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Response of phytoplankton to ecological engineering remediation of a Canadian Shield Lake affected by acid mine drainage

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ABSTRACT

Multivariate analyses were used to relate changes in water chemistry with those in the composition of the phytoplankton in two adjacent northern Ontario shield Lakes in Canada. One of the lakes is affected by both acid mine drainage (AMD) and a succession of remediation measures. The other, much larger lake is pristine and was monitored for both water quality and phytoplankton. The AMD lake, already contaminated at the start of the 17-year project, experienced further increases in Zn concentrations from around 10 mg L^{-1} to 35 mg L^{-1} and a pH decrease from 5 to 3 during the project. Over the same period, phytoplankton diversity declined from 52 taxa in 59 samples to 42 taxa in 74 samples. Only *Ochromonas* spp. and *Chlamydomonas* spp., apparently tolerant of a wide range of physical and chemical conditions, were consistently present in both lakes. Other taxa (*Peridinium*, *Pinnularia* and *Euglena*) were frequent in the AMD lake in the early stages of the project but then declined. *Asterionella* and *Botrycoccus* (although common in the pristine lake), were rarely observed in the AMD lake. *Lepocinclis* proliferated as metal concentrations increased and pH declined in the AMD lake but was rarely found in the clean lake.

Such gradual adaptation or changes in phytoplankton populations have not been reported previously for such extreme chemical conditions. The multivariate statistical analysis (PCA, CCA, DCA) revealed that the highest number of taxa were found to be controlled by pH and Ni in the years 1986–1992.

One-third of the taxa in that period were more closely associated with pH alone. In the late stages of the study (1999–2003) the predominant controlling factors appeared to be metals and conductivity. Most of the taxa followed the time/pH/metal axis, suggesting that occurrence changed with slowly changing water conditions. Those taxa which fell outside the time/pH/Zn/Cu/Al axis included mostly Chrysophytes, Cryptophytes, and Chlorophytes, although there were some Euglenophyceae and diatoms in this group. By the end of the study in 2003, the combined effect of the restoration measures brought about the development of an extensive periphytic underwater meadow, along with a slight improvement in water quality and an increase in the number of phytoplankton taxa.

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1. Introduction

Lakes become acidic and metal-contaminated through natural means (Earle et al., 1986, 1987), air pollution (Yan, 1979; Nicholls et al., 1992; Olaveson and Nalewajko, 1994; Pinel-Alloul et al., 1990), experimental manipulation (Findlay and Kasian, 1986, 1991), and as a result of mining (Austin et al., 1985; Fyson et al., 1998; Kalin et al., 1989). Depending on the cause, the levels of contamination can vary greatly, but even at low levels, the effect on resident phytoplankton populations, and consequently on the entire food web within the lake, is notable. For example, phytoplankton diversity appears to decrease in lakes only slightly acidified ($pH > 4$) by atmospheric sources (i.e. acid rain) (Yan, 1979; Findlay and Kasian, 1986; Nicholls et al., 1992). Is this due to the increased concentration of hydrogen ions or to increases in heavy metals which usually accompany acid deposition? The concentration of metals in lakes affected solely or predominantly by atmospheric deposition is likewise low, ranging from background to 40 μM for Cu and Ni (Yan, 1979), in comparison to lakes receiving AMD where it would be much higher.

Changes in phytoplankton community structure and function have been studied intensely in the acidic flooded coal pits in Germany and in four hard-rock, mine waste management areas in Canada (Nixdorf et al., 1998; Cao and Kalin, 1999; Lessman et al., 1999, 2000) with similar results. It is possible in such extreme environments to observe whether metal or hydrogen ion concentration has the greatest effect on phytoplankton diversity.

We report on phytoplankton populations in two Canadian Shield lakes, both low in buffering capacity and thus sensitive to acid rain, one affected by AMD from a Cu/Zn mine and the other not. Boomerang Lake, the impacted lake, drains into Confederation Lake, a trophy recreational fisheries lake. Thus, to prevent the contamination of Confederation Lake, as mandated by the provincial government, Boomerang Lake was subjected to variety of ecological engineering measures over the 17-year period of the study.

2. Methods and materials

2.1. Study area

The South Bay mine site is located in north-western Ontario, Canada, on a peninsula in Confederation lake, the head waters of the English River Drainage, 85 km east of Red Lake (longitude 92°40′W, latitude 51°08′N). The mine operated for 10 years until its closure in 1981 and generated nearly no waste rock and less then one million tons of tailings. However, the wastes are high in acid – generating capacity with 41% pyrite (FeS_2) and 4% pyrrhotite (FeS_{-n}) and will generate contaminants in perpetuity. The site is bordered on the one side by Confederation Lake and on the other by Boomerang Lake. Drainage ditches ensured that the surface and ground waters drained into Boomerang Lake.

Boomerang Lake, which is encompassed by the South Bay Waste Management Area (SBWMA), is 1.2 km long, and 400 m wide at its widest transect, with a mean depth of 4.2 m. It has a volume of about 1 million cubic meters and a surface area of 23.6 ha, giving it a surface to volume ratio of 24 m^{-1}. Since Boomerang Lake is shallow, the water is well mixed throughout the ice-free season. It receives AMD inputs from the southeast of the drainage basin from the tailings area through groundwater flow between stations B7–B10. From the south contaminated surface water run-off enters from the mine and mill yard around station B1. It also enters the lake around station B4 where there is effluent from the flooded underground mine (Fig. 1). Uncontaminated water enters the lake from the northern part of the drainage basin, resulting in a total flow of about 300,000 cubic meters per year, resulting in a 3-year turn over or residence time of 3 years.

Boomerang Lake drains into Confederation Lake, an important tourist fishery, with a surface area of 5665 ha composed of many connected deep lakes, forming the headwaters of the English River Drainage basin. The mine site sits on a small peninsula surrounded by Confederation lake shores on the west side, and to the east Boomerang Lake. The stated mandate of the remediation work at the South Bay Mine Site was to protect and preserve the water quality of Confederation Lake. No discharges of contaminants were tolerated.

2.2. Ecological engineering remediation

The pH of Boomerang Lake gradually dropped after mining operations started in 1971, due to tailings spills and mill discharges, although it was periodically corrected by the addition of a calcined lime (CaO) slurry. These actions, however, did not halt the acidification and the metal enrichment of the sediments. The remediation of the site began in 1986, 5 years after the closure of the mine. Ecological engineering concepts applied to mine water restoration were, at that time, in their formulation phase (Kalin, 1985, 1989; Kalin and van Everdingen, 1988) and therefore the work proceeded stepwise – experimentation followed by field trials and finally full – scale application.

Essentially the remediation in Boomerang Lake started in 1986 by gradually adding cut brush for the attachment for periphytic algae and the introduction of acid tolerant periphytic moss. Natural rock phosphate mining wastes (NPR) were added to the sediments gradually in 1991 and 1992, testing various particle size effects and in 1993, 80 tonnes of finely powdered NPR were scattered throughout the lake. In 1997, 1 tonne of calcium nitrate was also added (Kalin, 2001). Metallic magnesium was also tested in the laboratory as a means of consuming hydrogen ions generated by the oxidation of reduced iron. After testing, 16 tonnes of metallic magnesium were added to the lake in 1998.

2.2.1. Sampling site selection and description

In 1986, phytoplankton were sampled along the steep rocky shores of the peninsula in Confederation Lake (C1–C11) as part of a project to establish monitoring stations for water quality control. The sites were chosen so that they would be geomorphologically similar to locations in Boomerang Lake. Many of the larger lakes within the Confederation Lake system thermally stratify at about 4–8 m, but Boomerang Lake is shallow in comparison and does not stratify.

