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Production in Lake Superior,
May to November, 1973

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CHLOROPHYLL A AND PRIMARY PRODUCTION IN

LAKE SUPERIOR, MAY TO NOVEMBER, 1973

by

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ABSTRACT

Chlorophyll a and carbon-uptake studies from six lakewide cruises on Lake Superior from May to November, 1973, are presented. A maximum of 6.6 $\mu\text{g/litre}$ in September and a minimum of 0.3 $\mu\text{g/litre}$ in May of chlorophyll a (corrected for phaeophytins) and a range of cruise means of 0.9 - 1.4 $\mu\text{g/litre}$ was determined. C^{14} -uptake measurements showed a range of 0.3 to 5.7 $\text{mgC/m}^3/\text{hr}$ with carbon production having a range of 0.003 to 0.54 $\text{gC/m}^2/\text{day}$. Integration of the cruise means with time produced a minimal annual estimate of 30 $\text{gC/m}^2/\text{year}$.

RÉSUMÉ

Le présent document donne les résultats d'études faites sur la teneur en chlorophyll a et sur l'absorption de carbone, au cours de six expéditions sur le lac Supérieur entre mai et novembre 1969. Pour la chlorophyll a (données corrigées pour les phéophytines), on a déterminé une teneur maximale de 6.6 $\mu\text{g/litre}$ en septembre et une teneur minimale de 0.3 $\mu\text{g/litre}$ en mai, ainsi qu'un intervalle des moyennes observées au cours des expéditions compris entre 0.9 et 1.4 $\mu\text{g/litre}$. Les mesures de l'absorption du C^{14} ont donné un intervalle de 0.3 à 5.7 mg de carbone / m^3h et un intervalle de production du même élément compris entre 0.003 et 0.54 g/m^2 jour. L'intégration des moyennes observées selon le temps a donné une production estimative minimale et annuelle de 30 g de carbone/ m^2 .

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Introduction

There are little available data on the seasonal and lake-wide distribution of chlorophyll a concentration and primary productivity of Lake Superior. A few investigators have sampled portions of the lake, mostly nearshore and over a limited period of time (PUTNAM & OLSON, 1961), (PUTNAM & OLSON, 1966), (OLSON & ODLAUG, 1966), (PARKOS, OLSON & ODLAUG, 1969), (SCHELSKE & CALLENDER, 1970), and (SCHELSKE & ROTH, 1973).

This report presents the chlorophyll a and C^{14} -uptake results of six lake-wide surveys carried out by the Canada Centre for Inland Waters over the months May to November, 1973, as part of the programme of lake-wide coverage of the International and Canadian waters of the Laurentian Great Lakes.

Methods

Water samples were taken at a minimum of 114 and a maximum of 144 selected stations along the station grid (Fig. 1) on six cruises from May to November, 1973. On four cruises, samples were obtained from the top 20 m by a 0-20 m integrator (SCHROEDER, 1969). In shallow water, (< 22 m), the integrator was used down to two metres from the bottom. On the May cruise, samples were taken by a 0-50 m integrator, but because of the very slow lowering rate required by this size integrator, due to its narrow mouth, it was replaced on future cruises by the 0-20 m size. At the beginning of

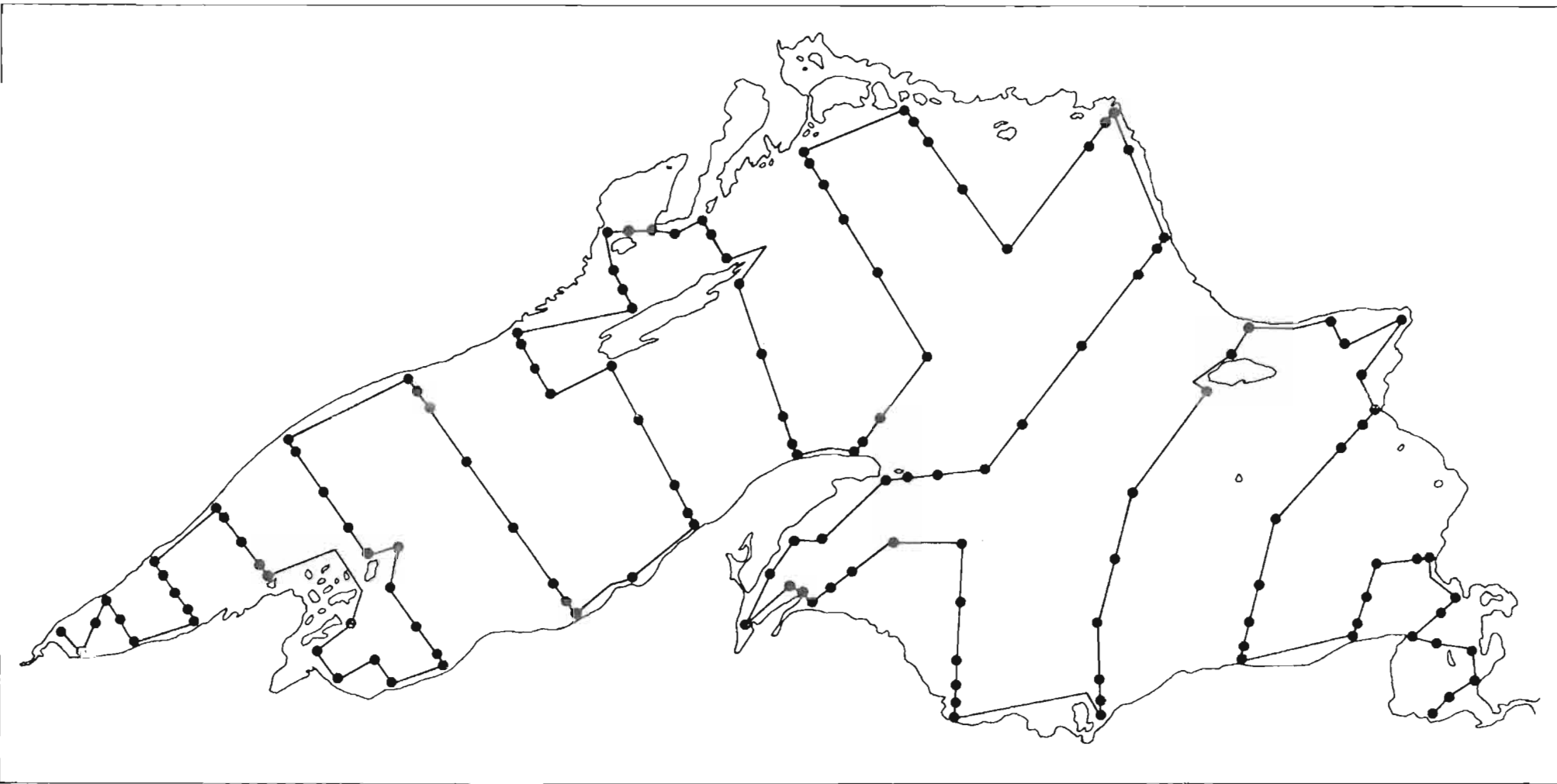


Figure 1. Lake Superior station grid, 1973. Biochemical stations at which chlorophyll samples were taken. Temperature only stations are not shown.

the October cruise, during sampling in rough weather, the integrator was lost when its supporting cable broke, and for the rest of the cruise determinations were made from a mixture of 5 m and 15 m water-bottle samples. The validity of integrator values was checked by comparing them with vertical profiles of chlorophyll a content from samples taken at 1, 5, 10, and 25 m.

