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Long-term (1927-1978) changes in the phytoplankton community of Lake Michigan at Chicago[1]

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BAYBUTT, R. I. and J. C. MAKAREWICZ (Dept. Biol. Sci., SUNY Brockport, Brockport, NY 14420). Long-term (1927-1978) changes in the phytoplankton community of Lake Michigan at Chicago. Bull. Torrey Bot. Club. 108: 240-254. 1981.—Fifty-one years of phytoplankton data from the South District Water Intake of the Chicago Water Filtration Plant were analyzed to determine changes in the phytoplankton community related to the eutrophication of Lake Michigan. From 1930 to 1940, a net biomass ($\sim$100 mg C/m^3) indicative of oligotrophic-mesotrophic conditions were implied by the net algal biomass. By 1961 net algal biomass was $\sim$600 mg C/m^3—a biomass indicative of a eutrophic lake. Much of the biomass increase is due to *Tabellaria, Stephanodiscus tenuis* and *S. binderanus*. Since the early 1970's, there has been a consistent general decrease in algal biomass to levels associated with oligotrophic-mesotrophic conditions. The decrease in net algal biomass, the decrease in abundance of eutrophic species, the small but general increase in genera that were decreasing in relative abundance until $\sim$1972, and the increase in dissolved reactive silica concentrations in Lake Michigan suggest a reversal of cultural eutrophication of Lake Michigan near Chicago. Only the increase in the relative abundance (22% of the total community biomass in 1978) of blue-green algae, mostly *Oscillatoria* and *Gomphosphaeria*, argues for accelerated eutrophication.

Key words: phytoplankton, Lake Michigan, community structure, biomass, eutrophication, blue-green, prokaryotes, diatoms.

Phosphorus limitation of phytoplankton growth, the effect of increased phosphorus (P) loading on phytoplankton abundance, the decrease in Lake Michigan water quality and the cultural eutrophication of Lake Michigan in general are well documented (Schelske and Stoermer 1971; Beeton 1965; Holland 1968; also see Tarapchak and Stoermer (1976) and Torrey (1976) for excellent reviews on the subject). In an attempt to halt and possibly reverse the cultural eutrophication of Lake Michigan, federal, state and local legislation was enacted to reduce P loading. Water-pollution control agencies of the states bordering Lake Michigan initially established an 80% P removal from waste water inputs in 1972 (Lee 1972). The 80% P removal from waste water was recently improved to a goal of 1 mg P/l for sewage effluent. Legislation banning or regulating phosphate in detergents exists in Michigan, Indiana, Illinois and most recently in Wisconsin.

Near Chicago, a marked decrease (40%) in P loading via the Indiana Harbor Canal between 1969 and 1973 has been attributed to improved sewage treatment and the regulation of phosphate content of detergents (Snow 1974). The Indiana Harbor Canal is within 15 km of the South District Water Intake Crib of the City of Chicago.

Control of P loading to Lake Michigan has been particularly evident in Illinois. Industrial discharge to Lake Michigan was to be eliminated by 1973 (Great Lakes Water Quality Board 1973). The Metropolitan Sanitary District discharges away from the Lake Michigan watershed (G.L.W.Q.B. 1973). In the North Shore Sanitary District, the Park Avenue and Ravine Drive sewage treatment plants (STP) at Highland Park and Lake Bluff STP were completely diverted in 1975, North Chicago STP in 1976, and Lake Forest and Waukegan STP in 1978 (S. Gardebring,[3] pers. comm.,

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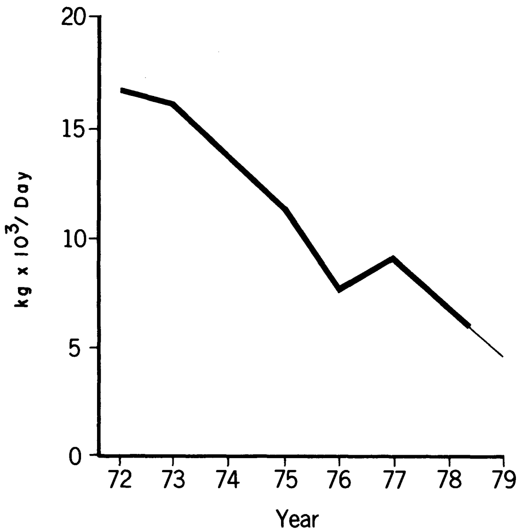

Fig. 1. Phosphorus loading from sewage treatment plants in Lake Michigan. Modified from Great Lakes Commission (1979) based on data from Great Lakes Water Quality Board (1974 and 1978).

1979). All the sewage treatment plants of the North Shore Sanitary District are now diverted away from Lake Michigan into the Skokie or Des Plaines Rivers, with the exception of the Hammond Sanitary District, a tertiary treatment facility, and some of the wet weather flows of the Waukegan STP.

The phosphate-in-detergents ban and the diversion and treatment of sewage have resulted in a decrease in P loading from sewage treatment plants (Fig. 1). A general decrease in ambient phosphate concentrations is evident since ~1975 for the nearshore waters off Chicago (Fig. 2).

Phytoplankton hold a unique position in aquatic ecosystems: they represent the interface between the physiochemical environment and biological communities of higher trophic levels (Saunders 1963; Tarapchak and Stoermer 1976). Thus, algal populations are sensitive to environmental

