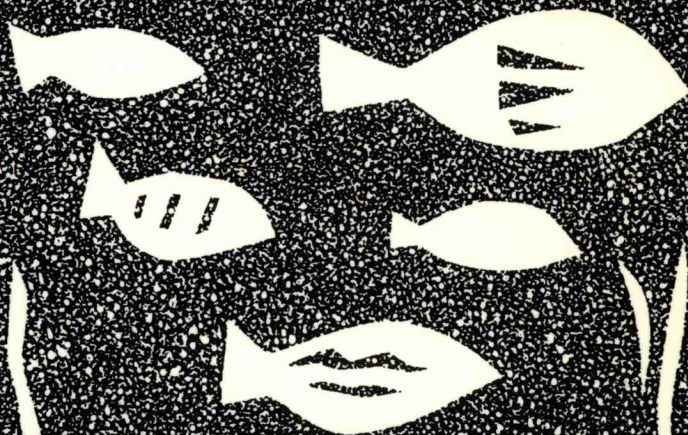
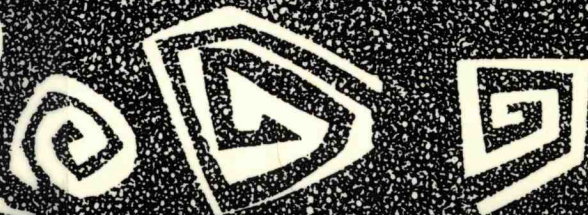


# Marine Ecosystem Enclosed Experiments

Proceedings of a symposium held  
in Beijing, People's Republic  
of China, 9-14 May 1987



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Editor: C.S. Wong and P.J. Harrison



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## Abstract

This symposium on marine ecosystem enclosed experiments (MEEE) consists of nine review papers that describe various types of ecosystem enclosures and a series of papers resulting from enclosure experiments in Xiamen, People's Republic of China, and Saanich Inlet, BC, Canada. The reviews on types of enclosures include benthic enclosures for rocky and sandy shores and the effects of pollutants (primarily hydrocarbons) on bacteria, macroalgae, and invertebrates. The pelagic enclosures were used to study the control of phytoplankton blooms, the uptake and release of dissolved organic substances, and the effects of pesticides on freshwater ecosystems.

Six enclosure experiments were conducted in China and Canada from 1986–87. Some of these experiments examined the effects of contaminated sediments, primarily heavy metals, on bacteria, phytoplankton, and zooplankton and the pathways and fates of these heavy metals in the seawater. Other experiments studied the chemistry and biological effects of chemically dispersed oil.

## Résumé

Ce compte rendu du symposium sur les expériences faites en écosystèmes marins comprend neuf communications qui décrivent les écosystèmes retenus et les expériences faites à Xiamen en République populaire de Chine et à Saanich Inlet, C.-B., au Canada. Les communications portent, notamment, sur les écosystèmes benthiques des littoraux rocheux et sablonneux et sur les effets des polluants (surtout les hydrocarbures) sur les bactéries, les grandes algues et les invertébrés. Les expériences sur le contrôle des brutales pullulations ("blooms") du phytoplancton furent menées dans les écosystèmes pélagiques, ainsi que l'absorption et le dégagement des substances organiques dissoutes et les effets des pesticides sur les écosystèmes d'eau douce.

Six expériences ont été faites en Chine et au Canada entre 1983 et 1987. Certaines ont porté sur les effets des sédiments contaminés, principalement par des métaux lourds, sur les bactéries, le phytoplancton et le zooplancton et sur le cheminement et le sort de ces métaux lourds dans l'eau salée. D'autres expériences portaient sur la chimie et les effets biologiques du pétrole dispersé chimiquement.

## Resumen

Este simposio sobre Experimentos Marinos en Ecosistemas Cerrados (MEEE) consistió en nueve trabajos de análisis que describen varios tipos de enclaustramientos ecosistémicos y una serie de trabajos derivados de experimentos con estos enclaustramientos en Xiamen, República Popular de China, y en Saanich Inlet, Canadá. Los estudios incluyen enclaustramientos bentónicos para costas rocosas y arenosas, y los efectos de los contaminantes (fundamentalmente hidrocarburos) sobre bacterias, macroalgas e invertebrados. Los enclaustramientos pelágicos se utilizaron para estudiar el control de la reproducción del fitoplancton, la ingestión y expulsión de sustancias orgánicas disueltas y los efectos de pesticidas en los ecosistemas de agua dulce.

Se realizaron seis experimentos en ecosistemas cerrados en China y Canadá, de 1983 a 1987. Algunos de estos experimentos examinaron los efectos que ejercen los sedimentos contaminados, fundamentalmente los metales pesados, sobre bacterias, fitoplancton y zooplancton, y el ciclo y destino final de estos metales pesados en el agua de mar. Otros experimentos estudiaron los efectos químicos y biológicos de los aceites crudos dispersados por medios químicos.



