VESIENTUTKIMUSLAITOKSEN JULKAISUJA
PUBLICATIONS OF THE WATER RESEARCH INSTITUTE
69

VESI- JA YMPÄRISTÖHALLITUS—
NATIONAL BOARD OF WATERS AND ENVIRONMENT, FINLAND
Helsinki 1986

ISBN 951-47-0864-4
ISSN 0355-0982

Helsinki 1987. Valtion painatuskeskus

EFFECT OF NITROGEN AND PHOSPHORUS REMOVAL FROM SEWAGE ON EUTROPHICATION OF LAKES

Lea Kauppi[1], **Kaarle Kenttämies**[2] **& Eeva-Riitta Puomio**[3]

Kauppi, L., Kenttämies, K. & Puomio, E-R. 1986. Effect of nitrogen and phosphorus removal from sewage on eutrophication of lakes. Publications of the Water Research Institute, National Board of Waters and Environment, Finland, No. 69.

Experimental enclosures were used to study the effects of different sewage treatment methods on primary production, biomass and species composition of plankton as well as on nitrogen fixation by blue-green algae in three lakes of different trophic status. The limiting nutrient was determined by algal test using *Selenastrum capricornutum* as test organism. The sewage treatment methods studied were: 1) biological + P removal and 2) biological + P removal + N removal by nitrification — denitrification. A preliminary experiment was performed using inorganic fertilizers. Three kinds of experimental enclosures were tested and a fairly large (50 m^3) one with a natural bottom and planktivorous fish population was found to be superior to small (1—2 m^3) ones.

In the chemical enrichment experiment, only nitrogen and phosphorus together were able to increase primary production to a significant extent in the eutrophic, previous recipient, lake Vesijärvi. Planktonic nitrogen fixation was enhanced by P-enrichment, while nitrogen alone inhibited it. Sewage resulted in a faster growth rate for periphyton than chemical P-enrichment, while only slight differences were observed in planktonic production. In spite of the different chemical composition the bloom of heterocystous blue-green algae occurred simultaneously in the lake and in all the enclosures.

In the oligotrophic, pristine forest lake, sewage enrichment in a benthic enclosure resulted in a rapid, short-term increase in algal growth followed by a decline in production. Grazing by zooplankton, together with the nutrient content, regulated primary production. Introducing fish fingerlings effectively favoured primary production by decreasing the zooplankton biomass. No N fixation could be observed, the biomass of blue-green algae reaching only 1.4 % of the total biomass at its maximum.

Benthic enclosures were also used in the third sewage enrichment experiment in a heavily loaded recipient. Enrichment clearly increased the phytoplankton biomass, although the internal phosphorus load from sediments — varying from 7.25 to 107 mg m^{-2} d^{-1} had a decisive impact on the P budget of the enclosures. A very dense zooplankton population caused overgrazing of phytoplankton towards the end of the experiment. Again, despite the differences in the quality of the sewage used for enrichment the phytoplankton succession during the summer was similar in all enclosures, *Pyrrophyta and Chlorophyta* dominating. The *Cyanophyta* biomass remained insignificant.

The results showed that decisions concerning nitrogen removal from sewage should be made case by case. Carrying out simple enrichment experiments in the actual recipient are recommended before decision-making.

Index words: Sewage, lakes, P removal, N removal, eutrophication, planktonic nitrogen fixation, enclosures

---

[1] Water and Environment Research Institute, National Board of Waters and Environment, P.O. Box 250, SF-00101 Helsinki, Finland.

[2] Ministry of the Environment, P.O. Box 306, SF-00531 Helsinki, Finland.

[3] Helsinki Water and Environment District, P.O. Box 58, SF-00421 Helsinki, Finland.

1. INTRODUCTION

Efficient removal of phosphorus from sewage has been accomphished in most treatment plants in Finland. On an average over 90 per cent of the phosphorus is removed, mainly by chemical precipitation. The organic matter is effectively removed at the same time. In order to further improve sewage treatment nitrogen removal should also be considered.

Of the known methods for removing nitrogen from sewage, physical-chemical processes are not regarded as suitable owing to the high costs and technical complexity. The biological denitrification process, in which nitrification occurs in the preceding phase, has been considered the most feasible in the municipal treatment plants. The effective removal of phosphorus is usually a prerequisite of the official permit if the plant is allowed to use a lake as a recipient. The chemical removal of phosphorus using ferrous sulphate as the precipitant is the most common method.

In Finland the dominant position of ferrous sulphate as precipitant is well explained by its availability as a cheap waste product from the titaniumdioxide industry. In biological sewage treatment plants the precipitant is mixed with sewage in the aeration basin in order to achieve simultanous decomposition of organic matter and the precipitation of phosphorus. Unintentional temporary nitrification of ammonium compounds is not a rare event in many plants during periods of low load. The plant can be made to nitrify effectively by making relatively small changes to the purification process. The main difficulty is the low alkalinity of sewage in Finland, which may cause too low pH-value in the process. The inhibitory effect of ferrous iron on nitrification is not a major problem as the usual concentration levels (Valve 1985).

The effects of nitrogen removal may, however, be conflicting: on the one hand the high concentrations of nitrogen compounds — which as such may be harmful — are reduced and algal growth decreases if the nitrogen supply becomes limited, while on the other nitrogen removal may enhance the growth of certain organisms that are able to fix molecular nitrogen. The most important group is cyanobacteria, which can cause odour and taste problems in water and fish when occurring in high biomasses (Persson 1982). Some cyanobacteria also contain endotoxins which are released after the death of these organisms. The relative significance of beneficial and detrimental effects has to be evaluated before making the decision whether to implement nitrogen removal. If the original problem is the harmfully high concentration of nitrate, nitrogen removal would have only beneficial effects, because it is very probable that phosphorus will in any case remain the limiting nutrient. If, however, eutrophication is the main problem then the probability and significance of the occurrence of nitrogen-fixing cyanobacteria has to be weighed against the decrease in primary production by algae.

This article is a summary report of the laboratory and field studies carried out at the Water Research Institute in 1981—1983, the aim of which was to estimate the effects of nitrogen removal on lake ecosystems. The emphasis was on phytoplankton composition, primary production and nitrogen fixation by cyanobacteria.

Experimental studies, involving the construction of enclosures in the lakes, were performed in a heavily loaded lake, in a lake where the earlier heavy loading has ceased and in an unpolluted forest lake.

2. BACKGROUND

2.1 Nitrogen: phosphorus ratios in wastewaters

In some industrial effluents the ratio of total N to total P is quite low (Table 1). The N:P of the effluents of the pulp and paper industry is, on an average, clearly less than 10. The food processing industry also produces effluents with a very low N:P. In treated sewage, on the other hand, the N:P ratio is at present quite high due to the efficient removal of phosphorus. At the beginning of the 1970's, however, the situation was quite different, the N:P value in treated sewage being less than 10.

Table 1. Nitrogen: phosphorus ratios in the industrial and domestic waste waters at the beginning of the 1980's (Yrjänä and Kauppi 1984).

Source	Tot.N:Tot.P
Pulp and paper industry	6.6
Mechanical wood processing	3.3
Oil and petrochemical industry	34
Fertilizer industry	15
Other chemical industry	11
Metal industry	190
Textile industry	12
Food processing industry	8.9
Domestic waste waters	16
Non-point sources	19
Fish farming	4.8

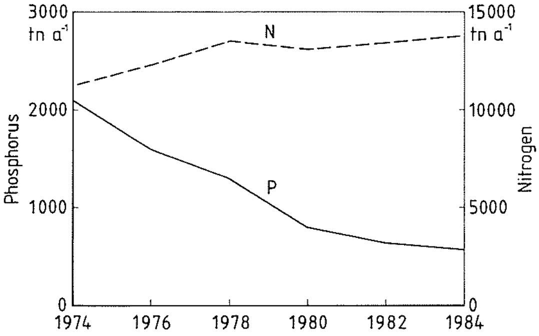

Fig. 1. Loads of phosphorus and organic matter from domestic effluents in Finland in 1974—1984.

During the last fifteen years the phosphorus load has rapidly decreased, while that of the nitrogen has steadily increased (Fig. 1). However, the main factors balancing the N:P ratio in Finnish lakes are natural input and agricultural runoff, which are strongly nitrogen-weighted (Kauppi 1979).

2.2 Nitrogen: phosphorus ratios in Finnish lakes

The ratio of total nitrogen to total phosphorus can be used as an initial estimate when determining the limiting nutrient. If the ratio is small, nitrogen can be assumed to limit algal growth. A range of values have been cited in the literature for the critical ratio, commonly varying between 8 and 17 (Vollenweider 1968, Seppänen 1970, Forsberg et al. 1978, Rhee and Gotham 1980).

The water quality data bank of the National Board of Waters and Environment was used in order to get an overview of the ratio of total N and total P in Finnish lakes (Yrjänä and Kauppi 1984). All the lake surface water (0.5—1.5 m) observations recorded between January and August from 1978 on were included in the study. The data was grouped into four groups according to the total P concentration and the season of observation.

In eutrophic (total P $> 30\ \mu g\ l^{-1}$) lakes the N:P ratio was, on an average, much lower than that in oligotrophic (tot. P $< 30\ \mu g\ l^{-1}$) lakes. The summer mean value of eutrophic lakes was only 16, whereas in oligotrophic lakes it was 34. The lakes where low N:P values were observed could be roughly identified on the basis of the type of loading. The biggest homogeneous group was that formed by the lakes heavily polluted by domestic or industrial effluents. The low N:P ratio in these lakes is due to the low N:P value of the effluents (eg. pulp and paper industry) and/or high internal phosphorus loading. The second distinctive group was formed by man-made lakes with a high organic load from former terrestrial soils, and the third one by lakes located in areas of phosphorus-rich mineral soils. In conclusion, it is clear that judging by the N:P values nitrogen is only rarely the primarily limiting nutrient in Finnish lakes. It may, however, limit decomposition and thus indirectly also production (Alexander 1977).