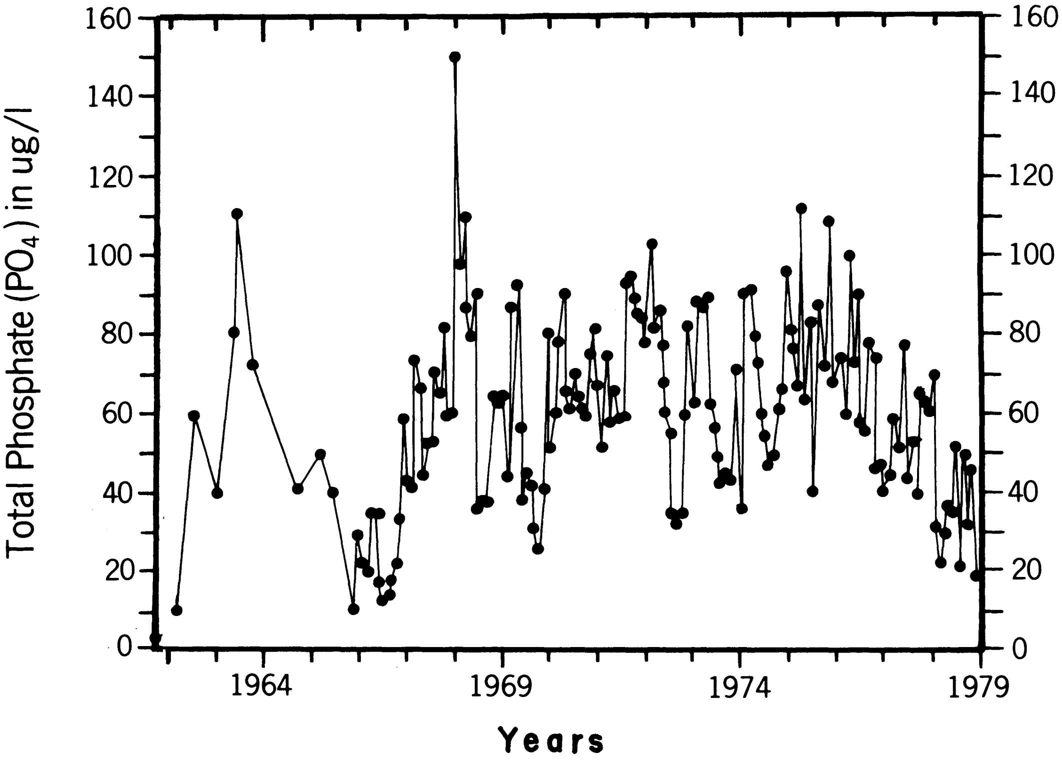

Fig. 2. Total phosphate concentrations at the South District Water Filtration Plant of the City of Chicago. Figure modified from Rockwell (1979). Prior to 1962 data sheets did not distinguish between ortho or total phosphate and thus are not reported here.

perturbations and can signal ecosystem improvement or degradation. Phytoplankton biomass, species composition in general and certain algal species can be used as indicators of water quality and trophic conditions (Vollenweider, Munawar and Stadelman 1974). For this reason, long-term changes in the phytoplankton of the nearshore waters of Chicago were studied.

Phytoplankton have routinely been collected and identified at the City of Chicago Water Filtration Plant for over 50 yr. This record is one of the longest for phytoplankton known to exist from one location. Portions of this data set have been analyzed by Damann (1945, 1960, 1966), Baylis (1957) and Vaughn (1961, 1970).

We have analyzed algal species composition and biomass for the entire 51 yr of data available from the Chicago Water Filtration Plant. In this study we document phytoplankton changes associated with the cultural eutrophication of the nearshore waters of Lake Michigan at Chicago since 1927 and provide evidence for a reversal of the eutrophication process in the inshore waters off Chicago in the past 5 to 10 years.

Methods. The Chicago Water Filtration Plant has undertaken regular quantitative analyses of phytoplankton organisms since 1926, often for 7 days a week, 52 weeks a year. Water chemistry data also exists for much of the same time period. Their samples have been obtained from untreated Lake Michigan water, coming directly through pipes from permanent intake structures. During this period, up to four water intake cribs at four locations have been in operation. Phytoplankton identification and counts over the 51-yr period (1927–1978) were made by Chicago Water Filtration Plant personnel.

We used phytoplankton data from the South District intake crib which had the longest continuous record. Between 1927 and 1934, phytoplankton abundance was available only as a mean value for four cribs (Wilson, Dever, Four-Mile and South District). No phytoplankton data could be located for 1948. In all other years, the reported data are from the South District water intake crib, with one exception (1946–1947). In a comparison of the counts from Wilson, Dever, Four-Mile and South District, we found no significant difference ($P = .01$) between cribs, except for 1946 and 1947. Furthermore, in the data summaries provided by the Chicago Water Filtration Plant, South District data were not included in the calculated means for 1946 and 1947. Although no reason is given, they apparently believed the South District data were inaccurate. Because exceedingly low densities were reported from South District from 1946–1947, mean densities of the other three cribs (Wilson, Dever and Four-Mile) were used.

The South District water intake crib is located 3.5 km from shore in 10 m of water. In the mid 1960's, a new crib with larger intake capacity was built approximately 16 m from the original South District crib and named the South District Crib. Further description of the cribs may be obtained in Damann (1945).

Water for phytoplankton samples was obtained at the filtration plant after being piped from the intake crib. Known volumes of water were concentrated by the Sedgewick-Rafter Method (A.P.H.A. 1960). In this procedure, phytoplankton are concentrated by filtration through sand supported in funnels by silk bolting discs. After filtration, the sand and silk disc are washed and a known aliquot of the washings is transferred to a Sedgewick-Rafter cell for counting at 200X magnification by the strip technique, a technique that would probably underestimate small flagellates. Even though other more modern techniques are currently available for phytoplankton enumeration, the use of the Sedgewick-Rafter Method was continued in an apparent attempt to maintain consistency in data handling over the 51-yr collection period.

Cooperating with personnel from the Chicago Water Filtration Plant, especially Mr. W. Ginsburg, we compared the Sedgewick-Rafter Method with the settling chamber method. On 1 November 1979, five duplicate samples were taken from the South District crib at Chicago. Using their routine procedure, the Chicago laboratory counted one set of samples. In our laboratory, 25 ml of each of the second set of five samples were stained with aniline blue and settled for 72 hr. Two field diameter transects (263X and 525X) were counted.

A more diverse complement of phytoplankton is evident with the settling chamber procedure (Table 1). Undoubtedly, the higher magnification possible with the inverted microscope is the reason for the great number of nannoplankters (e.g., *Cryptomonas* spp., *Chrysochromulina,* unidentified nannoplankters) observed. Vollenweider, Munawar and Stadelman (1974) and Tarapchak and Stoermer (1976) have also suggested that techniques similar to those used at Chicago (i.e., Sedgewick-

Table 1. Comparison of South District counts by the Sedgewick-Rafter and settling chamber procedures. H indicates count was made at 525X, while L indicates count was at 226X with settling chamber procedures.

