Water Quality Studies on the Great Lakes Based on Carbon Fourteen Measurements on Primary Productivity

William G. Parkos, Ph. D.
Research Fellow
School of Public Health
University of Minnesota, Minneapolis

Theodore A. Olson, Ph. D.
Professor of Public Health Biology
School of Public Health
University of Minnesota, Minneapolis

Theron O. Odlaug, Ph. D.
Professor and Head
Department of Biology
University of Minnesota, Duluth

The work upon which this publication is based was supported in part by funds provided by the United States Department of the Interior as authorized under the Water Resources Research Act of 1964, Public Law 88-379

NOVEMBER 1969
MINNEAPOLIS, MINNESOTA

WATER RESOURCES RESEARCH CENTER
UNIVERSITY OF MINNESOTA
GRADUATE SCHOOL

CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

PAGE

FOREWORD

This Bulletin is published in furtherance of the purposes of the Water Resources Research Act of 1964. The purpose of the Act is to stimulate, sponsor, provide for, and supplement present programs for the conduct of research, investigations, experiments, and the training of scientists in the field of water and resources which affect water. The Act is promoting a more adequate national program of water resources research by furnishing financial assistance to non-federal research.

The Act provides for establishment of Water Resources Research Institutes or Centers at Universities throughout the Nation. On Sept. 1, 1964, a Water Resources Research Center was established in the Graduate School as an interdisciplinary component of the University of Minnesota. The Center has the responsibility for unifying and stimulating University water resources research through the administration of funds covered in the Act and made available by other sources; coordinating University research with water resources programs of local, State and Federal agencies and private organizations throughout the State; and assisting in training additional scientists for work in the field of water resources through research.

This report is the seventeenth in a series of publications designed to present information bearing on water resources research in Minnesota and the results of some of the research sponsored by the Center. The study with which this report is concerned was designed to measure the primary productivity rates of the surface waters of Lake Superior, Michigan, Huron and Erie. Great Lakes ore carriers were made available for the field operations associated with this project which was carried out during the 1967 and 1968 shipping seasons. Production rates were determined using the carbon-14 technique with light, temperature and incubation time remaining constant. Uniform procedures also were followed with respect to collection and processing of samples onboard ship and at the lakeside laboratory. Sample activity was measured with an Ansitron II liquid scintillation counter and final productivity calculations were made for each lake station. Since project procedures were standardized, direct comparisons of the productivity levels, or water quality, could be made among the four lakes studied. Baselines of primary surface-water productivity were established for the lake studied. Such baselines are necessary and useful in any study of advancing eutrophication within the Great Lakes. Additional studies are being supported by the Center.

I. INTRODUCTION

Importance of Primary Productivity Studies

There has been much discussion in recent years concerning the enrichment and resultant productivity of the Great Lakes. Discussions both academic and socio-political have dealt extensively with this problem, and there are a number of reasons for the almost cosmopolitan interest in this phenomenon. Among these are the following:

(1) The phytoplankton may serve as a food source for invertebrates in the lakes involved. Therefore, an estimate of the production of organic matter by phytoplankton allows one to make estimates of the potential of a lake as a food source for man or other animals in the food chain.

(2) Productivity studies of this type also will help to answer some of the fundamental questions which arise in connection with problems of water quality and water pollution. Phytoplankton are primary producers in the food chain, and they represent organisms that utilize basic substances such as nitrates, phosphates, magnesium, carbon dioxide and various trace metals for nutrition and growth. If conditions of temperature and light penetration are optimum, an increase in nutrients in the aquatic environment will generally stimulate an increase in the phytoplankton biomass. Therefore, changes in phytoplankton biomass and the attendant productivity may reflect the advancing stages of eutrophication whether these are brought about as a natural phenomenon or as a result of increasing water pollution.

(3) Studies of seasonal fluctuations in productivity and the depth of the euphotic zone also can be useful to water supply engineers and others responsible for water treatment processes and plant operation.

(4) In an affluent society such as we enjoy in the United States, man is experiencing a reduction in the work day and an increase in leisure time. He, therefore, is faced with the challenge of profitably channeling his energies during these free periods. Hundreds of thousands of people have turned to stream , lakes, and other waters for relaxation and recreation. This is evidenced by the gigantic increase in boating, swimming, water-skiing, fishing, and the like. It is wise, therefore, for aesthetic as well as health reasons to attempt to preserve in a natural unpolluted state the lakes and waterways of our country. Productivity studies can provide information relating to the quality of water and hence to a better utilization of this natural resource.

Lakes Studied

Carbon fourteen productivity studies reported here were carried out in four of the five Great Lakes, namely, Superior, Michigan, Huron, and Erie, during the 1967 and 1968 shipping seasons.

Lake Superior ranks as the largest body of fresh water in the world with a surface area of 31,820 square miles. It is located at the head

of the Great Lakes chain and is 602 feet above sea level and more than 1300 feet deep at its deepest point. The lake is 350 miles in length, and its maximum width measures 160 miles. This was the only lake for which productivity determinations were made for two consecutive seasons.

With a surface area of 22,400 square miles, Lake Michigan ranks sixth in order among the largest lakes in the world. It is the only member of the Great Lakes chain that lies wholly within the boundaries of the United States. At an elevation of 580 feet above sea level and with a maximum depth of 923 feet, Lake Michigan's measurements are 307 miles by 118 miles.

Lake Huron, the fifth largest lake in the world, has a surface area of 23,010 square miles. It lies 580 feet above sea level and is 750 feet deep at its deepest point. Lake Huron is 206 miles long and 101 miles wide at its maximum breadth.

The fourth largest member of the Great Lakes group ranks as the twelfth largest in the world. It is Lake Erie, which has a surface area of 9930 square miles. The maximum dimensions of this lake are 206 miles in length and fifty-seven miles in width. It lies 572 feet above sea level and although the maximum depth of this lake is 210 feet, the average depth is only fifty-eight feet.

Many of the basic attributes of the Great Lakes, such as locations, depths, and shapes, resulted from the events that occurred one-half billion years ago when bedrock foundations were laid down. It is believed, however, that the immediate predecessors of the modern Great Lakes came into existence not more than 20,000 years ago (Hough 1958).

Objectives of the Carbon Fourteen Study

Since no integrated body of knowledge was available concerning the productivity of the Great Lakes as determined by the carbon fourteen method, it seemed important that a study of this sort be undertaken. The investigation reported here deals with such a study and was carried out on Lakes Superior, Michigan, Huron, and Erie. In each instance, sampling included the entire length of the lake and the methodology was uniform throughout.

Although a multitude of possibilities exist with respect to the goals which might have been selected, the following objectives were chosen as being especially important both from a practical and an academic point of view:

(1) To obtain base lines of primary productivity of the surface waters for the lakes investigated.

(2) To determine the effect of season on primary productivity; that is, does productivity increase or decrease, and to what degree as the season progresses.

(3) To determine whether or not differences in productivity exist in various water masses along longitudinal lake transects.

(4) To make comparisons of the productivity levels of the lakes under investigation.

II. LITERATURE REVIEW

Early Methods of Measuring Primary Productivity

Primary productivity studies are presently having considerable impact on quantitative biology. The early realization that organisms within a lake are interdependent and mutually highly sensitive to changes within their environment (Forbes 1887) probably gave rise to the conceptual development of the food webs of Shelford (1913), Perfiliev (1929), and MacFayden (1948). The resultant today of these early works is that limnologists are viewing lakes as ecosystems including both the living community and the nonliving environment functioning together as a unit.

Productivity measurements of the sea were first attempted by Atkins (1922, 1923) in the English Channel. The author measured productivity from the end of winter to the height of summer by determining the loss of carbon dioxide and the loss of phosphate under one square meter of ocean surface. Cooper (1933) estimated the productivity of the English Channel by measuring the change in the oxygen and nitrate content of seawater. By measuring the undersaturation of oxygen in a water layer below the euphotic zone in conjunction with calculations of the oxygen exchange occurring between the layers of water directly above and directly below the euphotic zone, Siewell (1935) calculated the productivity of plankton algae. In a somewhat similar manner, Riley and Gorgy (1948) estimated the productivity of the Sargasso Sea by measuring the vertical distribution of oxygen. According to Steemann-Nielsen (1952), he used a nitrate-phosphate metabolism calculation for the estimation of productivity in the sea (Steeman-Nielsen 1940).

The first method which directly measured phytoplankton productivity in the sea was devised by Gran. It later became known as the Gaarder and Gran dissolved oxygen method (1927). This method involved the collection of water samples from various depths, measuring the oxygen content of an aliquot of the sample, returning the sample to the collection depth for "in situ" incubation followed by remeasurement of the oxygen content. The change in oxygen concentration noted after incubation was considered to be an expression of the photosynthetic rate. The accuracy of this method was greatly increased by simultaneously suspending a sample contained in a black bottle. This was done for the purpose of excluding light. Such a sample provided information regarding the respiration rate. Since the oxygen needed in respiration must be added to the amount of oxygen produced in the "light" bottle to arrive at the total or gross photosynthetic rate, a combination of light and dark bottles provided a more precise method for measuring productivity.

The light and dark bottle oxygen method was used extensively by Marshall and Orr (1930); according to Steemann-Nielsen (1952), Gran and Thompson (1930) and Steeman-Nielsen (1951a) made use of this technique. However, it was found to be suitable only in waters that were slightly

eutrophic since the sensitivity in oxygen measurement was inadequate to detect differences in oligotrophic waters.

Riley (1938, 1939) had very little success using a modification of the Gaarder-Gran dissolved oxygen method (1927) which can be attributed to prolonged incubation time.

The Carbon Fourteen Method

It is quite evident from the above discussion that a more sensitive method for measuring primary productivity was needed. Steemann-Nielsen (1951a, 1952), while on cruise aboard the well-equipped oceanographic vessel Galathea, devised a new and much more sensitive method of measuring primary productivity, namely, the carbon fourteen method.

This method incorporates the use of a radioactive tracer to measure productivity and was found to work successfully in both oligotrophic and eutrophic waters.

The carbon fourteen method consists of adding a known amount of radioactive carbon dioxide in the form of a carbonate or bicarbonate to water samples which contain natural phytoplankton. The samples are exposed to light for a certain period of time and are subsequently filtered through membrane filters. The filters are washed thoroughly or treated with fuming vapors of hydrochloric acid to remove any excess carbonates which may be present in the seawater. The filters are allowed to dry thoroughly and then the activity present on the filter is measured with suitable radiation detection equipment. Knowing the initial activity of the carbon fourteen added and having measured the activity present on the filter, one determines the amount of carbon fourteen fixed. Since one is using the amount of carbon fourteen fixed as an indicator of the amount of organic carbon fixed in the environment, determination of the total carbon dioxide available in the environment is needed. This is done using hydrochemistry. Once the total carbon dioxide that is available to the phytoplankton in the sample is known, a simple proportionality equation is used to calculate the amount of organic carbon (carbon twelve) fixed. The mathematical relationship is as follows:

$$\frac{\text{amount carbon 14 added}}{\text{amount carbon 14 fixed}} = \frac{\text{amount carbon 12 present}}{\text{amount carbon 12 fixed}}$$

Thus the amount carbon 12 Fixed =

$$\frac{(\text{amount carbon 12 present})\ (\text{amount carbon 14 fixed}}{\text{amount carbon 14 added}}$$

Application of the Carbon Fourteen Method

The new carbon fourteen method was quickly adopted by many scientific workers studying the productivity of the sea, and the method received wide acclaim in a rather short period of time. In addition to the experimentation done by Steemann-Nielsen (1951a, 1952, 1954, 1958a, 1958b), Ryther and Vacarro (1954) studied marine photosynthesis using the carbon fourteen method and the oxygen technique.

The primary productivity of both the coastal and oceanic waters of the Northeast Atlantic was studied by Currie (1958) using the carbon fourteen method. In 1958, Corlett used Steemann-Nielsen's (1951a) method to determine the productivity of the western Barents Sea, and Berge (1958) used a modification of the carbon fourteen method to study productivity of the Norwegian Sea. Angot (1961), Holmes (1961), and Koblentz-Mishke (1961) used the carbon fourteen technique to study selected areas of the Pacific Ocean.

Several freshwater workers also used the carbon fourteen approach to study productivity. According to Vinberg (1960) the earliest applications of this method to freshwater were made in Russia by Kuznetsov (1955a, 1955b) and Sorokin (1955, 1956). Nygaard (1955) studied the productivity of five Danish lakes and Rodhe (1958a) similarly studied several Swedish lakes.

Frey and Stahl (1958) and Hobbie (1962) used the method to study the primary productivity of two inland lakes in the Arctic region. The productivity of some Alaskan freshwater lakes was studied by Goldman (1959, 1960). Jonasson and Mathiesen (1959) used the method to measure the productivity of two Danish eutrophic lakes.

Accuracy of the Carbon Fourteen Method

The following conditions must be met if the amount of carbon fourteen bound in the plankton algae upon completion of an experiment is to give an absolute measurement of photosynthesis:

(1) Assimilation rates of radioactive carbon fourteen dioxide and natural carbon twelve dioxide must be equal.

(2) Carbon fourteen dioxide must be incorporated in the plankton algae only through the photosynthetic process.

(3) No carbon fourteen dioxide must be lost during respiration which occurs simultaneously with photosynthesis.

(4) Organic matter must not be excreted from the plankton algae.

None of these conditions, however, are fully met and thus various errors are introduced into the method for which many scientific workers have provided correction factors.

Steemann-Nielsen (1958b) demonstrated that carbon fourteen dioxide is assimilated at a slightly slower rate than carbon twelve dioxide. The author suggests a 5 per cent correction factor be used but indicates that the factor varies under various experimental conditions and is very difficult to measure.*

*The variation usually consists of a 5 pcer cent increase beyond the rate observed in experimentation.

It was also found that carbon fourteen dioxide is incorporated into the plankton algae during dark fixation periods. Experimentation by Steemann-Nielsen (1958b) reveals that the dark fixation of carbon dioxide does not exceed more than 1 or 2 per cent of the assimilation rate under optimal light conditions.

Carbon fourteen dioxide assimilated during photosynthesis was also found to be involved in the respiration process and released into the external environment as free carbon fourteen dioxide. A variety of conditions can determine the fraction of radioactive carbon dioxide that will be given off during respiration, but the duration of the experiment seems to be especially significant. Steemann-Nielsen (1958b) states that under optimum light conditions, the respiration rate equals approximately 10 per cent of the photosynthetic rate. A 6 per cent correction factor is suggested by the author to include the amount of carbon fourteen dioxide lost during respiration. This value, however, is useful only under those conditions where the respiration rates do, in fact, equal 10 per cent of the photosynthetic rate and cannot be applied unconditionally to other experimental conditions. In these situations, different correction factors will be needed.

The question of whether or not organic material is excreted by plankton algae is not as yet fully resolved; hence, no correction factor is included for this.

Arthur (1967) concludes that a possible large source of error in the carbon fourteen method of measuring productivity may result from the breaking up and subsequent release of carbon dioxide from the phytoplankton cell during the filtration process. He found that a direct relationship existed between the volume filtered, the filtration time, and the destruction of the phytoplankton cell.

It is quite evident that any given set of correction factors is valid only for a certain set of experimental conditions and when these vary, so also must the correction factors vary. For this reason, Jitts (1958) according to Vinberg (1960) was first to suggest discarding any correction factors and rather confine one's work to exacting experimental conditions. Rodhe (1958b) and most other scientific workers have agreed to this viewpoint and have carried out their investigations on this basis.

Variations in the Carbon Fourteen Method

Steemann-Nielsen (1951a) used two variations in the method of measuring primary productivity of the marine plankton algae. The first method involved collection of water samples at various depths in the ocean, inoculating them with the radioactive carbon fourteen dioxide and resuspending the samples "in situ" at the various collection depths for one-half a solar day to include all light intensities. Photosynthetic rates were determined on the basis of the amount of carbon fixed per unit of time under one square meter of sea surface for each of these depths.

Appropriate productivity curves were constructed from the results obtained. While the "in situ" method is probably the best, attendant difficulties are many. Time needed to complete operations, manpower requirements, need to return to sampling points upon completion of

incubation period, and equipment loss in bad weather are but a few of the many problems confronting the investigator.

A second method which avoided these difficulties was therefore devised. According to Steemann-Nielsen (1951a) the procedure is as follows:

Samples were collected from the surface, from the 10 per cent blue-green light level and from the 1 per cent light transmission level to include various planktonic relationships that might exist under different light intensities. The samples were incubated under laboratory conditions for four hours at an illumination of approximately 1600 foot-candles. At this level of illumination, he found the photosynthetic rate to be approximately 75 per cent of the maximum. Ryther (1956) and Steemann-Nielsen (1958a) found that the productivity below the 1 per cent light level was negligible. On this basis, Steemann-Nielsen suggested that productivity in terms of carbon fixation could be determined by multiplying the maximum photosynthetic rate by one-half the depth of the euphotic zone. If one multiplies this value by the number of hours from sunrise to sunset, the total amount of carbon fixed in terms of milligrams carbon per square meter per day can be determined. This method produces results which correspond closely with those obtained by Corlett (1958) using a similar technique.

While on marine cruises, Steemann-Nielsen (1958a), Berge (1958) and Cushing (1958) modified the carbon fourteen method in another way. These authors used a series of light filters to simulate the light intensities at the various depths. Studies by Berge (1958) indicated good agreement between experiments conducted by this method and the "in situ" experiments.

In 1956, Sorokin (Vinberg 1960) modified the carbon fourteen method in still another way while working in the Ribinsky reservoir in Russia. He calculated the photosynthetic rate at every depth by determining the surface rate of photosynthesis and multiplying the resultant by two coefficients, one representing the light conditions at the various depths and the other representing the distribution of the phytoplankton. The coefficient needed for light correction was determined by collecting a number of water samples from one depth and suspending these at desired depths for half a solar day. To determine the second factor, he collected water samples from various depths and exposed these to corresponding light conditions. From the resultant productivity rates he obtained a coefficient representing the unequal distribution of phytoplankton.

As is evident from the discussion of the various methods used to measure primary productivity utilizing the carbon fourteen technique, light is a controlling factor. It must be realized, however, that light is not the sole factor, but rather a part of a system of complicated environmental factors. It would appear, however, that the photosynthetic process occurring in plankton algae under field conditions reacts to a greater degree to conditions of illumination than to any other environmental factor. Although the carbon fourteen method first devised by Steemann-Nielsen (1951a, 1952) received a wide acclaim initially, it can readily be seen that a variety of modifications of the original method soon arose. Each of these new modified methods had its own advantages and disadvantages. Thus, the method chosen to measure pri-

mary productivity should probably be selected on the basis of the problem at hand. Because of its high sensitivity and certain logistical advantages, the carbon fourteen method was chosen for this project.

III. METHODS AND MATERIALS

General Account of Field Operations

During the 1967 shipping season, the steamships Cason J. Calloway and Sewell Avery of the United States Steel Corporation, and during the 1968 season, the steamer Ernest T. Weir of the Hanna Mining Company were made available for the field operations associated with this study. In addition to laboratory space, both food and lodging were provided the investigators. Plate 1 illustrates the type of vessel utilized in the field operations.

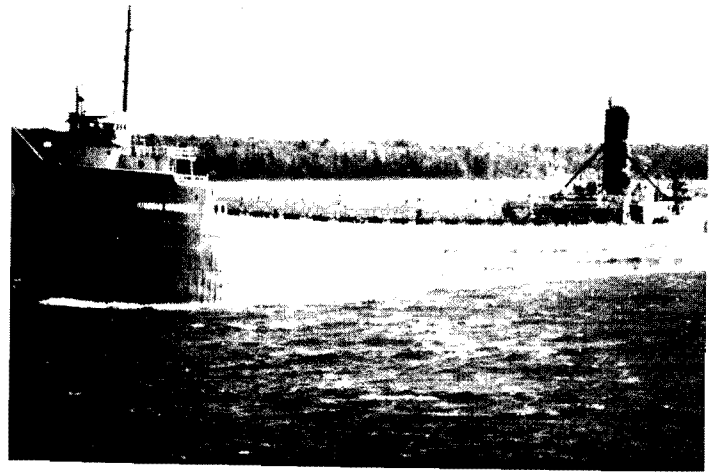


Plate I. Great Lakes Ore Carrier

The surface water productivity of Lakes Superior and Michigan was investigated during the 1967 shipping season with Lakes Superior, Huron and Erie being studied during 1968. Data were collected at irregular intervals from June 29 to October 25 during the 1967 season and from May 21 to August 25 in 1968. The shipping companies determined to a large extent the scheduling of the trips which accounted for the irregularity of the sampling runs.

The field portion of the carbon fourteen study involved bringing aboard ship all the necessary equipment needed for the productivity studies. A portion of the equipment was left aboard ship for the entire season. These included the following: incubator, preparation pan, vacauum pump, three millipore filter heads with suction flasks, pasteur pipettes and bulbs, carbuoys, indicator solutions, burettes and clamps, protective clothing and thermometers. Much of the miscellaneous equipment and supplies that were loaded aboard for each trip was removed at its conclusion for the purposes of washing glassware, replenishing distilled water, properly discarding isotope contaminated wastes, and various other activities.

Since the study was carried out aboard a moving vessel, modifications of the carbon fourteen method originally described by Steemann-Nielsen (1951a) became necessary. The term surface water as used in this study refers to the first five meters of lake depth.

Samples were collected immediately behind the bow wave because this represented the zone of thorough mixing. Since the hull of the ship is located approximately twenty-five feet below the surface, it is assumed that thorough mixing of the water occurs to this depth. The samples collected were incubated under conditions of constant illumination and constant temperature. The incubator was wired for twenty watt fluorescent daylight bulbs, four of which were used to provide an average illumination of 1000 foot-candles as suggested by Ryther (1956). The temperature was kept constant at 60° F by removing the door of the freezing compartment and installing an electric fan. The fan was vented through the side of the freezing compartment to circulate the cooler air and thereby distribute the heat produced by the fluorescent bulbs. The incubator used was a General Electric model with outside dimensions of 34½ inches by 23 inches by 22½ inches. This was large enough to accommodate two full sets of samples consisting of six bottles. The six samples represented collections from two stations and a distance of seventy miles.

Sampling Procedure

The sampling device used was extremely simple and inexpensive. It consisted of a weighted plastic jug which was modified by cutting a rectangular opening into its side (Plate 2). The lead weight was coated with teflon to avoid possible sample contamination. Plate 3 shows the sampler being lowered into the water along the port side of the ship immediately behind the foredeck. The port side of the vessel was chosen to avoid sample contamination from the sanitary facilities which were periodically flushed out of the starboard side of the vessel. Approximately one liter of surface water was collected per throw with this relatively primitive device. This was enough to provide all the water needed at any one station.

Method of Processing the Sample Aboard Ship

Upon being brought aboard ship, the sample was transferred to a one liter plastic beaker and immediately divided into three equal portions using biochemical oxygen demand bottles (B.O.D.) (Plate 4).

Plate 2. Shipboard Collection Point

Plate 3. Method of Sample Collection

Plate 4. Transfer of Sample Into B.O.D. Bottles

The B.O.D. bottles were then taken to the shipboard laboratory and inoculated with five microcurries of carbon fourteen bicarbonate within five minutes (Plate 5). The bicarbonate was dissolved in one mililiter of sterile water, pH 9.5. This is a product obtained in ampoule form from and standardized by the New England Nuclear Corporation. Protective clothing in the form of rubber gloves was used whenever handling the carbon fourteen ampoules. Pasteur pipettes were used in making the inoculations. Each ampoule was rinsed with water from the sample bottle to remove any remaining carbon fourteen. The empty ampoules and other waste materials collected during operations were stored in a plastic bag and then removed at the end of the ship's run.

As mentioned earlier, the samples were inoculated as quickly as possible into two clear and one wrapped bottle. The "dark bottle" was the one wrapped in opaque plastic (Plate 6) and rewrapped in aluminum foil (Plate 7). The opaque plastic served to shut out all light, and the aluminum foil caused the light energy within the incubator to be reradiated, thus keeping the contents of the bottle from being heated. This treatment of the "dark bottle" stops as quickly as possible any photosynthesis, thereby providing a control. The three bottles were then placed in the incubator (Plate 8) under a constant illumination of 1000 foot-candles and a constant temperature of 60° F and allowed to incubate for four hours. Upon the completion of the incubation time, the three samples were removed from the incubator and filtered, under vacuum, through .45 H.A. millipore filters (Lasker and Holmes 1957) as illustrated in Plate 9. An extremely important phase in the mechanics of filtration was the washing step (Plate 10). Samples were washed very thoroughly with approximately 250 mililiters of deionized distilled water per sample to remove any excess carbon fourteen that may have adhered to the outer surfaces of the phytoplankton or to the millipore filter. This excess carbon fourteen is present since an excess was placed in the sample originally to ensure that a sufficient amount of carbon fourteen would be available for the phytoplankton to assimilate during photosynthesis.

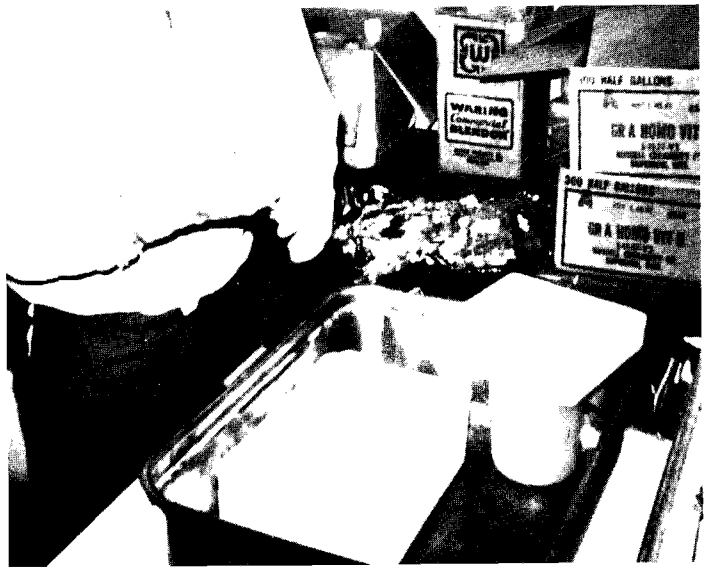


Plate 5. Inoculation of Samples

Plate 6. Wrapping of Control Sample with Black Plastic

Plate 7. Control Sample Rewrapped with Aluminum Foil

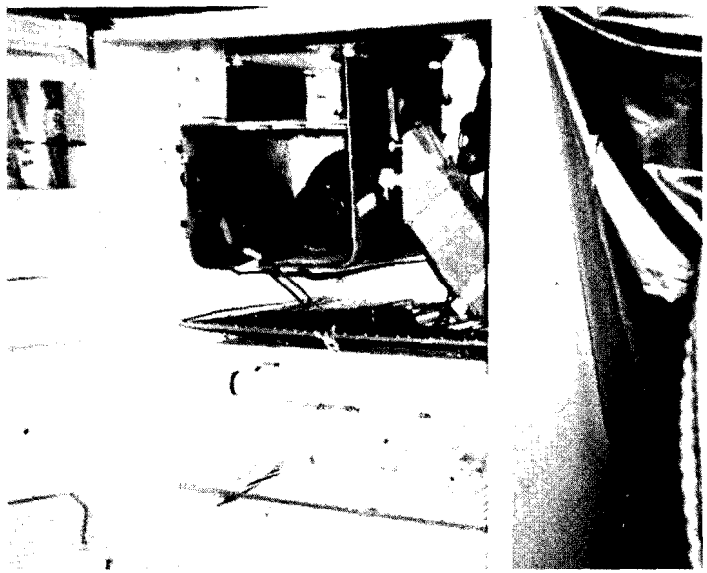


Plate 8. Placement of Samples in Incubator

Plate 9. Filtration of Samples

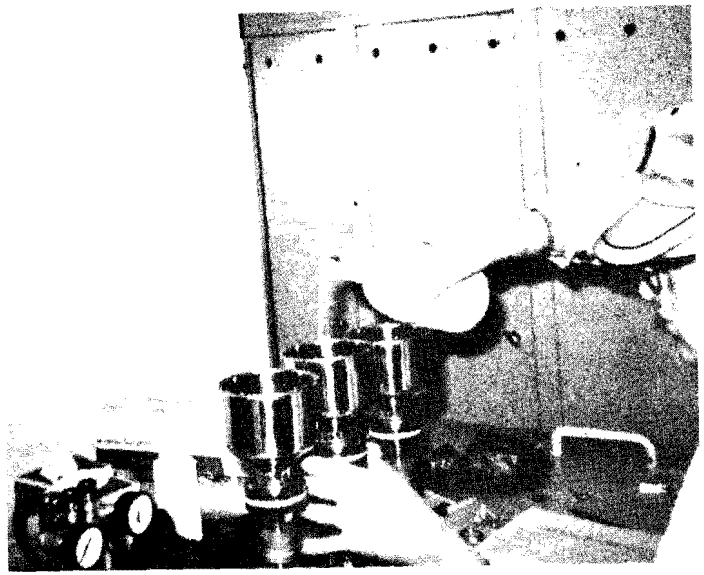


Plate 10. Washing of Filtered Sample

Plate 11. Placement of HA Millipore into Planchettes

After washing, the .45 H. A. millipore filters containing the phytoplankton were removed with bone tip forceps, and each was placed in a small milk bottle cap shaped drying container called a "planchette" (Plate 11). Plate 12 shows the planchettes being placed in a desiccator containing calcium chloride as the drying agent. The filters were allowed to dry for at least five days to ensure that any excess moisture from the filters had been removed. If all moisture is not removed, a phenomenon known as quenching occurs which produces inaccuracies when the radioactive disintegrations are later counted by the liquid scientillation procedure.

The waste water from the washing process contained radioactive material and thus was collected and saved aboard ship in specially marked carbuoys. Upon return to the laboratory, this waste water was disposed of by approved procedures.

Plate 12. Drying of Filters in Desiccator

Chemical Determinations

On each trip chemical data were collected to determine the amount of natural carbon dioxide that was available to the phytoplankton in the environment. Water samples were collected at three arbitrarily selected spots in each lake. On this basis, the lake was divided into thirds and one sample was collected from each section. The pH, water temperature, and alkalinity were determined immediately after collection of the sample. The titration procedure as carried out aboard ship is shown in Plate 13.

Plate 13. Chemical Analysis of Water Samples

At the time that a collection was made for chemical analysis, water was also collected for total solid determinations. The latter samples were analysed at the lakeside laboratory. The procedures found in Standard Methods for the Examination of Water and Wastewater (A.P.H.A. 1965) were used for all chemical determinations. The nomograph method was employed for the assessment of the amount of free carbon dioxide in the water, and by calculation the total available carbon dioxide in the water sample was determined.

Collection, Preparation and Counting Procedure of Plankton Samples

Plankton samples were collected at the same locations that water was taken for chemical determinations. Such samples were obtained on several trips to better determine the quantity and the types of organisms that are involved in the productivity of the lakes during various times of the year. Four-liter plastic jugs were used for these collections as shown in Plate 14, and 160 milliliters of formalin* was added as a preservative.

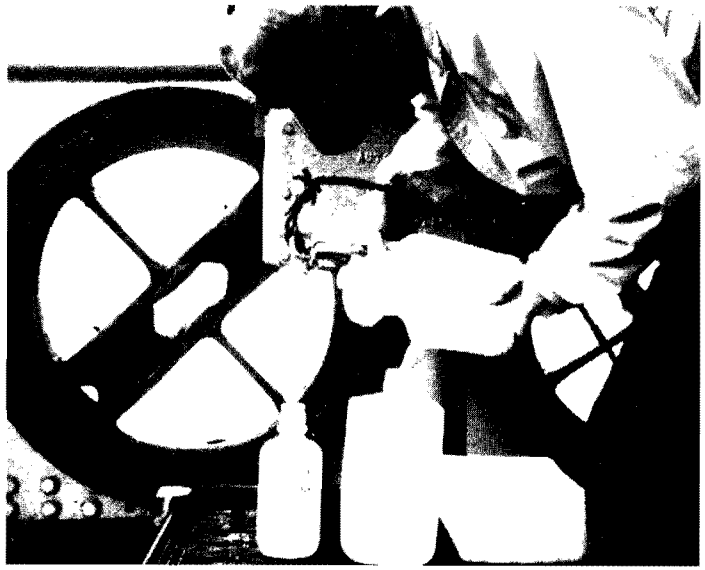


Plate 14. Collection of Plankton Samples

At the laboratory the plankton samples were placed in an isolated building and allowed to remain undisturbed for twenty-one days or more to ensure the complete settling of organisms. At the conclusion of the sedimentation period, the supernatant was carefully drawn off to a volume of approximately 500 milliliters using a teflon tube which had its end wrapped with a square of number ten bolting cloth. The remaining suspension was washed into graduated imhoff cones and allowed to settle for another twenty-one days. Again the supernatant was drawn

* Undiluted commercial formalin reagent (37% formaldehyde)

off, this time to a volume of thirty-five milliliters. The remaining suspension was agitated and poured into holding bottles. The imhoff cones were then washed with fifteen milliliters of distilled water to remove any organisms that might have adhered to the glass walls. This washwater was added to the thirty-five milliliters already present in the holding bottles, thus standardizing the sample at fifty milliliters. The sample was then vigorously shaken a total of thirty times and ten milliliters were drawn and spun down for two minutes in an angle head centrifuge after which the clean supernatant was removed, leaving a final volume of two milliliters. For counting purposes, the sample was again thoroughly agitated and a one milliliter aliquot was withdrawn and placed in a Sedgewick rafter cell. Ten random fields were counted using the twenty power objective which has a field diameter of 0.75 milliliters. Organisms which were questionable were examined under a standard coverslip at higher magnifications to permit closer inspection and the recognition of salient characteristics.

In making decisions relative to identity, the texts and keys of Tiffany and Britton (1952), Smith (1950), and Prescott (1962) were consulted. The qualitative and quantitative data for this study including total count of the plankton organisms are presented in Tables XXVI through XXXV (Appendix A).

Sample Preparation in the Laboratory

Upon return to the laboratory after the completion of a sampling trip which lasted from 5 to 6½ days, the filters containing the phytoplankton were placed in glass scintillation vials using bone tip forceps. The scintillation vials selected were the twenty-three milliliter size which permitted the complete submersion of the millipore filter in the scintillation fluid.

