

**THE REDUCTION OF PHOSPHORUS, IRON AND
CHLOROPHYLL A CONCENTRATIONS FOLLOWING CaCO_3
AND $\text{Ca}(\text{OH})_2$ ADDITIONS TO HYPEREUTROPHIC
FIGURE EIGHT LAKE**

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NWRI Contribution No. 89-15

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April 1989

Management Perspective

The Lakes Research Branch and The University of Alberta have collaborated to rehabilitate eutrophic Figure Eight Lake, Alberta. The object of the research was to develop a cost-effective replacement for copper sulphate use in lakes. Lime treatment of hardwater lakes to enhance water quality, costs approximately \$1,500 a hectare. At this site, treatments are required every two years.

As with many prairie lakes, nutrient sources are mostly natural and uncontrollable. Although undeveloped crown land surrounds Figure Eight, the phosphorus concentration in the inlet water can exceed 1.0 mg/L. The high influx of phosphorus produced dense algal blooms resulting in fish kills.

Previously, managers had used copper sulphate to suppress algal growth but the algae quickly recovered. Chronic copper toxicity restricted the fishery. The Alberta Ministry of Environment now bans the use of copper sulphate in Alberta lakes.

Lime (calcium carbonate or calcium hydroxide) was applied to the surface of the lake a total of four times during the summers of 1986 and 1987. The algal biomass decreased to 2-59% of pretreatment values. During 1987, the phosphorus concentrations were much lower and the water clarity was much greater than observed in the five earlier years. The oxygen consumption rates under the ice were 59% of pretreatment rates. The increase in winter oxygen resulted in fish surviving the winter. For the first time in years, Gammarus, an important food for trout, were common. Fishing was excellent in 1988.

Perspective-gestion

La Direction de la recherche sur les lacs et l'Université de l'Alberta ont collaboré dans le but de remettre en état le lac eutrophe Figure Eight en Alberta. L'étude visait à mettre au point un produit de remplacement rentable du sulfate de cuivre pour la réhabilitation des lacs. Le traitement des lacs alcalins à la chaux pour accroître la qualité de l'eau coûte environ 1 500 \$ l'hectare. Au site étudié, les traitements sont nécessaires tous les deux ans.

Comme pour de nombreux lacs des Prairies, les sources d'éléments nutritifs sont essentiellement naturelles, donc incontrôlables. Bien que ce sont des terres de la Couronne n'ayant pas fait l'objet de développement qui entourent le lac Figure Eight, la teneur en phosphore dans l'eau de l'inlet peut dépasser 1,0 mg/L. L'apport important de phosphore produit de denses proliférations algales entraînant des mortalités de poissons.

Auparavant, les gestionnaires avaient utilisé le sulfate de cuivre pour empêcher la croissance algale, mais les algues réapparaissaient rapidement. L'intoxication chronique au cuivre limitait la pêche. Le ministère albertain de l'Environnement interdit à l'heure actuelle l'utilisation de sulfate de cuivre dans les lacs de l'Alberta.

De la chaux (sous forme de carbonate de calcium ou d'hydroxyde de calcium) a été appliquée à la surface du lac quatre fois au total au cours des étés 1986 et 1987. La biomasse algale a diminué pour atteindre une valeur se situant entre 2 à 59 % des valeurs avant le traitement. Au cours de l'année 1987, les teneurs en phosphore étaient beaucoup plus faibles et la limpidité de l'eau beaucoup plus grande que ce qui avait été observé au cours des cinq années précédentes. La consommation d'oxygène sous la glace était de 59 % de ce qu'elle était avant le traitement. À cause de l'augmentation d'oxygène en hiver les poissons ont survécu. Pour la première fois depuis bien des années, les Gammarus, aliment important pour la truite, étaient nombreux. La pêche a été excellente en 1988.

Résumé

De la chaux (CaCO_3 ou Ca(OH)_2) a été ajoutée au total quatre fois au lac Figure Eight en Alberta au cours des étés de 1986 et 1987. Au cours de la période de 14 jours suivant le traitement, les teneurs en chlorophylle a (Chl_a) variaient de 2 à 59 % et les teneurs en fer total (FeT) variaient de 68 à 74 % par rapport aux valeurs avant le traitement (c.-à-d. des échantillons prélevés jusqu'à 24 heures avant le traitement). Les teneurs en Chl_a et FeT sont revenues aux valeurs qu'elles avaient avant le traitement, respectivement au bout de 35 et de 21 jours après le traitement. Bien que les niveaux d'oxygène dissous étaient très faibles à l'automne et au cours du premier hiver suivant les traitements à la chaux, les niveaux de phosphore total (PT) sous la glace étaient beaucoup plus faibles que ceux avant le traitement. Au cours de l'été de 1987, les teneurs en PT et Chl_a ainsi que la limpidité de l'eau se sont améliorées par rapport à ce qu'elles étaient au cours des cinq étés précédents. L'hiver suivant, la consommation d'oxygène dissous était de 59 % de la valeur avant le traitement. Le traitement à la chaux pourrait donc permettre d'accroître la qualité de l'eau dans des lacs alcalins eutrophes. Ce traitement semble supprimer les éléments nutritifs limitant la croissance des algues, n'est pas nocif pour les invertébrés ou les vertébrés et est relativement peu coûteux.

Abstract

Lime (CaCO_3 or Ca(OH)_2) was added a total of four times to Figure Eight Lake, Alberta, in the summers of 1986 and 1987. Within 14 d of treatment, chlorophyll *a* concentrations (Chl*a*) ranged from 2 to 59%, and total iron concentrations (TFe) ranged from 68 to 74%, of pre-treatment values (i.e., samples collected up to 24 h prior to treatment). Chl*a* and TFe returned to pre-treatment levels within 35 and 21 d, respectively, of treatment. Although dissolved oxygen levels were very low in the autumn and first winter following lime treatments, under-ice total phosphorus (TP) levels were much lower than those before treatment. During the summer of 1987, TP, Chl*a* and water clarity improved relative to the other five summers on record. The following winter, dissolved oxygen depletion rates were 59% of pre-treatment rates. Lime treatments could provide a new direction for enhancing water quality in eutrophic hard water lakes. The process appears to suppress growth-limiting nutrients for algae; it does not harm invertebrates or vertebrates, and is relatively inexpensive.

Introduction

Phosphorus (P) controls algal biomass and production in most freshwater lakes (30). For many eutrophic lakes, reductions in algal biomass have been achieved by decreasing the external P load (9, 10). External inputs cannot be controlled, however, when the major external source is from P-rich soils and rocks, such as in much of western Canada (22, 28). In western Canada, unsightly algal blooms and associated problems, such as unpleasant odour and winterkill, are common. Low-cost non-toxic approaches to control algal biomass and production are needed for these naturally eutrophic systems.