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# Ecological Impacts of Pollutants on Particulate Organic Carbon, Nitrogen, and Phosphorus in Marine Ecosystem Enclosed Experiments

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Shandong College of Oceanology, Qingdao,  
People's Republic of China

*Particulate organic carbon (POC), particulate organic nitrogen (PON), and particulate phosphorus (PP) were determined in the marine ecosystem enclosed experiments (MEEE) launched during the summer of 1985 at Saanich Inlet, BC, Canada. Time variations of POC, PON, and PP in the control were fairly consistent. The ratios of POC:PON and POC:PP were relatively stable at  $6.0:1 \pm 0.61$  and  $95:1 \pm 19.9$  respectively. The ratios were in good agreement with those measured in natural seawater in Saanich Inlet and in the open sea. Ratios of POC to chlorophyll a were less than 100:1. In the dark enclosure to which sediment had been added, phytoplankton declined greatly, corresponding with reductions in POC, PON, and PP. A very high ratio of POC to chlorophyll a suggested that the particulate matter was composed mainly of detritus. The higher value of POC:PON (average of 8:1) and the lower value of POC:PP (average of 58:1) displayed the following sequence of biological degradation:  $N > C > P$ . In the enclosure to which sulfide had been added, POC, PON, and PP increased significantly from day 5 to the end of the experiment. Lower ratios of both POC:PON ( $<5:1$ ) and POC:PP ( $<80:1$ ) displayed the characteristics of bacterial growth. In enclosures to which sediment only and sediment plus silt had been added, variations of POC, PON, and PP were consistent with those of chlorophyll a and  $^{14}\text{C}$  productivity. During diatom blooms, ratios of both POC:PON and POC:PP increased with simultaneous reductions in nitrate-N and phosphate-P in the water column.*

Over the last decade, many types of marine ecosystem enclosed experiments (MEEEs) have been used to investigate the ecological effects, biogeochemical behaviour, and fate of marine pollutants (Grice and Reeve 1982). Similarly, coastal and harbour dredging have received considerable attention because contaminated sediments are often resuspended as a result of dredging operations, thereby releasing adsorbed pollutants. An experiment designed to study the release of pollutants from sediments and their effects on ecosystems under different conditions was carried out at Saanich Inlet, BC, Canada, during the summer of 1985 using a

catamaran supporting several enclosures. This research project was jointly sponsored by the International Development Research Centre of Canada and the State Oceanic Administration of the People's Republic of China.

This paper discusses the effects of contaminated sediments on the composition of particulate organic carbon (POC), particulate organic nitrogen (PON), and particulate phosphorus (PP).

## Materials and methods

The experimental enclosures are supported on a catamaran barge (Fig. 1). It is constructed with aluminum supports and two parallel floats and is capable of holding five fibreglass tanks (each tank is 1 m in diameter and 2 m deep). All five tanks were used, each receiving a different treatment. Tank 1 was the control, containing seawater pumped from 17 m below the surface using a peristaltic pump. About 100 L of False Creek (near Vancouver, BC) sediment moderately polluted by heavy metals was added to each of the other tanks. Seawater was pumped into these tanks as it was in tank 1. To stop phytoplankton growth, the tanks were covered with black polyethylene sheets until the first sampling session 1 d later.

The following coastal environments were simulated in this study (see Whitney 1985 for details): tank 1 — no sediment, full sunlight (control); tank 2 — sediment bed, full sunlight; tank 3 — sediment bed, no sunlight (black cover); tank 4 — sediment bed, high silt load (to show its scavenging capacity); and tank 5 — sediment bed, anoxic water ( $\text{Na}_2\text{S}$  added).

