Schweiz. Z. Hydrol. 41/2, 1979, Birkhäuser Verlag Basel

MELIMEX, an experimental heavy metal pollution study: Behaviour of heavy metals in an aquatic food chain

By René Gächter and Wolfgang Geiger
Swiss Federal Institute for Water Resource and Water Pollution Control (EAWAG)
at Swiss Federal Institutes of Technology (ETH)

Manuscript received on 28 June 1979

ABSTRACT

Phytoplankton, periphyton and zooplankton samples, chironomid and *Sialis* sp. larvae, and fry of trout and bream collected from unpolluted and artificially metal-polluted limno-corrals were analyzed for mercury, copper, cadmium, zinc and lead. The results indicate that these metals are not accumulated through the food chain and suggest that increased metal concentrations in the environment favor the growth of phytoplankton organisms with a low metal sorption capacity.

1. Introduction

Phytoplankton organisms concentrate metal ions in their cells relative to the concentration in the water. The degree of concentration seems to be species dependent and to vary from metal to metal [23]. As with other plants, they are not able to exclude supposedly nonessential metals such as mercury [18], cadmium [25], lead [25, 29] or silver [23]. Thus, if the loading of any heavy metal is increased, organisms of higher trophic levels are exposed not only to increased metal concentrations in the water but also to increased concentrations in their food.

As discussed below, accumulation of metals by organisms of an aquatic food chain is influenced by many factors, e.g.

— the chemical speciation of metals, which controls their bioavailability,
— the excretion capacity of each trophic level and
— the growth/food consumption ratio.

Thus, it has been demonstrated by Hannerz [12] and Jernelöv et al. [17] that methylmercury is accumulated more readily than inorganic mercury compounds. Further it is well documented that copper and zinc complexed by organic ligands is not available to phytoplankton organisms [1, 7, 11, 15, 26] and complexed cadmium seems not to be available to invertebrates [27]. It is obvious moreover, that the metal content of an organism is higher, the less of the ingested or adsorbed metal is excreted, and the less the remaining daily load becomes diluted by a daily increase of body weight. The general decrease of the growth/food consumption ratio with increasing size of organisms might be partly responsible for the observed size

dependence of the heavy metal content of fish [21, 22] or the bivalve *Scrobicularia* [4].
Jernelöv [17] and Nuorteva et al. [22] gave evidence that the mercury content of organisms increases with increasing trophic level. However, in a study of the pelagic food chain phytoplankton and zooplankton anchovies, Krauer et al. [18] observed that the findings of Jernelöv and Nuorteva cannot be generalized. Their results show, on a dry weight basis, no significant differences in the mercury concentrations of anchovies, zooplankton and phytoplankton. Feldt et al. [6] reported that the Co, Mn, Fe, Zn and Ag content of fish caught in different German rivers was independent of the concentration in the water, indicating that the concentration of these elements was homeostatically maintained at a constant concentration, despite different concentrations in the water.
In as much as the metal content of an organism depends on many factors, it is not usually predictable solely from the total metal concentration in its environment. Furthermore, the correctness of the generalization that environmental pollutants are accumulated through the food chain and reach their highest concentrations in animals at the highest trophic levels seems to be questionable. It might hold for alkylated mercury and other persistent, nonpolar substances (e.g. chlorinated hydrocarbons), which may be accumulated in lipids of target organisms, but there is no a priori reason why this also should apply for metals in general.
The purpose of this paper is not primarily to elucidate the many open questions about mechanisms affecting the accumulation of a single heavy metal in an aquatic food chain, but to gain information about the behavior of Cd, Hg, Cu, Zn and Pb in a simple food chain [microplankton (mainly phytoplankton), crustacea zooplankton] in an unpolluted and an artificially metal-polluted freshwater system. It also includes some information about the metal content of fish fry (European lake trout and bream) as well as of chironomids and *Sialis* sp. grown in metal-polluted and unpolluted water.
Additional information needed for interpretation of the results can be found in other papers of the MELIMEX series: Baccini et al. [2]: Temporal variations of dissolved and particulate metal concentrations. Gächter [9]: Physicochemical description of the water. Gächter and Máreš [8]: Seasonale variations of primary production, chlorophyll concentration and shifts in phytoplankton species composition. Urech [29]: Variations in zooplankton species composition.

2. Methods

The detailed experimental design has been described elsewhere [9]. In summary: Three limno-corrals, each 12 m in diameter and 10 m in depth isolated about 1,100 m^3 of lakewater from the lake. Starting on 4 April 1977, a system of pumps, pumping water into and out of the corrals, yielded an average flow through rate of 11.5 m^3/day. Over the period of the study in the inflows of limno-corrals L1 and L2 metal concentrations were continuously elevated to approximately the limits legally tolerated for running waters in Switzerland (see Gächter [9], table 2). In the inflow to the third corral (C), which served as a control, metal concentrations equated to lake ambient levels.

The outflows of L2 and C were connected to two circular troughs (CTL2 and CTC), in which fish fry were kept and from which also chironomid and *Sialis* larvae were collected. Bream fry (without yolk sack) originating from adult fish caught in the Lake of Lucerne and eyed eggs of European lake trout *(Trutta fario* f. *lacustris)* were put into the circular troughs in October 1977 and December 1977, respectively. Eggs hatched at the end of January 1978, with some delay in CTL2, and yolk sacks were absorbed until mid-April.

Phytoplankton and zooplankton were sampled in the limno-corrals with vertical net hauls (−8 m to lake surface) using 300 μm and 20 μm aperture nets for zooplankton and phytoplankton, respectively, whereby a second plankton net having a pore size of 95 μm was inserted into the phytoplankton net. Thus zooplankton samples consisted of organisms larger than 300 μm and phytoplankton samples included particles larger than 20 μm but smaller than 95 μm.

