AN ABSTRACT OF THE THESIS OF

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The Role of Light and Nutrients in the

Phytoplankton Productivity of Lake Wooster

Abstract approved: David C Schroeder

Preliminary work had indicated that lakes in this geographic region do not fit productivity models developed for lakes in other areas of the United States. This study was undertaken to investigate the factors controlling phytoplankton productivity in a shallow, turbid lake. Lake Wooster on the campus of Emporia State University, Emporia, Kansas was selected as the study site.

Fourteen added nutrient trials were made between October 2, 1987 and November 30, 1989. Composite lake water samples with added concentrations of phosphate ion or nitrate ion were incubated in the lake along with untreated samples. Ammonium ion and a series of trace elements were also tested. Relative light intensity measurements were made between September 21 and November 30, 1989.

The phytoplankton productivity of Lake Wooster was extremely variable, however the results were found to be in the range for lakes classified as eutrophic. The lake's productivity was confined to a narrow range, generally from 0.5 m to 1.0 m. The region below 1.0 m was often phosphate limited despite the overall high concentration of total phosphorus found in the lake. Phosphate concentrations and relative light intensity patterns were followed during an algae bloom in the fall of 1989.

The chemical, physical and biological interactions in Lake Wooster were found to be complex. During the bloom the productivity reached levels which would place the lake in the hypereutrophic category. Given the very long exchange time for the lake, as nutrients continue to enter, Lake Wooster is likely to reach a state where it will be unquestionably hypereutrophic.

THE ROLE OF LIGHT AND NUTRIENTS IN THE PHYTOPLANKTON PRODUCTIVITY OF LAKE WOOSTER

A Thesis

Presented to

the Division of Physical Science

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Master of Science

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by

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INTRODUCTION

Freshwater lakes

Fresh water in the liquid phase comprises only two percent by volume of the water in the earth's hydrosphere [1]. Lakes, bodies of standing water occupying a basin [2], contain about 0.02 % by volume of all inland water and less than one percent of this is fresh water [1]. Although fresh inland water is a very small share of the earth's total water, lakes are of great importance to inland regions. These regions depend on the lakes for human personal use, agricultural endeavors, electrical energy production, and recreation. This dependence makes the condition of the lake a matter of importance.

A lake should be viewed as an interacting community composed of physical, chemical, and biological factors. The water contains dissolved and suspended materials which may serve as nutrients for plants. The plants associated with a lake range from relatively large species growing rooted in the bottom sediments in shallow areas to microscopic forms called algae. Some types of algae grow attached to materials on the lake bottom in sunlit shallows [3]. Other varieties of algae, called phytoplankton, drift freely in the water. Phytoplankton are among the major producers in the food-energy web of a lake. In this paper, it is the photosynthetic conversion of inorganic carbon to organic materials by the phytoplankton which will be meant when referring to the productivity of a lake.

Trophic states of lakes

Trophic states divide lakes into categories based on the nutrient concentrations in the water. Eutrophic lakes are rich in these nutrients and have large phytoplankton populations. Such lakes are subject to phytoplankton population surges commonly called "algae blooms". Oligotrophic lakes are seldom subject to blooms, sudden rapid population increases. Oligotrophic lakes have relatively low concentrations of nutrients needed for algal growth and generally low phytoplankton populations. A third trophic state, mesotrophic, fall between these two in nutrient concentration and phytoplankton populations [2].

The trophic state of a lake may be determined using a combination of criteria based on nutrient concentrations and phytoplankton populations. Rawson used the diversity of species within three families of algae and their distribution throughout a lake as indicators of a lake's trophic state [4]. He found that oligotrophic lakes were characterized by relatively low phytoplankton populations but contained many species distributed to great depth. Species in the class *Chlorophyceae*, green algae, and the class *Diatomaceae*, diatoms, predominated. In contrast, eutrophic lakes had relatively large populations of phytoplankton with only a few species. The predominant groups were *Diatomaceae*,and *Cyanophyceae*, blue-green algae. Among the genera of blue-green algae *Anabaena* and *Microcyctis* were common.

The trophic states of fifteen lakes or reservoirs in Kansas have been determined using Nygaard's Trophic State Indices [5]. This

indexing system uses a ratioing of algal groups which can tolerate nutrient rich waters against those groups which cannot. Four sets of taxonomic groups are compared giving four indices for the lake. A fifth index is obtained by combining the four indices. The trophic state of the lake is indicated from each of the five indices based on whether the index falls into the range established for oligotrophic or for eutrophic lakes. Five indices for each of the fifteen lakes were reported for three different dates, a total of fifteen indices for each. All reported values were in the eutrophic category for five of the lakes. Although the other ten lakes had one or more values judged as inconclusive or clearly oligotrophic, the majority of values in all cased classify the lakes as eutrophic.

If the entry of nutrients into a lake is slow enough, with runoff water or feeder streams bringing low concentrations of soluble materials into the lake, the buildup of nutrients is gradual. Overflow or released water from a lake carries some nutrients as it moves down stream. Except in times of severe drought, this results in a steady state balance between nutrient/water income and outgo.

Photosynthesis and productivity

Photosynthesis carried on by producers and respiration by the consumers also establishes a cyclic balance of nutrient consumption and release within a lake. If photosynthesis is viewed as production of organic material and respiration as the destruction of organic material then the stoichiometry of the process may be shown as

$$106CO_2 + 16NO_3^- + HPO_3^{2-} + 122H_2O + 18H^+ + \text{trace elements} + \text{energy}$$

$$\updownarrow$$

$$C_{106}H_{263}O_{110}N_{16}P + 138O_2 \qquad \text{reaction 1}$$

(algal protoplasm) [6].

It should be noted that while carbon dioxide, nitrate and hydrogen phosphate are the major nutrients, trace amounts of other elements are required for algal growth. A surplus of oxygen is generated and released to dissolve in the water.

Rather than the gradual influx of nutrients and steady state balance described above, lakes in many areas today are subject to high concentrations of nutrients in entering waters, especially nitrate and ammonia in runoff and phosphate originating as effluent into rivers or streams that feed the lake. The resulting heavy loading of nutrients increases algal growth resulting in blooms. This accelerated growth diminishes the nutrient concentrations to levels which can no longer sustain the high population of algae. As the bloom dies off, bacteria begin to decompose the dead algae in addition to other biodegradable organic matter present. Decomposition is a series of chemical reactions which in summary are the reverse of reaction 1, above. From that reaction one can see that oxygen is required for decomposition of organic matter. Given the right set of conditions the demand may be so high that it depletes the dissolved oxygen supply in the water.

Fresh water algae's requirements for growth involve complex relationships within the variety of nutrients needed. While certain optimum ratios, especially between nitrogen and phosphorus are

necessary, algal growth is controlled by the single nutrient in shortest supply relative to the algae's requirements [7]. In most fresh water systems either nitrogen or phosphorus is the limiting factor and phosphorus usually has the greater influence on productivity [6].

In addition to nutrients, algae require light to photosynthesize. Chlorophyll *a* is the major photoreceptor in green plants, including algae. It shows two absorption peaks, the more intense one in the blue region of the visible spectrum at 405 nm, the other in the red region at 640 nm [4]. Light intensity must also be considered. Above a threshold minimum, as intensity increases the rate of photosynthesis increases until a maximum limiting rate is reached. This rate is determined by the maximum rate at which some of the chemical reactions using the captured light energy can proceed [8].

In aquatic environments the amount of light available is determined not only by the quantity of sunlight transmitted to the water surface but by its angle of incidence and by the transparency of the water column. When the angle of incidence is far from vertical the percent of light penetrating the surface is small. Thus, for lakes in the temperate zone the amount of light penetrating the water surface varies seasonally as well as daily.

As light passes through the lake's water column its intensity decreases. In pure water the intensity of monochromatic light is given by

$$I_z = I_o e^{-nz} \qquad \text{Eq. 1.}$$

where I_z is the intensity at depth z, I_o the initial intensity, e the base of natural logarithms, and n the extinction coefficient for the medium. For natural waters additional factors must be included to account for suspended and dissolved substances. In deep, relatively clear lakes the intensity of light at one meter is only about 30% of that penetrating the surface [2].

The spectrum of light also changes as it goes through the column. The blue wavelengths are transmitted through natural waters more rapidly than are other wavelengths. Waters containing highly colored minerals or organic materials transmit red wavelengths deeper than do other waters.

At times light intensity may be sufficient to cause photooxidation of enzymes involved in some of the photosynthesis reaction. The loss of functional enzymes inactivates the chlorophyll and the rate of photosynthesis slows. This phenomenon is called photoinhibition [9].

Studies using radiocarbon methods to measure productivity of algae found that photoinhibition generally occurs near the surface. The inhibition was found to increase with time of exposure, at higher concentrations of oxygen, at higher temperatures, and when cells were nutrient deficient. In the same study, comparison of methods showed that photoinhibition was greater when productivity was measured in terms of oxygen release than when radiocarbon methods were used [10].

From the above discussion it can be seen that either of the primary nutrients, nitrogen and phosphorus, may be the factor

limiting algal productivity or that light may be a limiting factor either due to low intensity or to photoinhibition at high intensity.

Productivity is the rate at which inorganic carbon is converted into organic form [11]. As reaction 1 shows, this conversion is acccompanied by the release of oxygen to the surrounding water. Measuring the quantity of oxygen released is a convenient method for

limiting algal productivity or that light may be a limiting factor either due to low intensity or to photoinhibition at high intensity.

Productivity is the rate at which inorganic carbon is converted into organic form [11]. As reaction 1 shows, this conversion is acccompanied by the release of oxygen to the surrounding water. Measuring the quantity of oxygen released is a convenient method for determining productivity. The method involves determining the dissolved oxygen (DO) concentration at the beginning and end of an incubation period. DO concentrations are expressed in mg O_2/ L of water which corresponds to parts per million (ppm). The productivity calculation is based on the following summary reaction for photosynthesis:

$$6CO_2 + 6H_2O \rightarrow (C_6H_{12}O_6) + 6O_2 \qquad \text{Reaction 2}$$

in which one atom of carbon is fixed for each molecule of oxygen released [3]. The stoichiometry of this reaction differs from that shown in reaction 1. Although reaction 1 is a more complete expression of photosynthesis, the productivity calculations for this study were based on equations which use the stoichiometry of reaction 2. These equations were used so that the results of this study could be compared to the productivity values found in the literature.

The sequence of equations which follows lead to productivity based on measurements of oxygen released during incubation. Net photosynthesis is calculated by

$$\text{net photosynthesis} = DO_l - DO_i \qquad \text{Eq. 3}$$

where DO_l is the DO concentration concentration for a bottle incubated in the light and DO_i is the initial DO. Respiration, which

occurs concurrently with photosynthesis, is determined by

$$\text{respiration} = DO_i - DO_d \qquad \text{Eq. 4}$$

with DO_d being the DO concentration of a bottle incubated in the dark. Gross photosynthesis for the period is therefore,

$$\text{gross photosynthesis} = \text{net photosynthesis} + \text{respiration}. \qquad \text{Eq. 5}$$

Productivity in terms of milligrams of carbon fixed per cubic meter of water is given by

$$\text{productivity} = \text{gross photosynthesis} \times 1000\ m^3/L \times 12\ g\ C/\ 32\ g\ O_2 \qquad \text{Eq. 6}$$

Eutrophic lakes, those rich in nutrients needed for algal productivity, have been the subject of numerous studies. Some of these have been directed toward developing models of lake population behavior when subject to nutrient loading of various types and degrees. The most successful models have been based on a relationship between chlorophyll and a nutrient concentration, usually phosphate [12, 13].

Problem statement

Some preliminary work indicates that lakes in this geographic area do not fit the patterns found for lakes in other parts of the United States. Lakes in Kansas are generally not as deep and are more turbid than those described on other areas. Lakes in this area do not correspond well to the phosphate-chlorophyll models in that the productivity measured by chlorophyll content is not as high as the models predict for the phosphate concentration found in these lakes [14].

This study was intended to investigate the factors controlling algal productivity in a shallow, turbid lake. Lake Wooster on the campus of Emporia State University was selected as the study site. Lake Wooster was an appropriate choice since it is typical of small shallow lakes in this area with respect to nutrient content and productivity [14].

EXPERIMENTAL

Experimental design

Algal productivity is proportional to photosynthetic activity of the algae and may be calculated from oxygen produced by the algae over a period of time [11]. Composite lake water samples in dissolved oxygen bottles were incubated in the lake at various levels. Composite samples were made by mixing equal volumes of lake water from the surface, one half meter and one meter. Samples were collected using a Van Dorn sampler. Samples of the composite water were fixed for dissolved oxygen analysis at the time the apparatus was set out. These samples served as the initial or reference oxygen level. Air temperature, water temperature, barometric pressure, and a description of the lake conditions were recorded for each trial.

To investigate the oxygen production over several hours relative to nutrient levels, some samples were treated with additional phosphate or additional nitrate before incubation. During the fall of 1987, trials were carried out weekly from September 18 through October 23, and one trial was made on November 20. In the spring of 1988 the tests were repeated on February 24 and March 9, 23, and 30. On September 21, 28, October 12, 19 and November 30, 1989 trials were made. On these dates light intensity was measured and samples were analyzed for total phosphate content.

One hundred parts per million (100 mg as N or as P per liter of solution) stock solutions of KNO_3 and KH_2PO_4 were prepared. For each trial, 500 µL of stock solution was added to a 300 mL BOD bottle.

Upon filling the bottles, the added concentrations were then 0.1667 ppm as nitrogen and as phosphorus.

On April 6 and 13, 1988 the nutrients added were changed to nitrate and ammonia. The nitrate additions was the same as for other trials. The ammonium ion was added as NH_4Cl using 500 µL of 100 mg N/L. The final added concentration was 0.1667 ppm as nitrogen.

On March 30, 1988, an oxygen profile made of Lake Wooster. Samples were taken at half meter intervals beginning at the surface down to 2.5 m, just off the bottom. Two BOD bottles were filled, fixed and titrated for each depth. In addition to providing dissolved oxygen information, this data was used to calculate a pooled standard deviation for titrations [15].

One experiment was done using trace minerals on April 20, 1988. The final concentrations in the samples were 2.9 mg magnesium/L, 32.5 µg boron/L, 115.0 µg manganese/L, 1.57 µg zinc/L, 0.354 µg cobalt/L, 2.88 µg molybdenum/L, and 33 µg iron (III)/L. Manganese, zinc, cobalt and iron each had 300 µg/L of EDTA added to maintain them in solution. A sample containing 300 µg/L of EDTA was used in addition to the controls.

Apparatus

To allow samples to be maintained at lake temperature and light conditions, a frame-work supporting 300 mL glass BOD bottles at different depths was used. Figure 1 shows a diagram of the apparatus used. The frame-work was suspended from the south at the center of the middle arch of the bridge. The center of the bottles on the top

bar of the frame were about 0.2 m below the water surface. The second row of bottles were at a depth of 0.53 m, the third row at 0.86 m, and the bottom row at 1.2 m.

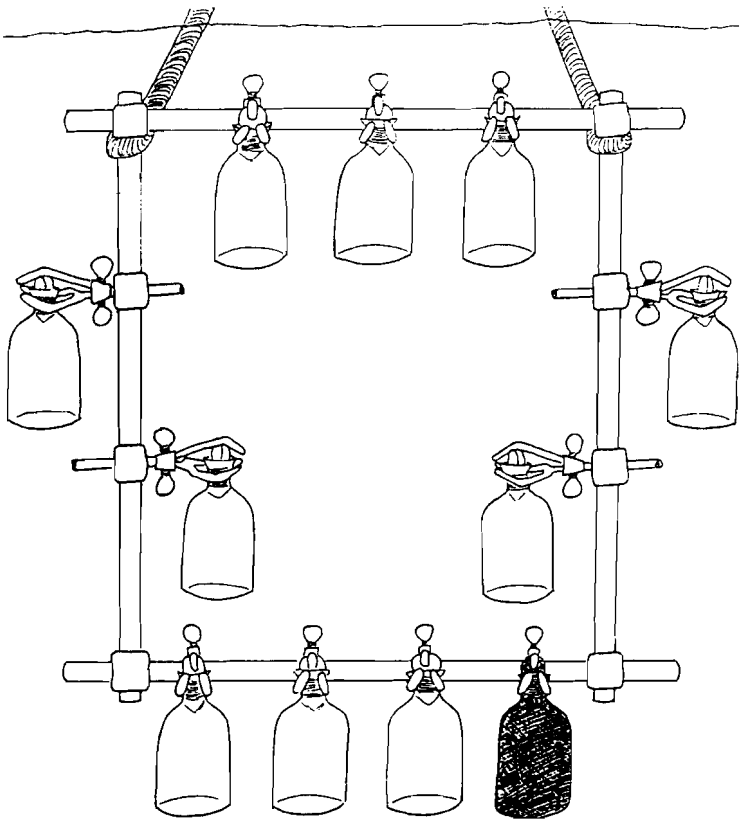


Figure 1. Apparatus used in nutrient studies

For trials during 1987 and 1988 the top row consisted of one control bottle, one with additional phosphate and one with additional nitrate. During the fall of 1987 and spring of 1988 the second and third rows consisted of two control bottles at each level. In the fall of 1989 the arrangement was changed to include two control bottles at the top and bottom levels. One trial was done with four bottles at a middle level, about 0.7 m below the surface. This row

consisted of two control bottles, one with additional phosphate and one with additional nitrate. The lowest row consisted of the same arrangement as the top row with the addition of a dark bottle. The dark bottle was a BOD bottle covered with black tape to exclude all light. This sample served as a measure of respiratory activity.

In the trials involving ammonia as an added nutrient, the bottles containing additional ammonia were placed the the positions used for additional phosphate samples in other trials. For the experiment with trace elements, the frame-work was suspended horizontally so all bottles were about 0.2 m below the water surface. A composite sample of lake water was used to fill the bottles and the apparatus was suspended in the lake for four hours.