Calcite precipitation is a natural phenomenon which occurs during the summer in hardwater lakes (35). This process reduces algal production by coprecipitation of phosphorus and calcium from the surface waters (1, 11, 17, 21, 23). Lime additions (CaCO_3 and Ca(OH)_2) can reduce P levels in water by the same principle (14, 29, 33). While both CaCO_3 and Ca(OH)_2 have been used for over 40 years to reduce colour (16 used $\text{Ca(OH)}_2 \cdot \text{MgO}$) and more recently to buffer acidified lakes (4), only recently has lime been used in the treatment of eutrophic surface waters.

waters. In a two-year study on a small British Columbia lake, four relatively low doses of $\text{Ca}(\text{OH})_2$ reduced available P and algal biomass (22). These data, however, are insufficient to evaluate long-term effects.

In this study, a small hypereutrophic lake in northwestern Alberta was treated with lime (both CaCO_3 and $\text{Ca}(\text{OH})_2$), and the water biogeochemistry was followed intensely over a two-year period.

The Study Lake

Figure Eight Lake is a small (36.8 ha), shallow (mean depth 3.1 m) lake situated in P-rich glacial till (long. $56^\circ 18'$, lat. $117^\circ 54'$) 48 km northwest of Peace River, Alberta. The drainage basin is small (4.7 km^2) and covered with aspen-popular forest with 8% cleared for pasture. Surface runoff is limited to one stream which flows only for a brief period in April; lake water residence time is > 4 yr. The lake has three basins: the largest and deepest (maximum depth 6 m) south basin contains 70.5% of the lake water; the other two basins have maximum depths of 5 and 3.5 m and contain 24.3 and 5.2% of the lake water. It is stocked annually with rainbow trout (*Salmo gairdneri*).

From 1980 through to 1984, the lake was treated a total of four times with copper sulfate (average dosage $36 \mu\text{g}\cdot\text{L}^{-1} \text{ Cu}$), resulting in reduced algal biomass for variable periods. There were some residual effects from the last CuSO_4 treatment on chlorophyll levels in evidence until October 1985 (26). Treatment of eutrophic lakes with CuSO_4 has since been discontinued in Alberta.

Materials and Methods

The lake was sampled at intervals from one day to two months from 05 June 1985 to 27 March 1988. Secchi disk data had been collected sporadically in 1980, 1983 and 1984. Two types of information were collected from the lake: 1) vertical profiles of biogeochemical properties (Table I) were constructed from discrete samples collected over the deepest part of the two deepest basins; and 2) integrated water samples for P and Chl_a analysis and phytoplankton identification were collected to a depth of 3 m (i.e., the epilimnion) from five representative stations on the lake

with weighted tygon tubing during the open-water period; on each date all integrated samples were pooled. Unless otherwise indicated, all values were calculated from discrete samples, integrated over the top 3 m and volume-weighted over the two basins; average summer values ($X \pm 1$ SE) represent the period 01 June to 31 August. Since an estimate of all Ca in solution was required, Ca data were volume-weighted over the entire water column, rather than just the epilimnion. Under-ice Ca concentrations ([Ca]) were corrected for freezeout; it was assumed that all Ca was frozen out of black ice and the winter volume-weighted [Ca] includes the water equivalent of the black ice cover. Winter oxygen depletion rates were calculated as outlined in 2.

The inflowing stream was sampled during runoff (08 April through 07 May 1986) with an ISCO automatic sampler set to collect 500 mL every 12 h; water samples were treated as outlined for lakewater samples. Flow was measured with a Price model #622 current meter.

On 16 July 1985, 15 and 16 July 1986, and 23 July 1987, aquatic macrophytes were harvested from six representative sites in the south basin. At each site, all above-sediment tissues were collected from within three quadrants of 0.25 m² each, from depths of 1 and 2 m (i.e., maximum depth of macrophyte colonization). Plants were thoroughly rinsed, separated according to species (with the exception of fine-leaved Potamogeton spp.), spin-dried and fresh-weighed. Results are presented as $X \pm 1$ SE for the six sites.

Lime was added a total of four times to Figure Eight Lake during the summers of 1986 and 1987 (Table II). It was applied as a slurry, evenly over the lake surface in proportion to water depth. In 1986 it was applied by pumping lake water from a 7.62-cm outlet pump into a wooden hopper with baffles mounted on a small barge (4.8- x 3.3-m deck) powered by a 9.9 hp outboard motor; bagged lime was poured into the hopper where it mixed with the lake water, then flowed into the lake. In 1987 the procedure was modified: the barge was larger (7.3 x 3.7-m deck); lime and lake water were mixed in a slurry box in the centre of the barge; the slurry was pumped forward and distributed through two 2.4-m long booms, one located on each side of the bow.

Results

Pre-treatment Conditions

Figure Eight Lake is a hardwater lake. In 1986, average summer conductivity was $215 \pm 3 \mu\text{S}\cdot\text{cm}^{-1}$; the dominant ions were HCO_3/CO_3 and Ca. From June through to August 1986, alkalinity averaged $111 \pm 2 \text{ mg}\cdot\text{L}^{-1} \text{ CaCO}_3$, Mg $10 \pm 0.05 \text{ mg}\cdot\text{L}^{-1}$, Na $2 \pm 0.02 \text{ mg}\cdot\text{L}^{-1}$, K $9 \pm 0.07 \text{ mg}\cdot\text{L}^{-1}$, Cl $1 \pm 0.08 \text{ mg}\cdot\text{L}^{-1}$, SO_4 $14 \pm 0.2 \text{ mg}\cdot\text{L}^{-1}$, and Ca $28 \pm 0.3 \text{ mg}\cdot\text{L}^{-1}$.

During the brief period when surface runoff flowed into the lake (64% of the total annual surface inflow entered over 4 d in early April 1986), TP and TFe concentrations ([TP], [TFe]) in the inflow exceeded $600 \mu\text{g}\cdot\text{L}^{-1}$.

