Pore water phosphorus and iron concentrations in a shallow, eutrophic lake – indications of bacterial regulation

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Abstract

Peak pore water SRP and iron(II) concentrations were found during summer in surface sediments in the shallow and eutrophic L. Finjasjön, Sweden, and the concentrations generally increased with water depth. The SRP variation in surface sediments (0–2 cm) was correlated with temperature ($R^2 = 0.82$–0.95) and iron(II) showed a correlation with sedimentary carbon on all sites ($R^2 = 0.42$–0.96). In addition, sedimentary Chl$a$, bacterial abundances and production rates in surface sediments (0–2 cm) varied seasonally, with peaks during spring and fall sedimentation. Bacterial production rates were correlated with phosphorus and carbon in the sediment ($R^2 = 0.90$–0.95 and $R^2 = 0.31$–0.95, respectively), indicating a coupling with algal sedimentation. A general increase in sediment Chl$a$ and bacterial abundances towards sediments at greater water depth was found. Further, data from 1988–90 reveal that TP and TFe concentrations in the lake were significantly correlated during summer ($R^2 = 0.81$ and 0.76, in the hypolimnion and epilimnion, respectively). The results indicate that the increase in pore water SRP and Fe(II) in surface sediments during summer is regulated by bacterial activity and the input of organic matter. In addition, spatial and temporal variations in pore water composition are mainly influenced by temperature and water depth and the significant correlation between TP and TFe in the water suggests a coupled release from the sediment. These findings support the theory of anoxic microlayer formation at the sediment-water interface.

Introduction

Studies of internal P loading have a long tradition within limnological research. In the early works of Mortimer (1941, 1942), the redox-coupled release of phosphorus and iron in stratified lakes with an anoxic hypolimnia was described. However, later research has added new information to the original theories and several authors have shown that a release of phosphorus and iron from 'oxic' sediments in shallow and polymictic lakes occurs, and may even be an important potential source of P (Kamp-Nielsen, 1975; Holdren &

Armstrong, 1980; Drake & Heaney, 1987; Löfgren, 1987; Jensen & Andersen, in press). Theoretically, the formation of anoxic microlayers at the sediment-water interface may cause a P and Fe release even at high oxygen levels in the water mass. Enhanced microbial activity in the sediment in summer during high water temperature is believed to contribute to the formation of these layers (Löfgren, 1987; Boström *et al.*, 1988).

Several papers discuss the effects of temperature on the P-release (e.g. Kamp-Nielsen, 1975; Holdren & Armstrong, 1980; Löfgren & Boström, 1989; Søndergaard *et al.*, 1990; Jensen & Ander-

sen, in press) and various authors have focused on the importance of microbial mineralization to pore water increase and/or sediment release of phosphorus and iron (e.g. Gächter et al., 1988; Sinke & Cappenberg, 1988; Boström et al., 1989; Löfgren & Boström, 1989; Boers, in press). Phosphorus in the pore water is of great importance for the internal loading due to a high mobility of the dissolved ions and can be used as an indicator of internal P loading in lakes (Holdren & Armstrong, 1986). A simultaneous increase in soluble reactive phosphorus (SRP) and ferrous iron (Fe(II)) in the pore water is often observed in eutrophic lakes during periods of high water temperature, where peak concentrations often are found close to the sediment-water interface, indicating an impact of microbial activities (Theis & McCabe, 1978; Enell & Löfgren, 1988; Löfgren & Boström, 1989; Boers, in press). However, some studies suggest that the P and Fe release may be partially uncoupled and caused by separate processes in the sediment (Boström et al., 1988; Gächter et al., 1988).

Further, in sediments with large amounts of P adsorbed to iron(III) compounds, the diffusive flux of P across the sediment-water interface is known to be low at high redox potentials. The adsorption capacity is however reduced at high pH, as demonstrated in several studies (e.g. Boström, 1984; Boers, 1991; Jensen & Andersen, in press). In shallow lakes where intense photosynthesis by phytoplankton can induce a high pH, it may have a crucial effect on the P-release (Jacoby et al., 1982; Drake & Heaney, 1987).

The present investigation was performed in the eutrophic, shallow and polymictic L. Finjasjön, Sweden. In this lake, trophic recovery after a reduction in the external P loading has been delayed and to improve water quality, lake restoration by partial sediment removal was introduced in the mid 1980s. However, despite efforts to restore the lake it still demonstrates an internal P loading, dense algal blooms with elevated pH-levels (> 10) and a rapid increase in total iron during summer. The aim of this paper is to discuss the following theories: i) the peak in SRP and Fe(II) in the surface pore water during summer is mainly

caused by the activities of sediment bacteria, ii) the formation of anoxic microlayers at the sediment surface during high sediment oxygen demand are promoting a P and Fe release, iii) year-to-year fluctuations in pore water concentrations of SRP and Fe(II) in surface sediments are regulating the internal loading in L. Finjasjön, and derive from differences in temperature, wind mixing and sediment bacterial activities.

Material & methods

Study site

The comparatively large and shallow L. Finjasjön (Fig. 1; lat. $56° 08'$, long. $13° 42'$) is a eutrophic and polymictic lake with a surface area of 11 km^2 and an average water residence time of 5 months. The mean depth is approximately 4 m and a maximum depth of ca. 12 m is found in the southern basin. Of the five inlets to the lake, two are recipients for chemically treated sewage (Löfgren, 1987). Chemical treatment of waste water was introduced in the late 1970s, which reduced the external P load to L. Finjasjön by approximately 90% (Forsberg & Ryding, 1985) and water from the sewage treatment plant in Hässleholm (chemical precipitation of P) is discharged into the southern basin of the lake (Fig. 1). In 1988–1990, the external P loading to the lake amounted to 6.2, 4.8 and 4.4 tons y^{-1}, respectively, whereas the net internal P loading reached 5.7, 4.1 and 6.9 tons y^{-1}, respectively (Löfgren, 1991).