Analytical methods

DO as measure of productivity

Molecular oxygen is produced by algae during the "light phase" as a by-product of photosynthesis. Reliable techniques have been developed for measuring dissolved oxygen in water [11]. For these reasons dissolved oxygen was used as a measure of photosynthetic activity in this investigation. The dissolved oxygen measurements were made using iodometric titration method known as the Winkler method, also called the azide modification [11].

In this method dissolved oxygen reacts with iodide oxidizing it to iodine which is then titrated with thoisulfate. Four moles of thiosulfate is equivalent to one mole DO. If 0.025 M thiosulfate is used 1 mL of thiosulfate is equivalent to 0.2 mg DO. The thiosulfate

solution was standardized against 25.00 mL of 0.0250 M $K_2Cr_2O_7$ and 2 KI under acidic conditions. Calculation of DO in mg/L is then given by

$$DO = 0.0270 \times V_{sample} \times V_{standard} \quad \text{Eq. 7}$$

with V_{sample} and $V_{standard}$ the volumes of thiosulfate required to titrate the sample and the standard, respectively.

Saturation level for oxygen in the water is calculated as

$$\text{saturation DO} = 0.678\ (P - Pw)/(35 + T) \quad \text{Eq. 8}$$

where P is atmospheric pressure in Torr, Pw is the vapor pressure of water at temperature T. Thus, percent saturation for a sample is

$$\% \text{ saturation} = \text{observed DO } (100\%) \ / \ \text{saturation DO} \quad \text{Eq. 9.}$$

Total phosphate analysis

Composite samples from the fall of 1989 were analyzed for total phosphate content using the ascorbic acid colorimetric method [11]. A HACH DR/3000 Spectrophotometer with matched one inch glass cells was used for the analysis. Preliminary digestion was carried out by persulfate digestion using the protocol given in Standard Methods [11]. The only modification was the addition of glass beads to the flasks during digestion to facilitate smoother boiling.

Phosphate ions react with molybdate in acid producing phosphomolybdic acid which is pale yellow. Further reaction with ascorbic acid as the reducing agent produces a blue color known as molybdenum blue [11, 16]. This species absorbs well at 882 nm obeying Beer's Law at concentrations normally expected in natural waters. Using uniform cell size for all readings one obtains the phosphate

concentration in the samples from

$$C_x = C_s (A_x - A_b) / (A_s - A_b) \qquad \text{Eq. 10}$$

where C_x and C_s are concentration in mg as P/L for the sample and standard, respectively, and A_x, A_b, and A_s are absorbance readings for the sample, blank, and standard, respectively.

Light intensity

Light intensity measurements were made with a G. M. Manufacturing and Instrument Corporation submarine photometer, Model 268WA 310. Only the sea cell was used to make measurements. The spectral sensitivity is adjusted to approximate that of the human eye [17]. Intensity readings were made just under the water surface, at 0.2, 0.4, 0.6, 0.8, 1.0, and 1.5 m. The light intensity readings were made from Septemeber 21 through November 30. 1989 on the each of the days that added nutrient studies were done. On September 21 and September 28 the readings were taken at 2:00 pm, at the time the samples were removed from the lake. Measurements on October 12, October 19, and November 30 were made at about 12:00 pm, midway through the incuabation period.

Calculations using a spreadsheet

Calculations were made using a personal computer and spreadsheet software. The tables included in this thesis were generated and printed from the spreadsheet. Graphs used in this thesis were also generated using the spreadsheet capabilities. Because of the limitations of the software, more significant figures are displayed for some calculated values than are justified by the experimental

measurements. For the productivity values, in any units, only three significant figures should be considered valid.

A further limitation of the spreadsheet software is the unavailability of customary symbols used in units, particularly letters of the Greek alphabet. As necessary, the substitutions used are noted at the bottom of the tables. Subscripting and superscripting capabilities are not available. The absence of these is not considered a problem in understanding the column or row titles in the tables or the axes labels on the graphs.

RESULTS AND DISCUSSION

Pooled standard deviation and significant differences

Data for the oxygen profile study on March 30, 1988 were used to calculate a pooled standard deviation for this study. Data and calculated pooled standard deviation values are shown in Table I. Results of pooled standard deviation calculations showed σ = ±0.07 mg O_2/L. Based on this value any sample with DO more than ±2σ (0.14 mg O_2/L) from the appropriate control was considered significantly different. That is, beyond ±2σ from the control the experimental condition is considered responsible for the variation in DO or in productivity. In the course of reporting and discussing results the terms "higher than" and "lower than" are used to mean that the treated sample showed a DO concentration with was significantly higher or lower, respectively, than the appropriate untreated sample, usually referred to as the control. It should be noted that if DO concentration differs significantly then values calculated from this, such as productivity, will also differ significantly for the same values for the control.

Determination of appropriate incubation time

Recommended incubation time for productivity determination by DO production is one half the photoperiod with a minimum time of two hours necessary to give reliable results [11]. The first trial, on September 18, 1987 was incubated for five and one half hours. Bubbles of gas had formed in the upper row of bottles. These bottles also were supersaturated with DO as high as 170% of saturation. A second

trial on September 25, 1987 was incubated for four and one half hours. Again bottles in the upper row showed gas bubbles collecting around the stopper and showed high levels of supersaturation. The DO measurements from these trials were considered invalid because of the gas bubbles and the extreme supersaturation. The next trial has the incubation time reduced to four hours. No gas bubbles formed and the measurements were considered valid. An incubation time of four hours was used for all further trials.

Dissolved oxygen profile

The dissolved oxygen profile for Lake Wooster on March 30, 1988 is shown in Figure 2. Table II contains the data and calculations for this profile. The DO average of the two samples at each depth were plotted against the depth from which the sample was taken. A line showing the saturated DO for each depth is also included on the graph. Percent saturation ranged from about 94% to 97%. The water temperature ranged from 11.5 C at the surface to 11.0 C at 1.5 m. At 2.0 m the water temperature was 11.3 C and at 2.5 m, just off the bottom for this part of the lake, it was 11.2 C. DO concentrations ranged from 9.88 to 10.30 mg O_2/L, less than 0.5 mg/L difference.

Data and calculations for oxygen profile measurements on February 17. 1988 are shown in Table III. The data was graphed as described for the March 30 data, see Figure 3. These samples had temperatures ranging from 2.2 °C at the surface to 3.4 °C at 2.5 m. The surface and 0.5 m samples were 96% saturated while the deeper ones were 100% or more saturated. Profile samples taken during the

fall of 1987 showed DO slightly greater than 100% saturation at all depths with surface samples being higher than deeper ones. Temperatures were warmer at the surface but varies by only 1 °C over the entire depth [18].

The March 30 oxygen profile showed samples from greater depths more saturated than those from the surface and from 0.5 m. The DO concentrations for these same samples are higher between 1.0 and 2.0 m than at the surface. A similar trend was seen in the February 17 profile. This may be related to temperature requirements of the algae. Since the deeper waters are slightly warmer the algae may be more productive in the deeper waters. Wind action at the surface tends to aid diffusion, thus, when the surface water is at or near saturation with respect to DO, oxygen would move from the water to the atmosphere. This, along with greater algae activity in the slightly warmer deep waters, would account for shallow waters being less saturated than deeper waters where the concentration of DO is allowed to build up.

The DO concentrations indicate that the lake is well mixed vertically as would be expected in a small shallow body of water. DO measurements made between October and December 1987 suggest that this lake shows the same uniformity of temperature and mixing in the fall [18]. Two fountains, one located near each end of the lake, draw water from the lake and spray it into the air. The action of the fountains increase diffusion of DO from surface water into the air when the water is at or near saturation, but their action is probably effective only in the immediate area of the fountain. Wind action on

the lake probably accounts for most of the mechanical mixing which occurs.

Lake Wooster shows a narrow range of temperatures through the water column and there is clearly no thermal gradient within the water column. Water temperatures of samples taken at 0.5 m intervals on February 17, 1988 ranged from 2.2 C at the surface to 3.4 C at 2.5 m. This is as would be expected in winter because water density is temperature dependent, being most dense at about 4 C. The temperature range is greater than during other seasons and is inverted with respect to depth, that is lower temperatures in the deeper waters [18].

The absence of a thermal gradient allows oxygen and other dissolved materials to diffuse freely throughout the water column. One would expect nutrient distribution to be fairly uniform except during short periods of unusual conditions, such as during an algae bloom.

Productivity as measured by DO

In order to compare the productivity of Lake Wooster the values found in the literature, productivity calculated by equation 6 were converted to units of mg C/m^2. This was done by allowing the bottles incubated at 0.2 m to represent the layer of water extending from the surface to 0.365 m. Bottles incubated at 0.53 m represented the layer from 0.356 m to 0.685 m, a layer thickness of 0.330 m. Two additional deeper layers of 0.330 m thickness were represented by the bottles at 0.68 m and 1.2 m. When the productivity in mg C/m^3 was divided by the representative layer thickness, productivity in mg C/m^2 resulted.

Appropriate modification of the layer thicknesses were made for the November 30, 1989 data since the depths of incubation were different from other trials.

Values for productivity by layers on each date are shown in Table IV. The table also included total productivity for the incubation period, obtained by summing the layers, and productivity for the day. Productivity for the day is taken to mean a total for the photoperiod and has been estimated by multiplying the total productivity of the layers over a four hour period by three to give a value for twelve hours.

Wetzel has tabulated mean daily productivities in units of mg C/m^2/day, averaged over an entire year, for numerous lakes [3]. The lakes are grouped by trophic states. Mean daily productivity for eutrophic lakes range from about 850 to 1750 mg C/m^2/day. Two lakes described as shallow and enriched had productivities of about 1000 mg C/m^2/day. The values observed for single day totals among eutrophic lakes ranged as high as 5000 mg C/m^2/day.

Single day totals for Lake Wooster range from a low of -530 mg C/m^2/day for March 23, 1988 to a high of 4500 mg C/m^2/day on September 28, 1989. Notes made concerning lake and weather conditions at the time measurements were made, indicate that on March 23, 1988 there was heavy cloud cover. Apparently the intensity or quality of light available did not allow for efficient photosynthesis by the algae. A range of 1000-2000 mg C/m^2/day would be representative of most of the single day totals.

Most of the single day totals estimated for Lake Wooster are in the highest ranges of Wetzel's reported values for eutrophic lakes. The productivity measurements for Lake Wooster were made during spring and fall when conditions would be expected to favor productivity and so they can be expected to be higher than a mean daily productivity which included year round measurements. Based on the values tabulated by Wetzel, Lake Wooster would be expected to have an mean daily productivity on the order of 1600 mg C/m^2/day.

Lake Wooster should be classified as eutrophic with periods when its productivity might be described as hypereutrophic. During the period from September 28 to November 30, 1989 single day productivity totals were above 3000 mg C/m^2/day for all sampling dates. This is consistent with other measurements for these dates during the occurrence of an algae bloom. For the trial on November 30, 1989 samples with added nitrate and added phosphate were incubated at three levels. Calculations from this data suggest that even a small increase in either nitrate or phosphate could increase productivity by about 50%.

DO, Productivity, and added nutrients

The data and calculated values including DO, percent saturation, net photosynthesis, gross photosynthesis, and productivity are tabulated and appear at the end of the text in chronological order in Table V through Table XV. Graphs of productivity for each incubation depth and sample treatment are shown in Figure 4 through Figure 16, again in chronological order. The same scale for productivity has been used for all graphs to facilitate comparisons.

Phosphate

Twelve trials were made between October 2, 1987 and November 30, 1990 in which samples incubated at 0.2 m and 1.2 m contained added phosphate. In seven of these trials the treated sample incubated at 1.2 m showed DO significantly higher than the control incubated at the same level. In five of these seven trials, samples at 0.2 m were not significantly different from their controls. Of these five two occurred in the fall of 1987 and two on corresponding dates during the fall of 1989. The added phosphate sample incubated at 0.2 m had DO concentration higher than the control in four trials. The 0.2 m samples were lower than controls three time and the 1.2 m samples were lower four times. Included in these results are two trials where the phosphate treated samples at both levels were higher, one where both were lower, one in which the 0.2 m sample was lower while the 1.2 m sample was higher, and two in which the reverse occurred. In one trial neither sample showed significant difference from its control.

These findings indicate that Lake Wooster is phosphate limited at times. The lake seems to be phosphate limited more often at greater depths than near the surface.

Nitrate

A total of fourteen trials between October 2, 1987 and November 30, 1990 included samples with added nitrate incubated at 0.2 m and 1.2 m. Samples incubated at 0.2 m were higher than controls in five trials and lower in five trials. At 1.2 m the results were higher in four trials and lower in four trials. Included are two trial when the

nitrate treated samples were lower than controls at both levels and once when they were both higher. In one trial neither level showed significant difference from controls. No seasonal trend appears in these trials.

There is no clear trend for Lake Wooster regarding nitrate limitation when only nitrate is considered. Adding nitrate may increase the concentration to a level which inhibits productivity.

Ammonium

During two trials, on April 6 and April 13, 1988, ammonium rather than phosphate was added to samples. Only one sample showed a significant difference from the control, at the 1.2 m level for on April 6 the ammonium treated sample was higher than the corresponding control.

Although plants are generally able to utilize ammonium as their nitrogen source, it becomes toxic under alkaline conditions [3]. In highly eutrophic lakes the pH frequently becomes alkaline during daytime periods of high photosynthetic activity as carbon dioxide is taken up by the phytoplankton more rapidly than it is replaced by respiration [3]. Given this, one might expect that added ammonium would have resulted in significantly lower DO in the treated samples. Apparently the natural concentration of ammonium in the lake is low enough that the added amount was insufficient to become toxic.

Trace elements

Table XIX shows the data and results for the evaluation of trace elements and productivity. With the exception of the Zinc-EDTA and

iron (III)-EDTA treated samples, all samples were higher than the controls. Of the samples significantly higher than the control manganese, cobalt, and molybdenum had EDTA added along with the trace element. Since additional EDTA alone increased the DO concentration it is possible that the elements are present but not in an available form. Cobalt and molybdenum showed a greater increase than the EDTA by itself although only the cobalt sample was significantly higher than the EDTA sample. This suggests that cobalt may be limiting the algae. Manganese-EDTA showed less increase than EDTA. This may be due to some other ion displacing the manganese from the EDTA. Although this arrangement was tested only once, it suggests that the trace elements may be limiting algal productivity. Further investigation for the trace elements is needed to assess their roll in the productivity of Lake Wooster.

Relative Light Intensity

Table XX contains information about relative intensity on five different dates between September 21 and November 30, 1989. Equation 1 can be rearranged to give

$$\ln(Iz) - \ln(Io) = - n(z) \qquad \text{Eq. 11}$$

where ln is the natural logarithm and the other symbols have the same meanings as in equation 1. Equation 7 indicates that the relationship between the natural log of light intensity, or the natural log of some measurement proportional to light intensity, and depth should be linear. Photometer readings were made in μAmps which are proportional to light intensity. Based on equation 7, the following relationship

was used to determine if the measured relative intensities were linear in relationship to depth:

$$\ln(RIz/RIo) = - m(z) \qquad \text{Eq. 12.}$$

RIz represents relative intensity, the photometer measurement, at depth z, RIo the relative intensity measured just under the surface of the water, and m is the slope of the best fit line for the data.

The least squares regression analysis function of the spreadsheet was used to calculate the slope and intercept for a line of best fit for the data. Figures 18 through 22 show the graphs of ln(RIz/RIo) verses depth for the five sets of data with the experimental values shown as points and the line of best fit values shown as a line. Examination of the graphs shows that the plots are linear. Values of the square of correlation coefficient (R^2) range form 0.977 to 0.996 indicating a close fit for the data.

It has been estimated that algae are able to carry on photosynthesis down to depths where light intensities are as low as about 1% of that entering the surface [1]. On each date for which light intensity data was collected, the relative intensity at 1 m, about the depth at with the lower row of bottles was incubated, was in excess of 1% of the surface reading. The lowest value was 1.57% on October 19, 1989. Descriptions of the appearance of the lake made on the dates of each nutrient trial, indicate that an algal bloom began in late September peaking about four weeks later. Lake Wooster is fairly turbid at all times but an obvious trend of increasing turbidity follows the bloom as the algal populations increase. By November 30, 1989 the bloom had died off and the water cleared.

Figure 23 shows ln(Riz/Rio) versus depth for measurements on five dates from September 21 through November 30. Beginning with September 21 and continuing through October 19 the slopes decrease, become more negative, as the bloom develops. This trend reflects the increasing turbidity of the water during this time. Once the bloom subsides, between October 19 and November 30, the slope increases corresponding to clearing of the water to allow greater light penetration in the lake.

The relative light intensity information gathered here indicates that except during the intense bloom between September 21 and November 30, 1989, light sufficient for photosynthesis penetrated to a depth of 2 m and possibly to the bottom over much of the lake. Photosynthesis occurring at or near the bottom of the lake most of the time should insure DO availability throughout the water column. The deeper layers of the lake are not generally dependent on oxygen being carried down by mixing.

Total phosphorus analysis

The persulfate digestion procedure was performed several times using standard phosphate solutions. Difficulties were encountered achieving acceptable absorbance values after the digestion process. It was found that during the digestion process the samples' volumes must be reduced from the original 50 mL to about 10 mL. Otherwise unreacted oxidizing agent remains causing large false positive absorbance readings.

Smoothness of boiling improves the digestion process. In samples where the volume was reduced by maintaining temperature at boiling for over an hour but the solution boiled only occasionally, the results were not valid. Absorbance reading were still excessively high. The addition of glass beads seemed to correct this problem.

In order to assure the validity of phosphate analysis results, the corrected absorbance of the standard divided by its concentration should be within the range 1.35 to 1.45. Even after the major problems with the digestion process were corrected, the quality of the total phosphate analysis are not as reliable as desired. The total phosphate analysis data and quality control values are shown in Table XXI.

The findings for the October 19 sample cannot be considered valid in comparison to the other four samples. The other four values are higher than literature values for eutrophic and hypereutrpohic lakes [3]. Their validity for comparison to the literature values is uncertain, but they can be used as a measure of the relative behavior of phosphate concentration for the time of interest.

