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Primary Production Studies on a Reservoir, Embalse del Rio Tercero, Argentina*

By

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Abstract. Diel and day-to-day variations in the amounts of chlorophyll *a* and phaeopigments and the daily primary production of phytoplankton were investigated for two or three consecutive days every month from March of 1980 to March of 1981 at a fixed station in a eutrophic reservoir in Argentina. The amount of chlorophyll *a* in the euphotic zone varied noticeably within a day or day by day from summer to autumn. It was suggested that the short-term variation in chlorophyll *a* was brought about by short-term displacement of water masses with different amounts of phytoplankton and was related closely to the variation in cell numbers of *Peridinium gatunense*. The day-to-day variation of daily primary production was remarkable during the period of summer-autumn. This variation was suggested to be caused by the noticeable change in phytoplankton standing crop during the investigated days. The recent trophic status of this lake was discussed with reference to some variables measured in 1971–1972.

Introduction

Eutrophication of reservoirs is enhanced rapidly by high sedimentation rates and nutrient enrichment (Kimmel and Lind 1972). Thus, many studies on primary production of phytoplankton in reservoirs have been performed from a view point of eutrophication and focussed on annual variation (Soltero and Wright 1975; Schwartzkopf and Hergenrader 1978; Bayne et al. 1983). In reservoirs, however, there is little information on short-term (diel or day-to-day) variations of the primary production of phytoplankton and related variables.

In the present study, some limnological characteristics of a eutrophic reservoir, Embalse del Rio Tercero, will be described and discussed mainly on the basis of diel or day-to-day variations of photosynthetic pigments and daily primary production of phytoplankton. Further, the trophic status of this lake will be discussed with reference to some variables measured in 1971–1972.

Description of the study area

Embalse del Rio Tercero located in the Province of Cordoba (32°11′ S, 64°13′ W), Argentina,

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is ca 5400 ha of the surface area and around 40 m in the maximum depth. This reservoir was built up in 1930.

Annual precipitation around the lake is relatively low (760 mm in 1980), and there is little

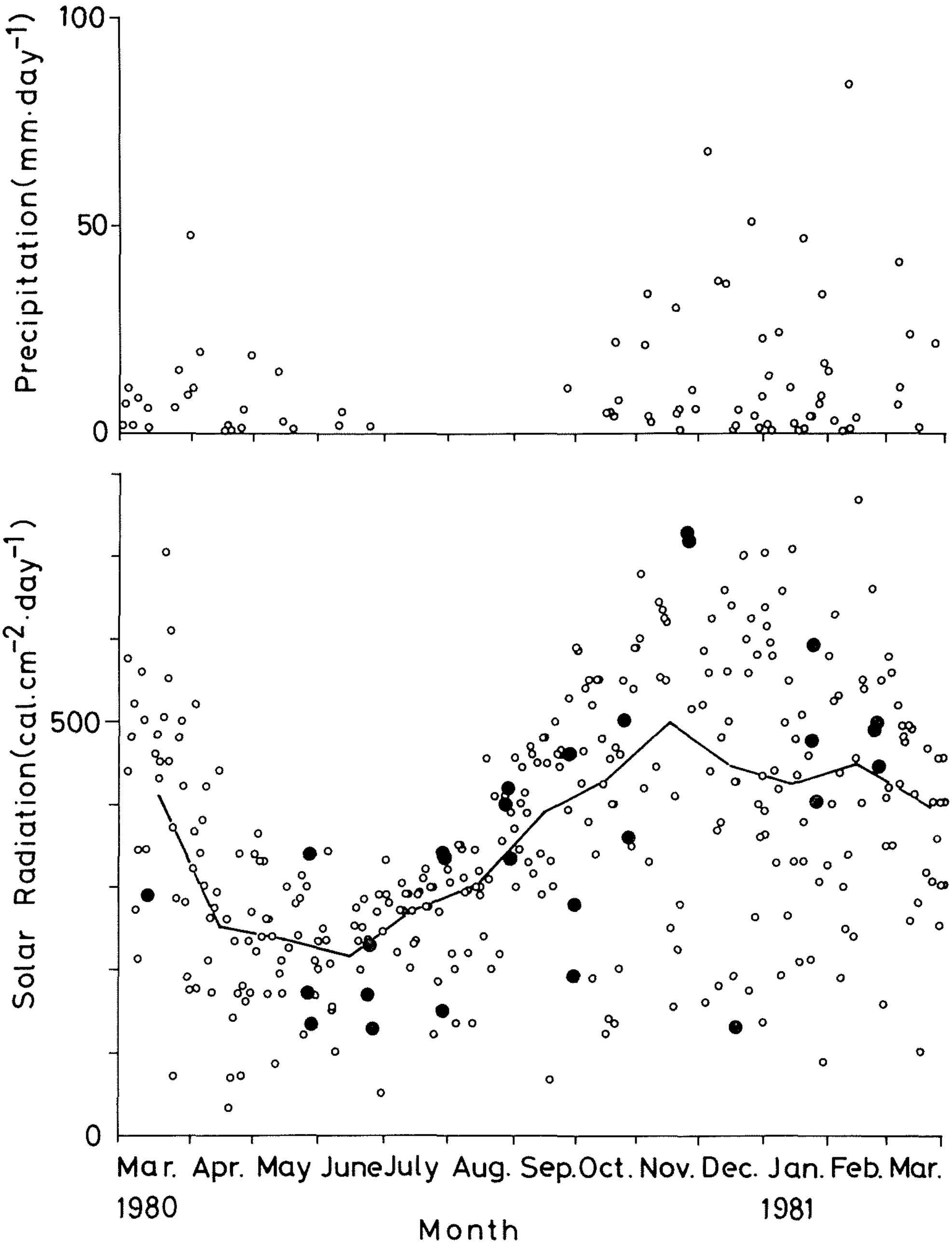

Fig. 1. Seasonal changes in precipitation and daily solar radiation around Embalse del Rio Tercero during the investigation period. Solid circles: solar radiation on the days when the primary production was determined. Solid line: monthly average radiation.

precipitation during July-September (Fig. 1). Solar radiation on the lake becomes maximum in November (monthly average: 500 cal·cm^{-2}·day^{-1}) and minimum in June (monthly average: 215 cal·cm^{-2}·day^{-1}).

