COO-2003-25

NUTRIENT ENRICHMENT AND EUTROPHICATION OF LAKE MICHIGAN

Progress Report

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DISCLAIMER

CONTENTS

INTRODUCTION

This progress report contains a brief summary of research completed on studies related to nutrient enrichment and eutrophication of Lake Michigan. It is divided into five parts: 1) experiments with natural phytoplankton, 2) ecological characteristics of the upper Great Lakes, 3) development of chemical techniques, 4) a list of reports completed under this contract, and 5) an appendix containing some of the completed reports.

The purpose of this progress report is to highlight some of the accomplishments and major conclusions resulting from the research support received in the past from the Atomic Energy Commission and presently from the Energy Research and Development Administration. Readers interested in the details of the research are referred to the Appendix which contains copies of the original reports. References to the original reports are made in the text by the contract report number (COO-2003-xx) which is found on the upper right hand corner of each of the reports. The reports in the Appendix are bound in numerical order, but some reports not discussed in the text are not included.

EXPERIMENTS WITH NATURAL PHYTOPLANKTON ASSEMBLAGES

One of the first accomplishments under this contract was the development of an experimental technique that could be used to study the effect of nutrients on natural phytoplankton assemblages. This technique was to use large plastic bags, volumes ranging from 1,000 to 4,000 liters, that were anchored in the lake. The bags were filled with lake water, the nutrients to be tested were added, and then water samples were taken frequently to determine the effects of the nutrients on the phytoplankton assemblages in the lake water. The major advantages of this technique are that questions can be answered by performing experiments under natural light and temperature conditions. Sampling problems are simplified because each bag represents a finite population and therefore all measurements and results are related theoretically to the initial environmental conditions and treatments and the subsequent interactions within the system. The major disadvantage is that the results are only directly applicable to the spatial and temporal sampling point so results must be interpreted for short-time intervals as conditions in the lake and the bags tend to diverge with time. It does not seem possible that one can simulate succession and dynamics of species in the lake with such small containers on a time scale longer than one or two weeks.

Three types of results have been obtained from these experiments (summarized on p. 67-70, COO-2003-15). 1) No response, an effect attributed to the presence of inhibitory or toxic substances in the lake water at the time the experiments were initiated or to the omission of a limiting factor in the treatments (COO-2003-6). The inhibitory substance may have been a toxin produced by the blue-green algal *Anabaena* which was present in the phytoplankton assemblage. 2) Response in all treatments, an effect attributed to the fact that the experiment was started with upwelled water which was rich in nutrients. Phytoplankton responsed in the control as well as in the treatments, with no discernible lag time (COO-2003-5). 3) Positive responses, generally characterized by an initial lag phase followed by logarithm growth in the treatments containing nutrients and by a control treatment showing little or no response with time (COO-2003-5). Not recognizing these types of responses would lead to erroneous conclusions and interpretations from the results.

Results of experiments conducted with plastic bags showed conclusively that phosphorus was a limiting nutrient, both in Lake Superior (COO-2003-13) as well as in Lake Michigan (COO-2003-5).

Experiments with plastic bags consumed large amounts of time and effort per experiment, making it nearly impossible to run experiments with replicates or large numbers of treatments. As a consequence, we initiated experiments that were run in the laboratory as well as in the field to determine whether smaller containers could be used. The answer to this question appears to be that such experiments with natural phytoplankton populations can be conducted either in the laboratory or in the field. Water from Lake Michigan was used in a carefully designed factoral experiment (COO-2003-21), using 20-liter experimental containers. In a field experiment, 2-liter bottles were used (COO-2003-24). Both of these experiments showed that typical lake populations of phytoplankton responded and that phosphorus was the limiting nutrient. We also have unpublished data from laboratory experiments (250 ml volume) conducted under an EPA grant, giving similar results.

In addition to determining limiting nutrients with phytoplankton populations, it has been possible to determine growth kinetics from our data on experiments with phosphorus. From a Michaelis-Menten model, the half saturation constant was of the order of 1.0 μg P/liter, a quantity of phosphorus not readily measurable by standard chemical techniques (COO-2003-21). This results indicates that, as is well known by limnologists, orthophosphate measurements have little meaning in oligotrophic waters and that the important question about phosphorus dynamics is not the standing stocks, but the rates of turnover within the system. The relatively small half saturation constant for phytoplankton in the Great Lakes appears to be quite general. Under an EPA grant we have determined half saturation constants in a number of experiments that are on the order of 1.0 μg P/liter for both water from Lake Huron as well as from Lake Michigan. Data from a field experiment at four locations in Lake Michigan indicate phosphorus stimulates phytoplankton growth at low levels (COO-2003-24).