An Ansitron II liquid scintillation counter, manufactured by the Picker Nuclear Corporation (Plate 15), was used in place of the open window Geiger Mueller tube used by many earlier workers in the field. The Ansitron II reduced problems of geometry and absorption encountered by the Geiger Mueller method and thus greatly increased the counting accuracy of the samples. Scintillation fluid was added to each individual sample with an automatic pipetter. The scintillation fluid was composed of 4.33 grams of 2,5 diphenyloxozole commonly referred to as PPO combined with .433 grams of 1, 4-bis-2 (5 phenyloxozole) benzene, commonly referred to as POPOP. These scintillators were dissolved in one liter of reagent grade toluene.

Glass and plastic scintillation vials are available for use, but it is advisable to use glass vials since the filter can be stored for much longer periods of time and recounted if necessary. Plastic vials tend to swell upon the addition of the scintillation fluid and are usable for only approximately twenty-four hours. After filling, caps were immediately placed on the vials to decrease the quenching effect that occurs when dissolved oxygen enters the system.

Quenching, when it occurs, is a phenomenon which causes a decrease in the counting accuracy of the sample due to the absorbance of energy produced during the disintegration of the carbon fourteen. The most common quenching agents involved in this study are dissolved oxygen,

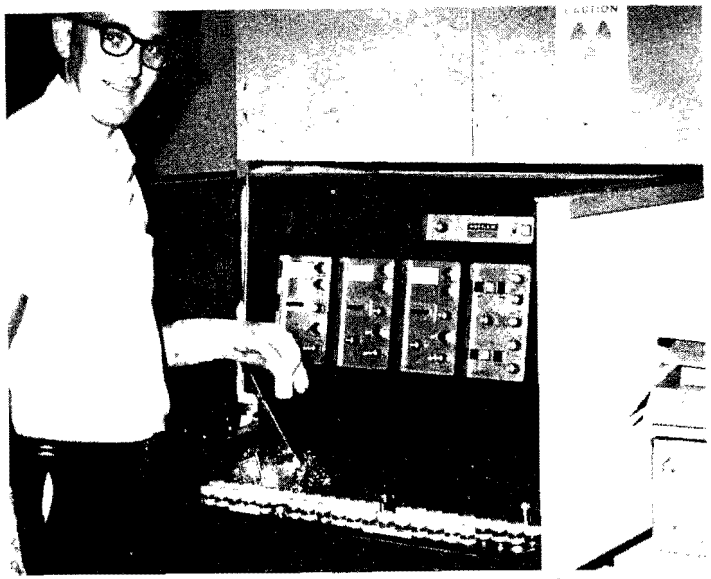


Plate 15. Ansitron II Scintillation Counter

water, the filter and any debris including the phytoplankton which may be on the filter. It is possible to remove the dissolved oxygen from the system by either purging the sample with inert gas or by using ultrasonic agitation (Rapkin 1967), but few workers feel it worthwhile. During this study samples were not deoxygenated.

Principles Regarding Liquid Scintillation Counting

After the samples had been prepared for counting, they were placed in the Ansitron II scintillometer. The general principles involved in liquid scintillation counting are as follows: The sample containing the radioactive carbon fourteen assimilated by the phytoplankton is lowered into a lead lined, totally dark counting chamber. The counting chamber contains matched photomultiplier tubes. As the carbon fourteen disintegrates, energy is produced which is converted by the scintillation fluid into photons or light energy. The photomultiplier tubes then detect and convert the photons into electrical impulses which can be recorded.

The samples were allowed to dark adapt and cool for twenty-four hours before being counted. It is necessary to dark adapt the samples as any external light source, especially fluorescent lighting, greatly excites the scintillation fluid and the metallic ions in the glass vials, even though low level potassium glass had been used in the latter. Great inaccuracies in sample counts may be produced if this procedure is not followed. Since the machine used for this project required that the photomultiplier tubes be refrigerated, the samples were also cooled to machine temperature (12° C) before being counted.

Calibration of the Liquid Scintillation Counter

Before the samples can be counted, it is necessary to determine the performance or efficiency at which the machine is operating. If the efficiency of the machine is not determined, only the apparent activity in the scintillation vials can be measured and not the true activity. Factors such as machine noise (electronics within the machine which cause counts to be recorded randomly by the machine), background, excited scintillation fluid, and any quenching agent all can account for inaccuracies in the final activity recorded for the sample. These must be recognized and proper corrections made.

To a large extent, careful machine setting will eliminate the machine noise, and proper sample preparation was, in this instance, relied upon to eliminate problems with the scintillation fluid. Background, as well as the remaining machine noise, was virtually eliminated by the control bottle since the activity measured in it (the dark bottle) included the unwanted counts which could then be subtracted from light bottle counts.

To correct for any quenching agents that may have been present within the samples, the counting efficiency of the machine had to be determined using various amounts of quenching agents. A calibration curve was then constructed and the true counting efficiency determined for each sample counted.

To calibrate the liquid scintillation counter, the following procedure was followed: Fifteen samples were collected and processed according to the procedure described earlier. These samples were designated as "standard samples" to be used as a reference and the basis for the construction of calibration curves for each successive trip thereafter. The samples were divided into three groups of five samples each. Into each sample within a group, 100 lambdas (0.1 ml) of carbon fourteen in toluene were injected. This material was obtained from and standardized by the Atomic Energy Commission. To four of the five samples prepared in this manner, increasing amount of acetone were added to produce varying degrees of quenching. Hence, while all the standards prepared contained a known amount of activity, a range of activity was recorded by the scintillation counter due to the quenching agent added.

The Ansitron II liquid scintillation counter has three independent counting channels which are regulated by potentiometers. The first channel was set to bracket the carbon fourteen energy spectrum while the second channel was set to bracket only a portion of the spectrum. In this instance, the third channel was used as a monitor of the first, but it can be used for counting purposes if dual labeled compounds are used.

The prepared standards were then counted six times each and the mean value selected to increase counting accuracy. Since a known amount of carbon fourteen in toluene had been added to each sample vial, it was possible to calculate the per cent efficiency of the machine by dividing the number of counts recorded (first channel printout) by the number of counts produced by the injected radioactive material and multiplying by 100. The counts recorded in channel two were then divided by the channel one counts to arrive at a ratio. The per cent efficiency was then plotted against the channels ratio for each of the three sets

of standards. Due to mechanical error, the three sets of standards produced slightly different calibration curves. A more accurate, best fitting, straight line curve was constructed by applying the statistical least squares method found in Standard Methods for the Examination of Water and Wastewater (A.P.H.A. 1965) to the counts obtained from the three sets of standards.

Determination of Sample Activity

All samples from a sampling trip were subsequently counted at machine settings identical with those used for the standards. By determining the channels ratio for each sample and consulting the calibration curve, it was then possible to accurately determine the efficiency at which each sample was counted. Thus, a factor was established for each sample which was used to determine the true activity present on the filter.

Counting Statistics

The samples were all counted to a 1 per cent standard error of the mean. This was accomplished by presetting the second channel to 10,000 counts. When this number of counts was reached the machine stopped counting and recorded the results. Ten thousand counts in the second channel was chosen because the standard error of this number of counts equals 1 per cent. This greatly increased the counting time of the samples because the dark samples contained very little activity. Most control samples required 300 minutes of counting time to achieve this degree of accuracy. Without the use of an automatic machine, it would not have been feasible in terms of man hours to attain this degree of accuracy.

Final Calculations and Methods of Data Analysis

Since two light samples and one dark control were collected at each sampling station, the final activity contained within the phytoplankton collected at each sampling station was determined by using the mean value of the light bottle count minus the control bottle count. The light bottle values, in most instances, were very similar as might be expected since experimental and sampling techniques were uniform.

In as much as the ultimate goal was to determine productivity in terms of carbon fixation, the results obtained had to be converted from disintegration counts to gravimetric units. To this end, the proportionality equation referred to in the literature review (page 4) was utilized. It is

$$\frac{\text{amount of } C^{14} \text{ added}}{\text{amount of } C^{14} \text{ fixed}} = \frac{\text{amount of } C^{12} \text{ present}}{\text{amount of } C^{12} \text{ fixed}}$$

In the above equation, three of the four elements are known, namely, the amount of carbon fourteen added, the amount of carbon twelve present as determined through the use of hydrochemistry, and the amount of carbon fourteen fixed which has been resolved through the use of the scintillation counter. Thus, by calculation, the amount of carbon

fixed can readily be determined. If incubation time is considered, the rate of carbon fixation can be defined as well. From the series of sampling stations observed, it was then possible to determine statistically whether or not differences in productivity occurred among the lakes studied. Comparisons of productivity levels between the lakes were also easily made. A multiple linear regression model was used to establish the variation which occurred seasonally or along the various transects of the lakes sampled. The model used for data analysis was as follows:

$$Y = A + BX + CT + e$$

where

Y = total amount of carbon fixed

A = amount of carbon fixed at time zero and distance zero

B = rate of change in Y seen in traveling one additional mile from a fixed point at a given calendar date

X = distance in miles from the fixed point

C = rate of change in Y noted per day at a given distance from the fixed point

T = time in days since beginning of sampling season

e = unexplained or unaccountable error

The complete analysis was carried out by the Biomedical Computer Center. This greatly accelerated the analysis of data.

IV. RESULTS OF 1967 AND 1968 DATA

Chemical Analysis

The chemical data including pH, water temperature, alkalinity and total solids were collected for the purpose of determining the total carbon dioxide available to the phytoplankton for carbon fixation. Initial inspection of the chemical results indicated that differences between samples within any given lake were very slight. To verify this, a two-way analysis of variance test was applied to the data. The procedure for this test is described by Dixon and Massey in their text. The actual calculation and the final results of this test have been tabulated in Appendices B, C, D and E. Appendices B and D present Lake Superior data; Appendix C represents data from Lake Michigan and Appendix E those from Lake Huron.

The test revealed that in 1967 no significant variations existed in the total carbon dioxide available within the areas sampled or as the season progressed either in Lake Superior or Lake Michigan. However, in Lake Superior during the 1968 sampling season, according to this test a significant difference existed in the available carbon dioxide as one moved from one area of the lake to another. There was, on the other hand, no indication of any seasonal variation in the carbon dioxide content of the waters. After much discussion, including comparisons with data collected during the 1967 season, it was decided that the variation noted was due to sampling error and did not represent a true variation. This view was supported by a statistical consultant (Bartch 1968). In any event, the variation noted would not significantly have affected the final calculated values of amount of carbon fixed. The two-way analysis of variance test, when applied to the 1968 Lake Huron data, revealed no significant variation in the carbon dioxide content of the waters. It was concluded that, in general, while appreciable differences may exist between lakes, there is very little variation in the total available carbon dioxide content within the waters of any given lake.

On the basis of this analysis, the mean value of all carbon dioxide data collected during the season from a given lake was used to calculate the amount of carbon fixed by the phytoplankton in that lake. The following values were used for each lake sampled during the 1967 and 1968 sampling seasons:

(1) Lake Superior, 1967 - 40.78 milligrams per liter

(2) Lake Michigan, 1967 - 97.05 milligrams per liter

(3) Lake Superior, 1968 - 39.99 milligrams per liter

(4) Lake Huron, 1968 - 71.72 milligrams per liter

Lake Superior, Trip 1, June 30-July 4, 1967

Due to various mechanical problems and rough weather sampling did not begin until 6:15 a.m., June 30. At that time, the ship was 125 miles from the Duluth, Minnesota, piers.

Figure 1 shows the sampling stations and the results obtained. Table 1 immediately following provides the detailed information. Due to the late start in sample collection, only nine samples were obtained on the downbound trip while fourteen samples were obtained on the upbound course.

It had been previously estimated that a total of twenty-four samples could be collected per trip if a two-hour sampling schedule was adhered to. However, this schedule had to be altered at various times due primarily to wind conditions which affected the speed of the ship. Upon completion of the downbound trip, it was decided to record surface water temperatures to determine whether productivity levels followed any temperature pattern throughout the lake. Thereafter, the temperatures were obtained for most of the sampling trips.

If one scans Figure 1 closely, it will be noted that variations in productivity levels do occur between the sampling stations although many appear to be very similar. Examination of Table 1 reveals productivity levels ranging from .8 to 4.5 X 10^{-3} milligrams carbon fixed per liter of surface water. The mean productivity value observed on this trip was 2.5 x 10^{-3} milligrams carbon fixed.

Closer examination of the productivity values for the various sampling stations indicates that the level of productivity for station 1 is 3.7 X 10^{-3} milligrams carbon fixed per liter surface water or higher than the next three successive sampling stations which are much closer to the shoreline. One might have expected the opposite result since nutrients washing from the land masses would presumably be available to the phytoplankton and would be more concentrated than in areas further from populated land masses.

In comparing the productivity levels from sampling station to sampling station, it will be noted that at station 5, only thirty miles from the previous sampling point, the productivity rate had increased considerably. The highest rate (4.5 X 10^{-3} milligrams carbon fixed) was reached at station 6, which incidentally is located in the deepest portion of the lake. The productivity value at station 7 remained high with respect to the mean value, but declined at sampling stations 8, 9, 10, and 11 which are located where the lake begins to narrow.

On the upbound course, sampling stations 12 and 13, located in the deepest portion of Lake Superior, again reveal increased productivity levels measured at 4.0 and 3.5 X 10^{-3} milligrams carbon fixed per liter of surface water respectively. The upbound course is usually located eight to twelve miles south of the downbound course.

Approaching the land mass named the Keweenaw Peninsula, the productivity levels for stations 14 through 17 are again reduced and are at approximately the same level as that observed at the downbound stations in this area. Stations 15 and 16 show a lower rate of productivity than some deeper water stations on either side even though the former are just three and four miles off shore respectively, where one might normally expect to observe increased productivity rates due

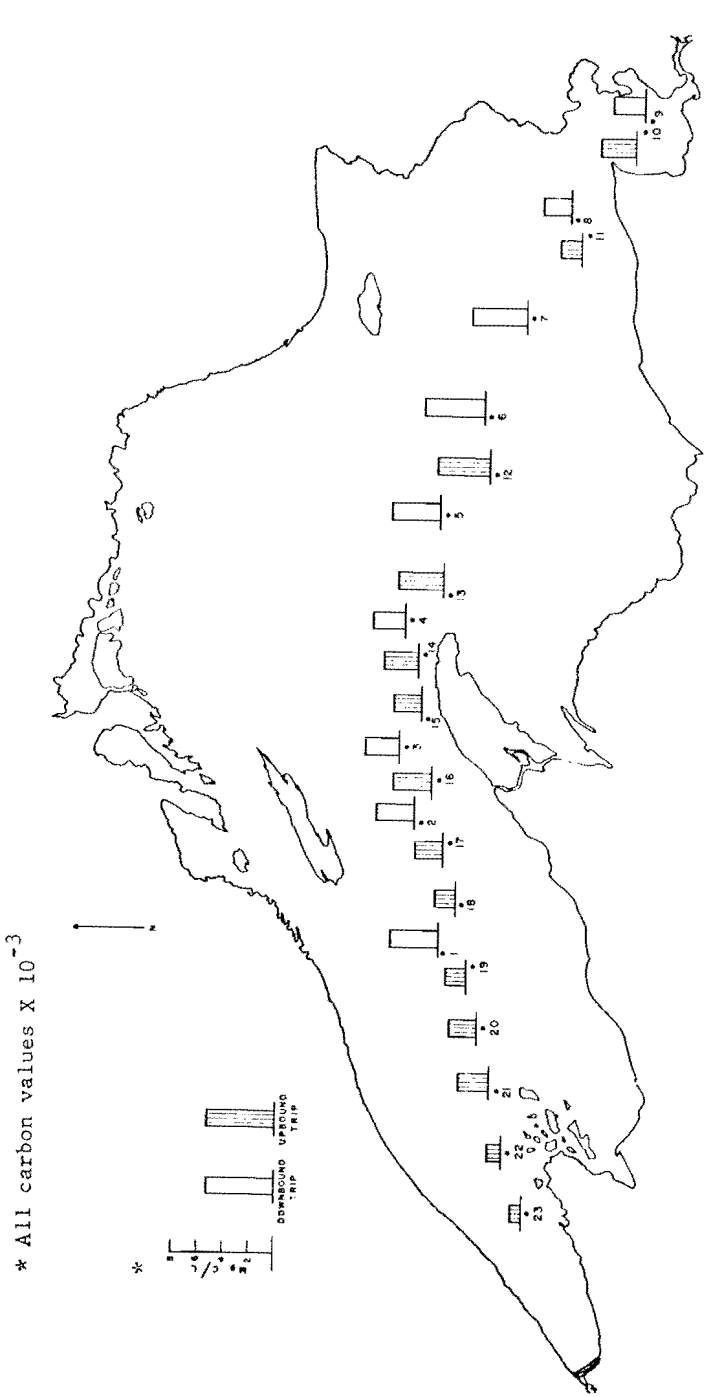


Figure 1. Milligrams carbon fixed per liter of Lake Superior surface water; Trip 1, June 30 - July 4, 1967; Four hours incubation, 60° F., 1000 foot-candles light.

Table I.

LAKE SUPERIOR PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 1.
JUNE 30 - JULY 4, 1967

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. ^{o}C	Carbon fixed in mg x 10^{-3} *
1	Duluth pier - 1 : 125	6/30	6:15 AM		3.7
2	1 - 2 : 37	6/30	8:30 AM		2.9
3	2 - 3 : 21	6/30	10:15 AM		2.7
4	3 - 4 : 35	6/30	12:30 PM		2.3
5	4 - 5 : 30	6/30	2:30 PM		3.7
6	5 - 6 : 30	6/30	4:30 PM		4.5
7	6 - 7 : 30	6/30	6:45 PM		4.3
8	7 - 8 : 30	6/30	8:30 PM		2.1
9	8 - 9 : 36	6/30	10:30 PM		2.4
10	9 - 10 : 3	7/4	12:30 AM	14.5	2.7
11	11 - 12 : 37	7/4	2:30 AM	11.5	1.7
12	12 - 13 : 36	7/4	4:30 AM	6.0	4.0
13	13 - 14 : 36	7/4	6:30 AM	7.0	3.5
14	14 - 15 : 36	7/4	8:30 AM	6.5	2.9
15	15 - 16 : 17	7/4	9:30 AM	7.0	2.0
16	16 - 17 : 17	7/4	10:30 AM	7.0	3.0
17	17 - 18 : 17	7/4	11:30 AM	7.0	2.2
18	18 - 19 : 17	7/4	12:30 PM	7.5	1.6
19	19 - 20 : 17	7/4	1:30 PM	8.0	1.6
20	20 - 21 : 17	7/4	2:30 PM	8.0	2.0
21	21 - 22 : 18	7/4	3:30 PM	7.2	2.5
22	22 - 23 : 36	7/4	5:30 PM	10.5	1.1
23	23 - Duluth pier: 18	7/4	6:30 PM	10.5	0.8

* 4 hrs. incubation time; 60°F.; 1000 Ft.-Candles Light.
(mg/l surface water)

to the influx of nutrients from the nearby land mass.

It is also noted that near the group of islands known as the Apostle Islands, located in western Lake Superior, the productivity levels are considerably lower than might be expected with the lowest productivity value of the entire trip being observed at sampling station 23 near the Apostle Islands and closest to the densely populated cities of Duluth, Minnesota, and Superior, Wisconsin.

Although surface water temperatures were recorded on only the upbound trip, it appears that productivity levels are not greatly influenced by temperature conditions at this time of the year. This is particularly emphasized by the fact that higher productivity values occurred where the lower surface water temperatures were recorded while lower productivity values were found in areas having higher surface water temperatures.

From previous observations near the western end of Lake Superior, the lake had been observed to be in an isothermal condition throughout June and into the month of July. The temperatures of the surface water observed on Trip 1 suggest the initial formation of a thermocline or layering of the water in the western and far eastern portions of the lake. This meant that the upper layer of water was warmer than the isothermal conditions which usually persists below the thermocline in oligotrophic lakes such as Lake Superior. When the lake is in an isothermal state, continuous mixing of the entire lake occurs. This mixing process redistributes vital nutrients that have settled out during the past season. Thus, when the early summer thermocline forms, increased productivity can be expected to occur due to the presence of a higher concentration of nutrients in the upper layer of water at a time when increased water temperatures and light intensity occur.

Lake Superior, Trip 2, July 15-July 20, 1967

The second sampling trip of the season occurred approximately two weeks after the first trip. A total of twenty-six samples were collected and processed on this trip. Figure 2 presents the results of the trip graphically, while Table II contains the basic data. As is very evident from Figure 2, station 1 reached a productivity level more than five times that of any other sampling station on this trip. The sample was collected two miles off the shoreline and just seven miles from the Duluth, Minnesota, piers (Table II). This is an area of shallow water which had a temperature of 12° C. The unusually high productivity rate suggests that some type of enrichment of the lake water has occurred and that it probably originated in or near the cities of Duluth, Minnesota, and Superior, Wisconsin. More research in this area of the lake is needed to determine whether this degree of eutrophication is, in fact, a reality or whether the sample represents an isolated and unrepresentative event.

One notes, if the remaining sampling stations on Figure 2 are examined, a general increase in the level of productivity over that observed on Trip 1. For example, the mean productivity value of sampling stations 2 through 26 is 2.9 X 10^{-3} milligrams carbon fixed per liter of surface water which is approximately 16% higher than that observed on the preceding trip.

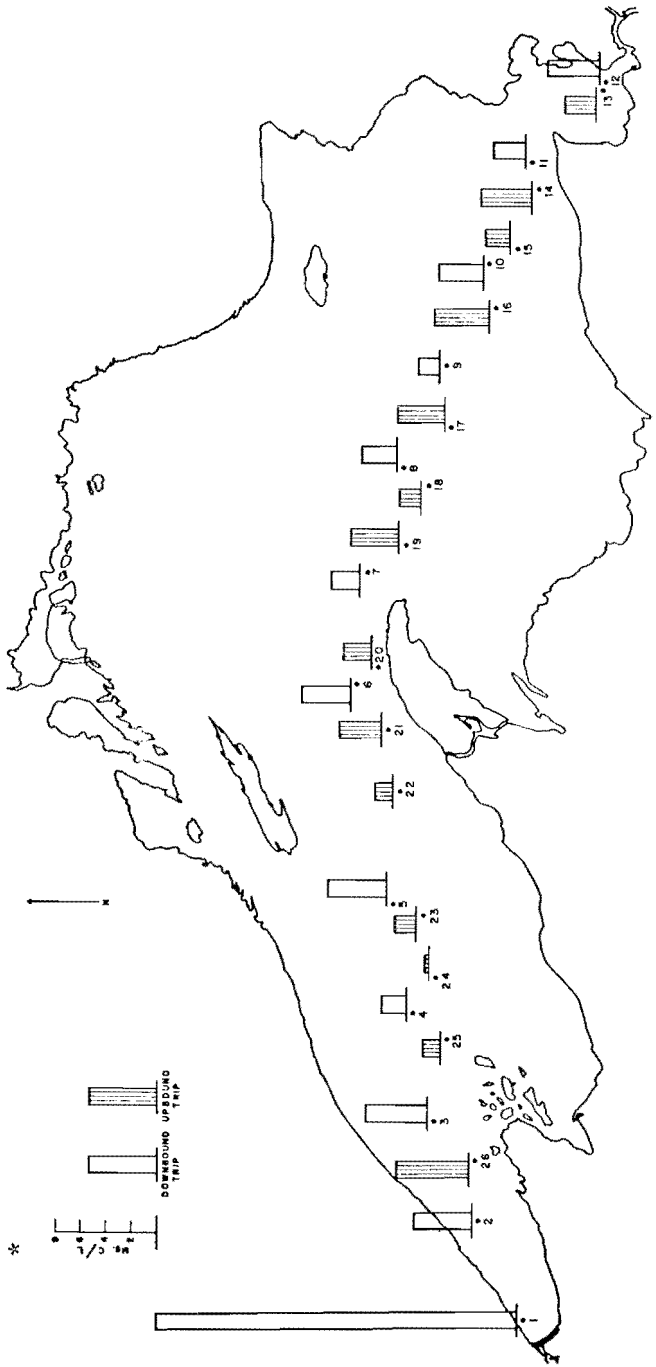


Figure 2. Milligrams carbon fixed per liter of Lake Superior surface water; Trip 2, July 15-July 20, 1967; Four hours incubation, 60° F., 1000 foot-candles light.

Table II.

LAKE SUPERIOR PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 2.
JULY 15 - JULY 20, 1967

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. °C	Carbon fixed in mg x 10^{-3} *
1	Duluth pier - 1 : 7	7/15	12:30 AM	12.0	28.4
2	1 - 2 : 31	7/15	2:30 AM	6.9	4.4
3	2 - 3 : 31	7/16	4:30 AM	7.1	4.8
4	3 - 4 : 31	7/16	6:30 AM	7.0	1.8
5	4 - 5 : 30	7/16	8:30 AM	5.2	4.6
6	5 - 6 : 61	7/16	12:30 PM	4.5	3.8
7	6 - 7 : 31	7/16	2:30 PM	5.6	2.1
8	7 - 8 : 30	7/16	4:30 PM	4.9	2.7
9	8 - 9 : 31	7/16	6:30 PM	5.0	1.6
10	9 - 10 : 31	7/16	8:30 PM	5.1	3.5
11	10 - 11 : 31	7/16	10:30 PM	11.0	2.5
12	11 - 12 : 31	7/16	12:30 AM	16.0	3.9
13	12 - 13 : 3	7/20	2:00 AM	15.9	2.4
14	13 - 14 : 35	7/20	4:00 AM	11.9	3.9
15	14 - 15 : 17	7/20	5:00 AM	7.0	1.8
16	15 - 16 : 17	7/20	6:00 AM	5.3	4.3
17	16 - 17 : 34	7/20	8:00 AM	4.5	3.7
18	17 - 18 : 17	7/20	9:00 AM	4.9	1.5
19	18 - 19 : 17	7/20	10:00 AM	5.2	3.7
20	19 - 20 : 34	7/20	Noon	15.5	2.0
21	20 - 21 : 17	7/20	1:00 PM	7.2	3.2
22	21 - 22 : 17	7/20	2:00 PM	11.8	1.3
23	22 - 23 : 35	7/20	4:00 PM	8.0	1.6
24	23 - 24 : 17	7/20	5:00 PM	9.6	0.1
25	24 - 25 : 17	7/20	6:00 PM	11.6	1.7
26	25 - 26 : 35	7/20	8:00 PM	11.6	5.5

* 4 hrs. incubation time; 60°F.; 1000 Ft.-Candles light. (mg/l surface water)

Closer scrutiny of Table II and Figure 2 discloses that at certain points rather marked variations occur in the levels of productivity. Sampling stations 2 through 6 with the exception of station 4 have values which are considerably higher than the mean. Station 4, however, only thirty-one miles from station 3 and 5, has a productivity level 2½ times smaller than the latter stations. Sampling stations 7 through 9 and station 11 show reduced productivity levels. Stations 10 and 12 represent carbon fixation at a rate well above the mean.

The upbound trip also indicated that no apparent linear trends of productivity occurred along the course traveled in Lake Superior. At sampling stations 13, 15, 18, 20 and 22 through 25, all productivity levels are considerably lower than the remaining stations. It should be noted that at station 24 there is a near absence of productivity. Although the downbound course was only nine miles from the upbound route, great differences were observed in productivity values for the same general area of the lake. This is especially obvious when one compares the rather high productivity rates of stations 2 through 6 to the very low productivity rates of stations 21 through 25. The mean rate of carbon fixation for stations 2 through 6 is 3.8×10^{-3} milligrams per liter surface water while the mean rate for stations 21 through 25 is only 1.5×10^{-3} milligrams per liter of surface water sampled.

An attempt to correlate the surface water temperatures with productivity rates was unsuccessful either in terms of relating increased productivity levels with increased water temperatures or decreased productivity values with decreased water temperatures. Also, it was not possible to associate increased productivity levels with any nearby land mass or reduction in depth although it had been assumed that such land masses and shallows might influence the nutrient concentration of the water.

Plankton samples were not collected on the first trip, but were collected on the three which followed. Unfortunately, the plankton collected on the second sampling trip were preserved with a contaminated formalin solution. The solution formed an orange precipitate that could not be separated from the plankton, thus making counting of the organisms an impossibility. As a result no plankton data are available for the first two sampling trips on Lakes Superior and Michigan.

Lake Superior, Trip 3, October 4-October 10, 1967

The third sampling run of the 1967 season was made during the first ten days of October, approximately 2½ months after the second trip. Because of scheduling problems, the steamship Cason J. Calloway could no longer be used for our study. As a result, all project equipment had to be transferred to another United States Steel Corporation steamship, the Sewell Avery. This accounts for the long lapse in time that occurred between the second and third sampling trips.

Beginning with the month of October and extending through approximately mid-December is a period referred to by all personnel working aboard the lake carriers as the "Fall Sea Season." This season is characterized by much heavier or rougher seas produced by the many storms that are quickly generated when cold air masses collide with warmer air masses over the Great Lakes.

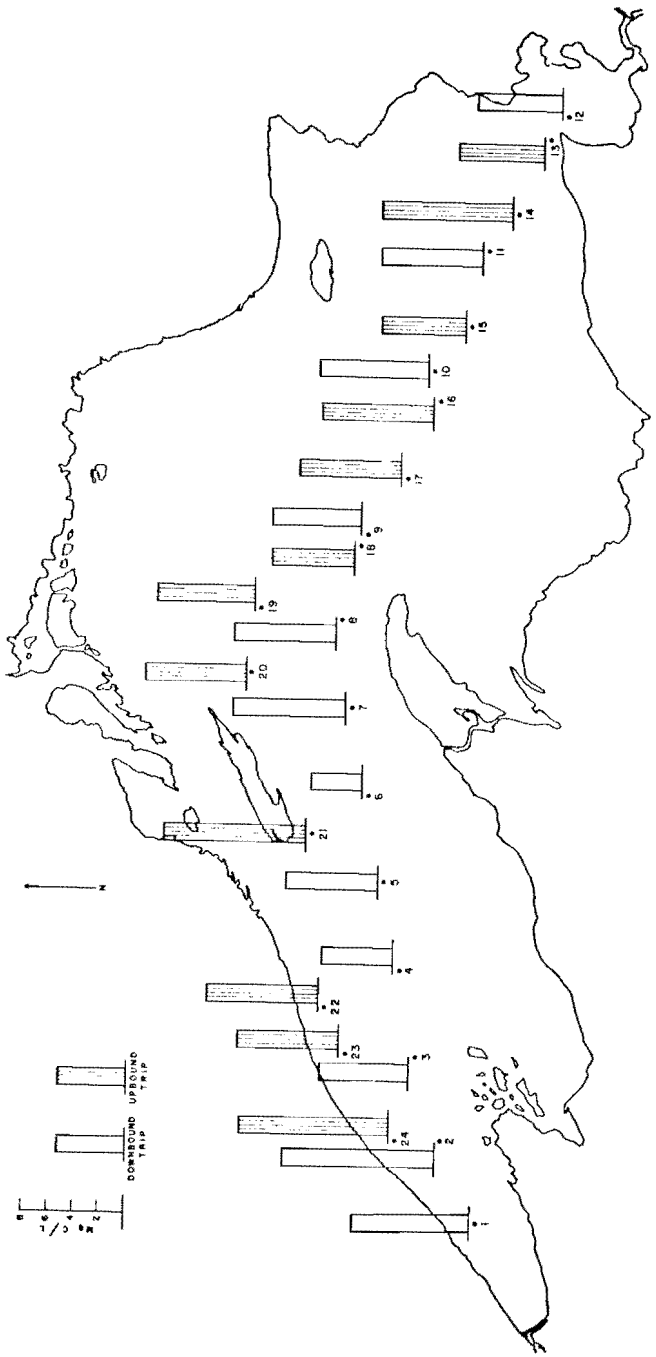
In the course of some thirty-eight individual runs on the Great Lakes, the investigator encountered rough weather on many occasions. One of the most violent of the storms occurred on this trip as is evidenced by the much altered upbound course shown in Figure 3. This particular storm blew out of the north-northwest with wind speeds measuring as high as fifty miles per hour. Since the wind was blowing across the entire lake, waves measuring between ten and thirteen feet were encountered on the first portion of the upbound course. When an ore boat is empty, as was the case in this instance, it rides approximately eight feet higher in the water. This produces a tremendous stress which is much greater than that experienced by a fully loaded vessel. Due to its great length, the stress on the vessel when empty occurs at mid-ship since the majority of its weight is confined to the forward and aft ends. This strain becomes especially obvious when the mid-deck of the vessel begins to undulate as much as one foot in high seas. After a three-day storm of this sort, one captain found that 35,000 rivets, approximately one inch in diameter, had to be replaced in the mid-section and other areas. Early on October 9, to reduce this stress on the vessel, the empty cargo holds were filled with about ten feet of water and the ship was headed directly into the storm path until protection was obtained from the northern shoreline of the lake on October 10. As the storm worsened, sampling and the processing of samples became much more difficult since all equipment used had to be lashed down. Even the samples in the incubator had to be immobilized.

At this time of year, water temperatures of most lakes drop and the thermocline begins to disappear. Complete mixing of the lake water then takes place primarily due to wind action. The temperatures of the surface water recorded on this trip (Table III) indicated that a thermocline was still present in Lake Superior. This assumption is based on the observation that temperatures at all sampling stations were well above 4° C. In the absence of a thermocline the water would have been nearly isothermal and very cold.

Twenty-four samples were collected and processed on this sampling trip. From Figure 3, it will be seen that the overall productivity level of the lake was much higher than that observed on the two previous trips. Productivity values ranged from 4.1 to 12.0×10^{-3} milligrams carbon fixed per liter of surface water. The lowest productivity value recorded for Trip 3 was 4.1×10^{-3} milligrams, which is considerably higher than the mean productivity values for either Trip 1 or 2.

The mean productivity value of Trip 3 was 8.0×10^{-3} milligrams carbon fixed per liter of surface water or more than three times the value observed for Trip 2. These steadily increasing productivity values indicate that a continuous build-up of the phytoplankton, or primary producers, is occurring in this lake as the season advances. No locational trends are obvious since sampling stations show intermittent high and low productivity values irregardless of the proximity of land masses, depth of water or surface water temperatures.

