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Effects of forest fertilization on phytoplankton in a boreal brown-water lake

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The quantity and composition of phytoplankton in a brown-water lake was studied from 1988 to 1994 after forest fertilization in its catchment area. The following spring after fertilization, phosphorus concentrations were high (in average 18 µg l^{-1}), and an evident vernal maximum of phytoplankton (chrysophytes and diatoms) was observed, but no further signs of trophicity changes could be observed. The extra nutrients must have been quickly utilized by bacteria or transported out of the lake through the outflowing brook during the spring high-flow. Mixotrophic algae, like e.g. *Cryptomonas* spp. and *Gonyostomum semen*, were the ones to mostly benefit from the increased amounts of organic compounds and nutrient concentrations. The typical brown-water lake phytoplankton composition, in general did not change during the study period.

Introduction

Many forest lakes in temperate and cold regions are characterized by their generally small size, dark water colour, and low pH due to the high abundance of humic compounds (Wetzel 1983). These lakes are usually surrounded by forests of economic importance. Forest management operations, such as drainage and fertilization, may have many effects on the aquatic environment. The most harmful environmental effect of fertilization is the flushing of nutrients from the fertilized area into the water courses (e.g. Kenttämies 1981). Flushing is especially intense during spring as the snow melts; the melt water carries material and nutrients into the lake. Thermal stratification of humic lakes develops rapidly with the warming of the dark surface water, and the availability of important algal nutrients such as phosphorus and nitrogen is often restricted (Salonen *et al.* 1984). Additionally, bacteria are effective competitors for available phosphorus (Currie and Kalff 1984). Further, some of the phosphorus associates with the humic material and is subsequently not available for phytoplankton (Jones 1992).

Phytoplankton have adopted several strategies to cope with changes which can be considered as different forms of ecological stress. The chlorophyll content of algal cells increases during low light conditions (Ahlgren 1970). The majority of algae in brown-water lakes are small flagellated species with the capacity for nutrient retrieval from

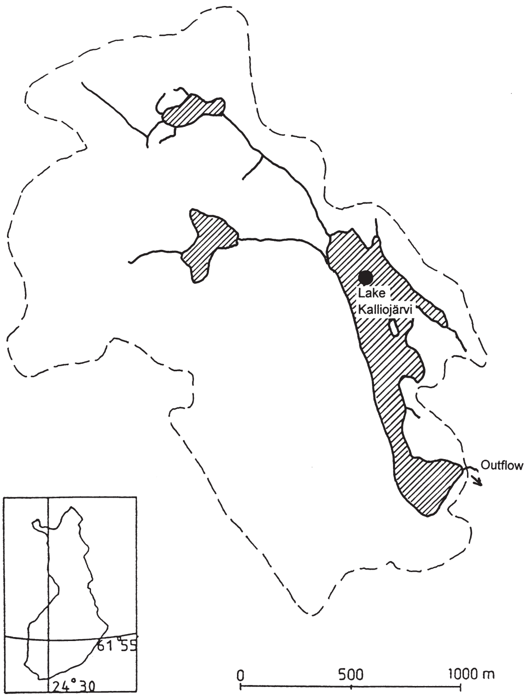

Fig. 1. Lake Kalliojärvi, its catchment area and location in Finland. The sampling site is indicated by a black dot.

deeper depths (Arvola 1984). Further, a large part of these flagellates are also reported to be mixotrophic, thereby able to ingest organic particles (Salonen and Jokinen 1988, Tranvik 1989). Mixotrophic behaviour is promoted during times of peak algal abundance. Thus besides nutrients and light, also different nutrient pathways as well as zooplankton grazing affects the phytoplankton communities in brown-water lakes (Arvola and Rask 1984, Salonen *et al.* 1992, Jansson *et al.* 1996).

Small lake ecosystems react quickly to changes in the environment (Elber and Schanz 1989). Particularly an increase of nutrients in lakes with, more or less, clear water is reflected in the quantity and composition of phytoplankton, and in the proportion of eutrophy indicating species (Trifonova 1988, Brettum 1989, Tikkanen and Willén 1992). Additionally, blue-green algae become more abundant in nutrient-rich waters than green algae, since green algae seldom dominate the biomass (Mantere and Heinonen 1983). Blue-green algae benefits partly from the elevated pH in these lakes, and the decrease in turbulence during summer stratification (Reynolds and Walsby 1975, Shapiro 1984, Willén 1992). According to Chow-Fraser and Duthie (1987), the artificial fertilization of a Canadian dystrophic lake with monoammonium phosphate did neither change the phytoplankton composition nor the biomass which was measured as total phytoplankton volume and chlorophyll *a* content.