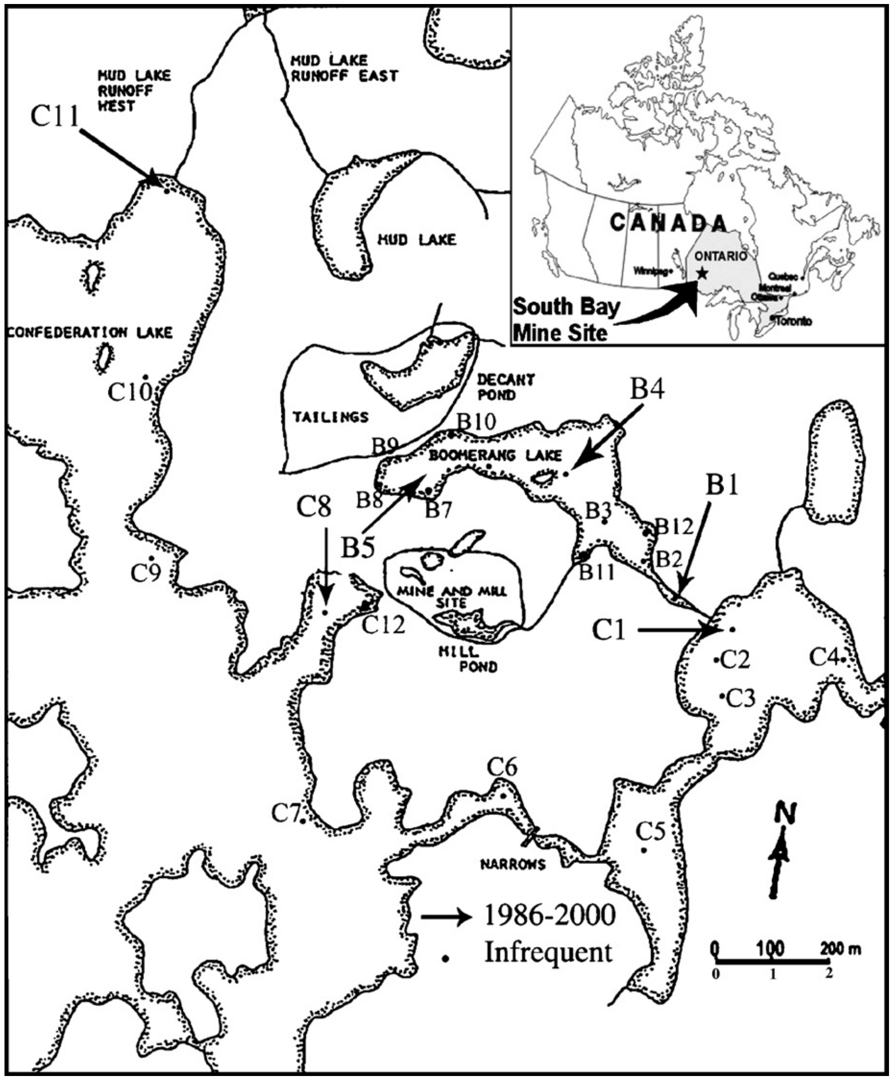


Fig. 1 – Map of Boomerang Lake and Confederation Lake with sampling locations.

The initial survey revealed that the number of taxa within Boomerang Lake was lower than in Confederation Lake, but no reduction in taxa numbers was noted at the junction where Boomerang Lake empties into Confederation Lake (Kalin et al., 1989). Further, long-term phytoplankton monitoring stations were selected at all of the discharge areas of the South Bay Waste Management Area (SBWMA).

Three locations in Confederation Lake were finally selected for further study: C1 in shallow (0.5 m) water 50 m beyond the outlet of Boomerang Lake and C11 in similarly shallow water 50–75 m from the discharge of the "SBWMA" drainage basin. C8 is located at a depth of 8 m, in a cove, 150 m from where the mine adit and underground workings were a potential source of ground water discharge (see Fig. 1).

The Boomerang Lake samples were collected from stations just offshore of the tailings area in shallow water (B7–B10), from the middle of the lake at a depth of 4.5 m (B4), and at the lake outflow at depths varying between 1 m and 2 m (B1, B2 and B3) (Fig. 1). All phytoplankton samples were collected from a depth of 0.5 m except for samples taken at C8 which were drawn several times from a depth of 4 m using plastic pipe to obtain a depth integrated water sample.

2.3. Water chemistry methods

Water quality samples were drawn quarterly during spring (under the ice), summer and fall. The samples were collected in 500 mL plastic bottles that were placed immediately in coolers and shipped within 36 h to the laboratory. Measurements of pH, E_h, and electrical conductivity were carried out in the field and/or in the laboratory after Rand et al. (1976).

In the laboratory, acidity and alkalinity titrations were performed using a Metrohm SM 702 Titrino Autotitrator using duplicate samples. Redox potential was measured using a Corning 103 m equipped with Fisher electrodes. E_m readings were converted to E_h according to $E_h = E_m + (241\,\text{mV} - (0.66 \times (T\,(^\circ\text{C}) - 25\,(^\circ\text{C}))))$.

The pH was measured using a WTW 196 m, and conductivity was measured with an Orion (WTW) Model 140 m. Samples for metal analysis were filtered through 0.45 μm membrane filters, acidified with nitric acid to <pH 1, sent to a certified

laboratory and analysed by Inductively Coupled Plasma Spectroscopy (ICP; US EPA method #200.7).

2.4. *Phytoplankton methods*

Phytoplankton samples were collected at intervals no less than once per year, but no greater than six times per year, with the exception of 1996 when no samples were taken. On each field trip, from 4 to 12 stations in Boomerang Lake and all three stations in Confederation Lake were sampled. For each sample, 2 L bottles were filled 0.5 m below the water surface and fixed with Lugol's (IKI) preservative immediately upon collection. The samples were allowed to settle for 1 week in the dark. After removing the supernatant by siphoning, a final concentrated sample of 20 mL, containing all the algal organisms from the original sample was transferred to a 25 mL glass scintillation vial for storage. Depending on the density of algal cells and the amount of debris, an aliquot of the concentrated sample was directly counted or diluted with distilled water. At the proper concentration, the cells were counted using the Űtermohl Counting chamber (with the appropriate settling column, 5 or 10 mL). The cell counts were calculated back to a fixed volume.

2.5. *Statistical methods*

Water quality and phytoplankton community data were assembled for three distinct time periods; 1986–1992, representing the pre-remediation time for Boomerang lake; 1993–1997, when remediation measures were gradually implemented, and 1999–2003, when the results of earlier efforts were becoming evident, although the remediation work itself was abating.

The interaction of phytoplankton and water contamination, which is dependent upon many physical and chemical variables, and the characteristics of particular species cannot effectively be defined by univariate statistics. Frequently, spatial/temporal trends can be detected only by long-term studies, but such research efforts generate large and "noisy" data matrices within which real trends can be obscured by sampling errors, random, non-defined variations, and non-interested variations. The data sets in this study consist of collections from the first two time periods (1985–1992 and 1993–1997) which were analysed using multivariate statistical analyses to determine the long-term spatial and temporal patterns in both the phytoplankton community changes and water quality parameters. For the period from 1998 to 2003 the phytoplankton community was monitored, but no further statistical analysis was carried out.

Data of the first two observation periods were transformed (Gauch, 1982; Cao et al., 1999), and subjected to a range of analytical techniques, including non-centred Principal Component Analysis (PCA), Detrended Correspondence Analysis (DCA) and Canonical Correspondence Analysis (CCA) after ter Braak (1987). Principal Components Analysis (PCA) is a multivariate procedure which rotates the data so that maximum variabilities are projected onto the axes. Essentially, a set of correlated variables are transformed into a set of uncorrelated variables which are ordered by reducing variability. The uncorrelated variables are linear combinations of the original variables. The main use of PCA is to reduce the dimensionality of a data set while retaining as much information as is possible.

The first principal component is the combination of variables that explains the greatest amount of variation. The second principal component defines the next largest amount of variation and is independent of the first principal component. There can be as many possible principal components as there are variables.

De-trended correspondence analysis (DCA) addresses a deficiency of correspondence analysis (Hill, 1979). The problem is known as the "arch effect", a non-monotonic relationship between two sets of scores derived by DCA. The basic idea is to split the first dimension into several intervals and to subtract the mean score of the second dimension from its values in each interval separately.

Canonical correlation analysis (CCA) measures the linear relationship between two multidimensional variables. It finds two bases, one for each variable, that are optimal with respect to correlations and the corresponding correlations. It finds the two bases in which the correlation matrix between the variables is diagonal and maximizes the correlations on the diagonal. The dimensionality of these new bases is equal to or less than the smallest dimensionality of the two variables.

Each of these techniques has its own strengths and weaknesses and, when used together, yield cohesive trends for Boomerang Lake, as the water quality declined concurrently but independently with the remediation efforts in the lake. For Confederation Lake, no water quality changes were detected which could be related to time changes, as during the time of observation only one Zn contamination took place, when the underground mine workings generated effluents. This was immediately corrected by diverting the effluent permanently to Boomerang Lake. As the water quality in Boomerang Lake started to gradually improve during the last observation period, the phytoplankton data from both lakes consisted of recording frequency of occurrence and the diversity of taxa, which were compared to the previous two observation periods.