During the summer, Figure Eight Lake is weakly thermally stratified; dissolved oxygen concentrations over the bottom sediments frequently reach $0 \text{ mg}\cdot\text{L}^{-1}$. When the water column is thermally stratified, [TP] and [TFe] build up over the bottom sediments, on occasion exceeding $1900 \mu\text{g}\cdot\text{L}^{-1}$. In the years prior to lime treatment (i.e. 1985 to mid-June 1986), [TP] and [TFe] in the epilimnion exceeded $200 \mu\text{g}\cdot\text{L}^{-1}$ (Figures 1 and 2). Phytoplankton biomass and [POC] also reached extreme values, exceeding $150 \mu\text{g}\cdot\text{L}^{-1} \text{ Chl}_a$ and $7 \text{ mg}\cdot\text{L}^{-1}$ [POC] in the epilimnion (Figure 3). The pH rose to 9.9 during the algal bloom in June 1986 (Figure 1). In the absence of treatment, water transparency was generally poor, with Secchi disk readings averaging 1 m (Figure 4). Although the water was colored ($X = 28 \pm 2 \text{ mg}\cdot\text{L}^{-1} \text{ Pt}$ summer 1986), it was not turbid ($X = 5 \pm 0.7 \text{ NTU}$, same time period); poor transparency was primarily due to algal blooms, dominated (>95% by weight) by the blue-green algae, Aphanizomenon flos-aquae.

The extreme summer algal productivity in Figure Eight Lake frequently caused winterkill of stocked rainbow trout. From 26 October (date of ice formation) through 18 December 1985 (when average dissolved oxygen levels for the whole-lake reached $2.2 \text{ mg}\cdot\text{L}^{-1}$; Figure 5) average whole-lake oxygen depletion rates were $0.611 \pm 0.036 \text{ g O}_2\cdot\text{m}^{-2}\cdot\text{d}^{-1}$. These rates are not significantly different ($P > 0.05$) from the under-ice oxygen depletion rate of $0.624 \text{ g O}_2\cdot\text{m}^{-2}\cdot\text{d}^{-1}$, predicted from average summer [TP] in the trophogenic zone and from lake depth (eq. 4, 2).

Effects of Lime Treatments

After the first treatment with CaCO_3 , $[\text{Chl}a]$ and $[\text{POC}]$ decreased dramatically (Figure 3). Within two weeks, $[\text{Chl}a]$ had dropped to 2% pretreatment values in both the euphotic zone and epilimnion, and $[\text{POC}]$ had dropped to 7% pretreatment concentrations in the epilimnion. Within five weeks, $[\text{POC}]$ and $[\text{Chl}a]$ returned to pretreatment levels. The second and third treatments were with low dosages of $\text{Ca}(\text{OH})_2$ (Table II) and occurred 10 d apart to ensure that the pH of the lakewater was not unduly elevated. After each treatment, $[\text{Chl}a]$ decreased briefly but quickly returned to pretreatment levels.

By the summer of 1987, $[\text{Chl}a]$ had decreased from $96 \pm 14 \mu\text{g/L}$ (average, summer 1986) to $12 \pm 7 \mu\text{g}\cdot\text{L}^{-1}$ (t-test, $P < 0.01$). Before the lake was treated with lime in July 1987, $[\text{Chl}a]$ was less than 10% of the pre-treatment 1986 level. In 1987, the decrease in $[\text{Chl}a]$ and $[\text{POC}]$ after CaCO_3 treatment was less than in 1986, however the pattern was similar, with a sharp, but short-term, decrease 10 d after the treatment (Figure 3). After the 1987 treatment, the dominant algae changed from blue-green to green (small flagellates) and diatoms (*Synedra* sp.) for the remainder of the summer. Much improved water clarity in 1987 (Figure 4) coincided with reduced $[\text{Chl}a]$.

$[\text{SO}_4]$ and $[\text{TN}]$ responded to the reduced algal productivity in 1987. For the June through to August period, SO_4 increased (t-test, $P < 0.01$) from 14 ± 0.2 in 1986 to $24 \pm 0.6 \text{ mg}\cdot\text{L}^{-1}$ in 1987, likely as a result of reduced pyrite formation in the bottom sediments (20). $[\text{TN}]$ dropped substantially (t-test, $P < 0.01$) over the same period, from 2782 ± 197 to $1021 \pm 167 \mu\text{g}\cdot\text{L}^{-1}$, likely as a consequence of reduced nitrogen fixation (25), enhanced sedimentation, and reduced sediment release.

After the CaCO_3 treatments (Table II), alkalinity in the epilimnion increased an average of $12 \text{ mg}\cdot\text{L}^{-1} \text{CaCO}_3$ within 10 to 14 d, then declined to pretreatment levels (Figure 1). In contrast, within 1 week of each of the two applications of $\text{Ca}(\text{OH})_2$, alkalinity decreased an average of $6 \text{ mg}\cdot\text{L}^{-1}$. With the lime treatments, inorganic carbon increased in Figure Eight Lake; the average summer values for alkalinity in 1985, 1986 and 1987 were 91 ± 5 , 111 ± 2 , and $122 \pm 5 \text{ mg}\cdot\text{L}^{-1}$

CaCO_3 , respectively. Following the CaCO_3 treatment, the decrease in pH was less in 1987 than in 1986 (1986 in Figure 1). These pH decreases reflect the lower Chl_a levels and the decay of algae which followed the treatments. In contrast, after the Ca(OH)_2 treatments, pH in the epilimnion increased from 9.0 to 9.5 and 9.5 to 9.7 after treatments two and three, respectively (Figure 1).

[Ca] did not change immediately after the initial treatment, and there were no detectable differences between filtered and unfiltered [Ca]. Rather, [Ca] increased slowly over the fall and winter of 1986-87 and remained elevated through to March 1988 (Figure 2). Average summer [Ca] in 1986 was $28.4 \text{ mg}\cdot\text{L}^{-1}$ and increased to $33.4 \text{ mg}\cdot\text{L}^{-1}$ by 22 October 1986 and to $39.6 \text{ mg}\cdot\text{L}^{-1}$ by March 1987. [Ca] remained significantly higher than 1986 throughout the summer of 1987, averaging $36.6 \pm 0.6 \text{ mg}\cdot\text{L}^{-1}$ (t-test, $P < 0.01$). The highest whole-lake value recorded was for October 1987, when [Ca] reached $40.7 \text{ mg}\cdot\text{L}^{-1}$. Under ice-cover during 1987-88, [Ca] ranged from 37.2 to $38.8 \text{ mg}\cdot\text{L}^{-1}$. The latter was recorded in March 1988.