By focusing on the changes in blue-green algae we aim at estimating the effects of fertilization on the quantity and composition of phytoplankton in a brown-water forest lake.

Table 1. Some characteristics of Lake Kalliojärvi.

Cathment area (ha)	284
Surface area (ha)	25
Mean depth (m)	4.4
Maximum depth (m)	13.0

Materials and methods

Study site

Lake Kalliojärvi (in southern Finland, Fig. 1) is a small polyhumic (Table 1), monomictic lake with autumnal overturn and with quite low pH. There is no agricultural activity in its catchment area which is mainly covered by forests.

Fertilization

Aerial spreading of fertilizers was carried out at the end of July 1988 over one third of the catchment area, ca. 100 ha, of Lake Kalliojärvi (Fig. 1). Water sampling was started immediately after that and carried out during seven subsequent years. The area applied with NP-fertilizer (phosphorus 18 kg ha^{-1}, nitrogen 150 kg ha^{-1}) was 74 ha, and 26 ha with PK-fertilizer (phosphorus 40 kg ha^{-1}).

Weather conditions

Weather data were obtained from Kuorevesi airport which is situated 16 km east of the lake. In the autumn of 1988, precipitation in the study area was larger than usual (Fig. 2), and the following winter was exceptionally warm (Fig. 3). Conse-

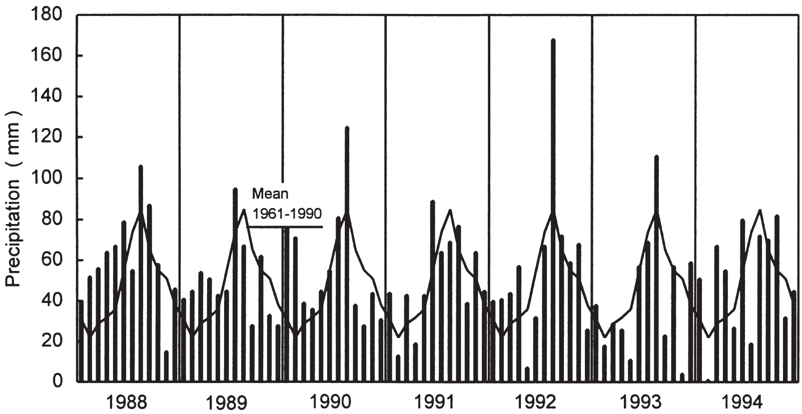

Fig. 2. Monthly precipitation (mm) during the study period. Long-term averages (1961–1990) from Kuorevesi airport are given as reference (solid line).

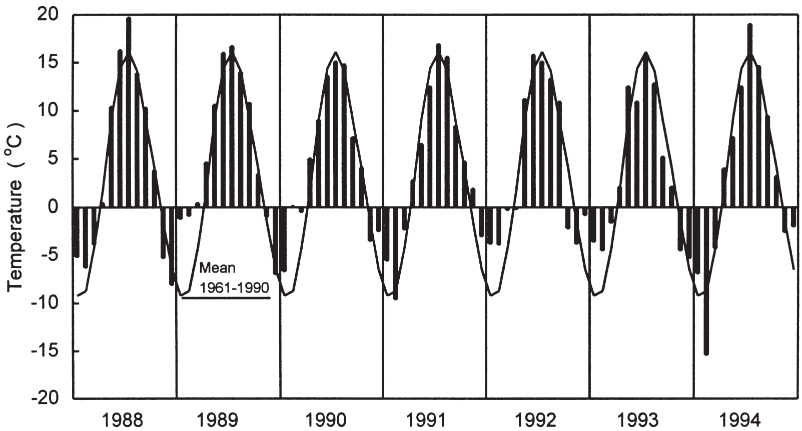

Fig. 3. Monthly averages of air temperature during the study period and long term data (1961–1990) from Kuorevesi airport (solid line).

quently, the period of growth started two weeks earlier than normal in 1989. Nevertheless, the annual drainage volume of 1989 corresponded to long-term average values due to the relatively dry summer. Weather conditions in 1990 were similar to those in 1989, and the spring floods occurred at a very early date. Water temperatures were above average in the spring but close to average in the summer. In summer 1991, precipitation was greater than usual and water temperatures were lower than normal, nevertheless, by August the waters had become exceptionally warm. In 1992, the summer began as a very warm one, however, in August precipitation had reached unprecedentedly high values for the area. In 1993 the summer water temperatures remained slightly below average, whereas April 1994 was warmer and had more precipitation than normal. Water temperatures rose to near record heights in July and August.