2.6. *Data selection and quality control (1986–1997)*

During the period 1986–1997, 157 water samples and 56 compatible algal samples were collected from Boomerang Lake and 111 water samples and 57 compatible algal samples from station C8 in Confederation Lake. The selected water quality data set was subjected to PCA ordination using 15 elements from the total set of 64 physical and chemical variables determined in the sample. The samples from Boomerang showed no location-based groupings, which was not surprising since the lake is well mixed. Based on this, the average value for each variable across all the Boomerang sites (B1–B12) was used to represent that variable on each sampling date, which resulted in a total of 52 monthly based samples used in the analysis. For Boomerang Lake, twenty composite phytoplankton samples were created based on sampling month and the presence or absence of species. Nineteen composite samples together with a corresponding subset of 52 water samples were subjected to CCA ordination. Station C8 in Confederation Lake yielded 36 binary phytoplankton samples which were subjected to DCA ordination.

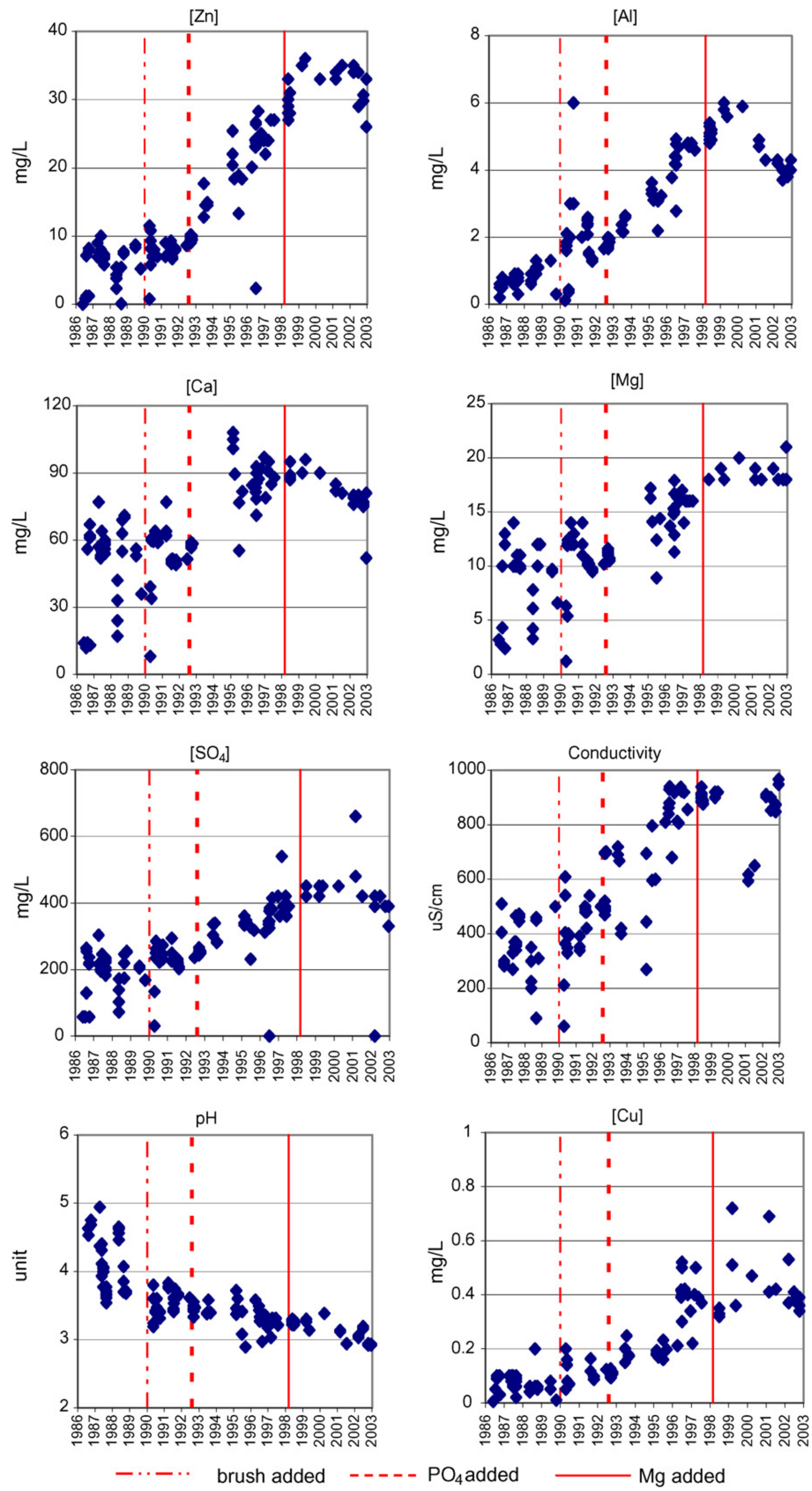


Fig. 2 – Trends in Boomerang Lake water chemistry 1986–2003.

3. Results

3.1. Water chemistry

The concentrations of Zn, Al, Ca, Mg, SO_4, electrical conductivity, pH, and Cu from each sampling date are given in Fig. 2 for Boomerang Lake from 1986 to 2003. Generally, the pattern is the same for the Zn, Al, SO_4, and Cu, reflecting the decreasing pH, which, by 1998, was beginning to release Ca from the sediments. In Fig. 2, vertical lines indicate the dates at which ecological engineering measures were implemented, which included the addition of cut brush in 1990, phosphate in 1993 and finally 16 tonnes of metallic Mg suspended from floating barges in 1998. Metal concentrations increased gradually, prior to 1992 but slowed somewhat after the 1993 addition of phosphate. Zinc increased from 5 mg L^{-1} to 37 mg L^{-1} (before 2000) and started to decrease to 27 mg L^{-1} by 2003. Aluminium increased from about 0.5 mg L^{-1} to 6 mg L^{-1} by 2000 but decreased to 4 mg L^{-1} by 2003. Calcium increased from 15 mg L^{-1} to a high of 90 mg L^{-1}. Sulphate increased from about 50 mg L^{-1} to 400 mg L^{-1}, but remained the same after 1998. Cu concentrations increased from 0.05 mg L^{-1} to around 0.7 mg L^{-1} by 2000. With the suspension of metallic Mg in the lake in 1998, Mg increased from 3 mg L^{-1} to 20 mg L^{-1}. The pH initially dropped quite rapidly from around 5 in 1995 to 3.5 by 1990, but since 1998, it has stabilized around 3.0 (Fig. 2).

3.2. Water quality changes and phytoplankton (1986–1997)

Fig. 3 analyses the Boomerang Lake water quality changes using PCA ordination. The large axis is the first PCA axis, the second longest axis perpendicular to the first is the second PCA axis and so forth. Thus these first few PCA axes represent the greatest amount of variation in the data set and contain significant patterns. After transformation, the PCA ordination explained about 66.3% of the variance in water quality with the first two axes (Fig. 3).

The first axis explained 52.7% of the variance, while the second axis explained 13.6%. The earliest samples (1986) which appear on the left of the origin and the most recent (1997), on the far right of the first axis, suggest that water quality variance is indicative of the gradual change over time. Lead, P, and Ni are associated with the second axis, which, because of the low correlation with the first axis, are less important determiners of water quality. Of the water quality variables on the