Organism	Settling Chamber	Sedgewick-Rafter Cell
Diatoms		
Asterionella	130.0 ± 14.4	52 ± 22.0 L
Tabellaria	34.8 ± 9.7	40 ± 24.7 L
Fragilaria	4.4 ± 1.3	— L
Synedra	16.0 ± 1.4	4 ± 3.6 L
Rhizosolenia	10.3 ± 2.4	— H
Surirella	0.4 ± 0.4	— L
Cyclotella (>15 μ)	15.6 ± 1.5	— L
Cyclotella (<15 μ)	55.2 ± 4.9	— H
Unidentified pennate diatoms	37.2 ± 5.9	— L
Navicula	—	4 ± 3.6 L
Blue-Greens		
Gomphosphaeria	14.0 ± 1.2	24 ± 8.8 L
Anacystis	25.6 ± 8.0	16 ± 8.8 L
Aphanocapsa sp. 1	20.0 ± 2.3	— H
Aphanocapsa sp. 2	32.2 ± 1.2	— H
Chroococcus spp.	19.2 ± 2.5	— L
Anabaena	19.6 ± 3.5	— L
Oscillatoria	2.0 ± 0.8	— L
Gloeocapsa	0.4 ± 0.4	— L
Cryptomonads		
Cryptomonas erosa	16.0 ± 2.0	— L
C. pusilla	157.6 ± 14.2	— H
Greens		
Cosmarium	2.4 ± 0.9	— L
Franceia	1.6 ± 0.4	— L
Dictyosphaerium	2.4 ± 0.4	— L
Oocystis	14.8 ± 3.1	4 ± 3.6 L
Elakaththrix	6.4 ± 2.1	— H
Scenedesmus	3.6 ± 1.0	— L
Greens		
Gloeocystis	6.0 ± 1.7	— L
Chlamydomonas	5.6 ± 1.5	— H
Pediastrum	0.4 ± 0.4	— L
Spinoclosterium	0.4 ± 0.4	— L
Unknown coccoid	46.0 ± 9.4	— H
Chrysophytes		
Dinobryon	2.0 ± 0.6	— L
Chrysochromulina	262.0 ± 26.2	— H
Ochromonas	32.8 ± 4.1	— H
Pseudokephyrion	7.2 ± 1.8	— H
Monosiga	22.4 ± 5.1	— H
Diceras	1.6 ± 0.9	— H
Chrysococcus	3.2 ± 0.7	— H
Dinoflagellates		
Gymnodinium	1.2 ± 0.7	— L
Unidentified Nannoplankters		
a. flagellate, 5μ	48.8 ± 8.1	— H
b. coccoid colony of three, 6μ	27.2 ± 4.1	— H
c. coccoid, 6–7 μ	20.8 ± 3.6	— H
d. other	417.6 ± 22.3	— H

Rafter membrane filter) would underestimate small flagellates. A cell size of perhaps 15 to 20 μm is the minimum size that can be effectively counted at 200X with the Sedgewick-Rafter cell. The counting and sampling technique employed at Chicago has a sensitivity of ~25 to 30 cells/ml for cells larger than 15 to 20 μm. These results suggest that the data from Chicago are not quantitative for nannoplankters and generally provide a conservative estimate of abundance with a greater counting variance of the larger phytoplankter cells (i.e., diatoms) than the settling chamber technique. The data collected at Chicago appear to represent the "net phytoplankton."

The data records of the past 51 yr indicate that different personnel with probably differing taxonomic ability, resulting in an unmeasurable variation in taxonomy and possibly technique, have counted phytoplankton at Chicago. For example, between 1928 and 1939, high densities of an unknown diatom(s) were reported in the Chicago data as "Other Diatoms." Damann[4] (personal notes, examined by authors, 1978) recounted and identified the unknown diatoms in samples from 1928, 1932, 1933 and eleven months of 1934, finding ~90% of the "Other Diatoms" to be *Nitzschia*. We have adjusted our data to account for the above.

After noting an increase in an unknown diatom, Baylis (1957) recounted samples from 1956 and early 1957. His abundance values for *Stephanodiscus hantzschii* are entered into our data. The large abrupt increase observed in *S. hantzschii* (Fig. 4) between 1955 and 1956 is questionable. Since Baylis apparently did not recount any samples prior to 1956, *S. hantzschii* was probably grouped in with the "Other Diatoms" prior to 1956.

Stoermer and Ladewski (1976) reexamined some of this material and concluded that *S. hantzschii* was actually *Stephanodiscus tenuis*. Ginsburg[5] (pers. comm., 1978) has recently questioned the identification of *S. tenuis* because of the inability to distinguish these species from similar species at the magnifications used in the routine counting at Chicago. We have followed Stoermer and Ladewski's identification, nonetheless.

In 1935 *Dinobryon* (Fig. 3) and possibly *Stephanodiscus* (Fig. 4) abruptly appear in the data. However, between 1932 and 1934 unidentified diatoms (Fig. 5) were high, suggesting that *Stephanodiscus* and the chrysophyte *Dinobryon* may have been counted and classified under the heading "Other Diatoms." When these unidentified algal persisted and increased in density, they were identified and recorded, resulting in the abrupt increases seen in Figures 3 and 5. In fact, in 1935 the data sheet from Chicago was redesigned to include *Dinobryon* and *Stephanodiscus*.

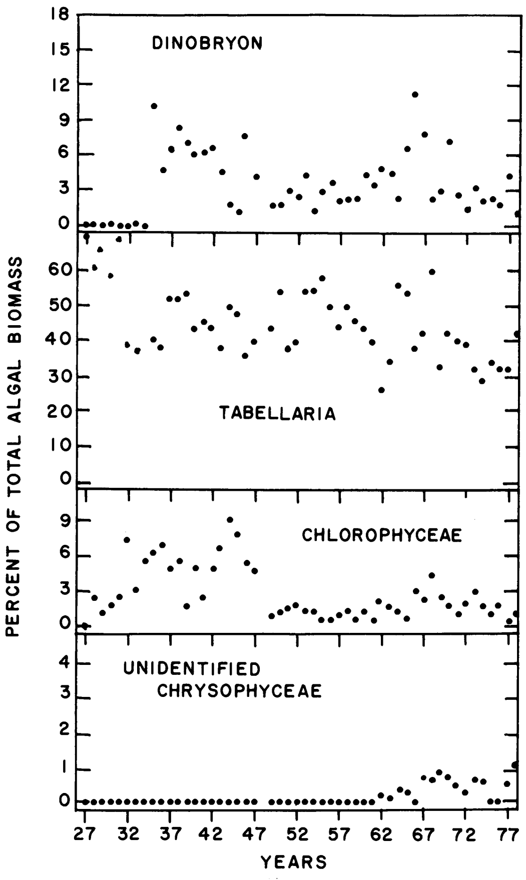

Fig. 3. Relative abundance of *Dinobryon, Tabellaria*, Chlorophyceae and unidentified Chrysophyceae in Lake Michigan at Chicago.

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[4] K. E. Damann, Prof. Biological Sciences, late, S.U.C., Brockport, N.Y.

[5] W. Ginsburg, Chief Water Bacteriologist, Water Purification Lab., Chicago, IL.

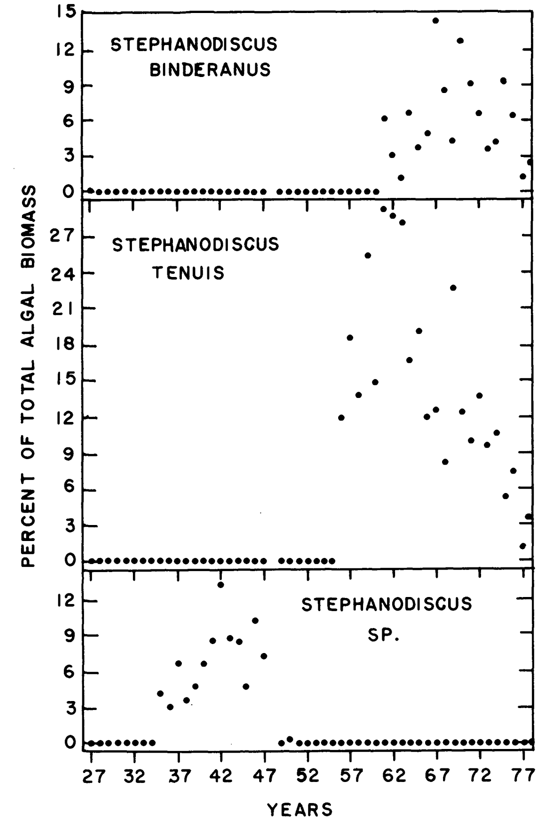

Fig. 4. Relative abundance of *Stephanodiscus binderanus*, *Stephanodiscus tenuis* and *Stephanodiscus* sp. in Lake Michigan at Chicago.