Sampling stations 19 through 24, though located in a part of Lake Superior not sampled on any other sampling trip, demonstrated productivity values that were very similar to those observed in other areas of the lake sampled (Figure 3 and Table III). This supports previous evidence that although individual variations in productivity



*All carbon values X 10^{-3}

Figure 3. Milligrams carbon fixed per liter of Lake Superior surface water; Trip 3, October 4-October 10, 1967; Four hours incubation, 60° F., 1000 foot-candles light.

Table III.

LAKE SUPERIOR PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 3.
OCTOBER 4 - OCTOBER 10, 1967

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. °C	Carbon fixed in mg x 10^{-3} *
1	Duluth pier - 1 : 34	10/4	10:00 AM	12.0	9.3
2	1 - 2 : 25	10/4	12:00 PM	12.0	12.0
3	2 - 3 : 25	10/4	2:00 PM	14.0	6.9
4	3 - 4 : 25	10/4	4:00 PM	14.5	5.7
5	4 - 5 : 25	10/4	6:00 PM	14.5	7.2
6	5 - 6 : 25	10/4	8:00 PM	13.5	4.1
7	6 - 7 : 25	10/4	10:00 PM	11.0	8.8
8	7 - 8 : 25	10/5	Midnight	10.5	8.1
9	8 - 9 : 25	10/5	2:00 AM	11.0	6.8
10	9 - 10 : 49	10/5	6:00 AM	9.0	8.4
11	10 - 11 : 38	10/5	9:00 AM	11.0	8.1
12	11 - 12 : 45	10/5	12:30 PM	12.0	4.3
13	12 - 13 : 9	10/9	5:00 AM	10.5	6.6
14	13 - 14 : 23	10/9	7:00 AM	10.5	10.4
15	14 - 15 : 24	10/9	10:00 AM	9.0	6.7
16	15 - 16 : 23	10/9	Noon	8.5	8.8
17	16 - 17 : 34	10/9	2:00 PM	8.5	7.9
18	17 - 18 : 23	10/9	4:00 PM	8.5	6.3
19	18 - 19 : 35	10/9	8:00 PM	8.5	7.7
20	19 - 20 : 14	10/9	11:00 PM	7.0	8.0
21	20 - 21 : 49	10/10	2:00 AM	10.0	11.2
22	21 - 22 : 50	10/10	6:00 AM	8.5	8.9
23	22 - 23 : 14	10/10	7:00 AM	7.5	8.0
24	23 - 24 : 28	10/10	9:00 AM	8.0	11.8

* 4 hrs. incubation time; 60°F.; 1000 Ft.-Candles light. (mg/l surface water)

levels do occur in localized areas across the lake, the entire lake becomes more eutrophic as the season progresses.

Plankton samples were collected at the same time that water was collected for chemical determinations. Table XXVI (Appendix A) lists the organisms found in the three respective areas of the lake. One notes very little difference in the types of organisms found in the various regions although an appreciably higher number of blue-green algae occurred in the central portion of the lake or in the other regions sampled. The Chrysophyte, Dinobryon, was found to be considerably more abundant in the eastern region of the lake than in other areas. Diatoms were found to be rather scarce in all regions of the lake during this time period.

"Unidentified nannoplankton" refers to those organisms that cannot be collected through the use of nets (Ruttner 1966). "Net plankton" is described as planktonic organisms that can be collected using nets (Welch 1948). On this trip, nannoplankton as well as net plankton organisms were scarce in the areas sampled.

The five predominant planktonic organisms in descending order of abundance are Lyngbya contorta, Dinobryon, Cylotella, Asterionella formosa, and Chroococcus.

Lake Superior, Trip 4, October 21-October 27, 1967

The fourth and final sampling trip on Lake Superior during the 1967 season occurred between October 21 and October 27. A total of twenty-four samples were collected and processed during this trip. Figure 4 pictorially presents the results of the trip with tabulated data listed in Table IV.

Comparing the data in Figure 4 with those in Figure 3, which represents the results of the third sampling trip, one again notes a general advancing seasonal increase in the productivity levels in Lake Superior.

Table IV discloses a productivity range extending from 3.9 to 42.9 X 10^{-3} milligrams carbon fixed per liter of surface water. The mean productivity value for the entire twenty-four sampling stations is 8.8 X 10^{-3} milligrams. This value is at least three times the mean carbon fixation value noted for the first two sampling trips on Lake Superior and represents a significant increase over the mean productivity level of 8.0 X 10^{-3} milligrams carbon fixed observed for the third sampling trip. This is especially true when one considers that only a maximum of eleven days time elapsed between Trips 3 and 4, respectively.

Closer examination of Table 4 reveals a much more uniform level of productivity on the downbound course than was observed on any previous trip. This, at first glance, might suggest more uniformity in the water masses across the lake. One might expect this to occur if isothermal conditions existed in the lake since complete mixing of the entire lake would be occurring possibly creating more uniformity in the environmental water conditions and thus more uniformity in productivity.

The upbound trip, however, shows intermittent high and low productivity values as experienced on previous trips although not quite as frequently. As before, it was not possible to correlate high or low

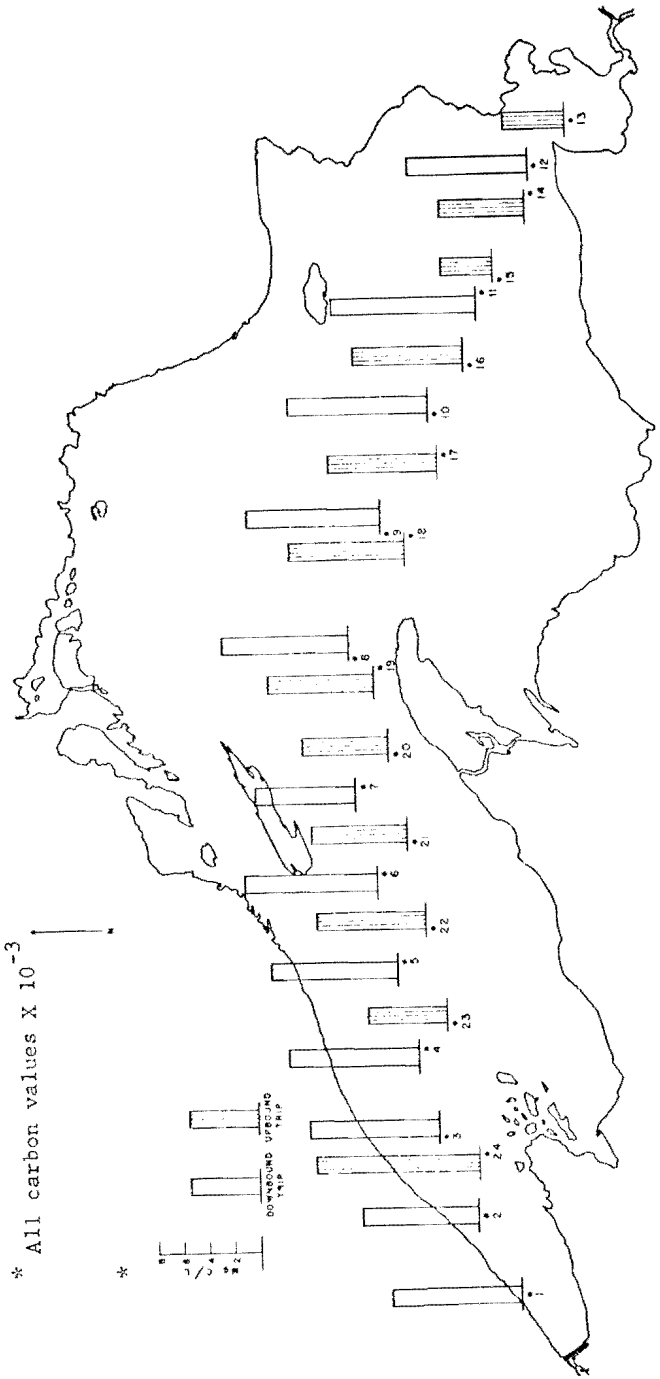


Figure 4. Milligrams carbon fixed per liter of Lake Superior surface water; Trip 4, October 21-October 27, 1967; Four hours incubation, 60° F., 1000 foot-candles light.

Table IV.

LAKE SUPERIOR PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 4.
OCTOBER 21 - OCTOBER 27, 1967

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. °C	Carbon fixed in mg x 10^{-3} *
1	Duluth pier - 1 : 20	10/21	3:00 AM		10.0
2	1 - 2 : 26	10/21	5:00 AM		9.1
3	2 - 3 : 25	10/21	7:00 AM		10.3
4	3 - 4 : 25	10/21	9:00 AM		10.0
5	4 - 5 : 25	10/21	11:00 AM		9.9
6	5 - 6 : 25	10/21	1:00 PM		10.3
7	6 - 7 : 25	10/21	3:00 PM		7.8
8	7 - 8 : 36	10/21	6:00 PM		9.9
9	8 - 9 : 35	10/21	9:00 PM		10.5
10	9 - 10 : 36	10/22	Midnight		10.8
11	10 - 11 : 36	10/22	3:00 AM		11.3
12	11 - 12 : 38	10/22	6:00 AM		9.2
13	12 - 13 : 17	10/26	10:00 PM		4.9
14	13 - 14 : 24	10/27	Midnight		6.6
15	14 - 15 : 25	10/27	2:00 AM		3.9
16	15 - 16 : 25	10/27	4:00 AM		8.6
17	16 - 17 : 25	10/27	6:00 AM		8.6
18	17 - 18 : 24	10/27	8:00 AM		9.0
19	18 - 19 : 38	10/27	11:00 AM		8.2
20	19 - 20 : 25	10/27	1:00 PM		6.6
21	20 - 21 : 25	10/27	3:00 PM		7.4
22	21 - 22 : 25	10/27	5:00 PM		8.6
23	22 - 23 : 27	10/27	7:00 PM		6.0
24	23 - 24 : 38	10/27	10:00 PM		12.9

* 4 hrs. incubation time; 60°F.; 1000 Ft-Candles light. (mg/l surface water)

productivity levels with proximity to land masses or with water depths.

Examination of plankton samples collected on this trip revealed very high concentrations of the blue-green algae Lyngbya contorta in all three regions of the lake, as shown in Table XXVII (Appendix A). It is also noted that much higher numbers of Dinobryon were found in the western and eastern regions of the lake than in the central revion. Extremely high numbers of unidentified nannoplankton were found in all three regions sampled with the highest concentrations noted in the western portion of Lake Superior.

The five predominant plankton organisms involved in the productivity of the lake during this time period were as follows:

(1) Lyngbya contorta, (2) Dinobryon, (3) Asterionella formosa,

(4) Synedra acus, (5) Synedra ulna.

Lake Michigan, Trip 1, July 1-July 3, 1967

The first sampling trip on Lake Michigan was made between July 1 and July 3, 1967, with the first sample being collected four miles from the Mackinac Bridge. The Bridge is the official landmark designated as the separation point between Lake Michigan and the Straits of Mackinac. These straits connect Lake Michigan and Lake Huron. From Lake Michigan, twenty-one surface water samples were collected and processed on this sampling trip.

The location of sampling stations and the findings are presented in Figure 5. It will be seen that the downbound course very nearly bisected the lake for its entire length. The upbound course, on the other hand, tended to follow the eastern shoreline of the lake. This reduced both the distance and time of travel significantly. Samples were taken approximately two hours apart which resulted in sampling intervals of thirty miles.

The productivity values observed ranged from 2.9 to 17.3 X 10^{-3} milligrams carbon fixed per liter of surface water (Table V). The mean productivity value was 8.1 X 10^{-3} milligrams.

If the productivity levels of the various sampling stations are examined, one will note that a great deal of variation exists between stations. Stations 1, 2, 20 and 21 located in the northern most portion of Lake Michigan illustrate productivity levels that are considerably below the mean. The least productive station of the entire trip was station 2. Productivity values at stations 3 through 7 are considerably higher than those at the north end of the lake. Four stations reflect levels of productivity that are greatly below the mean value; these stations are 2, 9, 13 and 14. Sampling stations 11 and 12, however, located at the very southern end of Lake Michigan, are considerably above the mean. In this case the values were 9.4 and 12.4 X 10^{-3} milligrams carbon fixed per liter of surface water, respectively. If the productivity levels of all stations are considered, one finds that an area of relatively low productivity in the south central portion of the lake and conversely an area of high productivity in the north central portion of the lake exist.

Although considerable variation occurred with regard to surface water temperatures, it would appear that at all stations for which

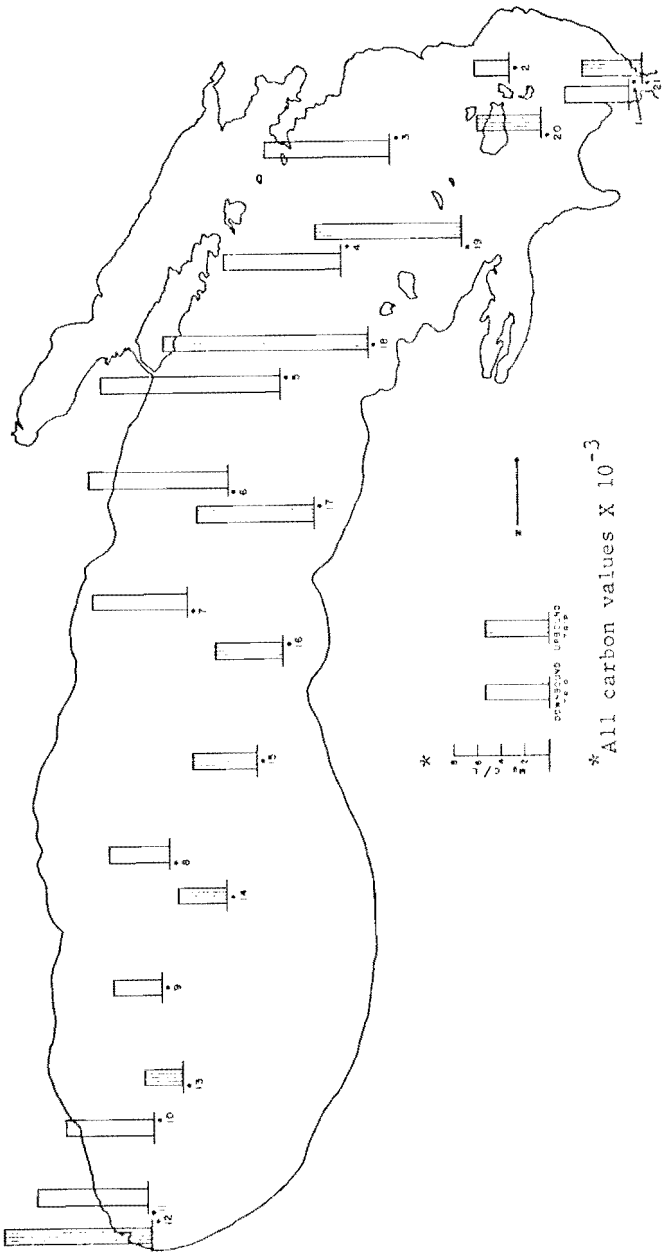


Figure 5. Milligrams carbon fixed per liter of Lake Michigan surface water; Trip 1, July 1-July 3, 1967; Four hours incubation, 60° F., 1000 foot-candles light.

Table V.

LAKE MICHIGAN PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 1.
JULY 1 - JULY 3, 1967

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. °C	Carbon fixed in mg x 10^{-3} *
1	Mackinac Brdg.- 1 : 4	7/1	9:15 AM		5.3
2	1 - 2 : 31	7/1	11:15 AM		2.9
3	2 - 3 : 37	7/1	1:30 PM		10.3
4	3 - 4 : 30	7/1	3:30 PM		9.9
5	4 - 5 : 36	7/1	5:45 PM		15.3
6	5 - 6 : 31	7/1	7:45 PM	9.5	11.9
7	6 - 7 : 32	7/1	9:45 PM	16.0	8.1
8	7 - 8 : 64	7/2	1:45 AM	15.0	4.9
9	8 - 9 : 32	7/2	3:45 AM	16.0	4.1
10	9 - 10 : 34	7/2	5:45 AM	18.5	7.6
11	10 - 11 : 24	7/2	7:30 AM	20.0	9.4
12	11 - 12 : 4	7/2	8:30 PM	21.0	12.4
13	12 - 13 : 35	7/2	10:30 PM	19.5	3.2
14	13 - 14 : 49	7/3	12:45 AM	16.0	4.2
15	14 - 15 : 35	7/3	2:45 AM	15.0	5.2
16	15 - 16 : 30	7/3	4:30 AM	15.0	5.6
17	16 - 17 : 35	7/3	6:30 AM	11.0	9.9
18	17 - 18 : 33	7/3	9:00 AM	10.0	17.3
19	18 - 19 : 35	7/3	11:00 AM	10.0	12.2
20	19 - 20 : 34	7/3	1:00 PM	16.5	5.4
21	20 - 21 : 35	7/3	3:00 PM	17.0	5.1

* 4 hrs incubation time; 60°F; 1000 Ft-Candles light. (mg/l surface water)

temperatures were recorded, a thermocline was well-established by this time. Since temperatures were recorded only for surface waters, one can not determine the depth of the thermocline.

The productivity levels did not show a linear relationship with respect to sampling location or surface water temperatures.

Lake Michigan, Trip 2, July 17-July 19, 1967

Approximately two weeks after the first trip, between July 17 and July 19, a second run was undertaken. Only seven stations are reported on the downbound course (Figure 6). This reduction in samples was due to very high counts that occurred in the control bottle. These high counts negated the light bottle counts from four stations. This was the only trip in which this problem arose. The cause is a matter for speculation only. Several factors could have been responsible. For example, contamination of the filters could account for such an error. Also, the problem could have been caused by extraneous material introduced into the control bottle. This material might have trapped significant amounts of the inoculated carbon fourteen during incubation. It is possible that material of this kind could have become embedded in the millipore filter and not have been removed during the washing process and thereby producing the very high activity recorded for the control bottle. However, the appearance of the filters was similar to others processed on this trip; no visual clue was provided relative to the actual cause of the problem.

The productivity levels of the seventeen samples analysed ranged from 2.8 to 17.5 X 10^{-3} milligrams carbon fixed per liter of surface water (Table VI). This is a slightly broader range than was observed on the preceding trip. The mean productivity level of the seventeen samples was 8.1 X 10^{-3} milligrams carbon fixed which is exactly the same value as that observed for the previous trip.

A general inspection of the data reveals that the greatest productivity occurs in the northern half of the lake with stations 1, 3 through 6, 14, 16 and 17 having much higher levels than the remaining stations. The great variation in productivity which occurred between station 1 and station 2 is particularly noteworthy. Station 1 has the highest productivity level observed on this run; yet, only thirty miles away is station 2, which represents an area with only one-sixth this rate of production. Another unanticipated finding was the very low productivity levels of sampling stations 8 through 10, which are located in the bowl end (extreme southern portion) of the lake where the water may be expected to be highly fertile since they might be greatly influenced by the highly industrial and highly populated cities of Chicago, Illinois, and Gary, Indiana.

Surface water temperatures ranged from 11.5° to 20.5°C with the highest temperature being recorded at station 8, the southern most sampling station in the lake (Table VI). These temperatures were generally higher than those observed on the preceding trip. However, they cannot be positively correlated with the higher productivity levels observed at individual sampling stations.

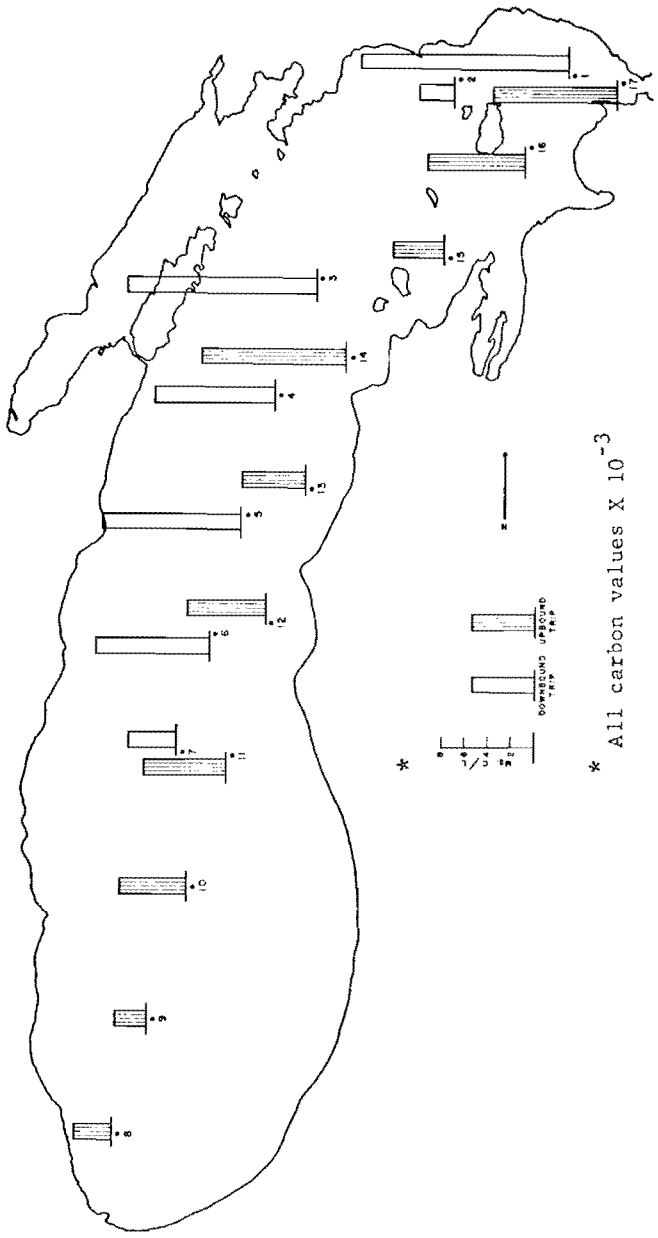


Figure 6. Milligrams carbon fixed per liter of Lake Michigan surface water; Trip 2, July 17-July 19, 1967; Four hours incubation, 60° F., 1000 foot-candles light.

Table VI.

LAKE MICHIGAN PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 2.

JULY 17 - JULY 19, 1967

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. ^{o}C	Carbon fixed in mg x 10^{-3} *
1	Mackinac Brdg.- 1 : 18	7/17	7:30 AM	17.3	17.5
2	1 - 2 : 30	7/17	9:30 AM	16.8	3.0
3	2 - 3 : 63	7/17	11:30 AM	15.5	16.0
4	3 - 4 : 33	7/17	3:30 PM	11.5	10.7
5	4 - 5 : 33	7/17	5:30 PM	11.5	11.7
6	5 - 6 : 32	7/17	7:30 PM	16.5	9.5
7	6 - 7 : 32	7/17	9:30 PM	17.1	3.9
8	7 - 8 : 99	7/18	10:45 PM	20.5	3.2
9	8 - 9 : 31	7/19	12:30 AM	18.9	2.8
10	9 - 10 : 35	7/19	2:30 AM	17.5	5.5
11	10 - 11 : 35	7/19	4:30 AM	17.1	6.9
12	11 - 12 : 35	7/19	6:30 AM	15.9	6.7
13	12 - 13 : 35	7/19	8:30 AM	15.5	5.3
14	13 - 14 : 34	7/19	10:30 AM	17.1	12.4
15	14 - 15 : 35	7/19	12:30 PM	17.8	4.3
16	15 - 16 : 35	7/19	2:30 PM	18.3	8.2
17	16 - 17 : 35	7/19	4:30 PM	19.6	10.3

* 4 hrs. incubation time; $60^{o}F.$; 1000 Ft-Candles light. (mg/l surface water)

Lake Michigan, Trip 3, October 6-October 8, 1967

From October 6 through October 8, 1967, the third sampling trip was made on Lake Michigan. Scheduling problems, already described in presenting the Lake Superior data, also apply to Lake Michigan and account for the great lapse in time (2½ months) that occurred between the second and third sampling trips. Twenty-four samples were collected and processed on this trip which resulted in a uniform and extensive coverage of the surface waters since most sampling stations were no more than twenty-five miles apart.

One is immediately impressed by the very significant increase in productivity levels that had occurred since the July runs (Figure 7). These levels ranged from 9.4 to 37.1 X 10^{-3} milligrams carbon fixed per liter of surface water sampled. The mean productivity level (16.5 X 10^{-3} milligrams carbon fixed) is more than twice the means observed on the two preceding trips.

Closer examination of the data discloses that in general the downbound samples taken along the mid-section of the lake were lower in productivity than upbound samples which were collected along a course east of the mid-line and nearer to shore. Extremely high productivity values were found at sampling station 12 and 13, which were located in close proximity to the Chicago area and in a region where the water temperatures were higher than in any other portion of the lake. High productivity levels may also be seen at stations 17 through 22 (Figure 7). The latter stations are all located in close proximity of the eastern shoreline and in fairly shallow regions of the lake. All the stations discussed above suggest that a relatively high degree of eutrophication exists in these areas of the lake.

Temperature data (Table VII) indicated that the lake was beginning to cool since temperatures were generally lower than those observed in July (Table VI). The temperatures observed indicated that a thermocline was still present at this late date.

Quantitative results of the plankton counts made on samples collected during this trip are presented in Table XVIII (Appendix A). It can be seen that very high concentrations of blue-green algae (Myxophyceae) were present in all three lake regions and that they constitute the predominant class.

Examination of the plankton samples also revealed a very high concentration of nannoplankton all across the lake. Unidentified larger algae, some of them filamentous, were found in high numbers in the central region of the lake. They were grouped under the heading "net plankton." The five most abundant organisms were all members of the Class Myxophyceae and include the following: (1) Microcystis incerta, (2) Coelosphaerium, (3) Lyngbya contorta, (4) Chroococcus, (5) Merismopedia glauca.

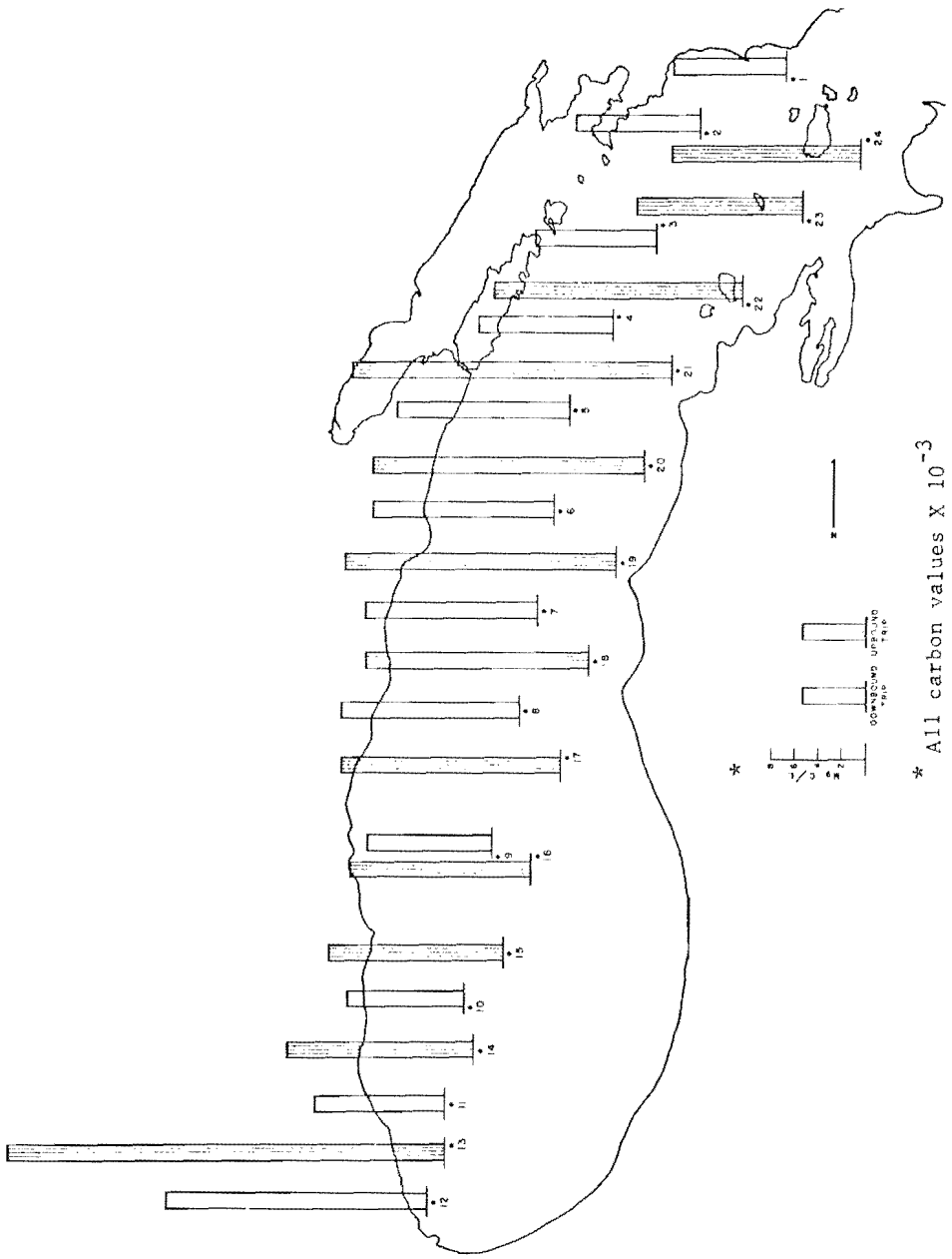


Figure 7. Milligrams carbon fixed per liter of Lake Michigan surface water; Trip 3, October 6-October 8, 1967; Four hours incubation, 60° F., 1000 foot-candles light.

Table VII.

LAKE MICHIGAN PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 3.
OCTOBER 6 - OCTOBER 8, 1967

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. °C	Carbon fixed in mg x 10^{-3} *
1	Mackinac Brdg.- 1 : 47	10/6	4:00 AM	11.0	9.4
2	1 - 2 : 26	10/6	6:00 AM	11.0	10.3
3	2 - 3 : 25	10/6	8:00 AM	12.0	10.1
4	3 - 4 : 25	10/6	10:00 AM	12.0	11.3
5	4 - 5 : 25	10/6	Noon	11.5	14.4
6	5 - 6 : 25	10/6	2:00 PM	14.5	15.3
7	6 - 7 : 25	10/6	4:00 PM	13.5	14.6
8	7 - 8 : 25	10/6	6:00 PM	14.0	15.0
9	8 - 9 : 37	10/6	9:00 PM	14.5	10.5
10	9 - 10 : 38	10/7	Midnight	14.0	9.9
11	10 - 11 : 25	10/7	2:00 AM	13.0	10.8
12	11 - 12 : 25	10/7	4:00 AM	17.5	22.1
13	12 - 13 : 15	10/7	4:30 PM	17.0	37.1
14	13 - 14 : 25	10/7	6:30 PM	15.5	15.7
15	14 - 15 : 26	10/7	8:30 PM	16.0	14.6
16	15 - 16 : 25	10/7	10:30 PM	15.0	15.3
17	16 - 17 : 26	10/8	12:30 AM	15.0	18.4
18	17 - 18 : 25	10/8	2:30 AM	14.0	18.6
19	18 - 19 : 25	10/8	4:30 AM	13.0	22.8
20	19 - 20 : 25	10/8	6:30 AM	12.0	22.7
21	20 - 21 : 25	10/8	8:30 AM	12.0	26.7
22	21 - 22 : 25	10/8	10:30 AM	13.5	20.7
23	22 - 23 : 26	10/8	12:30 PM	13.5	13.9
24	23 - 24 : 25	10/8	2:30 PM	13.0	15.8

* 4 hrs. incubation time; 60°F.; 1000 Ft-Candles light. (mg/l surface water)

Lake Michigan, Trip 4, October 23-October 26, 1967

The fourth and final sampling trip of the 1967 season was undertaken approximately two weeks after the third trip (October 23-October 26). Intense storm activity during the entire trip made every phase of the operation much more difficult. The first sample was collected fifty-eight miles from the Mackinac Bridge since severe storm activity made it unsafe to be on the deck of the ship earlier in the trip. The remainder of the downbound trip improved very little, but it was possible to collect and process the samples on schedule.

The upbound course followed the western shoreline of Lake Michigan closely (Figure 8). This course was taken to escape the same intense storm activity encountered on the downbound trip.

With the exception of sampling stations 18 through 21, it will be noted that the productivity level of the lake remained quite high. If one scans Figure 8, it will be seen that stations 6 through 17, excluding station 10, located in the central and southern lake regions have very high productivity values, while the remainder of the stations show reduced rates of production.

The productivity levels for this trip ranged from 4.1 to 33.2 X 10^{-3} milligrams carbon fixed per liter of surface water with station 12, located farthest south and closest to Chicago, exhibiting the highest level (Table VIII). The mean productivity value was 17.54 X 10^{-3} milligrams carbon fixed. This represented a slight increase over the mean of the previous trip and suggests that even at this late date, productivity levels were continuing their rise although this was occurring at a slower rate than observed earlier in the season.

Compared to the immediately preceding trip, surface water temperatures showed a definite reduction over the entire lake. This reduction, to some extent, could have been brought about by the storm activity which undoubtedly mixed the warmer surface water with the cold water from the hypolimnion. It must be remembered, however, that this is the time of year when lake temperatures normally decline as a result of falling air temperatures and other factors. Factors such as light intensity and length of day relate to this phenomenon. All these forces working together are responsible for the reduction in surface water temperatures observed each fall. In this instance, it will be noted that stations 18 through 21, which reflected the lowest productivity values, were the stations that had the lowest surface water temperatures.

Total plankton counts on this trip decreased significantly from the values observed in the first part of October as shown in Tables XXIX and XXVIII of Appendix A. Although members of the Class Myxophyceae were still the predominant planktonic organisms, their numbers were greatly reduced from those noted on the preceding trip. The diatoms, (Class Bacillariophyceae), were more abundant in the central and southern regions of the lake than in the northern portion. Unidentified nannoplankton remained at approximately the same level as on the previous trip. The unidentified net plankton grouping was considerably reduced. Coelosphaerium, Microcystis incerta, Chroococcus, Tabellaria fenestrata, and Asterionella formosa were the five most abundant plankton organisms collected on this trip.