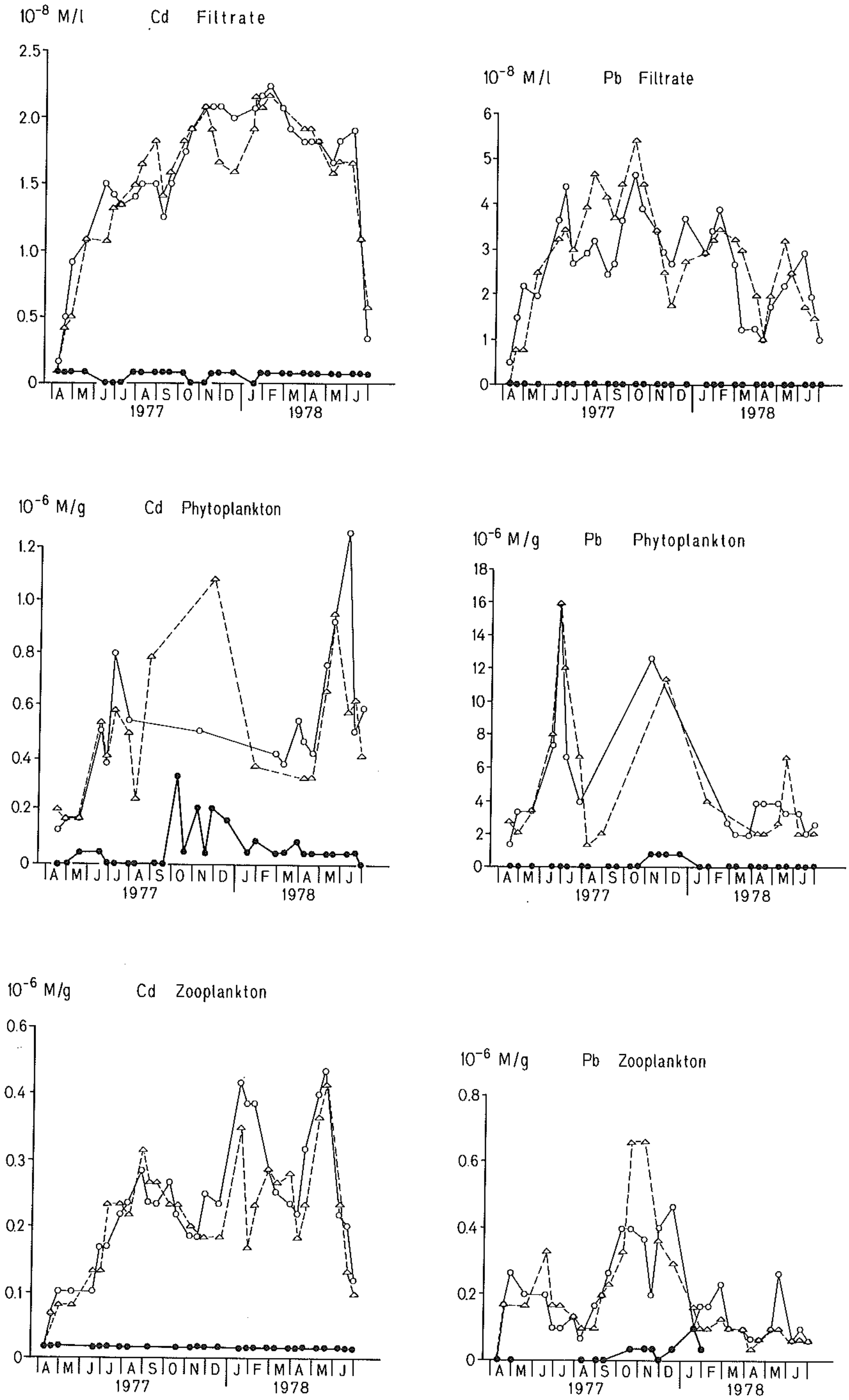
Prior to chemical analysis all samples (phytoplankton, periphyton, zooplankton, chironomids and *Sialis*) were deep-frozen (−33 °C) and freeze-dried in a Christ Gamma A lyophilisator. Fish were homogenized prior to freeze-drying. In order to measure Cu, Cd, Zn and Pb content of the samples about 50 mg of freeze-dried material was weighed into a liquid scintillation counting vial. 200 μl of concentrated H_2SO_4 (Merck p.a.) and 200 μl of H_2O_2 (Merck p.a.) were added and the samples kept at 60° during 12 hours. Then 10 ml of doubly distilled H_2O were added. Metal concentrations of these solutions were determined either directly of after appropriate dilution with a Perkin Elmer 100 atomic absorption spectrophotometer: acetylene air-flame for Zn and graphite furnace atomic absorption for Cu, Cd and Pb using a HGA 74 system. To calibrate measured absorptions, metal-spiked phytoplankton, zooplankton and fish samples were treated and measured as described above.

To determine the mercury content of freeze-dried samples, about 50 mg of sample was mixed with 10 ml of concentrated H_2SO_4 and 1.5 ml H_2O_2 in a Sovirel Bottle and kept at 60 °C during 12 hours. Then 90 ml of doubly distilled H_2O were added and Hg concentration was determined as described by Hatch and Ott [14] or in the Deutsche Einheitsverfahren [5]. Metal concentrations of water samples were determined as described by Baccini et al. [2].

3. Results

Seasonal variations of dissolved Pb, Zn, Cd and Cu concentration, determined in filtered water samples, as well as in phytoplankton and zooplankton samples, collected from the control C and metal-polluted limno-corrals L1 and L2 are presented in figure 1. It clearly indicates that increasing the metal loading of a lake system increases the metal concentration in all of the three compartments, e.g. filtrate, phytoplankton and zooplankton.

