biomass (biovolume) of Ciliata in the three lakes in 2001–2002. P is Lake Poppalijärvi, K is Lake Kento and UK is the reference lake Upper Kuito. The numbers refer to years.

The small cyclopoids *Mesocyclops leuckarti* Claus, 1857 and *Thermocyclops oithonoides* (Sars, 1863) were characteristic of all three lakes. Calanoida (mainly *Eudiaptomus* sp.) were found regularly only in the reference lake Upper Kuito, but even there their biomass was low (max 13% of total). Both total fish catch and the catch of potential zooplanktivores were much higher in the impacted lakes (Table 3).

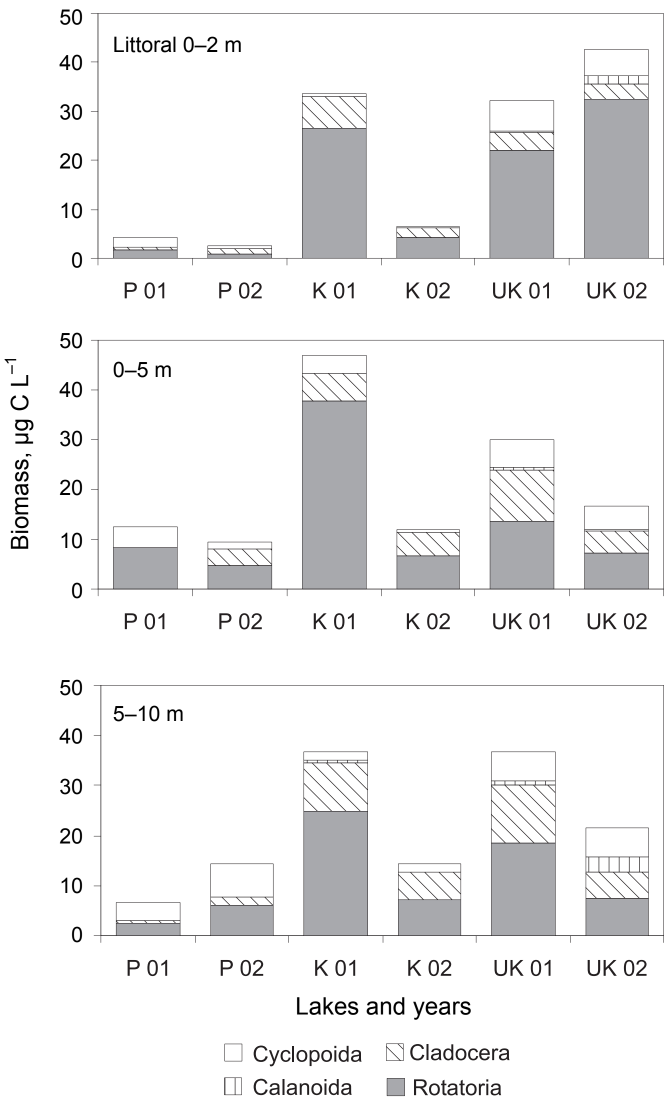

Fig. 5. The carbon biomass of zooplankton groups in three habitats in the three lakes in 2001–2002. For further explanations see Fig. 4.

DISCUSSION

Our singular or 'snapshot' type sampling from a single station gives limited information about the lake food web because it neglects temporal and spatial variations. Mehner et al. (2005) found the horizontal and daily variation to be less important than vertical and month-to-month variation. We sampled both the epiand hypolimnion, and the fact that we have data from August in two or three successive years increases the reliability of the results.

The changed water chemistry in the impacted lakes is due to wastewaters from iron mining and ore processing, and the high nitrogen levels derive from the explosives used in the mining pits (Lozovik et al., 2001). The unnaturally high absolute and distorted relative ion concentrations (Kalinkina et al., 2003) observed since 1994 are expected to affect organisms at different levels because many cations interact with biological membranes and regulate their permeability and ion transport. Although the heavy metal contents of the wastewaters are elevated, their concentrations in the lakes downstream from the mine and their bioavailability for biota are low at the ambient high pH and water hardness (Tkatcheva et al., 2004).