There was no clear pattern in changes in [TP] following the four treatments. After two treatments, epilimnetic [TP] increased in the short term; observed thermal mixing redistributed TP from the deeper waters into the epilimnion (Figures 1 and 2). Once [Ca] increased, however, [TP] decreased dramatically. Although dissolved oxygen levels were lower under ice in 1986-87 than 1985-86, [TP] was half that of previous winter values; volume-weighted whole-lake averages were 143 and $281 \text{ }\mu\text{g}\cdot\text{L}^{-1}$ TP in March 1987 and February 1986, respectively. The under-ice differences at a depth of 1 m below the ice surface were even more spectacular, 60 as compared with $200 \text{ }\mu\text{g}\cdot\text{L}^{-1}$ TP, respectively, for the dates indicated. By the summer of 1987, average [TP] was significantly lower than 1986 (246 ± 14 versus $75 \pm 8 \text{ }\mu\text{g}\cdot\text{L}^{-1}$ TP, t-test, $P < 0.01$).

[TFe] dropped within 5 to 14 d after each of the four lime treatments to values which ranged from 68 to 74% of pre-treatment values, then returned to pre-treatment levels within 16 to 21 d of treatment (Figure 2). [TFe] in the summer of 1987 was slightly lower than in 1986, 205 ± 21 and $146 \pm 16 \text{ }\mu\text{g}\cdot\text{L}^{-1}$ TFe, respectively. However, these differences are not significant ($P > 0.05$).

Under-ice oxygen concentrations did not respond initially to the lime treatments. The fall of 1986 was unusually warm, then winter came suddenly and the lake became ice covered while dissolved oxygen levels were at 45% saturation. An aerator installed in the lake was turned on soon after ice-on in 1986. The aerator was off for sufficient time (14 to 17 November 1986) to calculate a rough estimate of winter oxygen depletion rates, $0.54 \text{ g O}_2 \cdot \text{m}^{-2} \cdot \text{d}^{-1}$; this rate is slightly lower than for the same period one year earlier. The aerator was turned off 22 January 1987 when the lake became anoxic. In the fall of 1987, the lake became ice covered while oxygen saturation was close to 100%. Under-ice oxygen depletion rates in 1987-88 appeared to respond immediately to changes in summer algal biomass (Figure 5). The aerator was not turned on until 30 December 1987. Under-ice oxygen depletion rates from 30 November to 29 December 1987 were $0.363 \pm 0.018 \text{ g O}_2 \cdot \text{m}^{-2} \cdot \text{d}^{-1}$ or 59% of, and statistically less (t -test, $P < 0.01$) than, pretreatment rates.

Although average light transparency increased in Figure Eight Lake from 1985 through 1987, macrophyte biomass did not increase (Figure 4). Average macrophyte biomass dropped at the deeper (2-m depth) sites. Macrophyte species also shifted over the study period. In 1985, prior to treatment, the community was dominated by rooted aquatic plants. After treatment, a non-rooted plant, Lemna trisulca, represented 70 to 100% of macrophyte biomass at depths of 1 and 2 m.

Based on visual observations, lime treatments had no detectable negative impact on invertebrates and vertebrates in Figure Eight Lake. Amphipods returned to Figure Eight Lake in 1986 for the first time since 1980, when the lake was first treated with CuSO_4 . Stocked rainbow trout thrived in the summer of 1986, and from the summer of 1987 through to the following summer (D. Walty, unpublished data).

Discussion

The lime treatments resulted in immense improvements in water quality and clarity in Figure Eight Lake, Alberta. This is a lake with naturally high phosphorus loading, particularly from the bottom sediments (Figure 1, unpublished data), and with relatively long water residence. Algal biomass (estimated by Chl_a) was substantially reduced in the summer of 1987 relative to the

summer of 1986. This reduced algal biomass was paralleled by reduced [POC], and predictable changes in [SO₄] and [TN]. Reduced summer algal biomass in 1987 was followed by reduced oxygen consumption under the ice during the winter of 1987-88.

The short-term decreases in [Chl_a] reported for Figure Eight Lake following lime treatments were similar to those observed in Frisken Lake, British Columbia (22). Although the B.C. study also indicated short-term declines in [TP], we did not observe any consistent changes in [TP]. Short-term reductions in [TP] in Figure Eight Lake may have been masked by mixing events which incorporated deep P-rich water into the epilimnion (Figure 1). In contrast, Frisken Lake was permanently thermally stratified in summer and under these conditions, the impact of lime treatments on TP may be less equivocal.

A total of 12.4 mg·L⁻¹ of Ca was added via the lime treatments to the entire volume of Figure Eight lake in 1986, and 7.6 mg·L⁻¹ Ca was added in 1987. Over the long-term, open-water [Ca] responded to these additions. By October 1986, 40% of the added Ca was in solution, and by March 1987, 90% of the added Ca was in solution (Figure 2). In this lake, water residence time is approximately 4 yr, thus 25% of the added Ca which was still in the water column would be lost annually to the outflow. As most of the outflow takes place in spring, 22.5% or 2.8 mg·L⁻¹ of the Ca added in 1986 was lost to the outflow in the spring of 1987. Our data from 1986 in Figure Eight Lake and from other lakes and dugouts (3,18) indicate that there is no net change in openwater [Ca] the first 1-2 mo after treatment when similar levels of lime are added. Therefore, since the Ca added in 1987 did not make any immediate net change in open-water [Ca], 85% (i.e., 8.2 mg/L) of the Ca remaining from the 1986 additions was in the water column in the summer of 1987 (Figure 2). Over the winter of 1987-88, the fraction of the total Ca added in both summers and still in the water column, decreased to 65% in October 1987 and 60% in March 1988.

The observed changes in TP, Chl_a, SO₄, and Ca in Figure Eight Lake following the lime treatments are not likely due to natural year-to-year variation in these parameters. The University of Alberta and Alberta Environment have eight years (1980-1987) of continuous data on water quality parameters in seven lakes which cover the range of trophic conditions found in this region

(D.O. Trew and P.A. Mitchell, Alberta Environment and E.E. Prepas, unpublished data). In five of the seven long-term study lakes, average summer [Chl_a] was higher in 1987 than in 1986. These patterns are the opposite of what was observed in Figure Eight Lake. Also the relative differences between the 1986 and 1987 mean summer [Chl_a] and [TP] in Figure Eight Lake are much greater than the maximum differences between years in any of our long-term study lakes. In contrast, [Ca] and [SO₄] in lakes in this region, are relatively constant throughout the year. None of our long-term study lakes had changes in [Ca] and [SO₄] between 1986 and 1987 which were comparable to those in Figure Eight Lake. Thus, we believe the changes described in Figure Eight lake in 1986 and 1987 were a result of the lime treatments.