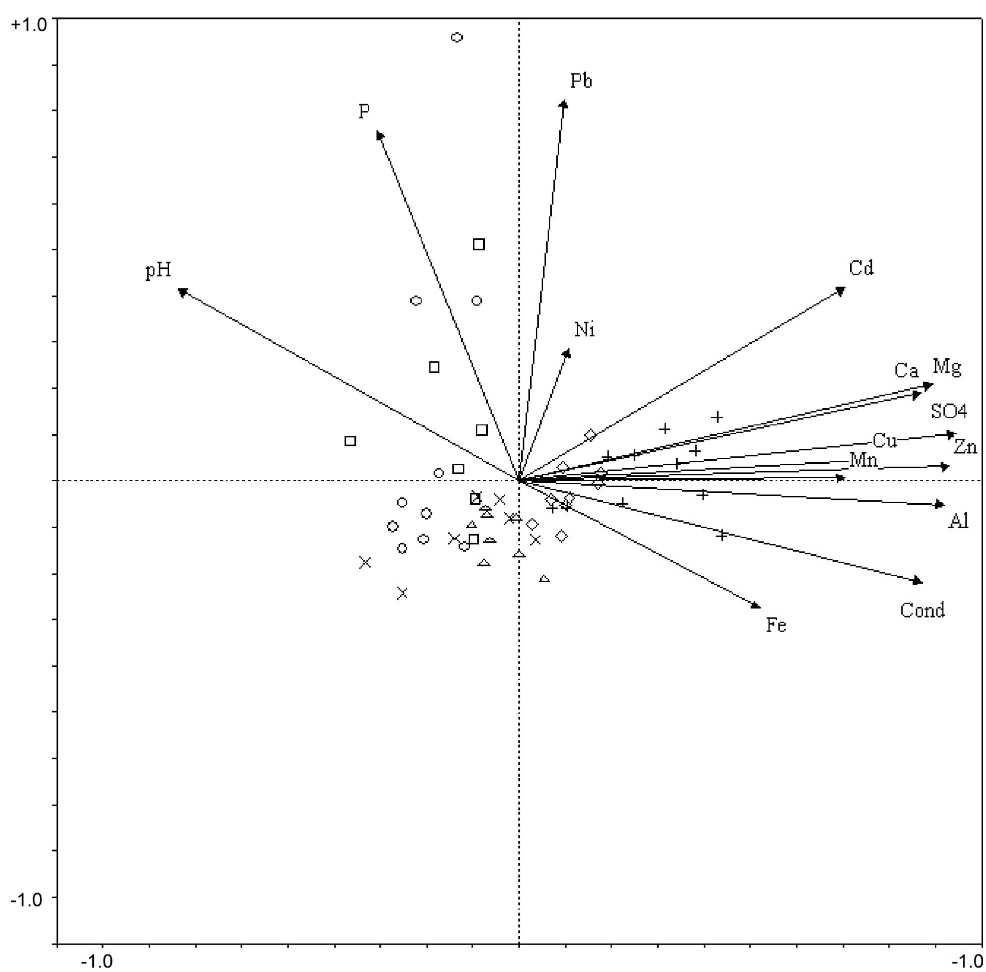


Fig. 3 – Two-dimensional PCA ordination of 52 water samples collected from Boomerang Lake during 1986–1997 with 14 water-quality variables on the first two-dimensional spaces. Sampling years are differentiated with symbols: 1986–1987 (○), 1988–1989 (□), 1990–1991 (×), 1992–1993 (△), 1995–1995 (◇), and 1996–1997 (+).

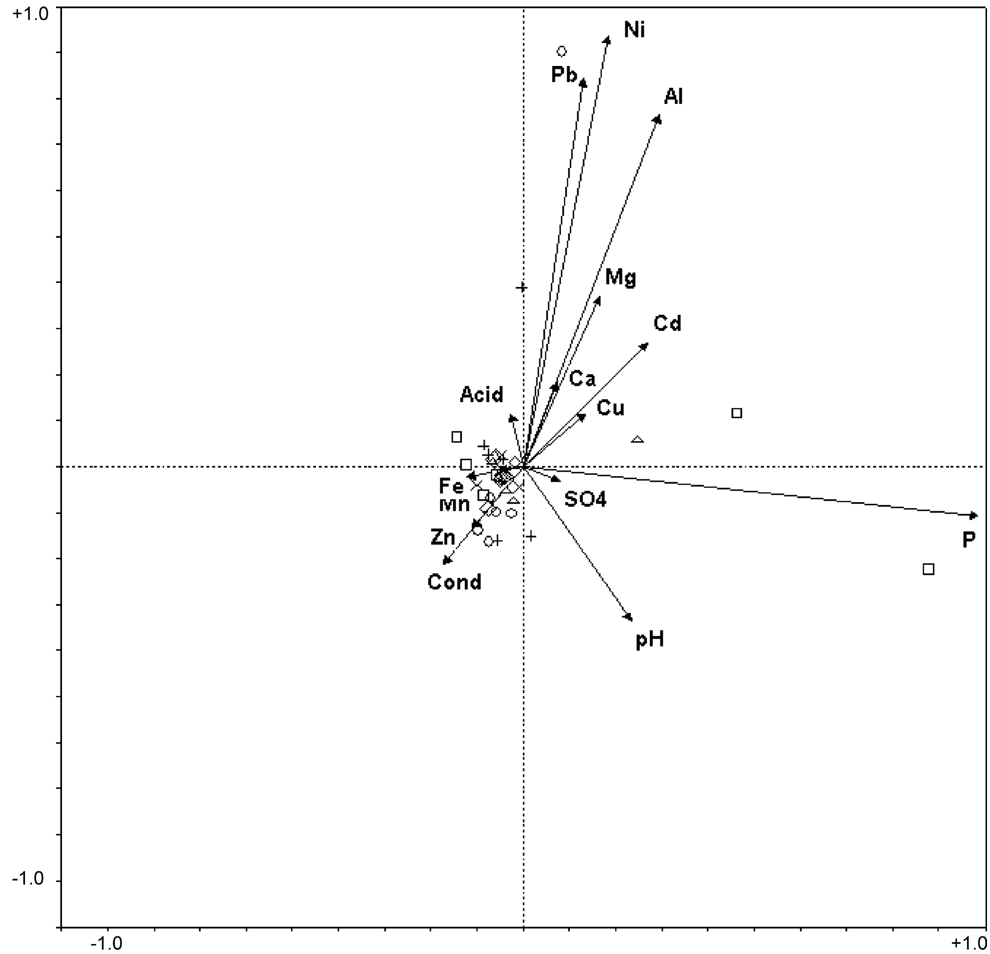
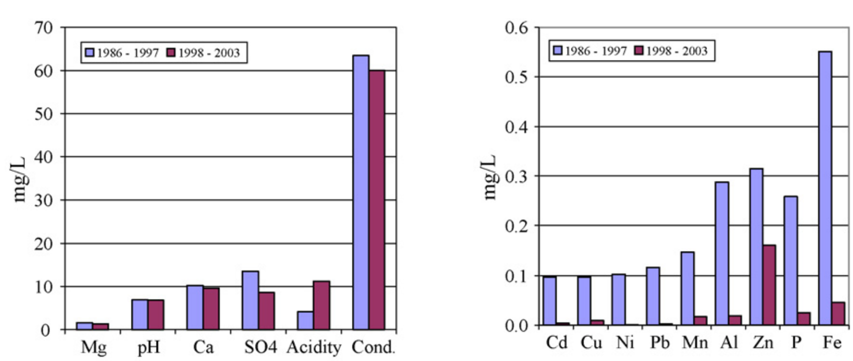


Fig. 4 – Two-dimensional PCA ordination of 36 water samples collected at C8 of Confederation Lake during 1986–1997 with 15 water-quality variables. Sampling years are differentiated with symbols: 1986–1987 (◯), 1988–1989 (□), 1990–1991 (×), 1992–1993 (△), 1995–1995 (◊), and 1996–1997 (+).

first axis, Zn, Al, sulphate, pH, and conductivity are weighed most heavily. Zinc, Al, Ca, and Mg are particularly significant from a statistical standpoint.

The same statistical analysis was carried out on Confederation Lake water quality data for station C8. After transformation, the PCA ordination suggested that water chemistry remained largely constant over the period from 1986 to 1997 (Fig. 4).

The first two axes of the PCA ordination accounted for 59.1% of the total variance. The primary axis accounted for



Detection Limit mg/L	Mg	Fe	Ca	SO_4	Acidity	Cond, uS/cm	Cd	Cu	Ni	Pb	Mn	Al	Zn	P
	1	<0.01	1	1	2	1	<0.005	<0.005	<0.01	<0.025	<0.01	<0.01	<0.01	<0.01

Fig. 5 – Trends in water chemistry in Confederation Lake, 1986–1997 and 1998–2003 and detection limits for measured parameters. Station C8.

only 33.5% of the variance. Total P weighed heavily on the primary axis while Zn, Al, and Pb were heavily weighted on the second axis. These heavily weighted data points suggest that these ions were behaving differently, as most of the other samples were very well compressed, suggesting an absence of time and spatial trends.