Sampling and analytical methods

In 1988 sampling of phytoplankton was initiated immediately after the fertilization event and the sampling lasted until the end of October. The sampling period during the other investigated years, 1989–1994 (excluding years 1991 and 1993), usually started in May and lasted until the end of September. In general, the samples were taken at intervals of two weeks. The samples were collected from the surface down to a depth of two metres with a Ruttner-type sampler, and preserved with acid Lugol-solution. Buffered formaldehyde was added later (Mäkelä *et al.* 1992).

Depending on algal amounts either 50 or 22 ml of sample was sedimented for 24 h. Cells from a constant area of the chamber bottom were counted under an inverted microscope by phase-contrast illumination using × 800 and × 200 magnifications. Cell counts were converted to biovolumes using the cell volumes of the phytoplankton database of the Finnish Environment Institute (FEI). The biomass values are given as fresh weight.

The proportion of nanoplankton (< 20 µm), of flagellated as well as heterotrophic species, of the total cell number and biomass was also calculated. The identification of heterotrophic and mixotrophic species was based on information from the literature. The species were classified into different indicator groups by applying the indices of Järnefelt (1952, 1956), Järnefelt *et al*. (1963) and Heinonen (1980).

Since the number of samples and the sampling frequencies of the various years differed we used the monthly mean biomass values from June to August to determine the average biomass of each summer period.

The physico-chemical samples were taken and analysed according to Finnish standardized methods (National Board of Waters 1981, Mäkelä *et al*. 1992). Results are from a depth of one metre and from a depth of 12 m in the hypolimnion. These values are treated as annual mean values. The non-parametric Seasonal Kendall-test was used to detect trends in the studied variables (a trend is indicated by $p < 0.05$). The phytoplankton data were also compared with the lake water characteristics using the Pearson correlation coefficient to determine if any significant relationships existed. The significant values will be indicated by * for $p < 0.05$, ** for $p < 0.01$, and *** for $p < 0.001$.

Results and discussion

Nutrients

Total phosphorus concentrations remained quite low after the fertilization in August 1988, on average 12 µg l^{-1} (range 7–12 µg l^{-1}). The total nitrogen concentration was higher, 580 µg l^{-1}, when compared to the average values measured during 1989–1994 (Tables 2 and 3). The autumn was rainy and the values, especially those of nitrogen can be considered a consequence of fertilization.

Table 2. The concentrations (µg l^{-1}) of nutrients in Lake Kalliojärvi from 1988 to 1994 at a depth of one metre. *n* = number of observations.

Year	*n*	Total P		PO_4-P		Total N		NO_2+NO_3-N		NH_4-N	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
1988	6	12	7–16	4	1– 6	580	420–670	150	34–190	41	9– 70
1989	13	18	13–23	5	2– 9	560	400–790	150	4–390	41	2–140
1990	19	18	13–25	3	1–11	420	330–610	50	1–210	19	2– 51
1991	19	17	11–23	3	1– 8	390	300–500	45	1–150	18	3– 56
1992	16	17	12–26	3	1– 7	420	330–640	38	0–140	19	2– 52
1993	9	17	13–21	3	1– 8	410	350–530	22	0– 81	19	2– 52
1994	15	17	11–25	3	1– 6	400	300–480	30	1–130	20	3– 55

Table 3. Hypolimnetic (12 m) concentrations (µg l^{-1}) of nutrients in Lake Kalliojärvi from 1988 to 1994. *n* = number of observations.