Despite efforts to restore the lake by partial sediment removal, large algal biomasses, mainly *Microcystis* sp., reappear every summer, and chlorophyll *a* in the epilimnion commonly reaches 150 μg Chl a l^{-1}. Due to its shallowness and large surface area, the lake seldom stratifies for longer periods, and earlier studies (Löfgren, 1987) even found stratifications with a duration of a few hours. Hence, the hypolimnion is usually oxic. However, temperature data from 1988 (Hässleholm sampling program) reveal 2 distinct stratifications between June and September with a duration of 1 and 5 weeks. Oxygen levels in the
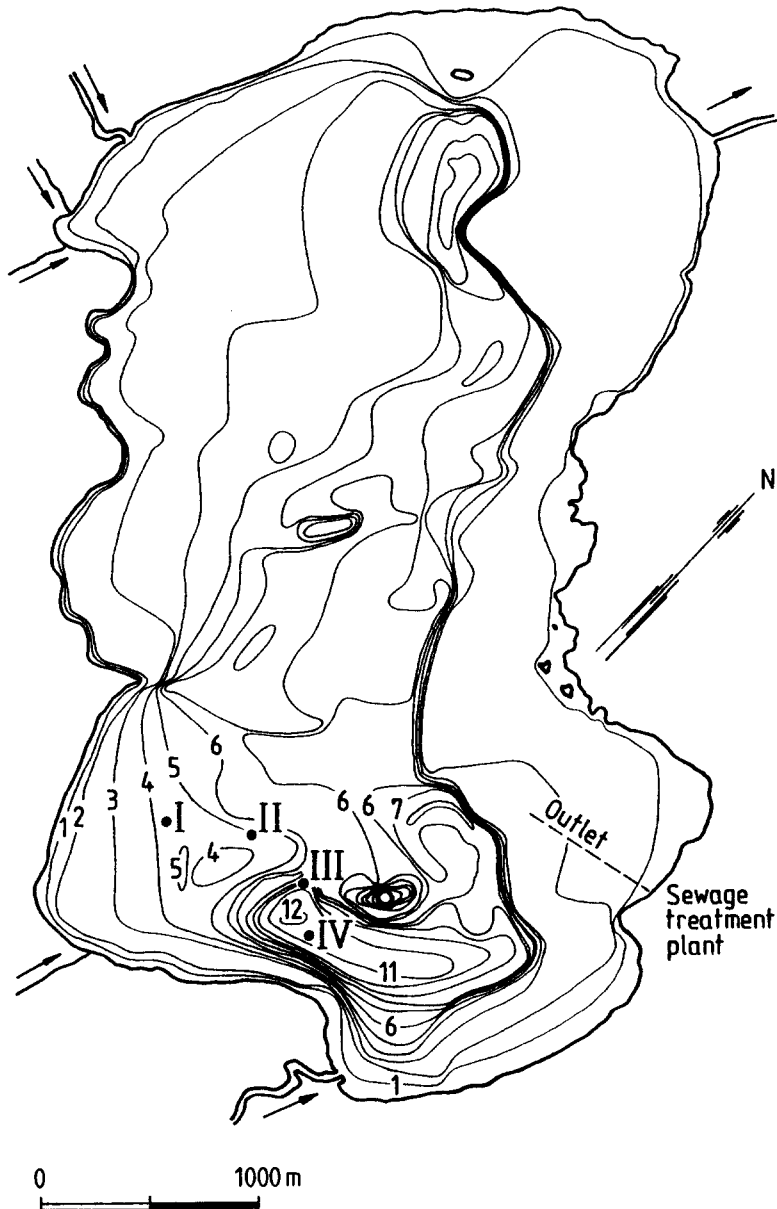
L. FINJASJÖN

Fig. 1. Location of sampling sites I–IV in L. Finjasjön.

bottom water reached 0.1 mg O_2 l^{-1} during the longest period. At the breakdown of the stratification, total phosphorus and total iron concentrations in the epilimnion rapidly increased from *ca.* 0.07 to 0.34 mg TP l^{-1} and from *ca.* 0.28 to 0.90 mg TFe l^{-1}, respectively (Hässleholm data). In 1989, 4 stratifications lasting between 1 and 5 weeks were recorded between May and September. Consequently, TP and TFe concentrations varied in accordance with this (Fig. 2). Regarding 1990, hypolimnetic water data are not available for the whole summer, which is why the duration of stratifications is unknown.
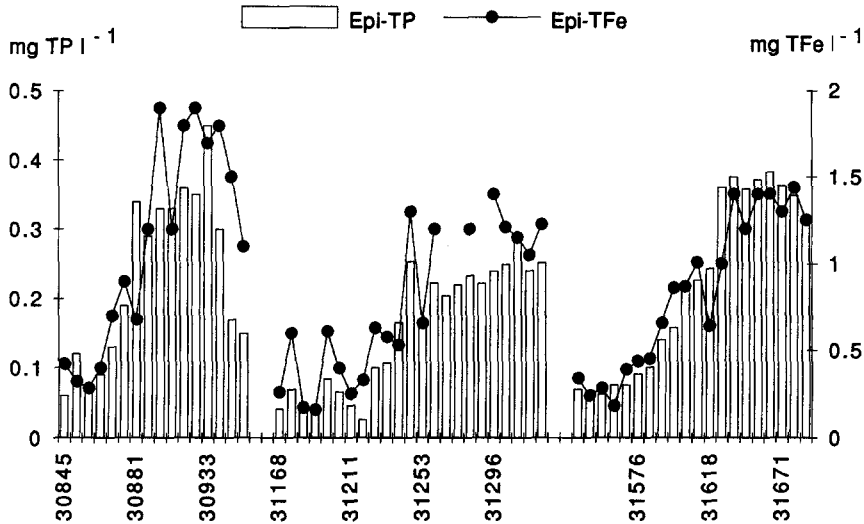
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Fig. 2. Total phosphorus (TP) and total iron (TFe) (mg l^{-1}) in L. Finjasjön epilimnetic water, 1988–1990. Data supplied by Hässleholm municipality.