For all metals, increased metal loading in limno-corrals L1 and L2 resulted in a sharp increase in metal concentrations in the filtrate during the first 2 months of the experiment. However after July 1979, copper, cadmium, zinc and lead behavied differently, probably owing to different elimination mechanisms. Whereas concentrations of dissolved copper remained rather constant, concentrations of dissolved



10^{-8} M/l Cd Filtrate
2.5
2.0
1.5
1.0
0.5
0
A M J J A S O N D J F M A M J
1977
1978
10^{-8} M/l Pb Filtrate
6
5
4
3
2
1
0
A M J J A S O N D J F M A M J
1977
1978
10^{-6} M/g Cd Phytoplankton
1.2
1.0
0.8
0.6
0.4
0.2
0
A M J J A S O N D J F M A M J
1977
1978
10^{-6} M/g Pb Phytoplankton
18
16
14
12
10
8
6
4
2
0
A M J J A S O N D J F M A M J
1977
1978
10^{-6} M/g Cd Zooplankton
0.6
0.4
0.3
0.2
0.1
0
A M J J A S O N D J F M A M J
1977
1978
10^{-6} M/g Pb Zooplankton
0.8
0.6
0.4
0.2
0
A M J J A S O N D J F M A M J
1977
1978

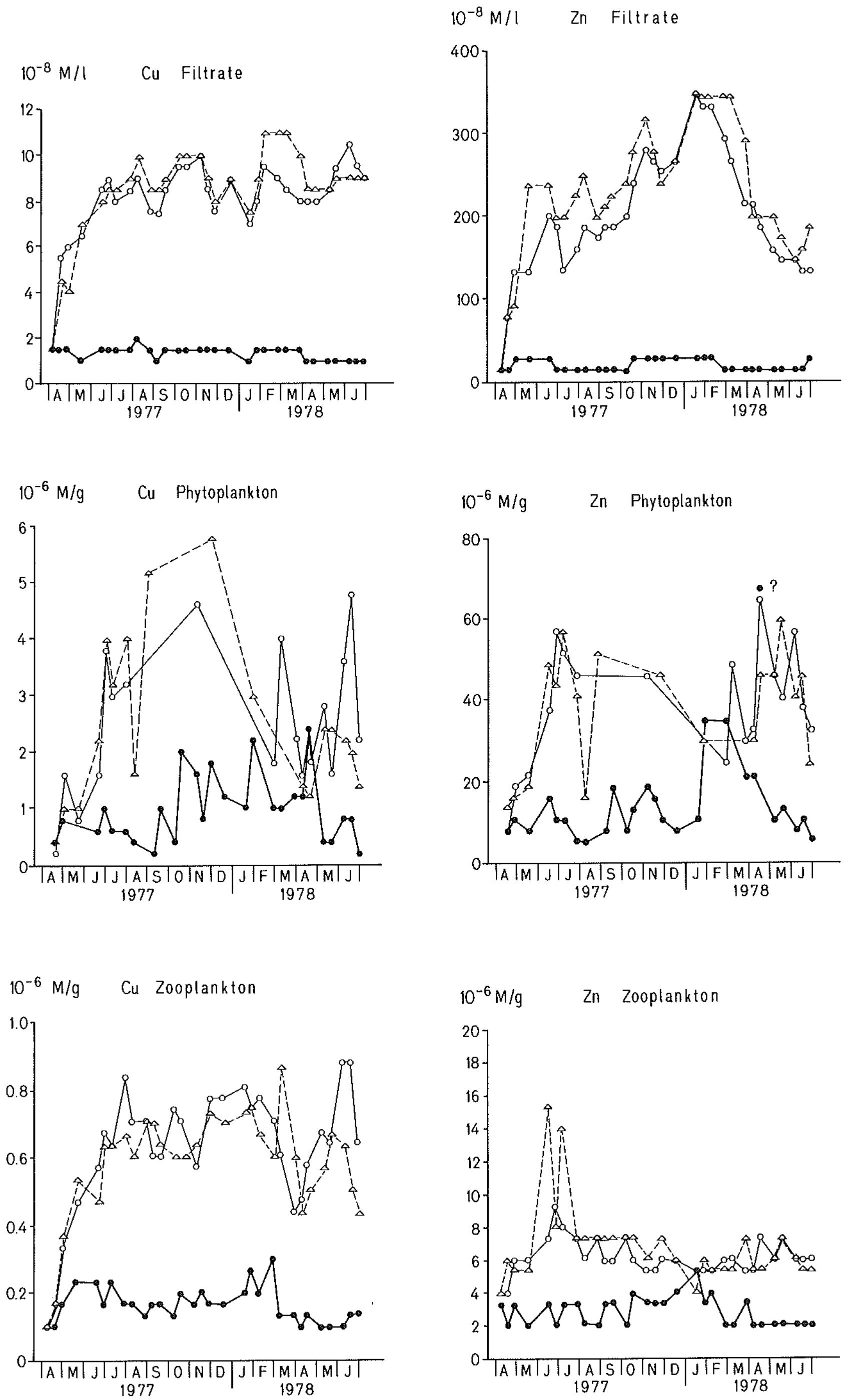


Figure 1. Seasonal variation of cadmium, lead, copper and zinc concentration in filtered lake water (average from the following depths: 0 m, 2.5 m, 5 m, 7.5 m), in phytoplankton and in zooplankton collected from metal polluted limno-corrals L1 (○), L2 (△) and control C (●).

Abb. 1. Saisonale Variation der Metallkonzentration im Filtrat (Mittelwert von 0,2, 5,5 und 7,5 m), im Phytoplankton und im Zooplankton in den Modellseen L1 (○), L2 (△) und der Kontrolle C (●).

Zn and Cd continued to increase until January 1978, and then decreased towards the end of the experiment. Dissolved lead concentration reached its maximum at the beginning of October 1977. In contrast with the significant seasonal variations observed in the metal-polluted limno-corrals L1 and L2, the concentrations of dissolved metals in the control corral remained practically constant.