One of the most interesting results of our work with kinetic models is the fact that growth data for a wide range of phosphorus concentrations could be fitted with one model (COO-2003-21). These phosphorus concentrations ranged from 5 to 60 μg P/liter. On the other hand, enrichment with phosphorus plus vitamins, trace metals, and a chelating agent doubled the growth rate of the phytoplankton assemblage. It also altered the species composition compared to the assemblage present when only phosphorus and nitrogen were used in the enrichments. This experiment demonstrated that the growth rate of the phytoplankton could be increased by the presence of nutrients and growth-promoting substances other than phosphorus. It also suggests that different phytoplankton assemblages have varing half saturation constants as well as different growth constants. We have speculated, as found by others, that the more eutrophic nearshore species would have higher growth rates and half saturation constants.

The synergistic effect on phytoplankton growth of other substances with additions of phosphorus was demonstrated in field experiments (COO-2003-24). In these experiments small additions of river water (1 to 3 per cent) increased the rates of chlorophyll production and carbon fixation. This effect was attributable either to the small amounts of phosphorus added with the river water or to growth-promoting substances other than phosphorus that were present in the river water, or to a combination of both.

These experiments have provided a technique by which direct evidence can be obtained for environmental perturbations. This approach should be useful for investigations of other environmental perturbations.

ECOLOGICAL CHARACTERISTICS OF THE UPPER GREAT LAKES

Through our efforts during the period of this contract we have obtained data that have increased the general understanding of the ecological relationships between nutrients and phytoplankton, as well as interrelationships with certain physical factors. Certain conclusions have been possible only through experimental work discussed in the section on Experiments with Natural Phytoplankton Assemblages. Other conclusions and insights on processes ~~in~~ the Great Lakes have been possible from data collected on research cruises on the upper Great Lakes. In a number of the examples cited below, the combination of data from experiments and cruises has been essential in formulating conclusions.

Understanding many ecological processes in the upper Great Lakes is dependent on knowing that phytoplankton growth and production are limited by phosphorus. With this knowledge, the dependence of rates of carbon fixation and chlorophyll standing crop on concentrations of phosphorus is easily conceived (Fig. 1). The conclusion that phosphorus inputs and supplies (including recycling) control the rate and state of eutrophication in the upper Great Lakes logically follows for a phosphorus-limited system.