2.3 Occurrence of nitrogen fixation in some Finnish lakes

Kanninen (1980) studied nitrogen limitation and the potential significance of nitrogen fixation for the N budget in three eutrophic lakes — Vesijärvi, Hiidenvesi and Tuusulanjärvi — in 1979. The study was based on phytoplankton biomass composition and algal assays. In lake Vesijärvi where mineral N, especially nitrate, was almost exhausted in June and July the growth of the test alga, *Selenastrum capricornutum* Printz, was limited by nitrogen from May to the middle of August. The highest biomasses were observed in July and August, when cyanobacteria dominated. 23—24 per cent of the total biomass consisted of heterocystous cyanobacteria (*Anabaena circinalis* Rabenhorst, A. *solitaria* f. *planctonica* (Brunnthaler) Komarek and *Aphanizomenon flos-aquae* (Linné) Ralfs f. *flos-aquae.*

In the two other lakes, concentrations of both mineral nitrogen and mineral phosphorus remained at quite a high level throughout the summer. According to their ratio, phosphorus would have been the primarily limiting nutrient in L. Tuusulanjärvi. In May this was confirmed by algal tests, but during the summer only both nutrients together increased the growth, the effect of N becoming stronger towards the end of the summer. The biomass maximum in L. Tuusulanjärvi occurred in early June, and after this point cyanobacteria dominated; a bloom of a heterocystous cyanobacteria, *Anabaena circinalis* was observed in July (Kanninen 1980). In Lake Hiidenvesi the algal tests confirmed nitrogen limitation, but no significant amounts of heterocystous cyanobacteria were observed (Kanninen 1980).

In 1980 the study was concentrated in L. Vesijärvi because the results from 1979 implied that nitrogen fixation by blue-greens could significantly contribute to the N budget of the lake. In addition to the cyanobacteria biomasses, nitrogen fixation was measured by the acetylene reduction method (Yrjänä 1982). In the main basin of the lake planktonic nitrogen fixation was responsible for 31 per cent of the total annual N input, and for 52 per cent of the N input during the growing season (Yrjänä 1982). These results encouraged us to carry out experiments on the influence of removing nitrogen from sewage on the recipients.

3. MATERIAL AND METHODS

3.1 Enclosures

The experiments involving the construction of enclosures in lakes (limnocorrals) were planned in order to gain a better understanding of the ecological consequences of removing nitrogen from sewage. Since the enclosures had originally been designed for pelagial plankton studies, a baglike, closed type enclosure with a size of 2.5 m^3 (Fig. 2 a) was introduced in 1981. During the course of the study the internal load of the recipients proved to demand much more attention. The chemical and biological effects of sediments subsequently were taken into account in the two types of benthic enclosures — a cylindrical one, 1 m^3 and a cubical one, 56 m^3 (Fig. 2 b and c). In one case fish fingerlings were introduced into the enclosure.

The wall material of the enclosures was a transparent, 0.20 mm thick polythene film. The transparent "collar" in the pelagial enclosures was made of PVC plastic. The enclosures were assumed to be absolutely waterproof. The benthic enclosures were made of twofold polythene film.

The water samples were taken from enclosures with a normal Ruttner-sampler. In the homothermal, relatively shallow enclosures chemical and plankton analyses were made on a composite sample obtained by mixing the vertical subsamples.

The chemical analyses were made by the standard methods of the Finnish Water and Environment Research Institute (National Board of Waters 1981). The algal test using *Selenastrum capricornutum* has been described by Kanninen et al. (1982) and the acetylene reduction method used in estimating nitrogen fixation by Yrjänä (1982).

Primary productivity "in vitro" and nitrogen fixation "in vitro" were preferred to "in situ" analyses from the practical point of view. Comparable results for the enclosures (treatments) were the most important goal.

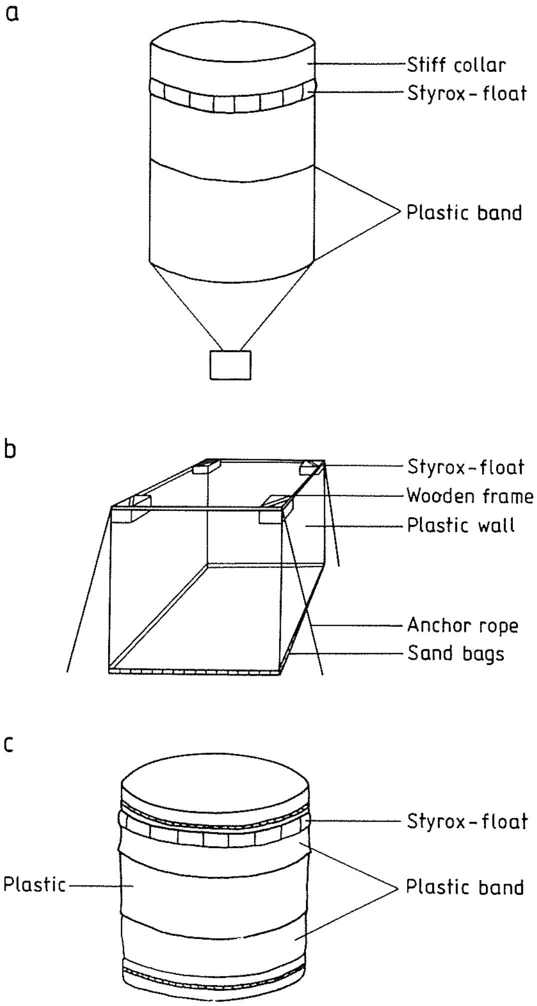

Fig. 2. Types of enclosures used in the enrichment experiments a) a bag-like, closed enclosure (2.5 m^3), b) a cubical, benthic enclosure (56 m^3) and c) a cylindrical, benthic enclosure (1 m^3).

3.2 Sewage from treatment plants

In this study, treated sewage from both pilot and full scale plants were used in the enclosure tests.

The Kariniemi sewage plant in the city of Lahti is a conventional active sludge plant with simultaneous phosphorus precipitation. The precipitant is ferrous sulphate. Phosphorus removal is usually of a high degree of efficiency. In the summer during higher temperature and low load phases especially, the plant tends to nitrify ammonium compounds. During the enclosure tests in Lake Vesijärvi the sewage plant was even too effective! The phosphorus concentration in the treated sewage was on occasions as low as 0.3—0.4 mg l^{-1} P and thus too far from the ”normal” Finnish mean of 1 mg l^{-1} P. Preclarified sewage was therefore added to the sewage used for enrichment of the enclosures in order to produce the typical, higher phosphorus level.

The pilot plant of the city of Hyvinkää was a biological plant that had simultaneous precipitation of phosphorus with ferrous sulphate as precipitant. The nitrification and denitrification processes were accomplished in the same reactor using the so-called intermittent method, in which oxic and anoxic phases were interchanged.

After passing through these two processes the water was reaerated and settled. The key problems in the process are the inhibitory effect of ferrous sulphate on nitrification, and ineffective phosphorus removal due to the presence of unsettled, fine sludge. Treated sewage from the pilot plant of Hyvinkää was used in the enclosure tests of lake Valkea Mustajärvi, an oligotrophic clearwater forest lake. Before addition to the test enclosure, the treated sewage was diluted with lake water (1:1 ratio) and aged in a separate enclosure for two weeks. This procedure was thought to better simulate the prevailing case where the oligotrophic recipient is relatively far from the loading point. Both phosphorus and nitrogen removal continued throughout the aging process before the treated sewage was added to the enclosure ecosystem proper.

The treatment plant of the city of Mikkeli carried out denitrification in a separate small unit for the enclosure tests in the heavily loaded lake Rohmavesi. However, the test has to be classified as being done on a whole plant scale. In the process, denitrification took place in the first reactor where carbon-rich raw sewage and nitrogen- rich water from the second effectively aerated nitrification unit were mixed (so called dn-process). After the third sedimentation phase the treated sewage was pumped into the enclosures. The phosphorus was precipitated simultaneously with ferrous sulphate. The conventionally treated, P-precipitated sewage was obtained from the main unit of the plant.

The chemical characteristics of all the types of sewage used in the study are presented in Table 2. All additions to the enclosures were done using a relatively high degree of dilution in order to achieve better simulation of the real conditions in the recipients. The continuous flow of sewage into enclosures was not realizable in pratice, even if it would have been theoretically the best way of carrying out the simulation.

4. RESULTS

4.1 Chemical enrichment experiment

A preliminary experiment with chemical enrichment was made in lake Vesijärvi. The bag-like enclosures (2.5 m^3) used in this experiment were closed at the bottom thus eliminating the effect of the lake sediment. They were enriched with pure chemicals, i.e. with polyphosphate ($Na_5P_3O_{10}$), ammonium nitrate (NH_4NO_3) and ammonium chloride (NH_4Cl) (Table 3).

Both the nitrogen and phosphorus concentrations decreased in the enclosures during the course of the experiment. The added phosphorus in particular disappeared rapidly from the water phase, although the concentrations still remained at a higher level than that in the control enclosure. Since nitrogen was much more stable, the tot.N:tot.P ratio increased in all the enclosures during the experiment. In mineral nutrients the

Table 2. Chemical characteristics of the treated sewage used in the enclosure experiments.