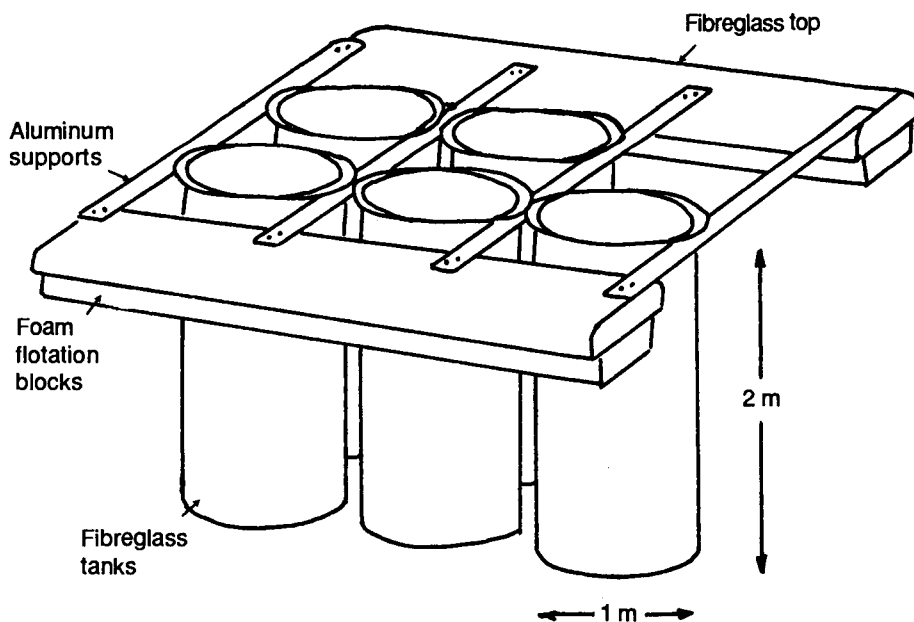


Fig. 1. Arrangement of experimental enclosures.

During the experiment, all of the tanks were covered with clear or black polyethylene sheets to restrict contamination by airborne particles. Sampling was carried out between 13 August and 6 September 1985.

About 2 L of seawater was filtered through a 47-mm precombusted glass fibre filter (Whatman GF/C). The filters were dried in an oven at 60°C for 24 h. Concentrations of POC and PON were measured using a Perkin-Elmer Model 240 elemental analyzer (Parsons et al. 1984). For particulate phosphorus determinations, 500 mL of seawater was filtered through a 24-mm precombusted glass fibre filter (Whatman GF/C) and the content was determined by colorimetry (Solorzano and Sharp 1980).

## Results and discussion

In the control (tank 1), ranges of POC, PON, and PP were close to natural values measured in the seawater of Saanich Inlet at the same time (Table 1) and showed the characteristic high productivity associated with coastal seawater (Sharp 1983). Variations in POC, PON, and PP were similar, with peaks on 15, 21, and 30 August (Fig. 2d). Ratios of C:N and C:P were stable (Fig. 2b). Average C:N and C:P ratios in tank 1 were close to the field ratios measured in Saanich Inlet seawater (Table 1) and were slightly less than the Redfield ratios for phytoplankton (C:N:P = 106:16:1) (Redfield 1934). The relative stability of the ratios in tank 1 suggested that the composition of phytoplankton remains relatively stable even when productivity is low. In the control, particulates were derived mainly from phytoplankton and weight ratios were representative of a relatively unpolluted area, such as Saanich Inlet.

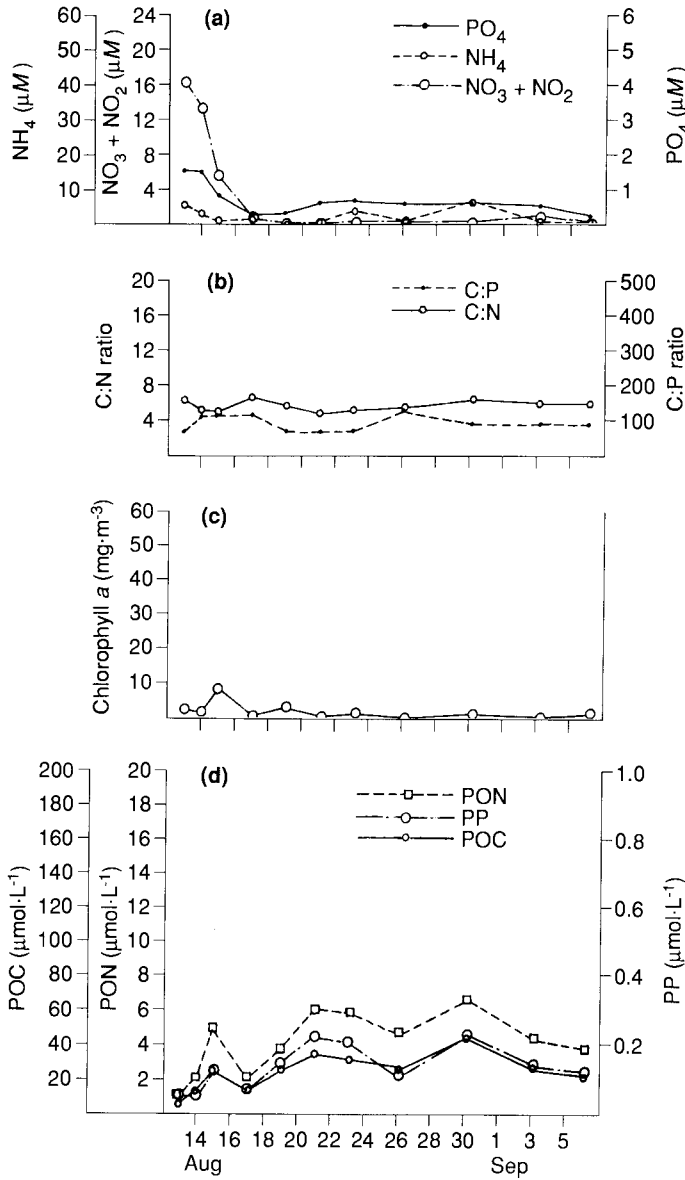
In tank 2, heavy metals (Cd, Cu, Pb, and Zn) in contaminated sediment were released (Fig. 3). The time variation of chlorophyll *a* showed that the phytoplankton bloom was delayed for about 1 week. At the same time, the biomass increased significantly as nutrients were released from the sediment. These results are similar to those reported from the 1984 Marine Ecosystem Enclosed Experiments (MEEE) (Parsons et al. 1986) in which mine tailings were added to the enclosures. The peaks of PON and POC on 21 and 23 August, respectively, coincided with the diatom bloom. It was followed by two flagellate blooms: the first between 23 and 26 August, overlapping the diatom bloom, and the second beginning on 3 September, coinciding with the second peaks of POC and PON. Ratios of C:N between of 17 August and 6 September were about 6:1 (Fig. 3), indicating that the particulate in tank 2 has the characteristics of phytoplankton. The higher C:N ratio (9.4:1) on