When judging the seasonal variation of metal content in phytoplankton, one must realize that, owing to extremely low phytoplankton densities in limno-corrals L1 and L2 [8] during summer and fall of 1977, it was often impossible to collect samples. But in spite of these gaps, figure 1 supports the conclusion that for all metals investigated, as a consequence of the increased metal loading, a first metal concentration peak in phytoplankton occurred at the end of June 1977, followed by sharp decrease in concentration which can in no way be related to a corresponding decrease in the concentration of dissolved metals. During March/April 1978, all metals investigated showed relative concentration minima in phytoplankton samples, although at this time zinc and cadmium, as well as copper, reached nearly maximum concentration in the filtrate. On the other hand, in May/June 1978, all metal concentrations increased again in the phytoplankton, although Zn and Cd decreased in the filtrate. In the control the zinc, copper and cadmium concentrations of the phytoplankton varied considerably, whereas metal concentrations in the filtrate were, as already mentioned, comparatively constant. Based on these observations, it might be concluded that the metal content of phytoplankton is not related solely to the concentration of total dissolved metal but in addition might be controlled by other seasonally variable factors, such as the affinity of different phytoplankton species towards metals, changes in the speciation of dissolved metals, or differences in population size and growth rates [3].

Figure 1 also indicates, that Cu and especially Zn concentrations of zooplankton are considerably less variable than those of phytoplankton, but this does not hold for lead and cadmium. Furthermore, peak concentrations in phytoplankton do not necessarily coincide with peak concentration in zooplankton (e.g. in the case of Zn); nor does the height of the concentration peaks in zooplankton correspond to the height of corresponding phytoplankton peaks (e.g. in the case of Pb). These observations suggest that there exists no constant relationship between the metal content of crustacea zooplankton and the metal concentration of the microplankton investigated.

Concentration factors (CFs) are defined as metal concentration in plankton (mole/kg) divided by concentration of dissolved metal in the medium (mole/l) and thus have the dimension l/kg. From figure 2, which presents CFs for phytoplankton and zooplankton collected from limno-corrals L1, L2 and the control the following inferences may be drawn:

- CFs are variable with time but do not show seasonal trends;
- phytoplankton CFs for copper, cadmium and zinc vary almost independently, suggesting that sorption of these three metals is controlled by different specific mechanisms;
- phytoplankton CFs are of the same order of magnitude for all three metals, but distinctly lower in L1 and L2 (about 0.3×10^5 l/kg) than in the control (about 1×10^5 l/kg);

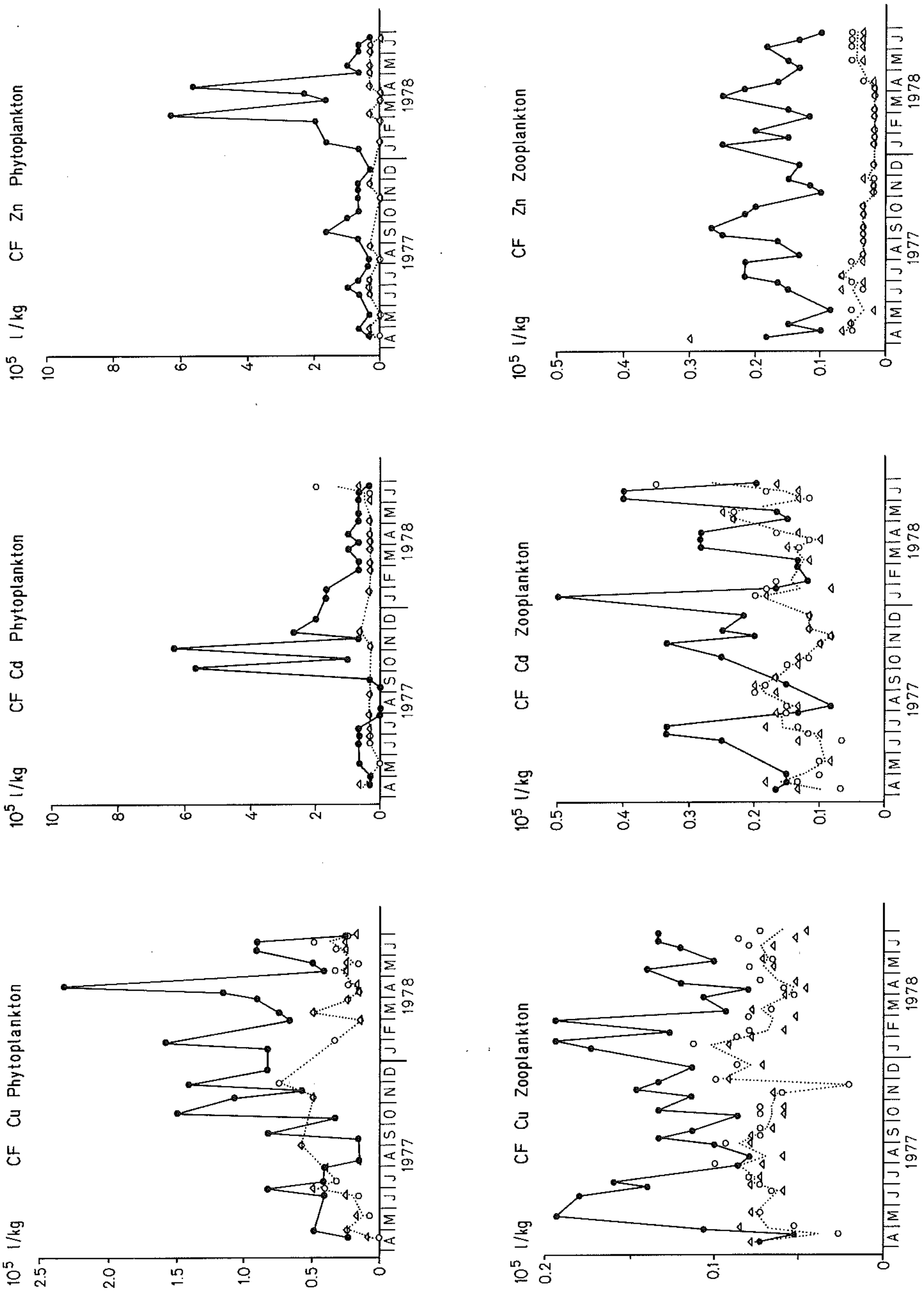


Figure 2. Seasonal variation of concentration factors (metal concentration in phytoplankton and zooplankton divided by concentration of dissolved metal) in limno-corrals L1 (O), L2 (Δ) and control C (●).