Sewage plant	Date	tot. P mg l^{-1}	tot. N mg l^{-1}	NO_2-N mg l^{-1}	NO_3-N mg l^{-1}	NH_4-N mg l^{-1}
Lahti city	22.7.1981	0.34	8.5	0.540	0.52	0.53
	12.8.1981	1.0	18	0.800	9.0	3.5
	9.9.1981	1.4	24	0.600	13	5.7
Hyvinkää pilot plant	6.7.1982	0.48	2.0	0.002	0	0.03
	17.8.1982	0.68	7.9	0.008	0.68	1.5
Mikkeli city ”denitrifying line”	29.6.1983	0.57	9.5	0.200	8.5	0.80
Mikkeli city ”conventional line”	29.6.1983	0.53	14	0.490	7.2	6.0
Mikkeli city ”denitrifying line”	27.7.1983	0.34	12	0.440	7.2	3.4

Table 3. Nutrient additions in the enrichment experiment with inorganic fertilizers in Lake Vesijärvi 1981.

Enclosure	Nutrient addition	Limiting nutrient based on algal assay	
		P_{tot}	N_{tot}
I	—		
II	0.21 g P(0.84 g $Na_5P_3O_{10}$)	120	
III	7.56 g N (10.8 g NH_4NO_3 + 14.4 g NH_4Cl)		4700
IV	0.21 g P + 7.56 g N (0.84 g $Na_5P_3O_{10}$ + 10.8 g NH_4NO_3 + 14.4 g NH_4Cl)	120	2900

development was not that straightforward (Table 4) perhaps due to uptake by algae.

Only the N+P enrichment significantly increased the primary productivity and chlorophyll a concentration (Figs. 3 and 4). These variables remained at the same level as the control in all the other enclosures. The chlorophyll a level reached a maximum in the N+P enclosure one week after the peak of primary productivity.

Nitrogen fixation by blue-green algae was enhanced by P enrichment, while nitrogen addition alone inhibited it (Fig. 5). The effect was even more pronounced in the "in situ" measurements made two weeks after the enrichment (Fig. 6). The maximum biomass of blue-greens occurred in the enclosure enriched with both N and P (Fig. 7). The dominant species in all the enclosures were *Oscillatoria agardii* Gomont and *Microcystis* sp.

Table 4. Nitrogen: phosphorus ratios and limiting nutrient according to algal assay in the enrichment experiment with inorganic fertilizers in Lake Vesijärvi in 1981.

Enclosure	Date	Tot.N: Tot.P	$N_m:P_{PO_4}$	Limiting nutrient based on algal assay
Control	24.6.	12	4.7	N
	1.7.	24	1.6	P, N
	7.7	20	5.3	P, N
	15.7.	90	4.2	N, P
P-enriched	24.6.	5.0	0,55	N
	1.7.	9.7	0,27	N
	7.7.	8.8	0,29	N
	15.7.	13	0,48	N
N-enriched	24.6.	130		P
	1.7.	120	490	P
	7.7.	150	440	P
	15.7.	520	540	P
N+P enriched	24.6.	24	37	?
	1.7.	27	220	P
	7.7.	34	120	P
	15.7.	44	93	P

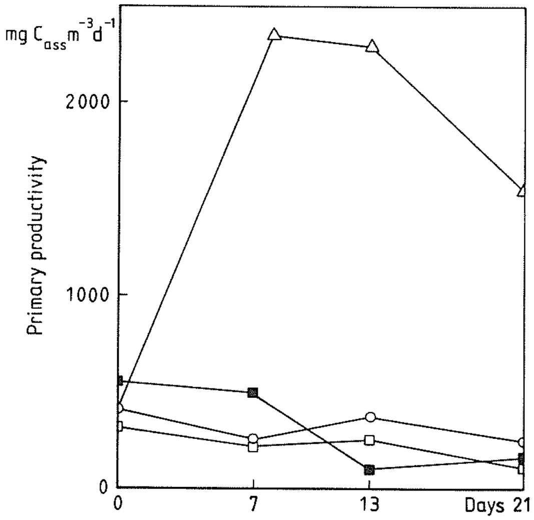

Fig. 3. Primary productivity in the chemical enrichment experiment in 1981. □ — □ control; ○ — ○ P-enriched; ■ — ■ N-enriched; △ — △ N+P -enriched.

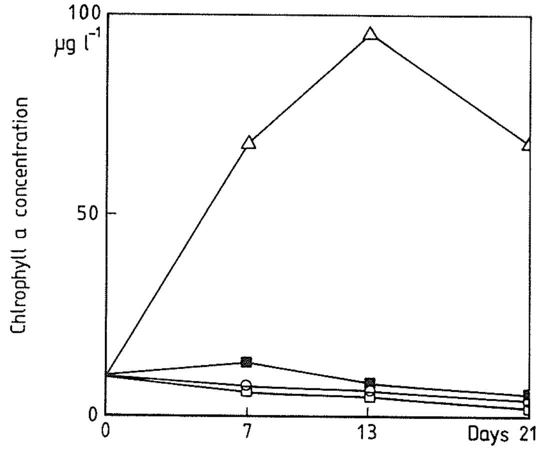

Fig. 4. Chlorophyll a concentration in the chemical enrichment experiment in 1981. Symbols as in Fig. 3.

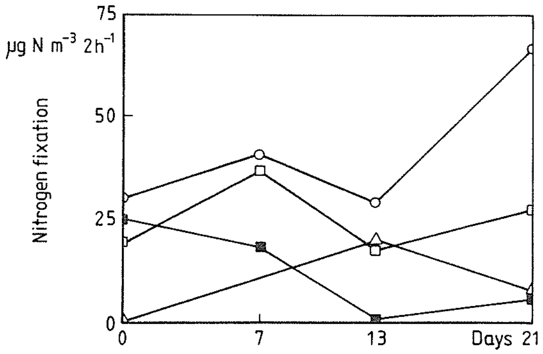

Fig. 5. Nitrogen fixation "in vitro" (measured by the acetylene reduction method) in the chemical enrichment experiment in 1981. Symbols as in Fig. 3.

The heterocystous blue-green algae increased during the experiment in the control enclosure and especially in the P-enriched enclosure, while N enrichment resulted in a decrease in their biomass.

According to the algal tests, nitrogen limited the growth of *Selenastrum capricornutum* in the P-enriched enclosure, while phosphorus was the limiting nutrient in the N-enriched and N+P-enriched enclosures. In the control enclosure nitrogen limited the growth of Selenastrum in the beginning, but during the course of the experiment only both nutrients together resulted in increased growth (Table 4). The results are in agreement with the nutrient ratios measured in the enclosures.

4.2 Sewage enrichment experiments

The results of chemical enrichment experiments cannot be directly applied to the estimation of the effects of sewage on recipients. In addition to phosphorus and nitrogen, sewage contains numerous compounds which influence the response of the lake. Therefore we continued the enclosure experiments with sewage enrichment.

4.2.1 Previous recipient

The first experiment with sewage enrichment was made in Lake Vesijärvi using pelagial bag-like enclosures (2.5 m^3). "Normal" biologically and chemically (P removal) treated sewage was obtained from the treatment plant of the city of Lahti. The treatment plant removed nutrients very efficiently, especially during the experiment in July. In order to get more "normal" sewage for the experiment

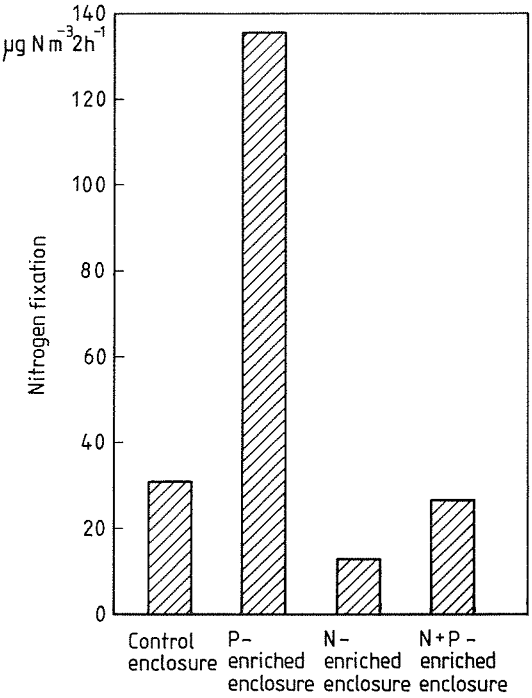

Fig. 6. Nitrogen fixation "in situ" (measured by the acetylene reduction method) in the chemical enrichment experiment in 1981 two weeks after the enrichment.

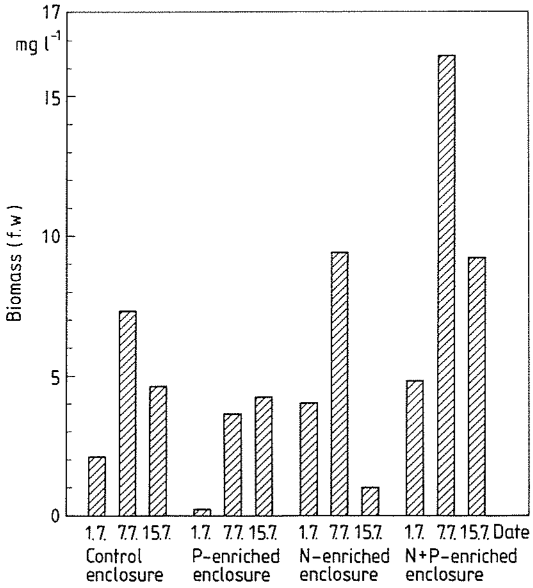

Fig. 7. Phytoplankton biomasses in the chemical enrichment experiment in 1981.

15 per cent preclarified sewage was mixed with it. Despite this, the nutrient concentrations of the enrichment were quite low (Table 2).