The method of STRICKLAND & PARSONS (1963) was used for chlorophyll extraction. Water samples, ranging in volume from 0.5 L to 5.0 L, depending on the turbidity of the water, were filtered through 55 mm diameter Whatman GF/C glass fibre filters at a vacuum not exceeding 7 ins Hg. A few drops of $MgCO_3$ suspension were added to the last 100 ml of sample. After filtration, the unused portion of the filter was trimmed off, the filter laid on a 55 mm diameter Whatman No. 1 filter paper circle, folded, and frozen for shore analysis. After grinding in 90% acetone with a teflon pestle and centrifuging at 3,000 r.p.m. for 10 minutes, the optical density at 750, 663, 645, and 630 $m\mu$ was determined using a Unicam SP1800B spectrophotometer and the chlorophyll a concentrations determined by the use of SCOR-UNESCO (UNESCO, 1966) equations. Chlorophyll a was corrected for phaeopigments by the acidification method of LORENZEN (1967).

Primary productivity samples (of the integrated 0-20 m stratum) were distributed to two light and one dark 100 ml bottles and inoculated with a constant quantity (approx. 2 μc) of $Na_2C^{14}O_3$. The light bottles were placed on a rotating wheel in a glass tank through which lake water was continuously pumped. On each side of the tank was a bank of vertical high-output daylight fluorescent lamps having a constant light intensity of 40.10×10^{11} ergs/m²/hr (STADELMANN & MOORE, 1974). A further measurement

during 1974 confirmed this value. The dark bottles, wrapped in black tape, were enclosed in aluminum containers and placed in an open deck tank through which lake water was continuously pumped. Night samples and those collected within two hours of dusk were stored in this open tank until the following morning to reduce any aberrant activity resulting from light shock. At the end of each incubation period (2-4 hrs.), the contents of each bottle were filtered through a 47 mm diameter, 0.45 μ pore size Sartorius membrane filter. These were air-dried in plastic scintillation vials prior to counting by the technique of LIND & CAMPBELL (1969). Each vial was filled with approximately 18 ml of a solution of 6 g PPO + 0.075 g POPOP made up in one litre of scintillation grade toluene. The vials were capped and counted for radioactivity using a Nuclear Chicago Unilux II liquid scintillation system.

For in situ production studies, water samples were taken from 1, 5, 10, 15, 20, 30, 40, and 50 m, sub-sampled and inoculated as above, and resuspended at their respective depths for 4-6 hrs over the noon period. A 0-20 m integrated sample was taken at the same time, treated as above, and placed in the shipboard incubator for the same time period, as a control (STADELMANN & MOORE, 1974).

Hourly incident light measurements and 1 m transmissometer readings were supplied by THOMSON & JEROME (1974).

Data Treatment

Previous work demonstrated that the light level of the incubator (40.10×10^{11} ergs/m²/hr) approximated I_k for many conditions on Lake Ontario and that P incubator approximated P_{max} for in situ moorings. THOMSON & JEROME (1974) have demonstrated a relationship between extinction coefficient

and beam transmissometer readings at 1 m. From these approximations it is possible to estimate production on an areal basis from shipboard incubator measurements of C^{14} uptake.

The primary productivity formula of VOLLENWEIDER (1965) was adapted as a basis to convert the rates of C^{14} uptake to mg/m^2 :-

$$\Sigma p = \frac{P_{max} \cdot F(I_0/I_k)}{\epsilon}$$

where for the purposes of this report,

P_{max} = C uptake in $mgC/m^3/hr$ of the incubated samples.

ϵ = the extinction coefficient $\frac{\ln 100}{Z'}$, where Z' is the depth of 1% surface light intensity.

I_0 = mean hourly incident solar energy from 1000 to 1400 hours on the day of sampling in $ergs/m^2/hr$, measured continuously by a solarimeter on the ship.

I_k = the output of the incubator lights (40.10×10^{11} $ergs/m^2/hr.$).

F = a dimensionless number and a function of the photosynthetic active incident light (VOLLENWEIDER, 1965).

To convert to day rates, the percentage of total daily photosynthesis ($mgC/m^2/day$) to be expected during a 4-hour exposure (1000-1400 hrs) for $47^{\circ}N$ latitude, which passes through Lake Superior, was obtained from GAECHTER (1973).

Results - Chlorophyll a

The chlorophyll a values found in this study are low compared with reported values for the other Great Lakes. A range of individual station values from 0.3 to 6.6 $\mu g/litre$ was found over all six cruises.

Highest values were found in embayments and inshore of thermal bar formations for each cruise. Cruise mean values over the whole lake ranged from 0.9 to 1.4 $\mu g/litre$, reflecting in part the large offshore area

Table 1 Cruise data, Lake Superior, 1973.
Chlorophyll a concentrations from 0-20 m integrator samples.*

CRUISE	N	$\mu\text{g Ca/Litre}$			
		MAX	MIN	MEAN	S.E.
73-03-101	114	3.6	0.3	0.9	0.04
73-03-103	143	4.0	0.6	1.0	0.03
73-03-104	142	2.5	0.4	1.1	0.03
73-03-106	144	6.6	0.4	1.2	0.05
73-03-107	144	3.0	0.6	1.4	0.05
73-03-108	119	2.9	0.4	1.0	0.03

* On cruise 73-03-107, observations were made on a mixed sample of 5 m and 15 m water-bottle samples.