It should be noted that for the September 21, 1989 sample the total phosphate was 0.48 ppm. Even though the measurement is of total phosphate, about 90% of which is in the form of organic phosphate [3], this high level of phosphate appears to have initiated the bloom discussed above.

Combined effects of nutrients and light

Photoinhibition

In several of the trials the controls incubated at deeper levels showed DO concentrations higher than the controls incubated at 0.2 m. In seven of the fourteen trial the 0.53 m controls were higher. During three of those seven trials, 0.86 m controls were higher than surface controls, and in two cases the 1.2 m controls were higher than the surface controls. Photoinhibition was occurring in the surface layers at these times. In this study productivity was being measured in a closed container which resulted in a build up of DO in the sample bottles. Since photoinhibition increases with increased DO concentrations [10] the extent of photoinhibition is probably greater in the samples than it would be in the open waters of the lake.

Photoinhibition also increases when the algae are in nutrient deficient conditions [10]. In the samples from March 23, 1987, the samples with added nitrate and added phosphate incubated at the 0.2 and 1.2 levels showed significantly higher DO than their respective controls. The 0.2 m control showed photoinhibition on that date.

Trends during an algae bloom

The measurements in this study suggest that an algae bloom occurred in the lake beginning in middle or late September 1989 and subsiding in late October or early November 1989. On September 28, the 0.2 m incubated sample with added phosphate was higher than the control while the 1.2 m sample with added phosphate was lower. The added nitrate sample incubated at 1.2 m was higher than the control but at the 0.2 m level added nitrate had no significant effect.

Sample from October 12 showed almost the reverse of the previous measurements. Samples with added nitrate were both lower than the controls while added phosphate at the 0.2 m level significantly reduced DO production and had no significant effect at the 1.2 m level. One week later, October 19, the added phosphate sample at 1.2 m was significantly higher while added nitrate at 0.2 m was significantly higher. November 30 samples showed both nutrients reduced the DO production in bottles at 0.2 m while added phosphate at 1.2 m was higher than the control.

During this same period the depth to which light penetrated decreased as the bloom developed (see Figure 22). After the bloom subsided, probably by the first week of November, the water began to clear and by November 30 sufficient light for photosynthesis was probably penetrating the the bottom sediments over much of the lake.

Total phosphorus for eutrophic lakes is in the range of 30-100 µg/L while for hypereutrophic lakes total phosphorus is >100 µg/L [3]. Analysis for total phosphorus on September 21 was 0.48 ppm, very high even for nutrient rich lakes. This level would certainly be sufficient to initiate a bloom. On the same date all samples with added nutrients at both 0.2 and 1.2 m were lower in DO than their controls. Total phosphorus on September 28, October 12, and on November 30 was about 0.2 ppm.

The total daily productivity followed the pattern one might expect for a bloom. The daily total increases as the bloom progresses then decreases near the end and increases again after the bloom dies off and the water clears. The decrease toward the end of the bloom is

the result of the high population of algae itself. The population becomes so dense that shading by algae decrease the productivity of other algae [3].

Since total phosphate is being measured in these analyses, one would not expect the variation indicated here. Dissolved inorganic phosphate, orthophosphate, is the form taken up by the algae and would be expected to decrease rapidly during periods of very high productivity. Phosphate exchange rates, conversion from inorganic phosphate to incorporation in organic matter and release back as inorganic phosphate, can be very rapid, taking only a matter of days [19]. Another fate of phosphate is precipitation into the sediments. A controlling factor in the rate of precipitation or release is the oxygen content at the water-sediment interface [4]. If the water layer in contact with the sediment is aerobic, phosphate is deposited to the sediment. When the water layer is anaerobic, phosphate is released. Additionally, agitation of the sediments favors the release of phosphate from the sediments.

Water at the bottom of Lake Wooster contains reasonably high levels of oxygen at most times. During a bloom high productivity and the accompanying high levels of DO favor the deposition of phosphate to the bottom sediments. This would account for the decline in total phosphate observed just after the beginning of the bloom. Once the over abundant algae die off and settle to the bottom they are decomposed by bacteria, a process requiring the use of oxygen. If the quantity of material to be decomposed is sufficient, the very deep layers of water, those in contact with bottom sediments could become

anaerobic. This would initiate the release of phosphate from the sediments.

The pattern described here for the bloom in Lake Wooster during September, October, and November 1989 is consistent with the descriptions in the literature. A sudden addition of some limiting nutrient causes a rapid increase in algal productivity which is temporary. The unusually high level of productivity is only sustained for a short time before levels return to levels normally observed in the absence of nutrient loading [3].

Trophic state of Lake Wooster

Eutrophic lakes have total phosphate concentration in the 0.30-1.00 mg/L range, single day productivity ranging as high as 5000 mg C/m^2/day, and *Cyanophyceae* as the predominant algae forms. The algal genera which are generally present in Lake Wooster are *Microcystis*, *Anabaena*, and *Oscillatoria* with *Microcystis* being the most predominant genus [20]. All of these genera are from the class *Cyanophyceae*, the blue-green algae.

Based on the productivity and algae types present, Lake Wooster would be considered eutrophic, however, the phosphate levels measured are in the range identified as hypereutrophic in the literature. This study found that the productivity levels measured by DO production were not as great as the models predicted given the phosphate level present in the lake.

Although the lake showed evidence of being phosphate limited at some depths during isolated periods, Lake Wooster was not considered to be phosphate limited. A similar pattern of occasional limitation

was found for nitrate. The lake was light limited in two respects. During times of nutrient limitation the algae near the surface may be less productive that algae in deeper water due to photoinhibition near the surface. During periods of excessive turbidity, either from a bloom or agitation due to wind or entering runoff waters, algae in the deeper waters are limited by insufficient light intensity.

This study found indication that several trace elements may act as limiting factors in algal productivity. Since the complexing agent, EDTA, stimulated a significant increase in algal productivity the necessary trace elements may be present but not in an available form for the algae. The trace elements may be incorporated in or on the suspended particulate matter of the lake. The roll of trace elements in algal productivity of Lake Wooster can be clarified only through further study.

CONCLUSIONS

The productivity of Lake Wooster was extremely variable, but was found to be in the range for lakes classified as eutrophic. The productivity occurs in a narrow range, from 0.5 m to 1.0 m. From the surface to a depth of 0.5 m the productivity indicated photoinhibition occurring on days of clear weather. Although the light intensity below 1.0 m is sufficient for photosynthesis, productivity is generally low compared to the middle depths.

The region below 1.0 m was often phosphate limited in spite of the overall high level of phosphate measured for the lake. The deeper waters were occasionally nitrate limited as well. Trace elements were also indicated in this study as potential limiting factors.

The total phosphate concentration for the lake placed it in the hypereutrophic category. The bloom in the fall of 1989 appeared to be initiated by an increase in phosphate. Lake Wooster is fed by runoff from grassed areas and concrete walks and blacktop driveways. These should contribute minimum additions of phosphate. Little water leaves the lake by overflow or release allowing dissolved materials to concentrate in the lake. Phosphate deposited in the lake bottom sediments may be released as soluble inorganic phosphate during periods when water in contact with the sediments is anaerobic or when agitation disturbs the sediments. This process must be considered as a source of phosphate which could initiate a bloom.

The interactions of the chemical, physical, and biological factors in Lake Wooster were found to complex and intricately

intertwined. The lake's productivity was greatest in a narrow range bordered above by a water layer where light, intense enough to induce photoinhibition, limits algal growth, and below by a combination of insufficient light penetration and inadequate phosphate concentration. Limitation of light penetration resulted from not only suspended solids, but also from overgrowth of algae.

The findings of this study classified Lake Wooster as bordering between eutrophic and hypereutrophic states. As nutrients continue to enter and concentrate, the lake is likely to reach a state where it will be unquestionably in the hypereutrophic category.

TABLE I
Pooled Standard Deviation Calculation
March 20, 1988

depth m	temp C	thio used mL	DO mg/L	|dev|	|dev|^2
0.0	11.5	14.90	10.18	0.1093	0.0119
0.0		14.58	9.96	0.1093	0.0119
0.5	11.4	14.68	10.03	0.0068	0.0000
0.5		14.70	10.04	0.0068	0.0000
1.0	11.3	14.70	10.04	0.0615	0.0038
1.0		14.88	10.16	0.0615	0.0038
1.5	11.0	14.79	10.10	0.0307	0.0009
1.5		14.70	10.04	0.0307	0.0009
2.0	11.3	14.68	10.03	0.0034	0.0000
2.0		14.69	10.03	0.0034	0.0000
2.5	11.2	15.01	10.25	0.0102	0.0001
2.5		14.98	10.23	0.0102	0.0001
Sum of squares of deviation			0.0337	0.03	
Pooled standard deviation			0.0749	0.07	

TABLE II

Dissolved Oxygen Profile for March 30 1988

DO concentrations in mg/L

depth	temp.	average	satur. at	best fit line		%sat
m	deg. C	at depth	temp.	exper.	saturated	
0.0	11.5	10.07	10.82	10.03	10.81	93.05
0.5	11.4	10.03	10.85	10.06	10.85	92.48
1.0	11.3	10.10	10.88	10.08	10.89	92.90
1.5	11.0	10.07	10.95	10.10	10.92	91.99
2.0	11.3	10.03	10.88	10.13	10.96	92.24
2.5	11.2	10.24	11.05	10.15	11.00	92.71

TABLE III

Dissolved Oxygen Profile for February 17, 1988

DO concentrations in mg/L

depth	temp.	average	satur. at	best fit line		%sat
m	deg. C	at depth	temp.	exper.	saturated	
0.0	2.2	12.83	13.34	12.91	13.40	96.18
0.5	2.2	12.77	13.34	13.04	13.32	95.73
1.0	2.6	13.53	13.20	13.17	13.24	102.51
1.5	2.7	13.23	13.36	13.30	13.16	99.03
2.0	3.1	13.92	13.02	13.43	13.07	106.91
2.5	3.4	13.11	12.92	13.56	12.99	101.47

TABLE IV
Productivity for control samples

Fall 1987

depth m	layer thickness m	Layer Productivity in mg C/ m^2 Oct 2, 87	Oct 9, 87	Oct 16, 87	Oct 23, 87	Nov 20, 87
0.20	0.365	428	199	167	196	29
0.53	0.330	532	330	81	92	138
0.86	0.330	307	98	38	67	133
1.20	0.330	110	41	32	24	83
Sum (0-1.4) in mg C/m^2		1377	668	318	379	383
Productivity for the day (12 hrs.) in mgC/m^2/day		4131	2004	954	1137	1149

Spring 1988

depth m	layer thickness m	Layer Productivity in mg C/ m^2 Mar 9, 88	Mar 23, 88	Apr 6, 88	Apr 13, 88
0.20	0.365	132	-62	127	144
0.53	0.330	212	11	174	155
0.86	0.330	174	-47	184	138
1.20	0.330	146	-77	132	162
Sum (0-1.4) in mg C/m^2		664	-175	617	599
Productivity for the day (12 hrs.) in mgC/m^2/day		1992	-525	1851	1797

Fall 1989

depth m	layer thickness m	Layer Productivity in mg C/ m^2 Sept 21 89	Sept 28, 89	Oct 12, 89	Oct 19, 89
0.20	0.365	471	440	469	453
0.53	0.330	358	428	289	321
0.86	0.330	316	369	277	183
1.20	0.330	221	253	158	67
Sum (0-1.4) in mg C/m^2		1366	1490	1193	1024
Productivity for the day (12 hrs.) in mgC/m^2/day		4098	4470	3579	3072

Nov. 30, 1989

depth m	layer thickness m	Layer Productivity in mg C/ m^2 control	+NO3-	+PO4-3
0.20	0.450	469	521	572
0.70	0.500	289	637	598
1.20	0.500	158	605	643
Sum (0-1.4) in mg C/m^2		916	1763	1813
Productivity for the day (12 hrs.) in mgC/m^2/day		2748	5289	5439

TABLE V
Added nutrient study for October 2, 1987

depth	treatment	thio used (mL)	DO (mg/L)	photosynthesis net	photosynthesis gross	productivity (mgC/m^3)	productivity (mgC/m^2)
	initial	12.60	8.57				
0.20	control	17.15	11.67	3.10	3.13	1173.46	428.31
0.20	+NO3-	17.58	11.96	3.39	3.42	1283.15	468.35
0.20	+PO4-3	17.58	11.96	3.39	3.42	1283.15	468.35
0.53	control	18.94	12.88	4.31	4.35	1630.09	537.93
0.53	control	18.80	12.79	4.22	4.25	1594.37	526.14
0.86	control	16.30	11.09	2.52	2.55	956.62	315.69
0.86	control	16.09	10.95	2.37	2.41	903.05	298.01
1.20	control	13.86	9.43	0.86	0.89	334.18	110.28
1.20	+NO3-	13.89	9.45	0.88	0.91	341.83	112.80
1.20	+PO4-3	14.18	9.65	1.07	1.11	415.81	137.22
1.20	dark	12.55	8.54	-0.03			

TABLE VI
Added nutrient study for October 9, 1987

depth	treatment	thio used (mL)	DO (mg/L)	photosynthesis net	photosynthesis gross	productivity (mgC/m^3)	productivity (mgC/m^2)
	initial	14.20	9.72				
0.20	control	14.94	10.23	0.51	1.45	544.35	198.69
0.20	+NO3-	16.26	11.13	1.41	2.36	883.29	322.40
0.20	+PO4-3	16.24	11.12	1.40	2.34	878.15	320.53
0.53	control	16.72	11.45	1.73	2.67	1001.40	330.46
0.53	control	XX	XX				
0.86	control	13.46	9.22	-0.51	0.44	164.33	54.23
0.86	control	14.28	9.78	0.05	1.00	374.88	123.71
1.20	control	14.22	9.74	0.01	0.96	359.48	118.63
1.20	+NO3-	12.55	8.59	-1.13	-0.18	-69.33	-22.88
1.20	+PO4-3	13.30	9.11	-0.62	0.33	123.25	40.67
1.20	dark	12.82	8.78	-0.94			

XX indicated sample not available for this date

TABLE VII

Added nutrient study for October 16, 1987

depth	treatment	thio used (mL)	DO (mg/L)	photosynthesis net	photosynthesis gross	productivity (mgC/m^3)	productivity (mgC/m^2)
	initial	12.62	8.56				
0.20	control	14.10	9.57	1.00	1.22	457.90	167.13
0.20	+NO3-	14.00	9.50	0.94	1.15	432.46	157.85
0.20	+PO4-3	13.96	9.47	0.91	1.13	422.29	154.14
0.53	control	13.14	8.91	0.35	0.57	213.69	70.52
0.53	control	13.40	9.09	0.53	0.75	279.83	92.34
0.86	control	12.78	8.67	0.11	0.33	122.11	40.30
0.86	control	12.72	8.63	0.07	0.28	106.84	35.26
1.20	control	12.46	8.45	-0.11	0.11	40.70	13.43
1.20	+NO3-	12.32	8.36	-0.20	0.01	5.09	1.68
1.20	+PO4-3	12.68	8.60	0.04	0.26	96.67	31.90
1.20	dark	12.30	8.34	-0.22			

TABLE VIII

Added nutrient sutdy for October 23, 1987

depth	treatment	thio used (mL)	DO (mg/L)	photosynthesis net	photosynthesis gross	productivity (mgC/m^3)	productivity (mgC/m^2)
	initial	13.72	9.26				
0.20	control	16.12	10.89	1.62	1.43	536.84	195.95
0.20	+NO3-	15.82	10.68	1.42	1.23	460.87	168.22
0.20	+PO4-3	16.14	10.90	1.63	1.45	541.90	197.80
0.53	control	15.10	10.20	0.93	0.74	278.55	91.92
0.53	control	15.04	10.16	0.89	0.70	263.36	86.91
0.86	control	15.24	10.29	1.03	0.84	314.00	103.62
0.86	control	14.36	9.70	0.43	0.24	91.16	30.08
1.20	contol	14.40	9.72	0.46	0.27	101.29	33.43
1.20	+NO3-	14.35	9.69	0.43	0.24	88.63	29.25
1.20	+PO4-3	14.29	9.65	0.38	0.20	73.44	24.23
1.20	dark	14.00	9.45	0.19			

TABLE IX

Added nutrient sutdy for November 20, 1987

depth	treatment	thio used (mL)	DO (mg/L)	photosynthesis net	photosynthesis gross	productivity (mgC/m^3)	productivity (mgC/m^2)
	initial	14.00	9.41				
0.20	control	14.99	10.08	0.67	0.21	78.15	28.53
0.20	+NO3-	15.02	10.10	0.69	0.23	85.72	31.29
0.20	+PO4-3	14.80	9.95	0.54	0.08	30.25	11.04
0.53	control	16.34	10.99	1.57	1.12	418.51	138.11
0.53	control	16.70	11.23	1.82	1.36	509.27	168.06
0.86	control	16.95	11.40	1.98	1.53	572.30	188.86
0.86	control	15.13	10.17	0.76	0.30	113.45	37.44
1.20	control	15.02	10.10	0.69	0.23	85.72	28.29
1.20	+NO3-	15.48	10.41	1.00	0.54	201.69	66.56
1.20	+PO4-3	15.68	10.54	1.13	0.67	252.11	83.20
1.20	dark	14.68	9.87	0.46			

TABLE X

Added nutrient study for March 9, 1988

depth	treatment	thio used (mL)	DO (mg/L)	photosynthesis net	photosynthesis gross	productivity (mgC/m^3)	productivity (mgC/m^2)
	initial	17.82	12.37				
0.20	control	19.09	13.26	0.88	0.97	362	129
0.20	+NO3-	19.00	13.19	0.82	0.90	339	121
0.20	+PO4-3	19.24	13.36	0.99	1.07	401	143
0.53	control	20.06	13.93	1.56	1.64	615	203
0.53	control	20.28	14.08	1.71	1.79	672	222
0.86	control	20.01	13.90	1.52	1.60	602	199
0.86	control	19.43	13.49	1.12	1.20	451	149
1.20	control	19.40	13.47	1.10	1.18	443	146
1.20	+NO3-	19.60	13.61	1.24	1.32	495	163
1.20	+PO4-3	19.70	13.68	1.31	1.39	521	172
1.20	dark	17.70	12.29	-0.08			