The first enrichment with phosphate and sewage, both aiming at the same total P concentration, was made on July, 22, and repeated twice, on August, 12 and September, 9. The highest total P concentration was found during the whole period in the chemically P-enriched enclosure. The same was true for phosphate. In the sewage-enriched enclosure the total P and PO_4-P concentrations decreased to the control level in one week, except after the last enrichment when they stayed above the control for the whole observation period (Fig. 8). Initial nitrogen concentrations were naturally highest in the sewage-enriched enclosure, i.e. the only one where nitrogen was also added. The decline was, however, quite rapid (Fig. 9). The mineral nitrogen concentrations were almost zero during the whole experiment in the control and P-enriched enclosures and in the sewage-enriched enclosure it was almost exhausted in three weeks after each enrichment. According to the ratio between mineral nutrients, nitrogen was limiting algal growth in the control and P-enriched enclosures. In the sewage-enriched enclosure, the N:P ratio was close to the optimum.

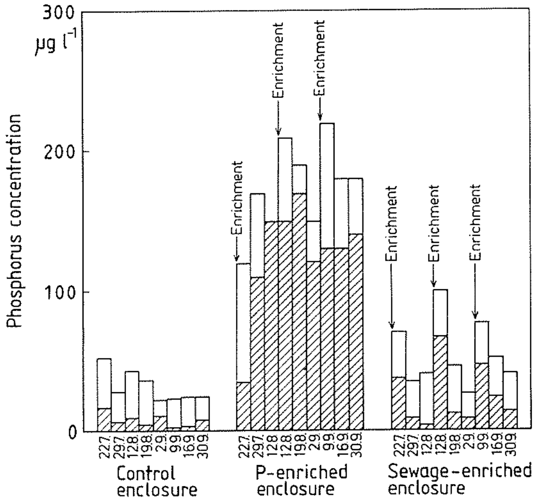

Fig. 8. Total phosphorus and phosphate phosphorus (shaded area) concentrations in the sewage enrichment experiment in 1981.

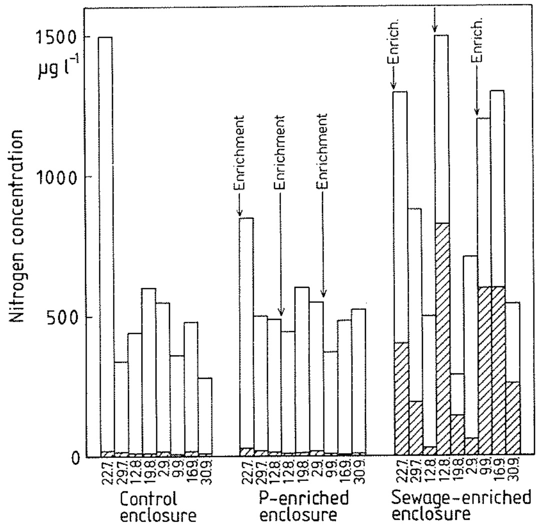

Fig. 9. Total nitrogen and mineral nitrogen (shaded area) concentrations in the sewage enrichment experiment in 1981.

Sewage strongly increased primary productivity after the second and third enrichment, while phosphorus alone had only a slight effect (Fig. 10). The chlophyll a values followed a slightly different trend: the sewage-enriched enclosure had the lowest chlorophyll values, except after the last enrichment (Fig. 11). The smaller algal biomass (measured as chlorophyll a) in the sewage-enriched enclosure was at least partly compensated by periphyton growth: almost no periphyton grew in the control and P-enriched enclosure, while sewage caused the development of a strong periphyton growth:

	Chl. a ($\mu g\ m^{-2}$)
Control	26
P-enrichment	38
Sewage enrichment	1 000

The biomass of blue-green algae in the enclosures remained smaller than that in the surrounding lake. At the time of the second enrichment the biomass of Cyanophyta was clearly higher in the sewage enclosure than in the others. The proportion of heterocystous blue-greens was normally less than 10 per cent of the total biomass, but immediately after the third enrichment they became dominating in all the enclosures (Fig. 12). Maximum nitrogen fixation was also observed at the same time (Fig. 13). The dominant heterocystous algae were *Aphanizomenon flos-aquae* and different *Anabaena*-species. For the rest of the time *Oscillatoria agardhii* was dominating. According to the algal tests, as well as the nutrient ratios, the P-enriched enclosure was continuously nitrogen limited, while in the two other enclosures the highest growth increase was normally obtained by

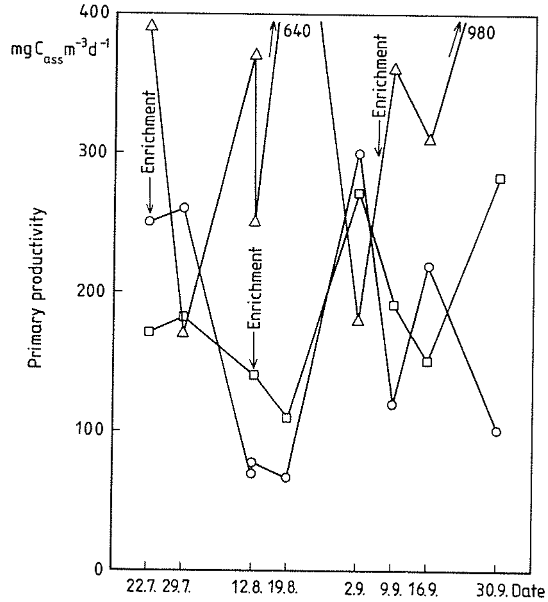

Fig. 10. Primary productivity in the sewage enrichment experiment in 1981. □ — □ control; ○ — ○ P-enriched; △ — △ sewage-enriched.

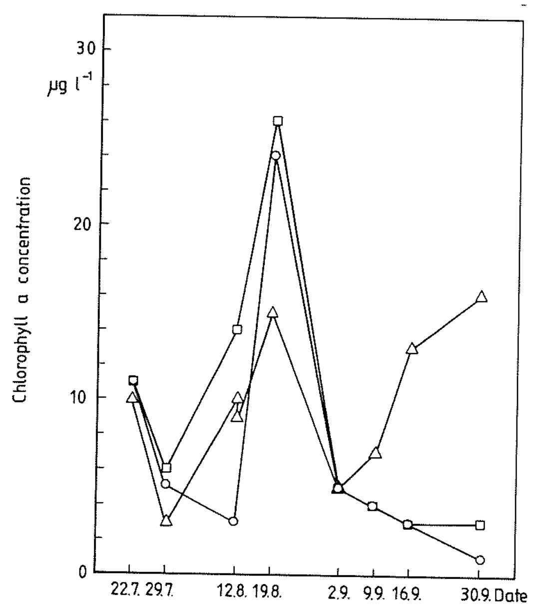

Fig. 11. Chlorophyll a concentrations in the sewage enrichment experiment in 1981. Symbols as in Fig. 10.

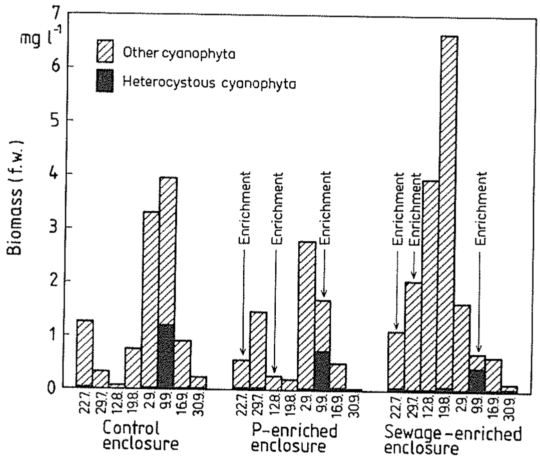

Fig. 12. Phytoplankton biomasses in the sewage enrichment experiment in 1981.

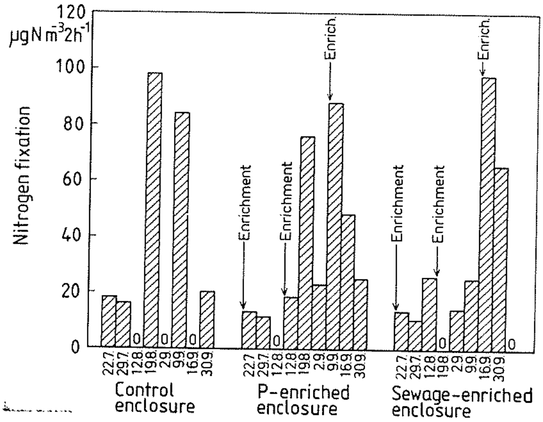

Fig. 13. Nitrogen fixation "in vitro" (measured by the acetylene reduction method) in the sewage enrichment experiment in 1981.

adding both nutrients (Table 5). This was not, however, reflected in nitrogen fixation: maximum nitrogen fixation was observed at the same time in all the enclosures, as well as in the surrounding water. No clear differences were observed in the rate of nitrogen fixation between the enclosures. Thus the growth of nitrogen-fixing blue-green algae in Lake Vesijärvi was obviously strongly regulated by environmental factors other than actual nutrient concentrations. Radiation, temperature and probably some micronutrients might be the factors which determine the succession of these algae during the growing season.

Table 5. Nitrogen: phosphorus ratios and limiting nutrient according to algal assay in the sewage enrichment experiment in Lake Vesijärvi in 1981.