CRUISE 73-03-101
MAY 12 - 24, 1973
Corrected Chl. a $\mu\text{g/litre}$



CRUISE 73-03-103
JUN. 15 - 28, 1973
Corrected Chl. a $\mu\text{g/litre}$



CRUISE 73-03-104
JUL. 26 - AUG. 9, 1973
Corrected Chl. a $\mu\text{g/litre}$

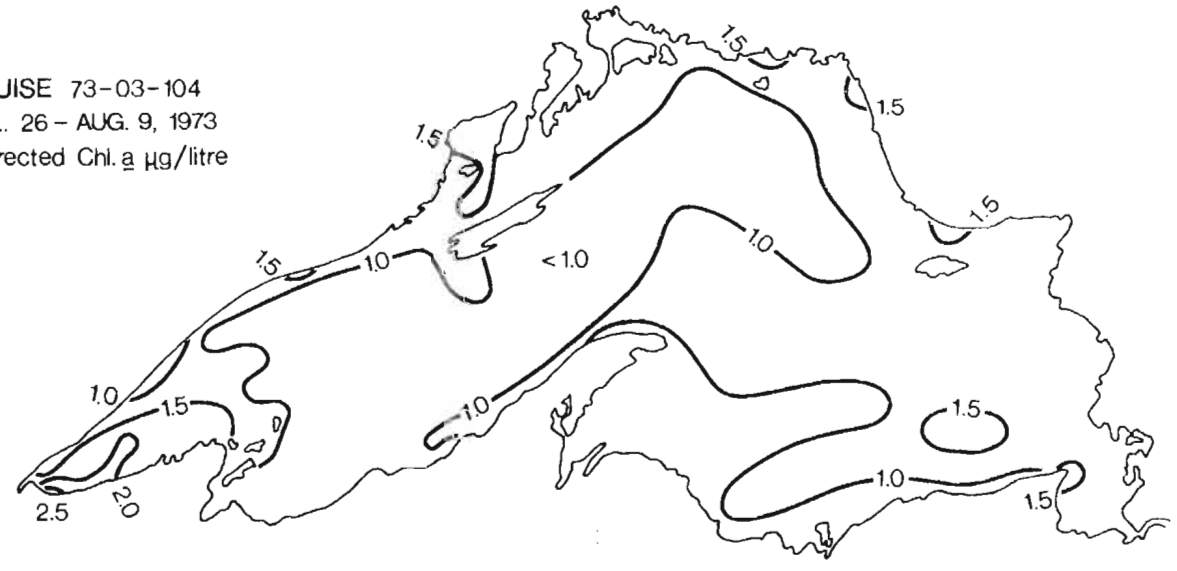
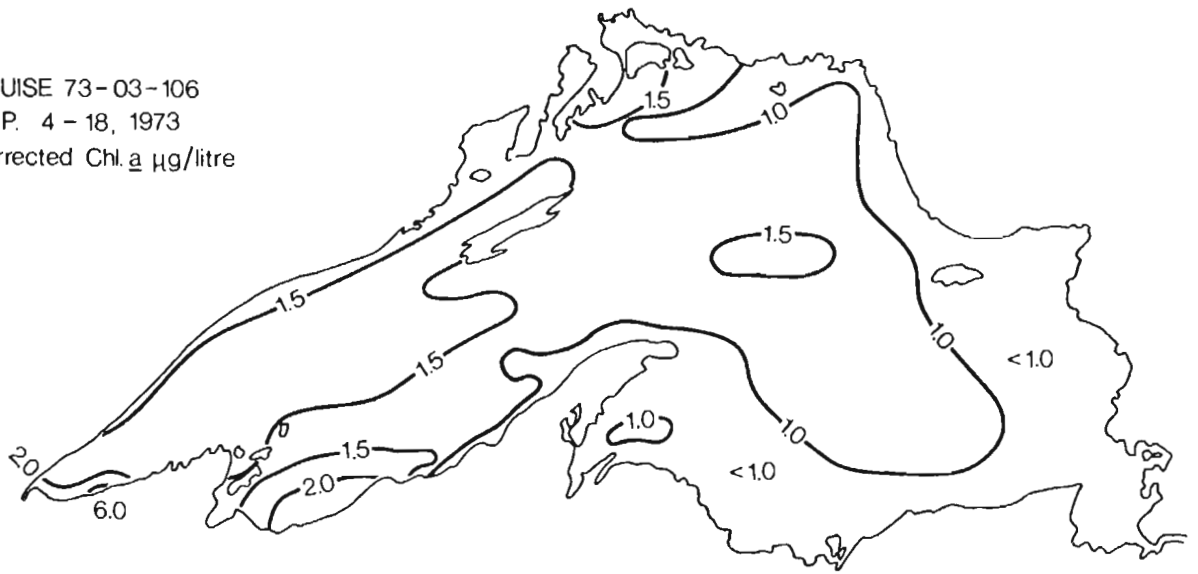


Fig. 2.a. Lake Superior, 1973. Surface water distribution of $\mu\text{g/litre}$ corrected chlorophyll a.

CRUISE 73-03-106
 SEP. 4 - 18, 1973
 Corrected Chl. a $\mu\text{g/litre}$



CRUISE 73-03-107
 OCT. 9 - 29, 1973
 Corrected Chl. a $\mu\text{g/litre}$



CRUISE 73-03-108
 NOV. 13 - DEC 3, 1973
 Corrected Chl. a $\mu\text{g/litre}$

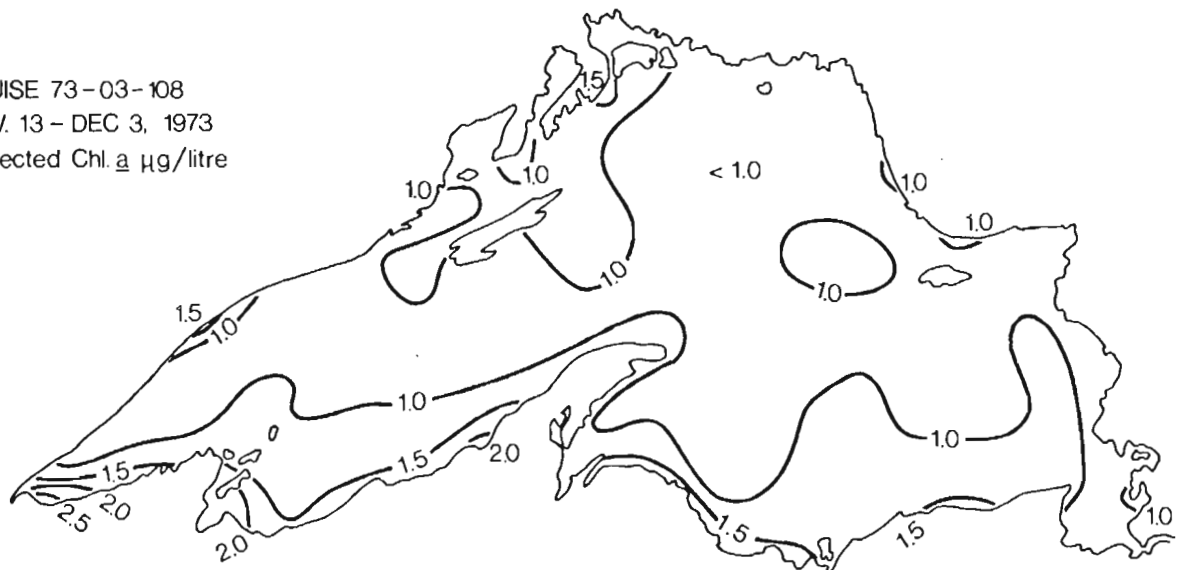


Fig. 2.b. Lake Superior, 1973. Surface water distribution of $\mu\text{g/litre}$ corrected chlorophyll a

of the lake where chlorophyll values scarcely exceeded $1.0 \mu\text{g/litre}$ at any time of the year (Table 1).

Vertical profiles of chlorophyll a from depths of 1, 5, 10, 25, 50, and 100 m from 20 stations on each of the cruises (to be described in detail elsewhere) indicate that except during the September cruise chlorophyll content was essentially uniform over the top 100 m. In September there was a marked concentration of chlorophyll at the 25 m stratum which was related by WATSON, THOMSON & ELDER (1974) to a layer of minimum light transmission profiles over much of the open water of the lake. Chlorophyll concentrations in this region were up to 3 times higher than in the top 20 m. Light extinction data from THOMSON & JEROME (1974) place much of this concentration below the 1% surface light level and hence the chlorophyll, while not in the form of degradation products, is considered to have sunk beyond the level where net production is appreciable.