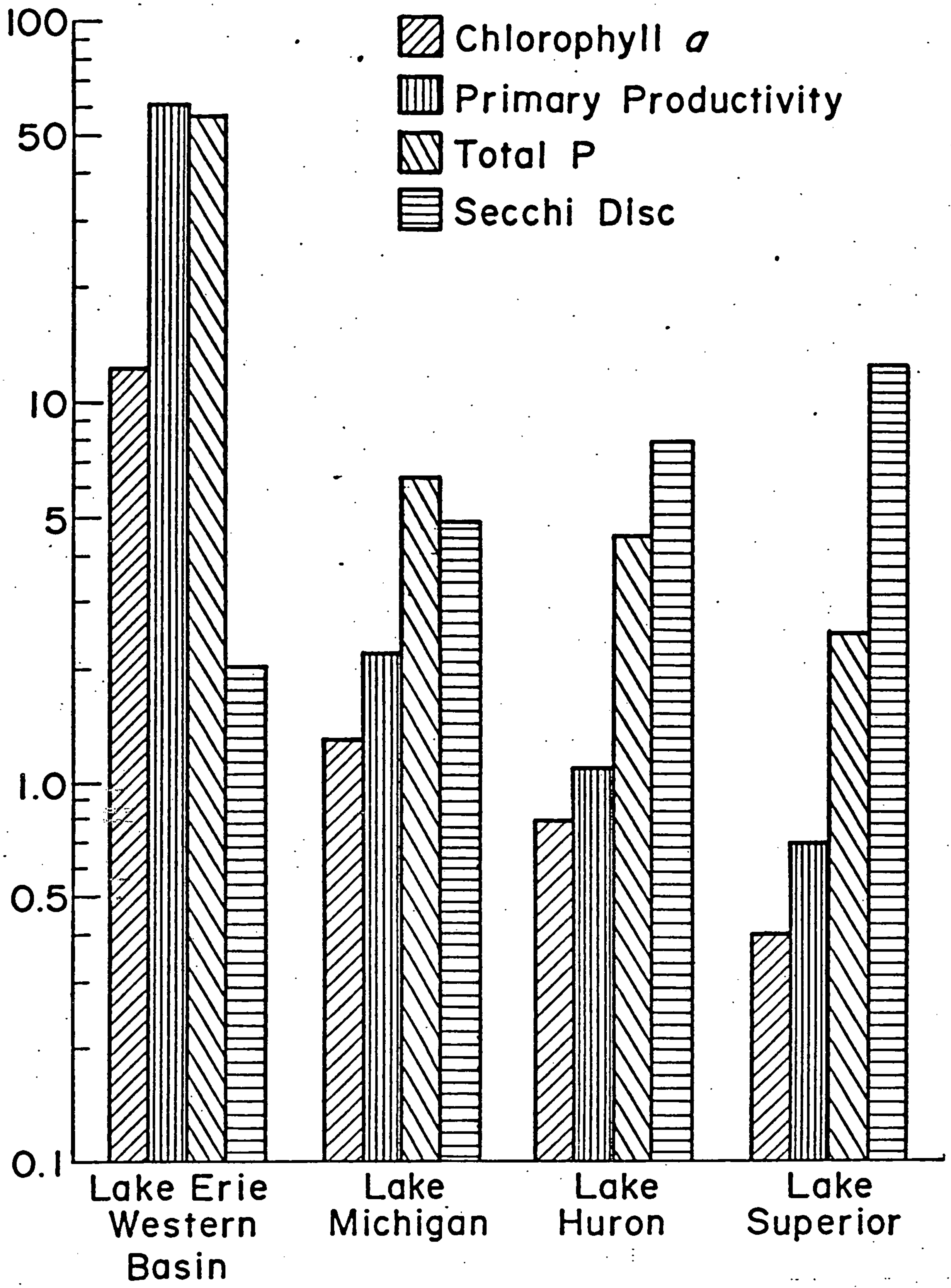


FIGURE 1. Chlorophyll *a* (mg/m^3), Primary Productivity ($mg\ C/m^3/hr$), Total Phosphorus ($mg\ PO_4\text{-}P/m^3$) and Secchi Disc Transparency (m) in the Great Lakes. (COO-2003-15)

Phosphorus inputs to the upper Great Lakes will control eutrophication and affect various ecological processes in the lakes. In Lake Michigan increased inputs of phosphorus have increased the standing crops of diatoms, increasing the demand for silica. This increased demand of silica has already produced summer depletion of silica in the surface waters of Lake Michigan, a phenomenon that does not occur in the open waters of either Lake Huron or Lake Superior. Since the phytoplankton assemblages in these lakes are typically composed of diatoms, silica depletion limits the growth of diatoms and with increased inputs of phosphorus is expected to produce a shift in the species composition of phytoplankton from assemblages dominated by diatoms to those with greater and greater percentages of green and blue-green algae. The ecological consequences of such a shift could affect consumer populations in the lake that are adapted to a food source composed of diatoms (COO-2003-8). It is obvious that this effect has resulted mainly from increased phosphorus inputs in the tributaries to Lake Michigan.

Data on concentrations of nitrate and silica from the upper Great Lakes have shown that the quantity of silica and nitrate depletion can be related to the trophic state, the greater the amount of depletion during the summer stratification the greater the degree of eutrophication (COO-2003-15). This relationship is evident from data for Lake Michigan, Lake Huron and Lake Superior (Fig. 2). Lake Superior is the most oligotrophic and Lake Michigan the most eutrophic of the three lakes. Yearly amounts of silica or nitrate utilized for phytoplankton growth as reflected by quantities of depletion can also be plotted as a function of time to indicate the rate of eutrophication (COO-2003-11).