Year	*n*	Total P		PO_4-P		Total N		NO_2+NO_3-N		NH_4-N	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
1988	5	44	17– 57	17	7–30	690	530– 810	55	18–170	180	71–280
1989	12	38	20– 67	15	9–31	730	600– 860	190	16–320	120	4–310
1990	18	56	18–100	18	3–52	650	400– 870	59	1–160	180	41–410
1991	18	36	16– 49	8	3–15	560	390– 650	110	41–160	78	26–130
1992	16	25	18– 36	8	4–12	500	370– 580	92	65–120	48	10–100
1993	8	49	24– 87	17	8–65	650	540– 860	37	2– 63	170	110–370
1994	15	26	17– 48	8	4–16	580	380–1000	68	22– 96	145	31–430

Nevertheless, no observations were made immediately before fertilization in L. Kalliojärvi, but the decrease of the ammonium and nitrogen concentrations two years after application indicates that the higher nitrogen concentration is caused by forest fertilizer (Table 2). Moreover, the leaching of nitrogen occurred immediately after application, although the application of water-soluble phosphorus on peatland areas usually cause a long-lasting leaching effect of phosphate phosphorus (M. Saura, T. Sallantaus, Ä. Bilaletdin and T. Frisk unpubl.).

Just before the break-up of ice in early May 1989, a maximum episodic concentration of total phosphorus of 300 µg l^{-1} was measured locally in the southern bay of L. Kalliojärvi — due to the leaching of fertilizers during the spring high-flow. The annual average phosphorus concentration in the surface water was 18 µg l^{-1}.

Phosphorus concentrations were relatively high during the years 1990 to 1994. In 1994, the average total nitrogen concentration decreased to 400 µg l^{-1}. In the hypolimnion, nutrient concentrations increased especially in 1993. Organic matter, water colour and conductivity, also increased (Tables 4 and 5).

Phytoplankton

In late summer 1988 the average total phytoplankton volume and the average chlorophyll *a* concentration were 0.8 mg l^{-1} and 6.1 µg l^{-1}, respectively (Table 6). *Cryptomonas* spp. contributed with 53% to the total biomass in August whereas chrysophyceans, like *Mallomonas allorgei*, *M. crassisquama* and *Pseudopedinella* spp. only contributed 33% (Table 7). Nevertheless, in early September chrysophyceans contributed with more than 50% to the total algal biomass.

In April 1989, the total biomass was still low,

Table 4. Annual mean, minimum and maximum of Secchi depth, pH, water colour, chemical oxygen demand and conductivity from one metre in Lake Kalliojärvi from 1988 to 1994. *n* = number of observations.

Year	*n*	Secchi depth m		pH		Colour mg l^{-1}Pt		$COD_{Mn}O_2$ mg l^{-1}		Conductivity mS m^{-1}	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
1988	6	1.8	1.6–2.2	5.6	5.4–5.7	120	100–140	15	14–16	3.0	2.7–3.3
1989	13	1.8	1.3–2.2	5.7	5.1–6.2	100	60–150	13	10–17	3.1	2.8–3.7
1990	19	2.1	1.6–2.8	5.8	5.0–6.2	79	60–120	11	9–15	3.0	2.8–3.5
1991	19	2.3	1.7–3.7	5.9	5.4–6.2	72	60–110	10	8–12	2.9	2.7–3.4
1992	16	2.0	1.3–2.7	5.8	5.3–6.1	83	50–140	13	10–19	3.0	2.8–3.2
1993	9	1.7	1.4–2.2	5.7	5.3–6.1	94	70–120	15	12–19	2.9	2.6–3.4
1994	15	2.0	1.1–3.5	5.9	5.2–6.2	80	50–100	13	10–15	2.8	2.5–3.1

Table 5. Hypolimnetic (12 m) annual mean, minimum and maximum of pH, water colour, chemical oxygen demand and conductivity from hypolimnion (12 m) in Lake Kalliojärvi from 1988 to 1994. *n* = number of observations.

Year	*n*	pH		Colour mg l^{-1}Pt		$COD_{Mn}O_2$ mg l^{-1}		Conductivity mS m^{-1}	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range
1988	5	5.7	5.4–5.9	250	140–300	22	15–25	3.9	3.2–4.4
1989	12	5.5	5.3–6.1	170	110–300	16	11–22	3.6	3.0–4.6
1990	18	5.7	5.0–6.1	150	70–250	15	10–20	3.6	2.9–4.7
1991	18	5.5	5.2–6.0	120	80–200	12	10–14	3.2	2.8–3.3
1992	16	5.4	5.2–5.7	110	80–140	13	11–15	3.0	2.9–3.2
1993	8	5.7	5.4–6.2	220	160–300	21	19–27	3.6	3.3–4.9
1994	15	5.6	5.4–5.8	150	90–240	16	13–20	3.1	2.8–3.6

Table 6. The mean phytoplankton biomass, chlorophyll *a*, total number of taxa and number of eutrophy and oligotrophy indicating species in Lake Kalliojärvi from May to September in 1988–1994. *n* = number of observations.