Material and Methods

Sampling stations are shown in Fig. 2. Water samples for the horizontal distribution of chlorophyll *a* plus phaeopigments were collected from the respective depths of 0, 1, 2, 3, 4, and 5 m at 31 stations. The water samples of 1 liter from each depth were mixed together and put to the determinations of chlorophyll *a* and phaeopigments.

Physico-chemical variables, photosynthetic pigments and primary production of phytoplankton were determined for two or three consecutive days every month from March of 1980 to March of 1981 at station A, the depth of which fluctuates seasonally from 15 to 27 m. Water samples were collected from the depths of 0, 0.5, 1, 2.5, 5, 7.5 and 10 m for the primary production measurements and, in addition to these depths, from 15 m and a layer just above the bottom for the analyses of nutrient, chlorophyll *a* and phaeopigments.

Physico-chemical variables and photosynthetic pigments were measured three times (morning, noon and evening) a day for three consecutive days every month. Water temperature and pH were measured with a thermister thermometer and a pH meter (glass electrode), respectively. Nitrate-N was determined by the reduction method using cadmium-copper column and nitrite-N by diazotizing with sulfanile amide (U.S. Environmental Protection Agency

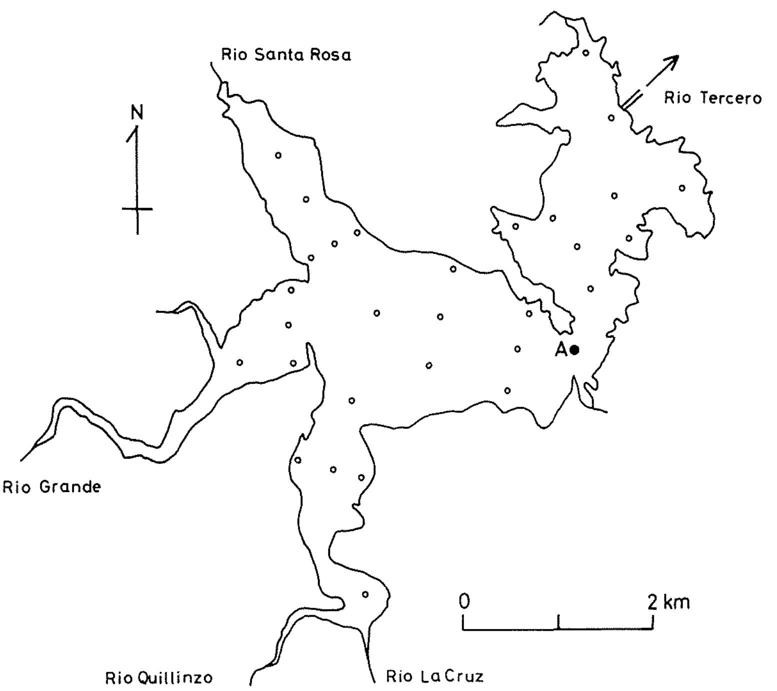

Fig. 2. Map of Embalse del Rio Tercero and the sampling stations.

1976). Ammonium-N and dissolved reactive phosphate-P were measured by Nesslerization and stannous chloride methods, respectively (APHA 1971). Particulate organic carbon and nitrogen in the samples on the GF/C filters pretreated at 420°C for 4 hours were determined with a CHN analyzer (Yanaco MT-2). Amounts of chlorophyll *a* and phaeopigments in the samples on the Whatman GF/C glass fiber filters were determined after the method of Lorenzen (1967a).

Primary production was measured by the *in situ* ^{14}C- and O_2-light and dark bottle techniques. The primary production measurement was performed twice in the daytime from sunrise to around noon and from around noon to sunset. In the case of the ^{14}C technique, the water samples after exposure were immediately filtrated through HA Millipore filters with 0.45 μm pore size. After fumed over concentrated HCl for 1 minute, each sample on the filter was placed in a scintillation vial with Bray's fluor. The ^{14}C radioactivity of the samples was measured by a liquid scintillation spectrometer (Ward and Nakanishi 1971). The dissolved oxygen was determined by the Winkler method.

Light extinction coefficient was calculated by the following formula (Ichimura, 1956): $k=\frac{1.9}{Tr}$, where k (m^{-1}) and Tr (m) are the extinction coefficient and Secchi disc reading, respectively. Daily compensation depth (a depth of 1% the surface light intensity) was roughly estimated using the values of k and Lamber-Beer law.

Water samples for algal observation were collected from the depths of 0, 1, 2.5 and 5 m and preserved with Lugol's solution. Algal cells were counted using a haematocytometer.

Results and Discussion

Physico-chemical variables at station A

Surface water temperature varied seasonally within the range of 7.9°C in July to 25.5°C in February. Weak thermal stratification was observed from October to May.

Dissolved oxygen in the euphotic zone was sometimes supersaturated during the thermally stratified period, whereas water near the bottom was almost anaerobic in December through March.

Secchi disc readings ranged from 0.9 m on December 20 to 2.6 m on April 16 during the investigated period (annual mean value: 1.7 m).

The pH was maintained at fairly high levels throughout a year, ranging rom 7.6 in July to 9.1 in March in the euphotic zone.