Table 1. Ranges of particulate organic carbon (POC), particulate organic nitrogen (PON), and particulate phosphorus (PP) ( $\mu\text{mol}\cdot\text{L}^{-1}$ ) and ratios of C:N and C:P in the control (tank 1) and in the seawater of Saanich Inlet, British Columbia.

	Control	Saanich Inlet
POC	8.1–44.8	13.9–65.6
PON	1.2–6.8	2.1–8.3
PP	0.11–0.46	0.07–0.51
C:N	6.0	5.9–8.0
C:P	95.4	109–199

23 August corresponded with the lowest levels of nitrate and ammonium, suggesting that the diatom bloom was approaching nitrogen limitation (C:N = 10:1) (Goldman and McCarthy 1978) with depleted nutrients.

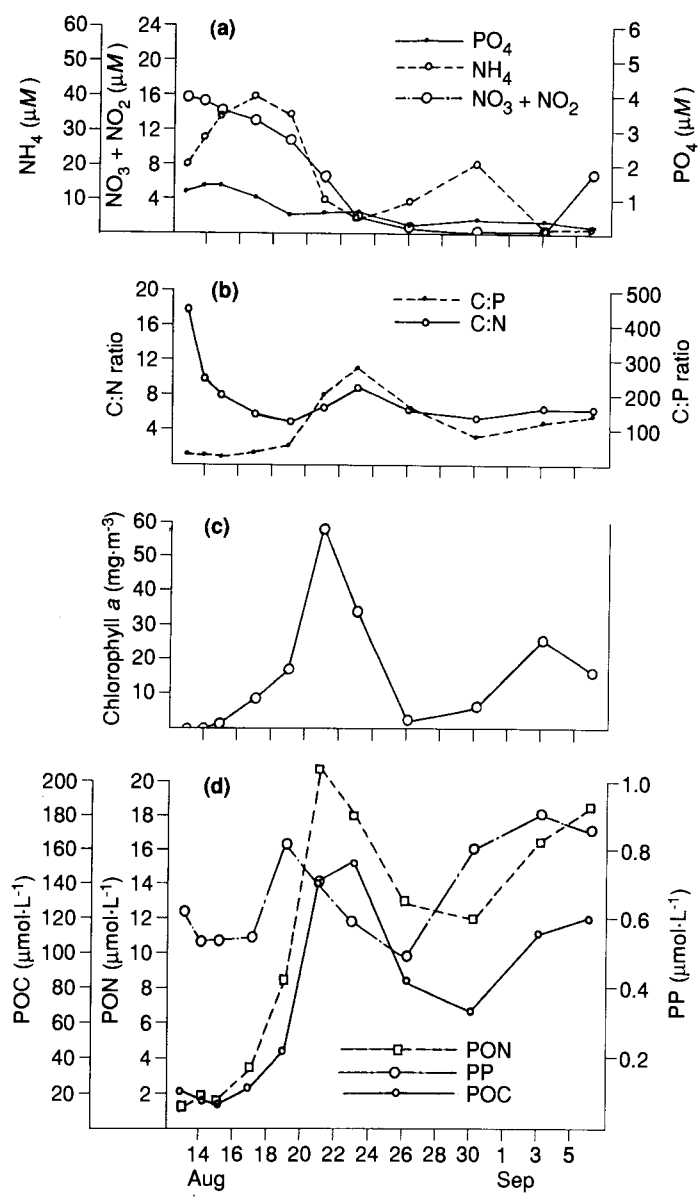
In tank 2, the PP peak occurred before the phytoplankton bloom; therefore, the C:P ratio increased (203:1–282:1) when the bloom occurred. This observation suggested an increase in the rate of uptake of phosphorus by phytoplankton, resulting



**Fig. 2.** Time variation of (a) nutrients, (b) C:N and C:P ratios, (c) chlorophyll *a*, and (d) particulate organic carbon (POC), particulate organic nitrogen (PON), and particulate phosphorus (PP) in tank 1.