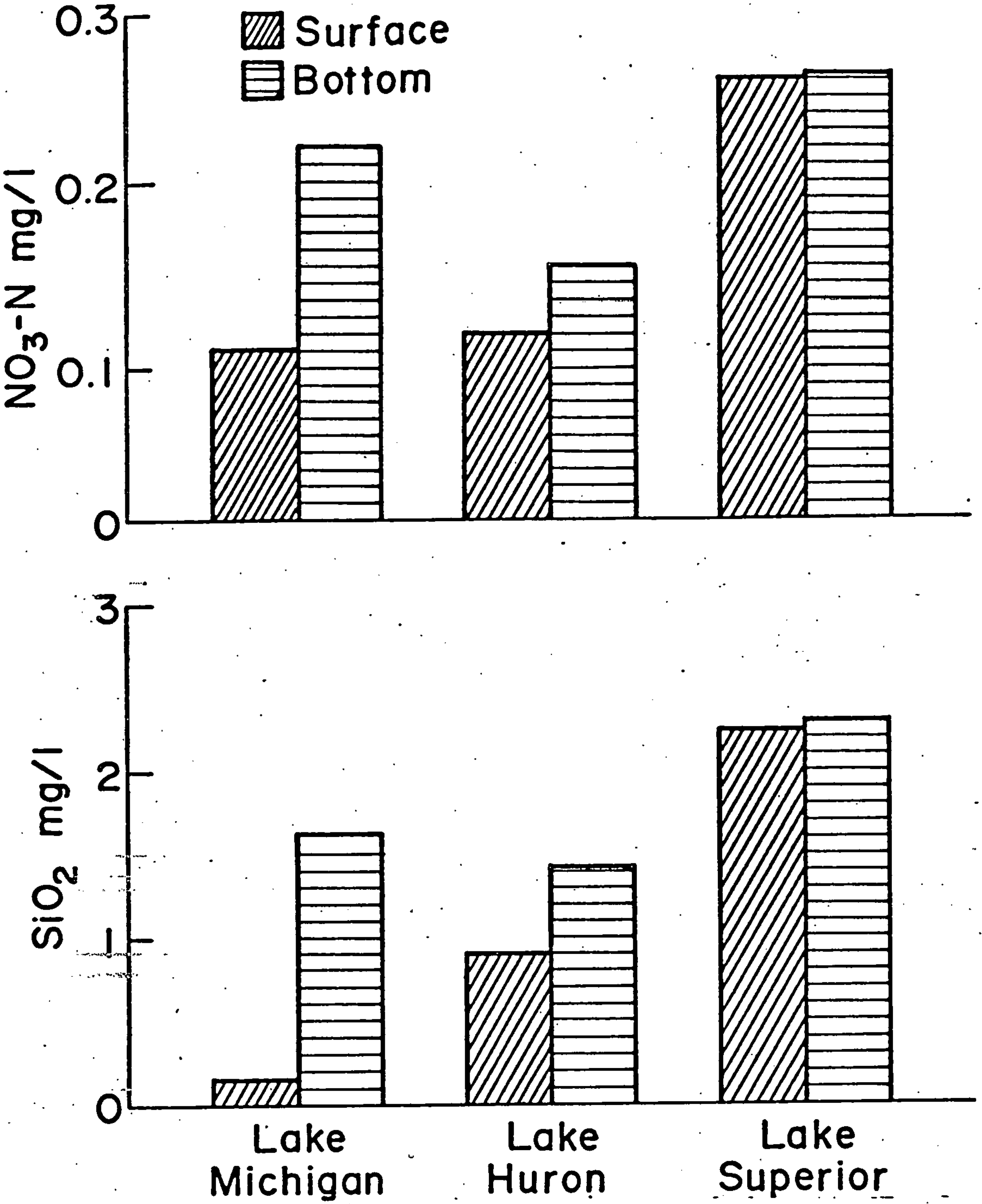


FIGURE 2. Silica and Nitrate in the Upper Great Lakes. (COO-2003-15)

There are two important conclusions about the roles of phosphorus and nitrogen in the trophic processes in the upper Great Lakes. First, nitrogen inputs are not an important factor in accelerated eutrophication. Large supplies of nitrate are present in all the upper Great Lakes, especially Lake Superior, so supplies of nitrogen do not control eutrophication (Fig. 2). This has been demonstrated experimentally in a factorial experiment with treatments of nitrogen and phosphorus in which nitrate levels ranged from 0.2 to 1.1 mg N/liter. In this experiment the effect of nitrate compared to phosphorus was insignificant (COO-2003-21). In addition we have performed numerous experiments in which treatments of phosphorus alone increased the growth of phytoplankton. Second, small concentrations of phosphorus are needed to stimulate algal growth. Additions of 5 and 10 μg P/liter consistently produce measurable results in experiments. Smaller additions may produce measurable responses also, but these have not been tested. Published and unpublished data on growth kinetics of phytoplankton determined from a Michaelis-Menten model indicate that the half-saturation constants are on the order of 1.0 μg P/liter (COO-2003-21). These results show that one can infer little about the relationship between orthophosphate concentrations measured on environmental samples to phytoplankton growth because orthophosphate is a control variable at concentrations that may not be measurable by routine chemical methods (COO-2003-3). These data, as is well known, substantiate the argument that the important consideration about phosphorus is the rate of turnover of various pools in the environment.