The mechanisms involved in the long-term reduction of Chl_a and TP in lime-treated lakes need further work. As calcite is known to adsorb organic matter (36), the precipitating calcite may have adsorbed algal cells. These cells could have been weakened by a shortfall of biologically available iron which is essential for photosynthesis and nitrogen-fixation by blue-green algae (15, 27). After each of the four lime additions, [TFe] dropped in Figure Eight Lake. The long-term increases in open water [Ca] were likely linked to the reduced [TP]. The impact of increased Ca in the bottom sediments is not clear (13,34). One unexpected result was that macrophyte populations did not respond significantly to the increased light penetration in Figure Eight Lake (Figure 4). Macrophyte biomass generally increases with increased light transparency (31). Possible interpretations for our results are that the increased Ca in the bottom sediments bound up some of the biologically available phosphorus in those sediments, or that enhanced calcite precipitation on the leaves blocked light.

Lime treatments hold new promise for naturally eutrophic lakes. Lime is relatively inexpensive; the delivered cost in Alberta runs between \$20 and \$100 per tonne. The treatments appear to be non-toxic to invertebrates and vertebrates; lime seems to suppress the growth-limiting nutrients for phytoplankton for an extended period. More research is required to ascertain the mechanisms involved in the short-term reduction in [Chl_a], the long-term reduction in openwater [TP], and the responses of macrophyte biomass and community structure following lime additions.

The appropriate dosage and form required for long-term improvements in water quality must be established, as well as the impact of variation in important parameters such as alkalinity and flushing rate.

Acknowledgments

We thank J. McKague, J. Ghitter, K. Sloman, T. Collette, M. Mawhinney, L. Harris, D. Sasaki, M. Serediak, and G. Hutchinson for field and analytical support. B. Maclock and J. Barica supported this project throughout.

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Funding was provided by a contract from Planning Division, Alberta Environment to E.E.P., and grants from NSERC to E.E.P. and from Bucks for Wildlife to D.T.W.

Table 1. - Parameters measured in Figure Eight Lake; information on collection and analysis, samples were treated and preserved as outlined in 12 and 24.

| <u>Parameter</u> | <u>Method</u> |
|---|---|
| temperature | 0.5 - to 1-m intervals; resistance thermometer |
| light penetration | 20-cm diameter Secchi disk |
| water samples | 0.5 - to 2-m intervals; 1.5 - L aluminum drop-sleeve water bottle |
| dissolved oxygen | <u>7</u> , within 24 h. |
| conductivity | Metrohm E587 conductometer immediately after collection |
| pH | Metrohm E588 pH meter immediately after collection |
| total alkalinity | <u>12</u> within 48 h |
| color | Hellige aqua tester model 611A within 7 d |
| turbidity | Hach turbidimeter model 2100A within 7 d |
| Cl, total Fe (TFe), SO ₄ , Na, | <u>12</u> within 1 mo |
| K, Ca (filtered and unfiltered), Mg | <u>12</u> within 1 mo |
| particulate organic carbon (POC) | <u>12</u> within 1 mo |
| NO ₂ + NO ₃ | <u>32</u> within 48 h |
| total Kjeldahl Nitrogen (TKN) | <u>8</u> within 48 h |
| total nitrogen (TN) | sum of TKN, NO ₂ + NO ₃ |
| total phosphorus (TP) | <u>28</u> within 14 d |
| total dissolved phosphorus (TDP) | <u>28</u> within 14 d |
| Chlorophyll <u>a</u> (Chl _a) | <u>5</u> and/or <u>6</u> within 1 mo |
| phytoplankton species composition | <u>19</u> |

Table 11 - Lime additions to Figure Eight Lake, 1986 and 1987. In-lake concentrations assume lime mixed with entire lake volume ($1.122 \times 10^6 \text{ m}^3$).

| Treatment number | Form | Date | Tonnes added | In lake concentration ($\text{mg}\cdot\text{L}^{-1}$) |
|------------------|--------------------------|----------------|--------------|---|
| 1 | CaCO_3 | 18 June 1986 | 15.8 | 14.0 |
| 2 | $\text{Ca}(\text{OH})_2$ | 30 July 1986 | 9.4 | 8.4 |
| 3 | $\text{Ca}(\text{OH})_2$ | 08 August 1986 | 5.4 | 4.8 |
| 4 | CaCO_3 | 14 July 1987 | 22.5 | 18.2 |

- Figure 1. Time-depth distribution of six parameters from June through August 1986 in the deepest basin of Figure Eight Lake. Arrows on top of each panel indicate dates of lime addition, solid arrows indicate CaCO_3 treatment, open arrows indicate Ca(OH)_2 treatment; those on the bottom indicate sampling dates.
- Figure. 2. Total iron and total phosphorus concentrations in the top 3m, and whole-lake volume-weighted concentrations for calcium in Figure Eight Lake, August 1985 through March 1988. Arrows as in Figure 1.
- Figure 3. Chlorophyll a and particulate organic carbon concentrations from May through August 1986 and 1987. Arrows indicate dates of lime addition, as in Figure 1.
- Figure 4. Average Secchi disk depth (with one standard error) from June through August and average macrophyte biomass at two depths from 1985 through 1987, Figure Eight Lake.
- Figure 5. Time-depth distribution of dissolved oxygen during the first two months of ice-cover in 1985 and 1987, Figure Eight Lake.