The surface distribution of corrected chlorophyll a values are plotted in Figs. 2a and 2b. These demonstrate the low concentrations and great uniformity encountered. During May, most of the lake was below or slightly above $1 \mu\text{g/litre}$, with a high spot of $3.6 \mu\text{g/litre}$ near Duluth, and another of $2.0 \mu\text{g/litre}$ outside Huron Bay. A slight nearshore increase, with a maximum of $1.5 \mu\text{g/litre}$ along the south-west coast from the Apostle Islands to Fourteen-Mile Point was noticed. A maximum of $1.6 \mu\text{g/litre}$ was found in Thunder Bay. The situation during the June cruise was much the same, with low values offshore and a slight extension of the higher values along the southern shore. The July-August cruise showed higher values along the north shore, a value of $1.9 \mu\text{g/litre}$ being recorded in Thunder Bay. Low values were evident around Chequamegan Bay and Keweenaw Bay, with a minimum of 0.4 and $0.5 \mu\text{g/litre}$ respectively. In September the picture again changed

with highest concentrations appearing in the western half of the lake, culminating in a maximum of 6.6 $\mu\text{g/litre}$ just east of Duluth. This situation continued throughout October, with slightly higher values offshore. In November, the lake-wide chlorophyll a distribution appeared to be reverting to the same as was found in May, with the highest concentrations along the shore-line (1.0 to 2.1 $\mu\text{g/litre}$), and the central region of the lake decreasing to less than 1 $\mu\text{g/litre}$.

In summary, chlorophyll a concentrations in the top 20 m of Lake Superior are generally lower than those for the other Great Lakes. In the open waters of the lake, May values are less than 1.0 $\mu\text{g/litre}$, are not highly variable, increase slowly through the season to a maximum of 1.5-2.0 $\mu\text{g/litre}$ in September, and decline thereafter. Most of the year chlorophyll a is uniformly distributed in the top 50-100 m.

Values from the inshore waters of the lake are higher, and tend to increase to higher values behind the thermal bar in June.

The highest values in the lake were found in embayments, Keweenaw Bay, the Duluth basin, and south of the Apostle Islands. Compared with other embayments in the Great Lakes however, the seasonal change was small.

PUTNAM & OLSON (1961), working in the western end of the lake, found a range of from 0.4 to 2.8 $\mu\text{g/litre}$ between July and October, 1960. The results of PUTNAM & OLSON (1966), from the same area, gave as a mean of the top 20 m, a range of from 0.8 to 1.6 $\mu\text{g/litre}$ over July to September, 1961. SCHELSKE & ROTH (1973), working in the southeastern end, found 0.66 ± 0.42 $\mu\text{g/litre}$ in the open lake and 1.46 ± 0.19 $\mu\text{g/litre}$ in Whitefish Bay and Munising Harbor in July, 1970. These results would be slightly lower if corrected for phaeopigments, and they would be within the range of concentrations found in 1973.

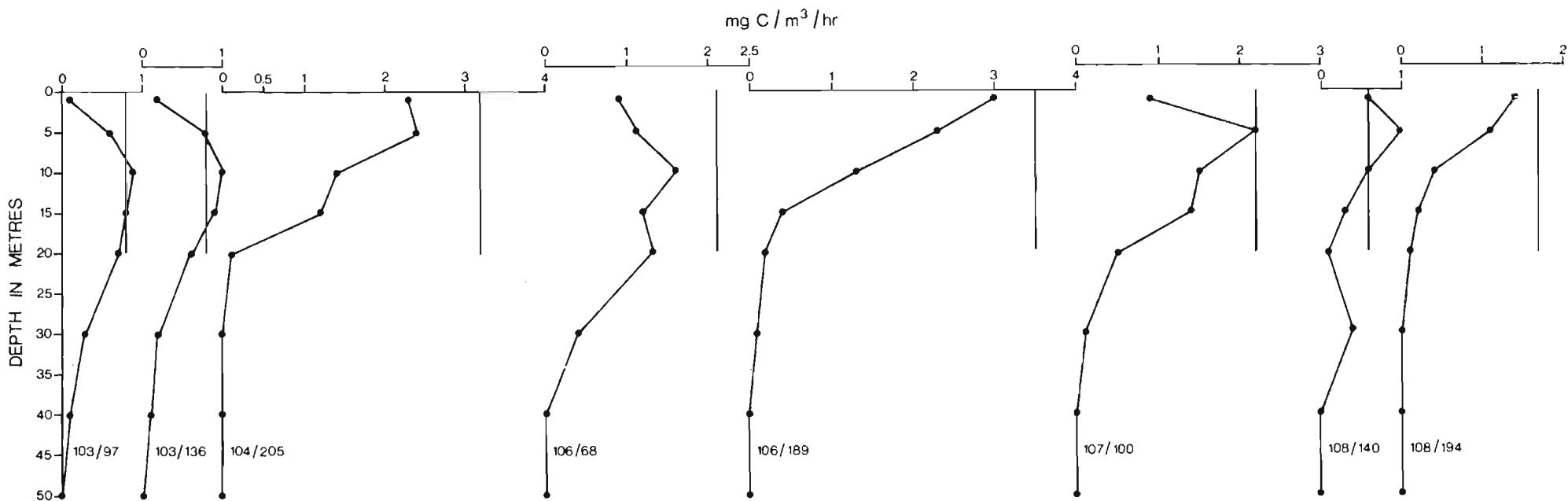


Figure 3. Lake Superior, 1973. Vertical profiles of *in situ* carbon-14 uptake. The numerals represent the cruise number and station number respectively.

Other lake-wide surveys have been carried out by the Canada Centre for Inland Waters and the cruise means are presented below in Table 2. The values for 1-metre samples as uncorrected chlorophyll a, are shown plotted in Appendix Figures 1 and 2.

Table 2 Uncorrected Chlorophyll a results, as $\mu\text{g/litre}$ from previous lakewide surveys on Lake Superior carried out by the Canada Centre for Inland Waters.

Cruise Data	N	$\mu\text{g/Ca/litre}$			
		Max.	Min.	Mean	S.E.
November 12 - 27, 1969	86	2.6	0.5	1.2	± 0.041
April 13 - 25, 1970	64	0.6	0.2	0.3	± 0.011
October 26 - November 10, 1970	85	4.0	1.2	2.2	± 0.054
May 25 - June 2, 1971	63	1.3	0.1	0.7	± 0.030
June 30 - July 7, 1971	70	1.7	0.5	0.6	± 0.021
October 5 - 13, 1971	67	2.9	0.7	1.4	± 0.055

Primary Production

Fig. 3 shows the eight in situ production profiles carried out from June to November. During the June cruise one series was taken offshore (103/97), southwest of the Slate Islands, and another (103/136) just outside and to the east of Thunder Bay. The production at both these stations were similar, having about the same small maximums at 10 m (0.9 and $1.0 \text{ mgC/m}^3/\text{hour}$) and decreasing to zero at around 45 m. On the July-August cruise, one series (104/205) was made in the vicinity of Two Harbors and showed a comparatively high uptake in the top 20 m with the Pmax

($2.4 \text{ mgC/m}^3/\text{hour}$) at 5 m. Two series were made during the September cruise, the one off Keweenaw Bay (106/68) having two maxima, at 10 m ($1.6 \text{ mgC/m}^3/\text{hour}$) and at 20 m ($1.3 \text{ mgC/m}^3/\text{hour}$), with carbon uptake occurring down to 35 m. This station was situated in the area where subsurface chlorophyll and transmissometer maxima occurred at 20 m. The other series, southeast of the Apostle Islands (106/189) showed a high surface production ($3.0 \text{ mgC/m}^3/\text{hr}$), decreasing with depth to zero at about 35 m. During the October cruise in Jackfish Bay, a production profile (107/100) showed a pronounced pulse at 5 m ($2.2 \text{ mgC/m}^3/\text{hr}$) and zero uptake again at about 35 m. During the November cruise, a profile (108/140) outside Thunder Bay showed two small but distinct pulses at 5 m ($1.0 \text{ mgC/m}^3/\text{hr}$) and at 30 m ($0.4 \text{ mgC/m}^3/\text{hr}$), and the other series (108/194), south of the Apostle Islands having its maximum ($1.4 \text{ mgC/m}^3/\text{hr}$) at the surface, decreasing to zero at around 25 m.