Year	*n*	Biomass mg l[–1]		Chlorophyll *a* µg l[–1]		Taxa		Eutrophic species		Oligotrophic species	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
1988	3	0.8	0.2–1.2	6.1	2.2–10.0	49	48–51	5	3–6	8	5–6
1989	9	1.1	0.3–3.9	10.4	4.3–32.0	57	46–65	5	1–6	6	0–8
1990	12	0.5	0.1–1.1	3.9	2.2– 6.7	43	22–64	3	0–7	4	3–7
1991	15*	–	–	4.5	2.7– 6.9	–	–	–	–	–	–
1992	10	0.9	0.4–1.2	5.6	3.9– 6.9	58	19–71	6	1–4	7	2–9
1993	8*	–	–	6.8	3.4–11.0	–	–	–	–	–	–
1994	8	1.2	0.3–2.9	7.4	3.3–15.0	46	31–60	3	0–2	7	5–9

* Only chlorophyll *a*.

Table 7. Abundant (> 10% of cell number, or > 10% of total biomass) phytoplankton species in Lake Kalliojärvi from 1988 to 1994. n = cell numbers, b = biomass.

Species		1988**	1989	1990	1992	1994
Merismopedia tenuissima Lagerheim		n .	n .	n.	n .	n .
Anabaena flos-aquae (Lyngb.) Brébisson		. .	. .	. b	. .	. .
Cryptomonas spp.	*	n b	n b	n b	n b	. b
Katablepharis ovalis Skuja		. .	n b	. .	. .	. .
Rhodomonas lacustris Pascher & Ruttner	*	. .	n b	n .	. .	. .
Gymnodinium spp.	*	. .	. b	. b	. .	. .
Chrysococcus cordiformis Naumann	*	. .	. b	. .	n .	. .
Dinobryon borgei Lemmermann	*	n .	. .	. .	. .	. .
Mallomonas akrokomos Ruttner		. .	. b	. b	. b	. .
M. allorgei (Defl.) Conrad		. .	. .	. b	. b	. b
M. caudata Ivanov em. Krieger		. .	. .	. b	. b	. .
M. crassisquama (Asm.) Fott		. b	n b	. b	. .	. b
Monochrysis sp. (*Pavlova* sp.?)	*	. .	n b	. .	n .	. b
Ochromonadales	*	. .	n .	n b	n .	n .
Paraphysomonas spp.		n b	. .	. .	. .	. .
Pseudopedinella spp.	*	n b	n b	n b	n b	n b
Synura spp.		. .	. .	. b	. .	. .
Uroglena spp.	*	n b	n b	. .	. .	n b
Rhizosolenia longiseta Zacharias		. b	. .	. .	. .	. b
Asterionella formosa Hassal		. .	n b	. .	. .	. .
Tabellaria flocculosa (Roth) Kützing		. .	. b	. .	n b	. b
Gonyostomum semen (Ehr.) Diesing	*	. .	. .	. .	. .	. b
Nephroselmis spp.		. .	. .	. .	n b	. .
Chlamydomonas spp.		. .	. b	. .	. .	. .
Monomastix spp.		n .	. .	n .	n .	n .
Oocystis parva W. & G.S. West		. .	. .	n b	. .	. .
Pedinomonas spp.		n .	n .	. .	. .	. .
Pediastrum privum (Printz) Hegewald		. b	n b	. b	. .	. .
Teilingia granulata (Roy & Biss.) Bourrelly		. .	n b	. .	. .	. .
Gloeotila spp.		. .	. .	. .	n b	. .
Koliella longiseta (Visch.) Hindák		. .	. .	. .	n b	. .

* Mixotrophic species , according to Holen and Boraas (1996), Jansson *et al*. 1996
** Only from August to October.