TABLE XI

Added nutrient study for March 23, 1988

depth	treatment	thio used (mL)	DO (mg/L)	photosynthesis net	photosynthesis gross	productivity (mgC/m^3)	productivity (mgC/m^2)
	initial	16.84	11.69				
0.20	control	15.84	10.93	-0.77	-0.46	-171	-61
0.20	+NO3-	17.19	11.86	0.16	0.48	178	64
0.20	+PO4-3	17.10	11.80	0.10	0.41	155	55
0.53	control	16.30	11.24	-0.45	-0.14	-52	-17
0.53	control	16.95	11.69	-0.00	0.31	116	38
0.86	control	16.00	11.04	-0.66	-0.34	-129	-43
0.86	control	15.90	10.97	-0.73	-0.41	-155	-51
1.20	control	15.60	10.76	-0.93	-0.62	-233	-77
1.20	+NO3-	16.20	11.18	-0.52	-0.21	-78	-26
1.20	+PO4-3	16.02	11.05	-0.64	-0.33	-124	-41
1.20	dark	16.50	11.38	-0.31			

TABLE XII

Added nutrient study for April 6, 1988

depth	treatment	thio used (mL)	DO (mg/L)	photosynthesis net	photosynthesis gross	productivity (mgC/m^3)	productivity (mgC/m^2)
	initial	14.96	10.39				
0.20	control	16.02	10.95	0.56	0.93	349	124
0.20	+NO3-	15.80	10.80	0.41	0.78	292	104
0.20	+NH4+	16.10	11.00	0.61	0.98	369	131
0.53	control	16.60	11.34	0.96	1.33	497	164
0.53	control	16.84	11.51	1.12	1.49	559	184
0.86	control	16.70	11.41	1.02	1.39	523	173
0.86	control	16.98	11.60	1.21	1.58	595	196
1.20	control	16.22	11.08	0.70	1.07	400	132
1.20	+NO3-	16.28	11.13	0.74	1.11	415	137
1.20	+NH4+	16.54	11.30	0.91	1.28	482	159
1.20	dark	14.66	10.02	-0.37			

TABLE XIII

Added nutrient study for April 13, 1988

depth	treatment	thio used (mL)	DO (mg/L)	photosynthesis net	photosynthesis gross	productivity (mgC/m^3)	productivity (mgC/m^2)
	initial	14.64	10.11				
0.20	control	16.20	11.19	1.08	1.05	394	140
0.20	+NO3-	16.65	11.50	1.39	1.36	510	182
0.20	+NH4+	16.08	11.11	0.99	0.97	363	129
0.53	control	16.52	11.41	1.30	1.27	477	157
0.53	control	16.46	11.37	1.26	1.23	461	152
0.86	control	16.26	11.23	1.12	1.09	409	135
0.86	control	16.32	11.27	1.16	1.13	425	140
1.20	control	16.58	11.45	1.34	1.31	492	162
1.20	+NO3-	15.76	10.89	0.77	0.75	280	92
1.20	+NH4+	16.50	11.40	1.28	1.26	471	156
1.20	dark	14.68	10.14	0.03			

TABLE XIV

Added nutrient study for September 21, 1989

depth	treatment	thio used (mL)	DO (mg/L)	photosynthesis net	photosynthesis gross	productivity (mgC/m^3)	productivity (mgC/m^2)	productivity (mgC/mcA)
	initial	12.98	8.72					
	initial	13.24	8.89					
0.20	control	17.00	11.42	2.61	3.37	1264	462	4.16
0.20	control	17.20	11.55	2.75	3.51	1315	480	4.33
0.20	+NO3-	15.98	10.73	1.93	2.69	1008	368	3.32
0.20	+PO4-3	15.82	10.63	1.82	2.58	967	353	3.18
0.53	control	16.19	10.87	2.07	2.83	1060	350	5.66
0.53	control	16.38	11.00	2.20	2.96	1108	366	5.92
0.86	control	16.15	10.85	2.04	2.80	1050	347	10.06
0.86	control	15.42	10.36	1.55	2.31	866	286	8.30
1.20	+NO3-	13.90	9.34	0.53	1.29	484	160	8.46
1.20	+PO4-3	14.38	9.66	0.85	1.61	605	199	10.57
1.20	control	14.90	10.01	1.20	1.96	735	243	12.86
1.20	control	14.37	9.65	0.85	1.61	602	199	10.53
1.00	dark	11.98	8.05	-0.76				

TABLE XV

Added nutrient study for September 28, 1989

depth	treatment	thio used (mL)	DO (mg/L)	photosynthesis net	photosynthesis gross	productivity (mgC/m^3)	productivity (mgC/m^2)	productivity (mgC/mcA)
	initial	14.00	10.23					
	initial	13.58	9.93					
0.20	control	17.17	12.55	2.47	3.27	1225	447	3.72
0.20	control	17.03	12.45	2.37	3.17	1187	433	3.61
0.20	+NO3-	17.24	12.60	2.52	3.32	1245	454	3.78
0.20	+PO4-3	17.58	12.85	2.77	3.57	1338	488	4.07
0.53	control	17.32	12.66	2.58	3.38	1267	418	6.75
0.53	control	17.55	12.83	2.75	3.55	1330	439	7.09
0.86	control	16.55	12.10	2.02	2.81	1055	348	10.91
0.86	control	17.00	12.43	2.35	3.14	1179	389	12.18
1.20	+NO3-	15.98	11.68	1.60	2.40	899	297	18.39
1.20	+PO4-3	15.31	11.19	1.11	1.91	716	236	14.63
1.20	control	15.20	11.11	1.03	1.83	685	226	14.01
1.20	control	15.80	11.55	1.47	2.27	850	280	17.38
1.20	dark	12.70	9.28	-0.80				

TABLE XVI

Productivity by depth and treatment for October 12, 1989

depth	treatment	thio used (mL)	DO (mg/L)	photosynthesis net	photosynthesis gross	productivity (mgC/m^3)	productivity (mgC/m^2)	productivity (mgC/mcA)
	initial	13.59	9.15					
	initial	13.55	9.13					
0.20	control	18.28	12.31	3.17	3.57	1339	489	1.29E-03
0.20	control	17.85	12.02	2.88	3.28	1230	449	1.18E-03
0.20	+NO3-	17.11	11.53	2.38	2.78	1043	381	1.00E-03
0.20	+PO4-3	17.71	11.93	2.79	3.19	1195	436	1.15E-03
0.53	control	17.82	12.00	2.86	3.26	1223	403	2.27E-03
0.53	control	15.07	10.15	1.01	1.41	528	174	9.82E-04
0.86	control	15.68	10.56	1.42	1.82	682	225	2.71E-03
0.86	control	16.92	11.40	2.26	2.65	995	328	3.95E-03
1.20	+NO3-	14.35	9.67	0.53	0.92	346	114	3.01E-03
1.20	+PO4-3	14.90	10.04	0.90	1.29	485	160	4.21E-03
1.20	control	14.88	10.02	0.88	1.28	480	158	4.17E-03
1.20	control	XX	XX	XX	XX	XX		
1.00	dark	12.98	8.74	-0.40				

XX indicated no sample was available for this date

TABLE XVII

Added nutrient study for October 19, 1989

depth	treatment	thio used (mL)	DO (mg/L)	photosynthesis net	photosynthesis gross	productivity (mgC/m^3)	productivity (mgC/m^2)	productivity (mgC/mcA)
	initial	12.60	8.53					
	initial	12.70	8.60					
0.20	control	17.20	11.65	3.08	3.20	1199	438	759.29
0.20	control	17.53	11.87	3.31	3.42	1283	468	6.00
0.20	+NO3-	17.57	11.90	3.33	3.45	1293	472	6.05
0.20	+PO4-3	17.46	11.83	3.26	3.37	1265	462	5.92
0.53	control	16.30	11.04	2.47	2.59	970	320	15.02
0.53	control	16.32	11.05	2.49	2.60	975	322	15.09
0.86	control	14.54	9.85	1.28	1.40	523	173	29.62
0.86	control	14.79	10.02	1.45	1.56	587	194	33.21
1.20	+NO3-	13.40	9.08	0.51	0.62	234	77	50.31
1.20	+PO4-3	14.60	9.89	1.32	1.44	538	178	115.94
1.20	control	13.28	9.00	0.43	0.54	203	67	43.75
1.20	control	XX	XX	XX	XX	XX		
1.20	dark	12.48	8.45	-0.12				

XX indicates no sample was available for this date

TABLE XVIII

Added nutrient study for November 30, 1989

depth	treatment	thio used (mL)	DO (mg/L)	photosynthesis net	photosynthesis gross	productivity (mgC/m^3)	productivity (mgC/m^2)	productivity (mgC/mgA)
	initial	16.90	11.59					
	initial	17.18	11.79					
0.20	control	18.24	12.51	0.82	3.95	1482	667	5.53
0.20	control	17.24	11.83	0.14	3.27	1225	551	4.57
0.20	+NO3-	16.98	11.65	-0.04	3.09	1158	521	4.32
0.20	+PO4-3	17.42	11.95	0.26	3.39	1271	572	4.74
0.70	control	17.22	11.81	0.12	3.25	1219	610	7.23
0.70	control	17.42	11.95	0.26	3.39	1271	635	7.53
0.70	+NO3-	17.43	11.96	0.27	3.40	1274	637	7.55
0.70	+PO4-3	17.13	11.75	0.06	3.19	1196	598	7.09
1.20	+NO3-	17.18	11.79	0.10	3.22	1209	605	10.25
1.20	+PO4-3	17.48	11.99	0.30	3.43	1286	643	10.90
1.20	control	17.02	11.68	-0.01	3.11	1168	584	9.90
1.20	control	17.48	11.99	0.30	3.43	1286	643	10.90
1.20	dark	12.48	8.56	-3.13				

TABLE XIX
Trace Element Study
Lake Wooster April 20, 1988

treatment	thio used (mL)	DO (mg/L)	diff from control	photosynthesis net	photosynthesis gross	productivity (mgC/m^3)	productivity (mgC/m^2)
initial a	15.28	10.48					
+Mg	16.20	11.11	0.37	0.63	0.63	237	86
+B	16.02	10.99	0.25	0.51	0.51	190	69
+Mn EDTA	16.08	11.03	0.29	0.55	0.55	206	75
+Zn EDTA	15.66	10.74	0.00	0.26	0.26	98	36
+Co EDTA	16.70	11.46	0.72	0.97	0.97	365	133
+Mo EDTA	16.34	11.21	0.47	0.73	0.73	273	100
+Fe EDTA	15.80	10.84	0.10	0.36	0.36	134	49
+EDTA	16.20	11.11	0.37	0.63	0.63	237	86
control a	15.71	10.78	ctrl ave	0.30	0.30	111	40
control b	15.60	10.70	10.74	0.22	0.22	82	30
dark	14.59	10.01					

TABLE XX
Relative Light Intensities

Readings in microamperes

depth	21 SEPT	28 SEPT	12 OCT	19 OCT	20 NOV
0.00	6600	7264	3440	5080	9680
0.20	5000	6520	2400	3600	9160
0.40	4280	4800	1680	1800	7360
0.60	2800	3400	1640	640	6400
0.80	2200	2160	1000	310	5680
1.00	1280	1360	410	80	4880
1.50	560	440	140	13.6	3280
2.00	200	160	37	3.3	2440

Relative light intensity as percent of surface intensity

depth	21 SEPT	28 SEPT	12 OCT	19 OCT	30 NOV
0.00	100.00	100.00	100.00	100.00	100.00
0.20	75.76	89.76	69.77	70.87	94.63
0.40	64.85	66.08	48.84	35.43	76.03
0.60	42.42	46.81	47.67	12.60	66.12
0.80	33.33	29.74	29.07	6.10	58.68
1.00	19.39	18.72	11.92	1.57	50.41
1.50	8.48	6.06	4.07	0.27	33.88
2.00	3.03	2.20	1.08	0.06	25.21

ln(Rlz/Rlo)

depth	21 SEPT	28 SEPT	12 OCT	19 OCT	30 NOV
0.00	0.000	0.000	0.000	0.000	0.000
0.20	0.278	0.108	0.360	0.344	0.055
0.40	0.433	0.414	0.717	1.038	0.274
0.60	0.857	0.759	0.741	2.072	0.414
0.80	1.099	1.213	1.235	2.796	0.533
1.00	1.640	1.675	2.127	4.151	0.685
1.50	2.467	2.804	3.202	5.923	1.082
2.00	3.497	3.816	4.532	7.339	1.378

TABLE XXI
Total Phosphate Analysis

	absorbance readings						
	standards		samples		quality control		Total P
date	0.20 ppm	0.50 ppm	a	b	for 0.2	for 0.5	(mg P/L)
Sept 21, 89	0.301	0.537	0.292	**	1.41	1.03	0.48
Sept 28, 89	0.301	0.598	0.259	0.225	1.48	1.19	0.21
Oct 12, 89	0.245	0.529	0.168	0.148	1.21	1.05	0.16
Oct 19, 89 *	0.170	0.311	0.022	0.015	0.84	0.62	0.03
Nov 30, 89	0.272	0.534	0.383	0.283	1.32	1.05	0.24

* Measurements not considered valid for this date
** Measurement was 1.185. Not considered valid