Ammonium-N concentration was relatively constant throughout a year in comparison with nitrate-N (Table 1). It varied seasonally from 0.04 to 0.11 $mg.l^{-1}$ (mean concentration during three consecutive days in the euphotic zone). Ammonium-N tended to be accumulated in the water near the bottom during the period of thermal stratification. This might have been caused by the decomposition of organic matter under anaerobic condition. Nitrate-N ranged from 0.00 to 0.27 $mg \cdot l^{-1}$ in the euphotic zone. Nitrite-N concentration was very low and always below 0.01 $mg \cdot l^{-1}$.

Ammonium-N was almost in the same level as nitrate-N. Thus, in this lake, ammonium-N as well as nitrate-N might be an important nitrogen stock for phytoplankton growth.

Dissolved reactive phosphate-P concentration was very low. The mean concentration in

Table 1. Mean concentrations of ammonium-N and nitrate-N in the euphotic and aphotic zones at station A

	NH_4-N ($mg \cdot l^{-1}$)		NO_3-N ($mg \cdot l^{-1}$)	
	Euphotic Zone	Aphotic Zone	Euphotic Zone	Aphotic Zone
Mar. 11–13, 1980	0.07 (0.05–0.08)	0.13 (0.10–0.17)	0.00 (0.00–0.02)	0.03 (0.01–0.07)
Apr. 15–17	0.10 (0.08–0.14)	0.11 (0.08–0.17)	0.06 (0.04–0.08)	0.08 (0.06–0.11)
May 27–29	0.04 (0.00–0.08)	0.04 (0.00–0.06)	0.09 (0.06–0.10)	0.08 (0.06–0.10)
June 23–25	0.07 (0.04–0.08)	0.07 (0.03–0.08)	0.12 (0.10–0.14)	0.11 (0.10–0.13)
July 28–30	0.09 (0.07–0.13)	0.09 (0.07–0.13)	0.06 (0.05–0.07)	0.06 (0.05–0.07)
Aug. 28–30	0.06 (0.04–0.07)	0.06 (0.05–0.07)	0.04 (0.04–0.05)	0.04 (0.04–0.05)
Sep. 28–30	0.11 (0.09–0.13)	0.11 (0.09–0.13)	0.01 (0.00–0.02)	0.02 (0.00–0.02)
Oct. 26–28	0.09 (0.07–0.10)	0.12 (0.08–0.16)	0.03 (0.01–0.05)	0.02 (0.02–0.05)
Nov. 24–26	0.09 (0.07–0.10)	0.12 (0.09–0.14)	0.12 (0.08–0.16)	0.14 (0.12–0.16)
Dec. 19–21	0.06 (0.05–0.08)	0.09 (0.05–0.20)	0.27 (0.21–0.30)	0.34 (0.28–0.35)
Jan. 27–29, 1981	0.06 (0.05–0.08)	0.08 (0.06–0.12)	0.09 (0.06–0.12)	0.14 (0.11–0.16)
Feb. 24–26	0.06 (0.04–0.08)	0.09 (0.05–0.17)	0.00 (0.00–0.01)	0.04 (0.02–0.05)
Mar. 26–28	0.07 (0.06–0.08)	0.07 (0.06–0.08)	0.00 (0.00–0.01)	0.00 (0.00–0.01)

The values in parentheses show the range during three consecutive days.

the euphotic zone was 0.01 $mg \cdot l^{-1}$ in March of 1980, 0.02 $mg \cdot l^{-1}$ in April and October and below 0.01 $mg \cdot l^{-1}$ in other months.

Diel and day-to-day variations in some variables mentioned above seemed not to be remarkable.

Short-term and seasonal changes in chlorophyll a and phaeopigments

In order to know the degree of short-term changes in phytoplankton standing stock, the amounts of chlorophyll *a* and phaeopigments at station A were measured vertically three times (morning, noon and evening) a day for three consecutive days every month. Figure 3 shows the seasonal differences of short-term variations of the amounts of chlorophyll *a* and phaeopigments in the euphotic zone. The short-term changes in amounts of chlorophyll *a* and/or phaeopigments were remarkable in March, April and May of 1980, and January-February of 1981, whereas they were negligible during June–October of 1980. It is worthy of note that such remarkable changes were found in the seasons with large precipitation (Fig. 1). It was expected that, when such noticeable changes were observed, the horizontal distribution of chlorophyll *a* in the water masses around station A might be remarkably heterogeneous and water displacement occurred quickly.

On the day before the consecutive three days survey, the horizontal distribution of chlorophyll *a* plus phaeopigments was investigated at 31 stations in the lake. Concentrations of chlorophyll *a* plus phaeopigments were distributed complicatedly, having their wide range in the months with noticeable short-term change in chlorophyll *a* amount (Fig. 4). Such a heterogeneous distribution seems to occur in the case of dense phytoplankton (Berman and Rodhe 1971). Thus, it is considered that a noticeable short-term change in the chlorophyll *a* amount at station A may have been brought about by displacement of water masses with extremely different standing crop of phytoplankton. Furthermore, it was interesting that *Peridinium gatunense* was