Enclosure	Date	Tot.N: Tot.P	N_m:P_{PO_4}	Limiting nutrient based on algal assay
Control	22.7.	29	1.3	
	29.7.	12	2.5	N, P
	12.8.	10	1.1	P, N
	19.8.	17	2.5	N, P
	2.9.	25	1.6	N, P
	9.9.	16	7.0	
	16.9.	20	5.7	P, N
	30.9.	12	0.86	N, P
P-enriched	22.7.	7.0	0.71	
	29.7.	3.0	0.20	N
	12.8.	3.3	0.1	N
	19.8.	1.7	0.1	N
	2.9.	3.8	0.04	N
	9.9.	1.7	0.06	
	16.9.	2.7	0.05	N
	30.9.	2.9	0.06	N
Sewage-enriched	22.7.	19	11	
	29.7.	25	21	P
	12.8.	12	5.8	N, P
	19.8.	6.3	12	N, P
	2.9.	28	7.5	P, N
	9.9.	16	13	
	16.9.	26	25	P, N
	30.9.	13	19	P, N

4.2.2 Unpolluted forest lake

Two types of benthic enclosures were used in Lake Valkea Mustajärvi, a large cubical, 4 m deep one (56 m^3) and a small cylindrical enclosure (1 m^3).

Lake Valkea Mustajärvi is an oligotrophic lake. After the sewage enrichments, the nitrogen and phosphorus concentrations doubled in the large enclosure (Fig. 14). Later on they rapidly decreased, however, to almost the same level as that in the lake. The sewage additions resulted in a rapid increase in primary production as well as in the chlorophyll a values (Fig. 15). The most dramatic increase was, however, short-term, and the values returned near to the original level.

The phytoplankton biomass also increased as a result of sewage addition, but decreased again already within one week simultaneously with an increase in the zooplankton biomass (Fig. 16). The dominant algal groups varied with time, starting with *Chrysophyta* (dom. species *Synura uvella* Stein emend. Korshikov), followed by *Pyrrophyta* (*Rhodomonas lacustris* Pascher & Ruttner). After the second addition *Chlorophyta* (*Kirchneriella obesa* (W. West) Schmidle) dominated. In September *Pyrrophyta* (*Cryptomonas sp.*) and *Chrysophyta* (*Uroglena americana* Calkins) became dominant. *Cyanophyta* were almost absent throughout the whole summer. They formed only 1.4 per cent of the total phytoplankton biomass at the maximum. No nitrogen fixation was observed, although some *Anabaena* and *Aphanizomenon* species were found in all the samples.

The zooplankton biomasses followed the variation in phytoplankton with a short time lag. Their highest biomass values were usually observed 2—3 weeks after the phytoplankton maximum (Fig. 17). *Cladocera* were dominant, except in the beginning of July, when zooplankton consisted

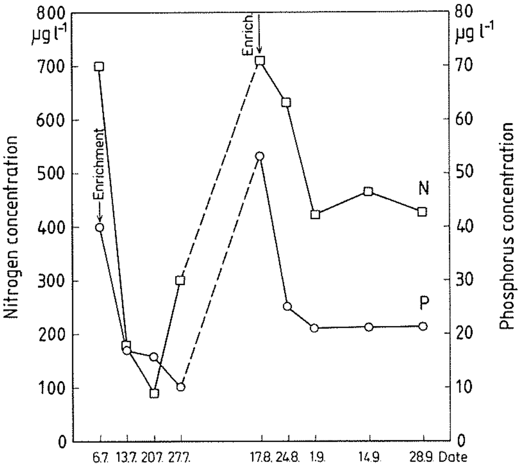

Fig. 14. Total nitrogen and total phosphorus concentrations in the sewage enrichment experiment in 1982.

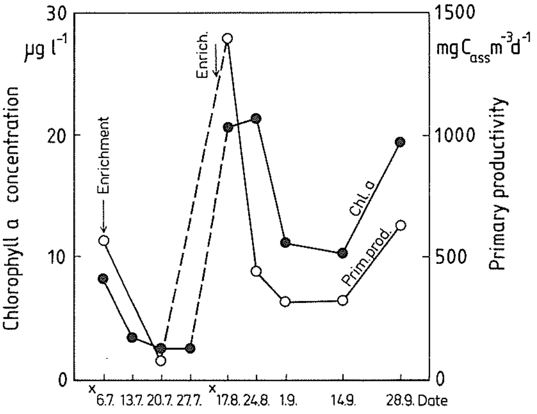

Fig. 15. Chlorophyll a concentration and primary productivity in the sewage enrichment experiment in 1982.

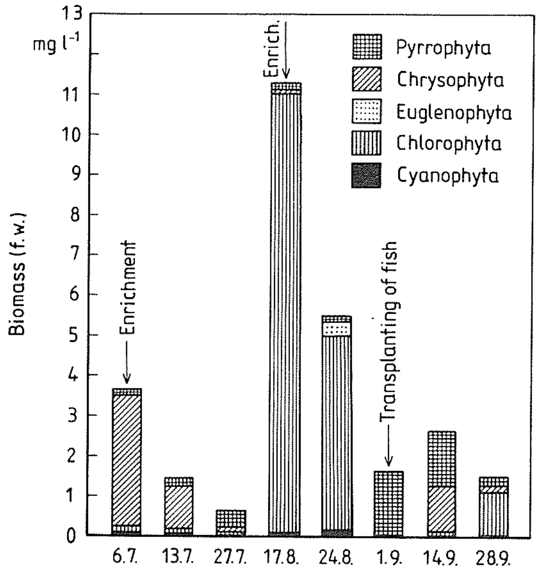

Fig. 16. Phytoplankton biomass in the sewage enrichment experiment in 1982.

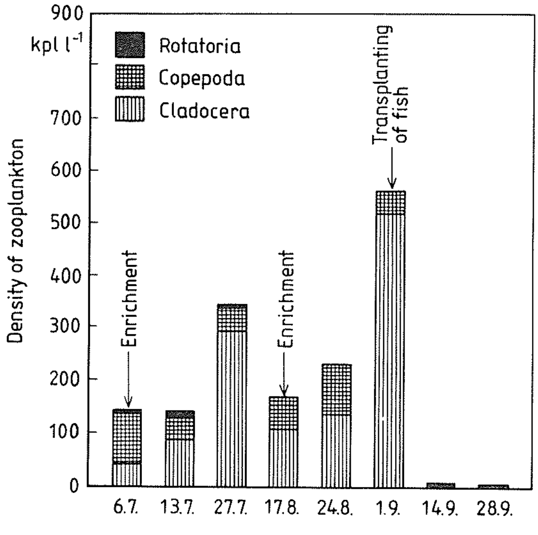

Fig. 17. Density of zooplankton in the sewage enrichment experiment in 1982.

mainly of *Copepoda*. After introducing the whitefish fingerlings (*Coregonus lavaretus* (L.)) the zooplankton density decreased rapidly, from 555 l^{-1} to 8 l^{-1} in two weeks. The phytoplankton biomass, chlorophyll a and primary productivity increased at the same time. This implies the significance of fish in regulating the biomass and production of different trophic levels of the ecosystem.

The phytoplankton biomasses and species composition in the small enclosures were almost identical despite the different sewage additions (6 % and 20 %). The maximum biomass values were observed one week after the addition, and during the next two weeks they decreased to one tenth. In addition to smaller biomasses, the small enclosures differed from the large enclosure as regards the species composition. The zooplankton biomasses were also smaller in the small enclosures.

The size of the enclosure seemed to affect the plankton biomasses. Despite the higher nutrient level in the small enclosures, the biomass values were clearly higher in the large enclosure. The main reason is probably the lack of turbulence (and thus efficient sedimentation) in small enclosures.

4.2.3 The heavily loaded recipient

The enclosures used in this experiment were of a large, cubical shaped benthic type with a natural, undisturbed sediment bottom. Sewage for the experiments was pumped directly from the Mikkeli municipal sewage treatment plant, which is situated about 100 m from the experimental area. It was possible during the experiment to operate the parallel treatment lines of the plant in different ways. Phosphorus removal in the treatment plant was very efficient and nitrogen removal was of considerable magnitude, too (Table 2). Thus the effect of the 2 per cent sewage addition on the enclosure recipient was not very drastic, especially because the recipient was already eutrophic without any enrichment.

The nitrogen concentration in the control enclosure remained at a relatively stable level (Table 6). However, because the phosphorus concentration increased markedly, the N:P ratio diminished in the course of the experiment. The overall decrease in the tot.N:tot.P ratio could be seen in the sewage-enriched enclosures, too. As was the case in the control enclosure, the internal load from the sediment makes it difficult to evaluate the significance of the nutrient ratios.

The chlorophyll a content in the enriched enclosures remained larger than that in the control throughout the time (Table 6). However, towards the end of the experiment the phytoplankton biomass in enclosure III (P removed sewage) decreased drastically, even below that of the control. The zooplankton densities in the control and enclosure III were very high, and were obviously the main cause of the decrease in the phytoplankton biomasses.

The phytoplankton in the control enclosure was

Table 6. Characteristics of the enclosure ecosystems after sewage enrichments in the eutrophic Lake Rohmavesi in 1983.