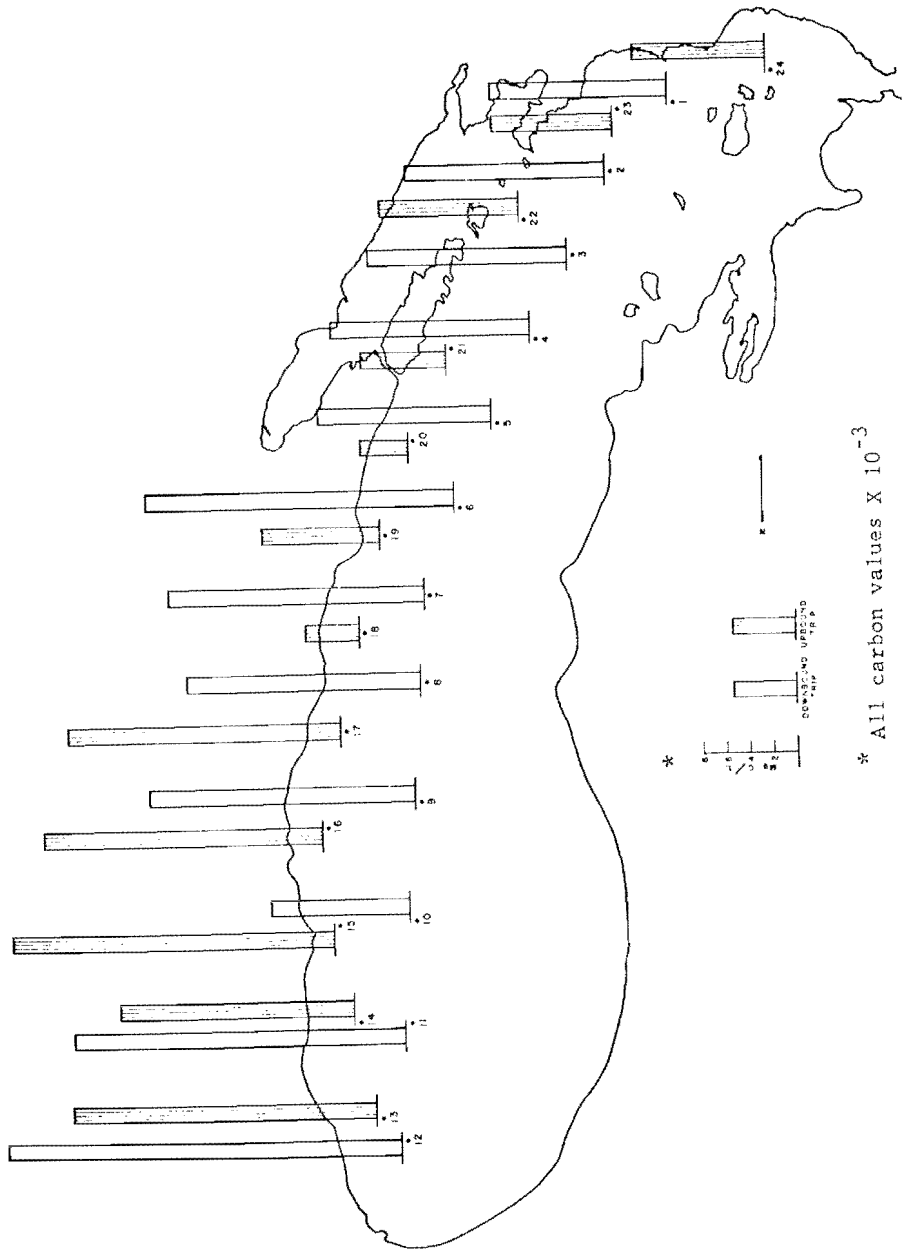


Figure 8. Milligrams carbon fixed per liter of Lake Michigan surface water; Trip 4, October 23-October 26, 1967; Four hours incubation, 60° F., 1000 foot-candles light.

Table VIII.

LAKE MICHIGAN PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 4.
OCTOBER 23 - OCTOBER 26, 1967

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. °C	Carbon fixed in mg x 10^{-3} *
1	Mackinac Brdg.- 1 : 58	10/23	1:00 AM	9.0	15.0
2	1 - 2 : 25	10/23	3:00 AM	9.0	16.7
3	2 - 3 : 24	10/23	5:00 AM	9.0	16.7
4	3 - 4 : 24	10/23	7:00 AM	9.0	16.7
5	4 - 5 : 24	10/23	9:00 AM	9.0	14.7
6	5 - 6 : 24	10/23	11:00 AM	9.0	26.2
7	6 - 7 : 24	10/23	1:00 PM	9.0	21.7
8	7 - 8 : 22	10/23	3:00 PM	11.0	19.7
9	8 - 9 : 30	10/23	6:00 PM	11.0	22.6
10	9 - 10 : 30	10/23	9:00 PM	11.0	11.7
11	10 - 11 : 26	10/24	Midnight	13.5	28.1
12	11 - 12 : 30	10/24	3:00 AM	13.5	33.2
13	12 - 13 : 9	10/25	7:00 AM	12.0	25.7
14	13 - 14 : 25	10/25	9:00 AM	11.5	19.8
15	14 - 15 : 25	10/25	11:00 AM	8.1	27.2
16	15 - 16 : 25	10/25	1:00 PM	11.3	23.4
17	16 - 17 : 25	10/25	3:00 PM	11.0	22.9
18	17 - 18 : 25	10/25	5:00 PM	5.0	4.7
19	18 - 19 : 25	10/25	7:00 PM	6.0	9.9
20	19 - 20 : 25	10/25	9:00 PM	5.0	4.1
21	20 - 21 : 25	10/25	11:00 PM	6.0	7.2
22	21 - 22 : 37	10/26	2:00 AM	7.5	11.7
23	22 - 23 : 36	10/26	5:00 AM	7.0	10.2
24	23 - 24 : 39	10/26	8:15 AM	8.0	11.2

* 4 hrs. incubation time; 60°F.; 1000 Ft-Candles light. (mg/l surface water)

Lake Superior, Trip 1, May 21-May 26, 1968

The 1968 sampling season was initiated approximately one month earlier than in 1967 with the first trip beginning on May 21. Sample collections and associated laboratory procedures were carried out aboard the steamship Ernest T. Weir, owned by the Inland Steel Corporation and operated by the Hanna Mining Company. The procedures were the same as those used during the 1967 season. Since the main steel plant owned by the Inland Steel Corporation is located at Detroit, Michigan, nearly all ore cargo was delivered to this point during the 1968 shipping season. Thus, while it became possible to extend the study to Lake Huron during this season, it was necessary to drop Lake Michigan and no samples were collected in that lake.

Figure 9 presents the Lake Superior data for the first sampling trip, and Table IX following immediately includes a tabulation of the detailed results. The sampling trip terminated at Taconite Harbor which is located approximately eighty-four miles up the North Shore of Lake Superior from Duluth, Minnesota. In all, twenty samples were taken.

With the exception of three stations, productivity levels were relatively uniform. Sampling station 12, one of the exceptions, is located at the very eastern end of Lake Superior and very close to the source of the St. Mary's River where one normally might not expect a low value because the water is comparatively shallow and large land masses are close by. The productivity level here was only 3.5 X 10^{-3} milligrams carbon fixed per liter of surface water as contrasted with a mean of 6.4 X 10^{-3} milligrams. It is also interesting to note the wide variation in the productivity levels of sampling stations 4, 5, 19 and 20, all located in the same general area of the lake. Of these stations, 19 and 20 represent the low values.

The surface water productivity ranged from 2.9 at station 19 to 9.0 X 10^{-3} milligrams carbon fixed per liter of surface water at station 1 with the highest productivity levels being observed at the first four stations.

As in 1967, plankton samples were collected from the surface waters of the lakes studied. During the 1968 sampling season, collections from Lake Superior and Lake Huron were made on Trips 1, 3 and 5. The lakes were again arbitrarily divided into three approximately equal portions and samples were collected within these areas. Such samples were subjected to chemical analysis, as well as plankton identification and quantitation.

Lyngbya contorta, a blue-green algae, was found in high numbers in all three regions of Lake Superior. The maximum concentration was found in the west end of the lake and the minimum at the east end, as shown in Table XXX (Appendix A). Although fewer in number, diatoms were found to be rather evenly distributed throughout the lake.

Unidentified nannoplankton were found to be in high concentrations all across the lake. The five most abundant phytoplankton organisms noted on this trip were Lyngbya contorta, Synedra acus, Synedra ulna, Asterionella formosa, and Melosira.

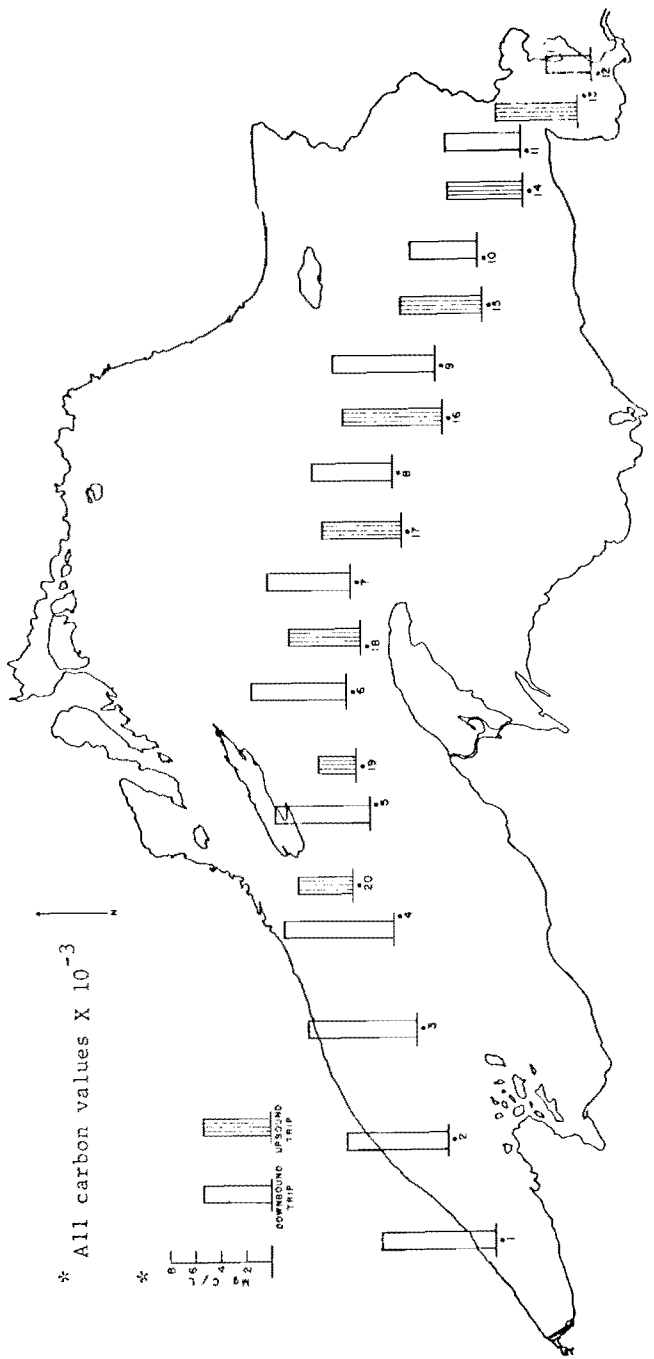


Figure 9. Milligrams carbon fixed per liter of Lake Superior surface water; Trip 1, May 21-May 26, 1968; Four hours incubation, 60° F., 1000 foot-candles light.

Table IX.

LAKE SUPERIOR PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 1.
MAY 21 - MAY 26, 1968

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. °C	Carbon fixed in mg x 10^{-3} *
1	Duluth pier - 1 : 31	5/21	4:30 PM	5.0	9.0
2	1 - 2 : 32	5/21	6:30 PM	8.0	8.1
3	2 - 3 : 33	5/21	8:30 PM	8.0	8.5
4	3 - 4 : 32	5/21	10:30 PM	8.0	8.6
5	4 - 5 : 33	5/22	12:30 AM	**	6.9
6	5 - 6 : 33	5/22	2:30 AM		7.4
7	6 - 7 : 31	5/22	4:30 AM		6.5
8	7 - 8 : 33	5/22	6:30 AM		6.2
9	8 - 9 : 32	5/22	8:30 AM		8.0
10	9 - 10 : 32	5/22	10:30 AM		5.2
11	10 - 11 : 32	5/22	12:30 PM		5.8
12	11 - 12 : 31	5/22	2:30 PM		3.5
13	12 - 13 : 8	5/25	2:30 PM		6.3
14	13 - 14 : 33	5/25	4:30 PM		5.8
15	14 - 15 : 34	5/25	6:30 PM		6.4
16	15 - 16 : 33	5/25	8:30 PM		7.7
17	16 - 17 : 34	5/25	10:30 PM		6.1
18	17 - 18 : 34	5/26	12:30 AM		5.5
19	18 - 19 : 33	5/26	2:30 AM		2.9
20	19 - 20 : 33	5/26	4:30 AM		4.2

* 4 hrs. incubation time; 60°F.; 1000 Ft-Candles light. (mg/l surface water)

** Failure of thermometers (including spare)

Lake Superior, Trip 2, June 22-June 26, 1968

The second sampling trip of the season began on June 22 and ended on June 26. Twenty-one samples were collected at intervals of approximately thirty-four miles. Results illustrated in Figure 10 show that sampling stations 2, 4, 5 and 19 at the western end of the lake have the highest productivity rates. Stations 3, 20 and 21, on the contrary, located in the same portion of the lake are much less productive. In general, the eastern one-half of the lake exhibits a lower productivity than the western half (Table X). Values for productivity ranged from 4.3 to 9.9 X 10^{-3} milligrams carbon fixed per liter of surface water. This range is slightly less than that seen on the previous sampling trip. The mean productivity value of 6.2 X 10^{-3} milligrams carbon fixed also is slightly less than the value noted for the preceding trip, which was 6.4 X 10^{-3} milligrams. This indicates that the productivity of the entire lake differs very little from that observed one month earlier.

Surface water temperatures ranged from 4° to 10° C. The large number of sampling stations exhibiting temperatures of 5° to 6° C suggested that no well established thermocline was present in the lake at this time.

Lake Superior, Trip 3, July 8-July 13, 1968

During the second week of July, a third sampling run was made. Twenty-two samples were obtained. In this series a considerable amount of variation was observed (Figure 11). The greatest variation was noted in the western two-thirds of Lake Superior. If one compares Figure 10 with Figure 11, it will be noted that a general decline in productivity seems to be occurring as the season advances. The carbon fixed at ten, or nearly half of the stations sampled, was below the lowest reported productivity level recorded on the previous trip. The low levels on this trip (July 8-13) were seen at stations 1, 3, 8, 9, 12, 13, 17, 18, 20 and 21, respectively.

Productivity ranged from 1.6 to 7.4 X 10^{-3} milligrams carbon fixed per liter of surface water with the mean value being 4.7 X 10^{-3} milligrams. Both the productivity range and the mean value of this trip are considerably lower than the values reported for the earlier trips. Worthy of mention are the very low productivity values noted for sampling stations 17 and 18. These stations are in close proximity to stations 7, 8 and 9, which represent much higher levels of productivity. This seemingly anomaly is again repeated with respect to sampling stations 3 and 21 (low productivity levels) and stations 4 and 22 (high productivity levels). It should be pointed out that a period of four days time elapsed between the upbound and downbound trips, which could allow for much shifting in the water masses to occur possibly causing a redistribution of the plankton. This could account for the variations noted.

Although temperature data recorded in Table XI do not indicate the presence of a thermocline at all points in the lake, sampling stations 1 through 3, 12 through 14, and 22, which are located in the relatively shallow and enclosed portions of the lake do illustrate the initial stages of a thermocline formation.

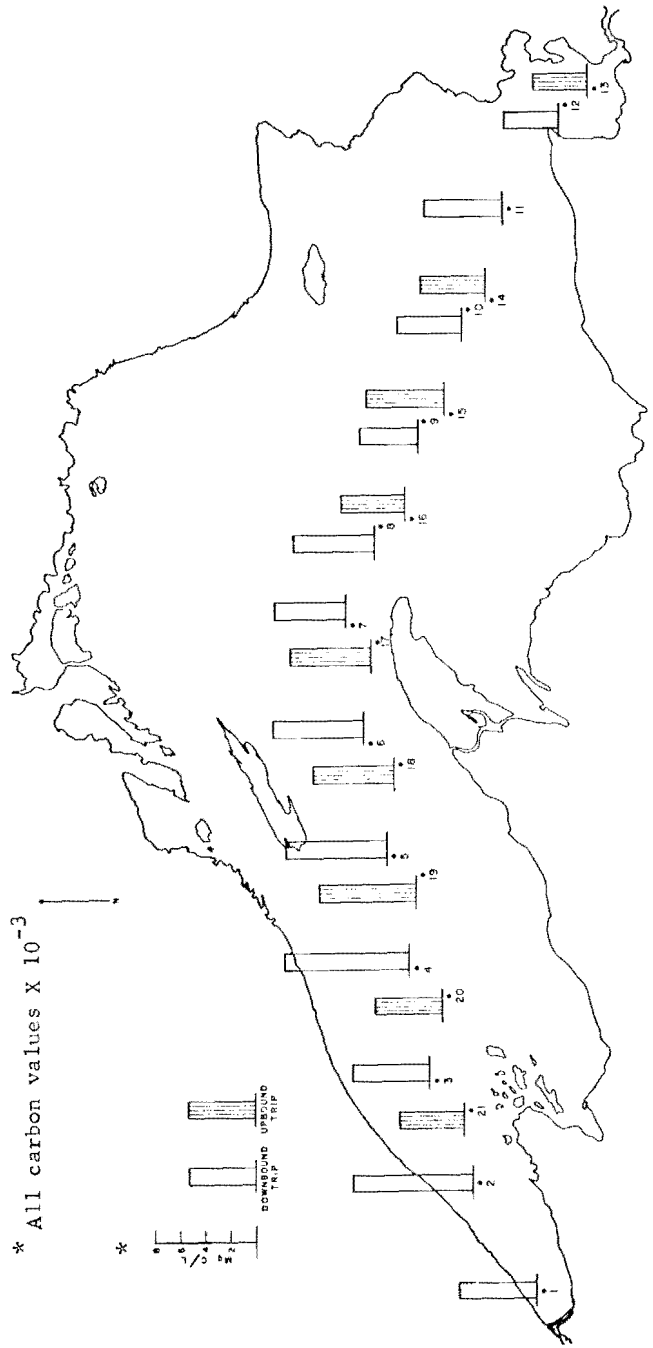


Figure 10. Milligrams carbon fixed per liter of Lake Superior surface water; Trip 2, June 22-June 26, 1968; Four hours incubation, 60° F., 1000 foot-candles light.

Table X.

LAKE SUPERIOR PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 2.
JUNE 22 - JUNE 26, 1968

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. °C	Carbon fixed in mg x 10^{-3} *
1	Duluth pier - 1 : 15	6/22	2:00 AM	8.0	6.1
2	1 - 2 : 33	6/22	4:00 AM	8.0	9.6
3	2 - 3 : 31	6/22	6:00 AM	8.0	6.1
4	3 - 4 : 32	6/22	8:00 AM	7.0	9.9
5	4 - 5 : 31	6/22	10:00 AM	5.0	8.1
6	5 - 6 : 32	6/22	Noon	5.0	7.1
7	6 - 7 : 35	6/22	2:00 PM	6.0	5.5
8	7 - 8 : 30	6/22	4:00 PM	6.0	6.3
9	8 - 9 : 32	6/22	6:00 PM	5.0	4.5
10	9 - 10 : 32	6/22	8:00 PM	4.0	5.1
11	10 - 11 : 32	6/22	10:00 PM	5.0	6.1
12	11 - 12 : 32	6/23	Midnight	10.0	4.3
13	12 - 13 : 8	6/25	9:00 PM	10.0	4.3
14	13 - 14 : 33	6/25	1:00 AM	5.0	5.1
15	14 - 15 : 33	6/26	3:00 AM	5.0	6.1
16	15 - 16 : 34	6/26	5:00 AM	5.0	5.0
17	16 - 17 : 34	6/26	7:00 AM	6.0	6.4
18	17 - 18 : 34	6/26	9:00 AM	6.0	6.3
19	18 - 19 : 34	6/26	11:00 Am	6.0	7.7
20	19 - 20 : 34	6/26	1:00 PM	6.0	5.2
21	20 - 21 : 34	6/26	3:00 PM	9.0	5.0

* 4 hrs. incubation time; 60°F.; 1000 Ft-Candles light.
(mg/l surface water)

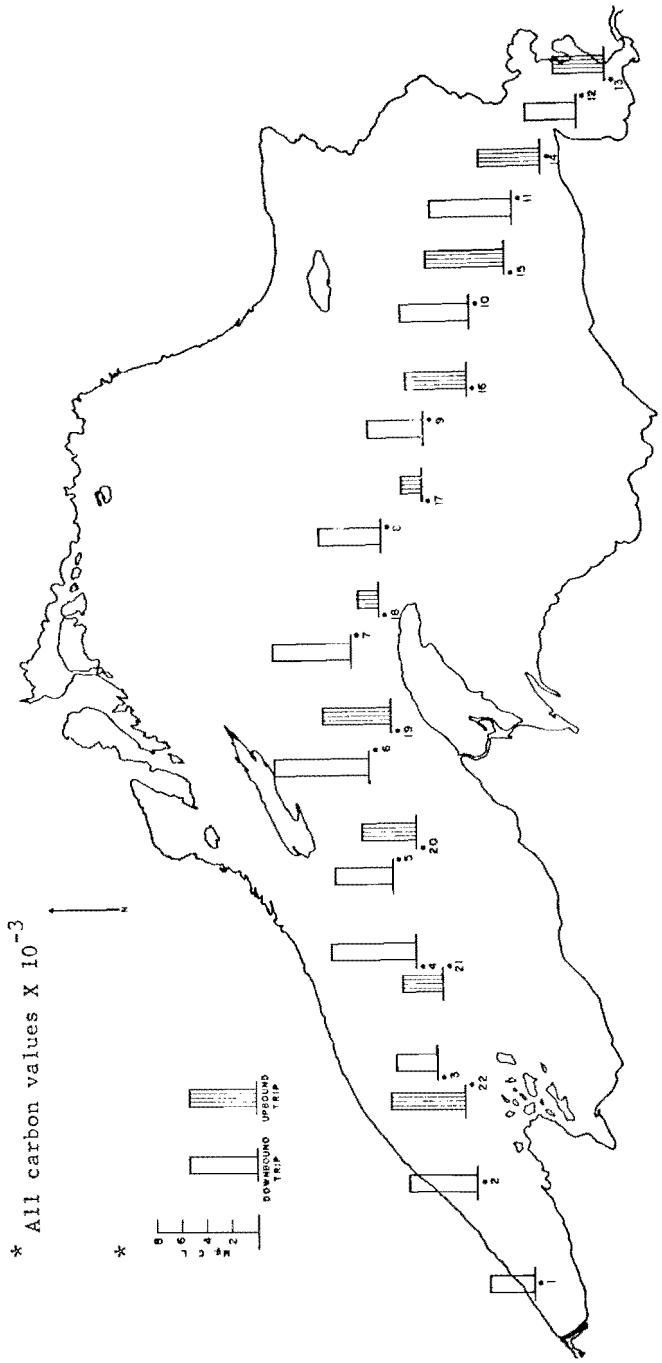


Figure 11. Milligrams carbon fixed per liter of Lake Superior surface water; Trip 3, July 8-July 13, 1968; Four hours incubation, 60° F., 1000 foot-candles light.

Table XI.

LAKE SUPERIOR PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 3.
JULY 8 - JULY 13, 1968

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. °C	Carbon fixed in mg x 10^{-3} *
1	Duluth pier - 1 : 17	7/8	8:00 AM	11.0	3.5
2	1 - 2 : 32	7/8	10:00 AM	10.0	5.4
3	2 - 3 : 33	7/8	Noon	9.5	3.3
4	3 - 4 : 32	7/8	2:00 PM	6.5	6.7
5	4 - 5 : 31	7/8	4:00 PM	6.0	4.5
6	5 - 6 : 31	7/8	6:00 PM	5.0	7.4
7	6 - 7 : 33	7/8	8:00 PM	5.0	6.1
8	7 - 8 : 32	7/8	10:00 PM	5.0	4.2
9	8 - 9 : 32	7/9	Midnight	4.5	4.3
10	9 - 10 : 35	7/9	2:00 AM	5.5	5.3
11	10 - 11 : 34	7/9	4:00 AM	5.5	6.4
12	11 - 12 : 35	7/9	6:00 AM	11.0	4.0
13	12 - 13 : 11	7/12	10:00 AM	14.0	4.1
14	13 - 14 : 32	7/12	Noon	12.0	4.7
15	14 - 15 : 34	7/12	2:00 PM	6.5	6.2
16	15 - 16 : 34	7/12	4:00 PM	5.0	4.7
17	16 - 17 : 34	7/12	6:00 PM	4.5	1.7
18	17 - 18 : 34	7/12	8:00 PM	6.0	1.6
19	18 - 19 : 33	7/12	10:00 PM	6.5	5.3
20	19 - 20 : 34	7/13	Midnight	5.0	4.2
21	20 - 21 : 34	7/13	2:00 AM	5.0	3.2
22	21 - 22 : 34	7/13	4:00 AM	11.5	5.8

* 4 hrs. incubation time; 60°F.; 1000 Ft-Candles light. (mg/l surface water)

Plankton samples were collected from all three regions of Lake Superior on the third sampling trip. Unfortunately, two of the samples were destroyed during the course of the complicated concentration procedure. For this reason, only the sample from the central lake region was available for study. See Table XXXI in Appendix A. The blue-green algae, Lyngbya contorta, was again the predominant organism. However, a considerable increase in numbers of Chrysophyceae and Bacillariophyceae was noted relative to the findings on Trip 1.

The nannoplankton concentration remained at approximately the same level as that observed on the earlier trip. On the same basis, the unidentified net plankton increased considerably. The vast majority of the unidentified net plankton were cyclotella-like organisms which lacked the characteristic striations found on the actual diatom. It is possible that these organisms may have been the cyst form of another planktonic organism found in the lake. Other than these forms, Lyngbya contorta, Synedra acus, Asterionella formosa, Dinobryon, and Rhizoselenia were the predominant organisms of the phytoplankton.

Lake Superior, Trip 4, July 24-July 29, 1968

Approximately two weeks after the third sampling trip, arrangements were completed for a fourth trip across the lake. This trip began at Taconite Harbor where the ore cargo was loaded aboard ship. This accounts for the change in origin noted in the downbound course (Figure 12).

The productivity level of the lake changed very little from the previous trip. Actually calculation of the mean productivity value indicates that the mean is exactly the same as that noted for the previous trip, or 4.7 X 10^{-3} milligrams carbon fixed per liter of surface water. The productivity ranged from 1.0 to 9.2 X 10^{-3} milligrams. (See Table XII.)

It is of interest to note the distribution of the productivity values found at the various stations sampled on this trip. Stations 1 through 5 illustrate a consistent increase in productivity at each successive point as one moves toward the open water on the downbound course. On the same course, sampling stations 6 through 10 all show reduced productivity when referred to station 5 (Table XII). With the exception of station 10, all these sampling stations are located in the open water and deepest portions of Lake Superior. At station 11, of the upbound course, located in an area of the lake known as Whitefish Bay, the highest productivity level of the entire trip was observed. The remainder of the sampling stations, with the exception of stations 16, 17 and 18, reflect productivity values that are below the mean value noted for the trip with stations 1, 12, 13 and 14 exhibiting the lowest values of all the stations sampled.

Temperature data recorded for the surface waters still indicate that the thermocline is incomplete.

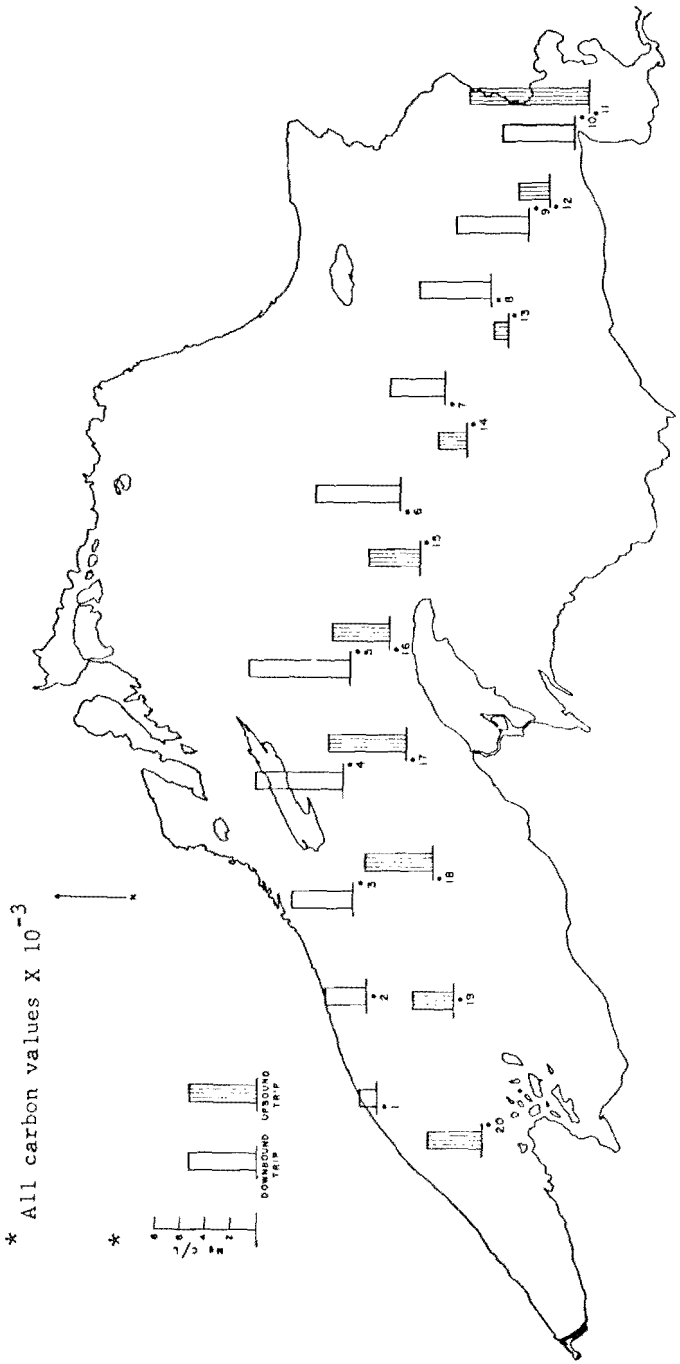


Figure 12. Milligrams carbon fixed per liter of Lake Superior surface water; Trip 4, July 24-July 29, 1968; Four hours incubation, 60° F., 1000 foot-candles light.

Table XII.

LAKE SUPERIOR PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 4.
JULY 24 - JULY 29, 1968

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. °C	Carbon fixed in mg x 10^{-3} *
1	Duluth pier - 1 : 84	7/24	2:30 AM	9.0	1.4
2	1 - 2 : 31	7/24	4:30 AM	6.5	3.3
3	2 - 3 : 32	7/24	6:30 AM	6.0	4.8
4	3 - 4 : 33	7/24	8:30 AM	5.0	6.9
5	4 - 5 : 33	7/24	10:30 AM	5.0	8.1
6	5 - 6 : 41	7/24	12:30 PM	6.5	6.9
7	6 - 7 : 33	7/24	2:30 PM	5.5	8.3
8	7 - 8 : 33	7/24	4:30 PM	5.5	5.7
9	8 - 9 : 28	7/24	6:30 PM	5.5	5.7
10	9 - 10 : 29	7/24	8:30 PM	6.2	5.5
11	10 - 11 : 4	7/29	1:00 AM	11.5	9.2
12	11 - 12 : 30	7/29	3:00 AM	7.0	2.5
13	12 - 13 : 33	7/29	5:00 AM	5.5	1.0
14	13 - 14 : 32	7/29	7:00 AM	6.5	2.0
15	14 - 15 : 35	7/29	9:00 AM	6.0	4.1
16	15 - 16 : 33	7/29	11:00 AM	6.5	4.6
17	16 - 17 : 31	7/29	1:00 PM	7.0	6.1
18	17 - 18 : 34	7/29	3:00 PM	9.0	5.3
19	18 - 19 : 34	7/29	5:00 PM	11.0	3.2
20	19 - 20 : 36	7/29	7:00 PM	14.0	4.3

* 4 hrs. incubation time; 60°F.; 1000 Ft-Candles light. (mg/l surface water)

Lake Superior, Trip 5, August 21-August 26, 1968

The fifth and final sampling trip of the season was made between August 21 and August 26, approximately one month after Trip 4. During the months of July and August, the entire region surrounding Lake Superior usually experiences its brightest and warmest days. The 1968 season was no exception to this pattern as was borne out by the marked increase in the surface water temperatures. Temperatures noted on this trip further indicate that a thermocline had been established in most areas of the lake (Table XIII). A total of twenty-two samples was collected and processed on this run.

It will be noted that in contrast to the preceding trip, a general increase had occurred in the productivity level of the lake. Stations 1, 2 and 3 reflect the highest values. The extremely low levels of productivity seen on the previous trip were not in evidence and a greater uniformity prevailed (Figure 13).

Productivity rates on this run ranged from 3.5 to 12.0 X 10^{-3} milligrams carbon fixed per liter of surface water with a mean of 5.6 X 10^{-3} milligrams. During the one month that elapsed between fourth and fifth sampling trips, the mean carbon fixation rate increased nearly one milligram per liter of surface water sampled.

Although temperatures of the surface water were considerably increased over those noted on the earlier trips, one can not interpret these as linear or as related to any linearity in the productivity values found at the various stations at this time.