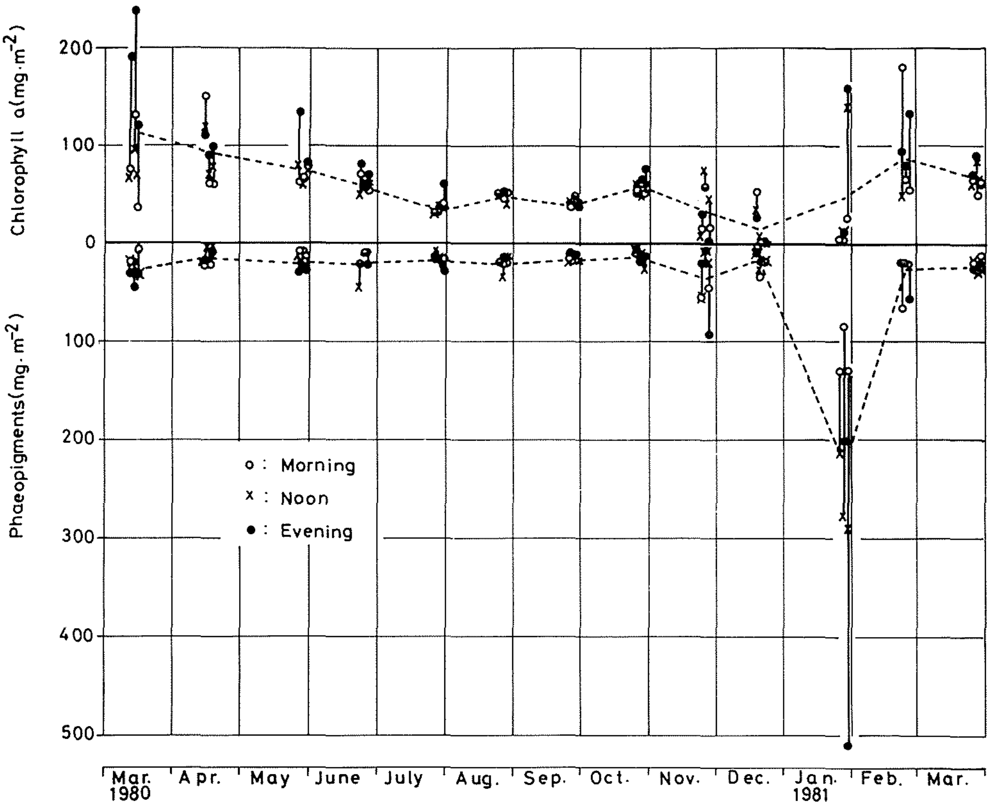

Fig. 3. Seasonal differences in short-term variations of the amounts of chlorophyll *a* and phaeopigments in the euphotic zone at station A.

dominant when such a noticeable short-term change in chlorophyll *a* amount occurred. Figure 5 shows comparisons between the vertical distributions of chlorophyll *a* plus phaeopigments and cell numbers of two major algae, *Melosira granulata* and *P. gatunense*, in the morning, at noon and in the evening on March 11, 1980. Vertical distribution pattern of the amount of chlorophyll *a* plus phaeopigments was closely related to that of *P. gatunense* (cell number). Taking into consideration the fact that *P. gatunense* was abundant in the months with remarkable short-term change in chlorophyll *a*, the short-term fluctuation of *P. gatunense* density in total phytoplankton seems to be a main cause in short-term change of chlorophyll *a* amount. The diel change in vertical profile of the amount of chlorophyll *a* plus phaeopigments might be caused to some extent by the migratory behaviour of a motile alga, *P. gatunense* (Nygaard 1977).

A remarkable increase in phaeopigments was observed on January 27–29 (cf. Fig. 3). The maximum amount of phaeopigments, 510 mg·m^{-2}, in the euphotic zone was obtained on January 29. The ratio of phaeopigments to chlorophyll *a* plus phaeopigments tended to increase from November to January (Fig. 6).

Two main processes for the increase in phaeopigments in natural waters have been considered. One is grazing by herbivorous zooplankton (Lorenzen 1967b; Glooschenko et al. 1972; Daley 1973; Shuman and Lorenzen 1975) and the other is due to the resuspension of bottom sediments rich in phaeopigments (Moss 1970; Glooschenko et al. 1974). Unfortunately, no available information was obtained for herbivores in the present study. Hence it is impossible to discuss such a sudden increase in phaeopigments in connection with herbivores' grazing.