Because phosphorus operates at low levels in the system, physical processes such as upwelling that bring nutrient-rich water into the euphotic zone have increased significance in relation to ecological processes. Even though these waters contain relatively small phosphorus concentrations, the supplies contributed can stimulate growth. In Lake Michigan, upwelled waters are important due to increased supplies of silica (COO-2003-7). During summer stratification these supplies of silica may stimulate the growth of the silica-limited diatom assemblages.

As part of one of our research cruises, we verified the importance of advective processes in relation to ecological processes in Lake Huron (COO-2003-23). Our sampling schedule coincided with a fall storm. This storm induced water mass transport from Saginaw Bay, a highly eutrophic area, into Lake Huron. The Saginaw Bay water could be traced by chloride concentrations as the Saginaw River is a major source of chlorides. In addition these water masses could also be identified by chlorophyll and silica concentrations (Fig. 3) and by population estimates of a blue-green alga, *Anabaena subcylindrica* (Fig. 4). Data plotted in these figures are from widely scattered stations on the survey, and the observed pattern can best be explained by invoking the effects of short-term advective processes. Transport of water with relatively rich plankton populations by these physical processes has an effect on the open-lake plankton communities through advection and on benthic communities through sedimentation.

One of the effects attributed to nutrient enrichment or accelerated eutrophication in aquatic systems is reflected in the species composition of phytoplankton. The existence of oligotrophic as well as eutrophic forms is accepted and has been documented in the Great Lakes by Stoermer at the University of Michgian and Holland at the University of Wisconsin-Milwaukee (COO-2003-21). Other data, however, indicate that specific phytoplankton

FIGURE 3. Plot of soluble reactive silica and chlorophyll *a* vs. chloride concentration in Saginaw Bay and Lake Huron. (COO-2003-23)