Plankton samples showed very high concentrations of the Chrysophyte Dinobryon in the western portion of Lake Superior. However, very few of these organisms were found in the other two areas of the lake. This is indicated in Table XXXII (Appendix A). The numbers of Lyngbya contorta were highest in the central region of the lake and lowest at the western end. In contrast, diatoms were found in highest concentrations at the western end of the lake. The five most numerous organisms in descending order were Dinobryon, Lyngbya contorta, Synedra acus, Asterionella formosa and Synedra ulna.

Lake Huron, Trip 1, May 22-May 25, 1968

The first sampling trip on Lake Huron was made May 22 to May 25 inclusive. The first sample was collected three miles from the Detour Reef Light which is located very near the mouth of the St. Mary's River. This light marks a separation point between Lake Huron proper, its North Channel, and the river systems emptying into the northern portion of the lake. The main navigation routes traveled by the shipping lines are situated in the western portion of Lake Huron. These navigation routes are followed primarily because they represent the shortest longitudinal route across the lake and also because many points in the more easterly portions of the lake are extremely shallow, making navigation in these areas very hazardous. The downbound and upbound courses traveled are separated by approximately seven miles.

Table XIII.

LAKE SUPERIOR PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 5.
AUGUST 21 - AUGUST 26, 1968

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. ^{o}C	Carbon fixed in mg x 10^{-3} *
1	Duluth pier - 1 : 9	8/21	4:30 AM	13.5	7.7
2	1 - 2 : 32	8/21	6:30 AM	12.0	9.3
3	2 - 3 : 31	8/21	8:30 AM	14.0	12.0
4	3 - 4 : 31	8/21	10:30 AM	13.0	6.6
5	4 - 5 : 32	8/21	12:30 PM	8.0	5.2
6	5 - 6 : 32	8/21	2:30 PM	9.5	5.2
7	6 - 7 : 22	8/21	4:30 PM	8.0	3.6
8	7 - 8 : 29	8/21	6:30 PM	12.0	4.3
9	8 - 9 : 32	8/21	8:30 PM	8.5	4.2
10	9 - 10 : 32	8/21	10:30 PM	9.5	4.9
11	10 - 11 : 32	8/22	12:30 AM	11.0	4.6
12	11 - 12 : 33	8/22	2:30 AM	16.0	5.2
13	12 - 13 : 33	8/25	4:30 PM	14.0	5.1
14	13 - 14 : 34	8/25	6:30 PM	13.0	5.0
15	14 - 15 : 33	8/25	8:30 PM	9.0	4.5
16	15 - 16 : 34	8/25	10:30 PM	8.0	3.5
17	16 - 17 : 31	8/26	12:30 AM	8.0	4.7
18	17 - 18 : 34	8/26	2:30 AM	13.0	5.5
19	18 - 19 : 32	8/26	4:30 AM	12.0	4.8
20	19 - 20 : 34	8/26	6:30 AM	12.0	5.8
21	20 - 21 : 33	8/26	8:30 AM	11.0	6.5
22	21 - 22 : 31	8/26	10:30 AM	15.0	5.8

* 4 hrs. incubation time; 60°F.; 1000 Ft-Candles light. (mg/l surface water)

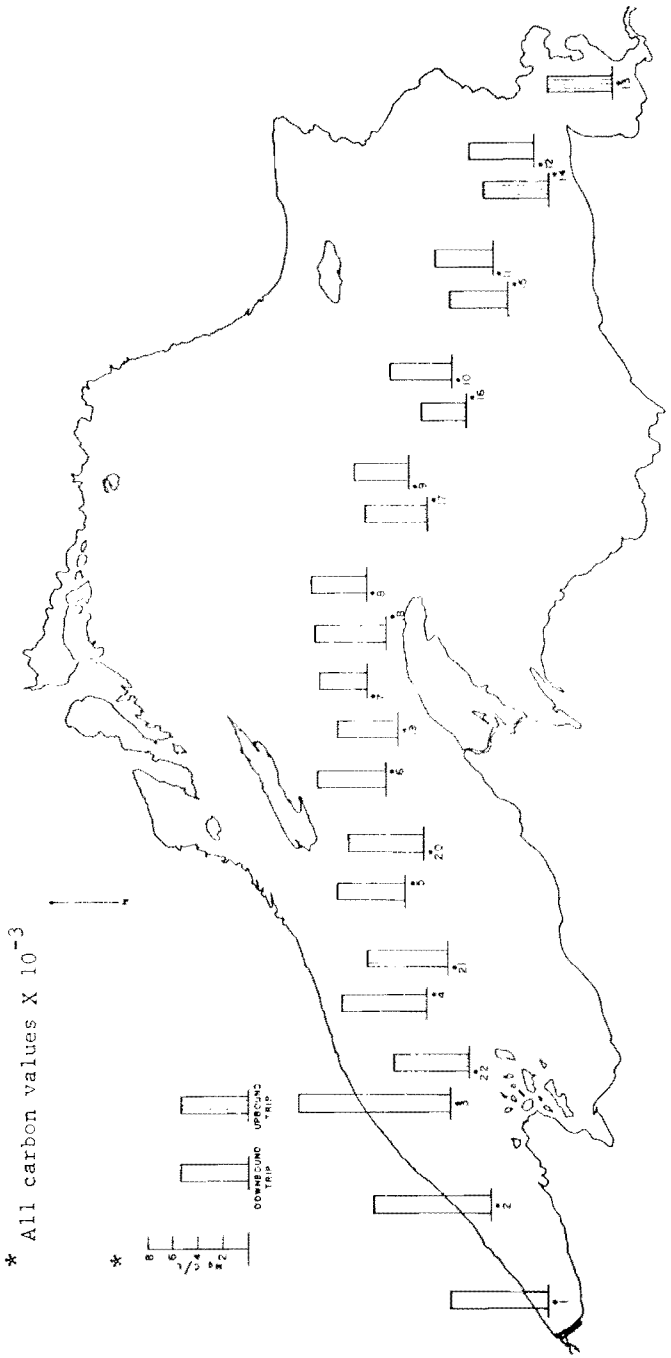


Figure 13. Milligrams carbon fixed per liter of Lake Superior surface water; Trip 5, August 21-August 26, 1968; Four hours incubation, 60° F., 1000 foot-candles light.

The same two-hour sampling schedule employed for the other lakes studied was followed here. This resulted in the collection of a maximum of fourteen samples on any given trip due to the shorter distance across this lake.

A very high level of productivity existed at nearly every station (Figure 14). Station 3 was the most productive (20.1 X 10^{-3} milligrams carbon fixed per liter of surface water). One also will see that the productivity levels of the downbound stations are higher in nearly every case than those observed for upbound stations. An extremely low rate of production will be noted at station 8B when it is compared to station 7. Only nine miles separated the stations. However, it should be recognized that a day of time had elapsed between the collections. Stations 3 and 11 illustrate a similar variation in productivity. In this instance, the time lapse between collections was, for all practical purposes, two days; the distance separating the stations was eighteen miles.

Productivity levels ranged from 3.0 to 20.1 X 10^{-3} milligrams carbon fixed per liter of surface water (Table XIV). The mean productivity value was 12.0 x 10^{-3} milligrams.

With the exception of the central region of the lake, counts of plankton samples revealed an absence of blue-green algae and a predominance of Chrysophytes, especially the diatoms as shown in Table XXXIII (Appendix A). The Chrysophyte Dinogryon was not found in the northern waters of the lake and was present in very low numbers in the central lake region. However, a high concentration of these organisms appeared in the southern portion.

In this lake, diatoms as a group were found to be more abundant both in terms of Genera and numbers of organisms than they had been in either Lake Superior or Lake Michigan. Very high concentrations of nannoplankton were also noted. The cyclotella-like organism previously mentioned was predominant in the net plankton.

The five organisms most frequently seen were (1) Dinobryon, (2) Melosira, (3) Asterionella formosa, (4) Synedra acus, and (5) Tabellaria fenestrata.

Lake Huron, Trip 2, June 23-June 25, 1968

The second sampling trip on Lake Huron was undertaken between June 23 and June 25, with a total of thirteen samples being collected and processed while crossing the lake. Figure 15 indicates that the highest level of productivity occurred at station 1, which was located just seven miles from narrows, the point where the river systems empty into the lake. Two days later, however, at sample station 13, located approximately four miles closer to the narrows, the productivity level was found to be less than one-third of that recorded for station 1. This represented the lowest carbon fixation level encountered on the entire trip. These findings again indicate that a great deal of variability can occur in productivity levels within a single lake. Stations 1, 3, 9 and 11 exhibit levels of productivity that are considerably greater than those observed at the remaining stations.

If one compares Figure 15 (Trip 2) with Figure 14 (Trip 1) it will immediately be noted that a significant reduction in productivity occurred during the one month which separated the trips. The productivity

Table XIV.

LAKE HURON PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 1.

MAY 22 - May 25, 1968

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. °C	Carbon fixed in mg X 10^{-3} *
1	Detour Light - 1 : 3	5/22	10:30 PM	**	14.0
2	1 - 2 : 31	5/23	12:30 AM		14.4
3	2 - 3 : 31	5/23	2:30 AM		20.1
4	3 - 4 : 33	5/23	4:30 AM		14.6
5	4 - 5 : 32	5/23	6:30 AM		9.6
6	5 - 6 : 32	5/23	8:30 AM		16.8
7	6 - 7 : 31	5/23	10:30 AM		13.7
8A	7 - 8A : 25	5/24	5:00 PM		10.9
8B	8A - 8B : 34	5/24	7:00 PM		3.0
9	8B - 9 : 34	5/24	9:00 PM		9.9
10	9 - 10 : 34	5/24	11:00 PM		11.6
11	10 - 11 : 34	5/25	1:00 AM		9.0
12	11 - 12 : 34	5/25	3:00 AM		13.1
13	12 - 13 : 36	5/25	5:00 AM		7.4

* 4 hrs. incubation time; 60° F.; 1000 Ft-Candles light. (mg/l surface water)

** Failure of thermometers (including spare)

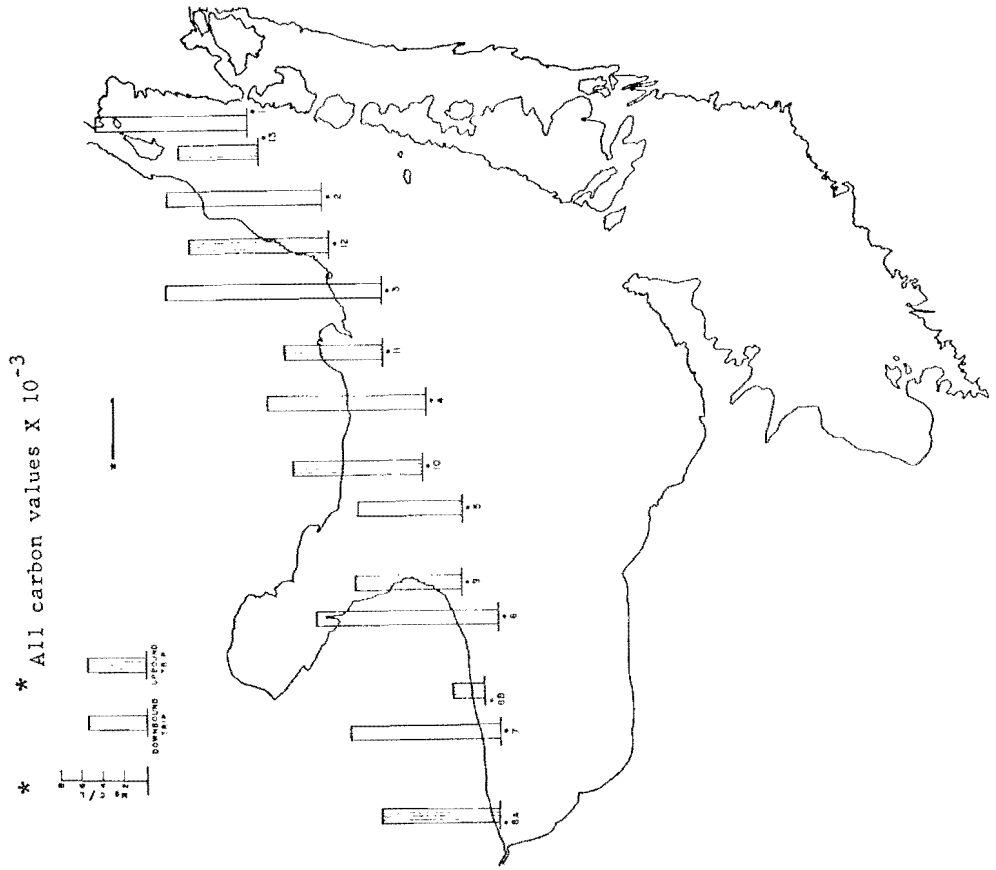


Figure 14. Milligrams carbon fixed per liter of Lake Huron surface water; Trip 1, May 22-May 25, 1968; Four hours incubation, 60° F., 1000 foot-candles light.

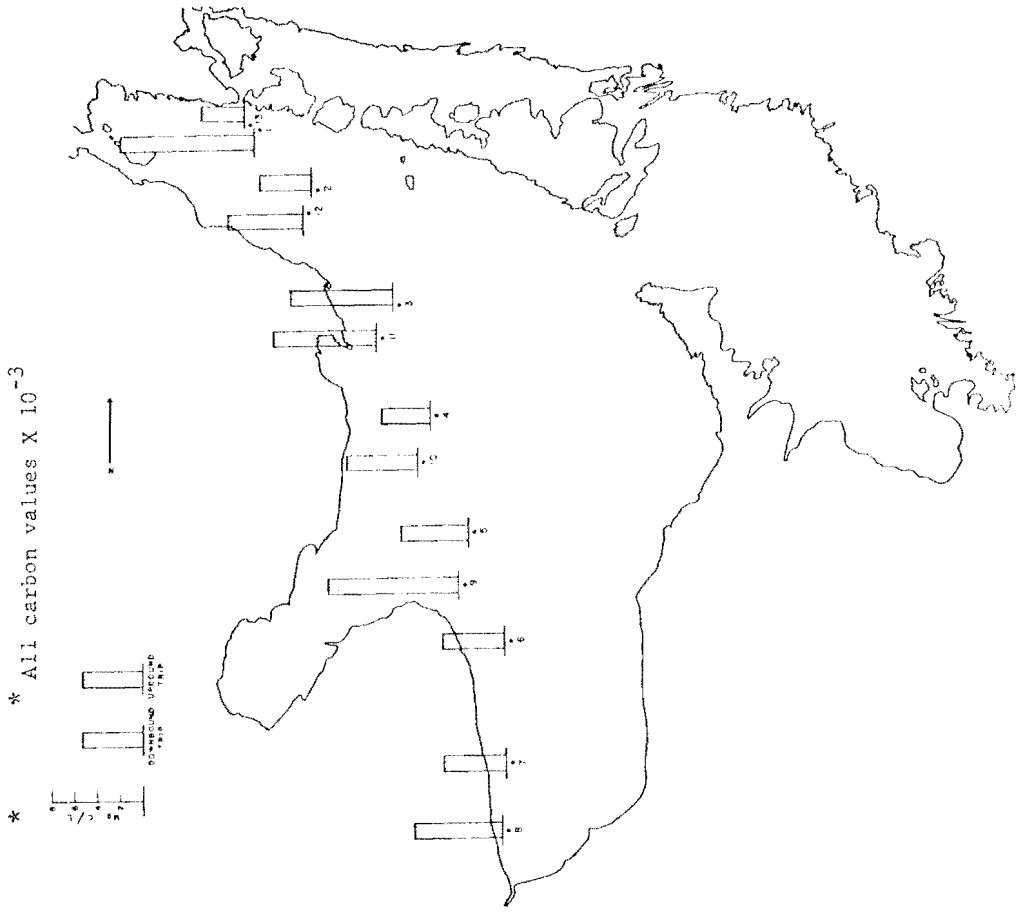


Figure 15. Milligrams carbon fixed per liter of Lake Huron surface water; Trip 2, June 23-June 25, 1968; Four hours incubation, 60° F., 1000 foot-candles light.

levels of the lake ranged from 3.8 to 12.1 X 10^{-3} milligrams carbon fixed per liter of surface water sampled (Table XV). The mean productivity value of the samples collected was 7.0 X 10^{-3} milligrams. This is approximately one-half the mean value observed on the previous trip.

Surface water temperatures ranged from 8.0 to 15.0° C which suggests that a thermocline existed throughout areas of the lake sampled. Although the highest surface water temperatures were observed in the more southerly portions of the lake, correspondingly high productivity levels were not found.

Lake Huron, Trip 3, July 9-July 13, 1968

Fourteen samples were collected and processed on the third sampling trip on Lake Huron (July 9 through July 13). On the downbound trip a rather uniform rate of productivity characterized stations 3 through 6 with reduced levels being seen at stations 1, 2 and 7 (Figure 16) However, on the return trip, productivity was found to be lower than values observed for any of the downbound stations. Sampling stations 11 and 12 showed nearly a sixfold reduction in rates over those observed in the same area two days earlier. Comparison of the mean productivity level of the two runs shows that mean rate of production on the downbound trip was nearly twice as high as that for the upbound trip. The productivity levels were 6.5 and 3.4 X 10^{-3} milligrams carbon fixed per liter of surface water respectively. Overall the productivity values ranged from 1.3 to 8.0 X 10^{-3} milligrams carbon fixed and the mean productivity value was 4.9 X 10^{-3} milligrams carbon fixed. The latter value, if compared with the mean of 7.0 X 10^{-3} milligrams recorded three weeks earlier, and the mean of 12.0 X 10^{-3} milligrams found approximately seven weeks earlier, represented a total reduction of almost 60 per cent.

Surface water temperatures increased as might be expected with the advancing season. On this trip, the temperatures ranged from 11.0 to 18.0° C. It was assumed that a thermocline was well established throughout the lake. (Table XVI).

Except for a small number of organisms collected at the southern end of the lake, blue-green algae (Myxophytes) were not found on this trip. The golden brown algae (Chrysophytes) predominated the phytoplankton as shown in Table XXIV (Appendix A). The Chrysophyte, Dinobryon, was found in high numbers in the north and central lake regions with the diatoms being most abundant in the southern portion of the lake. If one compares the findings of this trip to those of the first sampling trip (Table XXXIII, Appendix A) it will be seen that an increase in the diatom population occurred in all regions of the lake sampled. The phytoplankton, Dinobryon, was also found to be more abundant in both the north and central regions of the lake than was noted in the earlier trips. The numbers of nannoplankton decreased while the net plankton remained at approximately the same level as noted in the first sampling trip. Asterionella formosa, Dinobryon, Fragilaria crotenesis, Synedra acus, and Tabellaria fenestrata, all diatoms, with the exception of Dinobryon were the most abundant phytoplankton.

Table XV.

LAKE HURON PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 2.

JUNE 23 - JUNE 25, 1968

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. ^{o}C	Carbon fixed in mg x 10^{-3} *
1	Detour Light - 1 : 7	6/23	10:30 AM	11.0	12.1
2	1 - 2 : 23	6/23	12:30 PM	8.0	4.6
3	2 - 3 : 38	6/23	2:30 PM	8.0	9.0
4	3 - 4 : 31	6/23	4:30 PM	10.0	4.2
5	4 - 5 : 32	6/23	6:30 PM	12.0	5.8
6	5 - 6 : 30	6/23	8:30 PM	13.0	5.3
7	6 - 7 : 32	6/23	10:30 PM	15.0	5.2
8	7 - 8 : 18	6/25	2:00 AM	10.0	7.7
9	8 - 9 : 65	6/25	6:00 AM	14.0	11.4
10	9 - 10 : 34	6/25	8:00 AM	12.0	6.7
11	10 - 11 : 35	6/25	10:00 AM	11.0	9.1
12	11 - 12 : 38	6/25	12:15 PM	9.0	6.6
13	12 - 13 : 29	6/25	2:00 PM	9.0	3.8

* 4 hrs. incubation time; $60^{o}F.$; 1000 Ft-Candles light. (mg/l surface water)

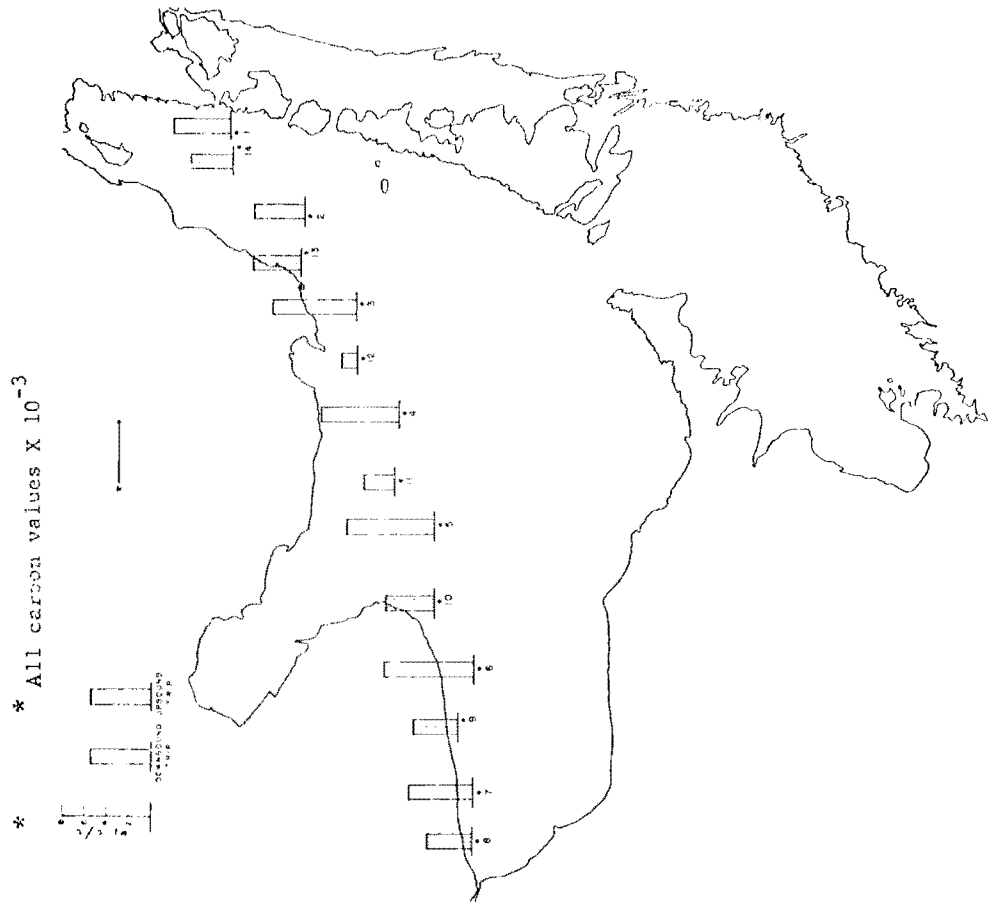


Figure 16. Milligrams carbon fixed per liter of Lake Huron surface water; Trip 3, July 9-July 13, 1968; Four hours incubation, 60^{o} F., 1000 foot-candles light.

Table XVI.

LAKE HURON PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 3.

JULY 9 - JULY 13, 1968

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. ^{o}C	Carbon fixed in mg x 10^{-3} *
1	Detour Light - 1 : 9	7/9	2:30 PM	13.0	5.0
2	1 - 2 : 30	7/9	4:30 PM	11.0	4.5
3	2 - 3 : 29	7/9	6:30 PM	13.5	7.5
4	3 - 4 : 31	7/9	8:30 PM	13.0	6.9
5	4 - 5 : 31	7/9	10:30 PM	14.0	7.8
6	5 - 6 : 40	7/10	12:30 AM	16.0	8.0
7	6 - 7 : 33	7/10	2:30 AM	16.0	5.6
8	7 - 8 : 13	7/11	3:00 PM	18.0	4.1
9	8 - 9 : 32	7/11	5:00 PM	18.0	3.9
10	9 - 10 : 33	7/11	7:00 PM	15.0	4.2
11	10 - 11 : 34	7/11	9:00 PM	15.0	2.6
12	11 - 12 : 34	7/11	11:00 PM	11.5	1.3
13	12 - 13 : 33	7/12	1:00 AM	14.0	4.4
14	13 - 14 : 34	7/12	3:00 AM	13.0	3.6

* 4 hrs. incubation time; $60^{o}F.$; 1000 Ft-Candles light. (mg/l surface water)

Lake Huron, Trip 4, July 25-July 28, 1968

Approximately two weeks after the third sampling trip preparations were completed for another run and supplies were once again loaded aboard the steamer Ernest T. Weir. A total of thirteen samples were collected and processed during the trip.

A general inspection of Figure 17 indicates that by July 25 through 28, the productivity level of the entire lake had increased considerably over that observed earlier in the month. The levels ranged from 2.9 to 9.2 X 10^{-3} milligrams carbon fixed per liter of surface water with stations 6 and 9 representing the low and high values respectively (Table XVII). The mean productivity value calculated for the entire trip was 6.5 X 10^{-3} milligrams as contrasted with a mean of 4.9 X 10^{-3} milligrams for the previous trip. Great variability is apparent in some parts of the lake. Sampling stations 6 and 8 as well as 5 and 9 particularly emphasize this variability. The stations concerned are located only seven miles apart with collection times differing by only three days.

Surface water temperatures when compared to those of the preceding trip showed a general and overall increase. They ranged from 14.0 to 20.0° C. However, the temperatures could not be specifically correlated to the productivity levels observed at a given sampling station. The high surface water temperatures everywhere indicated that a thermocline was being maintained.

Lake Huron, Trip 5, August 22-August 25, 1968

The final sampling trip on Lake Huron was made near the end of August. Fourteen samples were collected and processed during the run. Figure 18 indicates that another significant increase had taken place in the general productivity rate of the lake. It is interesting to note that the highest levels of productivity were found at the opposite ends of the lake with samples collected at stations 1, 2, 8 and 9 representing these highest values. Excepting three stations (7, 13 and 14), productivity levels were much higher than the mean observed on the preceding sampling trip a month earlier.

On this trip the productivity values ranged from 2.7 to 14.2 X 10^{-3} milligrams carbon fixed per liter of surface water. The mean value was 9.4 X 10^{-3} milligrams. If one scans Figure 18, it will be found that the samples representing the lowest and highest productivity levels were collected in very close proximity to one another (only eight miles apart). However, it also will be seen that as much as three days elapsed between collection times. (Table XVIII).

Surface water temperatures ranged from 17.0 to 24.0° C. On a lake-wide basis, this represents approximately a three degree rise in the mean surface water temperatures, during the one month which had elapsed between sampling runs. Although the general increase in surface water temperatures is undoubtedly associated with the rise observed in productivity levels across the lake as a whole, one must exercise caution when associations are made between productivity levels of individual sampling stations and recorded surface water temperatures.

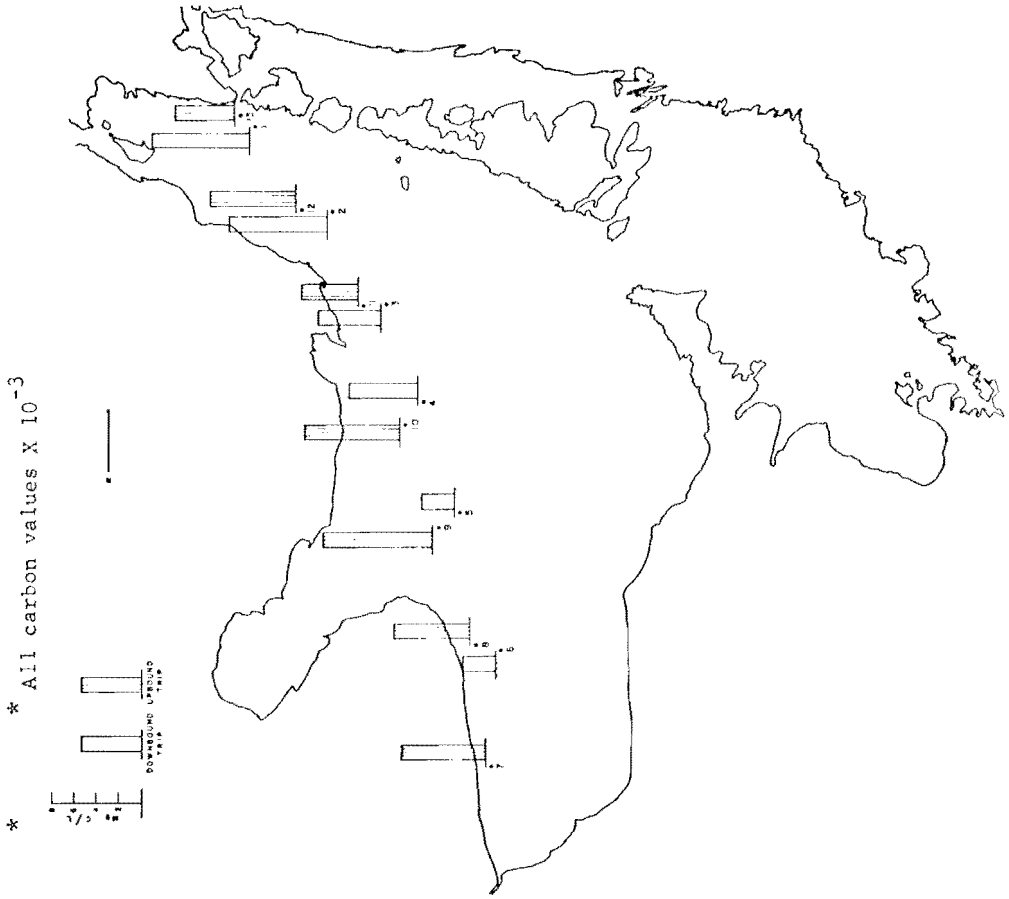


Figure 17. Milligrams carbon fixed per liter of Lake Huron surface water; Trip 4, July 25-July 28, 1968; Four hours incubation, 60° F., 1000 foot-candles light.

Table XVII.

LAKE HURON PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 4.

JULY 25 - JULY 28, 1968

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. °C	Carbon fixed in mg x 10^{-3} *
1	Detour Light - 1 : 8	7/25	5:30 AM	15.0	8.9
2	1 - 2 : 31	7/25	7:30 AM	14.0	8.2
3	2 - 3 : 28	7/25	9:30 AM	15.5	5.5
4	3 - 4 : 29	7/25	11:30 AM	17.0	6.1
5	4 - 5 : 31	7/25	1:30 PM	18.0	3.0
6	5 - 6 : 39	7/25	3:30 PM	20.0	2.9
7	6 - 7 : 32	7/28	5:30 AM	18.5	7.4
8	7 - 8 : 31	7/28	7:30 AM	17.5	6.6
9	8 - 9 : 32	7/28	9:30 AM	17.5	9.2
10	9 - 10 : 29	7/28	11:30 AM	18.0	8.6
11	10 - 11 : 34	7/28	1:30 PM	17.5	5.1
12	11 - 12 : 31	7/28	3:30 PM	15.0	7.7
13	12 - 13 : 31	7/28	5:30 PM	16.0	5.2

* 4 hrs. incubation time; 60°F.; 1000 Ft-Candles light. (mg/l surface water)

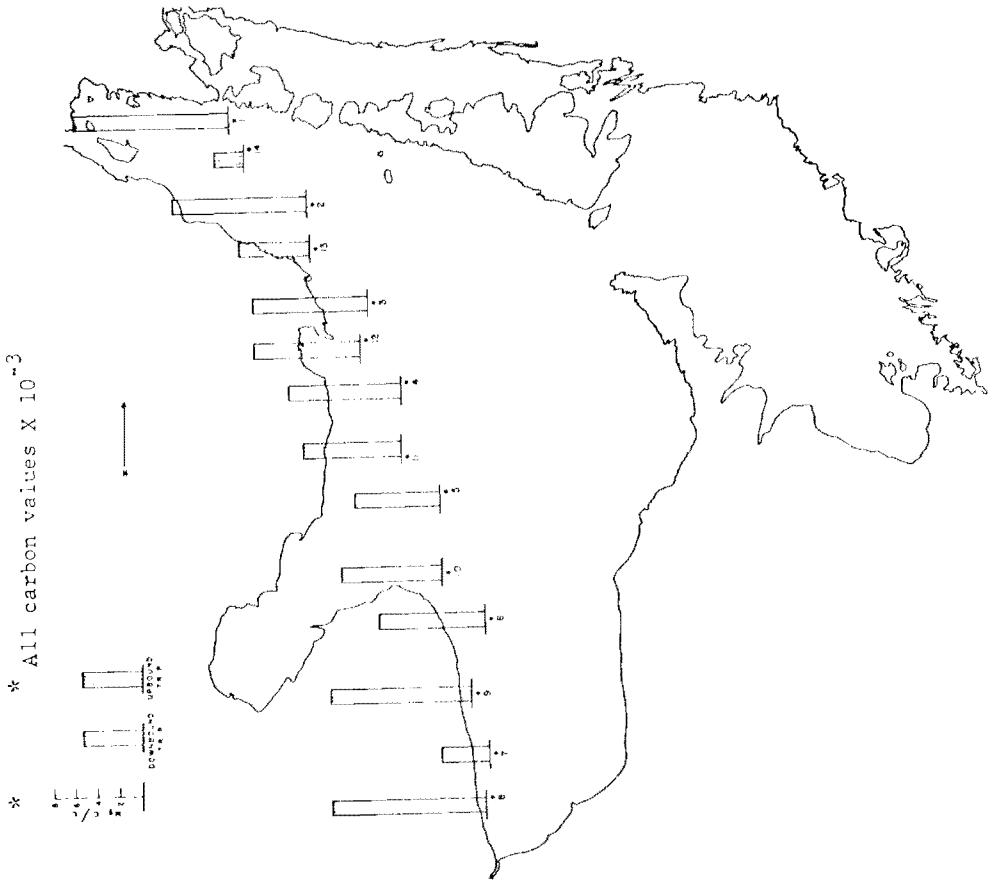


Figure 18. Milligrams carbon fixed per liter of Lake Huron surface water; Trip 5, August 22-August 25, 1968; Four hours incubation, 60° F., 1000 foot-candles light.

Table XVIII.

LAKE HURON PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 5.