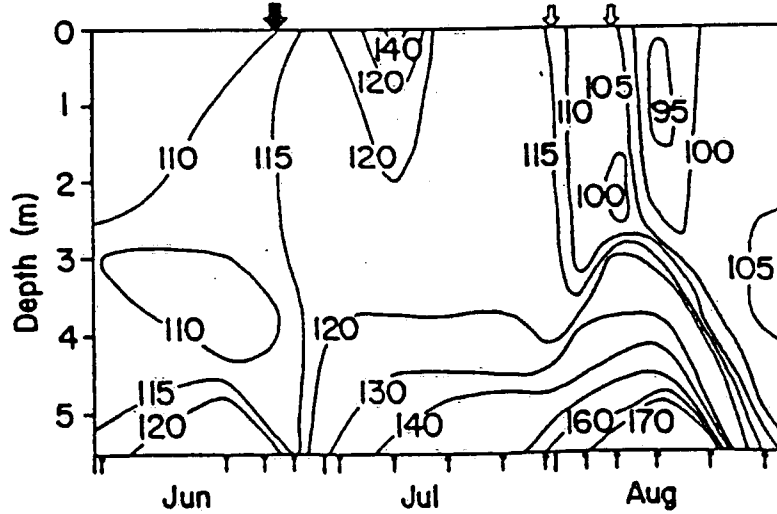
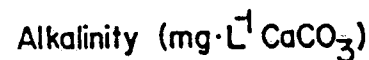
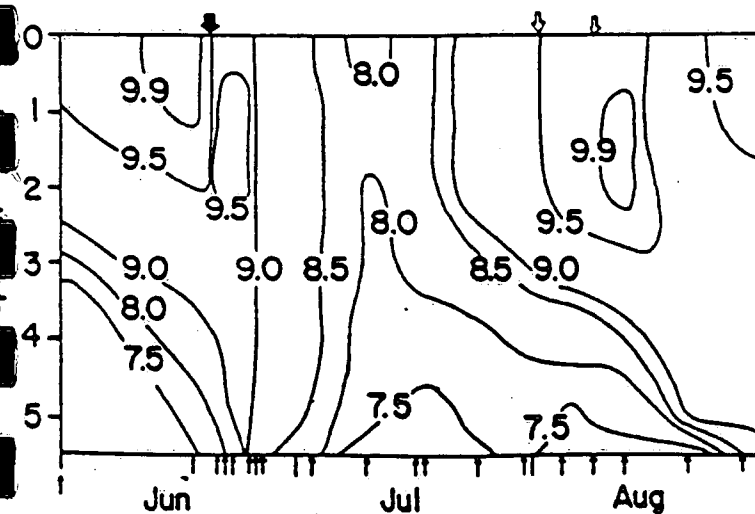
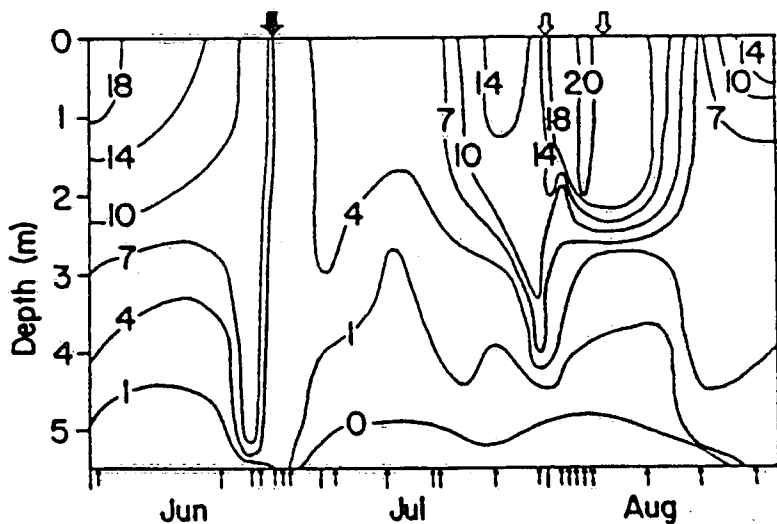
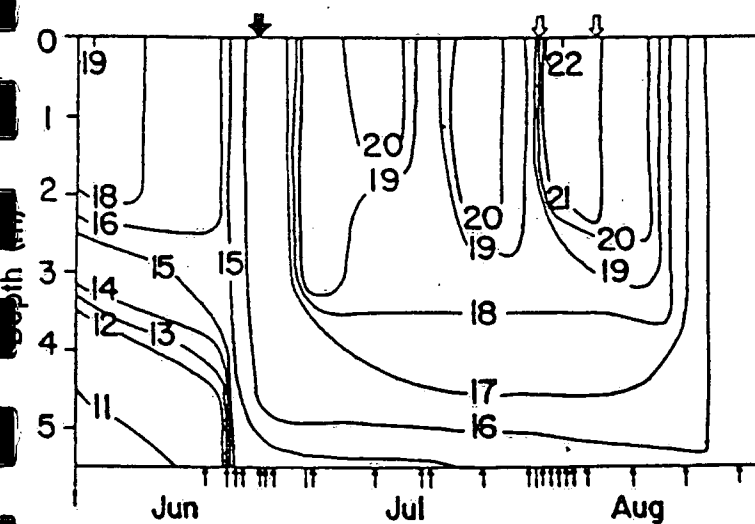
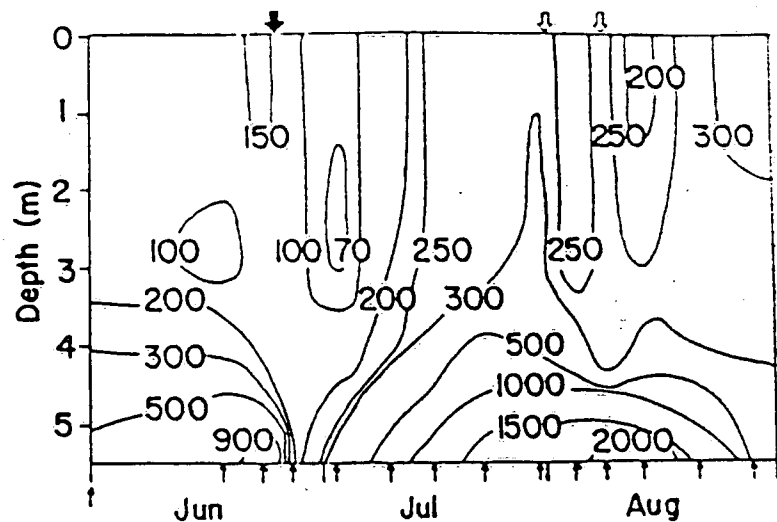
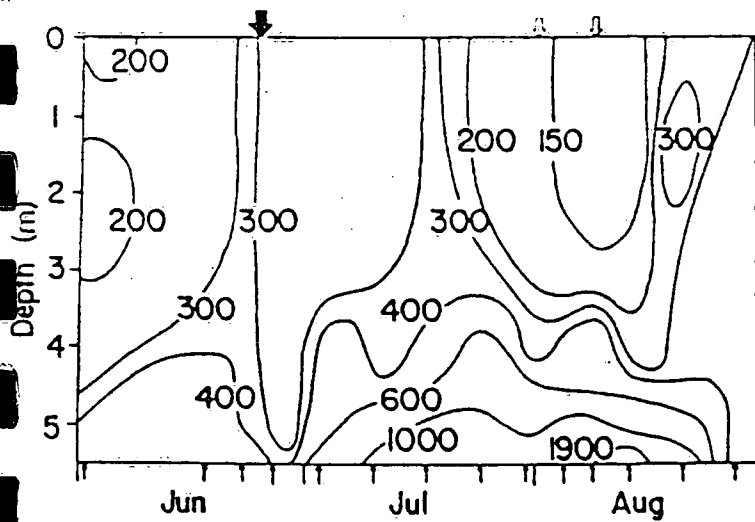