Between January 1927 and May 1928, *Fragilaria* was counted as 100-μm units. Using the average width of species observed in Lake Michigan, we multiplied densities of *Fragilaria* reported as 100-μm units by 24 to obtain cell counts per milliliter. Similarly, *Anabaena* and *Oscillatoria* abundances were multiplied by factors (17 and 24, respectively) converting their abundance into numbers of cells/ml.

Between 1934 and 1947, the Chlorophyceae were identified to genus (Table 2). Before and after this period, all the green algae were lumped together under the heading "Chlorophyceae." For the sake of continuity, we have lumped and reported together genera counts for the full 51 yr under the heading "green algae."

The relative importance of algal species may be misinterpreted if analyzed solely on a numerical basis. Several investigators, Davis (1946), Lund (1961, 1964), Cowell (1960), Newcombe (1950), Verduin (1954), Nalewajko (1966a, 1966b) and Tarapchak and Stoermer (1976), have emphasized the importance of cell volume or cell biomass, rather than cell numbers, as a better measurement of a species population importance within the phytoplankton community. The City of Chicago Water Treatment Plant has measured and calculated the volume of algal cells and colonies from their samples over the years. We used these volumes or volumes calculated from the formulas of similar geometric solids, using mean dimensions of specific phytoplankton obtained from the literature (Patrick and Reimer 1966; Huber-Pestallozzi 1975; Prescott 1962) (Table 3). Species used for the volume calculation were selected on the basis of relative abundance determined from the work of Stoermer and Ladewski (1976), Stoermer and Yang (1970) and Briggs (1872). Volumes of the unidentified blue-greens, greens and diatoms are averages based on direct measurements of several genera not routinely identified but which are on the species list compiled by the Chicago Water Filtration Plant (apparently "rare" organisms are not routinely

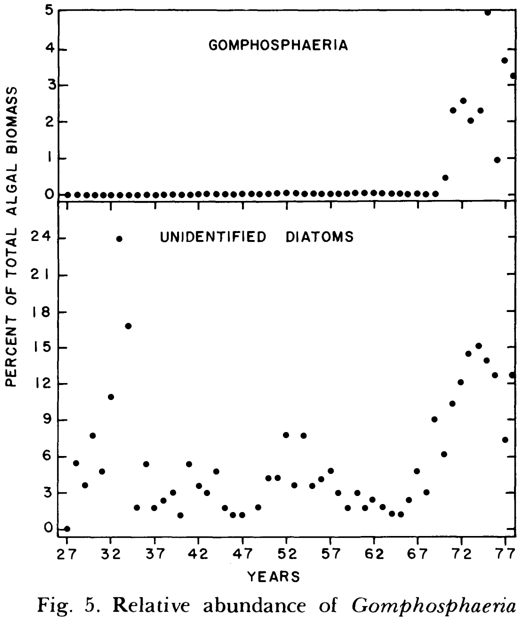

Fig. 5. Relative abundance of *Gomphosphaeria* and unidentified diatoms in Lake Michigan at Chicago.

Table 2. Chlorophyceae identified at Chicago between 1934 and 1947.

Ankistrodesmus
Botryococcus
Closteriopsis
Closterium
Coelastrum
Cosmarium
Dichotomosiphon
Dimorphococcus
Dictyosphaerium
Eudorina
Gloeocystis
Golenkinia
Hormidium
Hyalotheca
Kirchneriella
Micractinium
Palmella
Pandorina
Pediastrum
Pleodorina
Pyramimonas
Scenedesmus
Spirogyra
Sphaerocystis
Tetraspora
Volvox

identified but are counted and recorded in their respective class). We converted algal volume to C by using Strickland's conversion (1960):

$$\text{Mg C} = 0.12 \times \text{mm}^3 \text{ algal volume.}$$

Abundance of phytoplankton and dominance of certain reported genera are generally in agreement with other analyses of the diatoms (Holland and Beeton 1972) and the phytoplankton (Stoermer and Kopczynska 1967) of the inshore regions of southern Lake Michigan. As will be shown, major changes over the years have occurred gradually. In spite of the inevitable questions concerning the accuracy of the data base, it is unlikely that changes of technique would occur gradually over so many years. Because of the uniqueness of such a large data base, we felt it was worthwhile, even with the limitations presented, to bring it into the open literature.

Results. CYANOPHYTA. *Anabaena* (Fig. 6). Between 1943 and 1947 and from 1969 to 1977, *Anabaena* was observed at low densities (~12 cells/ml), never exceeding 1.2% of the total net algal biomass. Ahlstrom (1936) reported the presence of *Anabaena flos-aquae* (Lyngb.) Bréb. at low densities earlier in this century. More recently, *A. flos-aquae* has been reported in Lake Michigan by Stoermer and Kopczynska (1967) and Stoermer and Ladewski (1976).

Oscillatoria (Fig. 6). During the early 1940's, *Oscillatoria* was present but accounted for less than 1% of the total net algal biomass. There has been a spectacular increase in the relative importance of this genus in Lake Michigan at Chicago following 1969. In 1977 *Oscillatoria* comprised ~17% of the total net algal biomass.

Both Ahlstrom (1936) and Stoermer and Kopczynska (1967) list *O. mougeotii* as the only species of the genus *Oscillatoria*

Table 3. Calculated mean volumes for phytoplankton. See text for further discussion on volume calculations.

Genus or Species	Volume (μm^3/cell)	Genus or Species	Volume (μm^3/cell)
Asterionella	390	*Synedra*	650
Cyclotella	1,300	*Tabellaria*	2,900
Fragilaria	1,230	Unidentified diatoms[2]	20,900
Melosira	1,400	Chlorophyceae[1]	3,160
Nitzschia	860	*Anabaena*	113
Rhizosolenia	4,600	*Oscillatoria*[1]	160
Gomphosphaeria	4,000	Unidentified Myxophyceae[1]	4,000
Stephanodiscus sp.[1]	18,600	*Dinobryon*	1,600
S. binderanus	836	Chrysophyceae[1]	3,490
S. tenuis	2,290		

[1] Volumes were obtained from the Chicago Department of Water and Sewers.