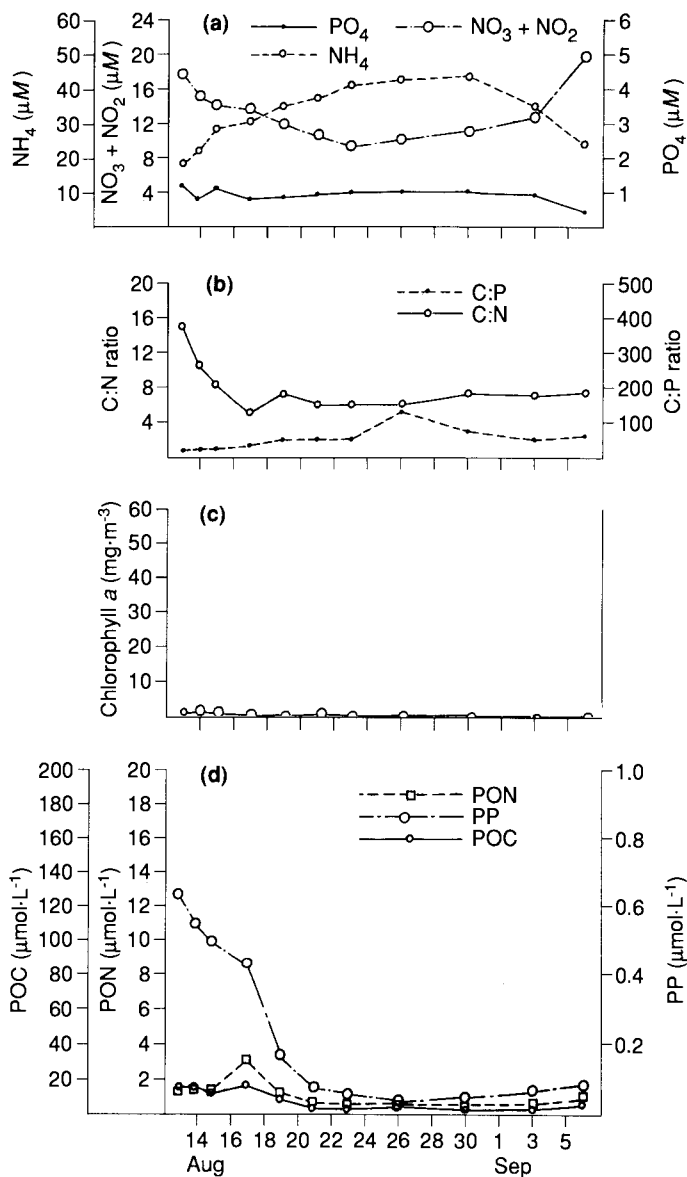
in the decrease in phosphorus in phytoplankton cells and the increase in the C:P ratio during the bloom. At the beginning of the experiment, there were higher C:N ratios and higher PP in tanks 3, 4, and 5. The similar trends suggest that particulates in these tanks probably originated from the polluted sediment used in the experiments.

In the dark enclosure (tank 3), although levels of nutrients were high,



**Fig. 3.** Time variation of (a) nutrients, (b) C:N and C:P ratios, (c) chlorophyll *a*, and (d) particulate organic carbon (POC), particulate organic nitrogen (PON), and particulate phosphorus (PP) in tank 2.

phytoplankton growth was suppressed significantly. Throughout the entire experiment, no peaks of chlorophyll *a* were observed (Fig. 4c), probably because of the low sensitivity of the method used. Peaks of POC and PON were similar to those in the control on 17 August and corresponded with the small bloom of diatoms (about 1 219 cells·mL<sup>-1</sup>). On 3 September, POC, PON, and PP increased slightly, corresponding with the small flagellate bloom. Thus, any one of these three parameters can be used as an indicator of phytoplankton growth. During the period of