0.2 mg l^{-1}, consisting mainly of the green algae *Chlamydomonas* spp., a genus typical for spring phytoplankton in brown-water lakes (Arvola and Rask 1984, Arvola *et al*. 1990). The small (2.6 × 3.6 µm) prymnesiophycean genus *Monochrysis* (cf. *M. parva, Pavlova* sp.), which is very typical for L. Kalliojärvi, contributed with 35% to the biomass. Its contribution to the total cell number was as high as 95%. The maximum chlorophyll *a* concentration, 32 µg l^{-1}, was measured in late May 1989 (Fig. 4). This maximum corresponded to a total phytoplankton volume of 3.9 mg l^{-1}. Chrysophyceans, like *M. crassisquama* contributed with 55% to the biomass and diatoms, mainly *Asterionella formosa* and *Tabellaria flocculosa*, with 42% (Table 7).

The proportion of blue-green algae was very low during the summer. In August, at the most, only 7% of the total biomass consisted of blue-green algae, mainly *Anabaena flos-aquae* (Fig. 4). The average chlorophyll *a* concentration during the growing period was 10.4 µg l^{-1}, and the average biomass 1.1 mg l^{-1} (Table 6).

During the years 1990 and 1992 no vernal phytoplankton maxima were observed (Fig. 4). Average chlorophyll *a* concentrations were low, approximately 3.9 to 5.6 µg l^{-1} (Table 6), and fluctuations during the growing season seemed to be minimal. Phytoplankton biomass values were also low. Chrysophyceans, mainly the genera *Mallomonas*, *Pseudopedinella* and *Synura* still dominated, although occasionally green algae, like *Oocystis parva,* were important (Table 7). The proportion of blue-green algae was low, only in early August 1990 mainly *Anabaena flos-aquae* contributed with 27% to the total biomass (Fig. 4).

In 1993 and 1994 there was an increase in mean chlorophyll *a* concentrations to 6.8 µg l^{-1} (max. 10 µg l^{-1}, in August) and to 7.4 µg l^{-1} (max. 15 µg l^{-1}, in September), respectively. This was due to the increase of *Gonyostomum semen* (obviously already in 1993). In 1994 (Fig. 4), at the end of August, *G. semen* contributed with 58% to the total phytoplankton volume. In late September this algae, more or less on its own, composed this study year's maximum biomass of 2.9 mg l^{-1}.

Phytoplankton composition

Altogether 247 taxa were identified in the available data. Chrysophyceans, prymnesiophyceans, like the small *Monochrysis* sp. which is obviously capable of bacterial consumption during times of algal abundance (Holen and Boraas 1995), green algae, e.g. the small *Monomastix* sp. and occasionally diatoms dominated either the biomass or cell density. Cryptomonads, also potentially mixotrophic (e.g. Tranvik *et al*. 1989), and favoured by N + P addition (Jansson *et al*. 1996) dominated only in 1988 (Fig. 4). This group correlated almost significantly ($r = 0.77^*$, $n = 9$) with PO_4-P. During the study period the decrease of cryptomonads (Fig. 4) was quite clear but statistically not significant ($p = 0.07$).

The small blue-green algae *Merismopedia tenuissima* (cell size 1.8 µm), was occasionally abundant when looking at cell density, and reached its maximum abundance during the warm and mild summer of 1992. Due to its small size, it is of minor importance when looking at total biomass. This species is typical for nutrient poor (tot. P ca. 5 µg l^{-1}), dark and acidic waters (where the pH is 5 to 6; Brettum 1989). Blomqvist (1996), observed the acidification-induced dominance of *M. tenuissima* and suggested that it is a "dead-end" for energy in an acidic, clear water lake. According to Rosén (1981), *M. tenuissima* (size of 0.4–1.6 µm) was abundant in oligotrophic Swedish lakes in general but it was also occasionally found in more nutrient rich waters (tot. P > 24 µg l^{-1}). Komárek and Ettl (1958) and Hindák (1992) concluded that *Merismopedia minima* (0.5–1.2 µm) has often been misinterpreted as *M. tenuissima* (1.3–2–2.5 µm). *M. minima* is commonly found in eutrophic waters, particularly in hot summers, as blue-green algae in general.

In this study the correlation between blue-green algae and water turbidity was highly significant ($r = 0.70^{***}$, $n = 21$), only significant with water temperature ($r = 0.52^{**}$, $n = 22$), but the correlation with pH was weak. The increase of blue-green algae biomass, mainly formed by small colonies such as *M. tenuissima*, was significant ($p = 0.02$).