[2] Based on volumes of the following genera measured and calculated by the Chicago Department of Water and Sewers (*Amphiphora, Amphora, Cymatopleura, Cymbella, Pleurosigma, Stauroneis, Surirella* and *Synedra ulna*).

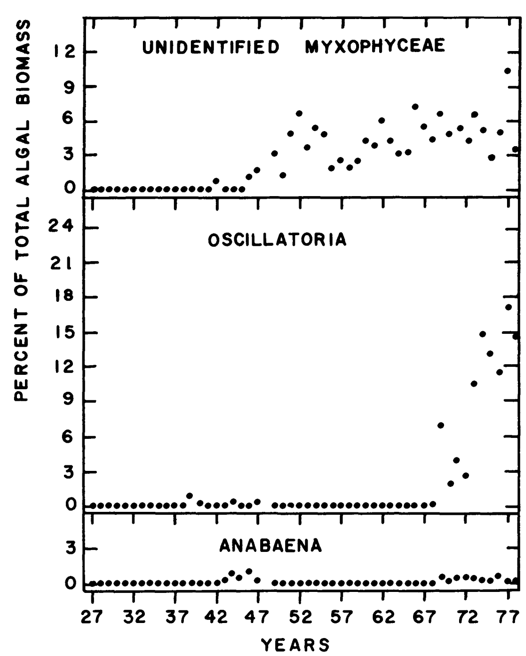

Fig. 6. Relative abundance of unidentified Myxophyceae, *Oscillatoria* and *Anabaena* in Lake Michigan at Chicago.

abundant in their collections. However, Stoermer and Ladewski (1976) reported the occurrence of both *Oscillatoria limnetica* Lemm. and *Oscillatoria bornetii* Zukal in Lake Michigan in 1971. *O. limnetica,* often abundant in polluted waters, has increased in abundance and was the most common member of this genus in 1971 (Stoermer and Ladewski 1976). The increasing population of *Oscillatoria* since 1969 observed in the Chicago data is probably *O. limnetica.*

Gomphosphaeria (Fig. 5). Prior to 1970, *Gomphosphaeria* was observed only occasionally and at extremely low densities. After 1969, *Gomphosphaeria* has increased in importance at Chicago, accounting for a maximum of 5% of the total net biomass in 1975. In a 1971 cruise of southern Lake Michigan, two species, *Gomphosphaeria aponina* Kütz. and *Gomphosphaeria wichurae* (Hilse) Dr. and Daily, were found to be minor constituents of the nearshore plankton (Stoermer and Ladewski 1976). Some species of *Gomphosphaeria* are associated with deep lakes which are not generally characterized by myxophyceaen plankton (Hutchinson 1967). *G. aponina* is sometimes associated with brackish waters (Huber-Pestallozzi 1975).

Unidentified blue-greens (Fig. 6). Since 1947, the unidentified blue-greens have increased in importance in Lake Michigan at Chicago. In 1977 the unidentified blue-greens accounted for ~11% of the total algal biomass but decreased to less than 4% of the total net biomass in 1978.

A number of species (Stoermer and Ladewski 1976) undoubtedly make up the unidentified blue-green algae observed at Chicago. However, *Anacystis cyanea* Dr. and Daily, a synonym of *Microcystis aeruginosa* Kütz., had relatively high populations in the Chicago area of Lake Michigan in the past (Griffith 1955). More recently, *Anacystis thermalis* (Menegh.) Dr. and Daily has increased greatly in abundance (Stoermer and Ladewski 1976).

CHRYSOPHYTA. *Asterionella* (Fig. 7). *Asterionella,* probably *Asterionella formosa* (Stoermer and Yang 1970), comprised 7 to 13% of the net algal biomass from 1927 to 1947. From 1947 to the early 1960's, *Asterionella* biomass decreased, relative to other genera. From 1972 to 1978, there was a general increase in the contribution of *Asterionella* to the total net algal biomass of ~1.2% to 4%.

Cyclotella (Fig. 7). Figure 7 is bimodal in shape with maxima of ~3.6% in the late 1940's, early 1950's and in 1959. Between 1927 and 1937 and between 1963 and 1977, this genus was relatively unimportant in Lake Michigan at Chicago. At least five species of *Cyclotella,* generally associated with oligotrophic or mesotrophic lakes, have been identified in Lake Michigan. Only two species *C. pseudostelligera* Hust. and *C. meneghiniana* var. *plana* Fricke, both rare at Chicago, are associated with polluted harbors or disturbed habitats (Stoermer and Yang 1970).

Dinobryon (Fig. 3). With *Dinobryon* a bimodal curve is somewhat evident. Two maxima are reached (late 1930's and mid 1960's). Ahlstrom (1936) emphasized the importance of *Dinobryon* and particularly *D. divergens* in phytoplankton assemblages during the early 1930's. Stoermer and La-

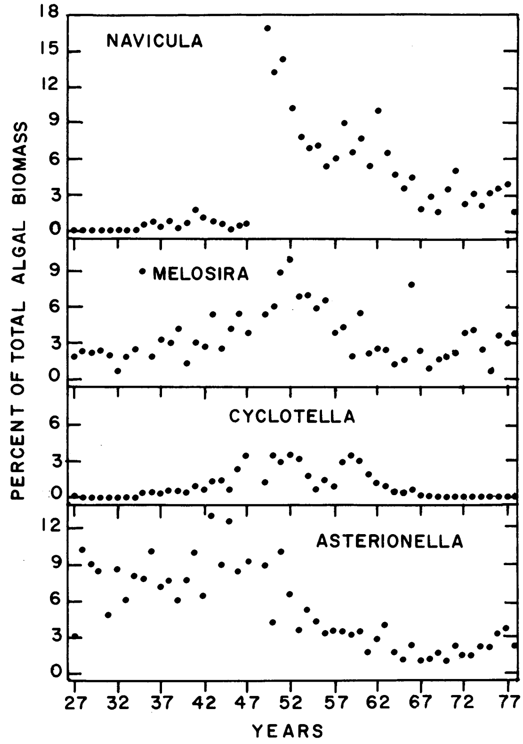

Fig. 7. Relative abundance of *Navicula, Melosira, Cyclotella* and *Asterionella* in Lake Michigan at Chicago.

dewski (1976) note that *D. divergens* did not appear to be as abundant as it was during Stoermer and Kopczynska's (1967) study of collection from the early 1960's. Similarly, these data indicate a peak in the mid 1960's and then a decrease.

Fragilaria (Fig. 8). From 1927 to 1978, there has been a steady decline in the contribution of *Fragilaria* to the total net algal biomass from ~11% in 1927 to ~3% in the late 1970's. Seven species and varieties of *Fragilaria* have been observed in Lake Michigan. Most are associated with eutrophic conditions. However, Stoermer and Yang (1970) suggest that *Fragilaria intermedia* var. *fallax* (Grun.) is associated with oligotrophic conditions and was common in the Chicago-Evanston area in the 1930's.