Field sampling and analyses

The four sampling sites chosen in this study were located at depths of 3–12 m in the southern basin (Fig. 1). Intact sediment was collected with a core sampler on 5 different occasions; in late summer (September '89/August '90) when sediment temperatures were high, in November following the fall overturn and settling of algae, in March following the winter period with low water temperature, and finally in early May, following the spring overturn and settling of the spring bloom. The sediment was transported to the laboratory and stored overnight at approximately *in situ* temperature after which the upper 0–2 cm layers were taken out and used for phosphorus fractionations and determination of bacterial abundance and production. Further, sediment samples were prefrozen, freeze-dried and analysed for water content, chlorophyll *a*, C, P and Fe. For pore water analysis, duplicate sediment cores were incubated in the laboratory with segmented channels which were filled with distilled water and covered with a dialysis membrane, modified after Löfgren & Ryding (1985a). The cores were incubated in the dark for 5 days at approximately *in situ* temperature, after which the dialysates were taken out with a micropipette. 0.1 ml of the sample was

preserved in 4.9 ml 0.07 M HNO$_3$, whereafter total-Fe(II) was analysed by atomic absorption spectrophotometry (Shimadzu, AA-670; A$_{248}$). Further, 0.1 ml of the dialysate was diluted to 10 ml with distilled water and SRP was analyzed spectrophotometrically (A$_{882}$) as molybdate-reactive P (Murphy & Riley, 1968).

General sediment analyses were made on freeze-dried (Edwards, minifast 680) sediment. After acid oxidative digestion with a mixture of 1/4 conc. H$_2$SO$_4$ + 1/5 conc. HNO$_3$ + 1/20 HClO$_4$ and 1/2 distilled water, sedimentary TP were filtered and analysed spectrophotometrically (A$_{882}$) as molybdate-reactive P (Murphy & Riley, 1968). TFe was analysed by atomic absorption spectrophotometry (A$_{248}$) after oxidative acid digestion with 7 M HNO$_3$ according to Swedish Standard (SS 02 81 84). Sedimentary total carbon (TC) was analysed using a Carlo Erba Elemental Analyzer (Mod. 1106). The fractional composition of phosphorus (triplicate samples from one core) was determined by wet sediment sequential extraction, modified after Hieltjes & Lijklema (1980). 1 M NH$_4$Cl (pH 7), 0.1 M NaOH and 0.5 M HCl were used in the extraction procedure. Sedimentary chlorophyll *a* (triplicate samples from one core) was extracted from freeze-dried sediment with 96% ethanol and

analysed spectrophotometrically at A_{750} and A_{665}. The method is modified after Hansson (1988). Bacterial abundances were determined from autofluorescence counting with epifluorescence microscopy, according to Boström et al. (1989). Formaldehyde-preserved (4%) sediment samples were diluted and filtered with 0.01% acridineorange on prestained (Sudanblack) 0.2 μm membrane filters. Bacterial production rates in surface sediments (triplicate samples from one core) were calculated from uptake of [^{3}H]-thymidine, after Bell & Ahlgren (1987). Incorporated [^{3}H]-thymidine was extracted in three steps; 1) hydrolysis with NaOH + sodium dodecyl sulphate (SDS) + EDTA, 2) precipitation with cold HCl + trichloroacetic acid (TCA), 3) hydrolysis with TCA. The samples were finally analysed on a liquid scintillation counter (LKB Wallace).

Data analyses

Relationships between pore water SRP, Fe(II) and various parameters were evaluated by single and multiple regression analyses on a StatView program (for MacIntosh). The number of observations (n) is given in Table 1.

Results

Water chemistry

Epilimnetic TP and TFe during 1988–1990 are shown in Figure 2 (data from Hässleholm sampling program). As expected, TP and TFe concentrations were correlated in the lake ($R^2 = 0.81$ and 0.76, in the hypolimnion and epilimnion, respectively). Phosphorus reached about the same level in 1988 and 1990, whereas in 1989, the concentrations were somewhat lower (Fig. 2). In addition, Fig. 3 illustrates SRP in the hypolimnion on sites I–IV. In accordance with epilimnetic data, much higher concentrations were found in the hypolimnion in late summer 1990, than in 1989.

Carbon, phosphorus and iron in surficial sediments

Generally, the sediment contained large amounts of organic material, which was reflected in the

Table 1. Characteristics of L. Finjasjön surficial sediment (0–2 cm), sites I–IV. Mean values and standard deviation (SD). P-fractionation, Chla and bacterial production are means from triplicate samples. Pore water data are means from duplicate cores.

	Site			
	I Mean ± SD	II[a] Mean ± SD	III Mean ± SD	IV Mean ± SD
Water depth (m)	3.5	4.5	7.0	11.5
Water content (%)	93.6 ± 2.0[b]	93.7 ± 1.9[c]	95.1 ± 1.4[b]	95.7 ± 1.9[b]
Total phosphorus (TP) (mg g^{-1} DW)	2.1 ± 0.3[c]	2.6 ± 0.4[d]	3.9 ± 1.0[c]	3.9 ± 0.8[c]
NH_4Cl-RP (% of TP)[d]	1.7	1.4	2.0	2.2
NaOH-RP (% of TP)[d]	51.6	52.4	55.8	48.6
HCl-RP (% of TP)[d]	26.8	21.9	20.2	13.9
Res-P (% of TP)[d]	16.9	24.1	21.8	35.1
Total iron (TFe) (mg g^{-1} DW)	69 ± 144[c]	59 ± 8[d]	61 ± 3[c]	76 ± 1[c]
Total carbon (TC) (mg g^{-1} DW)	115 ± 2[c]	102 ± 1[d]	125 ± 2[c]	132 ± 17[c]
SRP (mg l^{-1})	2.0 ± 1.8[e]	1.2 ± 0.7[f]	2.4 ± 1.8[e]	2.9 ± 2.9[e]
Fe(II) (mg l^{-1})	8 ± 7.3[e]	20.1 ± 4.1[f]	21.6 ± 7.7[e]	45.9 ± 28.3[e]
Chla (μg g^{-1} DW)	186 ± 32[g]	191 ± 44[g]	281 ± 20[h]	400 ± 104[h]
Bacterial abundance (10^{10} cells g^{-1} DW)	8.4 ± 1.3[c]	10.2 ± 4.5[d]	11.8 ± 4.7[c]	15.6 ± 4.7[c]
Bacterial production (μg C g^{-1} DW hr^{-1})	3.0 ± 3.5[g]	0.3 ± 0.2[i]	1.3 ± 0.4[h]	2.1 ± 2.4[h]