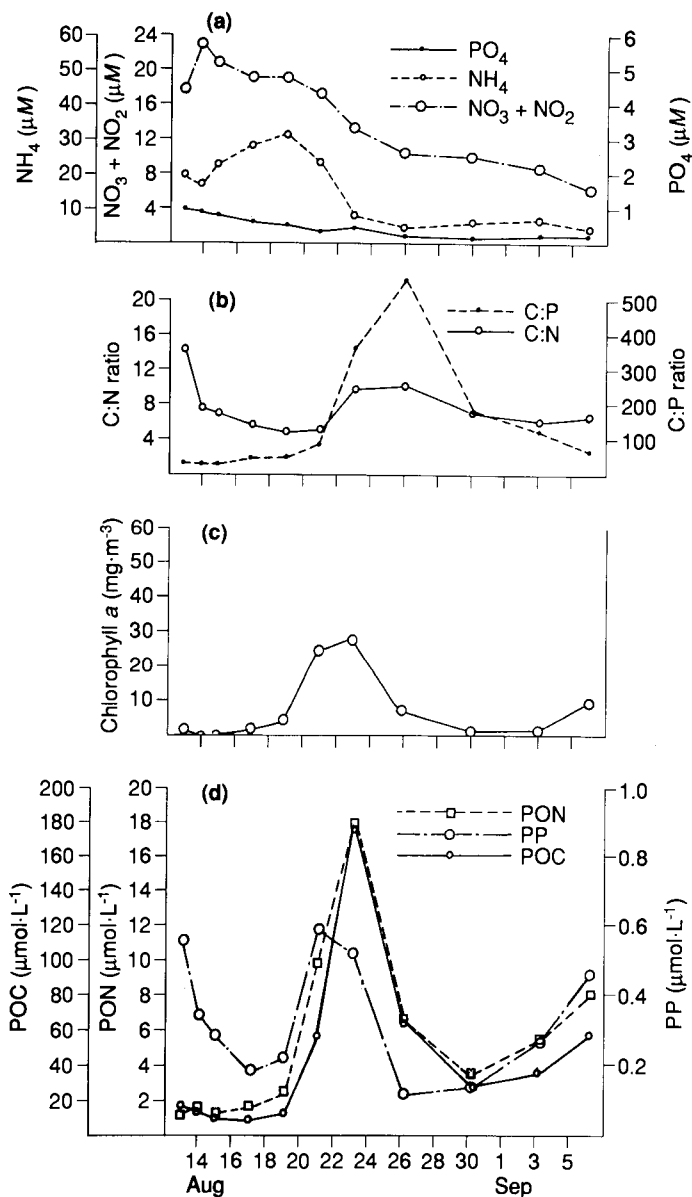


**Fig. 4.** Time variation of (a) nutrients, (b) C:N and C:P ratios, (c) chlorophyll *a*, and (d) particulate organic carbon (POC), particulate organic nitrogen (PON), and particulate phosphorus (PP) in tank 3.



phytoplankton growth, C:N ratios were about 7:1, higher than those in the control (C:N = 6:1). However, C:P ratios were about 65:1, lower than those in the control (C:P = 95:1). The low C:P ratios might have been a result of the following:

- The short-duration diatom bloom under suboptimal conditions was rapidly succeeded by flagellates, which possessed higher C:N and lower C:P ratios; and



**Fig. 5.** Time variation of (a) nutrients, (b) C:N and C:P ratios, (c) chlorophyll *a*, and (d) particulate organic carbon (POC), particulate organic nitrogen (PON), and particulate phosphorus (PP) in tank 4.

- The particulates were mainly composed of phytoplankton detritus (Parsons 1975) as primary productivity was nearly zero and the POC:chlorophyll *a* ratio was very high (about 3 850:1).

In tank 4, the enclosure treated with sediment and silt, levels of heavy metals in the water changed only slightly, but nitrate-N concentrations increased significantly (Fig. 5). Variations of POC, PON, PP, and chlorophyll *a* with time were similar to those occurring in tank 2, but their peaks were delayed even further. This delay was probably caused by the silt particles reducing light penetration. Individual peaks of PP (21 August) and POC and PON (23 August) reflected the diatom bloom. After the lowest point, on 30 August, a second peak appeared along with the flagellate bloom. The diatom bloom in this tank showed higher and sharper peaks than those in tank 2. The sharp peak was consistent with the very short growth period for diatoms (Fig. 6). The C:N ratios on 23 and 26 August were greater than 10:1 (Fig. 5), suggesting a nitrogen-limiting condition. On the other hand, dominant species of