In the impacted lakes, the biomass of pelagic bacteria and autotrophic picocyanobacteria was 2–3 times that of routine phytoplankton (Tables 2 and 3). The structure and function of autotrophic picoplankton (APP) communities have been reviewed by Callieri & Stockner (2002). APP appear to form a basis for microbial food webs with important effects on higher trophic levels, including fish, and may account for 10–90% of the total phytoplankton biomass or production, the highest values often being found in oligotrophic lakes (e.g. Callieri & Stockner, 2000; Bell & Kalff, 2001). The APP biomass values in six Quebec lakes varied between 16 and 80 $\mu g\ C\ L^{-1}$ (Pinel-Alloul et al., 1996). In a natural humic lake in southern Finland the bacterial biomass in the surface water was 14–19 $\mu g\ C\ L^{-1}$ (Tulonen et al., 2000), which agrees well with the values for our reference lake. Because of the large picocyanobacteria, the average cell volume of all bacteria in the impacted lakes was 0.09 μm^3, much larger than that in the reference lake (0.01 μm^3) or that given for a humic forest lake in Finland (0.02 $\mu m^3\ cell^{-1}$) by Tulonen et al. (2000). In Lake Maggiore the mean cell volumes of the most abundant species of picocyanobacteria fall between 0.2 and 0.8 μm^3 in August (Callieri et al., 2002).

Chekryzheva (1995) gives a list of phytoplankton species and total biomass in 1987 and 1994 for lakes Poppalijärvi and Kento. Diatoms predominated (30–50% of taxa richness) together with Chlorophyceae (20–30%) and Chrysophyceae (15–25%). In 1994 the biomass was higher in Kento than in Poppalijärvi (325 vs. 150 $\mu g\ L^{-1}$), whereas our results suggest similar biomasses for these two lakes (Table 3). In 1994 the number of taxa (71) was clearly higher in Lake Kento than in Lake Poppalijärvi (34). According to Arvola et al. (1999), the average number of phytoplankton taxa per sample in oligotrophic Finnish lakes is 54–67. The relative proportions of blue-green and green algae were highest in Lake Poppalijärvi. Chrysophyceae are negatively affected by high potassium content: *Dinobryon* spp. stop growing in water at 15 mg $K^+\ L^{-1}$, but high concentrations of the divalent cations Ca^{2+} and Mg^{2+} increase their tolerance to high K^+ (Lehman, 1976). In Lake Poppalijärvi Chrysophyceae were absent from all samples, except for a small *Pedinella* species. In Lake Kento Chrysophyceae predominated, but their species richness was low (7–8 taxa) compared to that in Lake Upper Kuito (10–16 taxa). In 1994 Chrysophyceae were well represented in all lakes, even upstream from

Lake Poppalijärvi (Chekryzheva, 1995). According to Kalinkina et al. (2003), potassium increased in Lake Poppalijärvi from 10.6 mg L^{-1} in 1993 to 42.4 mg L^{-1} in 1994 and to 60 mg L^{-1} in 1995, accompanied by some increase in Ca^{2+} and Mg^{2+}.

The chlorophyll *a* values (2–4 µg L^{-1}) in the reference lake are compatible with those in other oligotrophic lakes in the region (e.g. 1.1–1.5 and 1.9–3.4 µg L^{-1} in Lake Iso Hietajärvi and Lake Pesosjärvi, respectively; Rask et al., 1998). In 1990–2001 the July–August wet biomass of phytoplankton in single annual samples in Lake Iso Hietajärvi varied between 0.1 and 0.4 mg L^{-1} (Holopainen et al., 2003a). Our biomass values for all three lakes conform closely to these results (Table 3). However, in the impacted lakes, Poppalijärvi and Kento, the chlorophyll *a* content and the biomass of primary producers were much higher because of the high densities of picocyanobacteria, and owing to their small size and fast turnover rate the effect of these organisms on production could be even greater.