Figure 2 Dissolved Oxygen Profile for

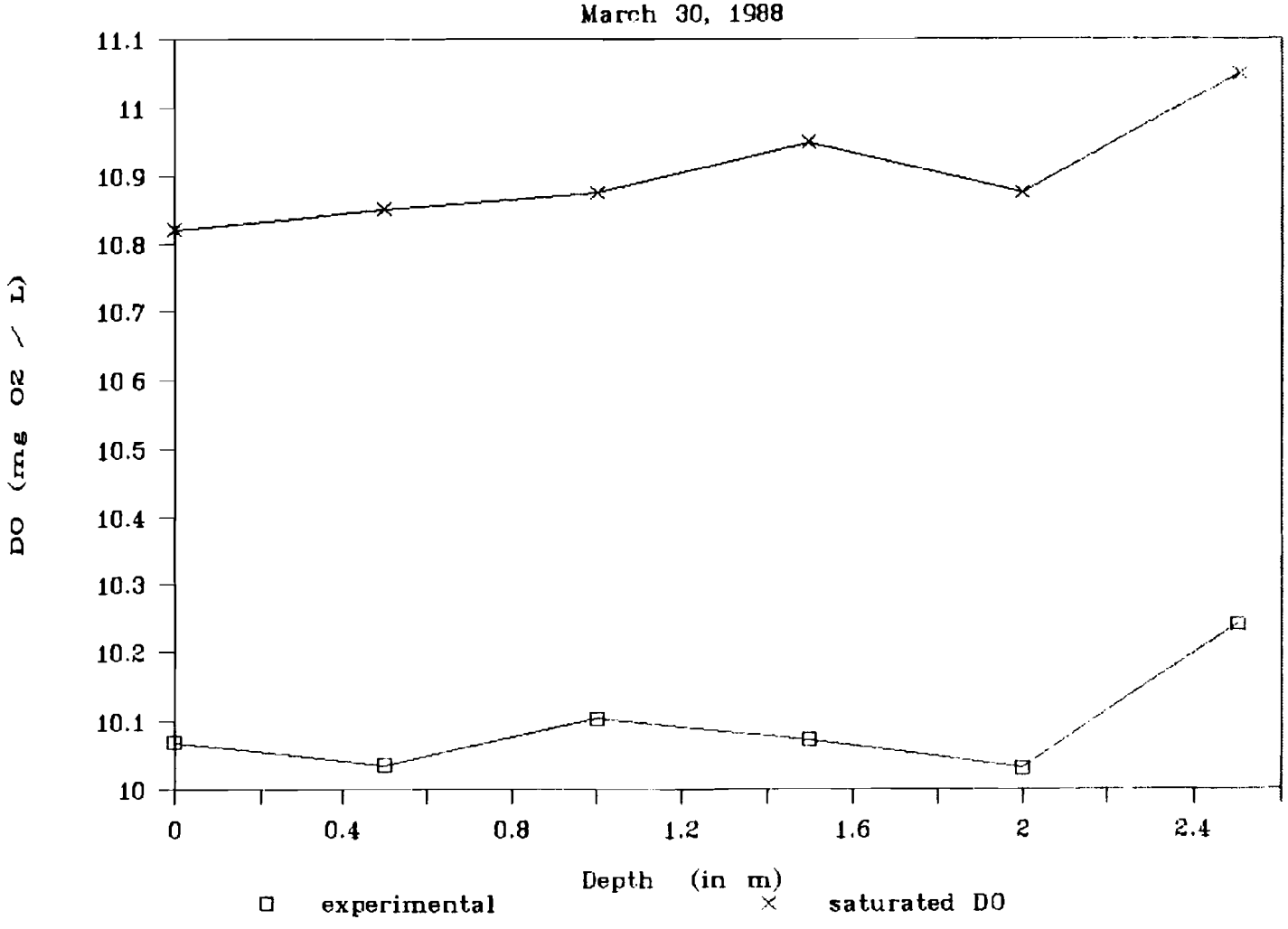


Figure 3 Dissolved Oxygen Profile for

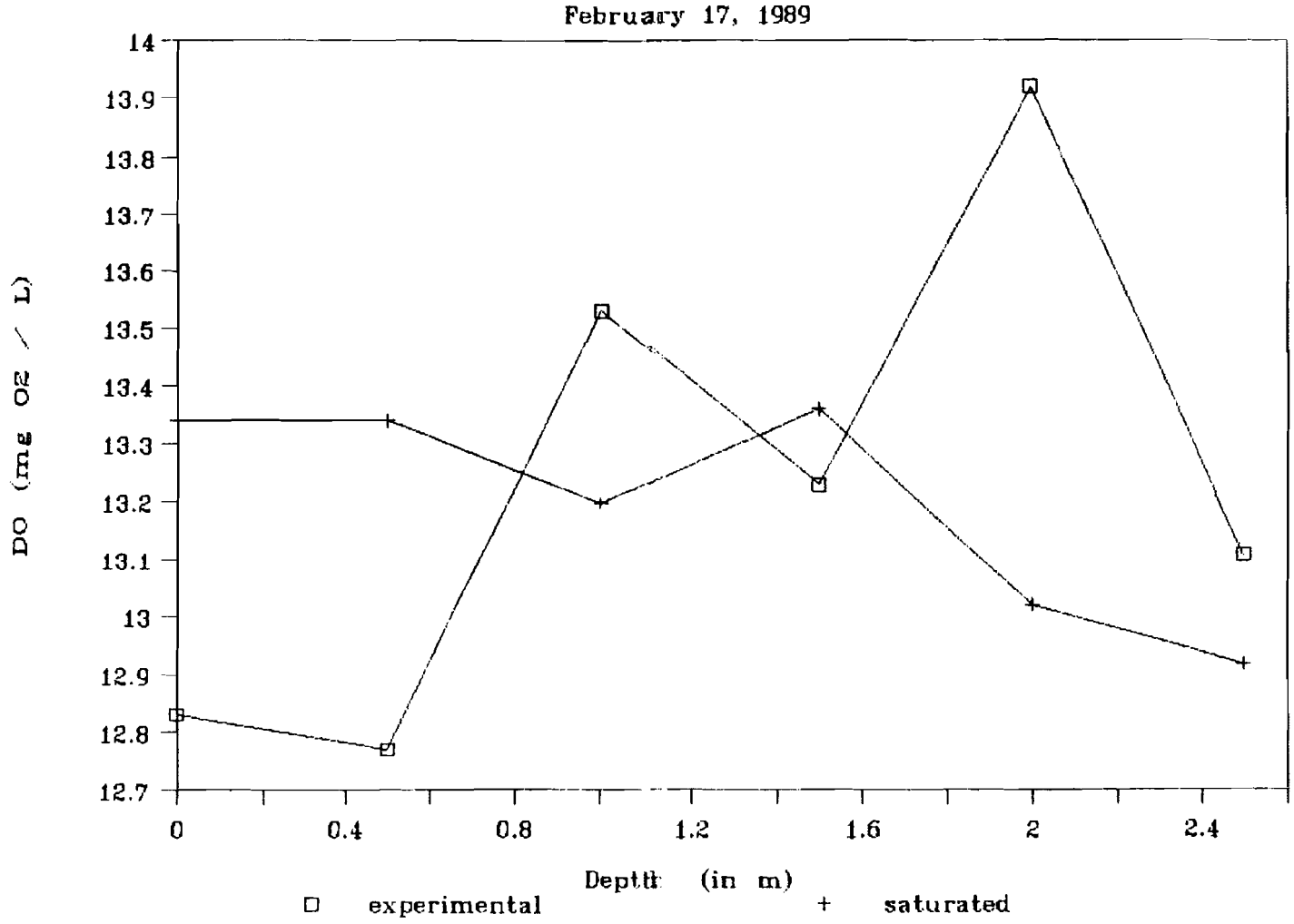


Fig. 4 Productivity for Oct. 2, 1987

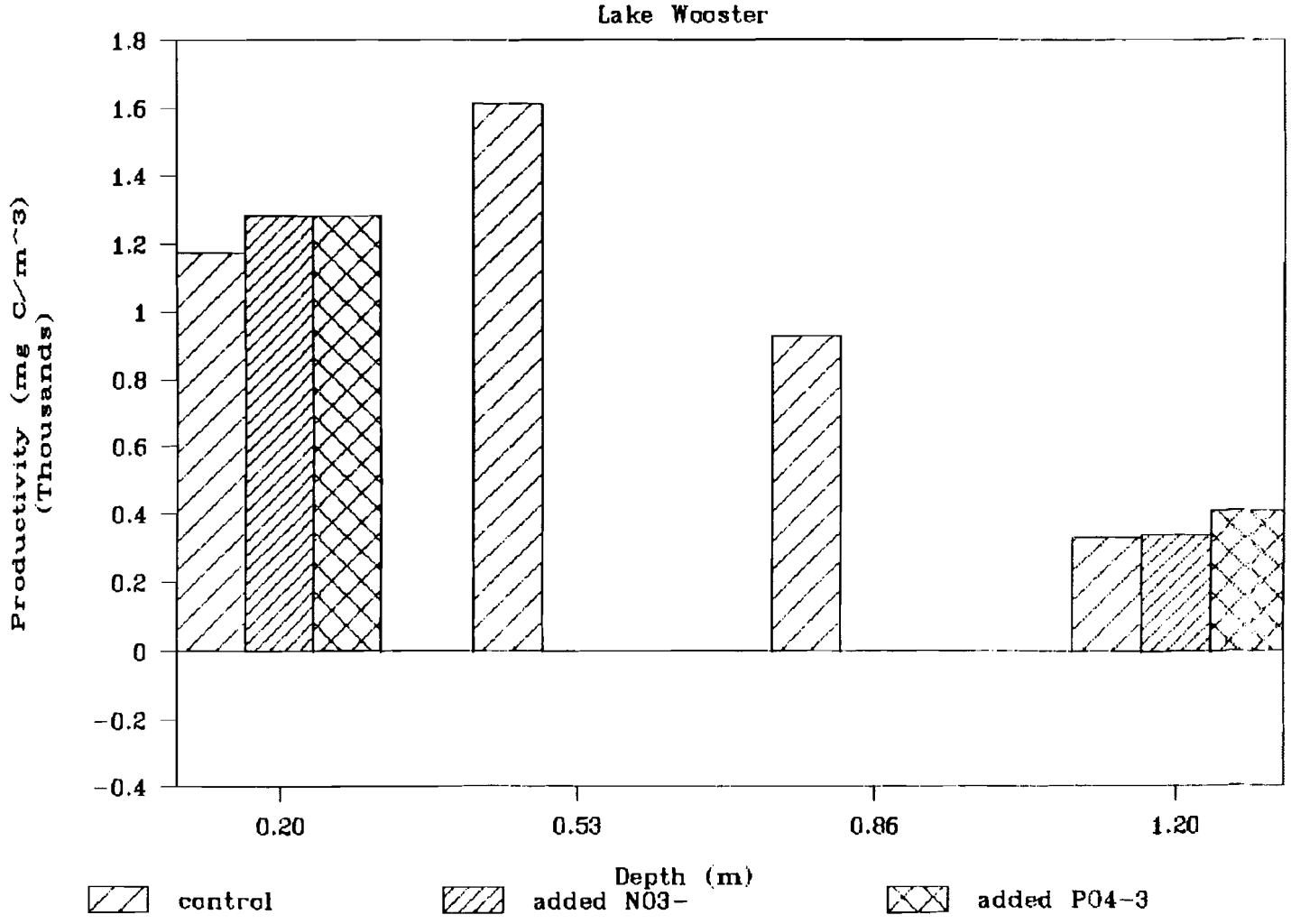


Fig. 5 Productivity for Oct. 9, 1987

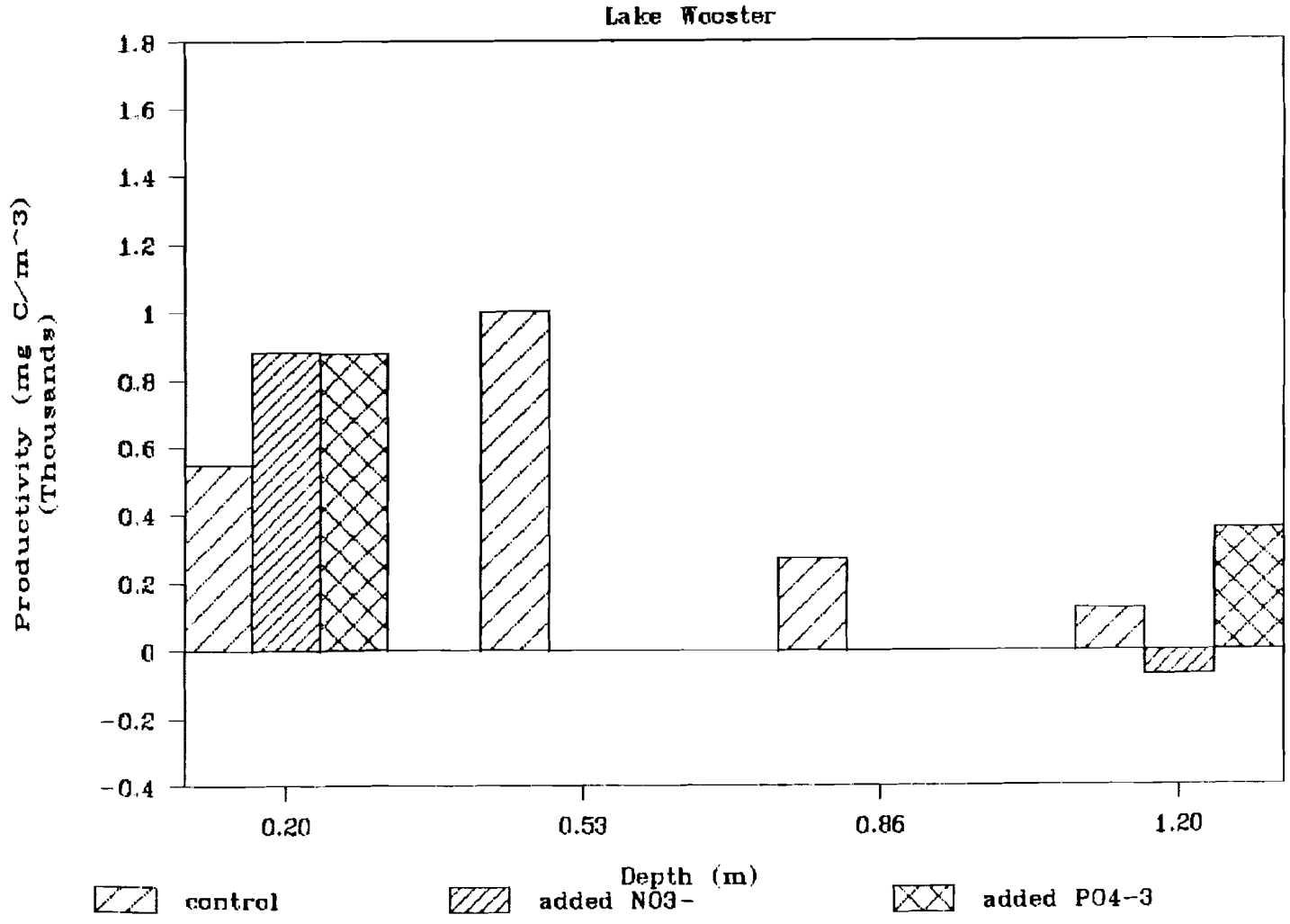


Fig. 6 Productivity for Oct. 16, 1987

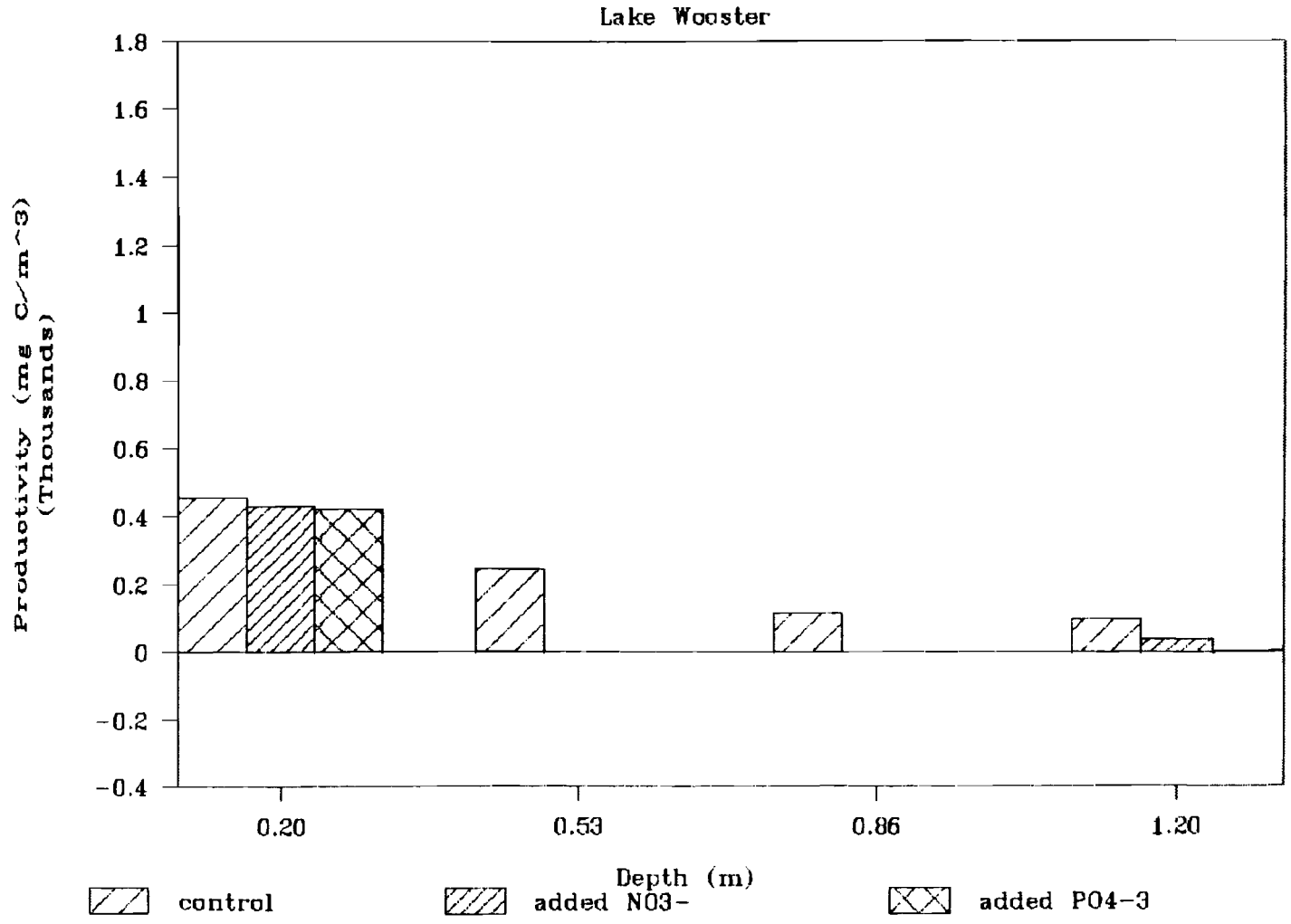


