Eutrophication, Silica Depletion, and Predicted Changes in Algal Quality in Lake Michigan

Abstract. *Accelerated eutrophication stimulated by pollution inputs is causing silica depletion in the surface waters of Lake Michigan during summer stagnation. Limitation of the reproduction of the presently dominant phytoplankton organisms, which require silica, may lead to drastic and, on the whole, undesirable changes in the ecosystem.*

Depletion of silica in Lake Michigan is important because previous investigations of offshore phytoplankton assemblages (*1*) have indicated that diatoms (Bacillariophyta) dominate the flora at all seasons. The dominance of diatoms (65 to 99 percent of the total cell counts) has been maintained at all but the grossly polluted nearshore localities, even though long-term records show severalfold increases in the maximum standing crops of phytoplankton at stations near Chicago (*2*) and changes in species composition throughout the lake (*3*).

Diatoms require silica (*4*) for cell division (*5*). Apparently the growth rates of these algae are independent of silica concentration until limiting concentrations are reached (*6*). Since limiting concentrations are on the order of 0.1 mg of SiO_2 per liter or less (*7*), silica seldom becomes an apparent limiting factor in natural waters except during intensive diatom blooms.

Chemical data collected at municipal water intakes near Chicago, located at depths ranging from 6 to 9 m, indicate that the yearly average concentration of silica has decreased at least 4 mg/liter in the last 44 years (*8*). In 1926, values of 5.0 and 6.0 mg/liter were reported. More recent data show that the decrease is general over the lake and is not restricted to nearshore waters. Concentrations of silica in surface waters were less than 2.5 mg/liter over most of Lake Michigan and less than 1.0 mg/liter at stations in the southern basin near Chicago in August 1955 (*9*); 14 years later soluble silica averaged 0.15 ± 0.07 mg/liter during July at 16 stations in the southern basin and 0.26 ± 0.07 mg/liter during August at 18 stations in the northern basin (*10*). Low concentrations of silica in surface waters reflect utilization by diatoms in the euphotic zone and indicate that depletion due to the reproduction of diatoms is greater in the southern basin than in the northern basin.

A comparison of concentrations of silica from surface samples with those from below the euphotic zone shows utilization by diatoms and provides evidence of a general decrease in the total amount of silica in the lake. Silica concentrations of 1.63 ± 0.49 and 1.26 ± 0.16 mg/liter were reported in samples taken below the euphotic zone in the northern and southern basins, respectively, during August and July 1969 at the same 34 stations at which surface values were determined (*10*). Values for similar samples ranged from 2.2 to 4.7 mg/liter in August 1955 (*9*) and are estimated to have been 6 mg/liter in 1926. It is evident from these trends that a limitation of diatom reproduction due to silica depletion is an important factor to be considered in predicting changes in the Lake Michigan ecosystem.

Data from ecological perturbation experiments provide direct evidence that the supply of silica limits the reproduction of phytoplankton. The greatest increase in cell counts occurred in the July treatment with nitrogen, phosphorus, and silica in which the concentration of silica before treatment was 0.10 mg/liter (Table 1) or near the limiting concentration (*7*). Concentrations of silica in the August inshore experiments were much larger, and increases in cell counts were not as great as in the July treatment with nitrogen, phosphorus, and silica. Maximum responses occurred after treatment with silica in combination with nitrogen and phosphorus; when only nitrogen and phosphorus were added, there was a smaller effect on the rate of carbon fixation and growth rate as measured by cell counts (Table 1). These experiments also show that the addition of phosphorus, or nitrogen, or both phosphorus and nitrogen is required in order that phytoplankton deplete available supplies of silica. As observed by others (*11*), additions of phosphorus enable diatoms to utilize silica to concentrations below 0.1 mg/liter, a result which also occurred in our experiments after 11 days.

Increases in cell counts and rates of carbon fixation (Table 1) were attributed to phosphorus and not to nitrogen in the treatments with nitrogen and phosphorus (*12*). Because the concentration of nitrate nitrogen was greater than 0.1 mg/liter at the beginning of the experiments and exceeded 0.05 mg/liter at the end of the experiments, nitrate nitrogen was not considered a limiting nutrient in the lake when the experiments were started. Nitrate nitrogen concentrations ranging from 0.02 to 0.04 mg/liter were found in surface waters of Green Bay, Saginaw Bay, and

Table 1. Responses of experimental systems to nutrient addition. Experiments were performed by adding nutrients to 4000-liter polyethylene bags containing lake water and phytoplankton. With the aid of scuba divers, bags were anchored 7 m below the surface, filled with water, and subsequently sampled at depth. Methods used for chemical analyses and for the determination of rates of carbon fixation are given in (*10*). Nutrient concentrations used in treatments were $NaNO_3$, 0.20 mg of nitrogen per liter; Na_3PO_4, 0.020 mg of phosphorus per liter; and $Na_2SiO_3 \cdot 9H_2O$, 0.70 mg of SiO_2 per liter. The responses were measured relative to controls for several days but values for only 1 day are reported here.