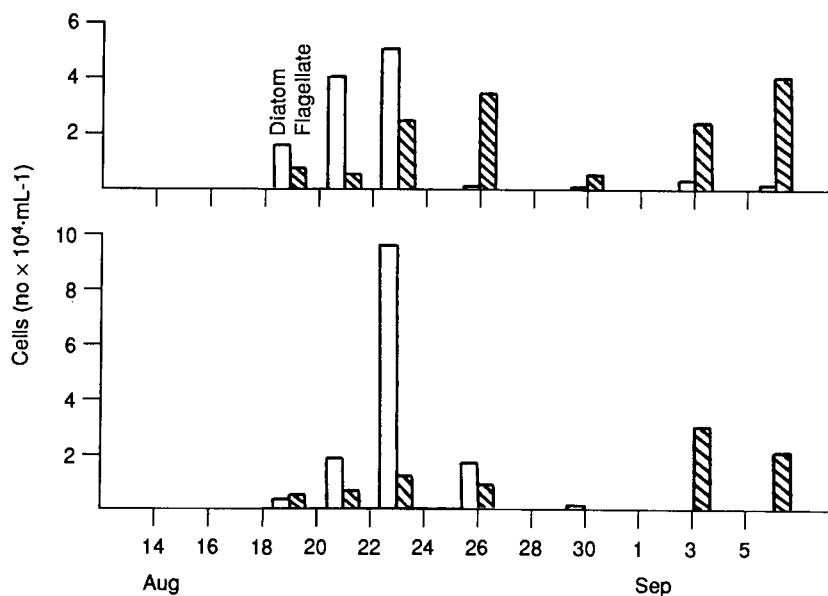


Fig. 6. Time variation of phytoplankton biomass.

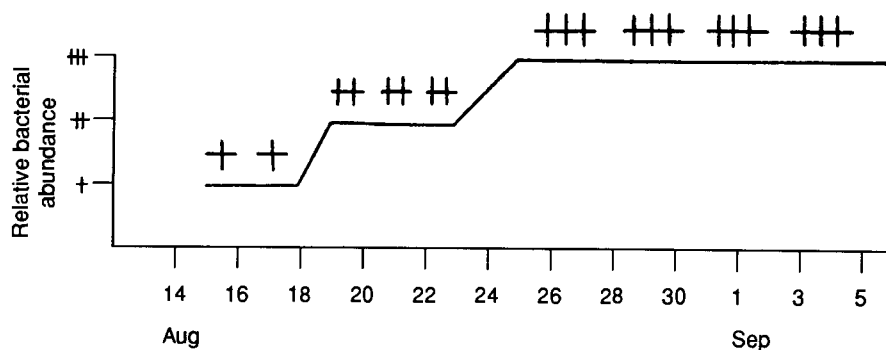
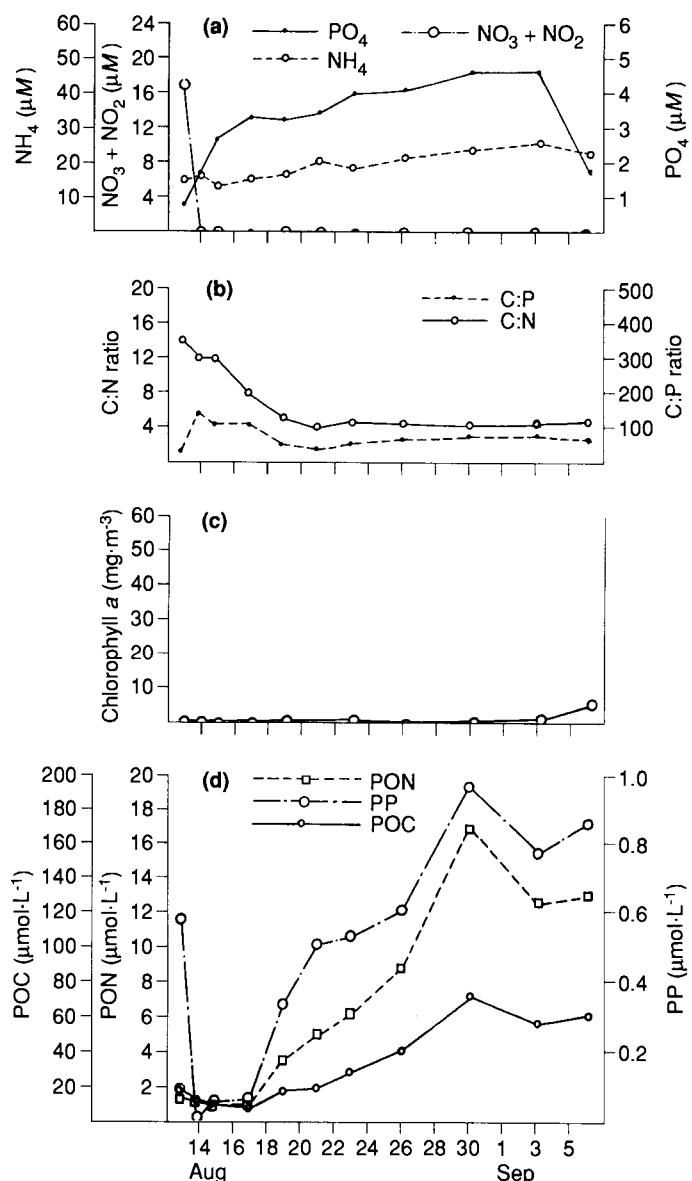


Fig. 7. Time variation of bacteria in tank 5.