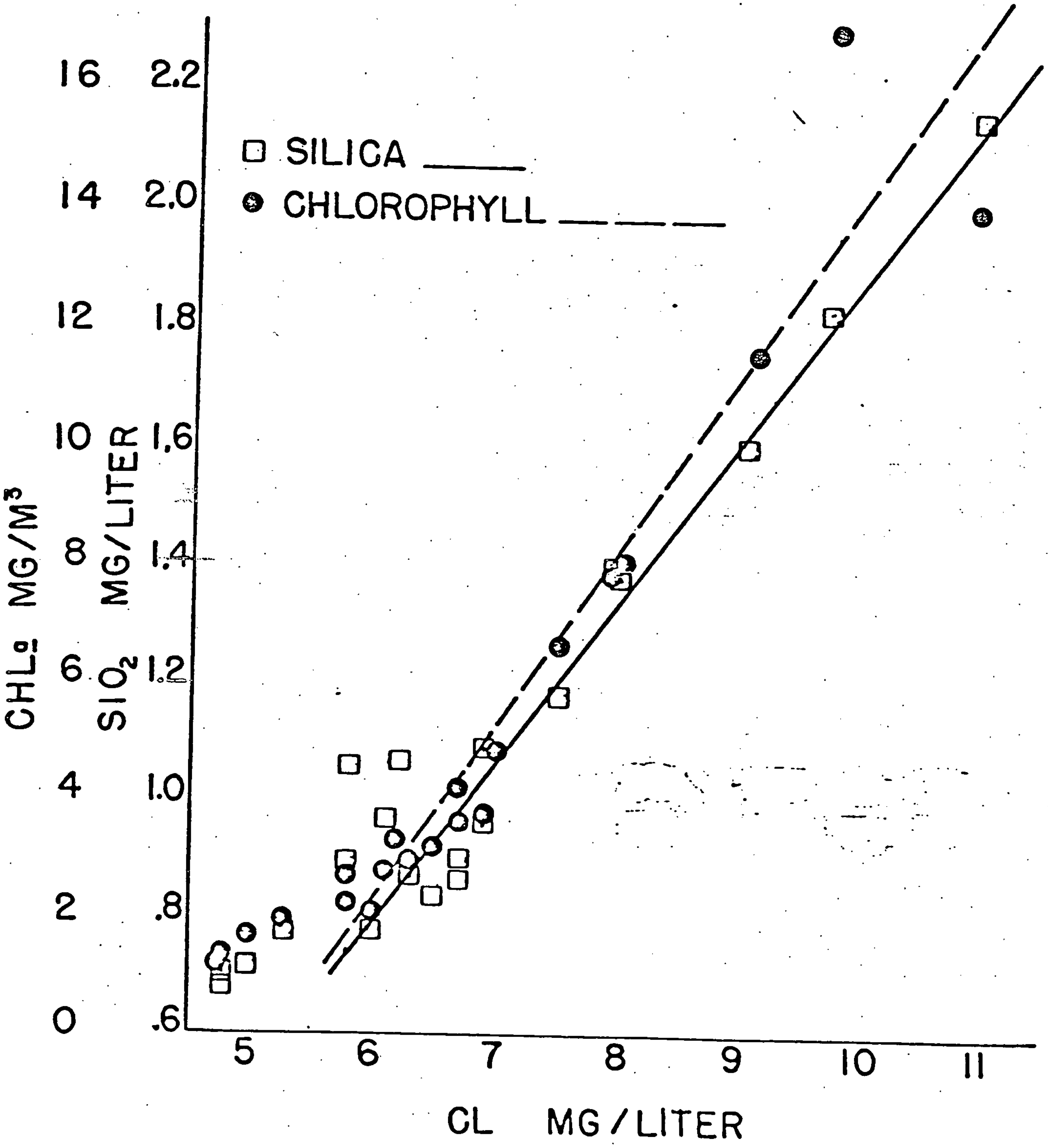
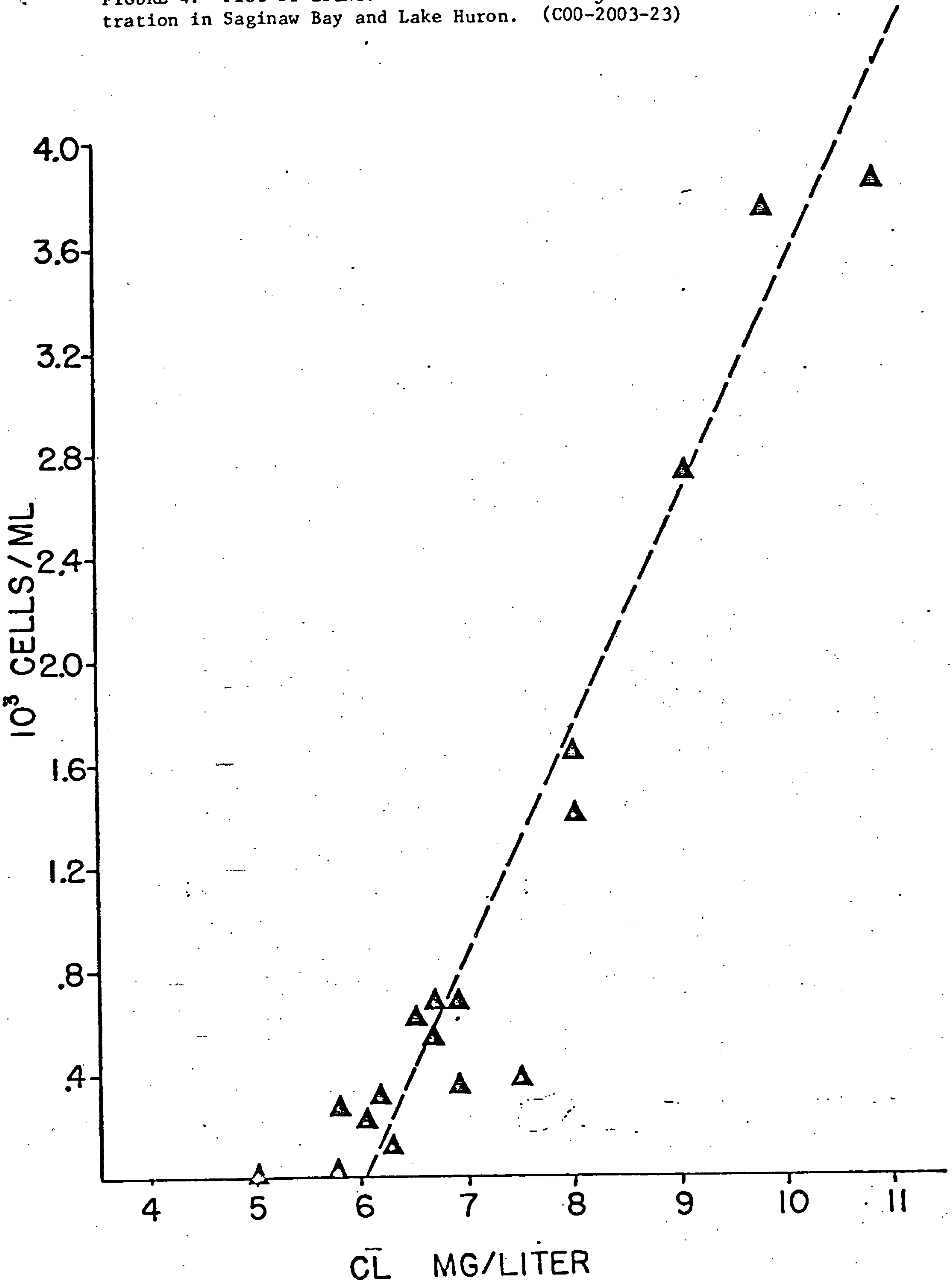