Because all but one of these in situ studies were taken near shore, at different positions and at different times, they have little value for the estimation of the productivity of the lake as a whole, but they have shown the close comparison with shipboard incubation of integrator samples for this purpose.

Comparisons of these in situ productivities integrated to a per m^2 basis and estimated areal productions from integrated water samples exposed in the shipboard incubator are shown in Fig. 4. It appears from the relatively close agreement that this treatment of the integrated samples will allow the calculation of lake-wide production estimates.

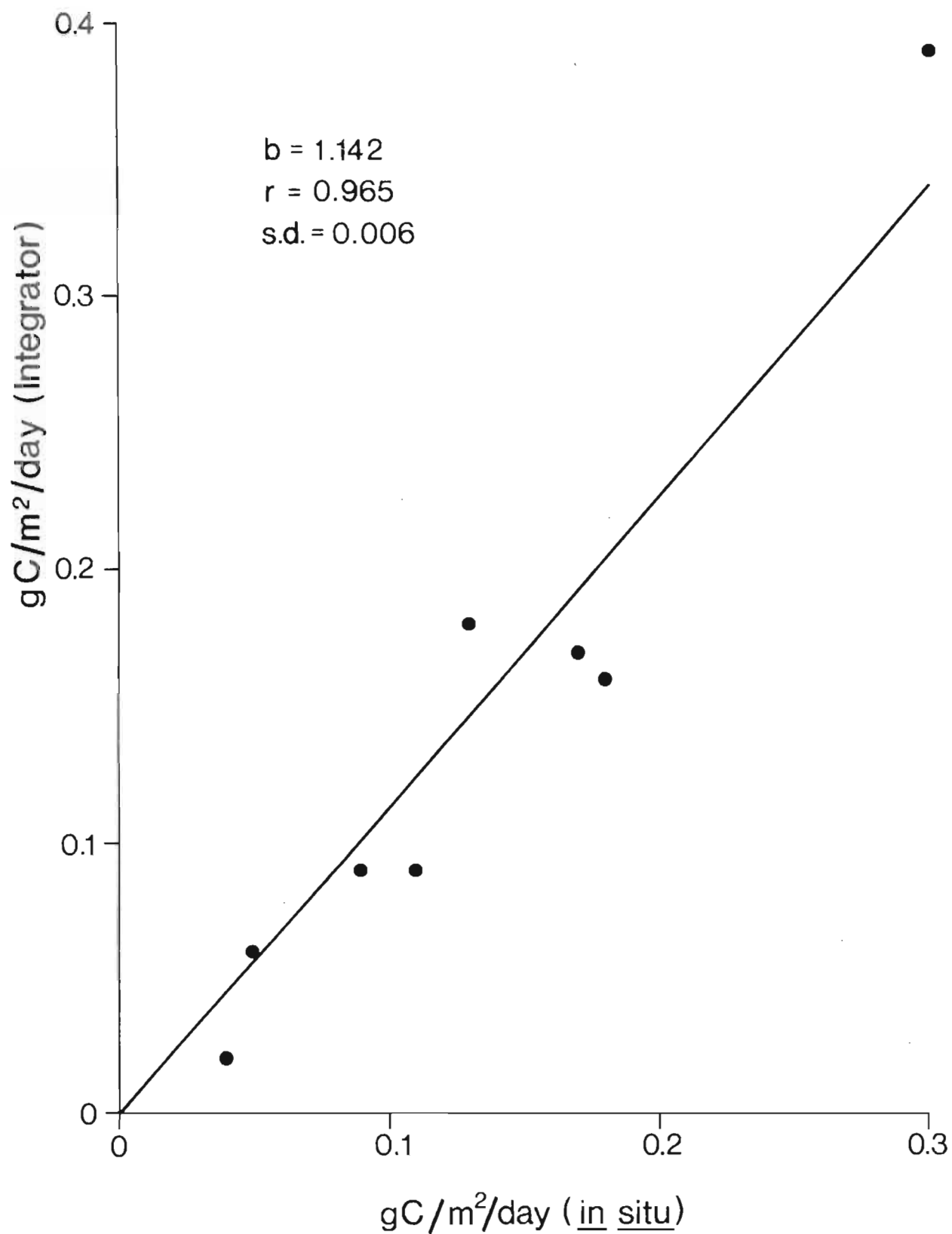


FIG. 4. Areal carbon-14 uptake from 8 in situ moorings plotted against calculated uptake from incubated 0-20m. integrated samples and light extinction data.

The results of the incubator C^{14} -uptake studies are charted in Figs. 5a and 5b. During the June cruise production was very low along the southern shore (0.03 to 0.10 $gC/m^2/day$), off Cape Gargantua (0.04 to 0.06 $gC/m^2/day$), and the Thunder Bay area (0.07 to 0.10 $gC/m^2/day$). The other lake values were slightly higher to a maximum of 0.32 $gC/m^2/day$ in the Pigeon River area. During the July-August cruise, the maximum (0.46 $gC/m^2/day$) was again in the Pigeon River area, and high values were found off Au Sable Point (0.36 $gC/m^2/day$) and Michipicoten Bay (0.31 $gC/m^2/day$). The lowest values (0.05 to 0.10 $gC/m^2/day$) were found in Whitefish Bay, Keweenaw Bay, and off the Apostle Islands. During September, a burst of production appeared off Huron Bay (maximum 0.54 $gC/m^2/day$) stretching easterly along the south coast to Whitefish Bay. Apart from a small high (0.33 $gC/m^2/day$) in the Pigeon River area, production in the rest of the lake remained low. A general lake-wide decrease in production occurred throughout the next two cruises, ranging from 0.01 to 0.24 $gC/m^2/day$ in October, to 0.003 to 0.14 $gC/m^2/day$ in November.

Cruise means of production are given in Table 3. These show the range of mean production per cruise as 1.0 to 2.7 $mgC/m^3/hr$ and 0.03 to 0.23 $gC/m^2/day$.