Melosira (Fig. 7). Over 51 yr the graph of percent of the total algal biomass of *Melosira* versus time approaches a bell-shaped curve. Relative biomass is low (~3%) through the mid 1930's, increases in the 1940's, peaks (7 to 9%) in the early 1950's and then decreases to 3 to 4% of the total net algal biomass in the 1970's. *Melosira granulata* and *M. islandica* were common at Chicago in the 1940's (Stoermer and Yang 1970).

Navicula (Fig. 7). Prior to 1949, *Navicula* accounted for less than 1.2% of the net algal biomass. In 1949 a large increase in the percent of the total biomass of this genus to ~17% is evident. Since 1949, *Navicula* has steadily decreased in importance in Lake Michigan at Chicago. Because the number of taxa known to occur in Lake Michigan of the genus *Navicula* is larger than for any other diatom group (Stoermer and Kreis 1978), it is impossible to designate any representative species.

The sudden increase in *Navicula* between 1947 and 1949 is suspicious. It may

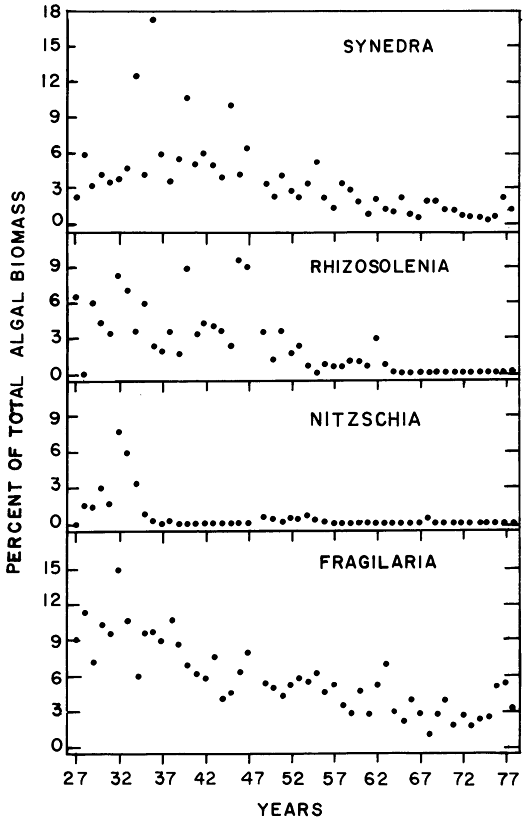

Fig. 8. Relative abundance of *Synedra, Rhizosolenia, Nitzschia* and *Fragilaria* in Lake Michigan at Chicago.

be real or it may be related to a reorganization of personnel and the laboratory that took place during this period. We know that a change in counters, calculators, checkers and the design of the data sheet took place (indicated by the signatures on data sheets from Chicago) between 1947 and 1949.

Nitzschia (Fig. 8). This genus was relatively important in the late 1920's and early 1930's. Since 1935, it has never exceeded 1% of the net algal biomass. Stoermer and Yang (1970) have reported on the five most common species present in Lake Michigan.

Rhizosolenia (Fig. 8). Never exceeding ~9.6% of the net algal biomass, this genus, probably *Rhizosolenia eriensis* H. L. Smith (Stoermer and Yang 1970), was more prevalent in the 1920's and 1930's. From 1955 onward, *Rhizosolenia* generally accounted for less than 1.2% of the total net biomass. Stoermer and Yang (1970) also found *R. eriensis,* a species not tolerant to advanced eutrophication, to be common in the 1930's and 1940's.

Stephanodiscus (Fig. 4). The unidentified species of *Stephanodiscus* were important in the late 1930's and early 1940's, contributing a maximum of 13% of the net algal biomass in 1942. Prior to 1935 and after 1947, this genus was rare. Prior to 1935 *Stephanodiscus* may not have been identified to genus but counted and included under the heading of "Other Diatoms" (see Methods). Two species *S. hantzschii* Grun. and *S. minutus* Grun., associated with mesotrophic to eutrophic lakes, have been observed at Chicago in the 1930's and 1940's. Of these two species, *S. minutus* was more common (Stoermer and Yang 1970).

Stephanodiscus binderanus (Kütz.) Krieg (Fig. 4). *S. binderanus* became increasingly prevalent during the 1960's. The maximum relative biomass was ~14.6% in 1967. Its increase in Lake Michigan has been suggested as an indicator of serious pollution (Stoermer and Yang 1970). Following 1967, the contribution of this species to the total net biomass has decreased to ~1.2% in 1977.

Stephanodiscus tenuis Hust. (Fig. 4). This eutrophic species (Stoermer and Ladewski 1976) was first noted in 1956 at Chicago. Prior to 1956 *S. tenuis* may not have been identified to genus but was counted and included under the heading of "Other Diatoms" (see Methods). Its importance in the lake rose quickly to a maximum of 29.9% of the net algal biomass by 1961. There has been a steady decrease in the relative biomass of this species after 1961. In 1978 it contributed only 3.2% of the total net biomass.

Synedra (Fig. 8). Over 51 yr there is generally a decreasing trend to the relative contribution of *Synedra* to the total algal biomass. In some isolated years (1934, 1936, 1940, 1945), relatively high contributions of *Synedra* (e.g., 17.4% in 1936) to the total net algal biomass are evident.

Stoermer and Yang (1970) identified five species of *Synedra* relatively common in Lake Michigan. Of these, *S. ulna* var. *chaseana* Thomas was previously abundant in the Chicago area but has declined in recent years. In recent years, *S. ulna* var. *danica* (Kütz.) V. H. abundance has increased in the Chicago area (Stoermer and Yang 1970).

Tabellaria (Fig. 3). In terms of biomass expressed as C, this genus has been the dominant group within Lake Michigan at Chicago. Contributions to the total net algal biomass are generally in the 40% to 50% range from 1927 to 1957.

Tabellaria fenestrata (Lyngb.) Kütz. and *T. flocculosa* (Roth) Kütz. have been common in the lake since the 1930's. Stoermer and Yang (1970) note that *Tabellaria* (i.e., *T. fenestrata*) is the overall dominant plankton diatom in Lake Michigan, which agrees with our observations.

Unidentified Diatoms (Fig. 5). Over the 51 yr studied, the relative abundance of the unidentified diatoms varied considerably, possibly reflecting the rise and fall of new species or genera to the Chicago area.

Unidentified Chrysophyceae (Fig. 3). Prior to 1962, the unidentified Chrysophyceae were present in extremely low numbers. Since 1962, they have generally increased in relative importance but have never exceeded 3.4% of the total algal biomass. Stoermer and Ladewski's (1976) report list species and information on relative abundance and ecology of Chrysophyceae in Lake Michigan.