diatoms in tanks 2 and 4 differed. *Thalassiosira* spp were dominant in tank 2, whereas *Skeletonema costatum* was dominant in tank 4. It appears that the dominant species were related to the nutrient composition of the seawater. *Thalassiosira* spp are bigger and contain more nitrate in their cells (Conover 1975), whereas *Skeletonema costatum* contains less nitrate per cell (Dortch 1982). The time variation of PP in tank 4 was also similar to that in tank 2, i.e., the PP peak occurred



**Fig. 8.** Time variation of (a) nutrients, (b) C:N and C:P ratios, (c) chlorophyll a, and (d) particulate organic carbon (POC), particulate organic nitrogen (PON), and particulate phosphorus (PP) in tank 5.

before the phytoplankton peak, indicating a rapid uptake of phosphorus and a high C:P ratio (573:1).

In the enclosure to which sulfide was added (tank 5), both nitrate- and nitrite-N were reduced. Diatoms and flagellates were not observed until 3 September. However, bacteria were present on 15 August and increased continuously with time. POC, PON, and PP also increased with time, corresponding with the increase in bacteria (Figs 7 and 8). The C:N and C:P ratios decreased constantly with time until they reached values of C:N = 5:1 and C:P = 80:1 on 17 August. Otsuki and Hanya (1968) have stated that the C:N ratio in bacteria could be less than 5:1. Meanwhile, Harrison et al. (1977) report that, in coastal waters, the uptake of phosphorus by bacteria could be very important. The abundance of bacteria is a plausible explanation for the low C:N and C:P ratios in the particulates. After 3 September, the diatom and flagellate blooms corresponded with increases in C:N and C:P ratios, declines in nutrients, and increases in POC, PON, PP, and chlorophyll *a*.

## Acknowledgments

We express our gratitude to Peter Thompson, University of British Columbia, Vancouver, BC, Canada, for providing the nutrient data; Chen Xingqun, Third Institute of Oceanography, Xiamen, for his chlorophyll *a* data; and Shen Liangfu, Institute of Marine Protection, Dalian, for providing data on species distribution and abundance of phytoplankton.

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- Conover, S.A.M. 1975. Partitioning of nitrogen and carbon in cultures of the marine diatom *Thalassiosira fluviatilis* supplied with nitrate, ammonium, or urea. *Marine Biology*, 32, 231–246.
- Dortch, F.Q. 1982. Effect of growth conditions on accumulation in three marine diatoms. University of Washington, Seattle, WA, USA. PhD thesis.
- Goldman, J.C., McCarthy, J.J. 1978. Steady-state growth and ammonia uptake of a fast-growing marine diatom. *Limnology and Oceanography*, 23, 695–730.
- Grice, G.D., Reeve, M.R. 1982. Introduction and description of experimental ecosystems. In Grice, G.D., Reeve, M.R., ed., *Marine mesocosms: biological and chemical research in experimental ecosystems*. Springer-Verlag, New York, NY, USA. 1–10.
- Harrison, W.G., Azam, F., Renger, E.H., Eppley, C.W. 1977. Some experiments on phosphate assimilation by coastal marine plankton. *Marine Biology*, 40, 9–18.
- Otsuki, A., Hanya, T. 1968. On the production of dissolved nitrogen-rich organic matter. *Limnology and Oceanography*, 13, 1 983.
- Parsons, T.R. 1975. Particulate organic carbon in the sea. In Riley, J.P., Skirrow, G., ed., *Chemical oceanography*. Academic Press, London, UK. 365–383.
- Parsons, T.R., Maits, Y., Lalli, C.M. 1984. A manual of chemical and biological methods for seawater. Pergamon Press, New York, NY, USA.
- Parsons, T.R., Thompson, P., Wu, Y., Lalli, C.M., Hous, S., Xu, H. 1986. The effect of mine tailings on the production of plankton. *Acta Oceanologica Sinica*, 5, 417–423.

- Redfield, A.C. 1934. On the proportions of organic derivatives in sea water and their relation to the composition of plankton. *In* Daniel, R.J., ed., James Johnstone memorial volume. Liverpool University Press, Liverpool, UK.
- Sharp, J.H. 1983. The distribution of inorganic nitrogen and dissolved and particulate organic nitrogen in the sea. *In* Carpenter, E.J., Capone, D.G., ed., Nitrogen in the marine environment. Academic Press, New York, NY, USA. 1–36.
- Solorzano, L., Sharp, J.H. 1980. Determination of total dissolved and particulate phosphorus in natural waters. *Limnology and Oceanography*, 25, 754–758.
- Whitney, F.W., ed. 1985. Metal fluxes from False Creek sediments under various chemical and biological conditions — Data Report MEEE 85-2. Institute of Ocean Sciences, Sidney, BC, Canada. 38 p.