At no time during the study did blue-green algae form mass occurrences, although small green flakes were visible on the water surface in August 1989. Nevertheless, these flakes were not detected in the samples. The sampler either pushes the floating blue-green algal colonies to the sides,

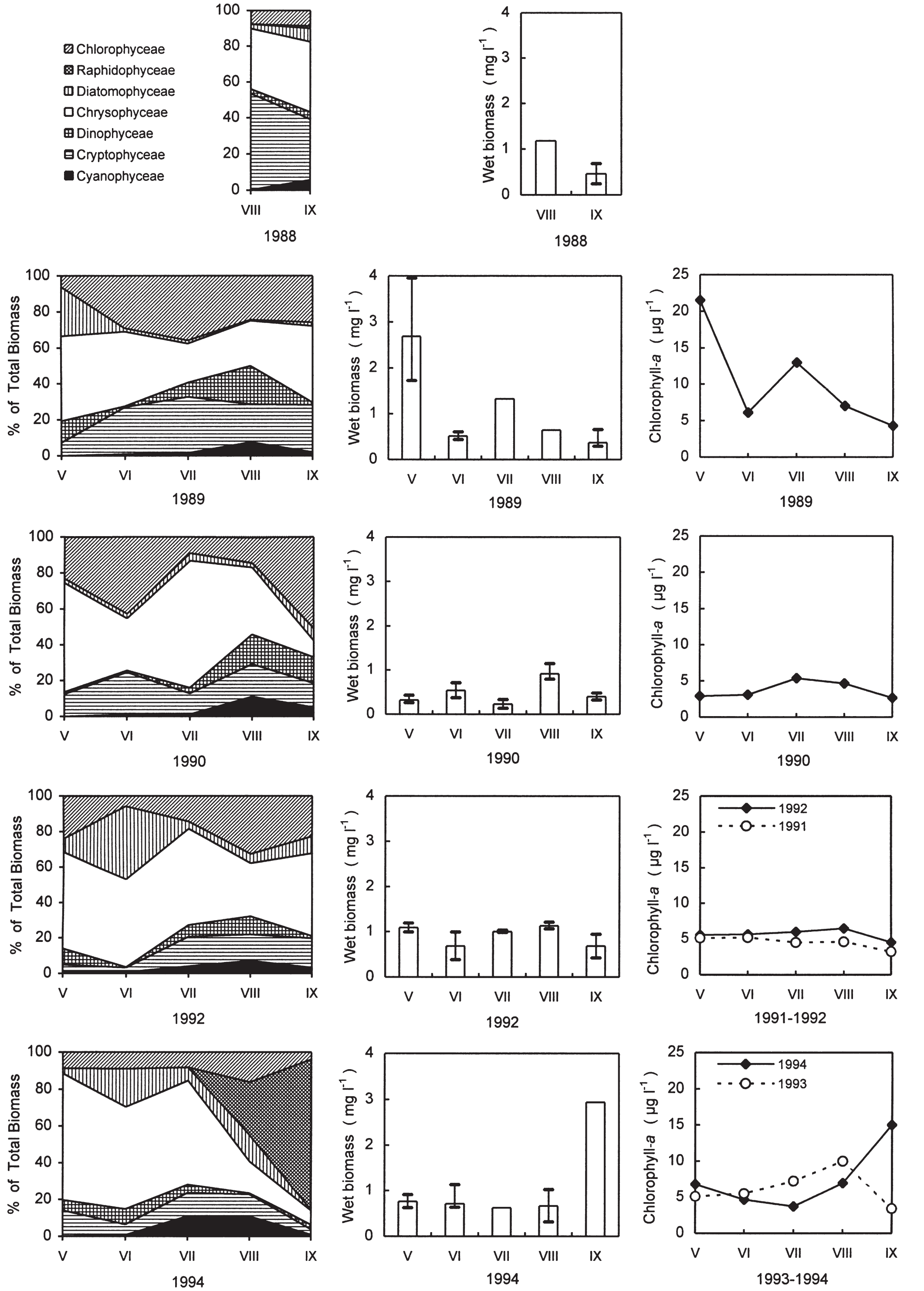

Fig. 4. Phytoplankton composition from May to September in Lake Kalliojärvi. Biomass and chlorophyll *a* values are monthly averages. The minimum and maximum values for biomass are shown. The genera *Monochrysis* and *Chrysochromulina* are included in Chrysophyceae.

as it consequently must do also with those in the water column. Or, it is possible that the blue-green algae form only a thin layer on the surface and that their measured proportion in the water sample is correct. The mass occurrence of blue-green algae could have been prevented by a low pH — much below 6 — of the humic water (e.g. Reynolds and Walsby 1975).