CHLOROPHYTA. *Greens* (Fig. 3). The unidentified greens generally increased in importance from 1927 to ~1945, reaching a maximum of 9% of the net algal biomass in 1944. After 1947 they never exceeded 4% of the net algal biomass. Stoermer and Ladewski's (1976) report list species and information on relative abundance and ecology of Chlorophyceae in Lake Michigan.

Discussion. With a decrease in P loading to Lake Michigan (Fig. 1), as would be expected with the phosphate controls initiated in 1972 and with the diversion of sewage effluent in the Chicago, Illinois, area, a concurrent decrease in phytoplankton biomass would be expected. Such a biomass would be strong evidence suggesting that a reversal in cultural eutrophication of the inshore waters of Lake Michigan near Chicago is now taking place, particularly if phytoplankton indicative of eutrophic waters have also decreased in relative importance. Since inshore regions of southern Lake Michigan have shown more distinct signs of eutrophication in the 1950's and 1960's than the offshore waters (Holland and Beeton 1972; Stoermer and Yang 1970; Tarapchak and Stoermer 1976), a general decrease in algal biomass and a decrease in eutrophic algal species in inshore regions would probably signify an improvement or potential future improvement of offshore waters.

In the inshore areas of Lake Michigan at Chicago, the trend in algal composition from 1927 to ~1970 has been a decrease in oligotrophic-mesotrophic forms and an increase in eutrophic forms. For example, *Rhizosolenia,* an oligotrophic-mesotrophic form (Tarapchak and Stoermer 1976), has decreased in importance over the 51 yr. The increase in *Melosira* till 1952 and subsequent decrease was probably due to *Melosira islandica,* a mesotrophic species. *Asterionella* (probably *A. formosa*), a probable mesotrophic eurytherm (Stoermer and Ladewski 1976; Tarapchak and Stoermer 1976), has decreased in relative abundance.

Since the mid 1950's, *Stephanodiscus binderanus* and *S. tenuis* have increased dramatically (Fig. 4). Both species are considered indicators of moderate to high nutrient enrichment (i.e., eutrophic species) in Lake Michigan (Tarapchak and Stoermer 1976). Similar trends have been reported by Stoermer and Yang (1970), Stoermer and Ladewski (1976) and by Tarapchak and Stoermer (1976).

Interestingly, the relative abundance of both *S. tenuis* and *S. binderanus* has decreased in recent years. A decrease in a eutrophic form may be interpreted as an encouraging sign, a sign of reversal of the eutrophication process. However, the decrease in the diatom species of *Stephanodiscus* may also be a response to accelerated eutrophication and decreasing silica levels as predicted by Schelske and Stoermer (1971). A further aspect of their prediction is that diatoms would be replaced by green and blue-green algae since their requirement for silica is minimal. Our data do indicate that the relative abundance of blue-green algae has increased in recent years (Fig. 11).

Primary productivity, chlorophyll *a* and phosphate concentrations, as well as phytoplankton biomass, are often used to classify a lake's trophic status. For example, a phytoplankton biomass of 20 to 100 mg C/m^3, 100 to 300 mg C/m^3, or greater than 300 mg C/m^3 is indicative of oligotrophic, mesotrophic or eutrophic conditions, respectively (Likens 1975). Figure 9 depicts the eutrophication of the inshore region of Lake Michigan at Chicago. From 1930 to 1940, a net biomass (~100 mg C/m^3) indicative of oligotrophic-mesotrophic conditions was observed, while between 1941 and 1955 mesotrophic conditions were implied by the net algal biomass (~200 mg C/m^3). By 1961 net algal biomass was ~600 mg C/m^3—a biomass indicative of a eutrophic condition. Much of this biomass increase is due to *Tabellaria, Stephanodiscus tenuis* and *S. binderanus* (Fig. 9). Because the counting technique underestimates abundance (see Methods), the total algal biomass is undoubtedly higher than presented, thereby giving the designations oligotrophic, mesotrophic and eutrophic limited meaning in this case. However, the

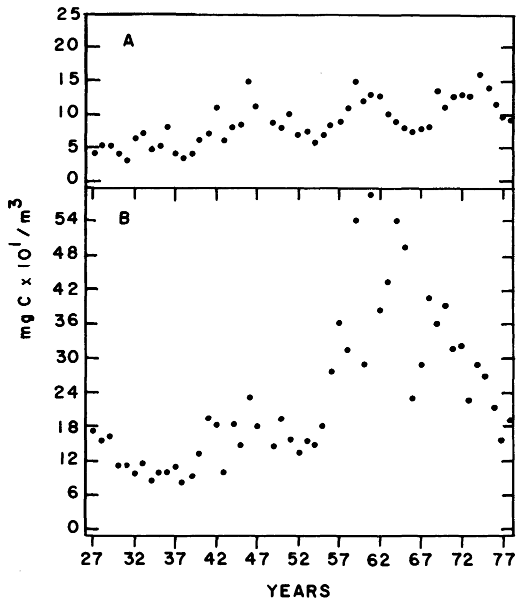

Fig. 9. Mean annual net phytoplankton biomass in Lake Michigan at Chicago. Panel A represents the total biomass minus *Tabellaria, Stephanodiscus tenuis* and *Stephanodiscus binderanus* while Panel B represents the total net phytoplankton biomass.

trend of increasing phytoplankton biomass by a factor of 6 from 1930 to 1961 indicates accelerating eutrophication.

From 1962 to 1970, biomass fluctuated with an average of ~400 mg C/m^3 for the period. Since the early 1970's there has been a consistent general decrease in algal density and net algal biomass to levels associated with oligotrophic-mesotrophic conditions—conditions not observed in Lake Michigan at Chicago since the early 1950's (Figs. 9 and 10). Furthermore, Figures 7 and 8 suggest a slight increase in the relative abundance of *Asterionella* and *Fragilaria* since 1972, genera that had decreased in relative abundance until ~1970. Also, the Great Lakes Program of the EPA reports an increase in dissolved reactive silica in Lake Michigan near Chicago from 0.29 mg/l in 1976 to 0.54 mg/l in 1977 (Rockwell 1979). Because this reported increase in silica represents only one year and could be due to upwellings along the southwestern shore of the basin, the significance of the increased silica concentration has to be viewed with caution. However, one line of evidence for cultural eutrophication has been that concentrations of dissolved silica are decreasing on a lakewide basis due to uptake by diatoms (Tarapchak and Stoermer 1976). The decrease in net algal biomass, the decrease in abundance of the eutrophic species *S. binderanus* and *S. tenuis,* the small increase in the relative abundance of the diatoms *Asterionella* and *Fragilaria,* and the reported increase in silica concentrations all suggest a reversal of cultural eutrophication in Lake Michigan at Chicago.