In 2001 the total ciliate abundance in the surface water of Lake Poppalijärvi was higher than in some oligotrophic Finnish lakes (Zingel at al., 2002), but still in the range typical of an oligotrophic environment (e.g. James et al., 1995). The predominant *Pelagostrombidium* species feeds on nanoplankton. In 2002 the bacterivorous Scuticociliatida were dominant in both the epilimnion and hypolimnion. The other groups present were also dominated mainly by small species that are known to feed on picoplankton. This suggests that microbial processes are important in Lake Poppalijärvi, especially in the hypolimnion, where the highest abundances were found. The picoplanktivorous nanoflagellates and Ciliata liberate the nutrients bound in the picoplankton biomass by grazing (e.g. Callieri et al., 2002), thus mediating their availability to higher trophic levels.

Lake Kento had higher ciliate abundances in the epilimnion than Lake Poppalijärvi, but much lower numbers in the hypolimnion. The predominant species (*Rimostrombidium* spp.) is a nanoplankton feeder. The abundances as well as the community composition were typical of oligo- and mesotrophic lakes. Both in 2001 and 2002 the ciliate community in Lake Upper Kuito was similar to that in Lake Kento, and in 2002 the differences between the epi- and hypolimnion were small.

The ciliate species richness in the reference lake was similar to that in oligotrophic Finnish lakes (Zingel et al., 2002), but was lower in the impacted lakes, especially in Lake Poppalijärvi. Nevertheless, the community structure in Lake Poppalijärvi resembled that found in eutrophic systems (Beaver & Crisman, 1989), which are usually rich in ciliate species (Zingel, 1999).

The results obtained by Kalinkina et al. (2003) agree well with those given in Vlasova (1998) and show biomass values between 80 and 800 mg ww m^{-3} for zooplankton in Lake Poppalijärvi in July–August 1992 to 1997, but only 12–15 mg ww m^{-3} in 1999 to 2001. Our results for the pelagic surface water (0–5 m) show that the zooplankton biomasses are highest in Lake Kento and Lake Upper Kuito (up to 850 mg ww m^{-3}; fresh mass is carbon mass $\times$18.093, Karjalainen et al., 1996). The biomass of Lake Poppalijärvi was the lowest (224 and 172 mg ww m^{-3} in 2001 and 2002, respectively) but still an order of magnitude greater than those given by Kalinkina et al. (2003) for 2001. This could be due, at least in part, to the large mesh size (99 µm) and consequent lack of small Rotatoria in their results (cf. Karjalainen et al., 1995). Vlasova (1998) stated that Rotatoria were counted separately from unfiltered samples; there is, however, no mention of this in Kalinkina et al. (2003).

The average biomass of crustacean zooplankton in 138 South Finnish lakes was 40 mg C m^{-3} (Sarvala et al., 1999). Owing to the predominance of Rotatoria and the low numbers of Calanoida (and Cladocera in L. Poppalijärvi), the carbon mass of Crustacea was much lower in our lakes (Table 3), with the highest values found at a depth of 5−10 m. According to Kalinkina et al. (2003), Calanoida (mainly *Eudiaptomus gracilis* Sars) and other species favouring soft waters practically disappeared from Lake Poppalijärvi in 1995. This was shown experimentally to be due to intolerance to the high (>50 mg L^{-1}) potassium content. In our results the abundance of Calanoida was exceptionally low, even in the reference lake. In 1994 the zooplankton of Lake Poppalijärvi was dominated by *Daphnia cristata* and *D. longispina* (O. F. Müller), but in 1996 by *Bosmina longirostris*. No marked changes have been detected in zooplankton of the natural Lake Middle Kuito (Vlasova, 1998).

Some trophic relationships that have commonly been used to characterize food chains in lakes (Table 4) suggest top-down control of zooplankton by fish in the impacted lakes. However, this material is not complete enough (e.g. lack of data on heterotrophic nanoflagellates) to explain all details of the microbial food web in the pelagic zone, or the possible functional coupling between the abundant pico-cyanobacteria and the large fish biomass. Furthermore, the predominant fish (roach) is benthi-planktivorous, and the higher biomass of benthic animals in both littoral and profundal zones of the impacted lakes (Aroviita et al., 2006) may be more important than the pelagic zooplankton for fish density. Recent studies have suggested that fish are strongly dependent on the littoral zone and there might be only a weak connection between the littoral and the pelagic food webs in oligotrophic lakes (e.g. Bertolo et al., 2005).