Variable	Control enclosure			Enclosure II*)			Enclosure III**)		
	0	7 days	14 days	0	7 days	14 days	0	7 days	14 days
Tot. N $\mu g\ l^{-1}$	1700	2200	1400	2900	2700	2200	4100	4500	3500
NO_3–N $\mu g\ l^{-1}$	540	290	100	1200	880	630	2000	2000	1700
NH_4–N $\mu g\ l^{-1}$	270	270	300	440	230	260	990	440	680
Tot. P $\mu g\ l^{-1}$	190	350	400	190	240	190	190	290	360
PO_4–P $\mu g\ l^{-1}$	99	220	300	71	67	56	59	110	250
Tot. N : tot.P	8.8	6.4	3.6	15	12	11	21	16	9.8
N_m : PO_4–P	8.9	3.0	1.6	24	18	17	55	26	11
Chl.a $\mu g\ l^{-1}$	59	45	27	76	91	86	83	45	5.3
Zooplankton (Cladocera + Copepoda) ind. l^{-1}	1300	1600	5000	820	460	710	1500	4600	1900

*) Enriched with P and N -removed sewage ("denitrifying line")
**) Enriched with P-removed sewage ("conventional line")

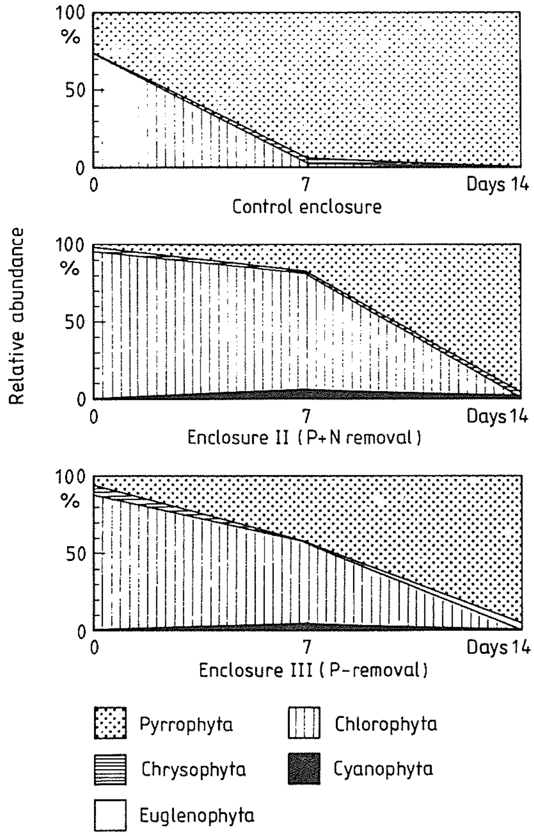

Fig. 18. Relative abundance of different phytoplankton groups in the sewage enrichment experiment in 1983.

dominated by *Pyrrophyta and Chlorophyta* (Fig. 18). The dominant species was *Chlamydomonas sp.* The enriched enclosures were first *Chlorophyta*-dominated, then became dominated by *Pyrrophyta.* It is remarkable that the phytoplankton composition developed in the same way in all the enclosures after the enrichments. Thus factors other than the nitrogen and phosphorus concentrations (which did not level off very much towards the end of the experiments) seem to have a very strong levelling effect on phytoplankton composition.

Cyanophyta are seldom dominant in this type of brown water recipient. In the control enclosure *Cyanophyta* did not exceed 0.5 % at its maximum. Their highest proportion was observed in enclosure II, but even then the percentage was only 2.8 %. Nitrogen fixing blue-green algae were naturally of even less importance in the enclosures. They were only occasionally present and their contribution to the nitrogen budget of the enclosures remained insignificant.

4.3 Internal phosphorus loading from the sediments

The enclosures with genuine lake sediment bottoms made it possible to estimate the release of phosphorus from sediment into the overlying water in the heavily loaded recipient. In June one enclosure was filled with lake water for control purposes. In late summer the same enclosure was emptied, refilled with lake water and enriched with sewage. The properties of the sediment remained the same as earlier.

The source of phosphorus, the surface layer of the sediment, had a P concentration of 6.6 mg P g^{-1} (dry weight). The chemical characteristics of the water in the enclosure in July (a) and August (b), after adding treated sewage revealed big differences in the weekly net phosphorus budgets (Table 7). The net load remained positive. Thus the minimum weekly load was +7.25 P mg m^{-2} d^{-1}, and the maximum +107.25 P mg m^{-2} d^{-1}.

It would appear that the sediment load was not temperature dependent. The oxygen concentration 1 m above the sediment surface also remained at the same relatively high level. The pH-value did not change much during the test. The COD, BOD and total N values increased during both of the high peaks in P release from the sediment. Especially prominent was the weekly BOD increase of 3.7 mg $O_2{}^{-1}$ in August, which occurred at the same time as the highest release of phosphorus, +107 mg m^{-2} d^{-2} was measured. On the other hand, the nitrate concentration decreased in both the (a) and (b) parts of the experiment uniformly from the beginning to the end. In test (a) the chlorophyll a concentration decreased all the time, while in test (b) it increased strongly. Thus the phytoplankton biomasses and production correlated positively with phosphorus in the latter part of the experiment only. Instead, the crustacean zooplankton biomasses correlated fairly well with total phosphorus in the first part of the experiment. It is obvious that very high zooplankton biomasses are temporarily able to maintain phosphorus concentrations in the water phase of the aquatic ecosystem. The net phosphorus loads from the sediment, calculated from the concentration changes in the enclosure, do not reveal whether these changes are due to changes in the sedimentation rate or to changes in release from the sediment.

5. DISCUSSION

5.1 The use of enclosures in enrichment experiments

Large enclosures are a useful alternative for laboratory tests and for wholelake experiments when studying the effects of sewage on lake recipients. Many natural phenomena are more easily quantified in enclosures than in lakes. It is also possible to make parallel experiments and to examine the effects of different factors in a controlled manner. Nevertheless, enclosures are partially closed systems and it is therefore not possible to make direct comparisons between the enclosure and the lake ecosystem. Moreover, observations made in the enclosures are not

Table 7. Changes in the chemical and biological characteristics of an enclosure with a polluted sediment in Lake Rohmavesi.

Variable	Untreated phase				After enrichment		
	22.6.	29.6.	6.7.	13.7.	27.7.	3.8.	10.8.
t°C	13.8	16.5	17.8	21.2	21.3	20.6	21.3
*) O_2, mg l^{-1}	13.5	10.5	9.3	7.9	9.6	8.4	7.8
pH	9.2	8.2	7.6	8.3	7.9	7.7	7.3
COD, mg O_2 l^{-1}	16.5	13.9	15.4	15.0	13.5	12.9	14.5
BOD_7, mg O_2 l^{-1}	11.0	7.3	9.3	7.0	5.8	5.5	9.2
Tot.N, μg l^{-1}	2300	1700	2200	1400	3100	1800	2200
NO_2–N, μg l^{-1}	45	67	94	90	65	44	33
NO_3–N, μg l^{-1}	730	540	290	100	1600	440	300
NH_4–N, μg l^{-1}	250	270	270	300	200	200	74
Tot.P, μg l^{-1}	170	190	350	400	500	560	860
ΔTot.P, μg l^{-1} d^{-1}		+2.9	+22.9	+7.1		+8.6	+42.9
PO_4–P, μg l^{-1}	50	99	220	300	440	470	590
ΔTot.P, mg m^{-2} d^{-1}		+7.2	+57.2	+17.8		+21.5	+107.2
Chl.a, μg l^{-1}	100	59	45	27	12	19	100
Zooplankton (Cladocera + Copepoda), ind. l^{-1}	410	1300	1600	5000	3600	1800	

*) 1 m above the bottom

necessary valid in a natural water body.

The physical, chemical and biological conditions in enclosures differ to some extent from those in the surrounding water. However, the larger the enclosure, the smaller the difference, and it may well be said that short-term experiments in fairly large enclosures reflect well enough the natural conditions in a lake.

These experiments were performed in three different plastic enclosures placed in lakes: (1) baglike, the lower end closed containing 2.5 m^3 of water, (2) cylindrical, each end open containing 1 m^3 of water and (3) cubical, each end open containing 56 m^3 of water.

The production of periphytic algae was significant in each type of enclosure. Detached wall growth caused problems in sampling and in the analyses. Periphyton caused the least sampling problems in large enclosures. A loss of illumination inside the cylinder was detected only in the baglike enclosures during the 9 weeks experiments. No shading-effects due to wall growth, measured with a submerged photocell, were detected in the large enclosures during the 3 month experiments.

The disturbing effects of enclosures increase during long-term experiments. Usually a period of 2—5 weeks is suitable in experiments with small (less than 10 m^3) enclosures. The larger the enclosures, the longer the experimental times that can be used. The phytoplankton communities can remain similar to those of the lake even after 2.5 years of isolation (Lack and Lund 1974).

A lack of turbulence caused a rapid loss of nutrients and a decline in the phytoplankton biomass in the smaller types of enclosures. However, the phenomenon was less pronounced in the larger ones. After sewage enrichment in the enclosures phytoplankton was more abundant in the large enclosures than in the lake. In contrast, plankton production in the smaller enclosures was less, or at its maximum as high as in the open lake in spite of nutrient enrichment. The ratio of water-volume to wall-area has to be large enough to maintain the natural phyto- and zooplankton communities (Smyly 1976, Kenttämies 1981). In large enclosures with a small volume to wall-area ratio, the plankton communities are similar to pelagic ones. In studies with enclosures of less than 10 m^3, the phytoplankton has changed to the type of community found in a pond or in the littoral zone (Lack and Lund 1974, Smyly 1976).

The effects of sewage addition on primary production were more pronounced after introducing fish in a large enclosure. Fish predation prevents zooplankton communities from becoming too large. Fish excretion and mechanical stirring stimulate the nutrient cycles and retard the oligotrophication of an enclosure.

The largest (56 m^3) experimental enclosure with a natural bottom and planktivorous fish population appeared to be the most suitable for limnological studies. The most notable difficulty was the significant wall growth of periphytic algae. This cannot be avoided in any kind of enclosure. However, analysis of the chlorophyll content of the periphytic algae gives a fairly good insight into the importance of periphytic production.