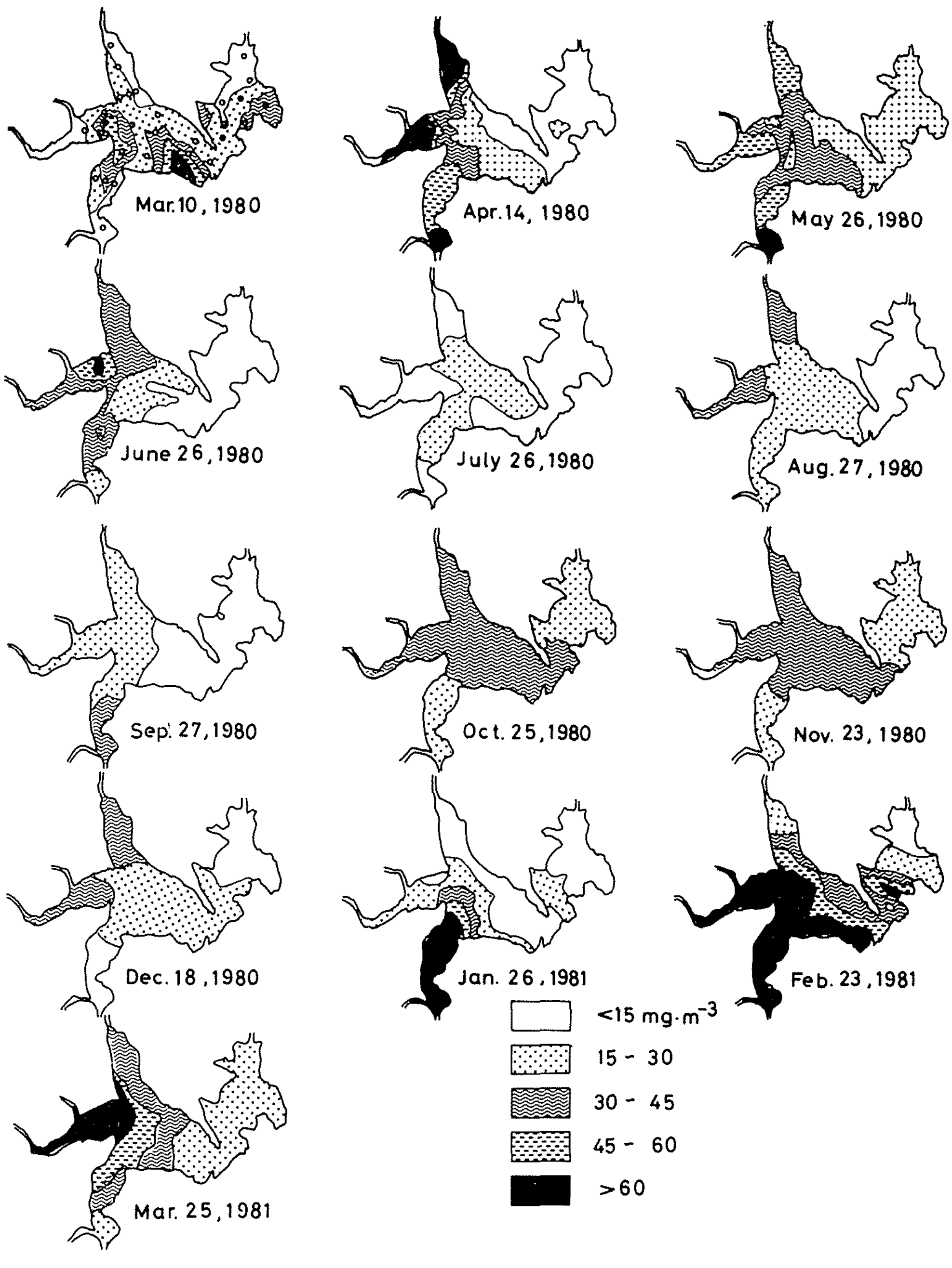

Fig. 4. Seasonal change in horizontal distribution of chlorophyll *a* plus phaeopigments amounts. The values are mean concentrations from 0 to 5 m depths.

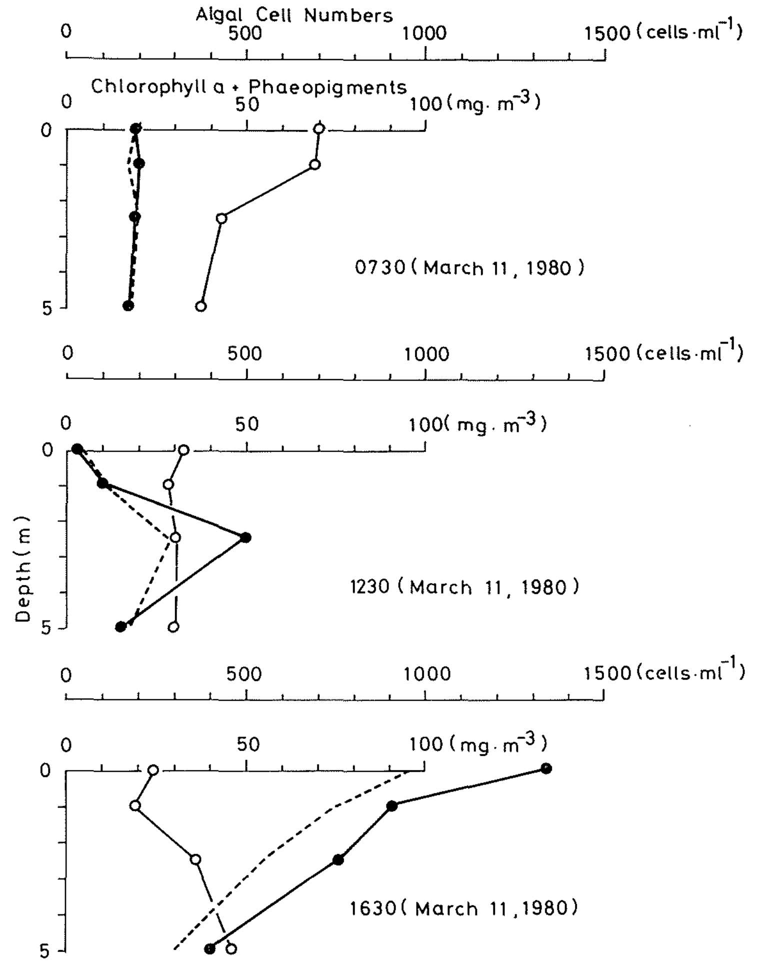

Fig. 5. Diel variations of the vertical profiles of cell numbers of *Melosira granulata* (—○—) and *Peridinium gatunense* (—●—) and of chlorophyll *a* plus phaeopigments amounts (dotted line).

After Moss (1970), a remarkable increase in phaeopigments in ponds and shallow lakes is derived from the resuspension of sediments rather than zooplankton grazing. The resuspension of sediments may be considered as one of the processes because water body around station A is relatively shallow.

Seasonal change in chlorophyll *a* amount in the euphotic zone was not so drastic as the short-term change observed in summer and autumn (cf. Fig. 3). Chlorophyll *a* amount increased in January–March and decreased gradually in April. Mean values of chlorophyll *a* in the euphotic zone for three consecutive days varied seasonally from 15 mg·m^{-2} in December of 1980 to 110 mg·m^{-2} in March of the same year.