[a] Site II not included in August 1990, [b] $n = 5$, [c] $n = 4$, [d] $n = 3$, [e] $n = 32$, [f] $n = 24$, [g] $n = 12$, [h] $n = 15$, [i] $n = 9$.

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mg SRP l^{-1}

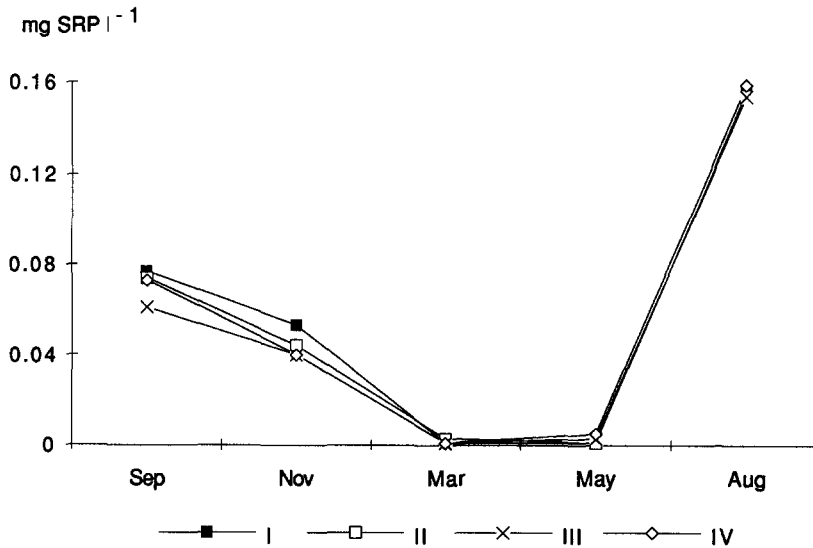*Fig. 3.* SRP in hypolimnetic water (mg l^{-1}) on sites I–IV, September 1989–August 1990.

water content of the surficial layer (*ca.* 94–96%). The thickness of the organic, nutrient-rich sediment layer increased with increasing water depth and varied between *ca.* 0.3 and 1.5 m. TC varied between *ca.* 100 and 150 mg C g^{-1} DW (dry weight), as illustrated in Table 1. In addition, an increase with water depth was found during fall sedimentation 1989 ($R^2 = 0.85$, $p < 0.1$). Total phosphorus in the surficial sediment varied sea-

sonally and a general increase towards deeper areas was found ($R^2 = 0.76$, $p < 0.2$). The concentrations ranged from 2.0 to 4.2 mg TP g^{-1} DW (Table 1). The fractional composition of phosphorus in the top 2 cm sediment was analysed in November 1989. As expected, iron + aluminium-bound phosphorus (NaOH-RP) constituted the main sediment fraction, *ca.* 50–60% of TP (Table 1). The amount of calcium-bound phosphorus

Table 2. Results from single and multiple regression analyses[a], expressed as R^2.

Analysis	Site							
	I		II[b]		III		IV	
	R^2	p	R^2	p	R^2	p	R^2	p
P_w-SRP:Temp[c]	0.95	<0.05	0.86	<0.5	0.90	<0.06	0.82	<0.5
P_w-Fe(II):Temp[d]	0.37	<0.1	0.75	<0.1	0.13	<0.6	0.68	<0.1
P_w-SRP:Sed-TC[d]	0.12	<0.7	0.78	<0.4	0.15	<0.7	0.62	<0.3
P_w-Fe(II):Sed-TC[d]	0.62	<0.3	0.96	<0.2	0.42	<0.4	0.65	<0.2
Bact. prod:Sed-TP[c]	0.95	<0.2	–	–	0.90	<0.2	0.95	<0.2
Bact. prod:Sed-TC[d]	0.95	<0.03	0.31	<0.7	0.92	<0.05	0.62	<0.3

[a] n-values are given in Table 1.

[b] Site II not included in August 1990.

[c] Multiple regression analyses (polynomial) performed with pore water SRP vs temperature, and bacterial production vs sedimentary TP, respectively. Adjusted R^2-value.

[d] Single regression analyses performed with pore water iron(II), pore water SRP and bacterial production rates vs temperature and sedimentary TC, respectively.