Abb. 2. Saisonale Variation der Konzentrierungsfaktoren (Metallgehalt im Plankton dividiert durch Metallkonzentration im Wasser) in den Modellseen L1 (O), L2 (Δ) und der Kontrolle C (●).

— zooplankton CFs are lower than corresponding phytoplankton CFs, and CFs of the control (about 0.15 to 0.25×10^5 l/kg) exceed the corresponding values estimated for L1 and L2 plankton (about 0.03 to 0.15×10^5 l/kg).

Table 1. Average concentrations and standard deviations of dissolved mercury and lead (10^{-8} mole/l) and phytoplankton and zooplankton metal content (10^{-8} mole/g) in the periode July 1977 to June 1978. n = number of samples.
Tabelle 1. Mittlere Konzentrationen an gelöstem Quecksilber und Blei (10^{-8} Mol/l) und mittlere Metallgehalte in Phyto- und Zooplankton (10^{-8} Mol/g) im Zeitabschnitt Juli 1977 bis Juni 1978.

Metal	Limno-corral	Dissolved metal	Phytoplankton	Zooplankton
Mercury	C	n.d.*	n.d.	n.d.
	L1, L2	n.d.	7 ± 3.9 (n = 15)	1.5 ± 0.5 (n = 27)
Lead	C	n.d.	22 ± 17 (n = 23)	3 ± 3 (n = 10)
	L1, L2	2.8 ± 1.2 (n = 30)	420 ± 318 (n = 26)	19 ± 15 (n = 49)

* Not detectable.

CFs for lead and mercury in the control corral could not be estimated because the concentrations of dissolved lead and mercury were mostly at or below detection limit. But, as can be seen from table 1, also Hg and Pb were much more highly concentrated in the phytoplankton than in zooplankton.
Metal concentrations in phytoplankton, periphyton, zooplankton, *Sialis* sp. and chironomidae collected from either metal polluted or unpolluted circular troughs are compiled in table 2. The results indicate that the metal concentrations of fish fry are lower than metal concentrations in the organisms of lower trophic levels. Further, the results suggest, that bream and trout, in contrast to other organisms, are able to maintain their copper and zinc content at a constant level regardless of environmental concentrations.
Krauss and Porter [19] have shown, that metals such as maganese, iron and zinc were taken up by *Chlorella* in proportion to their concentration in the medium. A linear relationship between cell content and concentration in the medium also was demonstrated for copper by Gibson [10], Hassal [13], Stokes [28] and Riley [23], for silver by Riley et al. [23], for lead by Schanz et al. [24] and for cadmium by Soeder et al. [25]. In order to ascertain whether this observation also applies to natural phytoplankton, the following experiment was conducted: Filtered water collected from limno-corral L2 was spiked with $CuSO_4$ and innoculated with phytoplankton collected from L2. After a 24-hour equilibration time the copper content of the phytoplankton, as well as the remaining copper concentration in the filtrate was determined. Figure 3 shows that at least up to an equilibrium concentration of 7×10^{-7} M the copper content of the phytoplankton is strongly linearly related to the concentration of dissolved copper. Note that in the MELIMEX experiment dissolved copper concentrations never exceed 1.3×10^{-7} M.

Table 2. Metal content of bream and trout fry, phytoplankton, periphyton, zooplankton, *Sialis* sp. and chironomidae, collected from circular troughs fed with effluents from limno-corrals L2 and C. Number indicate 10^{-8} mole/g. n.d. = not detectable.
Tabelle 2. Vergleich des Metallgehalts von Brachsen- und Forellenbrut mit dem Metallgehalt von potentiellen Futterorganismen. Herkunft der Proben: L2 = mit Metall belasteter Modellsee (bzw. Rundtrog); C = Kontroll-Modellsee (bzw. Rundtrog). Angaben in 10^{-8} Mol/g. n.d. = nicht nachweisbar.

Date of collection	Species	Cu		Cd		Pb		Zn		Hg	
		L2	C	L2	C	L2	C	L2	C	L2	C
19.10.77	Bream	12	6	1	0.9	1	n.d.	300	300	0.2	0.2
2.11.77			7		0.3		n.d.		200		
11.11.77			6		0.6		n.d.		300		
17.11.77			4		0.4		n.d.		500		
5.12.77		7	8	1.1	0.5	2	n.d.	300	500	0.7	0.2
12.12.77			12			0.6		500			
28. 2.78		8	6	1.3	0.3	2	n.d.	500	600	1.1	0.1
Average		9	7	1.2	0.5	1.4	n.d.	400	400	0.7	0.2
18.1.78	Trout	8	5	3.5	1.2	9	1	700	500	–	0.1
25.1.78		3	5	0.2	0.2	1	n.d.	100	100	n.d.	n.d.
8.3.78		3	3	0.4	0.4	n.d.	n.d.	100	100	n.d.	n.d.
10.4.78		4	5	0.6	1.3	2	n.d.	300	200	0.3	n.d.
19.4.78		4	–	0.2		n.d.	–	200	–	–	–
21.6.78			7		0.3		n.d.		300		n.d.
Average		4	5	1.0	0.7	4	–	280	240	–	–
Average	Phytoplankton	280	100	60	5	420	22	4000	1400	7	n.d.
Average	Periphyton	70	12	60	1	500	8	5000	400	3.5	0.1
Average	Zooplankton	70	15	25	2	20	3	650	250	1.5	n.d.
19.4.78	*Sialis* sp.	11	22	3	4	n.d.	n.d.	200	100		n.d.
21.6.78		34	31	9.3	2.4	3	n.d.	800	500	0.9	n.d.
21.6.78	Chironomidae	104	12	17	0.2	64	2	2200	600	–	–

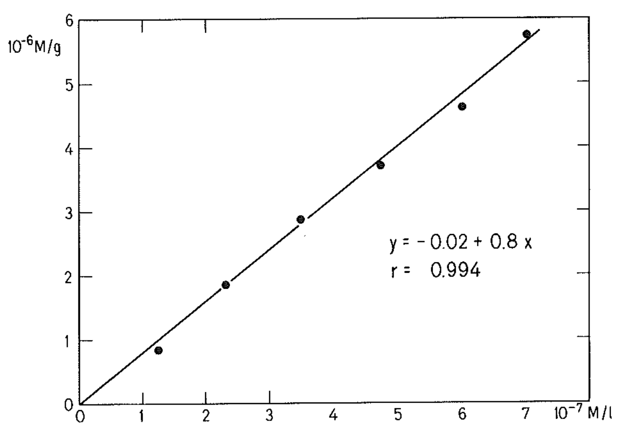


Figure 3. Copper content of phytoplankton as a function of the concentration of dissolved copper.
Abb. 3. Kupfergehalt des Phytoplanktons in Abhängigkeit von der Konzentration des gelösten Kupfers im Seewasser.