AUGUST 22 - AUGUST 25, 1968

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. °C	Carbon fixed in mg x 10^{-3} *
1	Detour Light - 1 : 6	8/22	12:30 PM	17.0	14.2
2	1 - 2 : 32	8/22	2:30 PM	17.0	12.5
3	2 - 3 : 31	8/22	4:30 PM	18.0	10.3
4	3 - 4 : 24	8/22	6:30 PM	18.5	10.1
5	4 - 5 : 31	8/22	8:30 PM	20.0	7.8
6	5 - 6 : 36	8/22	10:30 PM	20.5	9.7
7	6 - 7 : 36	8/23	12:30 AM	22.5	4.2
8	7 - 8 : 12	8/24	8:45 PM	24.0	13.8
9	8 - 9 : 28	8/24	10:30 PM	22.0	12.9
10	9 - 10 : 34	8/25	12:30 AM	21.0	9.0
11	10 - 11 : 33	8/25	2:30 AM	20.0	8.8
12	11 - 12 : 33	8/25	4:30 AM	19.0	9.6
13	12 - 13 : 30	8/25	6:30 AM	18.0	6.5
14	13 - 14 : 32	8/25	8:30 AM	17.0	2.7

* 4 hrs. incubation time; 60°F.; 1000 Ft-Candles light. (mg/l surface water)

The plankton samples collected in August showed that blue-green algae, which previously had been relatively insignificant, was the predominant organism (Table XXXV, Appendix A). The Chrysophyte, Dinobryon, was found to be most abundant in the northern region of the lake and completely absent in the southern region. This is a complete reversal of the results presented in Table XXXIII (Appendix A) which reports plankton data collected on the first sampling trip of the season.

Diatoms remained in rather high concentrations throughout the lake but compared to earlier trips their numbers were slightly reduced. Diatoms were much less concentrated in the southern part of the lake than in the other areas sampled.

Unidentified net plankton was composed primarily of a cyclotella-like organism. The five most common planktonic organisms were Coelosphaerium, Fragilaria crotenensis, Chroococcus, Tabellaria fenestrata, and Merismopedia glauca.

Lake Erie, Trip 1, July 27, 1968

During the fourth sampling trip of the 1968 season, word was received that the steamship Ernest T. Weir, with its load of ore, was bound for Rochester, New York, at the eastern end of Lake Erie. This provided an excellent opportunity to sample the much discussed waters of a lake that is reported to be the most eutrophic of all the Great Lakes. With the exception of surface water temperatures, no chemical or physical data were collected on this trip through Lake Erie. For this reason, data which could be used for calculation of the carbon dioxide content of the waters were obtained from the literature. For example, in arriving at the total solids value, a publication by Beeton (1965) was consulted. He reported a value of 180 milligrams per liter, a figure supported by Powers et. al. (1960). The alkalinity value used for Lake Erie was 90.4 milligrams per liter, a figure also reported by Beeton (1965). Kramer's findings (1961) based on values of fifteen samples collected along very nearly the same course as that followed by the S. S. Ernest T. Weir were used for the pH value. It was 7.9, which represented Kramer's mean. This value is very similar to pH values reported by Fish et. al. (1960) on work done in the central and eastern basins of Lake Erie in 1928-29. Through the use of the nomograph and the above chemical data, it was possible to determine the amount of free carbon dioxide available to the phytoplankton in Lake Erie waters. Final calculations establishing the total amount of carbon fixed per liter of surface water were readily made using the above approach (see methods section for details).

The results of the five samples collected and processed on July 27 while crossing Lake Erie are graphically presented in Figure 19 and in a tabulation, Table XIX. It will be seen that the productivity levels of this lake are phenomenally high. Although only five samples were collected the data obtained and analysed for this particular run suggest a definite linear increase in the productivity levels from the eastern to the western ends of the lake. More data would be needed, however, to completely substantiate this finding. Unfortunately, no other opportunity became available to sample this lake.

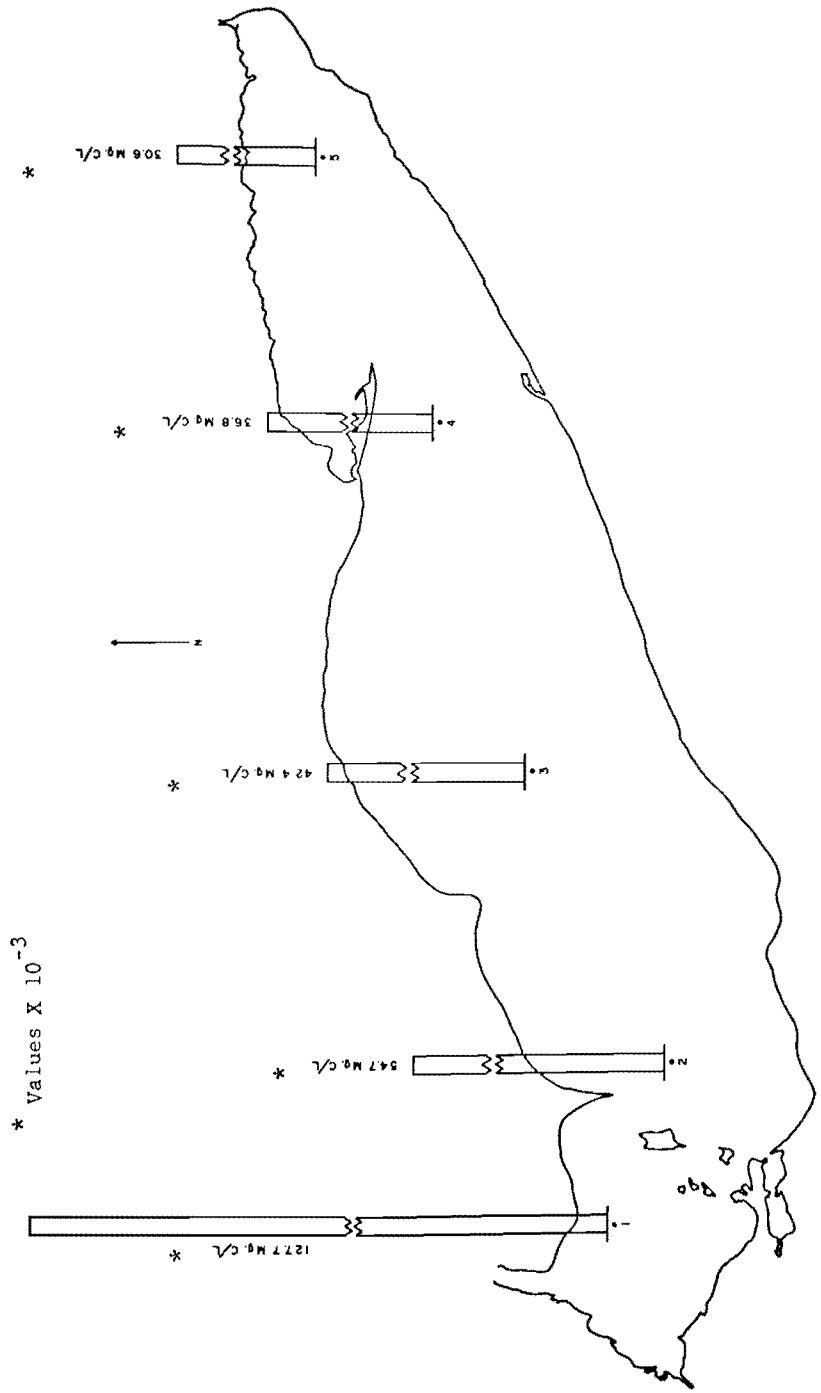


Figure 19. Milligrams carbon fixed per liter of Lake Erie surface water; Trip 1, July 27, 1968; Four hours incubation, 60° F., 1000 foot-candles light.

Table XIX.

LAKE ERIE PRODUCTIVITY STUDIES

SUMMATION OF DATA, TRIP 1.

JULY 27, 1967

Sample station	Station to Station : Distance in Miles	month day	Time of collection	Surface water Temp. °C	Carbon fixed in mg x 10^{-3} *
1	Detroit River Light - 1 : 13	7/27	6:00 AM	23.0	127.7
2	1 - 2 : 31	7/27	9:00 AM	22.0	54.7
3	2 - 3 : 57	7/27	Noon	23.0	42.4
4	3 - 4 : 62	7/27	3:00 PM	24.0	36.8
5	4 - 5 : 49	7/27	6:00 PM	25.0	30.6

* 4 hrs. incubation time; 60°F.; 1000 Ft-Candles light. (mg/l surface water)

Productivity levels ranged from 30.6 to 127.7 X 10^{-3} milligrams carbon fixed per liter of surface water with a mean of 58.4 X 10^{-3} milligrams. The sample collected at station 1 indicated that during a four-hour incubation period carbon was fixed by the phytoplankton at a rate exceeding one-tenth milligram per liter of surface water. This represents a productivity rate that exceeds the four other stations sampled by a factor of two. The extremely high productivity found at all stations supports the claims of those who state that this warm, shallow member of the Great Lakes family is indeed in a very advanced stage of eutrophication.

V. DISCUSSION OF RESULTS

Potential Causes of Variation in Productivity

The examination of virtually any one of the Figures presented in the previous section immediately demonstrates that productivity variations of considerable magnitude do occur between stations. This diversity was noted in all of the lakes except Erie and during both the 1967 and 1968 seasons. Many of the largest variations in levels of productivity occurred at stations that were located in the same general region of the lake, and some stations were actually in very close proximity to one another.

Pondering the reasons for overall variations in productivity, several explanations present themselves. For example, in large bodies of water such as those composing any one of the Great Lakes, surface currents exist which may cause a variety of circulation patterns to occur. Wind speed, wind direction, and temperature variations within the water masses of the lake are probably three of the most important forces governing such surface water movements. Barometric pressure above the water surface, rotation of the earth (coreolis force), expecially the moon, also play an important role in determining the various circulation patterns that occur in a large body of water and must not be overlooked.

Studies concerning the circulation pattern of western Lake Superior (Ruschmeyer and Olson 1958) indicate that typically the surface waters in this portion of the lake move in a counterclockwise direction. This causes surface waters to flow toward the western portion of the lake along the north shore and toward the eastern portion of the lake along the south shore. This counterclockwise pattern was found to exist in the region west of the Apostle Islands. The authors also found that a definite south shore drift occurred in an easterly direction along the south shoreline. Drift bottles and temperature measurements were used to determine the circulation pattern of the western region of the lake while drift bottles were used exclusively to determine the south shore drift pattern beyond the Apostle Islands. Although information regarding the circulation patterns for all regions of the Great Lakes is presently unknown, it seems safe to assume that a variety of patterns could exist within a large lake, each being composed of a series of distinct and relatively independent water masses. Since phytoplankton are free floating organisms, they can be considered an integral part of any water mass and will, therefore, be carried along by the prevailing currents in any given area of the lake. Hence, it is reasonable to assume that observed variations between sampling stations could be brought about by the movement of such masses of algae laden water from one area of the lake to another. Since in this study samples were collected as the ore boat moved steadily across the lake, many areas or patches of both heavily and sparcely concentrated phytoplankton would be encountered. Under these conditions, the concentration of plankton algae at the particular time of sampling would determine whether a high, moderate or low productivity level would be recorded at

that point. In small lakes, variations of this kind have been observed by Rodhe (1958b) who in Lake Erken noted very rapid changes in rates of production, in some instances amounting to several hundred per cent. He ascribed this to the horizontal redistribution of the plankton algae brought about by the wind.

Another factor which could directly affect the productivity level of particular sampling stations within a lake during the same time period is the concentration of nutrients. Lakes such as Superior, Michigan, and Huron undergo a spring and fall turnover, a period of time when the thermocline disappears and the lake literally undergoes a complete mixing process. This also is regarded as the time when essential nutrients from the bottom or lower levels of the lake are redistributed throughout the upper levels. By this process, the phytoplankton of the euphotic zone are supplied with nutrients essential for growth and reproduction. This usually results in an upsurge in numbers and biomass during these periods which are reflected by increases in productivity levels. As the season progresses, these essential nutrients are utilized by the phytoplankton. Ultimately, the nitrates, phosphates, and other essential nutrients may thus be reduced or even exhausted in areas where heavy concentrations of plankton algae occur. Such areas of depletion, when contrasted to areas of nondepletion, could account for the variations in productivity described earlier. It must be remembered, however, that a given water mass or lake area can remain highly productive for several days or even weeks after the nutrient supply has essentially vanished. Rhode (1958a) and Steemann-Nielsen (1954) state that freshwater algae are capable of storing large amounts of nutrient material, primarily phosphates, in the cells which for a time sustains the productivity rate of the area depleted in nutrients.

The variations observed in productivity during this study might also be attributed to light intensity and quality. For example, turbidity of the water would affect both the quality and intensity of the light energy. Thus the influx of turbid water from a river system or turbidity produced by wave action in a shallow area could be responsible for the reduction in productivity of a given water mass. This applies to the laboratory test conditions imposed by this study as well as to the field situations because increased turbidity would have an effect on both systems.

Temperatures might also be responsible for variations in the field, but these could not be directly checked by the procedure followed in this study since incubation temperatures were constant. However, it should be pointed out that while some samples were collected from waters which had temperatures of 5° C, others were taken from areas which had temperatures in excess of 20° C. According to van t'Hoff's law, the metabolic rate is doubled to tripled for every temperature rise of 10° C (Ruttner 1966). Since this could result in an increased number of organisms in the areas of highest temperatures, the results obtained by the laboratory procedure which, other conditions being equal, would relate directly to the number of organisms present and thus indirectly reflect lake temperature conditions.

Another physical phenomenon which could explain the wide variation often seen between sampling stations in the course of this study is that of upwelling. It is a well-known fact that cold water, water with the greatest density, sinks. However, sinking water is not limited to

regions in which waters of high densities are being formed but also occurs wherever there is a convergence of currents. Since, ultimately, sinking water must rise, regions evidently must exist where ascending motion of water prevails since the amount of water that sinks must equal that which rises. Diverging currents and strong winds of an appreciable duration will assist in this phenomenon. Such a movement of water from the deep parts of a lake to its surface is referred to as an upwelling (Sverdrup et. al. 1942). Steemann-Nielsen (1958b) stated that in the seas, wherever two circulation patterns or fronts combine, eddies are found which bring nutrient enriched waters to the upper levels. Furthermore, he found that samples collected wherever these fronts occurred were characterized by productivity rates which were very high. It is reasonable to assume that this phenomenon would also apply to the Great Lakes. In the present study, the low productivity rates in the same area of the lake found on the return trip several days later could be explained on the basis that a replenishment of nutrients by the upwelling process had occurred in the interim.

Still another explanation for the variations of productivity seen is that of "grazing." In this case, "grazing" refers to the consumption of algae by organisms of the second trophic level. According to Harvey et. al. (1935). who proposed the theory of grazing, copepods and other organisms were able to reduce diatom populations locally by the intensity of their feeding activity. Assuming that this is true for freshwater lakes as well as the seas, one can readily envision small areas in the lake where phytoplankton concentrations have been depleted by this means to the point where productivity levels are very low. In such a situation, a very highly productive area might be immediately adjacent to an area of low productivity. This could account for the very rapid changes in levels of production that occurred on some of the trips. Also, the presence of a substance toxic to the phytoplankton could account for the productivity variations seen. However, due to the very large dilution factor of the Great Lakes, the probability of this being a factor of major significance is doubtful.

In the preceding discussion, several possible explanations have been offered relative to the cause for variations in productivity levels. Among these were (1) variations in the population of individual water masses, (2) differences in nutrient concentrations, (3) variation in light intensity and quality, (4) temperature differences, (5) the upwelling of subsurface water, (6) "grazing" activity, and (7) variation due to the presence of a toxic substance.

Since, in general, the Great Lakes are deep lakes and because the shipping lanes were in the deep water portions, turbidity was not a noticeable factor. Thus it seems reasonable to assume that light intensity and quality were not a major cause for the variability in productivity that was noted. If one looks at surface water temperature differences (Tables I - XIX) it will be seen that for a large portion of a season, a thermocline was not definitely established in any of the lakes sampled except Erie. It can be assumed that during periods when the thermocline is absent, continuous mixing of the waters will occur and that temperature differences would not be great enough to account for the great variations seen in productivity. If one dismisses temperature as a major cause for productivity variation because of the

general mixing which occurs during much of the sampling season, it is difficult to conceive that upwelling would play an important part in productivity changes since this phenomenon can only be effective where thermal stratification exists. Although much remains to be learned about the "grazing" phenomenon and the importance of toxic metabolites, it seems unlikely that these factors could be responsible for the large productivity variations observed.

In the opinion of this investigator, the productivity variations seen were primarily caused by population differences within individual water masses encountered while crossing the lakes. The highly productive stations probably reflected water masses that contained high numbers of organisms and the stations exhibiting low productivity reflected masses of water that contained fewer organisms. Very intimately associated with the productivity of any water body is the concentration of essential nutrients. Without an ample supply of these, production would soon cease. The continuous movement or circulation of water masses could provide a method for enrichment. Thus it is very difficult to separate the nutrient concentration and the productivity of individual water masses. It must also be remembered that an ecological system was being studied and therefore all the factors previously discussed may be involved.

Productivity Trends, 1967 and 1968

The 1967 sampling season spanned a period of approximately four months during which four trips were made. Sampling began on June 30, 1967, and terminated on October 26, 1967.

The mean primary productivity values and the mean surface water temperatures observed on each Lake Superior sampling trip are shown in Table XX. This table indicates that the primary productivity level of Lake Superior was very low when the season began. As the season progressed, so also did the productivity rates. During the 2½ months that passed between sampling trip 2 and sampling trip 3, a significant increase in productivity occurred. During this period the mean surface water temperature of the lake increased nearly two degrees, which is noteworthy when one considers the water mass involved. It should also be noted that in the interim between trips 2 and 3, the surface water of the lake probably reached temperatures above the recorded mean. The increase of nearly one milligram carbon fixed, noted between sampling trips 3 and 4, also represents a distinct increase in productivity. This is especially impressive because only a two-week span of time had separated the two trips.

When this project was originally conceived, various statistical methods were considered to determine whether or not any changes seen in productivity levels across a lake were statistically valid. It was finally decided that the productivity trends, if they existed, might be related to two factors, namely, (1) distance from a given point (for example, the further out in the lake away from populated centers and surrounding land masses the lower the productivity rate), and (2) the span of time during which all samples were collected.

When a multiple linear regression model was used to analyse these factors, it was immediately noted that on this basis, no relationship existed between the productivity rates and distance from a given point in any of the lakes sampled.

It was, however, noted that a positive correlation existed between the productivity levels of the lakes sampled and the time of sampling. This indicates that the primary productivity of the lakes is cyclic in nature and that the rate of production varies depending upon environmental conditions.

The range in productivity values observed in Lake Superior during 1967 is shown in Figure 20. A distinct increase in productivity is seen as the season progressed.

For extended periods of time during the previous winter, very cold temperatures were experienced over the entire northern portion of the United States. This resulted in the greater part, approximately 95 per cent, of Lake Superior freezing over. This was also true for the other members of the Great Lakes group. In order for ice to form, the temperature of the entire body of water must first reach a temperature of 4°C, the temperature at which water is most dense. As the temperatures of the water decreases, its density also decreases and a layer of ice finally forms on the surface when 0° C is reached.

At these reduced temperatures, the physiological responses of the plankton algae to its environment are tremendously reduced or stopped. In order for the photosynthetic process to occur in the phytoplankton, sunlight also is necessary. The ice cover on the lake considerably reduces the available light reaching the organisms. If any snow cover is present on the ice, there is a further reduction in light. A combination of low temperatures of the lake water and low light levels would result in a reduced rate of productivity. The productivity rate would be further diminished by the normal die-off and settling of plankton algae which occurs during the winter period. The geographic location of Lake Superior is such that its water temperatures increase very little above the isothermal state of 4° C until late June or early July. This also is the time when the intensity of light reaching the earth's surface is greatest since the sun's altitude is at or near its maximum.

It can thus be reasonably assumed that the low temperatures which caused reduced physiological activity in the phytoplankton, the reduced light intensity during the months prior to the first sampling trip, and the relatively small number of organisms present at the beginning of the season are all interrelated and probably account for the low rate of productivity characterizing the first two sampling trips on Lake Superior during the summer of 1967. As the season progressed, water temperatures began to rise. This resulted in a more rapid assimilation of available nutrients by the phytoplankton and in a faster reproduction rate due to increased physiological activity. Larger numbers of organisms under the more favorable temperatures resulted in the increased productivity rates noted on the final two sampling trips of the season.

The results presented in Tables XXVI and XXVII (Appendix A) indicate that there was a tremendous buildup of the blue-green algae Lyngbya contorta during the summer. With the exception of Dinobryon

Table XX

1967 Mean Productivity Values and Surface Water Temperatures — Lake Superior Sampling Trips.

Trip Numbers and Dates	Carbon fixed in mg/liter x 10^{-3}*	Carbon fixed in mg/m^3/day **	Surface water temperature, °C.
Trip 1: June 30 - July 4	2.6	7.8	8.4
Trip 2: July 15 - July 20	2.9	8.7	8.5
Trip 3: Oct. 4 - Oct. 10	8.0	24.0	10.4
Trip 4: Oct. 21 - Oct. 26	8.8	26.4	

* 4 hr. incubation; 60°F.; 1000 foot-candles light.
** Calculated on basis of twelve-hour day.

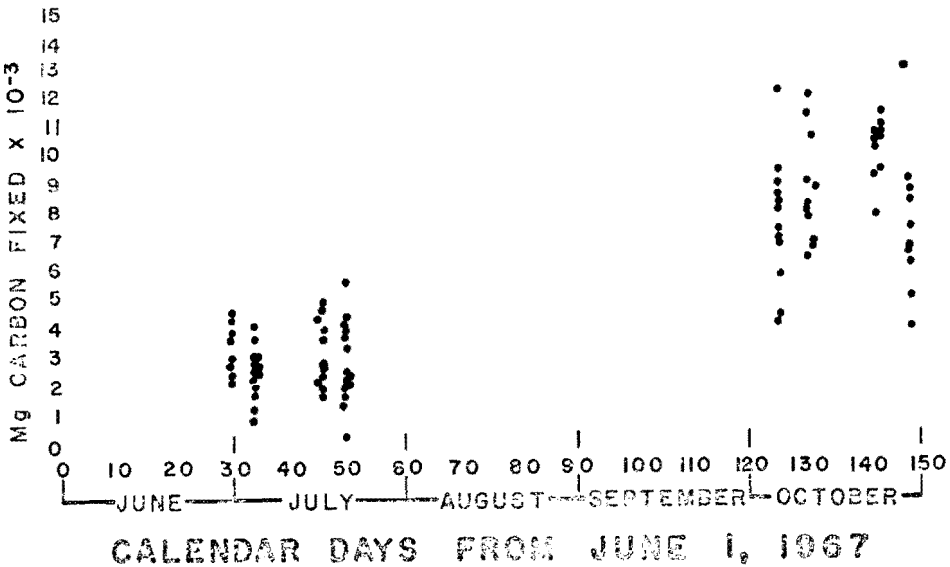


Figure 20. 1967 Lake Superior Seasonal Productivity Distribution

in western Lake Superior, there was no great change in the population size of other forms.

Results from the 1967 Lake Michigan runs (Table XXI) were quite similar to those of Lake Superior. The range in productivity is shown in Figure 21. Lake Michigan, in its entirety, lies to the south of Lake Superior. Thus, in Lake Michigan, in contrast to Lake Superior, there is a shifting of all seasonal events to an earlier date and an increase in the length of the season. If the two lakes are compared for the same time period, mean productivity values and mean surface water temperatures during the first trip illustrate this shifting of seasonal events in Lake Michigan (Tables XX and XXI). The progression of events remains the same for Lake Michigan as for Lake Superior although values for the individual parameters of light intensity, surface temperatures, photoperiod and seasonal length would be different.

The results reported in Table XXI indicate that productivity rates for the first and second sampling trips on Lake Michigan are the same. During the 1967 sampling season on Lake Michigan, an event occurred which significantly affected the nutrient concentration of the lake water in certain areas and may have affected the productivity rates as the season progressed. Reference is here made to the second sampling trip and to the "alewife" kill. On that trip, at certain points, literally millions of dead scavenger fish commonly referred to as "alewives" virtually blanketed the lake. These fish ranged in size from approximately three to six inches. Although considerable numbers of the dead fish were noticed in the northern portion of Lake Michigan, the greatest concentrations were found in the southern half of the lake. The deterioration of the "alewives" was well underway as was indicated by the partially decayed bodies, the slime around the fish, and the unmistakeable odor of rotting flesh. When fully broken down, the fish remains would return nutrients such as nitrates and phosphates to the lake. One agency estimated that 300 million pounds of "alewives" died in Lake Michigan during 1967. Analytical work by the U.S. Bureau of Commercial Fisheries has shown that alewives about six inches long contain 2.23 grams of phosphorus per pound of fish. On this basis, 735 tons of phosphorus were added to the lake water as a result of this kill (Michigan Water Resource Commission, Department of Conservation, and Michigan Department of Public Health 1968). No evidence of these fish remained when the third trip was made some 2½ months later. However, very high productivity values were generally observed across the lake on the final sampling trips of the season. Extremely high rates of production characterized the southern regions of the lake (Figures 7 and 8).

Another factor must be considered before one can assume that the extremely high productivity found in the southern part of the lake was caused by the "alewife" kill. The probability is very great that the waters of this region are enriched by the domestic and industrial effluents that are emptied into it from the densely populated and highly industrialized cities of Chicago, Illinois, and Gary, Indiana, both located at the southern end of the lake. These effluents, expecially if domestic sewage was involved, could greatly increase the supply of nutrients and the carbon fixation rates.

Table XXI

1967 Mean Productivity Values and Surface Water Temperatures — Lake Michigan Sampling Trips.

Trip Numbers and Dates	Carbon fixed in mg/liter x 10^{-3}*	Carbon fixed in mg/m^3/day **	Surface water temperature, °C.
Trip 1: July 1 - July 4	8.1	24.3	15.4
Trip 2: July 17 - July 19	8.1	24.3	16.7
Trip 3: Oct. 6 - Oct. 8	16.5	49.5	13.7
Trip 4: Oct. 23 - Oct. 26	17.5	52.5	8.8

* 4 hr. incubation; 60°F.; 1000 foot-candles light.
** Calculated on basis of twelve-hour day.

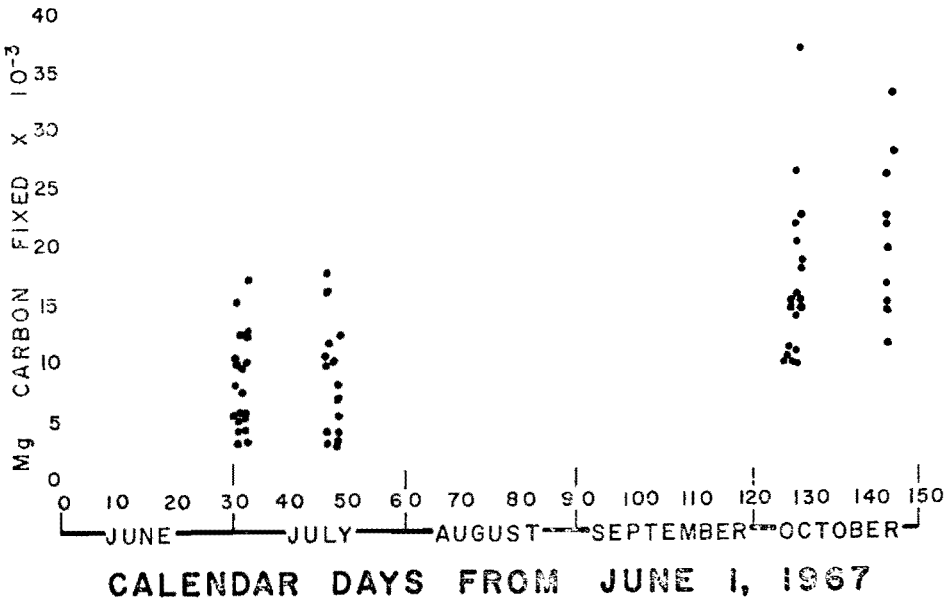


Figure 21. 1967 Lake Michigan Seasonal Productivity Distribution

It is unfortunate that due to conditions beyond our control, sampling on both Lakes Superior and Michigan had to be terminated in late October. Had it been possible to extend the period, it would have been most interesting to establish the time at which maximum productivity was attained and to ascertain the rate at which the productivity subsequently decreased.

In Lake Michigan, the blue-green algae far exceeded other plankton algae as shown in Tables XXVIII and XXIX (Appendix A). The increase in the diatom population noted during the last trip is indicative of colder water. An inspection of Table XXI shows that a considerable reduction in temperature had actually occurred. The temperature had dropped from 13.7° to 8.8° C.

The 1968 sampling season on Lakes Superior and Huron confirmed the fact that primary productivity in the Great Lakes is definitely cyclic in nature. An example of such a pattern is portrayed in Figure 22, which shows the carbon fixation values observed in Lake Superior.

The mean productivity rates noted for the first four sampling trips on Lake Superior indicate that a well-defined maximum had been reached by the third week in May. This high value persisted during the following month, but in the early part of July it dropped to approximately two-thirds of its original value and remained constant at that level for the next two weeks. By August 21, another distinct rise in productivity had taken place. The values involved here were 6.4 X 10^{-3} milligrams carbon fixed for May, 6.2 X 10^{-3} milligrams for June and 4.7 X 10^{-3} milligrams for July 8 and 24. The August rise brought the carbon fixation value up to 5.6 X 10^{-3} milligrams. Mean surface water temperatures were relatively low for Trips 2, 3 and 4 (Table XXII). Temperatures were not recorded for the first sampling trip. It is interesting to note that on the third trip, even though an increase in surface water temperatures of approximately 1° occurred between the second and third sampling trips, the mean productivity of the lake plunged to its lowest level for the season.

If one recalls the type of climatic conditions which prevailed during the months of May through July 1968, it will be remembered that the lake area was beset with unseasonably cold air temperatures accompanied by very dense fog and large amounts of rain. Very few days of bright clear weather were actually experienced before late summer. This is reflected by the surface water temperatures. The cloudy, rainy weather, in addition, reduced insolation and, therefore, the amount of light that could reach the lake surface. Since light is a primary limiting factor for photosynthetic activity at the northerly latitudes in which Lake Superior is located (Rodhe 1958b) the 1968 season could be expected to be less productive than normal because of the unusual climatic conditions which were experienced. The reduced light intensity and low surface water temperatures are therefore believed to be the two main factors responsible for the reduced productivity rates seen during the mid-summer period.

The 1968 winter season was one of rather mild temperatures and a very large portion of Lake Superior remained free from ice cover (personal observation). Due to the mild winter, the portions of the lake that actually were frozen did not have as thick a layer of ice as that observed during the previous winter. In addition to very mild temperatures, the winter was characterized by a scarcity of snow.

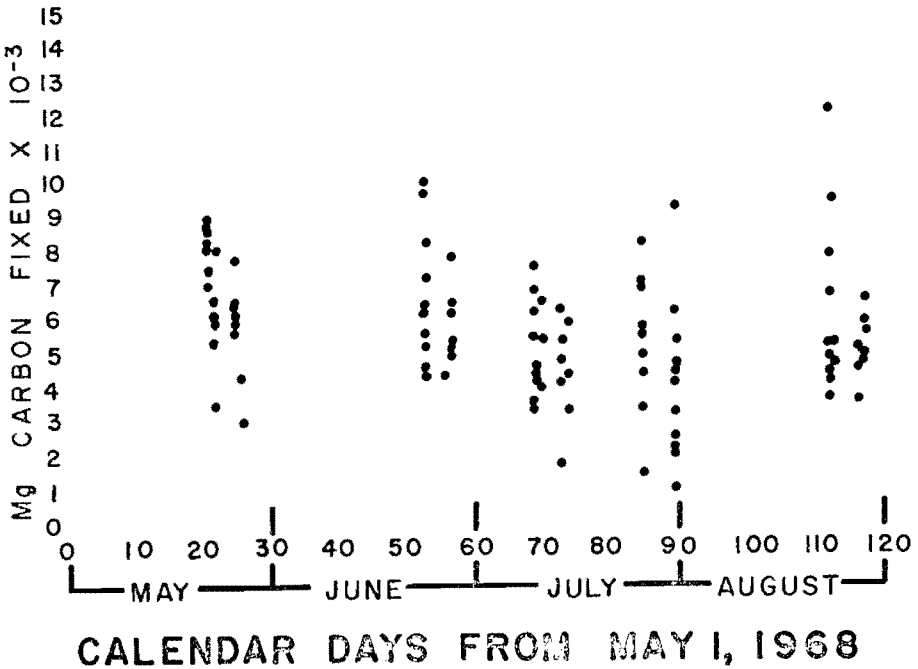


Figure 22. 1968 Lake Superior Seasonal Productivity Distribution

Table XXII

1968 Mean Productivity Values and Surface Water Temperatures — Lake Superior Sampling Trips.

Trip Numbers and Dates	Carbon fixed in mg/litor x 10^{-3}*	Carbon fixed in mg/m^3/day **	Surface water temperature, °C.
Trip 1: May 21 - May 26	6.4	19.2	
Trip 2: June 22 - June 26	6.2	18.6	6.4
Trip 3: July 8 - July 13	4.7	14.1	7.3
Trip 4: July 24 - July 29	4.7	14.1	7.2
Trip 5: Aug. 21 - Aug. 26	5.6	16.8	11.4

* 4 hr. incubation; 60°F.; 1000 foot-candles light.
** Calculated on basis of twelve-hour day.

Thus, most ice-covered areas of the lake were free of snow and there was relatively little reduction in photosynthetic light penetration. A greater rate of productivity was, therefore, possible during the winter season, both in the open and ice-covered regions of the lake. The mild winter was followed by an early spring breakup. This breakup occurred during the first part of March or approximately three weeks to one month earlier than usual. The outcome was that an earlier than usual redistribution of nutrients also took place. The higher concentration of nutrients available to a population of plankton algae which, because of the mild winter conditions, was well-developed, provided a basis for an early spring pulse which could be reflected by the relatively high productivity rates. It is believed that these conditions account for the late spring productivity peak observed during the first sampling trip.