Relationship between chlorophyll a plus phaeopigments and particulate organic carbon

Particulate organic carbon (POC) versus chlorophyll *a* plus phaeopigments (Chl) in the

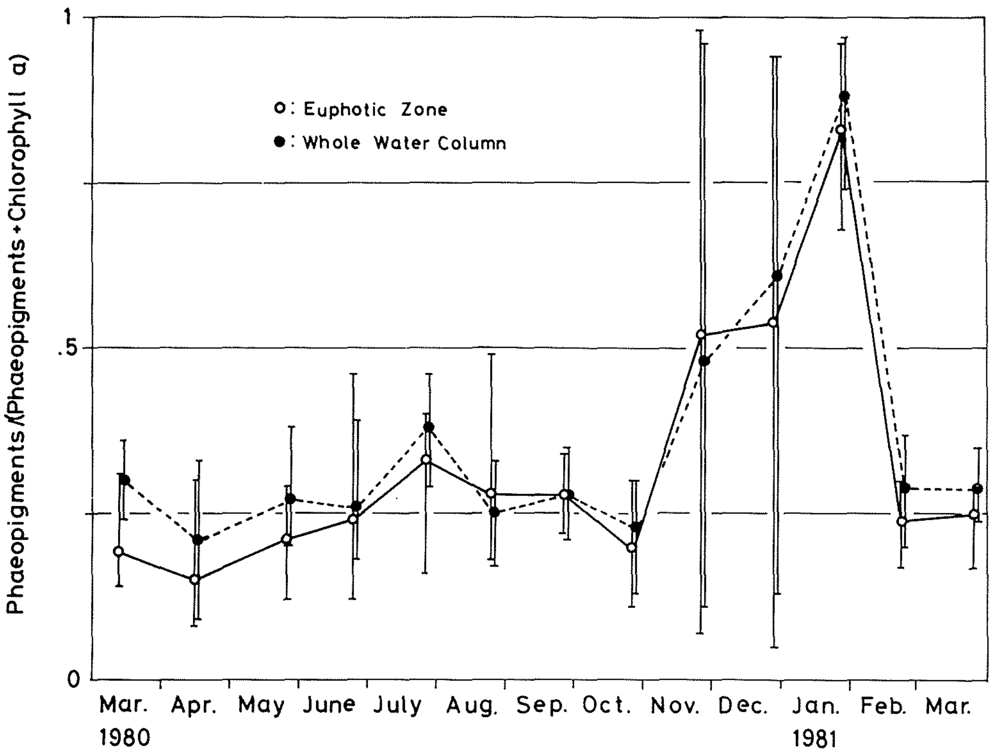

Fig. 6. Seasonal changes in the phaeopigments/chlorophyll a+phaeopigments ratio in the euphotic zone and in the whole water column. Vertical lines: ranges of the ratio during three consecutive days.

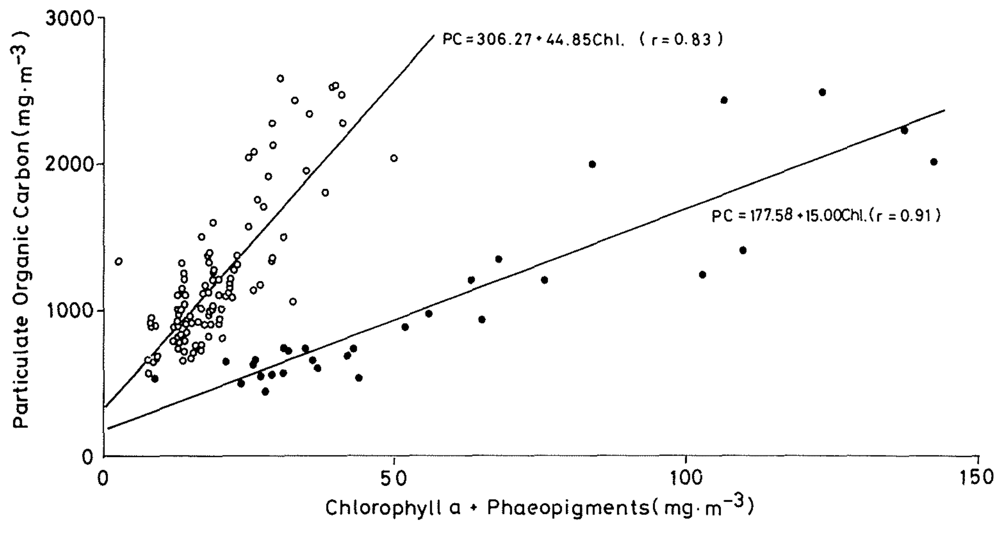

Fig. 7. Relationship between particulate organic carbon and chlorophyll a+phaeopigments. Solid circles: January. Open circles: other months.

water samples collected on the first day of each survey at station A were plotted in Fig. 7. The relation between both variables can be expressed as POC ($mg \cdot m^{-3}$) $=177.58+15.00$ Chl ($p<0.01$) in January and POC$=306.27+44.85$ Chl ($p<0.01$) in other months. The POC/Chl ratio was very low in January with rich phaeopigments in comparison with that in other months. The POC/PON (particulate organic nitrogen) ratio varied within the range from 6.5 ± 1.5 (SD) in February to 8.6 ± 1.3 (SD) in October. There was no significant difference in the POC/PON ratio between January and other months. It will be expected that the PON/Chl ratio in January was very low as well. The low PON/Chl and POC/Chl ratios suggest that particulate organic nitrogen and carbon in algal cells are decomposed or released faster than chlorophyll derivatives under certain condition.