Only the increase in relative abundance of blue-green algae (Fig. 11), mostly *Oscillatoria* and *Gomphosphaeria,* argues for accelerated eutrophication. It has been suggested that this shift is generally characteristic of north temperate lakes undergoing accelerated eutrophication (Hutchinson 1967; Tarapchak and Stoermer 1976). However, it should be noted that although the relative abundance of blue-green algae (Fig.

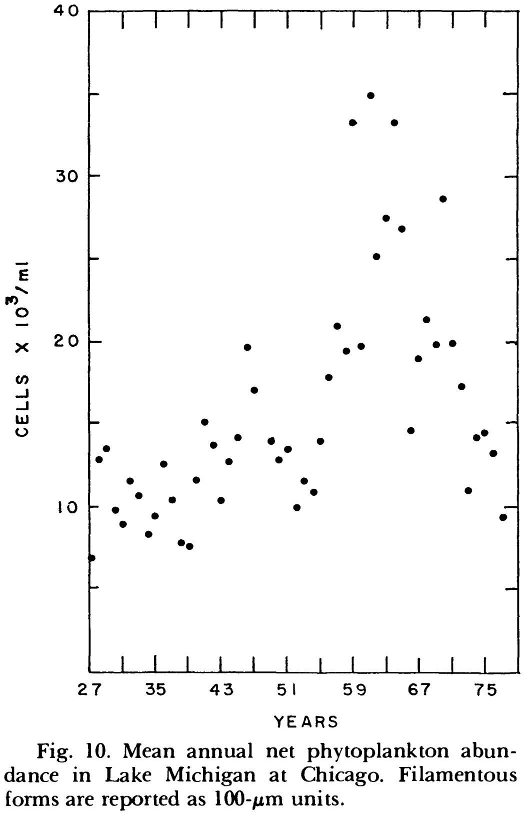

Fig. 10. Mean annual net phytoplankton abundance in Lake Michigan at Chicago. Filamentous forms are reported as 100-μm units.

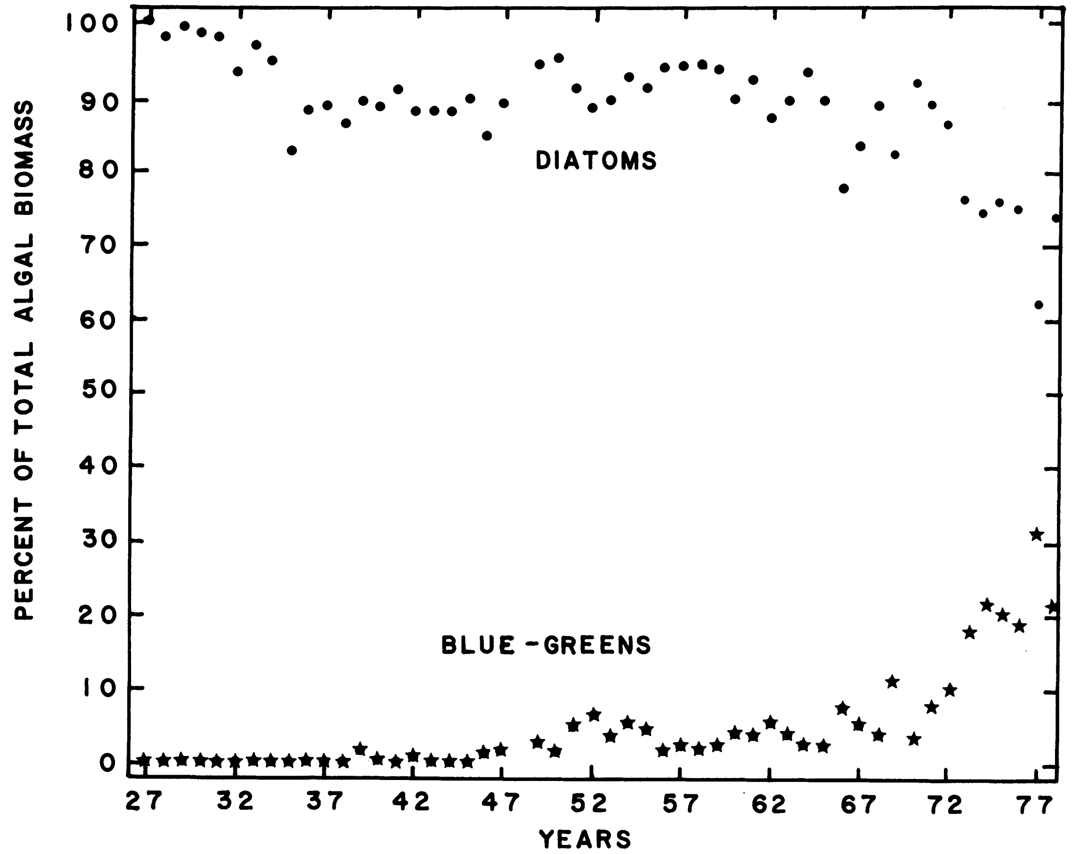

Fig. 11. Relative abundance of blue-green algae and diatoms in Lake Michigan at Chicago (1927-1977).

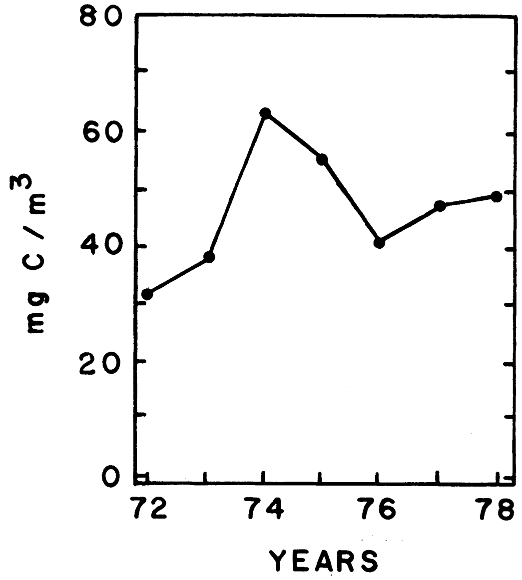

Fig. 12. Mean annual biomass of blue-green algae.

11) has increased through 1977, the biomass of blue-green algae has decreased slightly since 1974 (Fig. 12).

The fact that blue-green algae have become a large component (~22% of the biomass) of the phytoplankton community is significant. The insurgence of blue-green algae during a period of decreasing P loading and decreasing ambient P concentrations possibly reflects environmental factors other than enrichment with P. For example decreasing N:P ratios (Fee 1979), allelopathic effects (Keating 1977, 1978) and high pH and alkalinity indicative of low CO_2 availability (King 1972, Shapiro 1973) have been suggested as influencing blue-green algal growth. In Baybutt and Makarewicz (1981), these hypotheses are reviewed in relation to the Chicago Lake Michigan phytoplankton data by ordination and correlation analysis.

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