The results of the final sampling trip of the season show a reversal in the primary productivity trend (Table XXII and Figure 22). During the month of August, climatic conditions improved greatly and there were many warm, bright days. This is reflected by the increased mean surface water temperature and by a significant increase in the mean productivity.

It will be seen that a reduction in Myxophytes and an increase in Chrysophytes, especially Dinobryon, occurred as the season progressed. The diatom population peaked near midsummer and then decreased as the lake temperatures rose. See Tables XXX, XXXI and XXXII (Appendix A). This is in contrast to the normal expectation that the greatest diatom population and the lowest blue-green algae concentration would occur during the earliest portion of the season. A reversal of this trend might be expected to occur as the season progresses and water temperatures increase. The rather unusual phytoplankton sequence observed in 1968 might be attributed to the effects of unusual currents which carraied blue-green algae from warmer water areas or to the narrow surface water temperature range.

Again, as in 1967, it would have been advantageous to extend the sampling season. Unfortunately, shipping schedules did not permit such arrangements.

In Lake Huron, the productivity trend for 1968 was very similar to that discussed earlier for Lake Superior. As was true in Lake Superior, the highest mean productivity rates for the entire season were found during the first sampling trip the third week of May. On the second and third trips, marked reductions were seen in the rates of production. In late July, the productivity levels began to rise and by the fifth sampling trip, August 22, they had climbed to a value approximately three-fourths of that recorded at the outset of the season. See Table XXIII and Figure 23.

From the mean surface water temperatures, it appears that a thermocline was well-established in this lake by the second week in July. It seems strange that with increased water temperatures there was still a reduction in carbon fixation during the second and third trips, June 23 through July 13. Normally it would be expected that such conditions would result in an increase in the metabolic rate and photosynthetic activity on the part of the plankton algae. This would result in a faster rate of assimilation of nutrients, in accelerated reproduction,

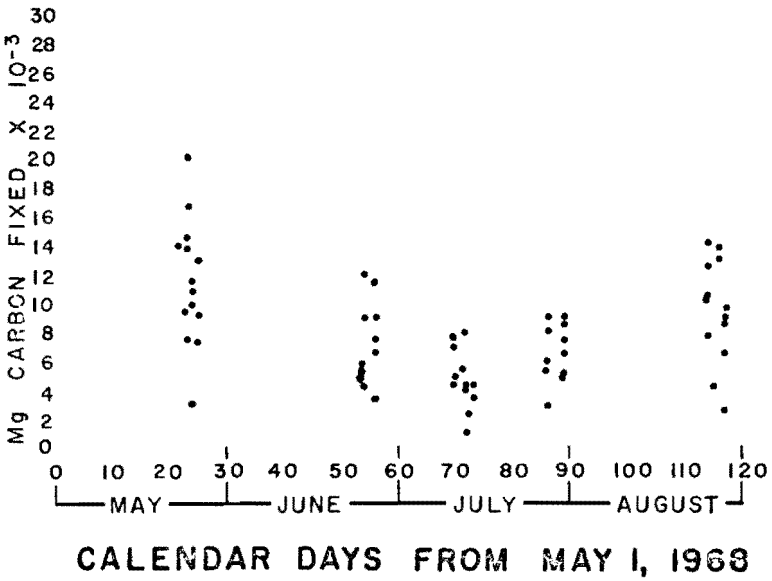


Figure 23. 1968 Lake Huron Seasonal Productivity Distribution

Table XXIII

1968 Mean Productivity Values and Surface Water Temperatures —— Lake Huron Sampling Trips.

Trip Numbers and Dates	Carbon fixed in mg/liter x 10^{-3}*	Carbon fixed in mg/m^3/day **	Surface water temperature, °C.
Trip 1: May 22 - May 25	12.0	36.0	
Trip 2: June 23 - June 25	7.0	21.0	10.9
Trip 3: July 9 - July 13	4.9	14.7	14.3
Trip 4: July 25 - July 28	6.5	19.5	16.9
Trip 5: Aug. 22 - Aug. 25	9.4	28.2	19.6

* 4 hr. incubation; 60°F.; 1000 foot-candles light.
** Calculated on basis of twelve-hour day.

and in increased productivity. As was pointed out in the discussion of Lake Superior data the 1968 winter season was unusually mild and relatively free from snow. Thus, the layers of ice which existed would have allowed good light penetration and continued algal activity. Therefore, in the spring algal productivity, because of a lesser winter kill, would get an earlier and better start. Since most of the lake is located much farther south than Lake Superior, it seems safe to assume that the spring breakup in Lake Huron occurred at an earlier date. After the breakup, the spring turnover takes place, generally redistributing essential nutrients. Thus, the plankton algae could be expected to show increased rates of production early in the season. Results of the first sampling trip, May 22 through May 25, show that this actually occurred.

The very sharp reduction in productivity noted on the second and third trips when the water temperatures were a good deal higher is difficult to explain. However, it will be recalled from the previous discussion of the Lake Superior data that the months of May, June and July were unseasonably cold, wet and frequently darkened by dense cloud cover. This statement, except for temperature, applies equally well to Lake Huron. It is, therefore, likely that light could have been the primary limiting factor responsible for the reduction observed in productivity during these two runs.

The final sampling trips, July 25 and August 22, showed the same reversal in the productivity as that observed during the final trip on Lake Superior. The bright, clear days, combined with appreciably increased water temperatures, presumably account for this late summer upsurge.

The results of a microscopic examination of the Lake Huron plankton samples are presented in Tables XXXIII through XXXV (Appendix A). The classic algae shift with corresponding temperature increases so often noted in smaller freshwater lakes was observed in this lake. During the early portion of the season when the water temperatures were low, Chrysophytes, composed primarily of diatoms, predominated. However, as the season progressed and surface water temperatures increased, blue-green algae, few in number at the outset, became dominant. The numbers of diatoms characteristically decreased.

Since no sampling trips could be scheduled before May 21 and after August 25, there is no basis on which one can establish the maximum rate of production that occurred in Lake Huron during this season.

Variations in Great Lakes Productivity Rates

Although the productivity rates and trends have been discussed for both the individual sampling trips and on the basis of years for each lake, it seems most appropriate to discuss the variation in seasonal productivity rates noted between years and between lakes. The mean productivity rates are presented in Table XXIV. An examination of the data presented in the table indicates that Lake Superior is by far the least productive of the four lakes sampled. Lake Huron, Lake Michigan, and Lake Erie show increased productivity rates in that order.

It will be seen that even though the length and dates of the two sampling seasons on Lake Superior did not coincide, comparison of the mean carbon fixation rates and the mean water temperatures indicates

Table XXIV

1967-68 Mean Surface Water Seasonal Productivity Rates, Temperature and Carbon Dioxide Data for Lakes: Superior, Michigan, Huron and Erie.

Lakes Sampled	Dates	Number of Samples	Carbon fixed in mg/l x 10^{-3} *	Carbon fixed in $mg/m^3/day$ **	Surface water temperature, °C	Available CO_2 in mg/l ***
Superior	June - Oct. 1967	97	5.57	16.72	9.1	40.78
Superior	May - Aug. 1968	109	5.52	16.56	8.1	39.99
Huron	May - Aug. 1968	68	7.68	23.04	15.4	71.72
Michigan	June - Oct. 1967	86	12.54	37.62	13.4	97.05
Erie	July 1968	5	58.40	175.20	23.4	90.40

* 4 hr. incubation; 60°F.; 1000 foot-candles light.

** Calculated on basis of twelve-hour day.

*** Values represent mean of 12 samples collected with exception of Lake Erie data which was obtained from the literature.

that for all practical purposes they remained the same. The mean production for Lake Huron was found to be approximately 30 per cent higher than the mean noted for Lake Superior. The mean temperature in Lake Huron, however, was nearly twice that of Superior. Applying van t'Hoff's rule, one might normally expect the productivity mean of Lake Huron to be nearly twice that of Lake Superior if temperature were the only controlling factor. The mean seasonal productivity level of Lake Michigan was more than twice that noted for Lake Superior and approximately 39 per cent higher than the mean rate observed in Lake Huron. Lake Erie's mean rate of production is most impressive as is its increased water temperature. The mean productivity value is more than twelve times greater than that of Lake Superior, seven times greater than the mean noted for Lake Huron, and nearly five times greater than the mean seasonal value observed for Lake Michigan. This indicates that Lake Erie is in a considerably more advanced stage of eutrophication than the other lakes studied.

In seeking an explanation for the differences in productivity rates or degrees of eutrophication, factors such as the following must be considered: (1) chemical characteristics of the lake, (2) light reaching the lake, (3) water temperature of the lake, (4) length of growing season, and (5) amount of industrialization and number of population centers surrounding the lake. All of the preceding and many additional factors are complexly interrelated and contribute to the trophic nature of the lake (productivity). Furthermore, the geographical location of a body of water can modify any one or all of the above factors and thus affects its productivity.

In pointing out the variations in the mean seasonal productivity rates observed during the 1967 and 1968 sampling seasons, Lake Erie deserves special attention. Lake Erie is literally surrounded by large population centers, all of which are highly industrialized. This lake, in addition, is small and very shallow with an average depth of only fifty-eight feet. Undoubtedly, the effluents discharged into the lake by these population centers greatly affect both the chemical and biological composition of the lake. It was not surprising, therefore, that this lake had a very much higher rate of production than the other lakes. As was indicated previously, if the mean seasonal productivity rates are compared, the value for Lake Erie was five times greater than that of Lake Michigan. However, if a comparison is made of the Lake Erie maximum productivity rate with the maximum for Lake Michigan, which was found near Chicago, this ratio is reduced to 3.5 to 1.

Primary Productivity Rates in the Great Lakes Versus Other Freshwater Lakes of the World and the Oceans

Although this study provides information concerning primary productivity rates of the surface waters of several of the Great Lakes, it does not deal with the integral photosynthetic rate of the entire euphotic zone. Due to logistical problems and the requirements for strictly comparable data, it was not possible in the course of this study to deal with this phase of Great Lakes productivity.

However in 1961, Putnam and Olson did investigate the integral photosynthetic rate in a portion of western Lake Superior. The sampling season of these authors corresponded closely to that used during the present study. Putnam and Olson used the "in situ" carbon fourteen method and the productivity rates at the 2.5, 5, 7.5, 10, 15, and 20 meter levels were determined. Since the 1 per cent light transmission level was found to be located at the twenty meter depth, samples were not collected below this point. It was assumed that only minute amounts of production occurred below this level.

By utilizing the data collected by Putnam and Olson (1961) relative to light penetration, temperatures and other factors, and the mean seasonal surface water productivity rate observed for the 1967 and 1968 sampling seasons, it was possible to calculate the approximate integral photosynthesis that occurred in Lake Superior. From this, a general estimate was made of the total productivity that occurred in the euphotic zone of the entire Lake during the two sampling seasons. Although the values calculated will only be approximate since data collected in 1961 are being applied to other data collected in 1967 and 1968, it is felt that this theoretical consideration may, in fact, be valid as an "order of things" assessment.

To carry out the calculations, the mean value was determined for seven samples collected by Putnam and Olson at each sampling depth throughout the season. The 2.5 meter sampling depth had the highest rate of photosynthesis throughout the entire season. Rates at all other sampling depths were converted to a percentage of the maximum rate. By calculating the mean of the percentages of production at all depths and multiplying this by twenty, which represented the depth, in meters, of the euphotic zone, a factor of 11.1 meters is obtained. Multiplying the mean of the 1967 and 1968 surface water productivity rates by this factor, one obtains the amount of productivity occurring under one square meter in the entire euphotic zone. Since the seasonal productivity rates of both sampling seasons on Lake Superior varied so little, the mean of the two seasons was calculated and used in the subsequent calculations. The calculations are as follows:

$$16.64 \text{ mg carbon/m}^3\text{/day} \times 11.1 \text{ m} = 184.7 \text{ mg carbon/m}^2\text{/day.}$$

Approximately 185 milligrams carbon were fixed per square meter of surface water per day throughout the euphotic zone in Lake Superior during the 1967 and 1968 sampling seasons. Multiplying this value by the number of square meters composing the surface area of Lake Superior one finds the total amount of carbon fixed throughout the euphotic zone of the entire lake. The equation below represents this calculation:

$$184.7 \text{ mg carbon/m}^2\text{/day} \times 82{,}367{,}000 \text{ m}^2 = 15{,}213{,}184{,}900 \text{ mg carbon/day}$$

In order for this value to be more meaningful, one can convert it to grams, pounds, and tons. These values are

(1) 15,213,185 g carbon fixed/day
(2) 33,509 lb. carbon fixed/day
(3) 16.7 tons carbon fixed/day

If the total amount of carbon fixed per day is multiplied by the number of days composing a sampling season, the total organic production of Lake Superior for both the 1967 and 1968 sampling seasons can be calculated. These values are reported only in tons for the sake of simplicity and are as follows:

(1) Lake Superior, 1967:

16.7 tons fixed/day X 120 days/season = 2004 tons fixed/season

(2) Lake Superior, 1968:

16.7 tons fixed/day X 98 days/season = 1637 tons fixed/season.

These values, although approximate, indicate that a great amount of primary organic production did occur in Lake Superior during the 1967 and 1968 sampling seasons. These values become even more impressive when one considers that this production was accomplished primarily by plankton algae, most of which are microscopic in size and are located in approximately the first sixty-six feet of lake water. Since no data were available on integral photosynthesis in the other Great Lakes, calculations such as those made for Lake Superior can not be made. However, on the basis of the data collected it seems reasonable to assume that the integral primary production in the other lakes would be greater.

It also would seem of value and interest to compare the surface water productivity rates of the Great Lakes with other freshwater lakes of the world and to selected areas of the ocean. Information of this type has been summarized in Table XXV. The surface water productivity rates recorded in this tabulation represent mean values from the first five meters of water and during comparable seasons.

It is interesting to note the very reduced rates of surface water productivity in Grand Traverse Bay and in Douglas Lake compared to the productivity levels noted for the open water regions of the Great Lakes sampled. Grand Traverse Bay is a rather isolated portion of northeastern Lake Michigan while Douglas Lake is an inland lake in the state of Michigan. This again illustrates the great variability that can exist in waters from the same general region and even in the same lake as was previously illustrated and discussed.

The mean seasonal productivity rate of Lake Huron corresponds closely to those noted for Bras d' Or Lake (Nova Scotia). Lake Erie values approach those of Lake Erken (Sweden) and the carbon fixation rate in Lake Superior approaches that of the northeast Atlantic near Denmark. Although the mean productivity rate of Lake Michigan surface waters is somewhat higher and the Lake Erie productivity rate is considerably higher than the productivity values noted for the various lakes and ocean areas of the world previously mentioned, they fall below the surface water productivity rates of Lake Erken in Sweden and far below the productivity rates of the two extremely eutrophic Danish freshwater lakes, Lake Esrom and Lake Fureso.

Table XXV

Mean Surface Water Productivity Rates of the Great Lakes and Other Freshwater Lakes and Ocean Areas.

Lake or Ocean and Location	Productivity Rate in mg.C/ m^3 /day	Investigator
Lake Superior	16.62	Parkos (1967-68)
Lake Huron	23.04	Parkos (1968)
Lake Michigan	37.62	Parkos (1967)
Lake Erie	175.20	Parkos (1968)
Grand Traverse Bay, N.E. Lake Michigan	0.34	Saunders et al. (1962)
Douglas Lake, Mich.	0.23	Saunders et al. (1962)
Bras d'Or Lake, Nova Scotia, Canada	23.5	Geen and Hargrave (1966)
Brooks Lake, Alaska	3.2	Goldman (1960)
Maknek Lake, Alaska	8.8	Goldman (1960)
Torne Träsk, Sweden	6.4	Rodhe (1958b)
Ransaren, Sweden	8.8	Rodhe (1958b)
Lake Erken, Sweden	221.0	Rodhe (1958b)
Lake Esrom, Denmark	1600	Jonasson and Mathiesen (1959)
Lake Furesø, Denmark	2100	Jonasson and Mathiesen (1959)
N.E. Atlantic - near Denmark	21	Steemann-Nielsen (1960)
North Atlantic, same lat. as Great Lakes	7.5	Steemann-Nielsen (1958b)
Southeast Pacific	3.3	Holmes (1961)
Southwest Pacific	7.2	Angot (1961)
North Pacific, Sub-Arctic Region	6.4	Koblentz-Mishke (1961)

VI SUMMARY AND CONCLUSION

This study was designed to measure the primary productivity rates of the surface waters of Lakes Superior, Michigan, Huron and Erie. Great Lakes ore carriers were made available for the field operations associated with this project which was carried out during the 1967 and 1968 shipping seasons. Production rates were determined using the carbon fourteen technique with light, temperature and incubation time remaining constant. Uniform procedures also were followed with respect to collection and processing of samples onboard ship and at the lakeside laboratory.

Sample activity was measured with an Ansitron II liquid scintillation counter and final productivity calculations were made for each lake station. Since project procedures were standardized, direct comparisons of the productivity levels, or water quality, could be made among the four lakes studied. Some of the more important findings and conclusions are summarized below.

(1) Baselines of primary surface water productivity were established for the lakes studied. Such baselines are necessary and useful in any study of advancing eutrophication within the Great Lakes.

(2) A comparison of the mean productivity rates shows Lake Superior to be the most oligotrophic of the Great Lakes studied. Eutrophication becomes more pronounced in Lakes Huron, Michigan, and Erie, respectively with Michigan and Erie being most productive.

(3) Productivity variations of considerable magnitude were found to exist within a given lake and during the same sampling trip. It is believed these variations represent population differences within individual water masses encountered while crossing the lake.

(4) Productivity rates with respect to time and lake position were not linear, with the exception of Lake Erie which was less extensively sampled. Productivity was found to be cyclic in nature, its rate depending upon the environmental conditions.

(5) Highest productivity tended to occur in those lake areas near large population centers, a fact which indicates possible enrichment from these sources.

BIBLIOGRAPHY

Angot, M. 1961 A Summary of Productivity Measurements in the Southwestern Pacific Ocean. In Proc. Conf. Prim. Prod. Meas., M.S. Doty (ed.), U.S.A.E.C. TID No. 7633, pp. 1-9.

A.P.H.A. 1965 Standard Methods for the Examination of Water and Wastewater (12th ed.). Am. Pub. Hlth. Assn., Inc. New York.

Arthur, C.R. 1967 A Possible Source of Error in the C^{14} Method of Measuring Primary Productivity. Limnol. Oceanogr., 12(1): 121-124.

Atkins, W.R.G. 1922 Hydrogen-ion Concentration of Sea Water in its Biological Relation. J. Mar. Biol. Assn. U.K., 12: 717-769.

_____ 1923 Phosphate Content of Waters In Relationship to Growth of Algal Plankton. ibid., 13:119-150.

Bartsch, G. 1968 Personal communication.

Beeton, A. M. 1965 Eutrophication of the St. Lawrence Great Lakes. Limnol. Oceanogr., 10:240-254.

Berge, G. 1958 The Primary Production in the Norwegian Sea, June 1954, as Measured by An Adapted C^{14} Technique. Rapp. P.-v. Reun. Cons. perm. int. Explor. Mer., 144:85-91.

Cooper, L.H.N. 1933 Chemical Constituents of Biological Importance in the English Channel. J. Mar. Biol. Assn. U.K., 18:677-728.

Corlett, J. 1958 Measurement of Primary Production in the Western Barents Sea. Rapp. P.-v. Reun. Cons. perm. int. Explor. Mer., 144: 76-78

Currie, R.I. 1958 Some Observations on Organic Production in the Northeast Atlantic. ibid., 144:96-102.

Cushing, D.H. 1958 Some Experiments Using the C^{14} Technique. ibid., 144:32-33.

Dixon, W.J. and F.J. Massey, Jr. 1957 Introduction to Statistical Analysis. McGraw-Hill, Inc., New York.

Fish, C.J., C.K. Green, P.R. Burkholder, C.J. Munter and C.B. Wilson 1960 Limnological Survey of Eastern and Central Lake Erie, 1928-1929. Spec. Scient. Rep. U.S. Fish & Wildl. Serv. No. 334, Washington, 198 pp.

Forbes, S.A. 1887 The Lake As A Microcosm. Illinois Nat. Hist. Surv. Bull., 15:537-550.

Frey, D.G. and J.B. Stahl 1958 Measurement of Primary Production on Southhampton Island in the Canadian Arctic. Limnol. Oceanogr., 3(2):215-221.

Gaarder, T. and H.H. Gran 1927 Investigations of the Production of Plankton in the Oslo Fjord. Rapp P.-v. Reun. Cons. perm. int. Explor. Mer., 42:1-48.

Geen, G.H. and B.T. Hargrave 1966 Primary and Secondary Production in Bras d'Or Lake, Nova Scotia, Canada. Int. Assn. Theoret. Appl. Limnol., 16:333-340.

Goldman, C.R. 1959 Primary Productivity and Limiting Factors in Brooks Lake, Alaska. ibid., 14(1):120-124

_____1960 Primary Productivity and Limiting Factors in Three Lakes of the Alaska Peninsula. Ecol. Monogr., 30:207-230.

_____1961 The Measurement of Primary Productivity and Limiting Factors in Freshwater with Carbon-14. In Proc. Conf. Prim. Prod. Meas., M.S. Doty (ed.), U.S.A.E.C. TID No. 7633, pp. 103-113.

Gran, H.H. and T. Thompson The Diatoms and the Physical and Chemical Conditions of the Sea Water of the San Juan Archipelago. Publs. Puget Sound Mar. Biol. Stn., 7:169.

Harvey, H.W., L.H.N. Cooper, M.V. LeBour and F.S. Russell 1935 Plankton Production and its Control. J. Mar. Biol. Assn. U.K., 20:407-442.

Hobbie, J.E. 1962 Carbon Fourteen Measurements of Primary Production in Two Arctic Alaskan Lakes. Int. Assn. Theoret. Appl. Limnol., 15(1):360-364.

Holmes, R.W. 1961 A Summary of Productivity Measurements in the Southeastern Pacific Ocean. In Proc. Conf. Prim. Prod. Meas., M.S. Doty (ed), U.S.A.E.C. TID No. 7633, pp. 18-57.

Hough, J. 1958 Geology of the Great Lakes. Univ. of Illinois Press, Urbana, Ill.

Jitts, H.R. 1961 The C^{14} Method for Measuring CO_2 Uptake in Marine Productivity Studies. Mar. Biol. Labor., Cronulla, Rept. 8.

Jonasson, P.M. and H. Mathiesen 1959 Measurements of Primary Production in Two Danish Eutrophic Lakes, Estrom So and Fureso. Oikos, 10(2):137-167.

Koblentz-Mishke, O.J. 1961 A Summary of Productivity Measurements In the North Pacific Ocean. In Proc. Conf. Prim. Prod. Meas., M.S. Doty (ed.), U.S.A.E.C. TID No. 7633, pp. 10-17.

Kramer, J.R. 1961 Chemistry of Lake Erie. Proc. 4th Conf. on Great Lakes Res., Int. Assn. for Great Lakes Research, Ann Arbor, Mich., pp. 27-56.

Kuznetsov, S.I. 1955a Application of Radioactive Isotopes in the Study of Processes of Photosynthesis and Chemosynthesis in Bodies of Water. Rep. Sov. Deleg. at Internat. Conf. on Peaceful Use of Atomic Energy. Geneva, pp. 411-430.

_____1955b Utilization of Radioactive Carbon Dioxide C^{14} for Determining Comparative Quantity of Photosynthesis and Chemosynthesis in a Series of Lakes of Different Types. Publs. Acad. Sci. USSR. pp. 126-135.

Lasker, R. and R.W. Holmes 1957 Variability in Retention of Marine and Phytoplankton by Membrane Filters. Nature,180:1295-1296.

MacFayden, A. 1948 The Meaning of Productivity in Biological Systems. J. Anim. Ecol., 17:75-80.

Marshall, S.M. and A.P. Orr 1930 A Study of Spring Diatom Increase in Loch Striven. J. Mar. Biol. Assn., U.K., 16:853-878.

Michigan Water Resource Commission 1968 Report on Water Pollution Control in the Michigan Portion of the Lake Michigan Basin and its Tributaries. Dept. of Conservation and Michigan Dept. of Public Health. State of Michigan. 31 pp.

Nygaard, G. 1955 On the Productivity of Five Danish Waters. Int. Assn. Theoret. Appl. Limnol., 12:123-133.

Perfiliev, B.W. 1929 Zer Mikrobiologie der Bodenablagerungen. Int. Assn. Theoret. Appl. Limnol., (English Summary), 4:107-143.

Powers, C.F., D.L. Jones, P.C. Mundinger, and J.C. Ayers 1960 Applications of Data Collected Along Shore to Conditions in Lake Erie. Proc. 3rd Conf. on Great Lakes Res., Publ. No. 5, Great Lakes Res. Div., Univ. of Michigan, Ann Arbor, 78 pp.

Prescott, G.W. 1962 Algae of the Western Great Lakes Area. Wm. C. Brown Co., Dubuque, Ia.

Putnam, H.D. and T.A. Olson 1966 Primary Productivity at a Fixed Station in Western Lake Superior. Proc. 9th Conf. on Great Lakes Res., Int. Assn. for Great Lakes Res., Ann Arbor, Mich., pp. 115-128.

Rapkin, E. 1967 Preparation of Samples for Liquid Scintillation Counting. In Instrumentation in Nuclear Medicine, C.J. Hine (ed.) Academic Press, New York. pp. 181-225.

Riley, G.A. 1938 Plankton Studies. I. A Preliminary Investigation of the Plankton of the Tortugas Region. J. Mar. Res., 1:335-350.

_____ 1939 Plankton Studies. II. The Western North Atlantic, May-June, 1939. ibid., 2:145-162.

Riley, G.A. and S. Gorgy 1948 Quantitative Studies of the Western North Atlantic. J. Mar. Res., 1:100-121.

Rodhe, W. 1958a The Primary Production in Lakes; Some Results and Restriction of the C^{14} Method. Rapp. P.-v. Reun. Cons. perm. int. Explor. Mer., 144:122-128.

_____ 1958b Primerproduktion and Seetypen. Int. Assn. Theoret. Appl. Limnol. (English Summary), 13:121-141.

Ruschmeyer, O.R. and T.A. Olson 1958 Water Movements and Temperatures of Western Lake Superior. School of Public Health, Univ. of Minnesota (mimeo), 65 pp.

Ruttner, F. 1966 Fundamentals of Limnology. Transl. by Frey, D.G. and F.E.S. Fry. Univ. of Toronto Press.

_____1956 Photosynthesis in the Ocean As a Function of Light Intensity. Limnol. Oceanogr., 1:61-70.

Ryther, J.H. and R.F. Vaccaro 1954 A Comparison of the Oxygen and C^{14} Methods of Measuring Marine Photosynthesis. J. Cons. perm. int. Explor. Mer., 20(1):25-34.

Saunders, G. 1964 Studies of Primary Productivity in the Great Lakes. Proc. 7th Conf. on Great Lakes Res., Int. Assn. for Great Lakes Res., Ann Arbor, Michigan. pp. 122-129.

Saunders, G.W., F.B. Trama, R.W. Bachmann 1962 Evaluation of a Modified C^{14} Technique for Estimation of Photosynthesis in Large Lakes. Proc. 5th Conf. on Great Lakes Res., Publ. No. 8. Great Lakes Res. Div., Univ. of Michigan, Ann Arbor. 61 pp.

Shelford, V.E. 1913 Animal Communities in Temperate America. Univ. of Chicago Press.

Siewell, H.R. 1935 The Annual Organic Production and Nutrient Phosphorus Requirement in the Tropical Western North Atlantic. J. Cons. perm. int. Explor. Mer., 10:20-32.

Smith, G.M. 1950 The Freshwater Algae of the United States. McGraw-Hill Book Co., Inc., New York.

Sorokin, Yu. I. 1955 Determination of Quantity of Chemosynthesis in Water of Rybinskii Reservoir by Application of C^{14}. Rep. Acad. Sci. USSR, 105:1343-1345.

_____ 1956 Application of Radiocarbon for the Study of Primary Production of Bodies of Water. Trans. All-Union Hydrobiol. Soc., 7:271-286.

Steemann-Nielsen, E. 1940 Die Produktionsbedingungen im Ubergangsgebiet zwischen der Nord- und Ostsee. Meddr. Kommn. Havunders. Serie: Plankton, 2:4.

_____ 1951a Measurement of the Production of Organic Matter in the Sea by Means of Carbon-14. Nature, 167:684-685.

_____ 1951b The Marine Vegetation of Iseford. A Study on Ecology and Production. Meddr. Kommn. Havunders., Serie: Plankton, 5:4.

_____ 1952 The Use of Radioactive Carbon (C^{14}) for Measuring Organic Production in the Sea. J. Cons. perm. int. Explor. Mer., 18:117-140.

_____ 1954 On Organic Production in the Oceans. ibid., 19:308-328.

_____ 1958a Experimental Methods for Measuring Organic Production in the Sea. Rapp. P.-v. Reun. Cons. perm. int. Explor. Mer., 144:38-46.

_____ 1958b A Survey of Recent Danish Measurement of the Organic Productivity in the Sea. ibid., 144:92-95

_____ 1960 Productivity of the Oceans. Ann. Rev. Plant Physiol., 11:341-362.

Sverdrup, H.H., M.W. Johnson and G.H. Fleming. 1942 The Oceans: Their Physics, Chemistry and General Biology. Prentice-Hall, Inc., New York.

Tiffany, L.H. and M.E. Britton 1952 The Algae of Illinois. Univ. of Chicago Press, Chicago, Ill.

Vinberg, G.A. 1960 The Primary Production of Bodies of Water. Translation from Inst. Biol. Acad. Sci. Byelorussian S.S.R., Minsk, U.S.A.E.C. Tr - 5692 (Book 1); 235 pp.

Welch, P.S. 1948 Limnological Methods. McGraw-Hill Book Co., Inc., New York.