Daily primary production of phytoplankton

Day-to-day variation of the daily primary production of phytoplankton measured by the ^{14}C technique for two or three consecutive days every month is shown in Fig. 8. Calculated daily compensation depth varied seasonally from 2.2 m on December 20 to 6.3 m on April 16 at station A. Day-to-day variation of the primary production was not so great in May–September as in October–April. In February, the daily primary production on the first day was two times larger than that on the second day, in spite of no great difference in insolation (cf. Fig. 1). Day-to-day variation of primary production is brought about not only by the daily change in insolation but also by the daily changes in standing crop and photosynthetic activity of phytoplankton (Spondniewska 1969; Soltero and Wright 1975). In this lake, a large day-to-day fluctuation of primary production occurred as often as the standing crop (expressed as chlorophyll *a*) varied considerably within a day or day by day (cf. Fig. 3). Thus, the day-to-day variation of primary production in this lake might have been related closely to the short-term change in standing crop. As mentioned before, this short-term change in standing crop at station A may have been brought about by displacement of waters with different amounts of phytoplankton. In addition to the water displacement, we have to pay attention to the occur-

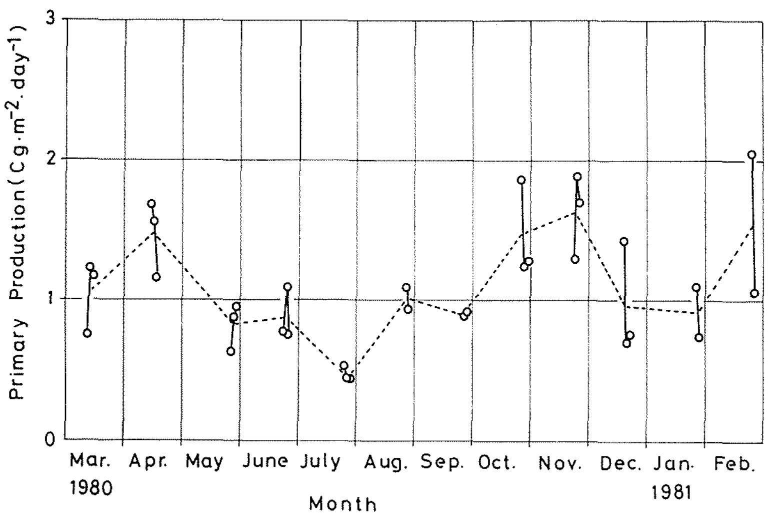

Fig. 8. Seasonal differences in day-to-day variation of the daily primary production of phytoplankton at station A.

rence of a vertically migrating alga, *P. gatunense*, for estimation of the daily primary production (Larson 1978).

Seasonal changing pattern of the daily primary production showed a tendency to decrease in winter and in mid summer (December and January). In spite of very high photosynthetic activity on a basis of chlorophyll *a* (Romero et al. 1983), decrease in the daily primary production was observed in mid summer. As one of the cause for the decrease in daily primary production in mid summer, it will be considered that photosynthetically active phytoplankton were very sparse (cf. Fig. 3). The daily primary production ranged from 0.4 $gC \cdot m^{-2} \cdot day^{-1}$ on July 29 to 2.1 $gC \cdot m^{-2} \cdot day^{-1}$ on February 24.

Ryther and Menzel (1965) pointed out that the primary production by the ^{14}C technique was approximately net production. The *in situ* measurements of primary production were carried

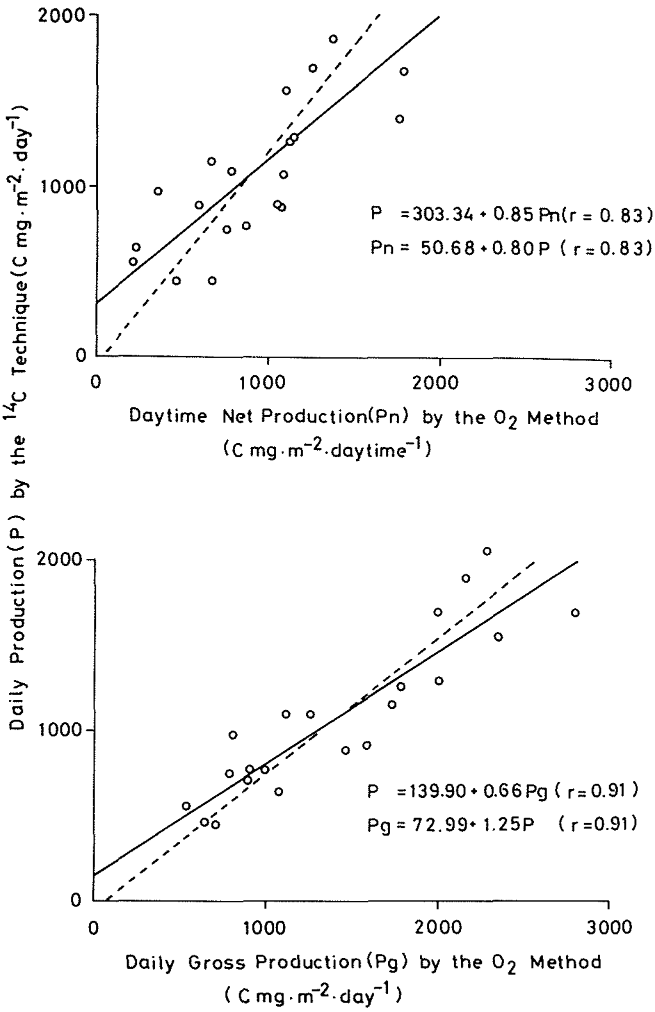

Fig. 9. Relationships of the daily production by the ^{14}C technique to the daytime net production and daily gross production by the O_2 technique. Solid line: the regression line of P on Pn or Pg. Dotted line: the regression line of Pn or Pg on P.

out by the O_2 technique concurrently with the ^{14}C technique during the investigated period. Relations of the daily primary production by the ^{14}C method to the daytime net production by the O_2 method or to the daily gross production are shown in Fig. 9. Here the amount of O_2 was converted to the amount of carbon using PQ=1.13 (Harris and Piccinum 1977). In accordance with the result obtained by Tilzer et al. (1977), the daily primary production (P) by the ^{14}C technique corresponded approximately to the daytime net production (Pn) by the O_2 technique though the former showed a tendency to be lower than the latter ($P=303.34+0.85$ Pn, $r=0.83$, $p<0.01$). Thus, the daily primary production obtained by the ^{14}C technique in the present study (Fig. 8) corresponds to the daytime net production with some possible underestimation.