Fig. 7 Productivity for Oct. 23, 1987

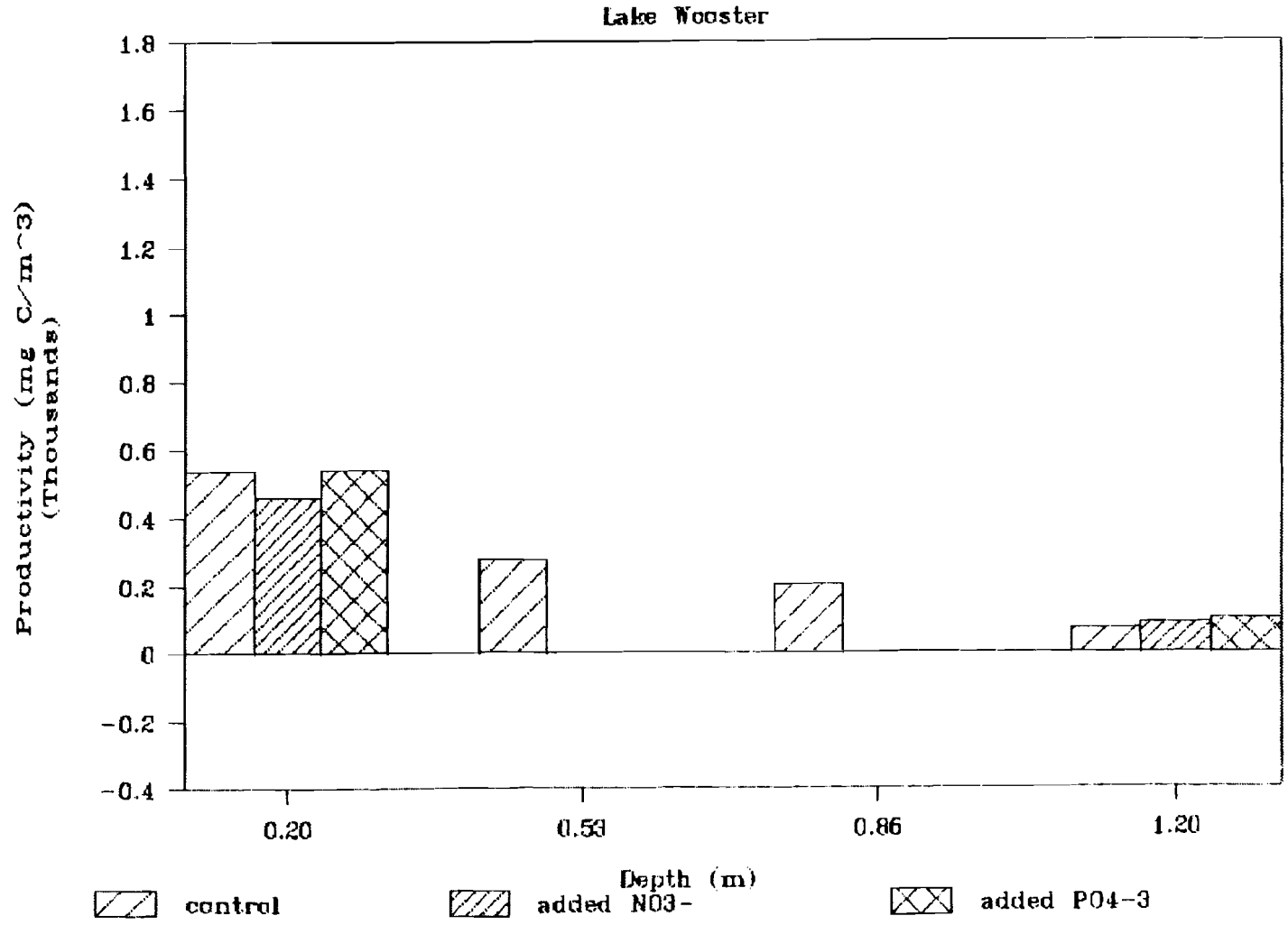


Fig. 8 Productivity for Nov. 20, 1987

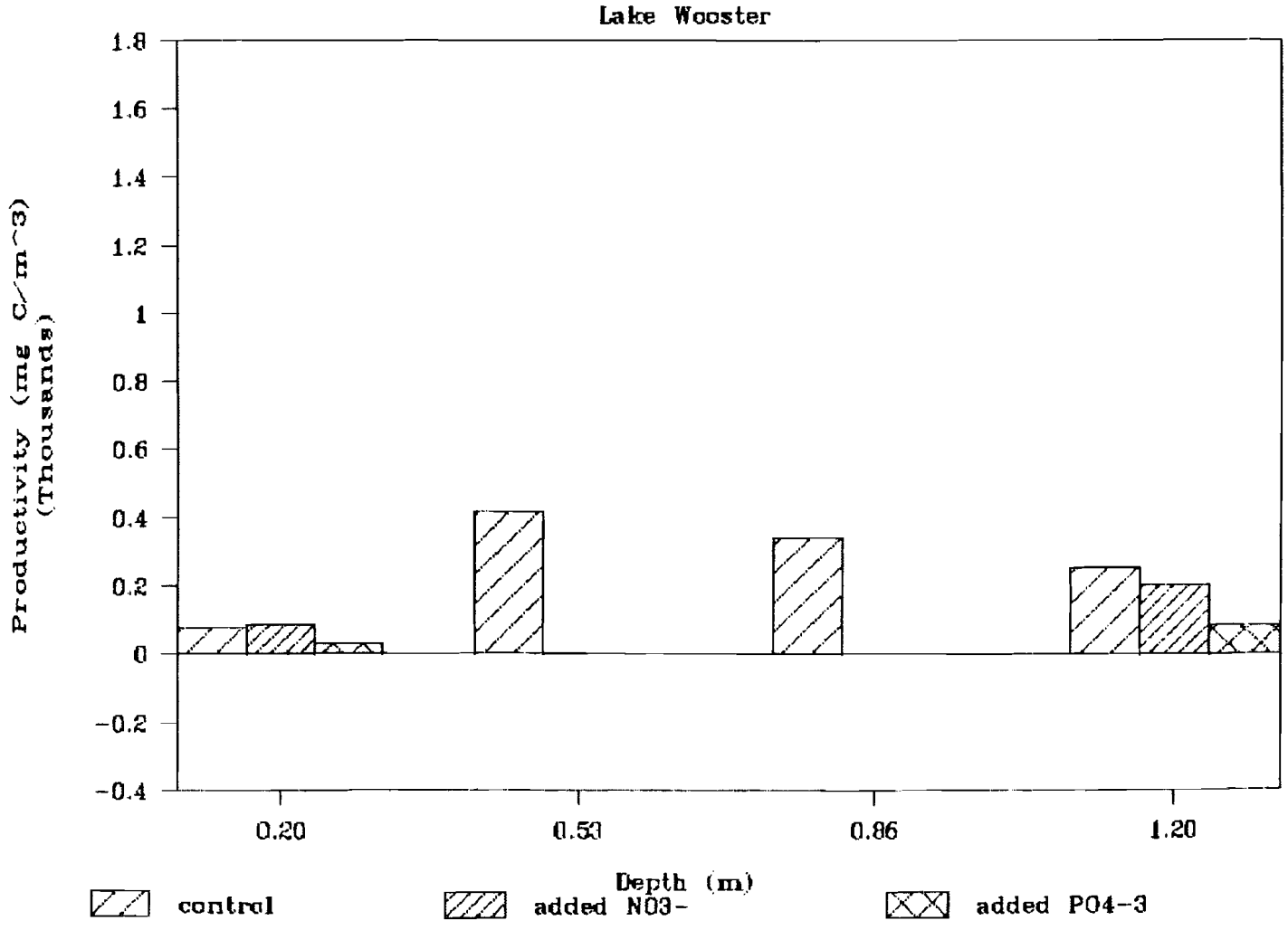


Fig. 9 Productivity for Mar. 9, 1988

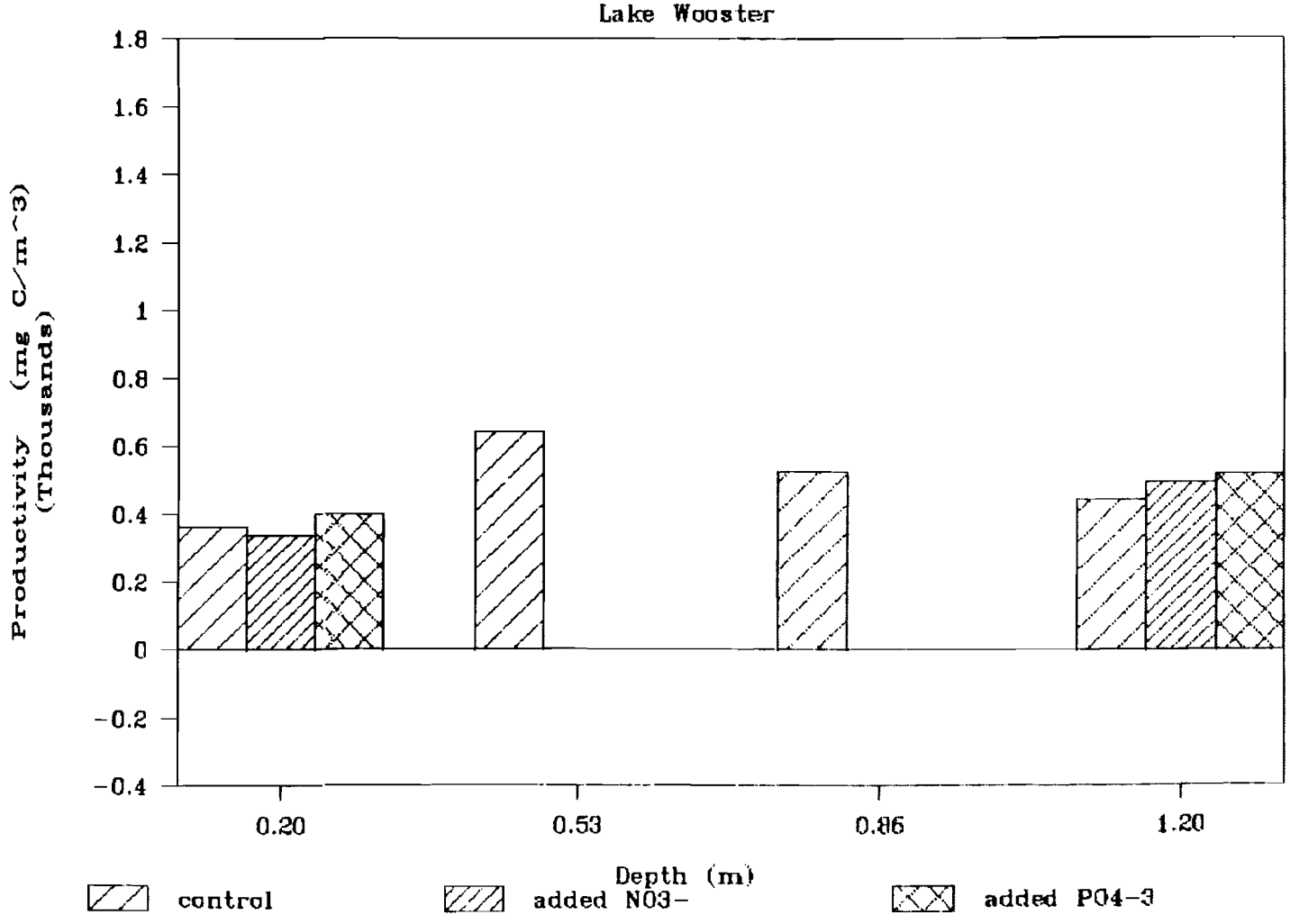


Fig. 10 Productivity for Mar. 23, 1988

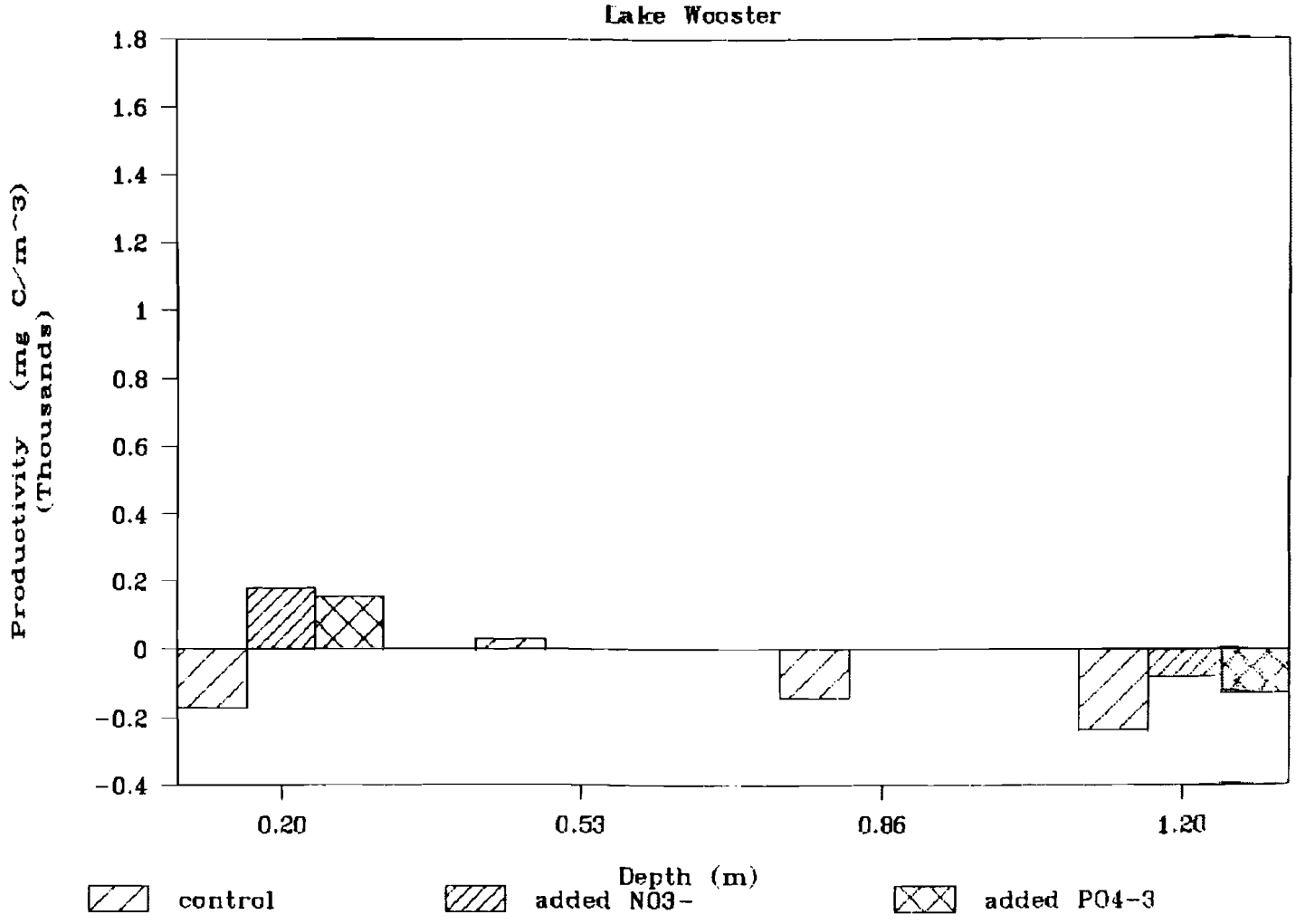


Fig. 11 Productivity for Apr. 6, 1988

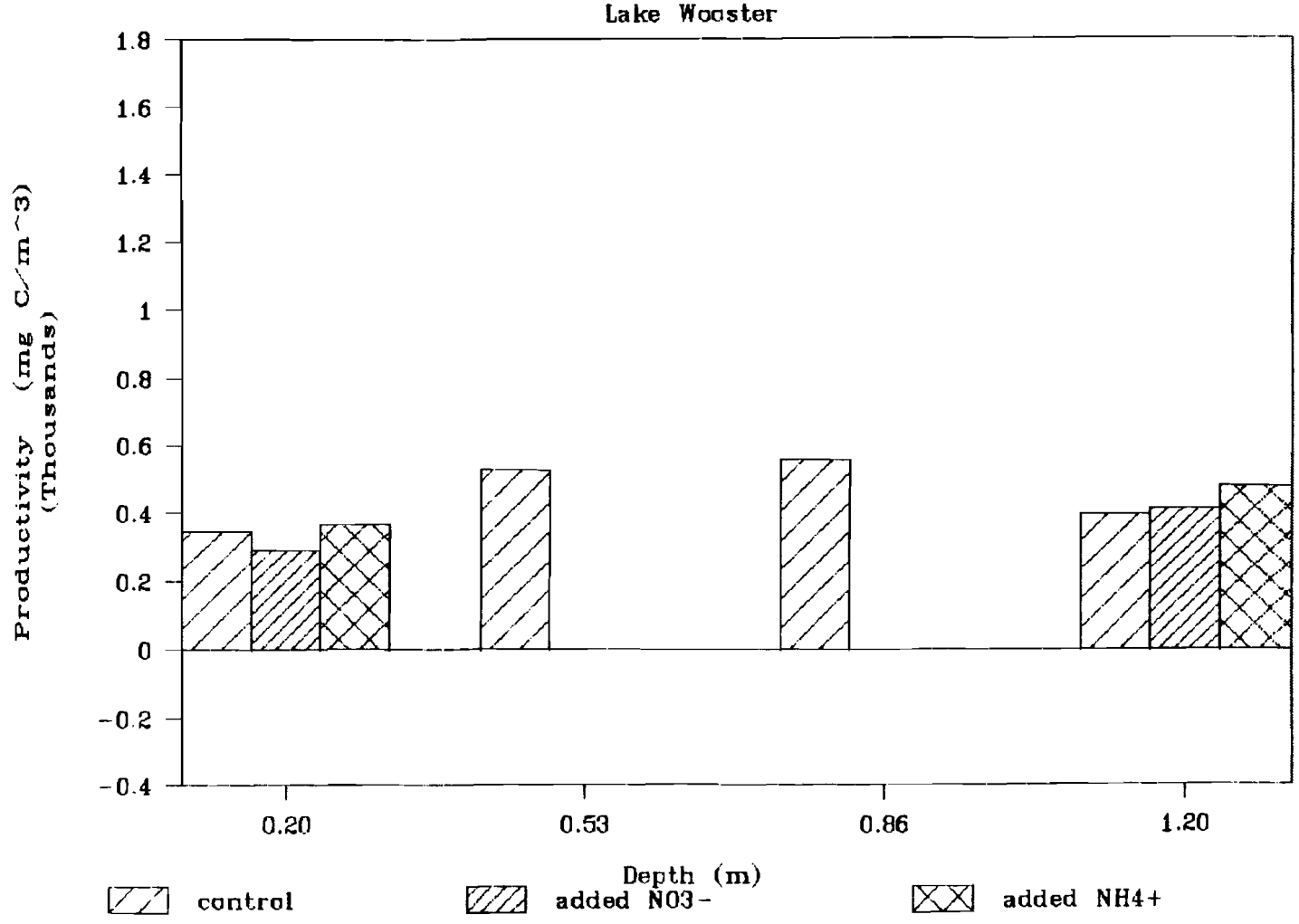