(HCl-RP) varied between *ca.* 15 and 30% of TP and decreased with water depth. The loosely adsorbed phosphorus fraction (NH4Cl-RP), reflecting the recently settled algal material, and the residual-P fraction (Res-P) both increased towards deeper sites ($R^2 = 0.85$ and 0.96, $p < 0.1$ and 0.05, respectively) and constituted between 1.4–2.2% and 17–35% of TP, respectively (Table 1). Further, L. Finjasjön sediment is characterized by its high iron content and concentrations between 50 and 90 mg TFe g^{-1} DW were measured in the surficial sediment (Table 1). However, iron was not correlated with water depth and did not show a particular co-variation with the sedimentation events. Compared to the concentrations on other sites between May and August 1990, a drastic TFe increase on site I, from 66 to 90 mg TFe g^{-1} DW, is somewhat unexpected and the cause of this anomaly is unknown.
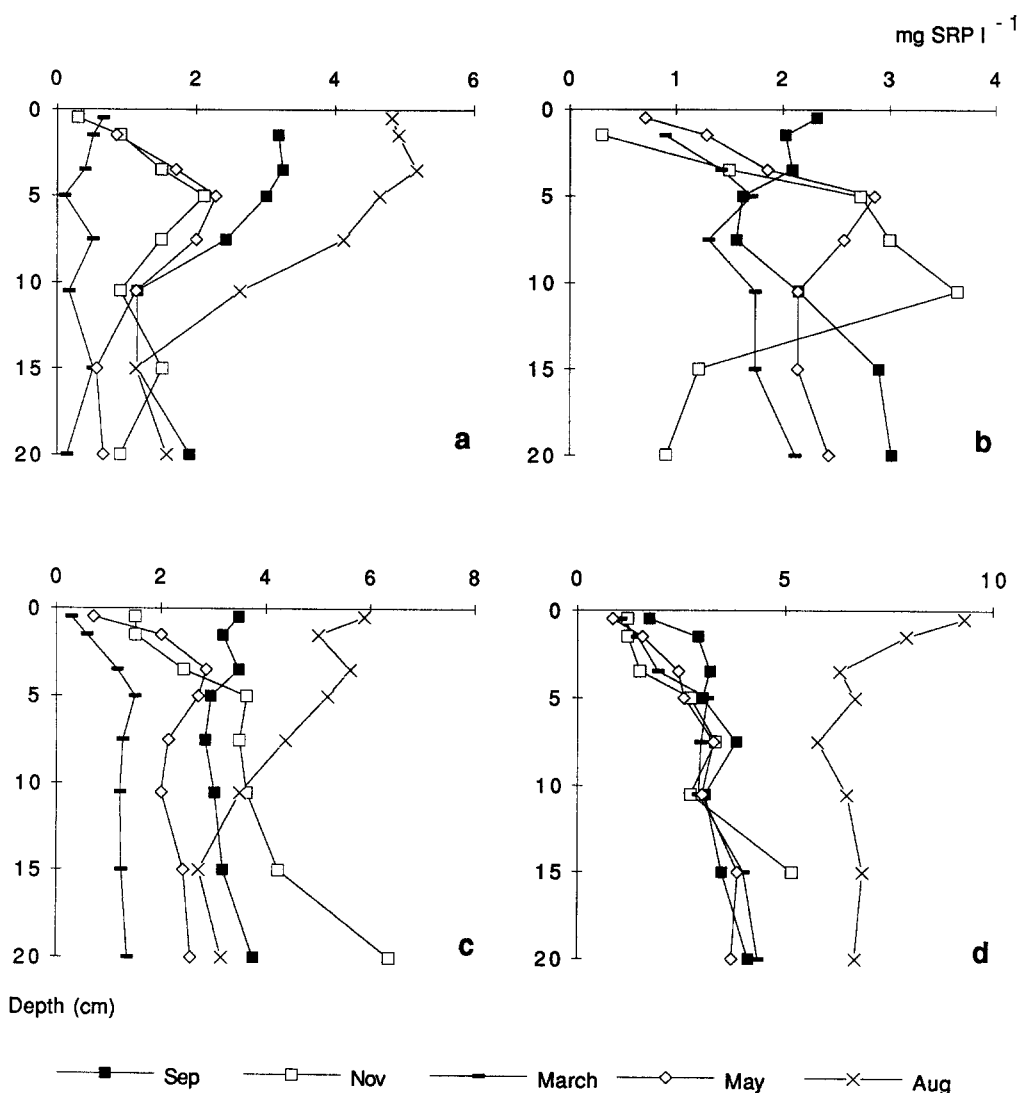

Fig. 4. 4a–d illustrate pore water SRP (mg l^{-1}) on sites I–IV, respectively. September 1989–August 1990. Mean values from duplicate cores, 0–20 cm sediment profile. Note different scales on X-axes.

Phosphate and iron (II) in pore water

Peak SRP concentrations were commonly found in surficial sediments, and varied between *ca.* 0.3 and 9.0 mg l^{-1} (means; 0–2 cm, Table 1). Generally, SRP increased with water depth (Fig. 4) and showed a temperature correlated variation on all sites ($R^2 = 0.82$–0.95, Table 2). A drastic change in the pore water was registered in 1990 when the concentrations in the 0–2 cm layer increased by 400–700% from May to August

(Fig. 4). Elevated SRP-concentrations were measured even at a sediment depth of 20–25 cm.