4. Discussion

Short-term experiments have shown that the metal content of algae increases in proportion to the metal concentration in the medium. In other words CFs would be expected to be independent of the concentration in the medium (i.e. constant). In contrast with these observations, in the long-term MELIMEX study phytoplankton CFs varied considerably with time and were distinctly lower in the metal polluted limno-corrals than in the control.

Riley [23] and Gibson [10] have documented, that different algal species vary in their capacity to sorb metals. Thus both, the observed variability of CFs with time and the lowered CFs in enclosures L1 and L2 might be explained by the observed seasonal variations and metal-induced shifts of phytoplankton species composition (see Gächter et al. [8]). These authors also showed that the phytoplankton species of the metal-polluted limno-corrals were less susceptible to metals. Mandelli [20] and Gibson [10] noted, that at a fixed copper concentration in the medium, copper tolerant species took up less copper per unit of biomass than did species more susceptible to copper. Stokes et al. [28] compared copper uptake of two strains of *Scenedesmus*, a copper tolerant lake isolate and a copper sensitive laboratory isolate. Their table 2 reveals that when the cells were grown in identical media (control) the copper content per cell was significantly lower in the copper-tolerant lake isolate than in the laboratory strain organisms. In addition, table 3 (this report) indicates, that at elevated but comparable total copper concentrations in the culture media the concentration factors were higher for the copper-sensitive laboratory strain than for the more tolerant lake isolate. Metal data reported by Jackson [16] for filtered lake water and phytoplankton collected in the Flin Flon region (Canada) (see table 4), also clearly show that CFs decrease with increasing metal concentrations in the water.

Table 3. Copper concentration factors (CF) for two *Scenedesmus* strains, derived from observations reported by Stockes et al. [28]. CF = (10^{-8} μg Cu/cell)/copper concentration in culture medium ([Cu]).
Tabelle 3. Konzentrierungsfaktoren (CF) für zwei Stämme von *Scenedesmus*, berechnet nach Angaben von Stockes et al. [28]. CF = (10^{-8} μg Cu/Zelle)/Kupferkonzentration im Medium ([CU]).

Strain	[Cu] mg Cu/l	CF time 0	in days 2	to harvest 6	10
Laboratory isolate	0.07	82	20	29	25
Lake isolate	0.10	40	16	7	8

Table 4. (Me) in phytoplankton and filtered lake water and resulting concentration factors (CF) in Schist Lake (SL) and Hamell Lake (HL) [16].
Tabelle 4. Metallgehalt im filtrierten Seewasser und im Phytoplankton im Schist Lake (SL) und Hamell Lake (HL) sowie sich daraus ergebende Konzentrierungsfaktoren (CF).

Lake	$(Me)_{filtrate}$ (10^{-6} mole/l)			$(Me)_{phytoplankton}$ (10^{-6} mole/g)			CF l/kg		
	Zn	Cd	Cu	Zn	Cd	Cu	Zn	Cd	Cu
SL	3.4	2.1	1.3	1381	0.13	0.24	406,000	60	180
HL	3.5	0.2	0.1	820	0.09	0.34	238,000	480	3,400

These observations support the hypothesis that metal pollution of the environment favors the growth of metal tolerant phytoplankton species which take up less metals per unite of biomass. Such an inverse relationship between metal concentration in the medium and metal sorption capacity of phytoplankton could play an important ecological role, by reducing metal concentrations in organisms of the lower trophic levels, thus reducing the danger of adversely affecting organisms of higher trophic levels, including the bottom fauna, which feed upon them.

The metal content of zooplankton depends on the metal content of the phytoplankton which they ingest, on the concentrations of dissolved metals in the water, and on rates of metal excretion by the zooplankton. The relative contribution of each component cannot be evaluated from the information available. But from figure 1 and table 1 it can be deduced that on a dry weight basis, metal concentrations of zooplankton were lower than corresponding metal concentrations in phytoplankton. Average phytoplankton/zooplankton metal content ratios observed in the period July 1977 to the end of June 1978 are given in table 5. Also at Flin Flon, higher metal concentrations in phytoplankton than in zooplankton were observed [16]. This emplies, that on a dry weight basis, surface sorption by zooplankton is smaller than by phytoplankton and that most of the metal ingested is excreted. A food/growth conversion ratio of 10 would result in a minimum excretion of 96% of the metal taken up by ingestion.

Table 5. Average Phytoplankton/zooplankton metal content ratios observed in the period July 1977 to June 1978. For original data see figure 1 and table 1.
Tabelle 5. Vergleich des Metallgehalts von Phytoplankton und Zooplankton in der Periode Juli 1977 bis Juni 1978 (Verhältnisse Phytoplankton/Zooplankton). C = Kontrolle, L1, L2 = mit Metall belastete Modellseen.

Cu		Cd		Zn		Pb		Hg
C	L1, L2	C	L1, L2	C	L1, L2	C	L1, L2	L1, L2
6.2	4	3.5	2.4	7	6.6	7	22	4.7

Of course, the zooplankton admittedly, may not feed primarily on the phytoplankton fraction investigated (20 to 95 µm) but rather on detritus or smaller nannoplankton forms. Owing to the increasing surface to dry weight ratio with decreasing particle size, and thus probably increasing metal sorption capacity, the average metal content of smaller particles ingested by zooplankton would be expected to be even higher. Thus, the results presented strongly suggest that copper, zinc, lead, mercury and cadmium are not bioaccumulated by zooplankton.