The most obvious change in species composition was the increase of *Gonyostomum semen* during the late summer in 1994. We assume that the increase of chlorophyll *a* concentration in 1993 (Fig. 4) indicated the abundance of this species with numerous chloroplasts. Concentrations of nutrients and organic matter were also elevated, mainly in the hypolimnion (Tables 3 and 5). Unfortunately, there is no phytoplankton data from 1993. The flagellated *G. semen* is able to optimize its growth in humic waters by migrating between the nutrient rich hypolimnion and the illuminated, but nutrient poor epilimnion (Salonen *et al.* 1984, Cronberg *et al.* 1988, Arvola *et al.* 1990, Eloranta and Räike 1995). It is favoured not only by nutrient input but also by bacterial production (Holen and Boraas 1995). The biomass of *G. semen* correlated only weakly with pH, and not at all with the other variables of the epilimnion. During the first study years, *G. semen* was only occasionally present and in very low cell numbers.

The observed species composition was typical for brown-water lakes (Ilmavirta 1983, Arvola 1983, Arvola *et al.* 1990, Jansson *et al.* 1996). The proportion of eutrophy indicating species decreased during the study period while the number of oligotrophy indicating species increased (Table 6).

Life forms

The response of algal communities to environmental conditions is often reflected by life forms, e.g. by cell size, flagellation, chlorophyll *a* content of cells (e.g. Ahlgren 1970, Harris 1986) and by differences in nutrient uptake mechanisms (Jansson *et al.* 1996). In L. Kalliojärvi the proportion of small (< 20 µm), as well as flagellated cells of the total cell number was on average ca. 60%, but in the biomass 40% and 70%, respectively (Table 8). These are values typical for brown-water lakes (Ilmavirta 1983, Arvola 1983, 1984). Mixotrophy was quite common in L. Kalliojärvi, ca. 30% of the abundant species were facultatively or obligatorily mixotrophic (Table 7). Heterotrophic species were on the other hand scarce, although their importance began to increase in autumn. During winter they dominate the biomass in brown-water lakes (e.g. Arvola and Kankaala 1989).

Phytoplankton succession

Only in 1989 was a vernal maximum of phytoplankton observed. Since then biomass values were very stable with only slight fluctuations until late summer 1994, when a maximum in biomass was caused by *Gonyostomum semen*. According to Arvola (1983), the phytoplankton succession in brown-water lakes has a vernal maximum in May and two summer maxima during the growth period, one in July and the other in August, which we were not always able to observe in L. Kalliojärvi. A highly significant correlation (r = 0.88 ***, n = 43) was

Table 8. The average proportion of flagellated, nanoplankton and heterotrophic species calculated as a percentage of the biomass and total number of cells in the Lake Kalliojärvi from May to September in 1988–1994.

Year	Flagellated		Nanoplankton		Heterotrophic	
	Biomass	Number	Biomass	Number	Biomass	Number
1988*	85	62	32	60	0	8
1989	68	58	54	57	2	8
1990	65	57	39	55	2	6
1991	–		–		–	
1992	67	60	46	61	2	10
1993	–		–		–	
1994	74	64	44	64	2	4

* Only August to September

found between total phytoplankton volume values and chlorophyll *a* concentrations.

Conclusions

Relatively high concentrations of nutrients were available to the plankton after fertilization, though only for a short time during the spring overturn. The quick consumption of extra nutrients via the microbial loop, or via transportation away from the lake during the spring flood, decreased the quantity of available nutrients. The transported nutrients may be found in another part of the same watercourse at the start of the growth season, resulting in increased eutrophication.

The quantity and composition of phytoplankton remained typical of a brown-water lake throughout the study. Small flagellated species capable of a mixotrophic life-style were dominants. *Cryptomonas* spp. was favoured by the abrupt addition of nutrients but decreased almost as quickly. The small colonial cyanophycean *Merismopedia tenuissima* increased during the study period, but the most obvious change in the species composition was the increase of *Gonyostomum semen*, five years after the fertilization. The total phytoplankton volume and chlorophyll *a* concentrations correlated well in our observations.

We do not know whether *Gonyostomum semen* remains a dominant member of the algal community in L. Kalliojärvi. Leaching of nutrients due to forest fertilization is clear, and higher concentrations of nutrients, compared with the natural background levels, are likely to be measured for several years to come.

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