A comparison of some limnological variables in 1980–1981 with those in 1971–1972

To know roughly the change in trophic status of this lake for the last ten years, some variables obtained in the present study are compared with those in 1971–1972 reported by Bonneto et al. (1976), who investigated some limnological parameters of this lake in spring (September), summer (January), autumn (May) and winter (July) from 1971 to 1972.

Ammonium-N, nitrate-N and dissolved reactive phosphate-P concentrations in the surface water and at 3 m depth were respectively 0.01–0.06, 0.00–0.12 and 0.00–0.04 $mg \cdot l^{-1}$ in 1971–1972. The respective nutrients seem not to be so different in their levels from the present results, though ammonium-N was a little lower in 1971–1972 than in 1980–1981. So far as judged from standing stock of the nutrients, eutrophication in this lake seems not to have been progressed during the last ten years. The pH values were 8.0, 8.3, 7.4 and 7.2–7.3 in September, January, May and July of 1971–1972, respectively, whereas they were 7.7–8.4, 8.1–8.9, 7.8–8.5 and 7.6–

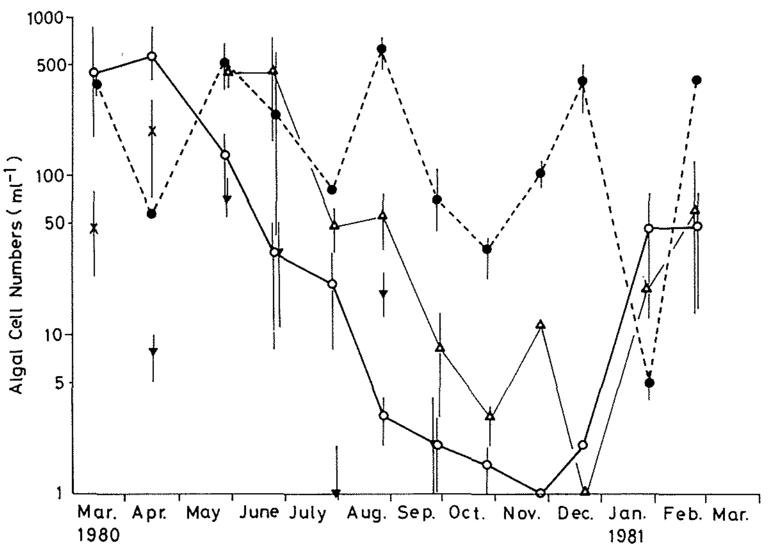

Fig. 10. Seasonal changes in major planktonic algae. Vertical lines: range of the counts in the morning, at noon and in the evening on the first day of each survery.
—○—, *Peridinium gatunense*; —△—, *Actinocyclus normanii*; --●--, *Melosira granulata*; ×, *Anabaena spiroides*; ▼, *Closterium aciculare*.

8.0 in the corresponding months of 1980–1981, respectively. It is noticed that the pH values became higher in 1980–1981, at least in autumn-winter, as compared with those ten years before.

Among the major species of phytoplankton in 1971–1972, *Anabaena spirodes* was observed abundantly in four seasons, *Aphanocapsa dellicattissima* and *Microcystis aeruginosa* in spring and summer, *Cryptomonas* spp. in autumn, and *Melosira granulata* in winter (Bonneto et al. 1976). In the present study, *M. granulata* was dominant or subdominant during the investigated period, *Closterium aciculare* and *Actinocyclus normanii* were abundant in spring, *Peridinium gatunense* and *A. normanii* in summer, *P. gatunense* and *A. spiroides* in autumn, and *A. normanii* and *P. gatunense* in winter (Fig. 10). It is clear that the major components of phytoplankton in this lake have changed noticeably and the pattern of their seasonal succession has also changed during the last ten years.

Chlorophyll *a* amounts in the euphotic zone were 27, 33, 2 and 14 $mg \cdot m^{-2}$ in spring, summer, autumn and winter, respectively, in 1971–1972 (Bonneto et al. 1976). In 1980–1981, they were 40–50 (mean value: 43), 5–130 (47), 60–130 (75) and 30–60 (36) $mg \cdot m^{-2}$ in the corresponding seasons, respectively. The chlorophyll *a* amounts seem to be higher in 1980–1981, especially in autumn-winter, than in 1971–1972.

The daily primary production was very high in spring of 1971 (1.6 $gC \cdot m^{-2} \cdot day^{-1}$) and summer of 1972 (5.3 $gC \cdot m^{-2} \cdot day^{-1}$) as compared with that in spring (0.9 $gC \cdot m^{-2} \cdot day^{-1}$) and in summer (0.8–1.1 $gC \cdot m^{-2} \cdot day^{-1}$) in 1980–1981. Taking into consideration the maximum daily production of 2.1 $gC \cdot m^{-2} \cdot day^{-1}$ in February of 1981, it can be concluded that the daily primary production of phytoplankton in photosynthetically active seasons was higher in 1971–1972 than in 1980–1981. It is not understandable why the daily primary production decreased in 1980–1981 in spite of higher amount of chlorophyll *a* in the euphotic zone.

It is true that the chlorophyll *a* amount and the pH value increased at least in autumn-winter and the major algal composition of phytoplankton noticeably changed during the last ten years, though it is very difficult to conclude how far the eutrophication has advanced in this lake.

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