APPENDIXES

- A -

Table XXVI LAKE SUPERIOR PLANKTON (Organisms/liter) TRIP 3 October 9, 1967

Western Lake Region		Central Lake Region		Eastern Lake Region	
CLASS MYXOPHYCEAE		CLASS MYXOPHYCEAE		CLASS MYXOPHYCEAE	
Lyngbya contorta	9,782	Lyngbya contorta	[illegible],130	Lyngbya contorta	2[illegible],9[illegible]
		G[illegible]	1,147		
CLASS CHRYSOPHYCEAE		CLASS CHRYSOPHYCEAE		CLASS CHRYSOPHYCEAE	
Dinobryon	1,720	Dinobryon	2,29[illegible]	Dinobryon	12,[illegible]
CLASS BACILLARIOPHYCEAE		CLASS BACILLARIOPHYCEAE		CLASS BACILLARIOPHYCEAE	
Asterionella formosa	573	Cyclotella	1,147	Asterionella formosa	[illegible]
[illegible]	[illegible]	Asterionella formosa	573	[illegible]	[illegible]
[illegible]	573	[illegible]	573	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	573	[illegible]	[illegible]
[illegible]discus	573	Synedra acus	573	[illegible]	[illegible]
Synedra ulna	573	Tabellaria fenestrata	573	[illegible]discus	[illegible]
				[illegible] acus	[illegible]
				[illegible] fenestrata	[illegible]
		CLASS CHLOROPHYCEAE			
		Cosmarium	573		
Unidentified nannoplankton*	4,[illegible]	Unidentified nannoplankton*	2[illegible],[illegible]	Unidentified nannoplankton*	[illegible],[illegible]
Unidentified net plankton**	1,147				
Total Count:	21,[illegible]	Total Count:	[illegible]	Total Count:	5[illegible],[illegible]

* Nannoplankton: two forms only; presumed to be bacteria
** Net plankton category based on size

Table XXVII LAKE SUPERIOR PLANKTON (Organisms/liter) TRIP 4 October 21-22, 1967

Western Lake Region		Central Lake Region		Eastern Lake Region	
CLASS MYXOPHYCEAE		CLASS MYXOPHYCEAE		CLASS MYXOPHYCEAE	
Lyngbya contorta	109,5[illegible]	Lyngbya contorta	[illegible],[illegible]	Lyngbya contorta	12[illegible],[illegible]
		[illegible]	1,147		
CLASS CHRYSOPHYCEAE		CLASS CHRYSOPHYCEAE		CLASS CHRYSOPHYCEAE	
Dinobryon	160,00[illegible]	Dinobryon	3,441	Dinobryon	21,7[illegible]
CLASS BACILLARIOPHYCEAE		CLASS BACILLARIOPHYCEAE		CLASS BACILLARIOPHYCEAE	
Asterionella formosa	4,[illegible]	Synedra acus	1,147	Synedra acus	2,[illegible]
Synedra ulna	2,[illegible]	Asterionella formosa	1,147	Asterionella formosa	1,1[illegible]
Tabellaria fenestrata	1,[illegible]	[illegible]	573	Tabellaria fenestrata	1,1[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]ria [illegible]sis	[illegible]
Stephanodiscus	[illegible]	Stephanodiscus	[illegible]	[illegible]	573
Synedra acus	573	Synedra ulna	573	Stephanodiscus	573
				Synedra ulna	573
				Tabellaria flocculosa	573
CLASS CHLOROPHYCEAE					
Closterium	573				
Unidentified nannoplankton*	270,[illegible]	Unidentified nannoplankton*	167,492	Unidentified nannoplankton*	116,99[illegible]
Unidentified net plankton**	2,[illegible]	Unidentified net plankton**	2,[illegible]	Unidentified net plankton**	1,[illegible]
Total Count:	553,[illegible]	Total Count:	27[illegible],174	Total Count:	277,[illegible]

* Nannoplankton: two forms only; presumed to be bacteria
** Net plankton category based on size

Table XXVIII LAKE MICHIGAN PLANKTON (Organisms/liter) TRIP 3 October 6-8, 1967

Northern Lake Region		Central Lake Region		Southern Lake Region	
CLASS MYXOPHYCEAE		CLASS MYXOPHYCEAE		CLASS MYXOPHYCEAE	
Coelosphaerium	293,058	Microcystis incerta	630,276	Microcystis incerta	1,218,687
Microcystis incerta	223,665	Coelosphaerium	311,410	Coelosphaerium	176,064
Lyngbya contorta	186,397	Merismopedia glauca	27,528	Chroococcus	93,480
Chroococcus	18,925	Chroococcus	25,234	Merismopedia glauca	4,588
Merismopodia glauca	16,058	Lyngbya contorta	11,470		
CLASS CHRYSOPHYCEAE		CLASS CHRYSOPHYCEAE		CLASS CHRYSOPHYCEAE	
Dinobryon	5,735	Dinobryon	8,029	Dinobryon	573
CLASS BACILLARIOPHYCEAE		CLASS BACILLARIOPHYCEAE		CLASS BACILLARIOPHYCEAE	
Fragilaria crotenensis	4,014	Cocconeis	5,161	Cocconeis	2,294
Cyclotella	3,441	Synedra acus	3,441	Cyclotella	1,720
Coratonois	2,867	Tabellaria flocculosa	1,147	Melosira	1,147
Tabellaria flocculosa	2,294	Cyclotella	1,720	Synedra acus	573
Synedra acus	1,720	Asterionella formosa	573	Tabellaria flocculosa	573
Cocconeis	573	Rhizosolenia	573		
Stephanodiscus	573				
CLASS CHLOROPHYCEAE		CLASS CHLOROPHYCEAE		CLASS CHLOROPHYCEAE	
Cosmarium	573	Scenedesmus	2,867	Scenedesmus	573
CLASS DINOPHYCEAE		CLASS DINOPHYCEAE		CLASS DINOPHYCEAE	
Ceratium hirundinella	573	Ceratium hirundinella	1,720	Ceratium hirundinella	1,147
Unidentified nannoplankton*	562,603	Unidentified nannoplankton*	292,485	Unidentified nannoplankton*	253,487
Unidentified net plankton**	48,741	Unidentified net plankton**	311,410	Unidentified net plankton**	29,248
Total Count:	1,371,806	Total Count:	1,496,257	Total Count:	1,784,154

Table XXIX LAKE MICHIGAN PLANKTON (Organisms/liter) TRIP 4 October 25-26, 1967

Northern Lake Region		Central Lake Region		Southern Lake Region	
CLASS MYXOPHYCEAE		CLASS MYXOPHYCEAE		CLASS MYXOPHYCEAE	
Coelosphaerium	155,992	Microcystis incerta	229,400	Coelosphaerium	129,037
Merismopedia glauca	9,176	Coelosphaerium	100,936	Microcystis incerta	83,157
Chroococcus	6,882	Chroococcus	26,381	Chroococcus	8,602
CLASS CHRYSOPHYCEAE		CLASS CHRYSOPHYCEAE			
Dinobryon	573	Dinobryon	573		
CLASS BACILLARIOPHYCEAE		CLASS BACILLARIOPHYCEAE		CLASS BACILLARIOPHYCEAE	
Fragilaria crotenensis	2,867	Tabellaria fenestrata	9,176	Tabellaria fenestrata	12,905
Stephanodiscus	2,294	Asterionella formosa	8,602	Melosira	9,749
Synedra acus	2,294	Synedra acus	4,014	Fragilaria capucina	7,455
Tabellaria flocculosa	1,720	Fragilaria capucina	1,147	Tabellaria flocculosa	5,161
Cocconois	573	Melosira	1,147	Synedra acus	4,588
		Tabellaria flocculosa	1,147	Asterionella formosa	4,014
		Cyclotella	573	Fragilaria crotononsis	1,147
				Stephanodiscus	573
				CLASS DINOPHYCEAE	
				Ceratium hirundinella	573
Unidentified nannoplankton*	296,499	Unidentified nannoplankton*	278,721	Unidentified nannoplankton*	475,431
Unidentified net plankton**	20,072			Unidentified net plankton**	1,720
Total Count:	505,251	Total Count:	661,817	Total Count:	748,412

Table XXX LAKE SUPERIOR PLANKTON (Organisms/liter) TRIP 1 May 25-26, 1968

Western Lake Region		Central Lake Region		Eastern Lake Region	
CLASS MYXOPHYCEAE		CLASS MYXOPHYCEAE		CLASS MYXOPHYCEAE	
Lyngbya contorta	164,021	Lyngbya contorta	90,613	Lyngbya contorta	38,424
Merismopedia glauca	1,147				
		CLASS CHRYSOPHYCEAE			
		Dinobryon	573		
CLASS BACILLARIOPHYCEAE		CLASS BACILLARIOPHYCEAE		CLASS BACILLARIOPHYCEAE	
Synedra acus	4,014	Synedra acus	2,867	Asterionella formosa	3,441
Synedra ulna	4,014	Synedra ulna	2,294	Synedra acus	2,294
Asterionella formosa	3,441	Asterionella formosa	2,294	Melosira	2,294
Diatoma	1,147	Melosira	1,147	Synedra ulna	2,294
Lavicula	1,147	Fragilaria crotenensis	1,147	Cocconeis	573
Tabellaria fenestrata	1,147	Cymbella	573	Cymbella	573
Cocconeis	573	Diatoma	573	Gomphonema	573
Cymbella	573	Tabellaria fenestrata	573	Stephanodiscus	573
Gomphonema	573			Tabellaria fenestrata	573
Unidentified nannoplankton*	334,777	Unidentified nannoplankton*	214,489	Unidentified nannoplankton*	318,836
Unidentified net plankton**	1,147	Unidentified net plankton**	573	Unidentified net plankton**	1,147
Total Count:	516,721	Total Count:	317,716	Total Count:	371,051

* Nannoplankton: two forms only; presumed to be bacteria
** Net plankton category based on size

Table XXXI LAKE SUPERIOR PLANKTON (Organisms/liter) TRIP 3 July 12, 1968

Western Lake Region	Central Lake Region		Eastern Lake Region
	CLASS MYXOPHYCEAE		
	Lyngbya contorta	111,832	
	CLASS CHRYSOPHYCEAE		
	Dinobryon	21,219	
	CLASS BACILLARIOPHYCEAE		
	Synedra acus	35,557	
	Asterionella formosa	22,640	
	Rhizoselenia	10,333	
	Cocconeis	1,720	
	Tabellaria fenestrata	1,147	
	Cymbella	573	
	Diatoma	573	
	Synedra ulna	573	
	Unidentified nannoplankton*	298,220	
	Unidentified net plankton**	25,817	
	Total Count:	509,848	

* Nannoplankton: two forms only; presumed to be bacteria
** Net plankton category based on size

Table XXXII LAKE SUPERIOR PLANKTON (Organisms/liter) TRIP 5 August 26, 1968

Western Lake Region		Central Lake Region		Eastern Lake Region	
CLASS MYXOPHYCEAE		CLASS MYXOPHYCEAE		CLASS MYXOPHYCEAE	
Lyngbya contorta	8,602	Lyngbya contorta	22,761	Lyngbya contorta	34,983
Chroococcus	1,147	Merismopedia glauca	7,455		
CLASS CHRYSOPHYCEAE		CLASS CHRYSOPHYCEAE		CLASS CHRYSOPHYCEAE	
Dinobryon	123,876	Dinobryon	1,147	Dinobryon	1,147
CLASS BACILLARIOPHYCEAE		CLASS BACILLARIOPHYCEAE		CLASS BACILLARIOPHYCEAE	
Synedra acus	12,043	Synedra acus	7,455	Rhizoselenia	3,441
Asterionella formosa	9,749	Asterionella formosa	6,308	Synedra acus	2,867
Synedra ulna	4,014	Synedra ulna	2,294	Asterionella formosa	2,294
Tabellaria fenestrata	2,294	Cyclotella	573	Cyclotella	573
Cocconeis	1,147	Stephanodiscus	573	Stephanodiscus	573
Rhizoselenia	573	Tabellaria fenestrata	573	Synedra ulna	573
Stephanodiscus	573				
Tabellaria flocculosa	573				
CLASS CHLOROPHYCEAE					
Scenedesmus	573				
Unidentified nannoplankton*	150,257	Unidentified nannoplankton*	157,712	Unidentified nannoplankton*	213,915
Unidentified net plankton**	4,014			Unidentified net plankton**	24,087
Total Count:	319,435	Total Count:	206,924	Total Count:	286,173

* Nannoplankton: two forms only; presumed to be bacteria
** Net plankton category based on size

Table XXXIII LAKE HURON PLANKTON (Organisms/liter) TRIP 1 May 23, 1968

Northern Lake Region		Central Lake Region		Southern Lake Region	
		CLASS MYXOPHYCEAE			
		Chroococcus	10,823		
		CLASS CHRYSOPHYCEAE		CLASS CHRYSOPHYCEAE	
		Dinobryon	4,014	Dinobryon	83,157
CLASS BACILLARIOPHYCEAE		CLASS BACILLARIOPHYCEAE		CLASS BACILLARIOPHYCEAE	
Melosira	16,058	Synedra acus	28,101	Asterionella formosa	26,381
Asterionella formosa	10,896	Melosira	27,528	Melosira	13,090
Synedra acus	5,735	Tabellaria fenestrata	9,749	Tabellaria fenestrata	13,090
Fragilaria capucina	5,161	Fragilaria crotonensis	8,029	Synedra acus	5,735
Tabellaria fenestrata	1,147	Asterionella formosa	5,161	Fragilaria capucina	1,147
Tabellaria flocculosa	1,147	Fragilaria capucina	4,588	Tabellaria flocculosa	1,147
Cyclotella	573	Tabellaria flocculosa	4,588	Cymbella	573
Cymbella	573	Diatoma	1,720	Gomphonema	573
Stephanodiscus	573	Cymbella	1,147		
		Cocconeis	573		
CLASS CHLOROPHYCEAE					
Closterium	1,720				
Unidentified nannoplankton*	737,531	Unidentified nannoplankton*	639,452	Unidentified nannoplankton*	381,377
Unidentified net plankton**	8,079	Unidentified net plankton**	8,029	Unidentified net plankton**	32,116
Total Count:	739,716	Total Count:	753,002	Total Count:	558,336

* Nannoplankton: two forms only; presumed to be bacteria
** Net plankton category based on size

Table XXXIV — LAKE HURON PLANKTON (Organisms/liter) — TRIP 3 — July 9-11, 1968

Northern Lake Region	
CLASS CHRYSOPHYCEAE	
Dinobryon	40,718
CLASS BACILLARIOPHYCEAE	
Synedra acus	28,101
Asterionella formosa	26,954
Tabellaria fenestrata	23,513
Melosira	9,750
Diatoma	9,749
Tabellaria flocculosa	8,029
Rhizosolenia	2,294
Synedra ulna	1,147
Cyclotella	573
Unidentified nannoplankton*	254,634
Unidentified net plankton**	9,749
Total Count:	463,903

Central Lake Region	
CLASS CHRYSOPHYCEAE	
Dinobryon	90,613
CLASS BACILLARIOPHYCEAE	
Synedra acus	39,571
Asterionella formosa	3[illegible],624
Tabellaria fenestrata	21,21[illegible]
Fragilaria crotonensis	16,[illegible]
Rhizosolenia	[illegible]
Diatoma	1,7[illegible]1
Synedra ulna	1,[illegible]
Unidentified nannoplankton*	165,168
Total Count:	3[illegible],4[illegible]9

Southern Lake Region	
CLASS MYXOPHYCEAE	
Merismopedia glauca	9,176
CLASS CHRYSOPHYCEAE	
Dinobryon	14,337
CLASS BACILLARIOPHYCEAE	
Asterionella formosa	114,700
Fragilaria crotonensis	[illegible],157
Tabellaria fenestrata	[illegible]
Melosira	13,[illegible]
Cocconeis	[illegible]
Fragilaria capucina	5,[illegible]
Tabellaria flocculosa	4,014
Synedra acus	4,014
Stephanodiscus	2,[illegible]
Diatoma	[illegible]
CLASS CHLOROPHYCEAE	
Scenedesmus	573
Staurastrum	573
Unidentified nannoplankton*	337,218
Unidentified net plankton**	56,77[illegible]
Total Count:	6[illegible],[illegible]

* Nannoplankton: two forms only; presumed to be bacteria
** Net plankton category based on size

Table XXXV — LAKE HURON PLANKTON (Organisms/liter) — TRIP 5 — August 22-23, 1968

Northern Lake Region	
CLASS MYXOPHYCEAE	
Coelosphaerium	87,172
Chroococcus	10,323
Merismopedia glauca	9,176
CLASS CHRYSOPHYCEAE	
Dinobryon	12,617
CLASS BACILLARIOPHYCEAE	
Fragilaria crotonensis	25,807
Tabellaria fenestrata	21,219
Tabellaria flocculosa	5,735
Cocconeis	3,441
Asterionella formosa	2,294
Fragilaria capucina	1,147
Synedra acus	1,147
Cyclotella	573
Rhizosolenia	573
CLASS DINOPHYCEAE	
Ceratium hirundinella	1,147
Unidentified nannoplankton*	91,137
Unidentified net plankton**	60,217
Total Count:	333,778

Central Lake Region	
CLASS MYXOPHYCEAE	
Coelosphaerium	52,762
Chroococcus	20,072
CLASS CHRYSOPHYCEAE	
Dinobryon	5,735
CLASS BACILLARIOPHYCEAE	
Fragilaria crotonensis	34,410
Melosira	2,602
Cocconeis	3,441
Asterionella formosa	[illegible]
Tabellaria fenestrata	1,721
Cyclotella	573
Stephanodiscus	573
Synedra acus	573
Unidentified nannoplankton*	75,128
Unidentified net plankton**	21,793
Total Count:	[illegible]

Eastern Lake Region	
CLASS MYXOPHYCEAE	
Chroococcus	14,[illegible]
Coelosphaerium	[illegible]
Merismopedia glauca	[illegible]
CLASS BACILLARIOPHYCEAE	
Fragilaria crotonensis	30,969
Cocconeis	4,014
Fragilaria capucina	2,2[illegible]
CLASS DINOPHYCEAE	
Ceratium hirundinella	573
Unidentified nannoplankton*	64,895
Unidentified net plankton**	5,602
Total Count:	145,667

* Nannoplankton: two forms only; presumed to be bacteria
** Net plankton category based on size

- B -

TWO-WAY ANALYSIS OF VARIANCE ON CO_2 DATA, LAKE SUPERIOR, 1967.

Sample Station	Total CO_2 available on seasonal intervals (mg/1)				Squares of Observed Data				$\sum_1^{N_r} X$	$(\sum_1^{N_r} X)^2$
	1	2	3	4	1	2	3	4		
I	40.12	39.10	37.68	40.88	1609.61	1528.81	1419.78	1671.17	157.78	24894.52
II	41.30	43.40	39.15	40.36	1710.13	1883.56	1532.72	1628.92	164.30	[illegible]
III	37.57	49.61	40.33	39.86	1411.50	2461.15	1626.59	1588.[illegible]	167.37	[illegible]
$\sum_1^{N_c} X$	119.08	132.11	117.16	121.10					489.45 ΣX	[illegible] $\sum_1^{K_r}(\sum_1^{N_r} X)^2$
$\sum_1^{N_c} X^2$					4734.24	5873.52	4579.00	4888.90	20075.66 ΣX^2	

N_c = number of items in column
N_r = number of items in row
K_c = number of columns
K_r = number of rows

$N_c = 3$, $N_r = 4$, $N = 12$

$\Sigma X = 489.45$

$(\Sigma X)^2 = (489.45)^2 = 239,561.30$

$\sum_1^{K_c}(\sum_1^{N_c} X)^2 = (119.08)^2 + (132.11)^2 + (117.16)^2 + (121.10)^2 = [illegible]$

SUMMARY OF COMPUTATIONS

Analysis of Variance - Lake Superior CO_2 Data, 1967.

SOURCE OF VARIATION	AMOUNT OF VARIATION	DEGREES OF FREEDOM	ESTIMATED VARIANCE
Between column means	44.91	3	14.94
Between row means	11.99	2	5.99
Residual	55.42	6	9.24
Total	112.22	11	

ANALYSIS OF VARIANCE CALCULATIONS

COMPARISON OF ESTIMATED VARIANCE WITH ESTIMATED RESIDUAL VARIANCE.

F test

A two-way analysis of variance involves four sources of variation:

I. Total variation.

$$\Sigma X^2 - \frac{(\Sigma X)^2}{N} = 20075.46 - \frac{239661.38}{12} = 112.22$$

II. Variation between column means.

$$\frac{\sum_{1}^{K_c} \frac{(\Sigma X)^2}{N_c}}{K_c} - \frac{(\Sigma X)^2}{N} = \frac{60024.76}{3} - \frac{239661.38}{12} = 44.81$$

III. Variation between row means.

$$\frac{\sum_{1}^{K_r} \frac{(\Sigma X)^2}{N_r}}{K_r} - \frac{(\Sigma X)^2}{N} = \frac{79921.72}{4} - \frac{239661.38}{12} = 11.99$$

IV. Residual variation =

(total variation) - (variation between column means + variation between row means).

112.22 - (44.81 + 11.99) = 55.42

Not significant at the 90% confidence level.

I. Column means.

$$F = \frac{14.94}{18.70} = 0.798 \qquad n_1 = 3,\ n_2 = 6.$$

Not significant at the 90% confidence level.

II. Row means.

$$F = \frac{5.99}{16.73} = 0.358 \qquad n_1 = 2,\ n_2 = 6.$$

Not significant at the 90% confidence level.

The above statements indicate that if there is no actual difference in the CO_2 content of samples collected in Lake Superior during the 1967 season, the chances of randomly obtaining a sample that would be significantly different from all other samples collected, would be less than 10%.

Thus, the 1967 CO_2 data on Lake Superior show no significant seasonal or locational variation.

In view of this, the mean value (mg/l) of the available CO_2 in the samples collected was used as the basis for all C^{14} calculations.

$$\text{Mean} = \frac{\Sigma X}{n} = \frac{469.45}{12} = 40.78 \text{ mg/l}.$$

- C -

TWO-WAY ANALYSIS OF VARIANCE ON CO_2 DATA, LAKE MICHIGAN, 1967.

Sample Station	Total CO_2 available on seasonal intervals (mg/l)				Squares of Observed Data				$\sum_{1}^{N_r} \Sigma X$	$\sum_{1}^{N_r} (\Sigma X)^2$
	1	2	3	4	1	2	3	4		
I	103.75	97.9	108.70	98.57	10764.06	9584.41	11815.69	9716.04	408.92	167215.56
II	96.13	97.13	94.78	98.34	9240.97	9434.23	8983.24	9670.75	386.38	149289.50
III	90.57	95.92	95.71	87.11	8202.92	9200.64	9160.40	7588.15	369.31	136389.87
$\sum_{1}^{N_c} X$	290.45	290.95	299.24	284.02					1164.61 ΣX	$\sum_{1}^{K_r} \frac{\sum_{1}^{N_c} (\Sigma X)^2}{K_r N_r}$ 452894.93
$\sum_{1}^{N_c} X^2$					28207.95	28219.28	29959.33	26974.94	113361.50 ΣX^2	

N_c = number of items in column
N_r = number of items in row
K_c = number of columns
K_r = number of rows

$N_c = 3,\ N_r = 4,\ N = 12$

$\Sigma X = 1164.61$

$(\Sigma X)^2 = (1164.61)^2 = 1,356,316.45$

$$\sum_{1}^{K_c} \sum_{1}^{N_c} (\Sigma X)^2 = \begin{array}{r} (290.45)^2 \\ (290.95)^2 \\ (299.24)^2 \\ + (284.02)^2 \\ \hline 339,225.04 \end{array}$$

SUMMARY OF COMPUTATIONS

Analysis of Variance - Lake Michigan CO_2 Data, 1967.

SOURCE OF VARIATION	AMOUNT OF VARIATION	DEGREES OF FREEDOM	ESTIMATED VARIANCE
Between column means	48.64	3	16.21
Between row means	197.36	2	98.68
Residual	89.13	6	14.85
Total	335.13	11	

ANALYSIS OF VARIANCE CALCULATIONS

A two-way analysis of variance involves four sources of variation:

I. Total variation.

$$\Sigma X^2 - \frac{(\Sigma X)^2}{N} = 113361.50 - \frac{1356316.45}{12} = 335.13$$

II. Variation between column means.

$$\frac{\sum_1^{K_c}(\sum_1^{N_c} X)^2}{N_c} - \frac{(\Sigma X)^2}{N} = \frac{330225.04}{3} - \frac{1356316.45}{12} = 48.64$$

III. Variation between row means.

$$\frac{\sum_1^{K_r}(\sum_1^{N_r} X)^2}{N_r} - \frac{(\Sigma X)^2}{N} = \frac{452894.93}{4} - \frac{1356316.45}{12} = 197.36$$

IV. Residual variation =

(total variation) - (variation between column means + variation between row means).

$$335.13 - (48.64 + 197.36) = 89.13$$

COMPARISON OF ESTIMATED VARIANCE WITH ESTIMATED RESIDUAL VARIANCE.

F test

I. Column means.

$$F = \frac{16.21}{14.85} = 1.05 \quad n_1 = 3, \quad n_2 = 6.$$

Not significant at the 90% confidence level.

II. Row means.

$$F = \frac{98.68}{14.85} = 6.64 \quad n_1 = 2, \quad n_2 = 6.$$

Not significant at the 90% confidence level.

The above statements indicate that if there is no actual difference in the CO_2 content of samples collected in Lake Michigan during the 1967 season, the chances of randomly obtaining a sample that would be significantly different from all other samples collected, would be less than 10%.

Thus, the 1967 CO_2 data on Lake Michigan show no significant seasonal or locational variation.

In view of this, the mean value (mg/1) of the available CO_2 in the samples collected was used as the basis for all C^{14} calculations.

$$\text{Mean} = \frac{\Sigma X}{N} = \frac{1164.61}{12} = 97.05 \text{ mg/1.}$$

- D -

TWO-WAY ANALYSIS OF VARIANCE ON CO_2 DATA, LAKE SUPERIOR, 1968.

Sample Station	Total CO_2 available on seasonal intervals (mg/1)				Squares of Observed Data				$\sum_1^{N_r} X$	$(\sum_1^{K_r} X)^2$
	1	2	3	4	1	2	3	4		
I	39.82	38.50	39.19	42.27	1585.63	1482.25	1535.86	1786.75	159.78	25529.65
II	41.01	37.72	40.89	41.67	1681.82	1422.80	1671.99	1736.39	161.29	26014.46
III	37.92	39.69	39.59	41.59	1437.93	1575.30	1567.37	1729.73	158.79	25214.76
$\sum_1^{N_c} X$	118.75	115.91	119.67	125.53					479.96 ΣX	76758.37 $\sum_1^{K_r}(\sum_1^{N_r} X)^2$
$\sum_1^{N_c} X^2$					4705.38	4480.35	4775.22	5252.87	19213.82 ΣX^2	

N_c = number of items in column
N_r = number of items in row
K_c = number of columns
K_r = number of rows

$N_c = 3, \quad N_r = 4, \quad N = 12$

$\Sigma X = 479.86$

$(\Sigma X)^2 = (479.86)^2 = 230,265.62$

$$\sum_1^{K_c}(\sum_1^{N_c} X)^2 = (118.75)^2 + (115.91)^2 + (119.67)^2 + (125.53)^2 = 57,615.38$$

SUMMARY OF COMPUTATIONS

Analysis of Variance - Lake Superior CO_2 Data, 1968.

SOURCE OF VARIATION	AMOUNT OF VARIATION	DEGREES OF FREEDOM	ESTIMATED VARIANCE
Between column means	16.32	3	5.34
Between row means	.79	2	.39
Residual	7.91	6	1.32
Total	25.02	11	

ANALYSIS OF VARIANCE CALCULATIONS

A two-way analysis of variance involves four sources of variation:

I. Total variation.

$$\Sigma X^2 - \frac{(\Sigma X)^2}{N} = 19213.82 - \frac{230265.62}{12} = 25.02$$

II. Variation between column means.

$$\frac{\sum_{1}^{K_c} \frac{(\Sigma X)^2}{N_c}}{N_c} - \frac{(\Sigma X)^2}{N} = \frac{57615.38}{3} - \frac{230265.62}{12} = 16.32$$

III. Variation between row means.

$$\frac{\sum_{1}^{K_r} \frac{(\Sigma X)^2}{N_r}}{N_r} - \frac{(\Sigma X)^2}{N} = \frac{76758.37}{4} - \frac{230265.62}{12} = 0.79$$

IV. Residual variation =

(total variation) - (variation between column means + variation between row means).

$25.02 - (16.32 + 0.79) = 7.91$

COMPARISON OF ESTIMATED VARIANCE WITH ESTIMATED RESIDUAL VARIANCE.

F test

I. Column means.

$$F = \frac{5.34}{1.32} = 4.04 \qquad n_1 = 3, \quad n_2 = 6.$$

Significant between 5 - 10 % confidence levels. However, considering last year's trends and all possible inherent errors, it was decided to attribute this to sampling error.

II. Row means.

$$F = \frac{0.39}{1.32} = 0.29 \qquad n_1 = 2, \quad n_2 = 6.$$

Not significant at the 90% confidence level.

The above statements indicate that if there is no actual difference in the CO_2 content of samples collected in Lake Superior during the 1968 season, the chances of randomly obtaining a sample that would be significantly different from all other samples collected, would be less than 10%.

Thus, the 1968 data on Lake Superior show no significant seasonal or locational variation.

In view of this, the mean value (mg/l) of the available CO_2 in the samples collected was used as the basis for all C^{14} calculations.

$$\text{Mean} = \frac{\Sigma X}{N} = \frac{479.86}{12} = 39.99 \text{ mg/l.}$$

TWO-WAY ANALYSIS OF VARIANCE ON CO_2 DATA, LAKE HURON, 1968.

Sample Station	Total CO_2 available on seasonal intervals (mg/l)				$\sum_{1}^{K_r} X$	Squares of Observed Data				$\sum_{1}^{K_r} (\Sigma X)^2$
	1	2	3	4		1	2	3	4	
I	70.52	67.26	71.28	69.92	278.98	4973.07	4523.91	5080.84	4888.81	77829.84
II	69.02	77.21	72.48	73.47	292.18	4763.76	5961.38	5253.35	5397.84	85369.15
III	70.23	75.31	70.04	73.85	289.48	4939.28	5671.60	4905.60	5453.82	83798.67
$\sum_{1}^{K_c} X$	209.82	219.78	213.80	217.24	860.64					246997.66
$\sum_{1}^{K_c} X^2$					ΣX^2	14676.11	16156.89	15239.79	15740.47	$\frac{\sum_{1}^{K_r} \sum_{1}^{K_c} (\Sigma X)^2}{185,231.34}$

N_c = number of items in column
N_r = number of items in row
K_c = number of columns
K_r = number of rows

$N_c = 3, \quad N_r = 4, \quad N = 12$

$\Sigma X = 860.64$

$(\Sigma X)^2 = (860.64)^2 = 740,701.21$

$$\frac{\sum_{1}^{K_c} \sum_{1}^{K_r} (\Sigma X)^2}{N} = \frac{(209.82)^2 + (219.78)^2 + (213.80)^2 + (217.24)^2}{3} = 185,231.34$$

SUMMARY OF COMPUTATIONS

Analysis of Variance - Lake Huron CO_2 Data, 1968.

SOURCES OF VARIATION	AMOUNT OF VARIATION	DEGREES OF FREEDOM	ESTIMATED VARIANCE
Between column means	16.68	3	6.23
Between row means	24.31	2	12.15
Residual	45.17	6	7.53
Total	88.16	11	

ANALYSIS OF VARIANCE CALCULATIONS

A two-way analysis of variance involves four sources of variation:

I. Total variation.

$$\Sigma X^2 - \frac{(\Sigma X)^2}{N} = 61813.26 - \frac{740701.21}{12} = 88.16$$

II. Variation between column means.

$$\frac{\overset{K_c}{\underset{1}{\Sigma}} \overset{N_c}{\underset{1}{\Sigma}} (\Sigma X)^2}{N_c} - \frac{(\Sigma X)^2}{N} = \frac{185231.34}{3} - \frac{740701.21}{12} = 18.68$$

III. Variation between row means.

$$\frac{\overset{K_r}{\underset{1}{\Sigma}} \overset{N_r}{\underset{1}{\Sigma}} (\Sigma X)^2}{N_r} - \frac{(\Sigma X)^2}{N} = \frac{246997.66}{4} - \frac{740701.21}{12} = 24.31$$

IV. Residual variation =

(total variation) - (variation between column means + variation between row means).

$$88.16 - (18.68 + 24.31) = 45.17$$

COMPARISON OF ESTIMATED VARIANCE WITH ESTIMATED RESIDUAL VARIANCE.

F test

I. Column means.

$$F = \frac{6.22}{7.53} = 0.827 \qquad n_1 = 3, \quad n_2 = 6.$$

Not significant at the 90% confidence level.

II. Row means.

$$F = \frac{12.16}{7.53} = 1.61 \qquad n_1 = 2, \quad n_2 = 6.$$

Not significant at the 90% confidence level.

The above statements indicate that if there is no actual difference in the CO_2 content of samples collected in Lake Huron during the 1968 season, the chances of randomly obtaining a sample that would be significantly different from all other samples collected, would be less than 10%.

Thus, the 1968 CO_2 data on Lake Huron show no significant seasonal or locational variation.

In view of this, the mean value (mg/l) of the available CO_2 in the samples collected was used as the basis for all C^{14} calculations.

$$\text{Mean} = \frac{\Sigma X}{N} = \frac{860.64}{12} = 71.72 \text{ mg/l.}$$

1967 LAKE SUPERIOR SUPPLEMENTARY CHEMICAL DATA

Area Number	Sample Number	Date	pH	Bicarbonate Alkalinity (mg/l)	Total Solids (mg/l)	Water Temp. °C	Free CO_2 (mg/l)	Available CO_2 (mg/l)
1	1	7/4	7.56	42.62	65.4	11.5	2.70	58.52
1	15	7/5	7.50	40.78	53.7	6.5	5.50	51.89
1	114	7/4	7.70	40.19	54.8	6.9	2.79	57.22
1	1	7/5	7.99	42.74	50.4	5.2	1.09	59.18
2	51	7/5	7.95	42.74	45.5	4.5	5.89	53.49
2	241	7/6	7.80	42.74	45.5	1.5	12.00	39.61
2	1	7/6	7.75	40.80	42.7	8.5	1.78	57.68
3	111	10/10	7.52	42.08	41.2	7.0	2.19	59.15
3	7	10/11	7.38	43.26	56.8	7.8	3.95	40.88
3	111	10/11	7.51	41.08	58.2	7.0	3.40	40.36
4	1	10/12	7.60	42.08	58.4	7.0	2.90	39.56

1967 LAKE MICHIGAN SUPPLEMENTARY CHEMICAL DATA

Area Number	Sample Number	Date	pH	Bicarbonate Alkalinity (mg/l)	Total Solids (mg/l)	Water Temp. °C	Free CO_2 (mg/l)	Available CO_2 (mg/l)
1	1	7/4	8.25	84.58	116.5	16.0	1.25	143.25
1	31	7/3	8.30	102.76	170.2	19.0	1.38	99.18
1	111	7/3	8.12	100.77	165.9	16.0	1.89	98.57
2	1	7/17	8.18	100.15	156.7	13.4	1.90	97.90
2	111	7/18	8.28	98.57	159.6	16.9	1.19	97.13
2	1	10/6	8.20	102.32	156.4	18.3	1.30	95.92
3	1	10/6	8.45	106.70	142.2	12.0	.98	108.70
3	111	10/8	8.50	102.30	134.6	14.0	.88	94.78
4	1	10/25	8.20	110.10	147.6	12.0	1.28	95.71
4	11	10/25	8.05	109.00	149.5	11.5	1.68	98.57
4	111	10/26	8.05	96.58	136.8	8.0	2.42	98.34
5	1	10/26	8.05	96.58	136.8	8.1	2.19	87.11

1968 LAKE SUPERIOR SUPPLEMENTARY CHEMICAL DATA

Trip Number	Sample Number	Date	pH	Bicarbonate alkalinity (mg/l)	Total solids (mg/l)	Water Temp. °C	Free CO_2 (mg/l)	Available CO_2 (mg/l)
1*								
2	I	6/22	7.4	40.14	50.3	4.0	4.50	39.82
2	II	6/22	7.4	41.26	46.3	10.0	4.70	41.81
2	III	6/25	7.6	40.14	54.6	5.0	2.60	37.92
3	I	7/8	7.7	41.25	52.0	13.0	2.20	38.50
3	II	7/12	7.6	40.14	53.6	4.5	2.40	37.72
3	III	7/12	7.7	42.37	46.8	5.0	2.40	39.69
4	I	7/24	7.8	42.37	54.4	6.0	1.90	39.19
4	II	7/24	7.5	42.37	51.4	6.5	3.60	40.80
4	III	7/29	7.7	42.37	55.6	13.0	2.30	39.59
5	I	8/21	7.4	43.49	49.4	13.0	4.00	42.27
5	II	8/21	7.5	43.49	61.6	8.0	3.40	41.67
5	III	8/21	7.4	42.37	53.3	10.0	4.30	41.59

*data missing

1968 LAKE HURON SUPPLEMENTARY CHEMICAL DATA

Trip Number	Sample Number	Date	pH	Bicarbonate alkalinity (mg/l)	Total solids (mg/l)	Water Temp. °C	Free CO_2 (mg/l)	Available CO_2 (mg/l)
1*								
2	I	6/23	7.7	75.82	97.2	8.0	5.80	70.52
2	II	6/23	7.9	75.82	102.7	10.0	2.30	69.82
2	III	6/25	8.1	78.05	101.6	10.0	1.60	70.35
3	I	7/9	7.8	73.59	110.1	15.0	2.30	67.26
3	II	7/9	7.6	82.51	100.5	14.0	4.60	77.31
3	III	7/11	7.8	82.51	109.9	18.0	2.70	15.51
4	I	7/25	7.8	78.05	112.4	18.0	2.60	71.28
4	II	7/25	7.6	78.05	109.6	20.0	3.80	72.48
4	III	7/28	7.6	74.71	106.6	15.0	4.30	70.04
5	I	8/22	7.7	75.82	114.8	18.0	3.20	69.92
5	II	8/22	7.6	79.12	106.8	20.0	3.80	73.47
5	III	8/23	7.7	80.28	104.4	22.5	3.20	73.85

*data missing