Further, pore water concentrations of iron(II) showed a seasonal variation, a general increase with water depth and were correlated with TC on all sites ($R^2 = 0.42$–0.96, Table 2). The concentrations (means; 0–2 cm) varied between *ca.* 20–300 mg Fe(II) l^{-1} and the peak value was found in sediments at site IV (Fig. 5). Further, iron(II) concentrations in the surface layer at site IV increased by nearly 375% from May to August
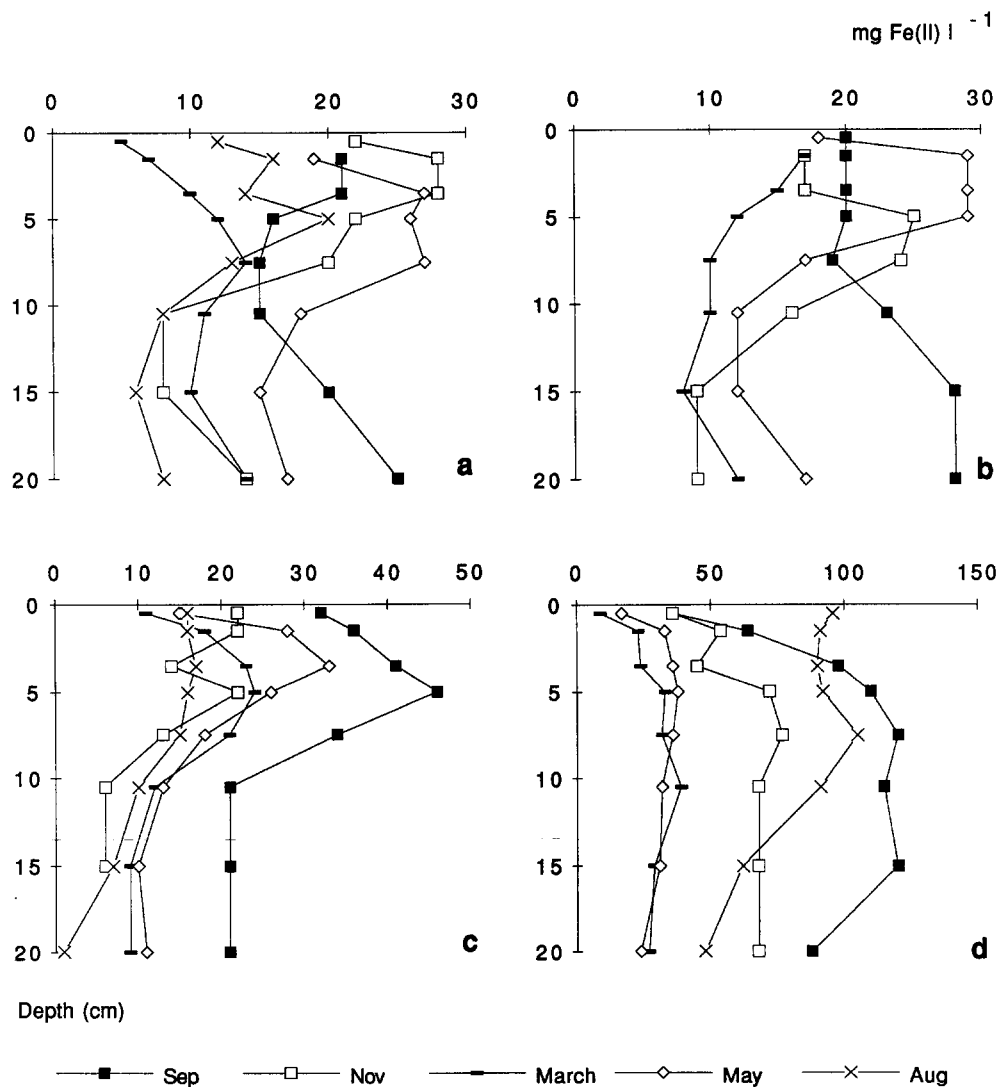
mg Fe(II) l^{-1}

Depth (cm)

——■—— Sep ——□—— Nov ——■—— March ——◇—— May ——✕—— Aug

Fig. 5. 5a–d illustrate pore water Fe(II) (mg l^{-1}) on sites I-IV, respectively. September 1989–August 1990. Mean values from duplicate cores, 0–20 cm sediment profile. Note different scales on X-axes.
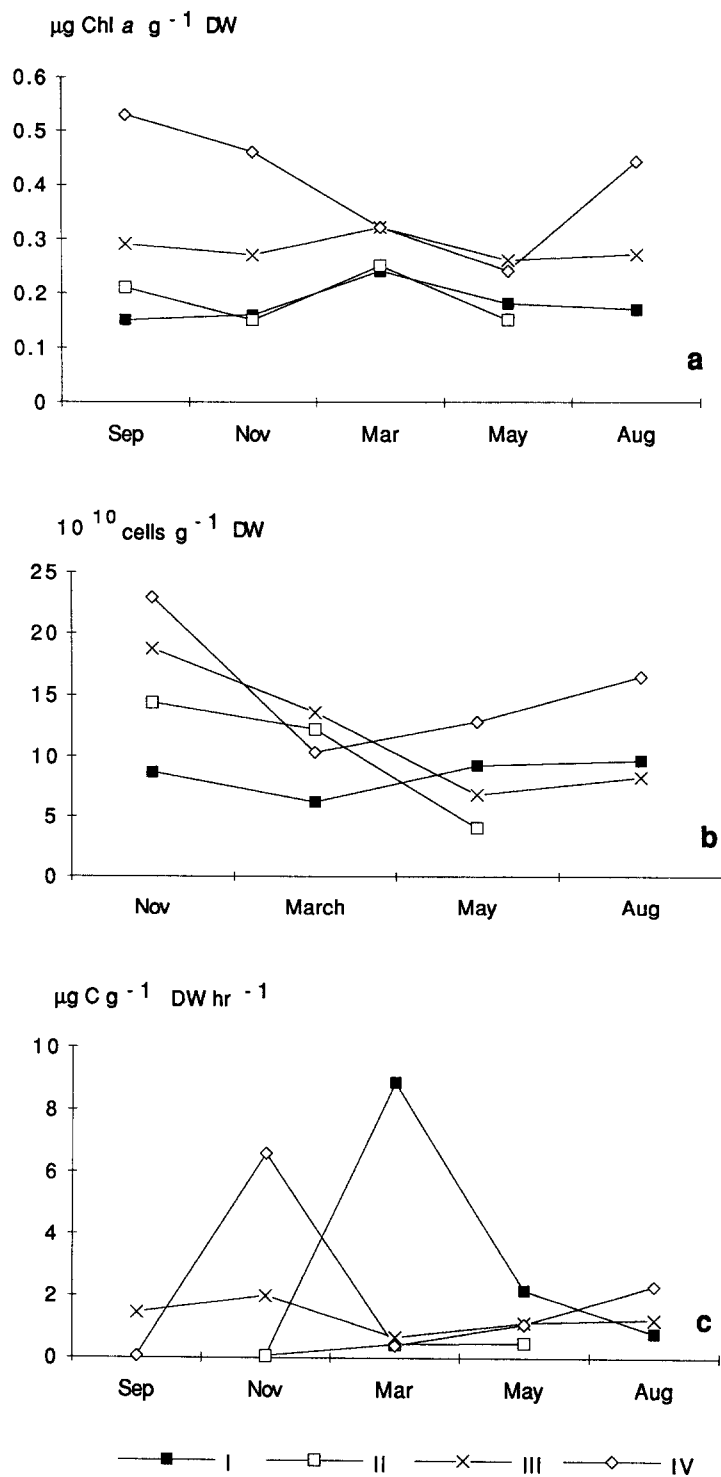
μg Chl *a* g⁻¹ DW