Nutrients added	Ratio of treated samples to controls: ^{14}C fixation	Ratio of treated samples to controls: Cell counts	Silica (mg of SiO_2 per liter): Initial	Silica (mg of SiO_2 per liter): Final
	*July offshore**			
Nitrogen, phosphorus, silica	6.8	19	0.85	0.20
Nitrogen, phosphorus	2.4	1.8	.10	.08
Silica	1.1	2.3	.85	.57
	August inshore†			
Nitrogen, phosphorus, silica	6.6	3.9	1.6	.22
Nitrogen, phosphorus	2.9	2.7	1.0	.15
Silica	1.6	1.8	1.7	.98

* Measurements were made on 25 July 1969, 8 days after the start of the experiment. In the control, there were 1.7×10^3 cells per milliliter and the rate of carbon fixation was 3.5 mg of carbon per cubic meter of water per hour. † Measurements were made on 29 August 1969, 3 days after the start of the experiment. In the control, there were 4.8×10^3 cells per milliliter and the rate of carbon fixation was 13.6 mg of carbon per cubic meter of water per hour. This experiment was initiated during a phytoplankton bloom; thus responses occurred sooner than in the July experiment.

western Lake Erie (*12*), an indication that phytoplankton in the Great Lakes reduce this nutrient to low concentrations if supplies of phosphorus are sufficient and that a concentration of 0.1 mg/liter would not be limiting. Concentrations of phosphorus are also low —total concentrations of all forms of phosphorus are less than 0.010 mg of phosphate phosphorus per liter, except in grossly polluted areas. Experiments conducted in June 1970 showed that the rates of carbon fixation and growth of phytoplankton could be increased by adding phosphorus alone when silica was not in short supply (*12*).

The relationship between depletion of silica and eutrophication in Lake Michigan suggests that data on long-term changes in the concentrations of silica may be one means of determining the rate of eutrophication in deep oligotrophic lakes. Little depletion of silica in the euphotic zone relative to that in bottom waters occurs in Lake Superior (*10*), the least eutrophic of the Great Lakes, and available data indicate that Lake Huron, in terms of the supply of silica, is at an intermediate stage relative to Lake Michigan and Lake Superior. Direct comparison of the situation in the upper lakes with Lake Erie is not feasible. The highly eutrophied western basin of Lake Erie receives appreciable silica addition, relative to its volume, through stream inflow and is also so shallow that periodic wind-driven mixing of the water column makes nutrients, including silica, regenerated from the sediments, available for phytoplankton growth. Moreover, the eutrophication of Lake Erie has proceeded to the point where the quantitative and qualitative aspects of the phytoplankton assemblages are grossly different from those found in the upper lakes.

Future effects of silica depletion on the Lake Michigan ecosystem can be predicted in general terms. Depletion of the available silica in the euphotic zone during the summer stagnation followed by partial replenishment during the fall overturn will undoubtedly lead to greater seasonal variability in the phytoplankton assemblages. Perennial diatoms will be replaced, at least partially, by algae that do not require silica because diatoms will not be able to compete with green and blue-green algae for available pools of other nutrients when the supply of silica is limited. It is doubtful that changing conditions in Lake Michigan will immediately result in massive and obnoxious summer blue-green algal blooms that have become characteristic of Lake Erie and Lake Ontario in the past few decades, but the potential and general trend will be toward such occurrences. Phytoplankton samples collected in 1969 indicate that diatoms have been replaced in Lake Michigan by blue-green and green algae (*13*). The system, however, will be more susceptible to further ecological insult as the result of these environmental changes. Estimates of the future effects of added nutrient or of thermal effluents based on the present system, consequently, are apt to be very conservative, especially relative to secondary effects on higher trophic levels.

We have concluded that the prime, if not the sole, cause of silica depletion in Lake Michigan is phosphorus pollution (*12*). The principal role of this element in stimulating undesirable levels of biological productivity has long been recognized (*14*), and efforts are currently under way to limit the phosphorus input to the Great Lakes. The real question is whether specified levels of control (*15*) will be sufficient to reverse present trends in Lake Michigan. Consideration of the long retention time in Lake Michigan (*16*) and the probable time scale involved in implementing presently envisioned controls presents a dubious prospect. In the United States, the best documented case of the reversal of artificial eutrophication is Lake Washington where (*17*) it was possible to completely divert sewage effluents from the system. Diversion of the many possible sources in a system the size of Lake Michigan has practical as well as economic disadvantages. Control of water levels, for example, would be a major problem. Lake Michigan, however, represents a trial case of lake restoration through nutrient control which bears careful monitoring and further investigation. Trends in environmental conditions will continue to measure the effectiveness of all types of pollution control that may be instituted.

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References and Notes

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