Fig. 12 Productivity for Apr. 13, 1988

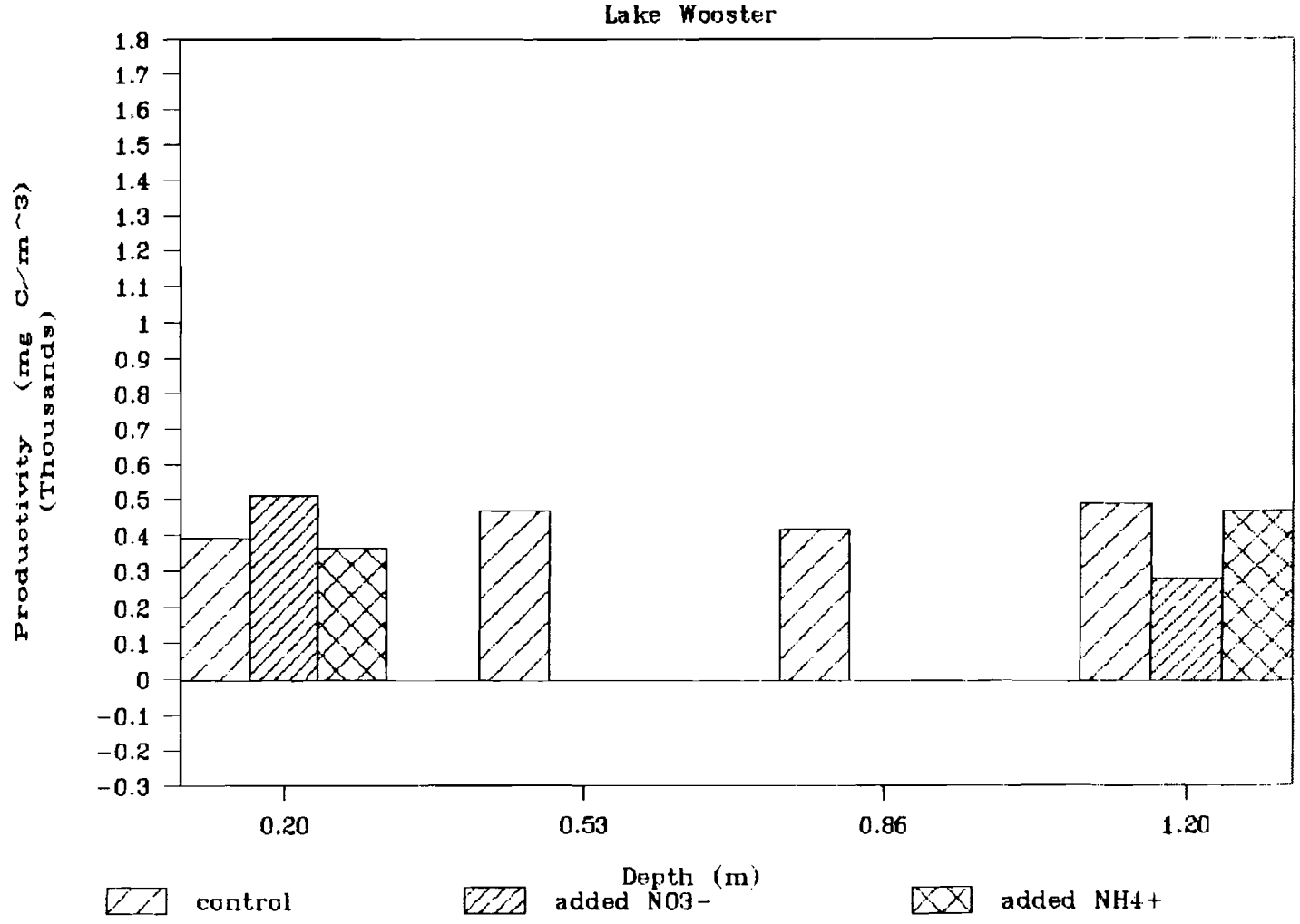


Fig. 13 Productivity for Sept. 21, 1989

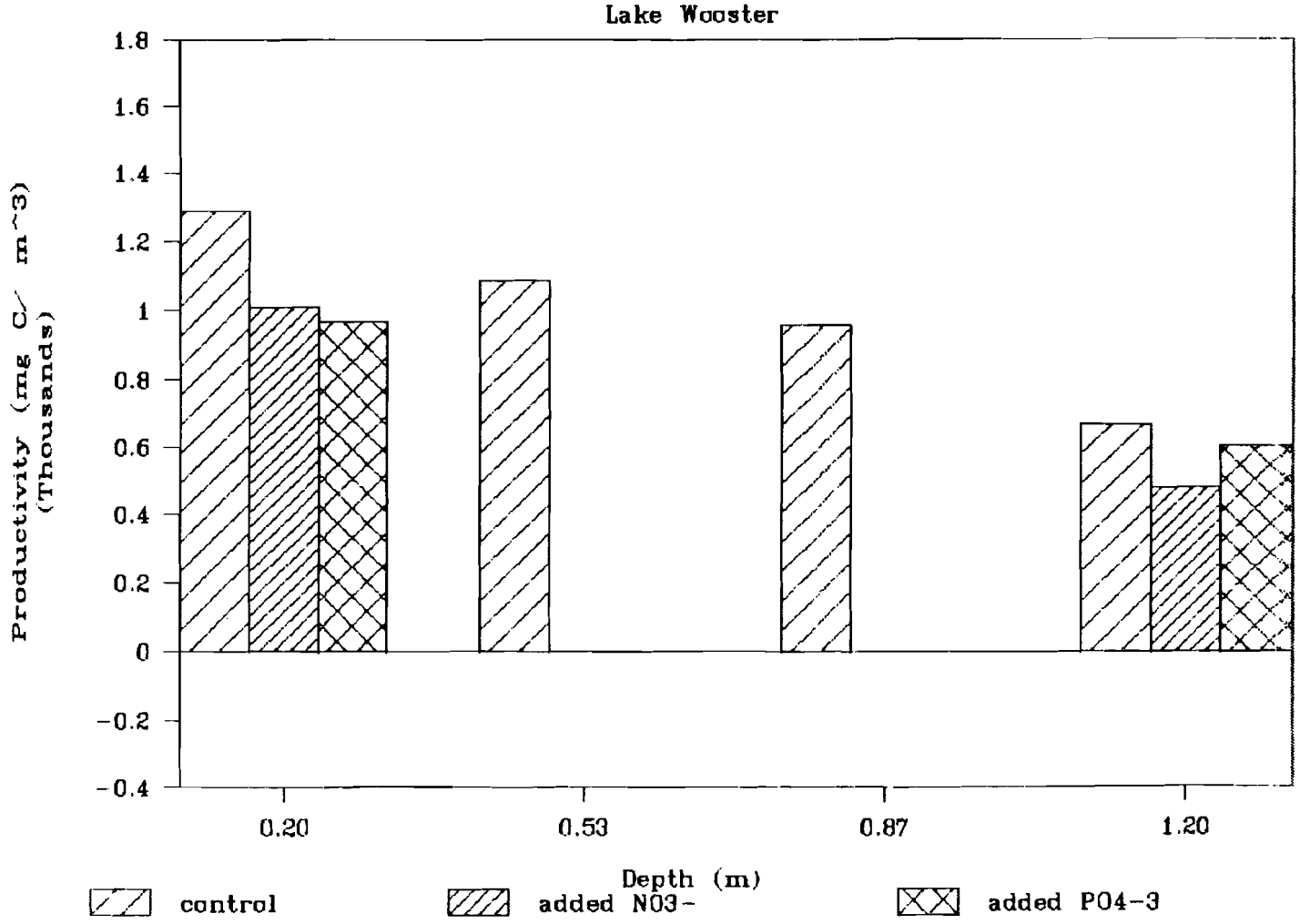


Fig 14. Productivity for Sept. 28, 1989

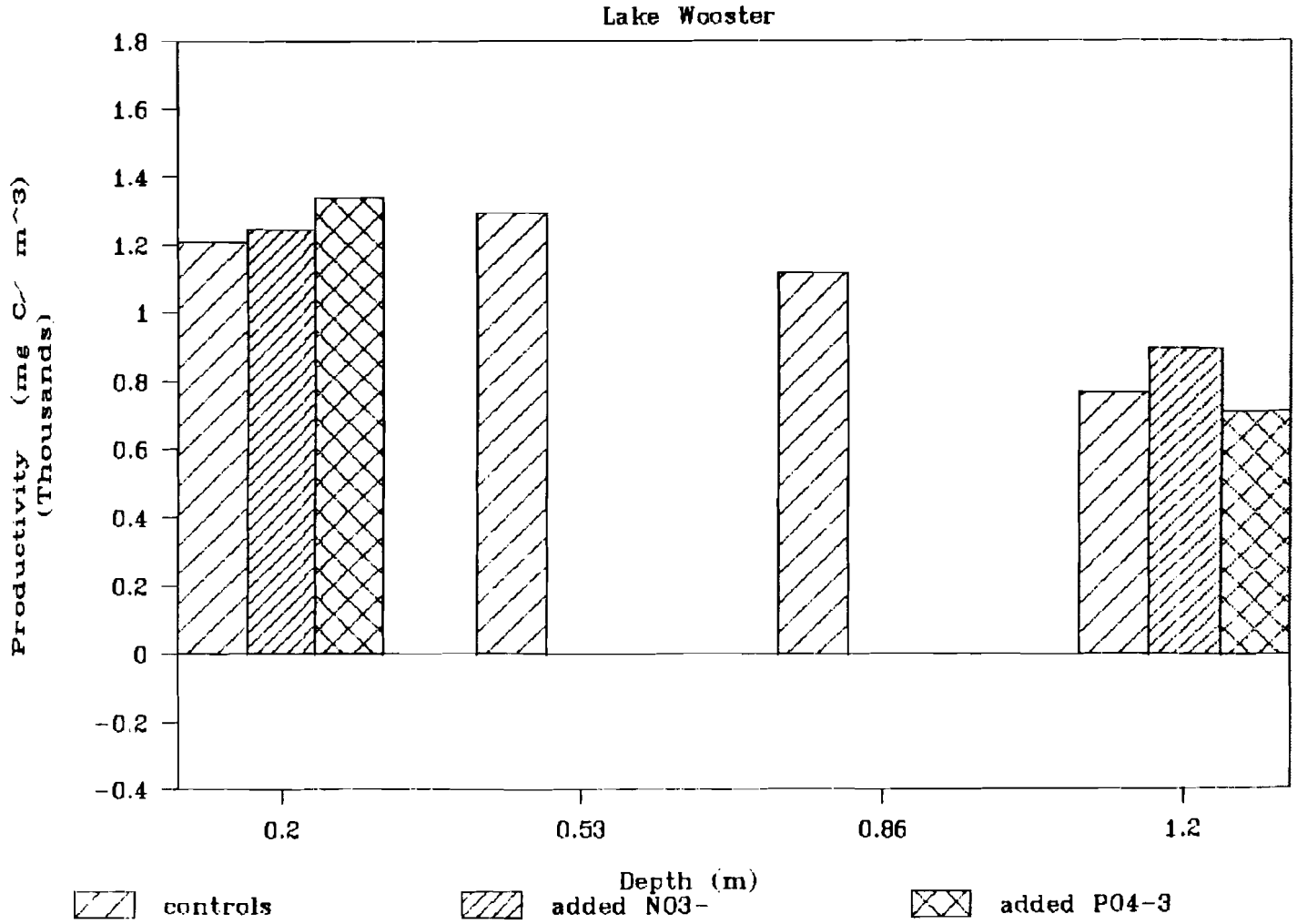


Fig. 15 Productivity for Oct. 12, 1989

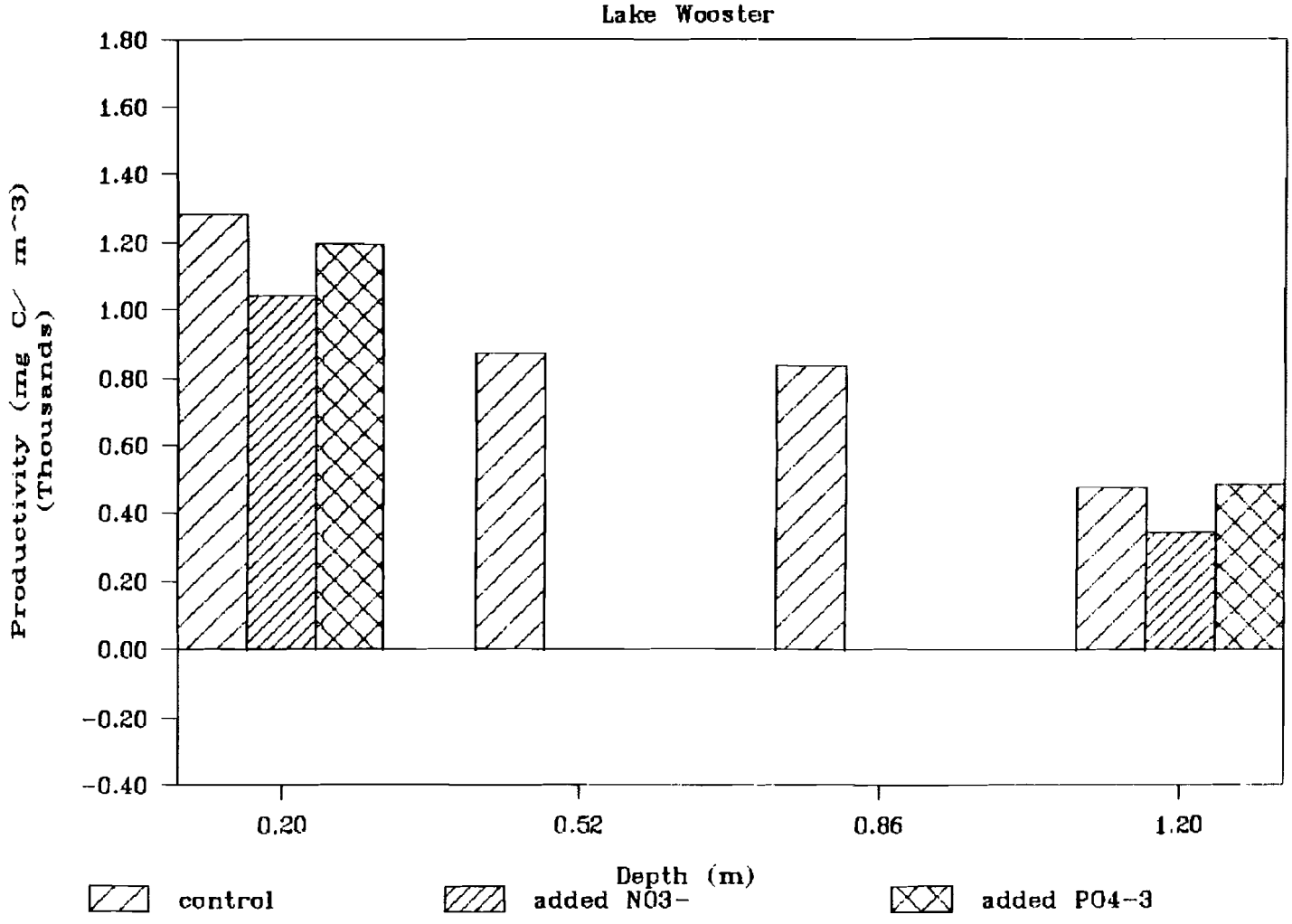


Fig. 16 Productivity for Oct. 19, 1989

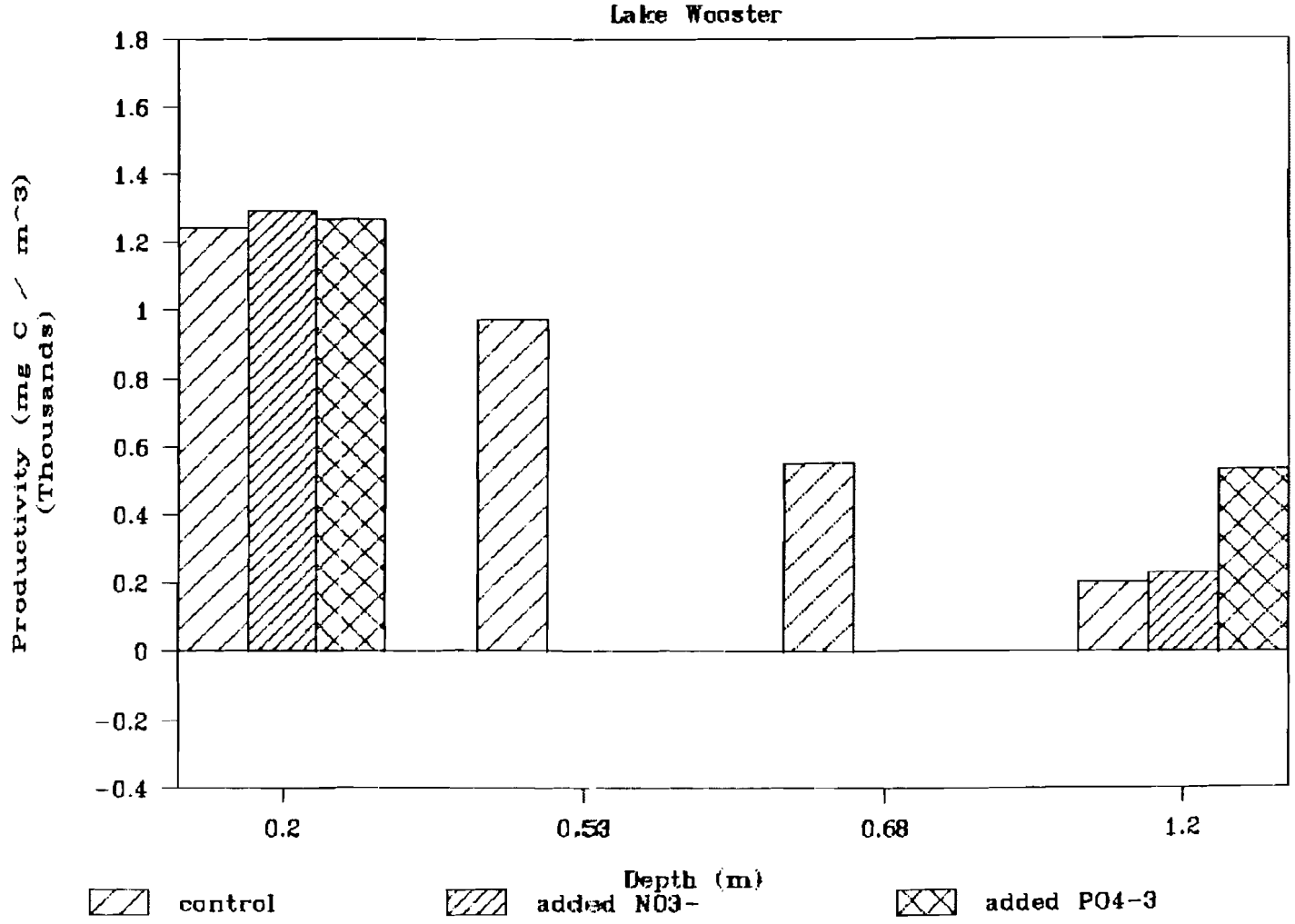