a

10¹⁰ cells g⁻¹ DW

b

μg C g⁻¹ DW hr⁻¹

c

■— I   □— II   ×— III   ◇— IV

Fig. 6. Chlorophyll *a* (μg g^{-1} DW, 6a), bacterial abundances (10^{10} cells g^{-1} DW, 6b) and production rates (μg C g^{-1} DW y^{-1} hr, 6c) in L. Finjasjön surficial sediment (0–2 cm), sites I–IV.

1990 concurrent with the SRP increase. Hence, the iron(II) variation was correlated with pore water SRP and temperature ($R^2 = 0.85$ and 0.78, respectively).

Chlorophyll a *and bacteria in surficial sediments*

Peak chlorophyll a concentrations in the 0–2 cm layer coincided with, or soon followed, high algal biomasses in the water. The concentrations varied between 0.15 and 0.53 mg Chl$a$ g^{-1} DW (Fig. 6a, Table 1) and generally increased with water depth ($R^2 = 0.66$, $p < 0.001$). Further, bacterial abundances ranged from 4×10^{10} to 23×10^{10} cells g^{-1} DW (Fig. 6b) and were correlated to sediment chlorophyll$a$ during fall sedimentation ($R^2 = 0.98$, $p < 0.05$). In addition, a seasonal variation and an increase with water depth ($R^2 = 0.86$, $p < 0.1$) were registered. Bacterial production in the 0–2 cm layer varied between sites, from 0.05 to 9 μg C g^{-1} DW hr^{-1} (Table 1) and increased during spring and fall sedimentation (Fig. 6c). The production rates were correlated with TP and TC on all sites ($R^2 = 0.90$–0.95 and $R^2 = 0.31$–0.95, respectively, Table 2), indicating a coupling to algal sedimentation. A significant correlation with sediment Chl$a$ was accordingly found on the shallow site I ($R^2 = 0.997$, $p < 0.005$). Further, the maximum production rate (9 μg C g^{-1} DW hr^{-1}) was found on site IV in November 1989, concurrent with the fall sedimentation and peak bacterial abundances on this site (Fig. 6).

Discussion

Earlier studies have focused on the P retention capacity of L. Finjasjön sediments (Pettersson, 1984; Löfgren & Ryding, 1985b; Löfgren, 1987). Due to the high iron content, Fe(III) and P interactions have been known to dominate the sediment-water flux of P. In conclusion, previous investigations of the phosphorus retention capacity in L. Finjasjön sediments suggest a strong correlation to temperature, pH and redox conditions.

These findings indicate that bacterial activities in surface sediments may have a crucial impact on the P/Fe dynamics during summer and significantly contribute to the observed release. To our knowledge, bacterial abundances and production rates in L. Finjasjön have yet been analysed neither in the field nor in laboratory experiments.

Pore water dynamics

Pore water SRP and Fe(II) showed a clear seasonal variation and a temperature correlated increase was found regarding SRP ($R^2 = 0.82$–0.95, Table 2). As expected, maximum concentrations were found in late summer both years, and minimum concentrations after the winter, in March 1990 (Figs 4–5). These seasonal variations are in accordance with previous studies of other lakes (e.g. Holdren & Armstrong, 1986). A rapid increase in pore water SRP was measured on sites I–III prior to a rise on site IV in spring 1990 (Fig. 4). The high bacterial production rates and bacterial abundances at the time suggest that bacteria in shallow sediments rapidly responded to the temperature increase (6–12.5 °C) and to the input of algal material during the settling spring bloom (Fig. 6). This is further supported by the concurrent Fe(II) increase that co-varied with the SRP profiles in the top 5 cm of sediment (Figs 4–5). Although P and Fe levels in the pore water increased, the P/Fe molar ratios actually decreased. This indicates that some P may have been incorporated into bacterial biomass and/or released into the bottom water. The concurrent TP increase in the epilimnion indicates a P contribution from shallow areas.

Maximum P/Fe molar ratios in the surface pore water (0.18–0.63) were measured on sites I–III in September 1989 and August 1990. The sediment on site IV, however, differs considerably from the shallower locations. Thus, due to a much more reduced environment (the sediment is black, smells of H_2S and methane gas frequently generates bubbles in the cores in summer), iron(II) levels are substantially higher on this site and the P/Fe molar ratios are consequently lower. Max-

imum ratios were measured in March and August, 1990 (0.14 and 0.17, respectively). These results support the other data and illustrate the impact of water depth to the pore water composition. The elevated P and Fe concentrations in site IV indicate that phosphate mineral formation might occur, such as vivianite [$Fe_3(PO_4)_2 * 8H_2O$], and that Fe(II) bound to e.g. carbonates might be dissolved (Holdren & Armstrong, 1986; Enell & Löfgren, 1988). Previous investigations (Löfgren & Ryding, 1985a) have suggested that apatite [$Ca_5(PO_4)_3(OH)$] may be important in regulating P concentrations in anaerobic sediment layers. According to Löfgren & Boström (1989), earlier studies have shown a P/Fe molar ratio of ca. 0.06–0.2 in the Fe(III)/hydroxide-P complex at pH = 7, which is the approximate sediment-pH in L. Finjasjön (measured in November and March). Hence, the shallow areas in the lake may be incapable of retaining P in the sediment in late summer due to the high P/Fe molar ratios (0.18–0.63), whereas the deepest sites appear to have low enough ratios all year round (0.05–0.17).