The water quality at station C8 in Confederation Lake is summarized in table form in Fig. 5. Only those elements used in the PCA ordination were used. Detection limits for each element are shown at the bottom of the figure. During the period of 1986–1997, the underground workings from the mine site were discharging AMD effluent, which lead to a slight increase in Zn, Al, and Fe. The groundwater discharge was diverted to Boomerang Lake in 1994. Thus, for the period, 1998–2003, the concentration of these elements returned to a base state, confirming the success of the measures taken (Fig. 5).

3.3. *Phytoplankton*

The frequency with which the most common taxa occurred in Boomerang Lake is shown in Table 1 which reports 40 taxa which occurred with a frequency higher then 8% for the first two observation periods, and a frequency of 1.3% for the last period. The taxa are shown as genera. Species within genera were recognised and counted but listed as genera in the table as identification to the species level was not always possible. For example, three species of *Euglena* were noted, *E. mutabalis* and two others which could not be identified.

Table 1 – Boomerang Lake phytoplankton taxa by class, genus and frequency (%) over three contiguous time periods

	1986–1992			1993–1997			1998–2003		
1	CHL	Unid-Chlor-spp.	62.7	CHR	*Ochromonas*	66.7	CHR	*Ochromonas*	62.3
2	CHR	*Ochromonas*	54.2	CHL	Unid-Chlor-small	66.7	EUG	Lepocinclis	61.0
3	CHL	*Chlamydomonas*	49.2	DES	Staurastrum	58.3	CHL	Klebshormidium	53.2
4	CHR	Chromulina	40.7	CHL	Ulothrix	41.7	BAC	Eunotia	36.4
5	CHL	Sphaerellopsis	33.9	CHL	Ulothrix	41.7	DES	Staurastrum	36.4
6	BAC	Pinnularia	32.2	EUG	Euglena	33.3	DIN	Gymnodinium	33.8
7	BAC	Synedra	30.5	DIN	Glenodinium	33.3	CHL	*Chlamydomonas*	26.0
8	CHL	Ulothrix	30.5	EUG	Lepocinclis	33.3	CHL	Unid-Chlor-spp.	19.5
9	CHL	*Chlamydomonas*	28.8	CHR	unid-Chrys-1	33.3	CHR	Chromulina	14.3
10	BAC	Navicula	28.8	CHL	*Chlamydomonas*	25	CHL	Mesotaenium	14.3
11	CHR	Unid-Chrys-sp	27.1	CRY	Cryptomonas	25	BAC	Eunotia	9.1
12	BAC	Achnanthes	25.4	BAC	Eunotia	25	CHR	Micromonas	9.1
13	CHL	Chlorella	25.4	EUG	Lepocinclis	25	BAC	Nitzschia	9.1
14	BAC	Nitzschia	25.4	CYA	Unid-Cyano-small	25	EUG	Euglena	7.8
15	CHL	Mougeotia	23.7	EUG	Euglena	16.7	DIN	Glenodinium	7.8
16	DIN	Peridinium	23.7	DIN	Gymnodinium	16.7	BAC	Pinnularia	7.8
17	CRY	Cryptomonas	22.0	BAC	Melosira	16.7	BAC	Synedra	7.8
18	BAC	Fragilaria	22.0	BAC	Navicula	16.7	BAC	Navicula	6.5
19	BAC	Synedra	22.0	DES	Netrium	16.7	DIN	Peridinium	6.5
20	BAC	Unid-Diatom	22.0	DES	Netrium	16.7	CHL	Sphaerellopsis	6.5
21	EUG	Euglena	20.3	BAC	Pinnularia	16.7	DES	Staurastrum	6.5
22	BAC	Achnanthes	18.6	CRY	Unid-Crypt	16.7	BAC	Tabellaria	6.5
23	EUG	Euglena	18.6	BAC	Unid-Diatom	16.7	CHL	Ulothrix	6.5
24	BAC	Tabellaria	18.6	CHL	Zygnema	16.7	BAC	Achnanthes	5.2
25	BAC	Pinnularia	16.9	CHL	Zygogonium	16.7	CHL	Ankistrodesmus	5.2
26	BAC	Tabellaria	16.9	CHL	Chlorella	8.3	CRY	Cryptomonas	5.2
27	CHR	Kephyrion	15.3	CHR	Chlorocloster	8.3	BAC	Pinnularia	5.2
28	BAC	Melosira	15.3	CYA	Chroococcus	8.3	EUG	Euglena	3.9
29	BAC	Navicula	15.3	CYA	Chroococcus	8.3	EUG	Lepocinclis	3.9
30	CHL	Oocystis	15.3	CRY	Chroomonas	8.3	CHL	Mougeotia	3.9
31	BAC	Stauroneis	15.3	CHL	Cosmarium	8.3	CHL	Oocystis	3.9
32	BAC	Achnanthes	13.6	CHL	Dictyosphaerium	8.3	BAC	Unid-Diatom	3.9
33	CRY	Cryptomonas	11.9	CHR	Dinobryon	8.3	BAC	Cymbella	2.6
34	BAC	Eunotia	11.9	CHR	Dinobryon	8.3	CHL	Microspora	2.6
35	BAC	Eunotia	11.9	EUG	Euglena	8.3	CHR	Unid-Chrys-1	2.6
36	CHR	Dinobryon	10.2	BAC	Eunotia	8.3	CYA	Unid-Cyano-2	2.6
37	BAC	Eunotia	10.2	BAC	Melosira	8.3	CRY	Cryptomonas	1.3
38	DIN	Peridinium	10.2	BAC	Nitzschia	8.3	CHL	Dictyosphaerium	1.3
39	BAC	Tabellaria	10.2	BAC	Pinnularia	8.3	DES	Netrium	1.3
40	BAC	Cyclotella	8.5	CRY	Rhodomonas	8.3	EUG	Euglena	1.3
Total taxa			52			68			42
Total samples			60			15			74

The columns indicate the taxon's class, the taxon's genus, and finally the frequency in percent. Note that only the 40 most frequent taxa are presented for each time period.

The most prominent taxon throughout Boomerang Lake was *Ochromonas* sp. Other taxa which appeared commonly in the frequency tables for all 3 periods included species of *Chlamydomonas*, *Chromulina Cryptomonas*, *Euglena*, *Lepocinclis*, *Navicula*, *Nitzschia*, *Peridinium*, *Sphaerellopsis,* and *Synedra* (Table 1).

In the pre-remediation period (1986–1992), there were a total of 52 algal taxa (60 samples) in Boomerang Lake. This increased to 68 taxa (15 samples) in the remediation period (1993–1997), but decreased again to 42 taxa in 74 samples in the post-remediation period (1998–2003). After construction of a second diversion ditch for the effluents from the underground workings, acidity increased from 45 to 120 $CaCO_3$ mequiv. L^{-1}, Zn concentration increased from 8 mg L^{-1} to 25 mg L^{-1}, and, as expected, the number of algal taxa dropped to 42. Between 1999 and 2000, metallic Mg was added to the lake, to prevent further reductions in pH. Although some water quality variables responded favourably, diversity (as defined by the frequency) in the lake did not increase (Table 1).

Boomerang Lake experienced major reductions in the number of taxa in most algal classes, except the Euglenophyceae (Table 1). In the first 6 years, the five most common taxa were members of the Chrysophyceae and Chlorophyceae but more variation was evident in the post-remediation period when Chrysophyceae, Chlorophyceae, Euglenophyceae, and Dinophyceae were all common.

Canonical Correspondence Analysis (CCA) was conducted to detect patterns of species distribution related to physical and chemical parameters. The results contain the environmental variables plotted as arrows emanating from the center of the graph along with points for the samples and taxa. Arrows representing the environmental variables indicate the direction of maximum change of that variable across the diagram. The position of the species points indicates the environmental reference of the species. The CCA plot of Boomerang Lake phytoplankton and water quality variables during periods 1 (1986–1992) and 2 (1993–1997) is shown in Fig. 6.