Fig 1

Fig 2

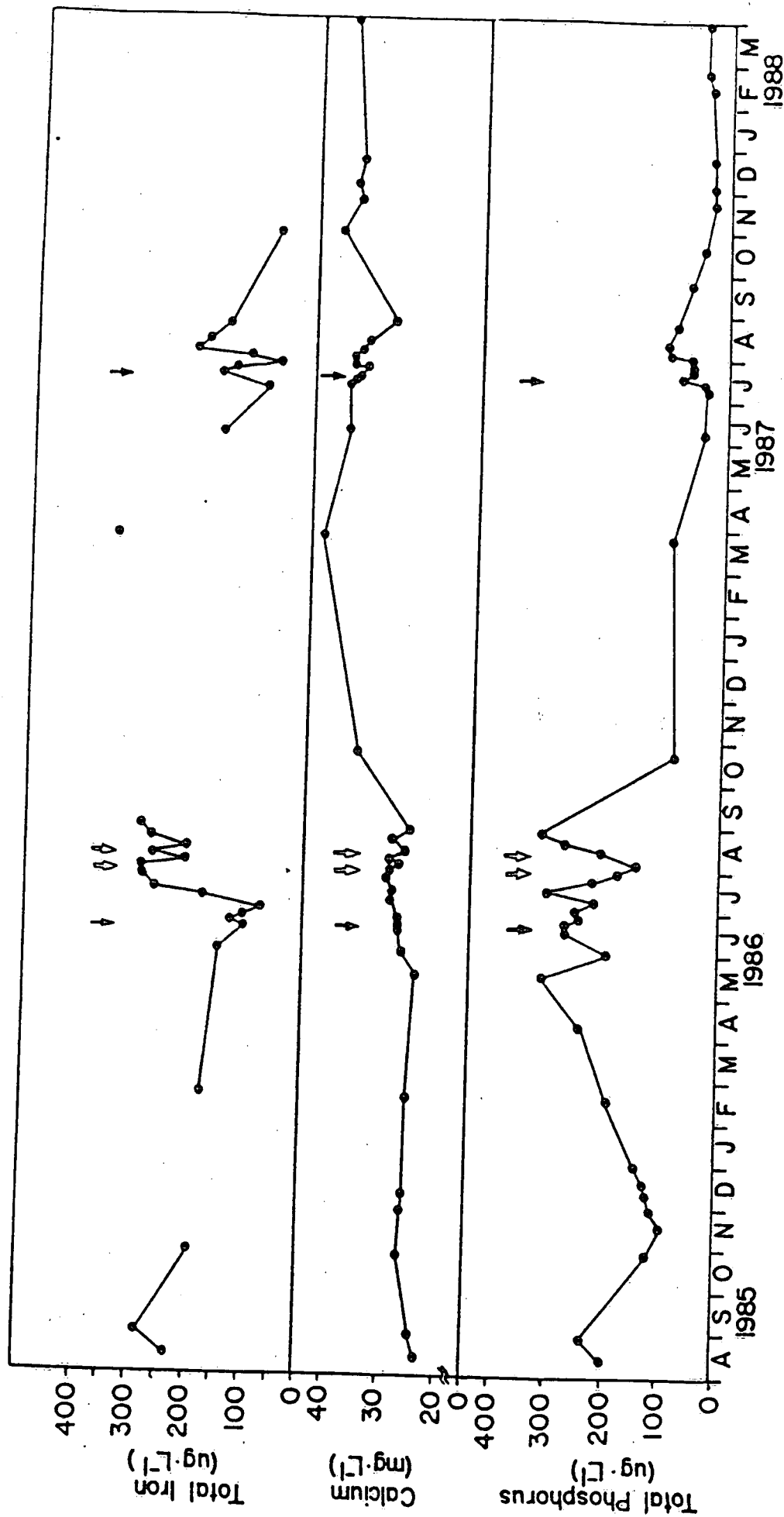
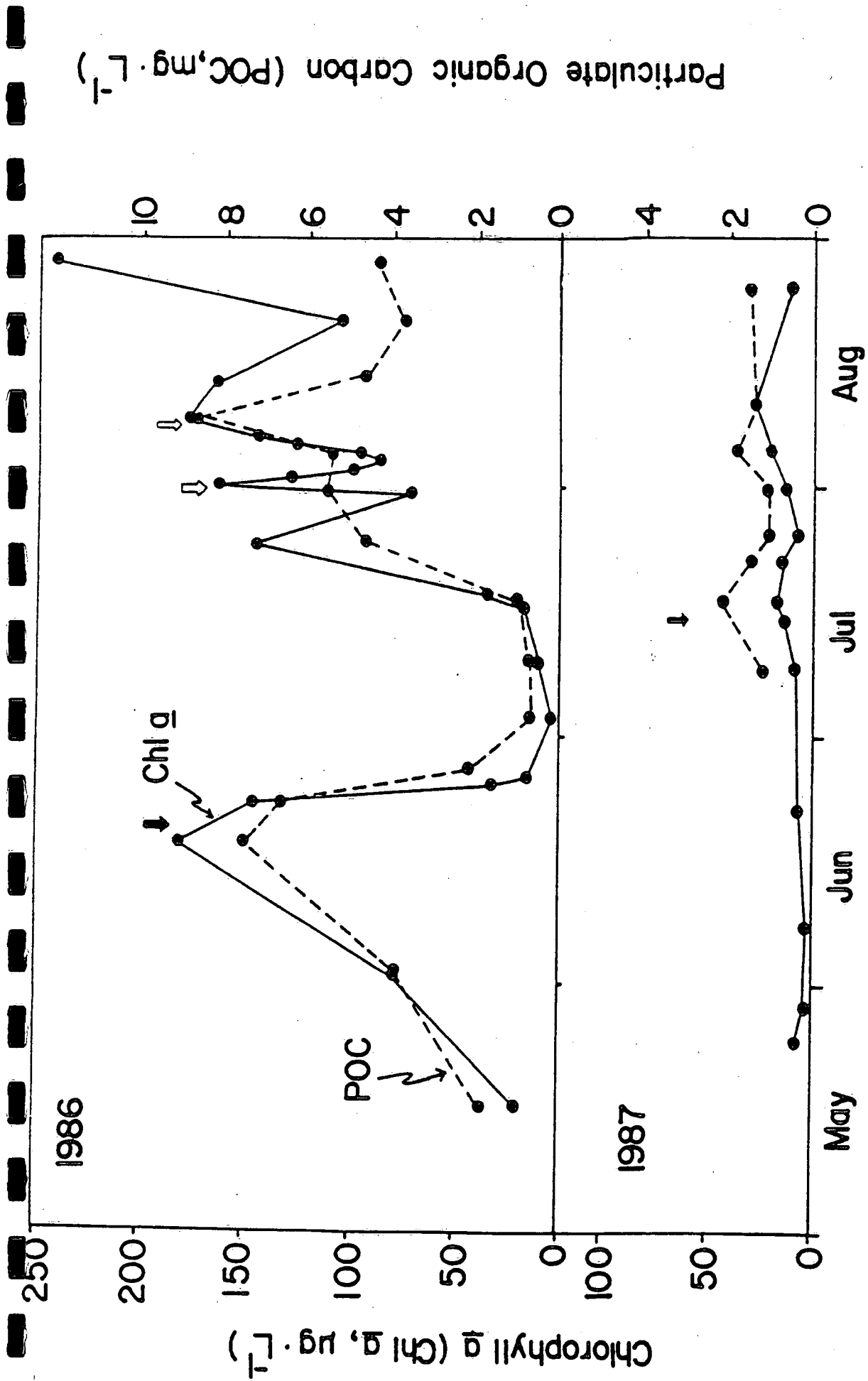