Table 4. Some trophic relationships (in biomass) often used to characterize the resource supply and predator control in lakes. Both the biomass of planktivorous fish (see Table 3) and that of crustacean zooplankton represent means over the three habitats sampled

Relationship	Poppalijärvi		Kento		Upper Kuito	
	2001	2002	2001	2002	2001	2002
Chl *a* : tot P (1 m)	0.82	0.91	0.91	0.43	0.34	0.18
Ciliata : chl *a* (1 m)	1.6	0.3	1.6	2.7	6.9	2.1
Zooplankton : chl *a* (0–5 m)	1.7	1.5	9.0	3.5	8.1	10.2
Zooplankton : phytoplankton (0–5 m)	0.4	0.3	1.7	0.4	0.8	0.8
Zooplankton : Ciliata (0–5 m)	1.1	5.6	4.0	1.3	1.2	4.8
Daphnia : chl *a* (0–5 m)	0.02	0.01	0.30	–	2.56	2.36
Daphnia : zooplankton (0–5 m)	0.01	0.01	0.05	–	0.31	0.23
Planktivorous fish : crustacean plankton	160	79	82	141	19	32

ACKNOWLEDGEMENTS

We wish to thank Mr. Kari Ratilainen and Dr. Markku Viljanen for their assistance in the field, and Prof. (emer.) Heikki Hyvärinen for his help with the electron microscope. Discussions with Dr. Tiina Tulonen have been helpful. Rosemary Mackenzie kindly checked the English language. The support provided by Maj and Tor Nessling's Foundation is gratefully acknowledged.

REFERENCES

Aroviita, J., Hämäläinen, H. & Holopainen, I. J. 2006. Benthic macroinvertebrates in lakes affected by iron mining waste waters in the Kostomuksha area, northwest Russia. *Verh. Int. Verein. Limnol.*, **29**, 2039–2044.

Arvola, L., Eloranta, P., Järvinen, M., Keskitalo, J. & Holopainen, A.-L. 1999. Food webs of humic waters. Phytoplankton. In *Limnology of Humic Waters* (Keskitalo, J. & Eloranta, P., eds), pp. 137–171. Backhuys Publishers, Leiden.

Beaver, J. R. & Crisman, T. L. 1989. Role of ciliated Protozoa in pelagic freshwater ecosystems. *Microb. Ecol.*, **17**, 111–136.

Bell, T. & Kalff, J. 2001. The contribution of picophytoplankton in marine and freshwater systems of different trophic status and depth. *Limnol. Oceanogr.*, **46**, 1243–1248.

Bergström, I., Heinänen, A. & Salonen, K. 1986. Comparison of acridine orange, acriflavine and bisbenzimide stains for enumeration of bacteria in clear and humic waters. *Appl. Environ. Microbiol.*, **51**, 664–667.

Bertolo, A., Carignan, R., Magnan, P., Pinel-Alloul, B., Planas, D. & Garcia, E. 2005. Decoupling of pelagic and littoral food webs in oligotrophic Canadian Shield lakes. *Oikos*, **111**, 534–546.

Callieri, C. & Stockner, J. G. 2000. Picocyanobacterial success in oligotrophic lakes: Fact or fiction? *J. Limnol.*, **59**, 72–76.

Callieri, C. & Stockner, J. G. 2002. Freshwater autotrophic picoplankton: A review. *J. Limnol.*, **61**, 1–14.

Callieri, C., Karjalainen, S. A. & Passoni, S. 2002. Grazing by ciliates and heterotrophic nanoflagellates on picocyanobacteria in Lago Maggiore, Italy. *J. Plankton Res.*, **24**, 785–796.

Chekryzheva, T. A. 1995. Phytoplankton in the Kenti River. In *The Effect of Man-caused Effluents from Kostamus Mining Plant on Kenti-River System* (Kukharev, V. I., ed.), pp. 68–79. Petrozavodsk (in Russian).