The first two axes account for 28.7% of the variance with 15.5% of the variance explained by the primary axis alone. The samples are aligned along the primary axis by sampling year, suggesting that the primary axis is some combination of variables with time. More taxa are associated with the 1986–1987 samples, corresponding to a higher algal richness at that time (Table 1). The fact that pH, Zn, Cu, Al, SO_4, and electrical con-

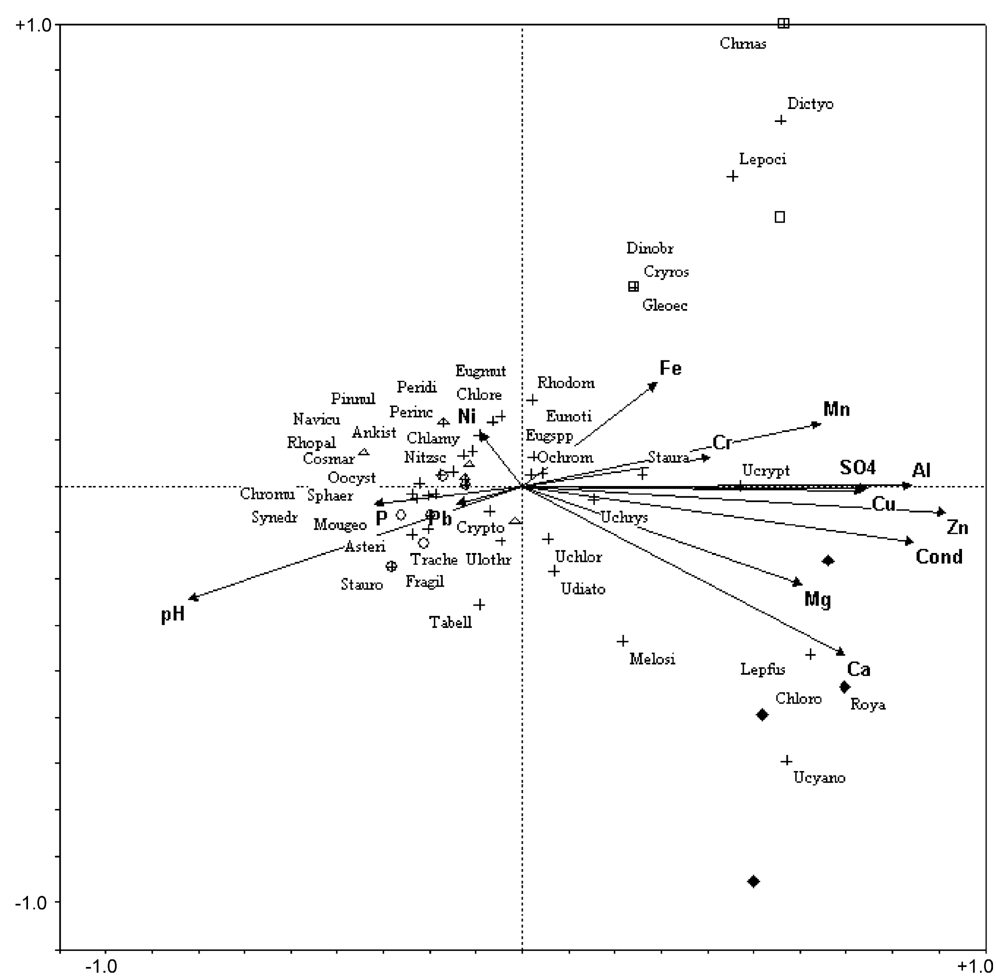


Fig. 6 – Two-dimensional CCA ordination of 19 phytoplankton and water samples collected from Boomerang Lake during 1986–1997. Sampling years are differentiated with symbols: 1986–1987 (○), 1988–1989 (△), 1994–1995 (□), and 96–97 (♦). See Table 2 for taxon labels.

ductivity fall out close to the primary axis also suggests that these parameters varied with time, which they did (Fig. 2). Most of the phytoplankton taxa fall in a cloud around the primary axis. We will call these the primary group taxa. Those that did not fall within the primary group were more influenced by the secondary axis. To analyse this a little further, we compared the phytoplankton taxa in the primary group (associated with pH and Ni and earlier time), against those associated with the metals (Mn, Cu, Al, Zn, SO_4) and later time, and those other taxa which seem to be associated with Fe and Ni, against those taxa associated with water hardness, Mg, and Ca (Table 2).

By far, the highest number of taxa fell into the main group with pH, Ni and time. Those data points on the left of the vertical axis were described as coordinated with an "earlier time." Those on the right side of the 2nd axis were described as coordinated with a "later time." Only 1/3 of the number of taxa associated with pH, the remainder were associated with metals and conductivity. Those taxa which fell outside the time/pH/Zn/Cu/Al axis included mostly Chrysophytes, Cryptophytes and Chlorophytes, although there were some Euglenohpyceae (*Lepocinclis* sp. and *Lepocinclis fusciformis*) and one diatom, *Melosira* (Table 2).

DCA is an eigenanalysis technique- an algebraic technique that uses a data matrix to calculate eigenvectors after Hill and Gauch (1980). The data matrix is composed of plots and species, with a value given for each species in each plot that is a measure of that species presence (for example, cover or basal area). In DCA, sample scores are calculated from the matrix to order the plots (axis 1 and axis 2) and the eigenvalue is a measure of the strength of the ordination.

In Confederation Lake, DCA ordination showed some time-trending; e.g., 1996–1997 samples were slightly separated from the others on the second axis (Fig. 7). However, this time-trend is weaker than that in Boomerang Lake (Fig. 3), but may be linked with the decrease in the number of taxa with time in Confederation Lake (Table 3). Given the long time period covered in this data set, several parameters not quantified here, such as changes in solar irradiation and water temperature, may also be relevant.

Table 2 – Two groupings of taxa (primary and other) as defined by the two-dimensional CCA shown in Fig. 6

Fe, Ni		Ca/Mg	
Code	Taxon	Code	Taxon
Other taxa			
Chrnas	Chroomonas	Melosi	Melosira
Dictyo	Dictyospharium	Lepfus	Lepocinclis fusciformis
Lepoci	Lepocinclis	Chloro	Chlorogonium
Dinobr	Dinobryon	Roya	Roya
Cryros	Cryptomonas rostriformes	Ucyano	Unid Cyanophyte
Gleoec	Gleocapsa		
pH/Ni		**Mn, Cr, SO_4, Cu, Zn, Cond.**	
Code	Taxon	Code	Taxon
Primary group taxa			
Tabell	Tabelleria	Rhodom	Rhodomonas
Ulothr	Ulothrix	Eunoti	Eunotia
Crypto	Cryptomonas	Eug spp.	Euglena spp.
Trache	Trachelomonas	Ochrom	*Ochromonas*
Fragil	Fragilaria	Ucrypt	Unid Cryptophyte
Stauro	Staruoneis	Staura	Staurastrum
Asteri	Asterionella	Uchrys	Unid Chrysophyte
Mougeo	Mougeotia	Uchlor	Unid. Chlorophyte
Synedr	Synedra	Udiato	Unid Diatom
Chromu	Chromulina		
Sphaer	Shaerolopsis		
Eugmut	Euglena mutabilis		
Chlore	Chlorella		
Peridi	Peridinium		
Perinc	Peridinum inconspicuum		
Chlamy	*Chlamydomonas*		
Nitszc	Nitzschia		
Pinnul	Pinnularia		
Ankist	Ankistrodesmus		
Navicu	Navicula		
Rhopal	Rhopalia		
Cosmar	Cosmarium		
Oocyst	Oocystis		

The taxa are further divided by association with the major metal or chemical variable. Codes for taxa are the same as for Fig. 6.

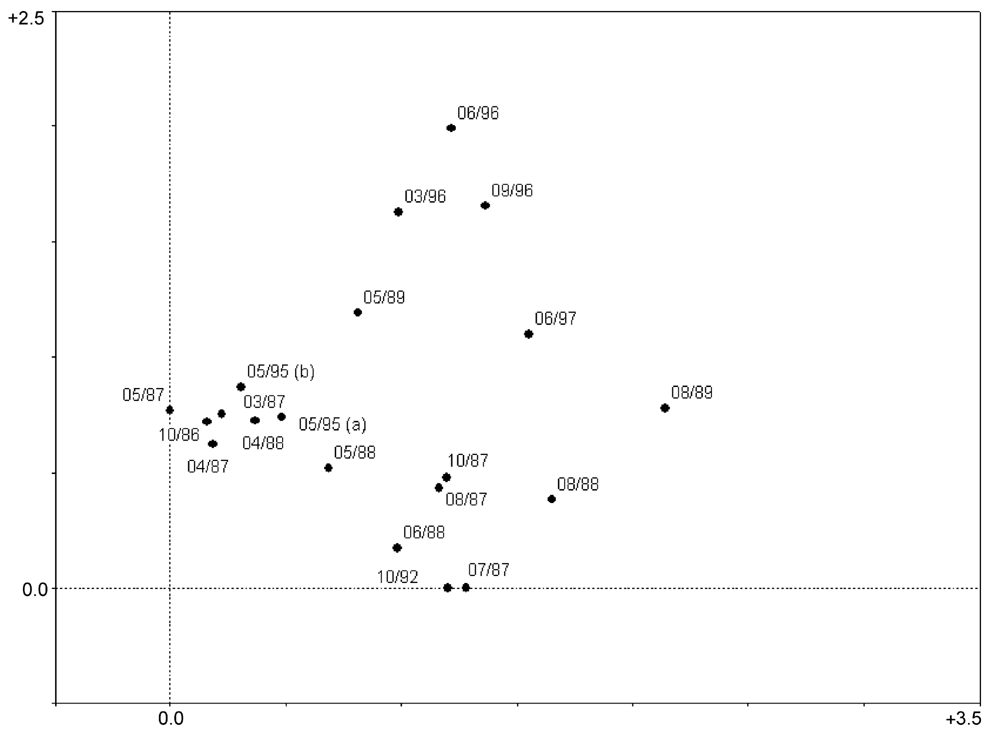


Fig. 7 – Two-dimensional DCA ordination of 36 phytoplankton samples collected from C8 of the Confederation Lake during 1986–1997.