Fig 3



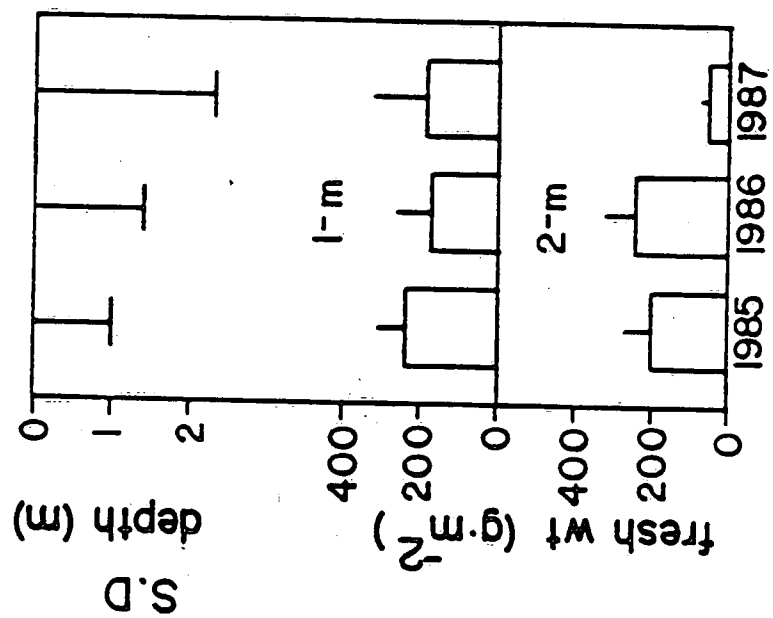
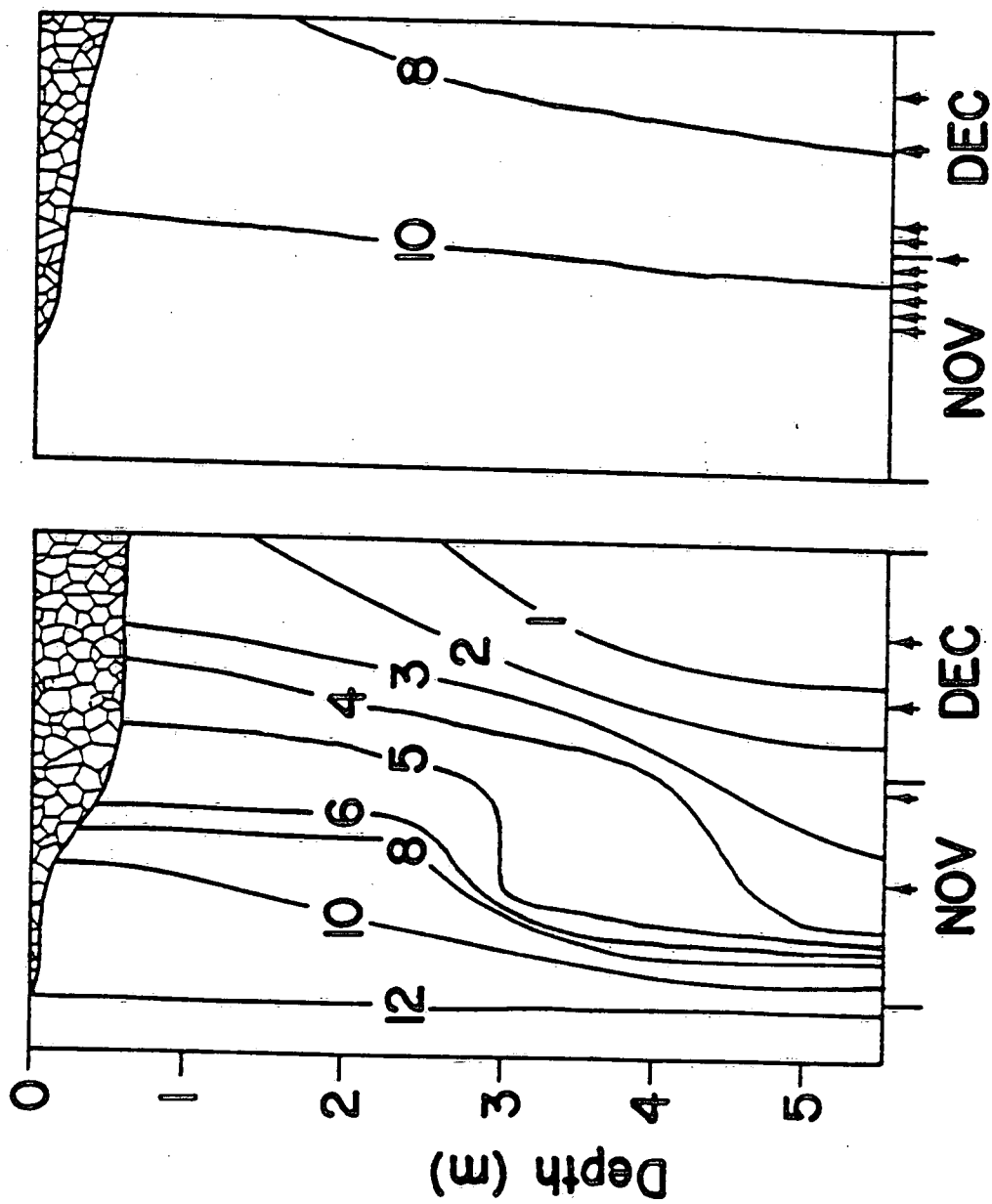


Fig 4

Dissolved oxygen ($\text{mg} \cdot \text{L}^{-1}$)



1987

1985