The presented data about metal accumulation by phytoplankton and zooplankton are net results of a variety of different time dependent variables, such as e.g. species composition, growth rate, biomass, pH, alkalinity, concentrations of dissolved and particulate metals, DOC and hence metal speciation. Although most of these variables have been monitored, this variety of concomitant parameters, which is characteristic for every natural ecosystem, does not allow to sort out clear cause-effect relationships. Nevertheless these data support the following tentative conclusions:

- Increased metal concentrations in lake water favor the growth of metal tolerant phytoplankton species with a decreased metal sorption capacity. Thus, when the loading of metals into a lake is increased, phyto- and zooplankton metal concentrations increase less than in proportion to the concentration of dissolved metal.
- In lakes, sedimentation of phytoplankton seems to be mainly responsible for the elimination of metals from the water column [2, 16]. At many sites all over the world, increased metal concentrations of recent sediments give evidence to increased metal loadings. Based on this study, it must be assumed, that most probably in these environments, metal concentrations increased even more strongly in the water than in the sediments.
- The copper, cadmium, mercury, zinc and lead content of phytoplankton and zooplankton is variable with time, but highest for phytoplankton, lower for zooplankton and lowest for fish fry. Thus, the presented results confirm observations made by Feldt [6] and Krauer [18], indicating that it is very unlikely that inorganic metals are bioaccumulated in the food chain.

5. Summary

Phytoplankton, periphyton and zooplankton samples, chironomid and *Sialis* sp. larvae, and fry of trout and bream collected from unpolluted and artificially metal-polluted limno-corrals were analyzed for mercury, copper, cadmium, zinc and lead. On a dry weight basis, metal concentrations were highest in phytoplankton and periphyton samples, lower in zooplankton, chironomidae and *Sialis* and lowest in fish, indicating that inorganic Hg, Cu, Cd, Zn and Pb are not accumulated through the food chain and do not reach highest concentrations in highest trophic levels. The results further suggest that increased metal concentrations in the environment favor phytoplankton organisms with a lower metal sorption capacity. This negative feed-back mechanism may play an important ecological role by reducing the metal content in organisms at lower trophic level, thereby reducing the danger of adversely affecting the organisms of higher trophic levels which feed upon them.

ZUSAMMENFASSUNG

Phytoplankton-, Periphyton- und Zooplanktonproben, Chironomiden und *Sialis*-Larven sowie Forellen- und Brachsenbrut wurden aus der Kontrolle und den mit Metall verunreinigten Modellseen entnommen und auf ihren Hg-, Cu-, Cd-, Zn- und Pb-Gehalt hin untersucht. Bezogen auf das Trockengewicht wurden im Phytoplankton und Periphyton die höchsten Metallkonzentrationen gemessen (siehe Abb. 1, Tab. 1, 2). Im Zooplankton und in den Insektenlarven wurden niedrigere und in den Fischen die niedrigsten Gehalte beobachtet. Diese Untersuchungen widerlegen somit die Hypothese, wonach anorganische Schwermetalle in Analogie zu gewissen persistenten organischen Verbindungen in der Nahrungskette akkumuliert werden und die höchsten Gehalte in den Organismen der höchsten Trophiestufe auftreten sollen.

Diese Untersuchung ergab ferner, dass die erhöhten Metallkonzentrationen Verschiebungen in der qualitativen Zusammensetzung des Phytoplanktons bewirkten und das Wachstum von Algen begünstigten, die sich im Vergleich zum Kontrollplankton durch eine herabgesetzte Metallsorptionskapazität auszeichneten (siehe Abb. 2).

Dieser negative Feed-back-Mechanismus könnte auch für Organismen höherer Trophiestufen von Bedeutung sein, indem er den Metallgehalt im Futter möglichst niedrig hält.

RÉSUMÉ

Des échantillons de phytoplancton, périphyton et zooplancton, des larves de chironomides et de *Sialis*, ainsi que des alevins de truites et de brèmes ont été pris dans des modèles de lac contaminés par les métaux lourds, ainsi que dans un bassin de contrôle. On a analysé leur teneur en Hg, Cu, Cd, Zn et Pb. En considérant leurs poids secs, le phytoplancton et le périphyton ont les concentrations les plus élevées de métaux (fig. 1, tabl. 1, 2). Dans le zooplancton et dans les larves d'insectes, on a mesuré des teneurs plus faibles, tandis que les teneurs les plus faibles étaient mesurées dans les poissons. Ainsi, ces recherches contredisent l'hypothèse selon laquelle les métaux lourds inorganiques, par analogie à certaines combinaisons organiques persistantes dans la chaîne alimentaire, sont accumulés et les taux les plus élevés doivent apparaître dans les organismes dont le degré trophique est le plus élevé.
D'ailleurs, de cette recherche résulte que les concentrations élevées de métaux provoquent des déplacements dans la composition qualitative du phytoplancton et que ces concentrations favorisaient la croissance des algues qui, par comparaison au plancton de contrôle, se distinguent par une diminution de leur capacité d'adsorption du métal.
Ce mécanisme feed-back négatif pourrait être aussi significatif pour des organismes de degrés trophiques plus élevés, en maintenant le plus bas possible, la teneur en métaux de la nourriture.

ACKNOWLEDGMENTS

Joan Davis and Togwell A. Jackson critically reviewed this paper and helped very much to clearify it. The figures were drafted by H. Bolliger and A. Widmer typed the manuscript.