FIGURE 4. Plot of abundance of *Anabaena subcylindrica* vs. chloride concentration in Saginaw Bay and Lake Huron. (C00-2003-23)



assemblages are tolerant of fairly broad ranges of enrichment. Data from Grand Traverse Bay showed that the standing crop of phytoplankton decreased, but the species composition remained unchanged on a transect of stations away from the nutrient source, the Boardman River (COO-2003-14). Phytoplankton production also increased without changing species composition by phosphorus enrichment in a laboratory experiment (COO-2003-21). These data indicate that species composition is affected only by severe nutrient perturbations or that the important factor or factors involve interactions with a number of environmental variables. In many systems where the effects of eutrophication are manifest, the number of potential environmental variables that may influence the process is rather large. In the Great Lakes, these areas are at river mouths or harbor entrances.

Several interesting observations have been made about phytoplankton populations in the Great Lakes. Samples collected from Lake Superior revealed the presence of morphologically abnormal populations of *Synedra* (COO-2003-20). Two species of *Synedra* have been observed with the morphological abnormality and from the available limited data and samples, appear to have originated since 1966. Three hypotheses have been advanced to explain the occurrence: 1) the populations are a mutant form, 2) the occurrences are attributable to a clonal population that originated due to mechanical or some other form of damage to the cell, or 3) the observed morphological abnormality is produced continually by some persistent causal factor. Since the highest levels of abnormal organisms are found in the western basin, the most disturbed part of Lake Superior, the third hypothesis has some basis. Additional studies of Lake Superior phytoplankton are needed to test these hypotheses. Knowledge about Lake Superior phytoplankton is very limited due to inadequate sampling. Some of the basic characteristics of the typical assemblages are not understood generally. As an example, we pointed out that the typical phytoplankton assembalge in Lake Superior is dominated by the small species of *Cyclotella*, the generally accepted oligotrophic diatom assemblage of oligotrophic lakes. Hutchinson had noted in 1967 that the Great Lakes did not conform with this concept of phytoplankton assemblages and trophic state (COO-2003-13).

DEVELOPMENT OF TECHNIQUES

Two chemical techniques have been developed in conjuction with this study. One is for an automated method of determining sulfate in fresh water (COO-2003-19). The other, unpublished, is a technique for determination of particulate silica by decomposition with hydrofluoric acid and measurement with atomic absorption spectrophotometry. This technique is being tested and if applicable will be very useful in our studies of silica dynamics in the Great Lakes.

COMPLETED REPORTS

under Contract AT(11-1)-2003

with U. S. Energy Research and

Development Administration

COO-2003-1

Progress Report, November 1, 1968 to July 31, 1969. C. L. Schelske, E. Callender, and E. F. Stoermer. MS. July 1969.

COO-2003-2

Nutrient enrichment experiments on phytoplankton populations in Lake Michigan. C. L. Schelske, E. Callender, and E. F. Stoermer. MS. October 1969.

COO-2003-3

Survey of phytoplankton productivity and nutrients in Lake Michigan and Lake Superior. C. L. Schelske and E. Callender. Proc. 13th Conf. Great Lakes Res. 1970. pp. 93-105.

COO-2003-4

Progress Report, November 1, 1969 to July 31, 1970. C. L. Schelske, E. F. Stoermer, and E. Callender. MS. July 1970.

COO-2003-5

Phosphorus, silica, and eutrophication of Lake Michigan. C. L. Schelske and E. F. Stoermer. Symposium on Nutrients and Eutrophication, Spec. ASLO Symp. Vol. 1. pp. 157-171. 1972.

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Phytoplankton assemblage differences at inshore versus offshore stations in Lake Michigan, and their effects on nutrient enrichment experiments. E. F. Stoermer, C. L. Schelske, and L. E. Feldt. Proc. 14th Conf. Great Lakes Res. 1971. pp. 114-118.