Table 3 summarizes frequency of taxa (as genus and species) in samples from Confederation Lake for each of the three periods corresponding to those used for Boomerang Lake. The water quality in Confederation Lake did not change over the course of the study (Fig. 4 and Fig. 5), but, the numbers of taxa changed dramatically. In the 1986 to 1992 period, a total of 196 taxa were found in 52 samples. The taxa number dropped to 127 (16 samples) during 1993–1997, and decreased even further to 104 (22 samples) in the last period from 1998 to 2003. Some, but not all of the variation in taxa number, may be due to the unequal number of samples collected in the respective periods.

Interestingly, there are some genera in Confederation Lake that have similar frequencies to those in Boomerang Lake. *Ochromonas*, *Cryptomonas* are among the thirty most commonly found genera in both lakes during all three time periods. *Chromulina*, *Synedra*, and *Staurastrum* are among the top thirty for both lakes, occurring at least twice during the three time periods. All genera present in Boomerang Lake are found in Confederation Lake, with the exception of *Neidium*. Some cyanobacterial species, an unidentified cyanobacterium and *Oscillatoria* while rare in Boomerang Lake, were common in Confederation Lake, perhaps because they were less tolerant to low pH and high metal concentrations.

In 1986–1992 and 1998–2003, the largest number of taxa by far belonged to the Chlorophyceae and Bacillariophyceae. In 1993–1997, the number of Chrysophyte taxa was also relatively high. The overall reduction in the number of taxa in the absence of water quality changes in Confederation Lake might be related to reported changes in phytoplankton populations in boreal forest lakes due to altered solar radiation and associated nutrient availability (Donahue et al., 2003). Whatever the cause, these changes have affected some classes more than others.

If the data collected from station C8 are analysed alone, the picture is slightly different. C8 was chosen because it was least affected by mine effluent. These data include taxa identified to the species level (Table 4). Because only one of the three stations in Conferderation Lake is analysed here, the number of samples and taxa are lower. The number of taxa belonging to the Cyanobacteria, Bacillariophyceae, and the Chlorophyceae dropped by more than half. The Chrysophyceae was the third most common algal class, behind Bacillariophyceae and Chlorophyceae.

Boomerang Lake clearly experienced major reductions in the number of genera and species from the pre-remediation period with 69 genera and 121 species to the post-remediation period with 28 genera and 39 species (Table 4). The largest drop in taxa occurred in the first period, where the most drastic pH change occurred. During the following periods (1993–1997) and (1998–2003), the largest number of taxa belonged to the Chlorophyceae and Bacillariophyceae. The taxa in these classes increased slightly during the last period in both Confederation and Boomerang Lake.

4. Discussion

Both the time trends (Fig. 2) and multivariate analysis (Fig. 3) showed that Boomerang Lake experienced a rapid and significant change in water quality from 1986 to 1997. The rapid deterioration of water quality after 1992 was expected after a

Table 3 – Confederation Lake phytoplankton taxa by class, genus and frequency (%) over three contiguous time periods.

	1986–1992			1993–1997			1998–2003		
1	CHL	Unid-Chlor-spp.	86.5	CHL	Zygnema	100	CHR	*Ochromonas*	86.4
2	CHR	*Ochromonas*	75	BAC	Asterionella	100	BAC	Synedra	86.4
3	BAC	Asterionella	71.2	CHR	*Ochromonas*	100	BAC	Asterionella	77.3
4	BAC	Asterionella	71.2	CHL	Unid-Chlor-small	93.8	BAC	Tabellaria	63.6
5	CHR	Chromulina	71.2	CYA	Unid-Cyano-small	93.8	CHL	Botrycoccus	45.5
6	BAC	Navicula	67.3	CRY	Cryptomonas	81.3	BAC	Eunotia	40.9
7	CHL	*Chlamydomonas*	65.4	BAC	Tabellaria	81.3	BAC	Eunotia	40.9
8	BAC	Synedra	65.4	DIN	Peridinium	75	DES	Staurastrum	40.9
9	BAC	Tabellaria	65.4	DIN	Tabellaria	75	CHR	Dinobryon	36.4
10	CHL	Merismopedia	59.6	CHL	Botrycoccus	68.8	DES	Arthrodesmus	31.8
11	BAC	Neidium	59.6	CHR	Dinobryon	68.8	CHR	Chromulina	31.8
12	CRY	Cryptomonas	57.7	CHR	unid-Chrys-1	68.8	BAC	Fragilaria	31.8
13	BAC	Pinnularia	57.7	CHR	Chromulina	62.5	CRY	Cryptomonas	27.3
14	CHL	Ankistrodesmus	53.8	CRY	Unid-Crypt	62.5	BAC	Cyclotella	22.7
15	CRY	Cryptomonas	51.9	BAC	Unid-Diatom	62.5	BAC	Navicula	22.7
16	BAC	Synedra	51.9	BAC	Rhizosolenia	56.3	DIN	Peridinium	22.7
17	CHL	Chlorella	50	BAC	Synedra	56.3	CHL	Scendesmus	22.7
18	CHL	Cosmarium	50	CHL	Ankistrodesmus	50	CYA	Anabaena	18.2
19	EUG	Euglena	50	CHL	*Chlamydomonas*	50	CHR	Chroomonas	18.2
20	BAC	Unid-Diatom	50	CRY	Rhodomonas	50	CRY	Cryptomonas	18.2
21	CHR	Unid-Chrys-sp	46.2	CHR	Chrysolykos	43.8	CHR	Dinobryon	18.2
22	CHR	Dinobryon	44.2	BAC	Fragilaria	43.8	BAC	Epithemia	18.2
23	CYA	Merismopedia	44.2	CYA	Merismopedia	43.8	DIN	Gymnodinium	18.2
24	CYA	Oscillatoria	44.2	CHL	Oocystis	43.8	CYA	Oscillatoria	18.2
25	BAC	Stauroneis	44.2	BAC	Synedra	43.8	BAC	Pinnularia	18.2
26	CYA	Unid-Cyano-2	44.2	CHR	Bitrichia	37.5	CHR	Pseudokephyrion	18.2
27	DIN	Peridinium	42.3	CRY	Cryptomonas	37.5	CHL	Quadrigula	18.2
28	CHL	Merismopedia	40.4	CHR	Dinobryon	37.5	BAC	Rhizosolenia	18.2
29	CHL	Arthrodesmus	38.5	DES	Staurastrum	37.5	CHL	Temnogametum	18.2
30	BAC	Tabellaria	38.5	BAC	Stephanodiscus	37.5	CHR	unid-Chrys-1	18.2
31	BAC	Cymbella	36.5	CYA	Anabaena	31.3	BAC	Achnanthes	13.6
32	BAC	Melosira	36.5	CHL	Dictyospaherium	31.3	CHL	Ankistrodesmus	13.6
33	DES	Staurastrum	36.5	CHL	Gyromitus	31.3	CHL	*Chlamydomonas*	13.6
34	CHR	unid-Chrys-1	36.5	CHR	Mallomonas	31.3	CHL	Coelastrum	13.6
35	CHL	Botrycoccus	34.6	CYA	Merismopedia	31.3	CRY	Cryptomonas	13.6
36	CHR	Dinobryon	34.6	CHL	Mougeotia	31.3	BAC	Cymbella	13.6
37	CHL	Ulothrix	34.6	BAC	Synedra	31.3	EUG	Euglena	13.6
38	BAC	Fragilaria	32.7	CHL	Temnogametum	31.3	EUG	Euglena	13.6
39	CHL	Gyromitus	32.7	CYA	Anabaena	25	DIN	Gymnodinium	13.6
40	BAC	Tabillaria	32.7	CHR	Dinobryon	25	CHL	Klebshormidium	13.6
Total number of taxa			196			127			104
Total number of samples			52			16			22

The columns indicate the taxon's class, the taxon's genus, and finally the frequency in percent. Note that only the most frequent 40 taxa are presented for each time period (shown at the bottom of the table).

newly built ground water diversion ditch delivered mine discharges and mine/mill site run-off to the lake. In contrast, Confederation Lake remained stable with good water quality.