Holopainen, A.-L., Niinoja, R. & Rämö, A. 2003a. Seasonal succession, vertical distribution, and long-term variation of phytoplankton communities in two shallow forest lakes in eastern Finland. *Hydrobiologia*, **506–509**, 237–245.

Holopainen, I. J., Holopainen, A.-L., Hämäläinen, H., Rahkola-Sorsa, M., Tkatcheva, V. & Viljanen, M. 2003b. Effects of mining industry waste waters on a shallow lake ecosystem in Karelia, north-west Russia. *Hydrobiologia*, **506–509**, 111–119.

James, M. R., Burns, C. W. & Forsyth, D. J. 1995. Pelagic ciliated protozoa in two monomictic, southern temperate lakes of contrasting trophic state: Seasonal distribution and abundance. *J. Plankton Res.*, **17**, 1479–1500.

Kalinkina, N. M., Kulikova, T. P., Morozov, A. K. & Vlasova, L. I. 2003. Causes of technogenic changes in a freshwater zooplanktonic community. *Biol. Bull.*, **30**, 627–632.

Karjalainen, J., Rahkola, M., Viljanen, J., Andronikova, I. & Avinsky, V. 1995. 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.

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.

Kukharev, V. I., Palshin, N. I. & Salo, J. A. 1995. General characteristics of Kenti–Kento Lake–River system. In *The Effect of Man-caused Effluents from Kostamus Mining Plant on Kenti-River System* (Kukharev, V. I., ed.), pp. 4–8. Petrozavodsk (in Russian).

Kurkilahti, M. & Rask, M. 1996. A comparative study of the usefulness and catchability of multimesh gillnets and gillnet series in sampling of perch (*Perca fluviatilis* L.) and roach (*Rutilus rutilus* L.). *Fish. Res.*, **27**, 243–260.

Lehman, J. T. 1976. Ecological and nutritional studies on Dinobryon Ehrenb.: Seasonal periodicity and the phosphate toxicity problem. *Limnol. Oceanogr.*, **21**, 646–658.

Lozovik, P. A., Markkanen, S.-L. & Regerand, T. 2001. *Kalevalan piirin ja Kostamuksen alueen pintavedet ja kuormituksen vaikutus niihin*. Petrozavodsk (in Finnish and in Russian).

Mehner, T., Hölker, F. & Kasprzak, P. 2005. Spatial and temporal heterogeneity of trophic variables in a deep lake as reflected by repeated singular samplings. *Oikos*, **108**, 401–409.

Niinioja, R., Holopainen, A.-L., Hämäläinen, H., Heitto, L., Luotonen, H., Mononen, P. & Ramö, A. 2003. State of Lake Sysmäjärvi, Eastern Finland, after loading with mine water and municipal waste water for several decades. *Hydrobiologia*, **506–509**, 773–780.

Pinel-Alloul, B., Bourbonnais, N. & Dutilleul, P. 1996. Among-lake and within-lake variations of autotrophic pico- and nanoplankton biomass in six Quebec lakes. *Can. J. Fish. Aquat. Sci.*, **53**, 2433–2445.

Pomroy, A. J. 1984. Direct counting of bacteria preserved with Lugol iodine solution. *Appl. Environ. Microbiol.*, **47**, 1191–1192.

Putt, M. & Stoecker, D. K. 1989. An experimentally determined carbon : volume ratio for marine "oligotrichous" ciliates from estuarine and coastal waters. *Limnol. Oceanogr.*, **34**, 1097–1103.

Rahkola, M., Karjalainen, J. & Avinsky, V. 1998. Individual weight estimates of zooplankton based on length–weight regressions in Lake Ladoga and Saimaa lake system. *Nord. J. Freshwater Res.*, **74**, 110–120.

Rask, M., Holopainen, A.-L., Karusalmi, A., Niinioja, R., Tammi, J., Arvola, L., Keskitalo, J., Blomquist, I., Heinimaa, S., Karppinen, C., Salonen, K. & Sarvala, J. 1998. An introduction to the limnology of the Finnish Integrated Monitoring lakes. *Boreal Environ. Res.*, **3**, 263–274.