PUTNAM & OLSON (1961), working in the southwestern end of the lake between July and September, 1961, measured a range of production of 0.8 to 0.51 $gC/m^2/day$. OLSON & ODLAUG (1966) in the western end in July and August, 1964, found a mean carbon production of 0.43 $mgC/m^3/hr$ or, assuming a photic zone of 20 m, 0.18 $gC/m^2/day$. The results of PARKOS, OLSON & ODLAUG (1969), from samples taken from Duluth to Whitefish Bay, gave cruise

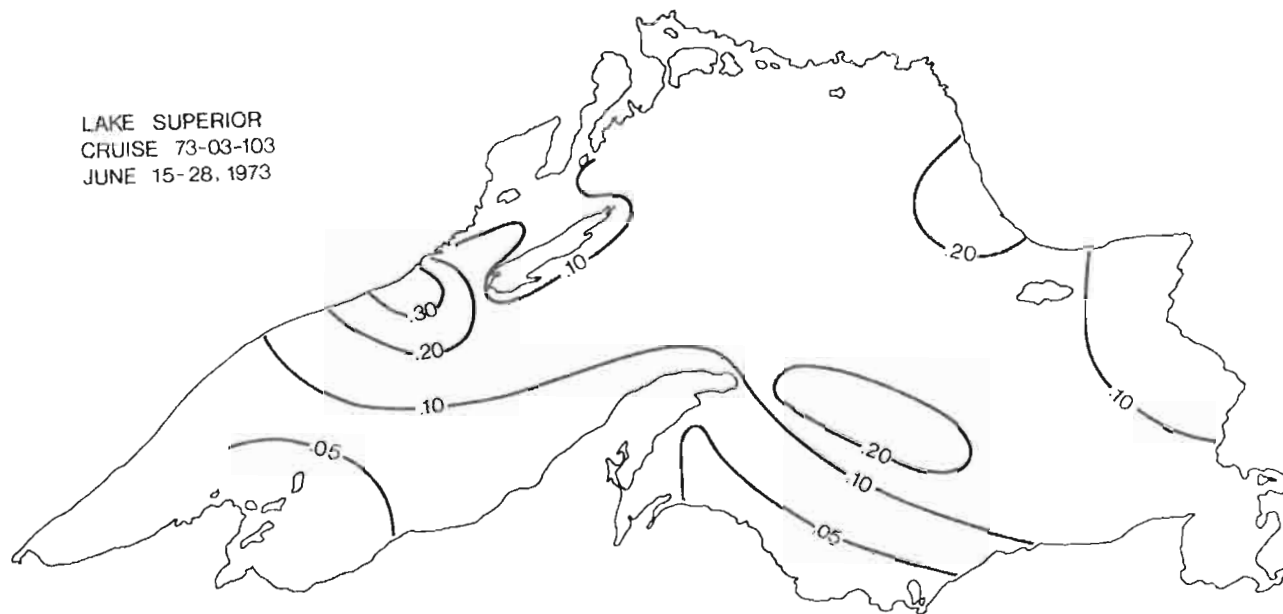
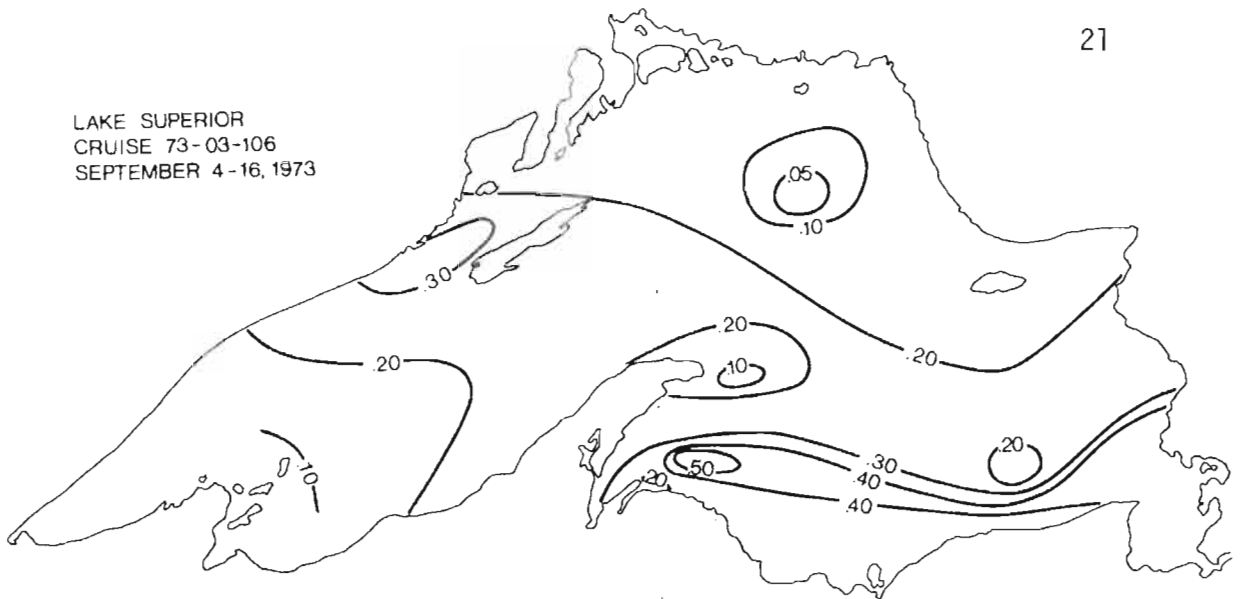
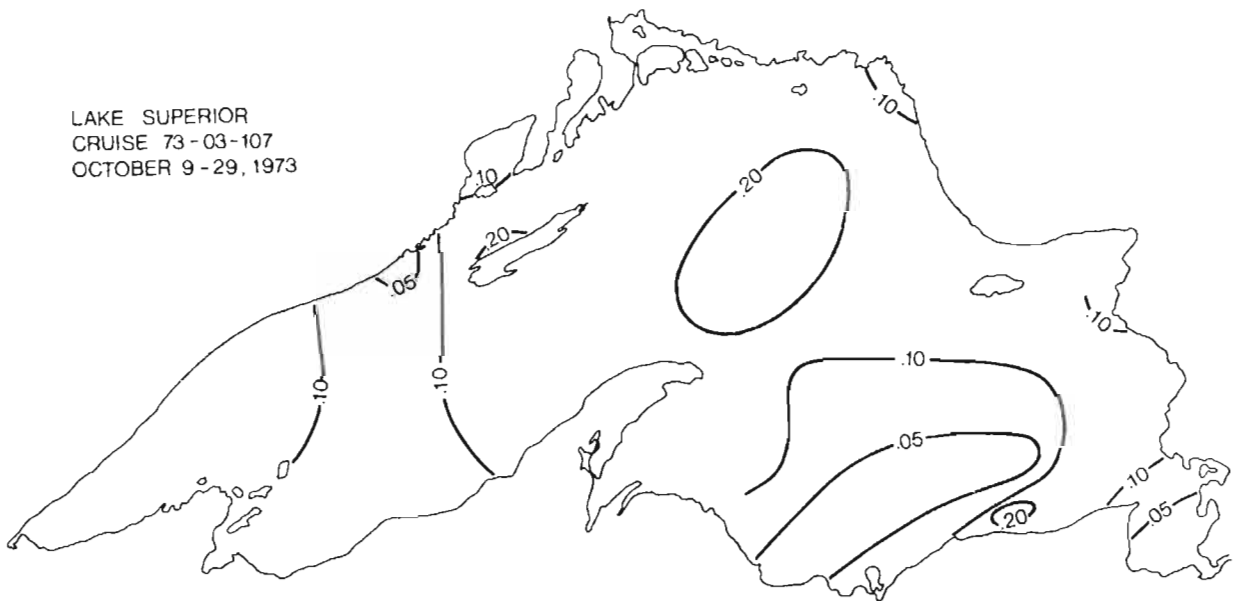


Figure 5.a. Lake Superior, 1973. Primary production in $g.C/m^2/day$.

LAKE SUPERIOR
CRUISE 73-03-106
SEPTEMBER 4-16, 1973



LAKE SUPERIOR
CRUISE 73-03-107
OCTOBER 9-29, 1973



LAKE SUPERIOR
CRUISE 73-03-108
NOV. 13 - DEC 3, 1973



Figure 5.b. Lake Superior, 1973. Primary production in g.C/m²/day.