5.2 Chemical vs. sewage enrichment

Pure chemical enrichment, instead of sewage, is preferred in many empirical studies on the effects on lakes of municipal waste water. Besides being more practical, chemical addition has been regarded as a more scientific way of study. Our results from chemical enrichment were quite similar to those obtained in corresponding studies elsewhere (Lundgren 1978a, b, Flett et al. 1980, Schindler 1980). Phosphorus enrichment enhanced nitrogen fixation, but only phosphorus and nitrogen enrichment together increased primary productivity. However, this study was planned to provide answers concerning the total effects of a new type of sewage treatment method on the recipients. The total effects of older, widely used treatments can be seen in thousands of eutrophied lakes and rivers! According to this study, the total phosphorus and nitrogen concentrations did not very well explain the effects of sewage even on primary production. Many other factors, such as inhibition, heterotrophic activity and species succession, affect the results of such experiments. The effects of loading on the whole ecosystem may be the most prominent, in the hypertrophic level of production especially. The separate testing of all the components of sewage (macro- and micronutrients, toxic compounds organics etc.) in a whole ecosystem is not a practical possibility. It was hoped that testing and comparing the total effects of a sewage type, a real treatment method, on lake ecosystems would give straight answers to its usefulness.

5.3 Effects of nitrogen removal on the aquatic ecosystem

The primary hypothesis that cyanophyta would be favoured by a relatively small lowering of the nitrogen load from sewage, had to be abandoned at least in the circumstances prevailing in the heavily loaded, brown water lake Rohmavesi, the recipient of the city of Mikkeli. Nutrient loads from the sediments were high and dominated primary production. The duration of the internal phosphorus load from sediments might be fairly long after the implementation of phosphorus removal from sewage, and thus the total benefits of better treatment will only be seen in the future, maybe not until decades have passed. The problems associated with restoring polluted lakes to their former condition are well known in many countries where the chemical removal of phosphorus from sewage has been implemented (Björk 1982). However, the internal load of phosphorus can be controlled to some degree by external measures such as regulation of the oxygen consuming load or artificial oxygenation of the hypolimnion. The chemical oxygenation of water with nitrates from nitrifying sewage treatment plants has been introduced as a new mitigation method, too (Ripl 1976).

6. CONCLUSIONS

The role of nitrogen as a factor limiting primary production in lakes is not yet well understood. In addition to direct effects, nitrogen also has indirect effects on primary production by regulating heterotrophic activity. Therefore the question of nitrogen removal from sewage also has no simple answer. Our results imply that the decision on nitrogen removal should be made case by case. In some lakes, like lake Vesijärvi, blooms of nitrogen-fixing blue-green algae may at least partly compensate for nitrogen removal and, as such, cause problems for recreation and other forms of water use. In typical Finnish humic lakes, however, blue-greens hardly ever occur in high biomasses. This might reflect the lack of some natural prerequisites for their growth. In such cases nitrogen removal would have only beneficial effects.

A simple test procedure, like algal assays and enrichment experiments in enclosures, would form a more solid basis for decision-making. Taking into account the high costs of the implementation of nitrogen removal in the treatment plants, the costs of this type of testing are only marginal.

7. SUMMARY

Eutrophication is the main problem resulting from the discharge of municipal waste waters to watercourses. In Finland an average of about 90 per cent of sewage phosphorus is removed in treatment plants. During the last fifteen years the phosphorus load has steadily gone down, while the nitrogen load has increased. Today the N:P ratio of treated sewage is clearly over 10, whereas in the early 1970's it was still less than 10. However, since in many cases the effects of purification on lakes have remained smaller than expected, nitrogen removal has been considered as the next step in improving sewage treatment. If the problem to be solved is the toxic level of nitrogen compounds in the recipient, the removal of nitrogen from sewage would have only beneficial effects. However, it has been proposed that nitrogen-fixing cyanobacteria increase in eutrophic lakes, thus compensating for the benefits of nitrogen removal in the treatment plant and as such being harmful for recreational and other water use.

The aim of this study was to increase our understanding of the eutrophication process, and especially knowledge concerning the role of nitrogen fixation in heavily loaded recipients.

According to a preliminary study carried out in lake Vesijärvi, southern Finland, planktonic nitrogen fixation was responsible for 31 per cent of the annual nitrogen input to a eutrophic lake where sewage loading had been ceased entirely a couple of years earlier.

The experimental part of the study was performed using enclosures (limnocorrals). A fairly large (56 m^3), benthic type enclosure with a natural sediment bottom proved to be suitable for the ecosystem studies in which the effects of both treated sewage and internal load from old sediments were investigated. All three treatment plants used in the study as sewage producers employed the active sludge method and simultaneous phosphorus precipitation with ferrous sulphate. Nitrogen removal with a nitrification-denitrification process was employed in two plants. The effects on the ecosystem were tested a) in a heavily loaded, b) in a previously loaded and c) in a pristine forest lake.

The experiment with chemical N and P enrichment proved that only nitrogen and phosphorus together could increase primary production significantly in the eutrophic lake Vesijärvi. Nitrogen fixation by blue-green algae was enhanced by P enrichment, while nitrogen addition alone inhibited it. The dominant species both in

the control and in all three manipulated enclosures were *Oscillatoria agardhii* and *Microcystis* sp.

The results of algal tests on the limiting nutrient carried out using a green alga *Selenastrum capricornutum* were in good agreement with the chemical nutrient ratios. The different response of periphyton growth to the same total P concentration in the chemically enriched enclosure and that in the sewage enriched enclosure was prominent. Sewage resulted in much better growth of periphyton than chemical P enrichment, while only slight differences were observed in planktonic production. In spite of the different chemical composition, heterocystous blue-green algae appeared to dominate simultaneously in the lake and in all the enclosures. Different nutrient ratios did not appear to regulate nitrogen fixation very strongly if N or N+P are limiting factors.

The response in the benthic enclosure in an oligotrophic, pristine forest lake to sewage enrichment was a peak in growth followed by a decrease in production. Grazing by zooplankton, together with the nutrients concents, regulated primary production. Thinning of zooplankton by fish fingerlings effectively favoured primary production. The addition of efficiently treated (N+P removal) sewage did not favour blue-green algae, which reached a maximum of only 1.4 per cent of the total phytoplankton biomass. No nitrogen fixation could be observed, either.

In the third, heavily loaded recipient only large, benthic type enclosures were used. Treated sewage clearly increased the phytoplankton biomass in this case, too. The internal load made the ratio of total N to total P decrease in all the enclosures, including the control one. A very dense zooplankton population caused overgrazing of phytoplankton towards the end of the experiment. Despite differences in the sewage used for enrichment, the phytoplankton succession during the summer was similar in all enclosures, changing from *Chlorophyta* to *Pyrrophyta*. *Cyanophyta* remained rare thus implying that the removal of nitrogen from sewage was not able to enhance their growth in this recipient.

The internal net load of phosphorus from sediments of the heavily loaded recipient varied from 7.25 mg m^{-2} d^{-1} to 107 mg m^{-2} d^{-1}. Since the net load was calculated on the basis of concentration changes in the water phase, changes in sedimentation rate and the actual release from sediments could not be separated from each other. In any case, the internal load from sediments was of decisive importance in the phosphorus budget of this heavily polluted lake area.

AKNOWLEDGEMENTS

The study was financed by the National Board of Waters and Environment and the Foundation for Research on Natural Resources in Finland. However, without the collaboration with many authorities and laboratories this study would not have been possible. We would like to thank Helsinki and Mikkeli Water and Environment Districts for analytical work, as well as Lahti, Hyvinkää and Mikkeli municipal water and sewage works for providing the sewage for the experiments. The Game and Fisheries Research Institute, Evo field station, helped in the field work in Valkea Mustajärvi. Numerous persons contributed to the study. In particular we wish to express our gratitude to Juha Keto, Jarmo Kivinen and Olavi Sandman for collaboration. Matti Valve and Markku Mäkelä gave valuable comments during the study. Liisa Lepistö, Pirkko Kokkonen, Reija Jokipii and Maija Niemelä did the microscopy on phyto- and zooplankton, for which our thanks are due. Finally we would like to thank John Derome for revising the English language of the text.

TIIVISTELMÄ

Järvien rehevöityminen on asumajätevesien huomattavin vesistöhaitta. Nykyään n. 90 prosenttia asumajätevesien fosforista poistetaan Suomessa puhdistamoilla. Viimeisten viidentoista vuoden aikana asumajätevesista johtuva fosforikuorma onkin jatkuvasti laskenut, kun taas typpikuorma on lisääntynyt. Puhdistetun jäteveden N:P on nykyään selvästi yli kymmenen kun se 1970-luvun alkupuolella oli selvästi sen alle. Kuitenkin monissa vesistöissä puhdistuksen vaikutus vesistön tilaan on jäänyt odotettua vähäisemmäksi. Typen tehokkaampaa poistoa on harkittu seuraavaksi, jätevesien puhdistusta parantavaksi askeleeksi. Mikäli typen liian korkea, myrkyllinen pitoisuustaso on typpiyhdisteiden pääongelmana vastaanottavassa vesistössä, on typenpoiston tehostamisesta yksiselitteisesti hyötyä. Rehevöitymishaittojen torjuntaan typenpoiston on odotettu soveltuvan huonommin, mikäli tällöin stimuloidaan typpeä sitovien, vedenkäytölle huomattavan haitallisten sinilevien massaesiintymistä.

Tämän tutkimuksen tarkoituksena oli lisätä jätevesien aiheuttaman rehevöitymisilmiön tuntemusta ja erityisesti tietoa typensidonnasta raskaasti kuormitetuissa vesistöissä.

Esitutkimuksessa todettiin että rehevöityneessä Hollolan Vesijärvessä, jota Lahden kaupunki oli lakannut kuormittamasta pari vuotta aikaisemmin, planktinen typensidonta oli 31 prosenttia typen vuosikuormasta.