It was expected that most phytoplankton would not survive the continued and increasing contaminant load, concurrent with the decrease in pH and increase in electrical conductivity (Fig. 2). Although the phytoplankton experienced an overall decline in number of taxa over nearly two decades, the remaining diversity (as defined by frequency) is rather surprising for these extreme chemical conditions.

Early in the study period the moss, *Drepanocladus fluitans,* was introduced from a uranium tailings pond in northern Ontario (Kalin, 1981) to Boomerang Lake along with the brush cuttings. It established itself gradually, but following the application of phosphate to the lake sediment, the moss rapidly spread throughout the lake. It formed an extensive oxygen-consuming cover over the sediments, which helped to reduce the iron oxidation cycle. Kleeberg and Gruneberg (2005) suggest that phosphate mobility is increased in acid mining lakes, which may have contributed to the spread of the moss. The existence of this underwater meadow may well be contributing to the stable phytoplankton diversity.

Ochromonas and *Chlamydomonas* remained very frequent in Boomerang Lake throughout the study. These genera were also frequent in Confederation Lake indicating a tolerance to a wide range of conditions. *Lepocinclis* appeared in Boomerang Lake during remediation but was rarely found in Confederation Lake, suggesting a specialised ability to compete in the most contaminated conditions. Several genera which were frequent during the first period, showed substantial declines during the last two periods (*Peridinium*, *Pinnularia*, and *Euglena*) indicating intolerance to the lowest pH values and highest

Table 4 – Number of species phytoplankton genera and species by class found in Confederation Lake (at station C8) and in Boomerang Lake (all stations)

Algal classes	1986–1992		1993–1997		1998–2003	
	Genera	Species	Genera	Species	Genera	Species
Confederation Lake—site C8						
Cyanobacteria	12	24	5	5	10	10
Chlorophyceae	30	52	13	13	28	33
Euglenophyceae	3	4	1	1	2	2
Chrysophyceae	13	21	10	15	9	11
Bacillariophyceae	21	52	12	18	18	23
Cryptophyceae	3	6	3	3	4	8
Pyrrhophyceae	4	10	4	5	4	6
Total	86	169	48	60	75	93
Number of samples	18	18	7	7	15	15
Boomerang Lake						
Cyanobacteria	6	10	1	1	1	1
Chlorophyceae	24	36	8	13	12	14
Euglenophyceae	3	5	2	5	2	3
Chrysophyceae	7	12	3	5	4	4
Bacillariophyceae	24	46	7	9	6	12
Cryptophyceae	2	6	4	4	2	3
Pyrrhophyceae	3	6	1	1	1	2
Total	69	121	26	38	28	39
Number of samples	60	60	15	15	74	74

metal concentrations. *Asterionella*, and *Botrycoccus*, were frequent in the uncontaminated Confederation Lake but absent in Boomerang Lake indicating a more general intolerance to contaminants.

Our phytoplankton data have characteristics similar to those reported from a number of acidic lake systems in Ontario and elsewhere. Some of these studies are of lakes affected by acid rain, hence not subjected to the very low pH values and high metal concentrations of Boomerang Lake. The response of native phytoplankton communities to Zn additions was studied in River Platt water in Buenos Aires, Argentina (Loez et al., 1998). With a concentration of 40–50 $mg\,L^{-1}$ of Zn only *Chlorella vulgaris* and some diatoms survived. The Cyanophyceae, Euglenophyceae, Tribophyceae, Chrysophyceae, Zygophyceae, and Dinophyceae were particularly sensitive to Zn. In general, as Zn concentration increased, *Chlorella vulgaris* gradually became the dominant taxon decreasing the algal diversity (Loez et al., 1998). In Boomerang Lake, the Euglenophyceae are among the dominant algal classes, perhaps due more to their tolerance for acid than Zn.

The toxicity of Al is strongly dependent on pH (Havens and Decosta, 1987; Havens and Heath, 1990; Pillsbury and Kingston, 1990). However, among the Chlorophyceae, several species tolerate such heavy metals as Zn, Cu and Al, regardless of pH. These include *Klebshormidium* (Chlorophyceae; Douglas et al., 1998), *Mougeotia* (Graham et al., 1996), *Scenedesmus* (Michnowicz and Weaks, 1984; Starodub et al., 1987), *Chlamydomonas* (Nishikawa and Tominaga, 2001), and *Chlorella vulgaris* (Loez et al., 1998). Several Bacillariophyceae are also widely tolerant, including *Skeletonema* (Rijstenbil et al., 1991) and *Asterionella* (Gensemer et al., 1993). Some algae, such as *Chlamydomonas acidophila* (Chlorophyceae: Nishikawa and Tominaga, 2001) and *Cyanidium caldarium* (Yoshimura et al., 1999), can tolerate extremely high concentrations of metals. Almost all of these taxa are common in Boomerang Lake under considerably more severe chemical conditions than previously documented.

Studies on phytoplankton of 32 acidic lignite pit lakes of Lusatia (northeastern Germany) have shown that *Ochromonas* and *Chlamydomonas* are the most abundant genera where pH is less than 3 (Nixdorf et al., 1998; Lessman et al., 2000). These taxa were also frequently encountered in Boomerang Lake with a slightly higher pH. Overall, though, phytoplankton diversity was greater in Boomerang Lake than in the German lignite lakes, possibly because the German pit lakes have only recently been created and have a shorter retention time due to greater groundwater through-put.

All genera found in the German study except *Scourfeldia* and *Nanochlorum* (both chlorophytes) were also frequent in Boomerang Lake. Some genera including *Klebshormidium*, *Staurastrum* and *Ulothrix,* as well as cyanobacteria, which were frequently found in Boomerang Lake, were absent in the German lakes. Chlorophytes, Chrysophytes and diatoms were abundant in the German pit lakes and in Boomerang Lake.

If metal toxicity plays a significant role in the determination of phytoplankton community structure, then metals would have fallen out more prominently in the PCA (Fig. 3). The CCA (Fig. 6) did show some taxa that may have been associated with iron and nickel (*Chroomonas, Dictyosphaerium, Lepocinclis, Dinobryon, Cryptomonas and Gleocapsa*). The primary grouped taxa followed the time/pH/metal axis, suggesting that the taxa changed with slowly changing water conditions. So what controls the population structure of the Boomerang Lake phytoplankton? Certainly, metals affect phytoplankton growth and structure while at pH 3, hydrogen ion concentration must play a significant role. However, ecological engineering can bring about a transformation in such lakes, creating conditions within which phytoplankton and periphyton can adapt and contribute to the retention of metals in the sediments.

Over the course of the study it has become clear that the acid lake phytoplankton diversity and productivity are controlled not by pH or by "toxic" levels of heavy metals, but by one factor not quantified in the data set. That factor is the lack of inorganic carbon. In fact, Williams and Turpin (1987) suggest that the phytoplankton which flourish in acidic environments may be those that can extract C most efficiently and Turner et al. (1995) suggest further that the ammonium/ammonia system in acid lakes can play a role.

Iron oxidation in the sediments of Boomerang Lake drives most of the acidity reactions in the lake. The addition of Mg and the development of a moss sediment cover may not only suppress iron oxidation, but also support the phytoplankton community. While we may never know whether acidity, inorganic carbon, nutrients or toxic metals control phytoplankton populations, the fact that a relatively diverse phytoplankton population is present in Boomerang Lake indicates that these populations are an essential component of the sustainable ecological engineering approach to the restoration of mine waste management areas.

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