Table 3 Cruise data, Lake Superior, 1973. C-14 uptake from 0-20 m integrator samples.*

CRUISE	N	mgC/m ³ /hr				gC/m ² /day			
		MAX	MIN	MEAN	S.E.	MAX	MIN	MEAN	S.E.
73-03-103	51	2.0	0.6	1.0	0.05	0.32	0.03	0.12	0.010
73-03-104	58	5.7	0.3	2.2	0.13	0.46	0.03	0.17	0.013
73-03-106	53	5.4	0.4	2.7	0.15	0.54	0.04	0.23	0.013
73-03-107	44	3.7	0.4	2.1	0.11	0.24	0.01	0.12	0.009
73-03-108	45	3.0	0.5	1.1	0.07	0.14	0.003	0.03	0.004

* On cruise 73-03-107, observations were made on a mixed sample of 5 m and 15 m water-bottle samples.

means between 0.65 and 2.18 mgC/m³/hr for the period June to October, 1967, and between 1.18 and 1.57 mgC/m³/hr for the period May to August, 1968. SCHELSKE & CALLENDER (1970), sampling along the southern shore from the Apostle Islands to Whitefish Bay, July 2-9, 1969, calculated a mean production of 0.39 ± 0.11 mgC/m³/hr. SCHELSKE & ROTH (1973), working in the southeastern end of the lake in July, 1970, calculated a C¹⁴-uptake of 0.37 ± 0.18 mgC/m³/hr in the open lake and 0.59 ± 0.14 mgC/m³/hr in Whitefish Bay.

Estimates of Annual Production

Fig. 6 shows the mean gC/m²/day for each cruise plotted against time. Each end of the curve has been extended to zero production so that an estimate of annual production can be made. By summarizing the average production for each month an estimate of 30 gC/m²/year is obtained. This value would be slightly greater if winter primary production was included in the calculations.

According to Vollenweider et al (1974), long-term estimates of chlorophyll a concentrations can be used to estimate annual production using the formula:-

$$\text{gC/m}^2/\text{year} = 420 \cdot \frac{1.15 (\text{mgCa/m}^3)^{1.33}}{9 + 1.15 (\text{mgCa/m}^3)^{1.33}}$$

The mean uncorrected chlorophyll a concentration from May to November 1973 in Lake Superior was 1.2 mg/m³. An annual production of 58 gC/m²/year is found using this formula. This is about twice as much as was calculated from the C¹⁴ studies, but since the mean chlorophyll a concentration figure did not cover the period December to April, when algal concentration must be low, the above estimate will have a positive bias.

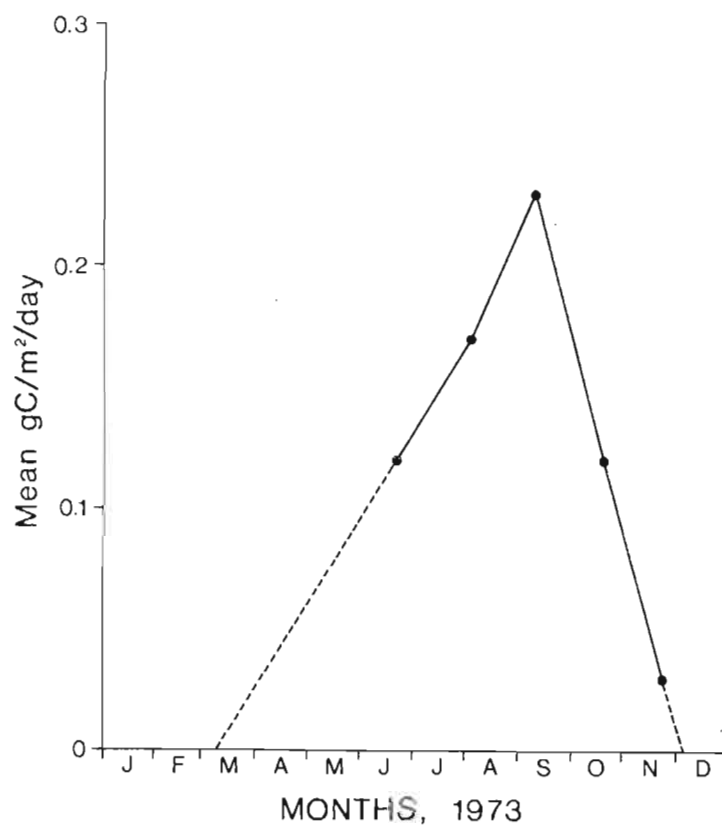


Figure 6. Lake Superior, 1973. Graph showing seasonal trends of production, and extended to zero winter values in order to provide a means of estimating annual production.

Vollenweider et al (1974) also assessed a production of 40-50 $\text{gC/m}^2/\text{year}$ from the data of PARKOS et al (1969).

It can be assumed that the true annual carbon production of Lake Superior in 1973 lay within the ranges quoted above, and all three estimates are within the ranges for oligotrophic lakes as suggested by most limnological investigators.

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Acknowledgements

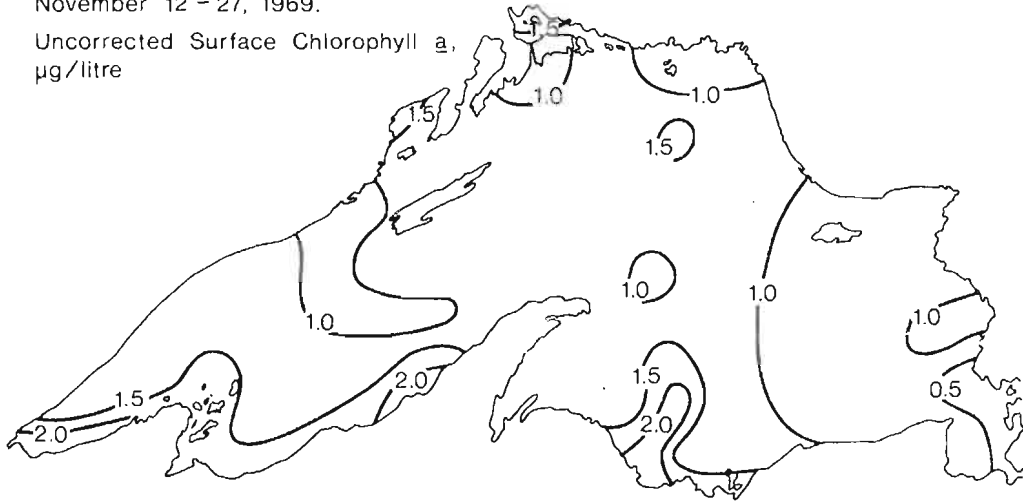
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Lake Superior

Cruise 69-03-02
November 12-27, 1969.