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.

Sarvala, J., Kankaala, P., Zingel, P. & Arvola, L. 1999. Zooplankton. In *Limnology of Humid Waters* (Keskitalo, J. & Eloranta, P., eds), pp. 173–191. Backhuys Publishers, Leiden.

Tkatcheva, V., Hyvärinen, H., Kukkonen, J., Ryzhkov, L. P. & Holopainen, I. J. 2004. Toxic effects of mining effluents on fish gills in a subarctic lake system in NW Russia. *Ecotoxicol. Environ. Safety*, **57**, 278–289.

Tulonen, T. 1993. Bacterial production in a mesohumic lake estimated from (^{14}C)-leucine incorporation rate. *Microb. Ecol.*, **26**, 201–217.

Tulonen, T., Kankaala, P., Arvola, L. & Ojala, A. 2000. Growth and production of bacterioplankton in a deep mesohumic boreal lake. *Arch. Hydrobiol.*, **147**, 311–325.

Utermöhl, H. 1958. Zur Vervollkommnung der quantitativen Phytoplankton-Methodik. *Mitteilungen/Int. Verein. Theor. Angew. Limnol.*, **9**, 1–38.

Virtanen, K. & Markkanen, S.-L. 2000. Monitoring the Kostomuksha mining combine waste waters and water quality in the receiving water system 1990–1998. *Mimeographed series of Kainuu Regional Environment Centre*, **6**, 3–28 (in Finnish, abstract in English).

Vlasova, L. 1998. Zooplankton in the area of the Kostomuksha. In *Current State of Water Objects in the Republic of Karelia. Result of Monitoring, 1992–1997*, pp. 134–137 Petrozavodsk (in Russian).

Wetzel, R. G. & Likens, G. E. 2000. *Limnological Analyses*. Springer, New York.
Zingel, P. 1999. Pelagic ciliated protozoa in a shallow eutrophic lake: Community structure and seasonal dynamics. *Arch. Hydrobiol.*, **146**, 495–511.
Zingel, P., Huitu, E., Mäkelä, S. & Arvola, L. 2002. The abundance and diversity of planktonic ciliates in 12 boreal lakes of varying trophic state. *Arch. Hydrobiol.*, **155**, 315–332.

Pelaagilised toitumisahelad Loode-Venemaa metsajärvedes, mida mõjutavad aluselised kaevandusveed

Ismo J. Holopainen, Anna-Liisa Holopainen, Eeva Huitu, Minna Rahkola-Sorsa ja Priit Zingel

Reoveed Loode-Venemaal asuvatest rauakaevandustest on muutnud mõnede metsajärvede veekvaliteeti: algsetest pehmeveelistest ja madala pH-ga järvedest on saanud karedaveelised ning kõrge pH-ga veekogud. Uuriti kaht reostatud ja üht puhast kontrolljärve. Kolmel aastal võeti augusti algul veeproove ja analüüsiti vee kvaliteeti, planktonit ning kalu. Reostatud järvi iseloomustasid kõrged kaaliumi, liitiumi ja sulfaatide kontsentratsioonid. Üldfosfor oli madal (~10 $\mu g\ L^{-1}$) kõigis uuritud järvedes. Autotroofide biomass ja klorofülli *a* sisaldus oli reostatud järvedes kõrge, kuna esines ohtralt pikotsüanobaktereid (*Synechococcus* spp.). Kõikides planktonikooslustes oli märgata muutusi liigilises koosseisus ja vähenenud liigirikkust. Zooplanktonis domineerisid kõigis järvedes peamiselt keriloomad. Reostatud järvedes oli kõige levinumaks vesikirbuks *Bosmina* ja kõige tavalisemateks aerjalalisteks väikesed sõudikulised. Kõige ilmsemalt kahjustas osa planktereist kaalium. Kõrge pH ja suur mineraalide sisaldus alandavad reostatud järvedes tõenäoliselt nii raskmetallide toksilisust kui ka bioloogilist kättesaadavust.