REFERENCES

1 Anderson, D.M., and Morel, F.M.M.: Copper sensitivity of *Gonyaulax tamarensis.* Limnol. Oceanogr. *23,* 283-295 (1978).
2 Baccini, P., Ruchti, J., Wanner, O., and Grieder, E.: MELIMEX, an experimental heavy metal pollution study: Regulation of trace metal concentrations in limno-corrals. Schweiz. Z. Hydrol. *41,* 202-227 (1979).
3 Briand, F., Trucco, R., and Ramamoorthy, S.: Correlations between specific algae and heavy metal binding in lakes. J. Fish. Res. Bd Can. *35,* 1482-1485 (1978).
4 Bryan, G.W., and Hummerstone, L.G.: Heavy metals in the burrowing bivalve *Scrobicularia plana* from contaminated and uncontaminated estuaries. J. mar. biol. Ass. UK *58,* 401-419 (1978).
5 Deutsche Einheitsverfahren, Bestimmung des Quecksilber-Ions, Blatt E 12 (1975).
6 Feldt, W., and Melzer, M.: Konzentrationsfaktoren der Elemente Kobalt, Mangan, Eisen, Zink und Silber für Fische. Arch. Fischereiwiss. *29,* 105-112 (1978).
7 Gächter, R., and Davis, J.S.: Regulation of Copper Availability to Phytoplankton by Macromolecules in Lake Water. Envir. Sci. technol. *12,* 1416-1421 (1978).
8 Gächter, R.: MELIMEX, an experimental heavy metal pollution study: Effects of increased heavy metal load on phytoplankton communities. Schweiz. Z. Hydrol. *41,* 228-246 (1979).
9 Gächter, R.: MELIMEX, an experimental heavy metal pollution study: Goals and experimental design. Schweiz: Z. Hydrol. *41,* 169-176 (1979).
10 Gibson, C.E.: The algicidal effect of copper on a green and blue-green alga and some ecological implications. J. appl. Ecol. *9,* 513-518 (1972).
11 Green, J.C., Miller, W.E., Shiroyama, T., Soltero, R.A., and Putnam, K.: Use of laboratory cultures of *Selenastrum, Anabaena* and the indigenous isolate *Spaerocystis* to predict effects of nutrient and zink interactions upon phytoplankton growth in Long Lake, Washington. Mitt. int. Ver. Limnol. *21,* 372 (1978).
12 Hannerz, L.: Experimental investigations on the accumulation of mercury in lake water organisms. Inst. Freshwater. Res. Drottningholm, Rep. No. *48,* 120-176 (1968).
13 Hassal, K.H.: Uptake of copper and its physiological effects on *Chlorella vulgaris.* Physiol. Plant. *16,* 323-332 (1963).

14 Hatch, W.R., and Ott, W.L.: Determination of sub-microgram quantities of mercury by atomic absorption spectrophotometry. Analyt. Chem. *40,* 2085–2087 (1968).
15 Jackson, G.A., and Morgan, J.J.: Trace metal-chelator interactions and phytoplankton growth in seawater media: Theoretical analysis and comparison with reported observations. Limnol. Oceanogr. *23,* 268–282 (1978).
16 Jackson, T.A.: The biogeochemistry of heavy metals in polluted lakes and streams at Flin Flon, Canada, and a proposed method for limiting heavy metal pollution of natural waters. Envir. Geol. *2,* 173–189 (1978).
17 Jernelöv, A., and Lann, H.: Mercury accumulation in food chains. Oikos *22,* 403–406 (1971).
18 Krauer, G.A., and Martin, J.H.: Mercury in a pelagic food chain. Limnol. Oceanogr. *17,* 868–876 (1972).
19 Krauss, H.L., and Porter, J.W.: The absorption of inorganic ions by *Chlorella pyrenoidosa.* Pl. Physiol., Lancaster *29,* 229–234 (1954).
20 Mandelli, E.F.: The inhibitory effects of copper on marine phytoplankton. Contr. mar. Sci. *14,* 47–57 (1969).
21 Mathis, B.J.: Distribution of Mercury, Cadmium, Lead and Thallium in an eutrophic lake. Hydrobiologia *46,* 207–222, (1975).
22 Nuorteva, P., and Häsänen, E.: Bioaccumulation of mercury in *Myxocephalus quadricornis* (L.) (Teleostic, Cottidae) in an unpolluted area of the Baltic. Ann. Zool. Fenn. *12,* 247–254 (1975).
23 Riley, J.P., and Roth, I.: The distribution of trace elements in some species of phytoplankton grown in culture. J. mar. biol. Ass. UK *51,* 63–72 (1971).
24 Schanz, F., and Thomas, E.A.: Cultures of Cladophoraceae in water pollution problems. Mitt. int. Ver. Limnol. *21,* 57–64 (1978).
25 Soeder, C.J., Payer, H.-D., Runkel, K.-H., Beine, J., and Briele, E.: Sorption and concentration of toxic minerals by mass cultures of Chlorococcales. Mitt. int. Ver. Limnol. *21,* 575–584 (1978).
26 Sunda, W., and Guillard, R.R.L.: Relationship between cupric ion activity and the toxicity of copper to phytoplankton. J. mar. Res. *34,* 511–529 (1976).
27 Sunda, W.G., Engel, D.W., and Thuotte, R.W.: Effects of chemical speciation on toxicity of cadmium to grass shrimps *Palaemonetes pugio:* Importance of free cadmium ion. Envir. Sci. technol. *12,* 409–413 (1978).
28 Stokes, P.M., Hutchinson, T.C., and Krauter, K.: Heavy metal tolerance in algae isolated from polluted lakes near Sudbury, Ontario Smelters. Wat. Pollut. Res. Canada *8,* 178–201 (1973).
29 Urech, J.: MELIMEX, an experimental heavy metal pollution study: Effects of increased heavy metal load on crustacea plankton. Schweiz. Z. Hydrol. *41,* 247–260 (1979).
30 Weber, A., Melkonian, M., Lorch, D.W., and Wettern, M.: Accumulation of lead by several green algae. Mitt. int. Ver. Limnol. *21,* 254–260 (1978).

Address of the authors: Dr. R. Gächter, Dr. W. Geiger, Seenforschungslaboratorium EAWAG/ETH, CH-6047 Kastanienbaum, Switzerland.