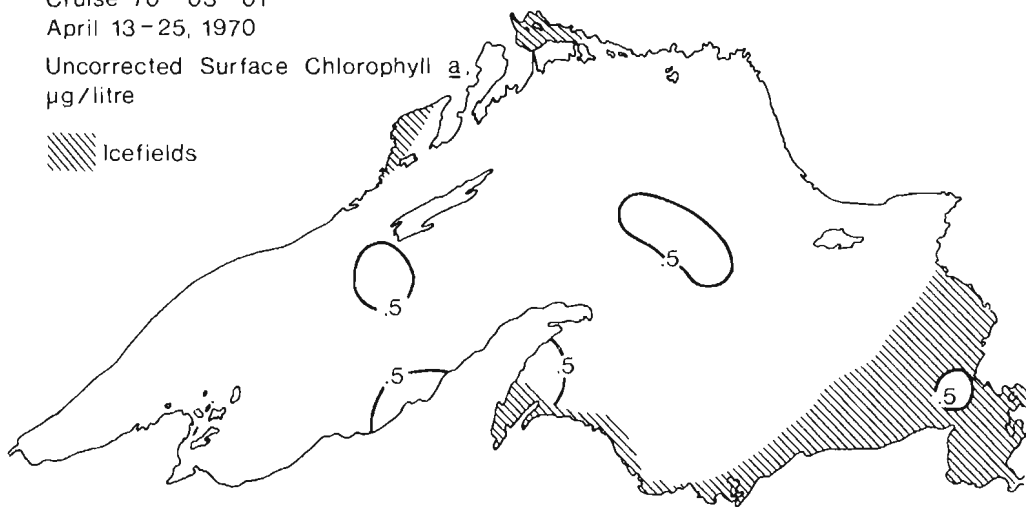
Uncorrected Surface Chlorophyll a,
 $\mu\text{g/litre}$



Cruise 70-03-01
April 13-25, 1970

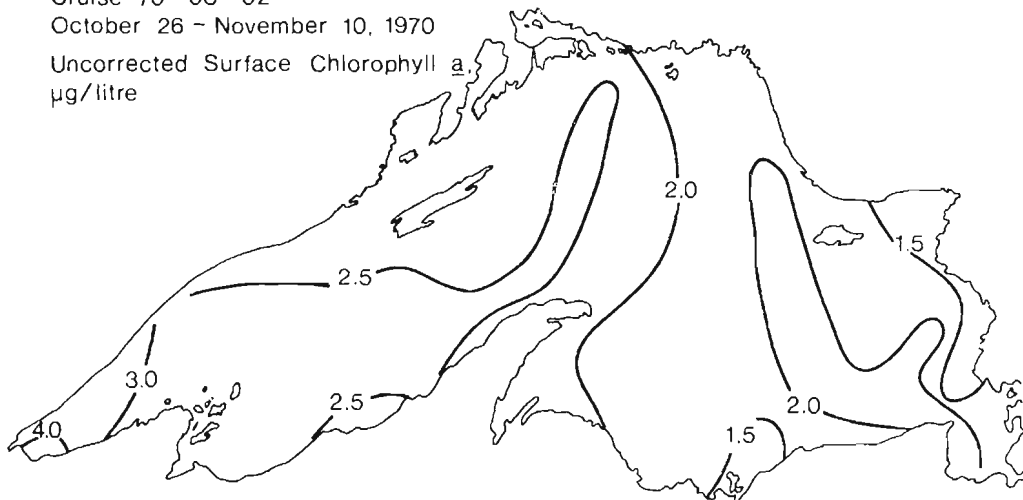
Uncorrected Surface Chlorophyll a,
 $\mu\text{g/litre}$

Icefields

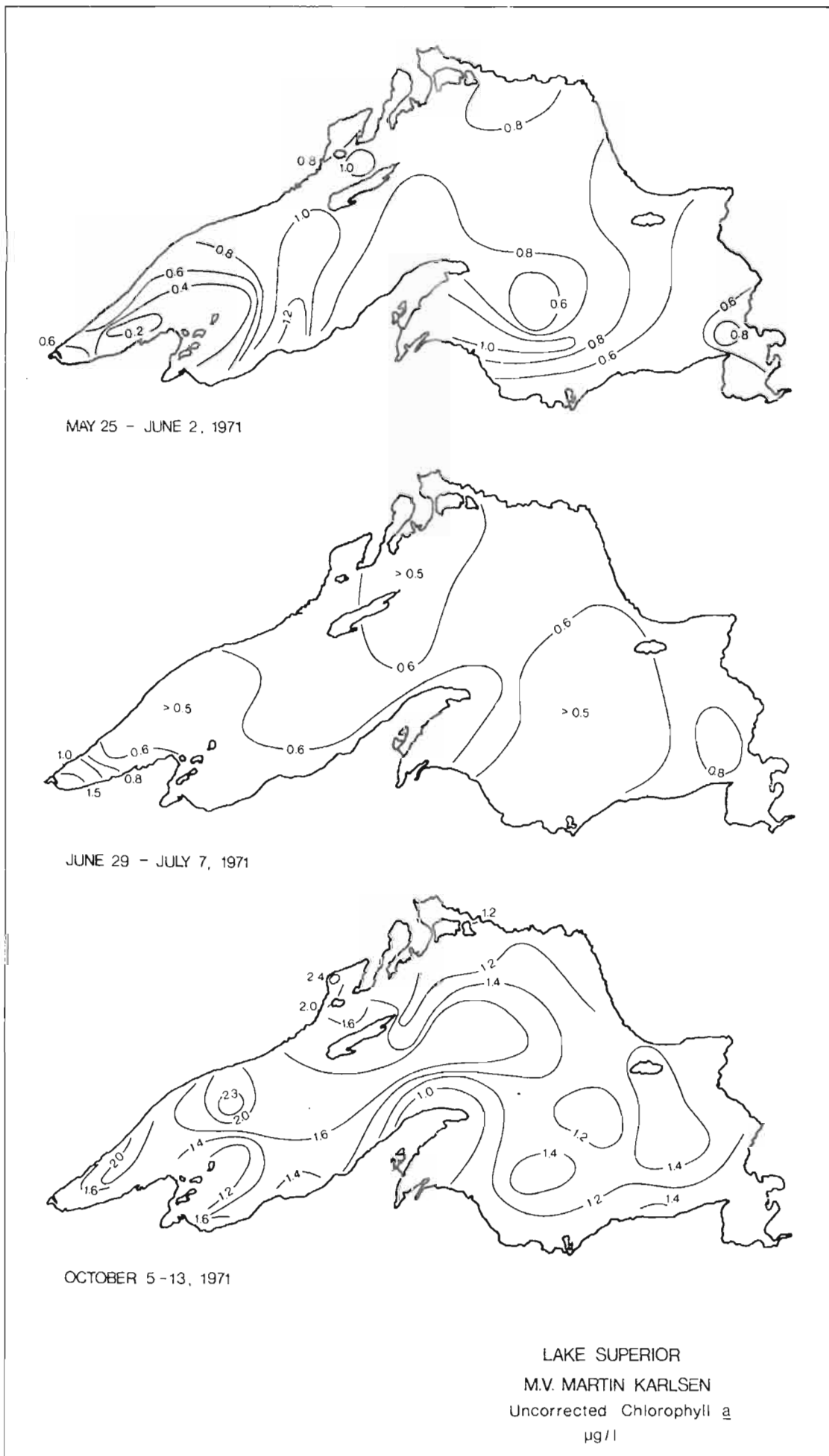


Cruise 70-03-02
October 26 - November 10, 1970

Uncorrected Surface Chlorophyll a,
 $\mu\text{g/litre}$



App. Figure 1. Lake Superior 1969 and 1970. Surface distribution of uncorrected chlorophyll a.



App. Figure 2. Lake Superior, 1971. Surface distribution of uncorrected