Further, the SRP increase by 400–700% (0–2 cm layer) over the summer of 1990 occurred during a temperature increase of 12.5° to 19.5 °C. The results can be compared to the results of Kamp-Nielsen (1975) who found that an increase in temperature by 5 °C would lead to an increase in the P release by 100% or more, at temperatures above 15 °C. Kamp-Nielsen (op. cit.) ascribed this to a breakdown of the oxidized microlayer on the sediment surface. Søndergaard et al. (1990) presented similar results in the temperature range of 14–18 °C for L. Søbygaard, Denmark and concluded that the temperature-dependent release might be explained by microbial and benthic activity. Thus, the coupled P and Fe increase in L. Finjasjön in summer (Fig. 2), indicates the formation of anoxic microlayers on the sediment surface. A pH dependent release is less probable, due to the simultaneous increase in TP and TFe. A high pH may induce a phosphorus release, but it does not enhance the solubility of iron (Löfgren, 1987). Further, the pH in the water mass may not affect the sediment pH, especially during periods of high microbial activity, as demonstrated by Revsbech et al. (1983). Thus, elevated pH levels cannot explain the TFe increase in the lake during summer.

Implication of anoxic microlayers for P and Fe release

According to Jørgensen & Revsbech (1985), the potential for bacterial oxygen respiration may increase by 300–800% between 5–25 °C. Bacterial mineralization of organic matter increases the ion concentrations in the pore water and a simultaneous reduction of Fe(III) may occur (Lovley & Phillips, 1986). Lovley and Phillips (op. cit.) found the most intense Fe(III) reduction occurring in the top 0.5 cm sediment, and the reduction was limited to the top 4 cm or less. This is in accordance with the Fe(II) profiles in L. Finjasjön, where peak concentrations frequently were found in the top 5 cm of sediment (Fig. 5). In addition, the correlation between iron(II) and organic carbon (TC) on all sites ($R^2 = 0.42$–0.96, Table 2), strongly indicates that Fe(III) reduction was coupled to mineralizing bacteria, as proposed by Lovley & Phillips (op. cit.). However, iron can only be released to the overlying water when anoxic conditions develop at the sediment surface (Löfgren, 1987). The diffusion of Fe(II) through the diffusive boundary layer (DBL) is an oxygen consuming process which partially may explain the development of anoxic microlayers, and it is likely that the chemical oxidation of iron(II) to iron(III) can compete with the biological uptake of oxygen in this layer (Löfgren, 1987). The joint effect of biological respiration and chemical oxidation processes in summer lowers the likelihood of P adsorption at the sediment surface and favours a substantial P release. However, rapid shifts between oxidized and reduced conditions might occur in shallow lakes. Hence, low bacterial production rates were found in September 1989 and August 1990 at maximum SRP levels in the surface pore water (Figs 4, 6c). The profiles indicate a shift from oxidized to reduced conditions, as well as a collapse and sedimentation of

a dense phytoplankton bloom (Enell & Löfgren, 1988). The high Chl*a* values in the sediment at the time support this theory (Fig. 6a). Similar results were also documented by Löfgren & Boström (1989) in the eutrophic L. Vallentunasjön, where high SRP concentrations were found in the pore water despite a decrease in bacterial respiration. However, temporal and spatial variations in bacterial activity may be expected, and the limited number of observations during summer 1990 does not permit any firm conclusions.

Regulation of internal loading

The redox-coupled release of P and Fe in L. Finjasjön is apparent, as illustrated in Fig. 2. In 1990, P in the epilimnion increased from 0.07 to 0.36 mg TP 1^{-1} over a 4-months' period, meaning that the P pool in the lake increased by *ca.* 12 tons. Porewater concentrations revealed a similar pattern. In shallow areas, the SRP increase in the 0–2 cm layer corresponds to *ca.* 0.7 mg SRP m^{-2} day^{-1}, whereas the increase in deeper areas amounted to *ca.* 1.2 mg SRP m^{-2} day^{-1}. The TP increase in the epilimnion, however, corresponds to an estimated flux of 104 mg P m^{-2} day^{-1} (mean; 4-months' period) meaning that also deeper sediment layers must be involved in the release. The results are comparable with the findings of Boström (1984) and Löfgren (1987) who estimated the net release rates in L. Finjasjön at 63 and 91 mg P m^{-2} day^{-1} from laboratory and field data, respectively. Further, the TFe increase in epilimnetic water amounted to 37 tons during the same period. The pore water Fe(II) increase on site IV (0–2 cm layer) was *ca.* 11.5 mg Fe(II) m^{-2} day^{-1}, as compared to the TFe increase in the epilimnion, corresponding to 3093 mg TFe m^{-2} day^{-1}. Thus, to explain the increasing TFe concentrations in the water, considerable amounts of Fe(II) must be released from deeper sediment layers.

The calculated net internal P loading was nearly 2.8 tons, or 70%, higher in 1990, than in 1989 (Löfgren, 1991) and may be related to pore water SRP concentrations which were *ca.* 60–80%

higher in the late summer of 1990 (Fig. 4). The results strongly indicate that yearly variations in pore water concentrations are regulating the internal loading in L. Finjasjön.

Conclusion

In conclusion, the results indicate that the phosphorus and iron increase in L. Finjasjön surficial pore water in summer is mainly governed by the activities of sediment bacteria. Further, spatial and seasonal variations in the lake are influenced by temperature, water depth and wind mixing. Thus, the aerobic P and Fe release will likely continue, although year-to-year shifts in the internal loading may be expected.

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