Kokeelliset vesistötutkimukset tehtiin muovikelmusta rakennetuissa, vesistöön sijoitetuissa koealtaissa. Vertailtaessa eri allastyyppien sopivuutta osoittautui kohtalaisen tilava (56 m^3), n. 3,5 m syvyiseen veteen sijoitettu kuutionmuotoinen allas parhaaksi silloin, kun haluttiin tutkia myös pohjan kuormitusvaikutusta. Jätevesiä saatiin tutkimuksiin kolmesta eri aktiivilietepuhdistamosta, jotka kaikki käyttivät fosforin rinnakkaissaostusmenetelmää ferrosulfaatti saostuskemikaalina. Kahdessa laitoksessa toteutettiin typenpoistoa biologisella nitrifikaatio-denitrifikaatio-menetelmällä. Koevesistöinä, joissa jätevesien vaikutuksia testattiin oli a) aikaisemmin kuormitettu vesistö (Vesijärvi) b) luonnontilainen metsäjärvi (Valkea Mustajärvi, Evo), c) raskaan kuormituksen vaikutuksen alainen vesistö (Rohmavesi).

Tutkittaessa Vesijärvellä epäorgaanisen typen ja fosfaatin vaikutusta perustuotantoon todettiin, että vain nämä ravinteet yhdessä aikaansaivat merkittävän tuotannon lisäyksen. Sinilevien typensidonta voimistui fosfaatin lisäyksestä, kun taas yksinomainen typpiravinteiden lisäys ehkäisi typensidontaa. Kokeiden aikana olivat valtalajeina kaikissa, niin kontrolli- kuin käsittelyaltaissakin sinilevälajit *Oscillatoria agardhii* ja *Microcystis* sp. Koealtaiden vedestä tehdyt levätestit, joissa käytettiin testilevänä viherlevä *Selenastrum capricornutumia*, antoivat kemiallisten ravinnesuhteiden kanssa yhtäläisiä tuloksia minimiravinteesta. Perifytontuotanto reagoi jätevesilisäykseen ja sen fosforipitoisuutta vastaavaan fosfaattilisäykseen täysin eri tavoin siten, että jätevesilisäys aikaansai kertaluokkaa suuremman kasvun. Planktinen perustuotanto erosi altaissa sen sijaan vain vähäisessä määrin. Huolimatta veden erilaisesta kemiallisesta koostumuksesta heterokystillisistä sinilevistä kehittyi dominoiva ryhmä samanaikaisesti järvessä ja eri koealtaissa. Jossain määrin erilaiset N:P-suhteet eivät näyttäneet säätelevän typensidontaa, jos minimiravinteena oli N tai N+P.

Pienessä, kirkasvetisessä metsäjärvessä koealtaaseen tehty jätevesilisäys aikaansai tuotantohuipun jota seurasi nopea eläinplanktonin "laiduntamisesta" johtuva lasku. Eläinplankton sääteli näin yhdessä ravinnepitoisuuksien kanssa perustuotantoa. Runsaan kalanpoikaspopulaation siirto koealtaaseen nosti tehokkaasti perustuotantoa, kun eläinplanktontiheys laski romahdusmaisesti kalojen predaation seurauksena. Jätevesi, jonka fosfori- ja typpipitoisuutta oli huomattavasti alennettu puhdistuksessa, ei kuitenkaan suosinut sinilevien kasvua. Sinileväbiomassa oli suurimmillaan vain 1,4 % kasviplanktonin kokonaisbiomassasta. Typensidontaa ei myöskään havaittu.

Mikkelin jätevesien kuormittaman Rohmaveden tutkimuksessa käytettiin Valkea Mustajärven tapaan suurta koeallastyyppiä, jossa on luonnonpohja. Puhdistetun jäteveden lisäys (2 %) altaaseen nosti myös täällä jonkin verran perustuotantoa. Sedimentistä lähtevä altaan sisäinen kuorma oli kuitenkin vanhalla jätevesien purkualueella huomattava ja se sai ravinnesuhteen tot.N:tot.P pienenemään kaikissa koealtaissa kontrolli mukaan lukien. Altaisiin kasvoi ylitiheä eläinplanktonkanta, joka ilmeisesti rajoitti perustuotantoa. Kasviplanktonsukkessio oli koealtaissa samantapainen vaikka ravinnelisäykset altaisiin erosivatkin eri jätevesityypeissä. Alkutilanteen *Pyrrophyta-Chlorophyta* dominanssi muuttui ensin *Chlorophyta-* ja sitten takaisin *Pyrrophyta*-dominanssiksi. Sinilevät (*Cyanophyta*) jäivät kaikissa kokeiden vaiheissa melko vähämerkityksellisiksi, eikä fosforinpoistoon yhdistettyä typenpoistoa voida pitää Rohmaveden olosuhteissa sinilevien kasvua suosivana.

Rohmavedellä oli fosforin nettokuorma sedimentistä 7,25—107 mg m^{-2} d^{-1}. Nettokuorma määritettiin veden konsentraatiomuutosten perusteella suljetussa systeemissä, eikä siitä voida näin erottaa todellisia liukenemis- ja sedimentoitumisnopeuksia. Huomattavan suurella sedimentistä lähtevällä fosforikuormituksella oli ratkaiseva merkitys raskaasti kuormitetun vesistönosan fosforitaseessa.

REFERENCES

Alexander, M. 1977. Introduction to soil microbiology. 2nd ed. 467 p. New York.

Björk, S. 1982. Goals, methods and possibilities for directing development of limnic ecosystems. *Hydrobiologia* 86:177—183.

Burris, R.M. 1972. Measurements of biological N_2 fixation with 15 N_2 and acetylene. pp. 3—14 *in* Sorokin, J. and Kadota, M. (eds.): Techniques for the assessment of microbial production and decomposition in fresh waters. IBP Handbook No. 23.

Flett, R.J., Schindler, D.W., Hamilton, R.D. & Campbell, N.E.R. 1980. Nitrogen fixation in Canadian precambrian shield lakes. *Can. J. Fish. Aquat. Sci.* 37:494—505.

Forsberg, C., Ryding, S-O., Claesson, A. & Forsberg, A. 1978. Water chemical analyses and/or algal assay? — Sewage effluent and polluted lake water studies. *Mitt. Int. Ver. Limnol.* 21:352—363.

Kanninen, J. 1980. Typen merkitys perustuotannon rajoittajana kolmessa eutrofisessa Etelä-Suomen järvessä. [Role of nitrogen as a growth limiting factor in three eutrophic lakes in southern Finland.]. M. Sc. Thesis. Univ. of Helsinki. Dept. of Limnology. 91 p.

Kauppi, L. 1979. Phosphorus and nitrogen input from rural population, agriculture and forest fertilization to watercourses. *Publications of the Water Research Institute,* 34:35—46.

Kenttämies, K. 1981. Asumajätevesien kasvinravinteiden, erityisesti typen vaikutus vesien perustuotantoon; allaskokeita oligotrofisissa järvissä. [Effect of waste water nutrients, especially nitrogen, on aquatic primary production.] pp. 61—72 *in* Sipponen, M. (ed.), Tarvitaanko typen poistoa jätevesistä. Vesi- ja Kalatalousmiehet ry. Helsinki.

Lack, T.J. & Lund, J.W.G. 1974. Observations and experiments on the phytoplankton of Blelhem Tarn, English Lake District. 1. The experimental tubes. *Freshwat. Biol.* 4:399—415.

Lundgren, A. 1978a. Nitrogen fixation induced by phosphorus fertilization of a subarctic lake. *Ecol. Bull.* (Stockholm) 26:52—59.

Lundgren, A. 1978b. Experimental lake fertilization in the Kuokkel area, northern Sweden: Changes in sestonic carbon and the role of phytoplankton. *Mitt. Int. Ver. Limnol.* 20: 863—868.

National Board of Waters 1981. Vesihallinnon analyysimenetelmät. Methods of water analyses used by water authorities. National Board of Waters, Finland, Report 213. 136 p.

Persson, P-E. 1982. Muddy odour: a problem associated with extreme eutrophication. *Hydrobiologia* 86:161—164.

Rhee, G.Y. & Gotham, I.J. 1980. Optimum N:P ratios and coexistence of planktonic algae. *J. Phycol.* 16:486—489.

Ripl, W. 1976. Biochemical oxidation of polluted lake sediment with nitrate — A new lake restoration method. *Ambio* 5:132—135.

Schindler, D.W., Ruszczynski, T. & Fee, E.J. 1980. Hypolimnion injection of nutrient effluents as method for reducing eutrophication. *J. Fish. Res. Bd. Can.* 37:320—327.

Seppänen, P. 1970. Typpikysymys vesiensuojelussa. [The problem of nitrogen in water protection.] *Vesitalous* 11:12—15.

Smyly, W.J.P. 1976. Some effects of enclosure on the zooplankton in a small lake. *Freshwat. Biol.* 6:241—251.

Valve, M. 1984. Combined nitrogen and phosphorus removal from wastewaters. *Publications of the Water Research Institute,* 58:28—54.

Vollenweider, R.A. 1970. Scientific fundamentals of the eutrophication of lakes and flowing waters, with particural reference to nitrogen and phosphorus as factors in eutrophication. OECD. 159 p.

Vuorio, H. 1977. Fixation of molecular nitrogen by planktonic cyanobacteria in the Helsinki sea area in 1974. English summary. Rep. Water Conservation Lab., City of Helsinki 9(1):1—58.

Yrjänä, E-R. 1982. Planktisten sinilevien typensidonta Hollolan Vesijärvessä. [Nitrogen fixation by planktonic blue-green algae in lake Vesijärvi, Hollola]. M.Sc. Thesis. Univ. of Helsinki. Dept. of Limnology. 89 p.

Yrjänä, E-R. & Kauppi, L. 1984. Kasvinravinteet rehevyystason säätelijöinä. [Plant nutrients and regulation of the trophic status of lakes.] pp. 103—117 *in:* Kylä-Harakka T. & Heinonen P. (eds.) Vesiensuojelun tavoitteiden asettaminen. Vesi- ja kalatalousalan ammattijärjestö VKA ry., Helsinki.