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Nutrients, phytoplankton productivity, and species composition as influenced by upwelling in Lake Michigan. C. L. Schelske, E. F. Stoermer, and L. E. Feldt. Proc. 14th Conf. Great Lakes Res. 1971. pp. 102-113.

COO-2003-8

Eutrophication, silica depletion, and predicted changes in algal quality in Lake Michigan. C. L. Schelske and E. F. Stoermer. Science. Vol. 173. 1971. pp. 423-424.

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Ecological implications of fallout radioactivity accumulated by estuarine fishes and mollusks. C. L. Schelske, D. A. Wolfe, and D. E. Hoss. Radionuclides in Ecosystems. Proc. 3rd Nat. Symposium on Radioecology. 1971. pp. 791-806.

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Ecological concept of the coastal zone in the Great Lakes. C. L. Schelske. Proc. Conf. on Coastal Zone and Shoreline Management in the Great Lakes. 1971. Unpublished manuscript.

COO-2003-11

Silica and nitrate depletion as related to rate of eutrophication in Lakes Michigan, Huron and Superior. C. L. Schelske. *In* Coupling of land and water systems, A. D. Hasler (ed.), Springer-Verlag New York Inc. 1975. pp. 277-298.

COO-2003-12

Progress Report. Vol. 1, 1968 to Oct. 31, 1971. Nutrient enrichment and eutrophication of Lake Michigan. C. L. Schelske. MS. October 1971.

COO-2003-13

Nutrient enrichment and its effect on phytoplankton production and species composition in Lake Superior. C. L. Schelske, L. E. Feldt, M. A. Santiago, and E. F. Stoermer. Proc. 15th Conf. on Great Lakes Res. 1972. pp. 149-165.

COO-2003-14

Spring phytoplankton abundance and productivity in Grand Traverse Bay, Lake Michigan, 1970. E. F. Stoermer, C. L. Schelske, M. A. Santiago, and L. E. Feldt. Proc. 15th Conf. on Great Lakes Res. 1972. pp. 181-191.

COO-2003-15

Nutrient inputs and their relationship to accelerated eutrophication in Lake Michigan. C. L. Schelske. *In* Biological effects in the hydrobiological cycle, E. J. Monke (ed.), Proc. of the 3rd Internat. Symp. for Hydrology Professors, Purdue Univ., Dept. of Agricultural Eng. 1971. pp. 59-81.

COO-2003-16

Fallout Mn-54 accumulated by bay scallops *Argopecten irradians* (Lamarck) near Beaufort, North Carolina. C. L. Schelske. *In* Symposium on the Interaction of Radioactive Contaminants with the Constituents of the Marine Environment, International Atomic Energy Agency. 1973. pp. 331-346.

COO-2003-17

Progress Report. Nutrient enrichment and eutrophication of Lake Michigan. November 1, 1968 to July 31, 1972. C. L. Schelske. July 1972.

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Limnological survey of Lakes Michigan, Superior, Huron, and Erie. C. L. Schelske and J. C. Roth. 1973. Univ. Mich., Great Lakes Res. Div., Pub. 17, 108 p.

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An automated method for sulfate determination in lake water. M. A. Santiago, S. Fielek and C. L. Schelske. Water Quality Parameters, ASTM STP 573, Amer. Soc. for Testing and Materials, pp. 35-46. 1975.

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Occurrence of morphologically abnormal *Synedra* populations in Lake Superior phytoplankton. L. E. Feldt, E. F. Stoermer and C. L. Schelske. Proc. 16th Conf. Great Lakes Res. 1973. pp. 34-39.

COO-2003-21

Responses of phosphorus limited Lake Michigan phytoplankton to factorial enrichments with nitrogen and phosphorus. C. L. Schelske, E. D. Rothman, E. F. Stoermer and M. A. Santiago. 1974. Limnol. Oceanogr. 19: 409-418.

COO-2003-22

Progress Report. Nutrient enrichment and eutrophication of Lake Michigan. C. L. Schelske. April 1974.

COO-2003-23

Storm induced relationships among chemical conditions and phytoplankton in Saginaw Bay and western Lake Huron. C. L. Schelske, L. E. Feldt, M. A. Simmons, and E. F. Stoermer. Presented at 17th Conf. Great Lakes Res., Hamilton, Ontario, Aug. 1974. In press.

COO-2003-24

Phytoplankton responses to phosphorus and silica enrichments in Lake Michigan. C. L. Schelske, M. S. Simmons, and L. E. Feldt. Presented at 19th SIL Congress, Winnipeg, Manitoba. Aug. 22-29, 1974.