Fig. 17 Productivity for Nov. 30, 1989

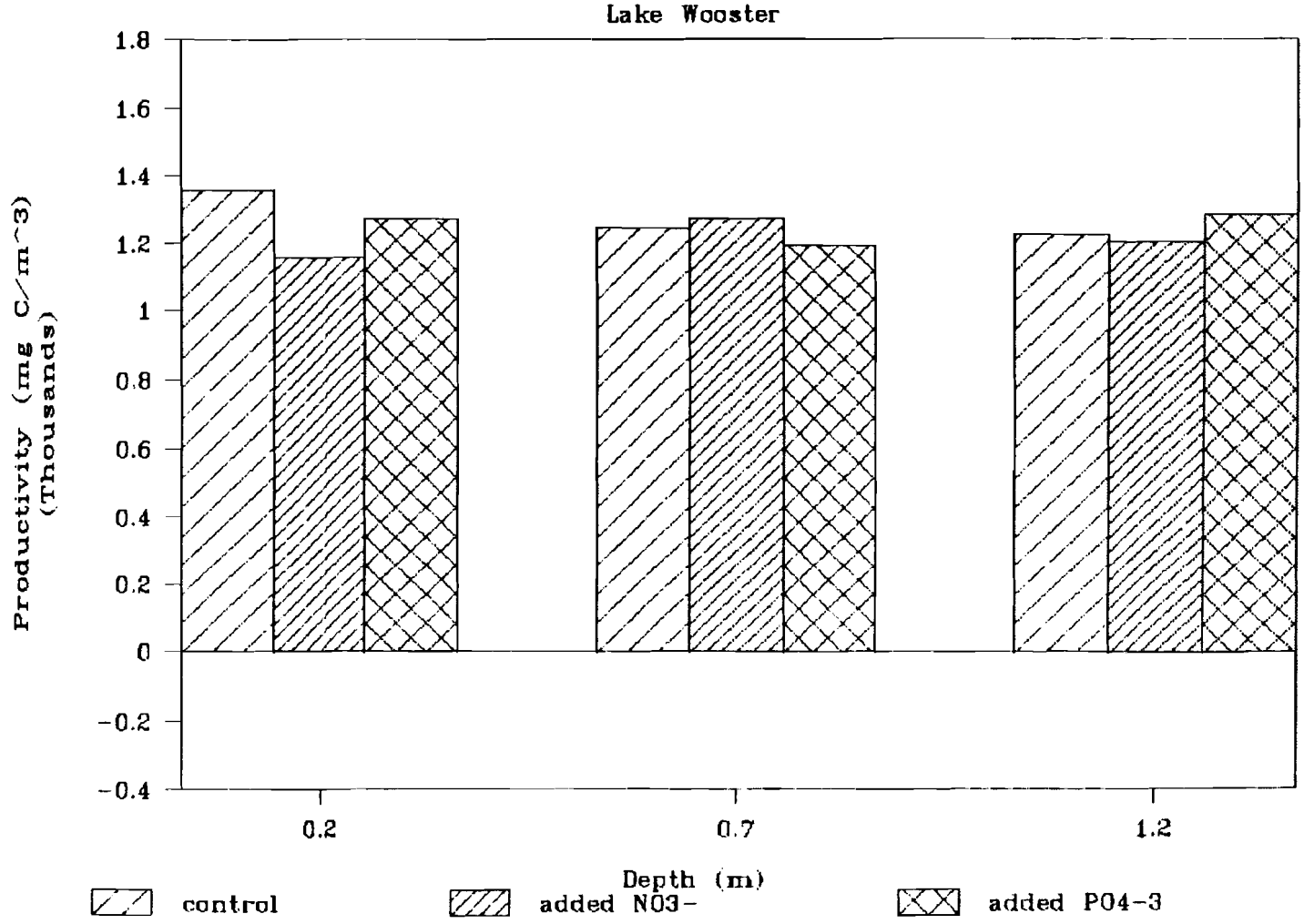


Fig. 18 Relative Light Intensity

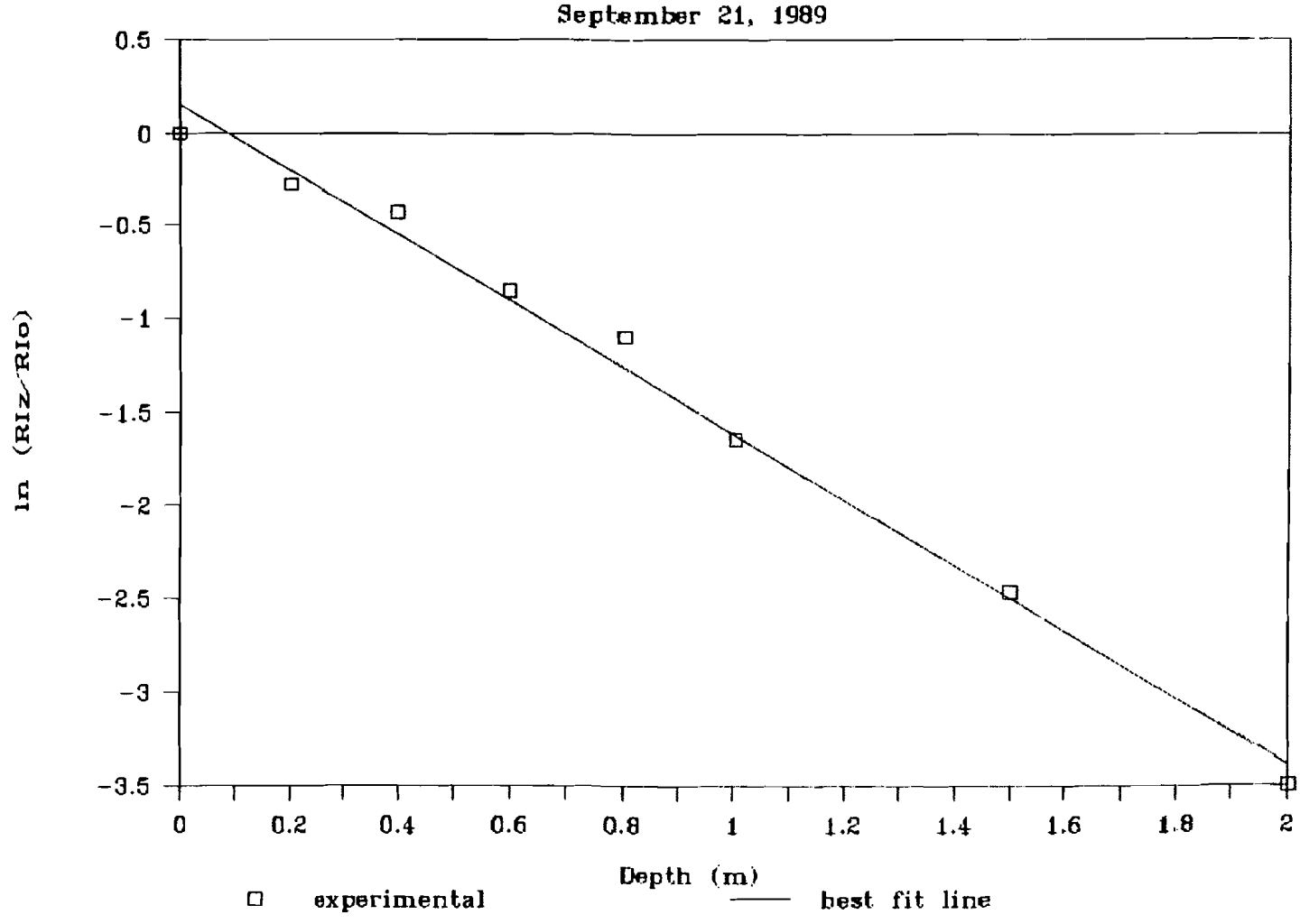


Fig. 19 Relative Light Intensity

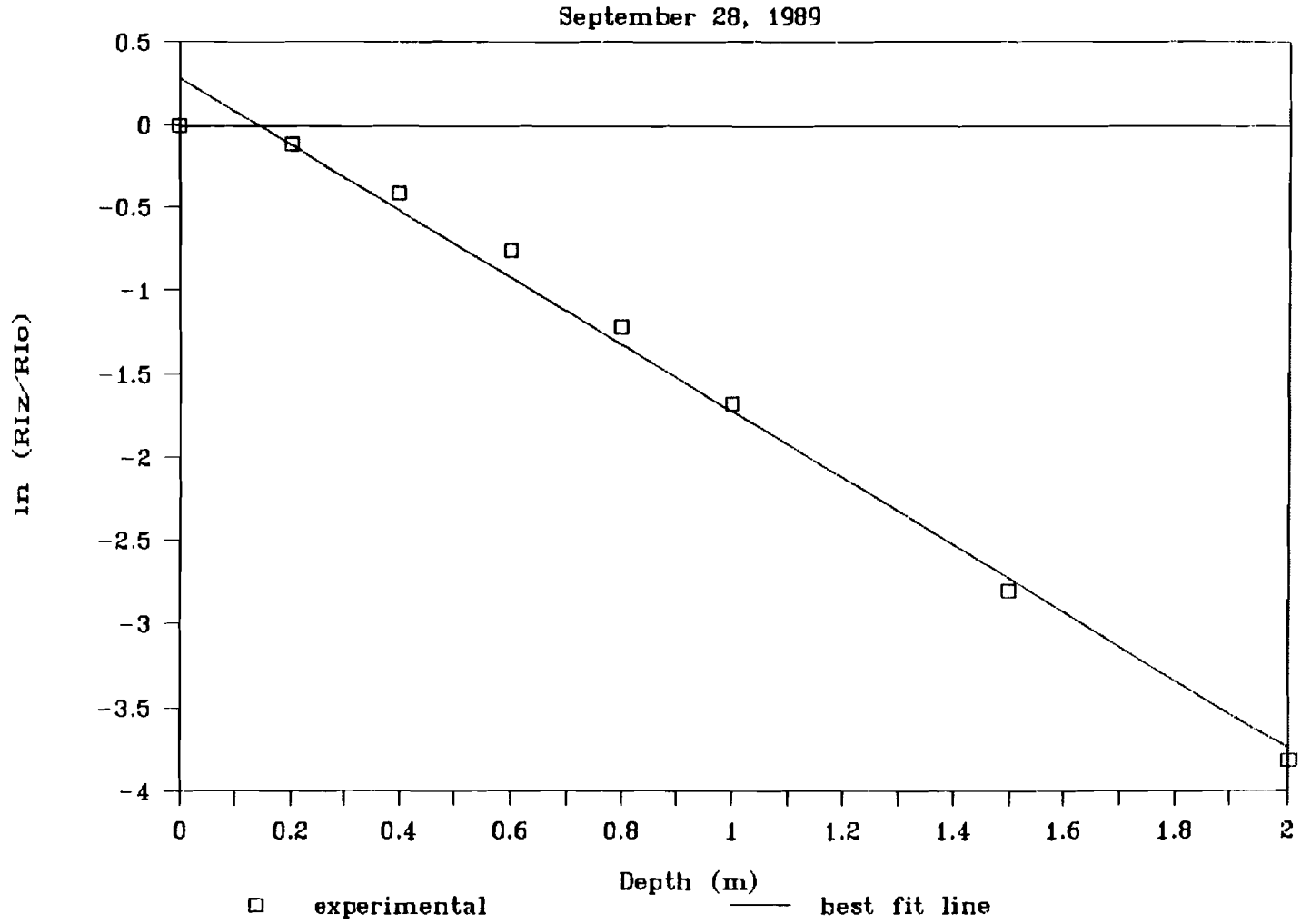


Fig. 20 Relative Light Intensity

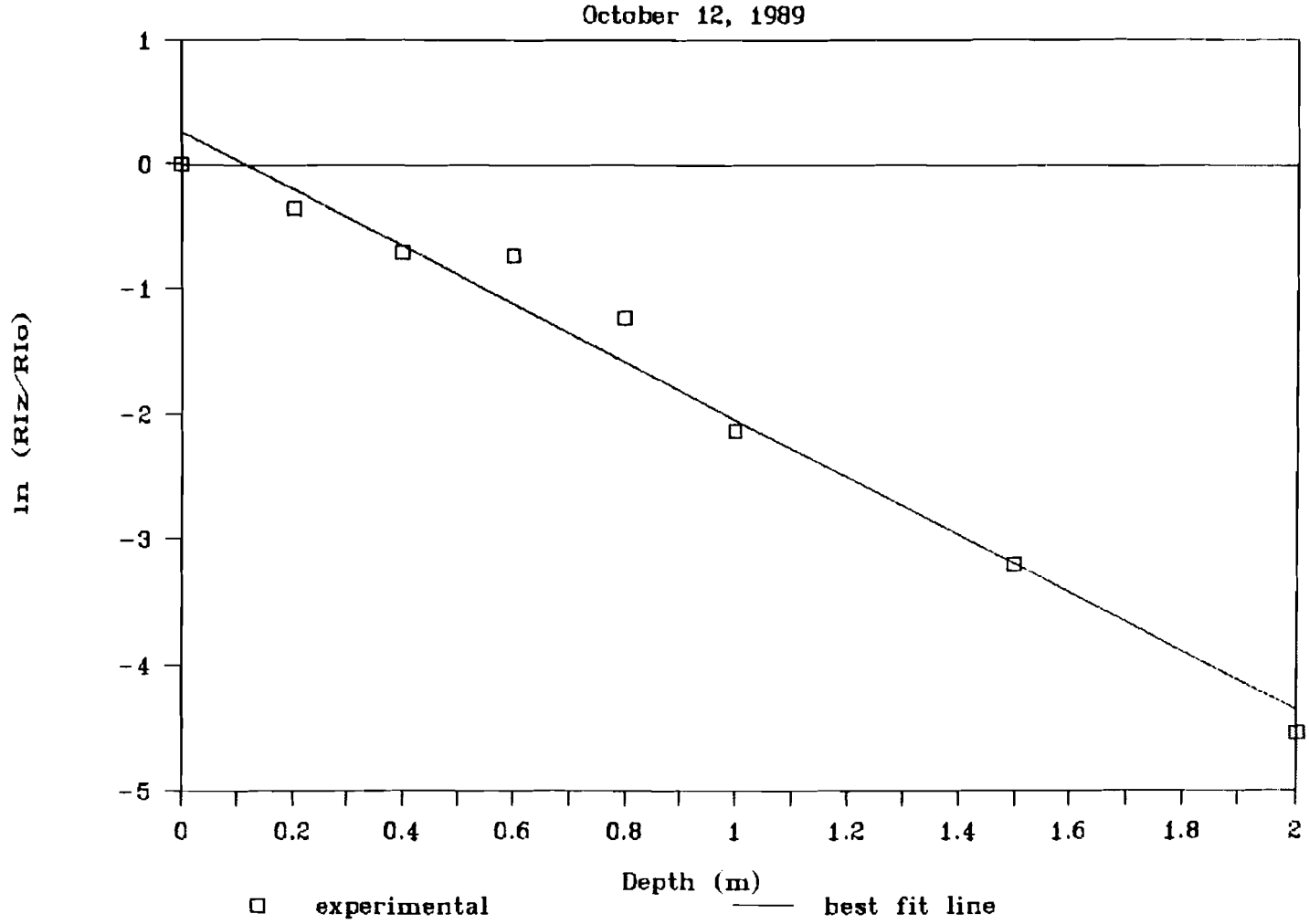


Fig. 21 Relative Light Intensity

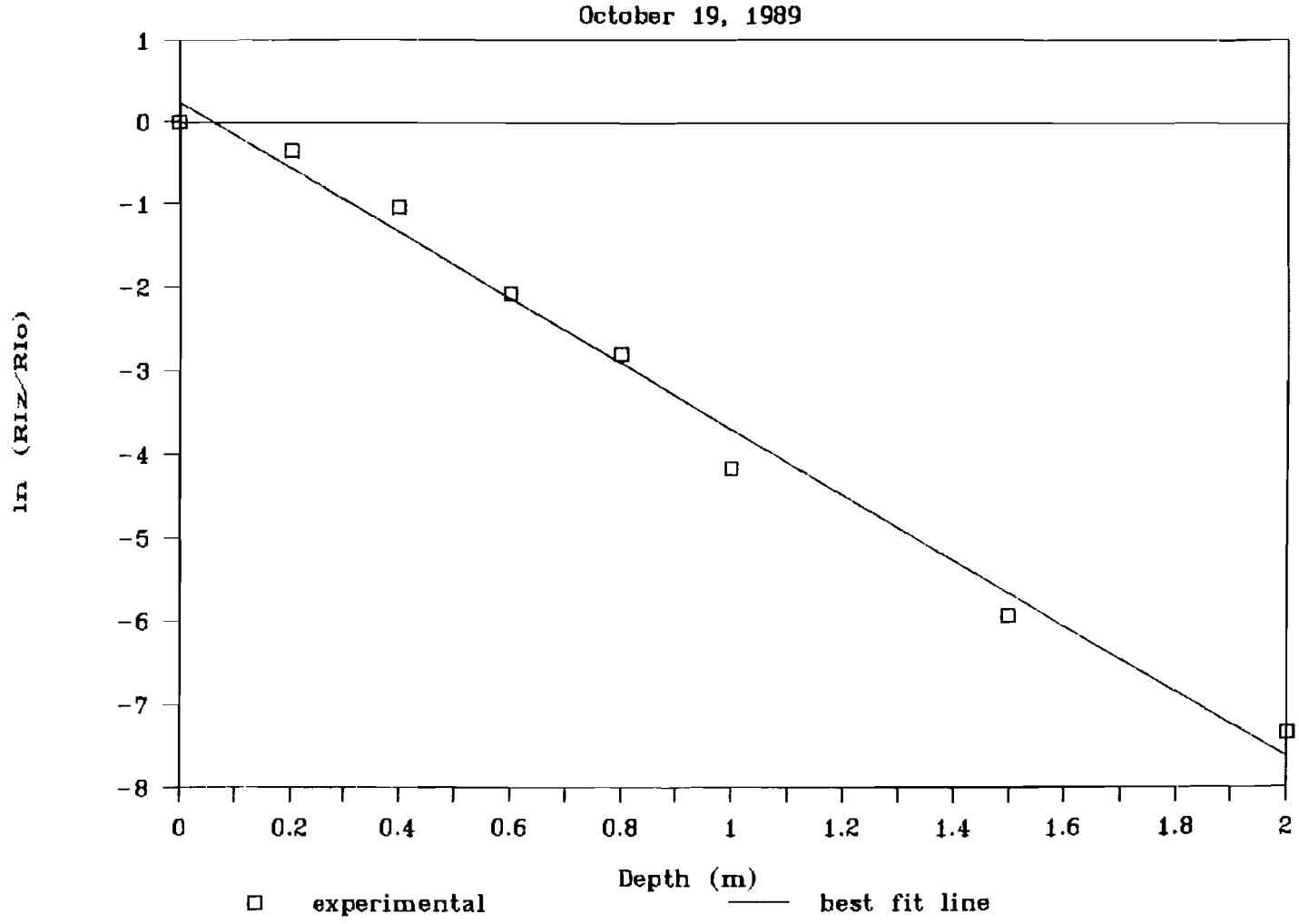


Fig. 22. Relative Light Intensity

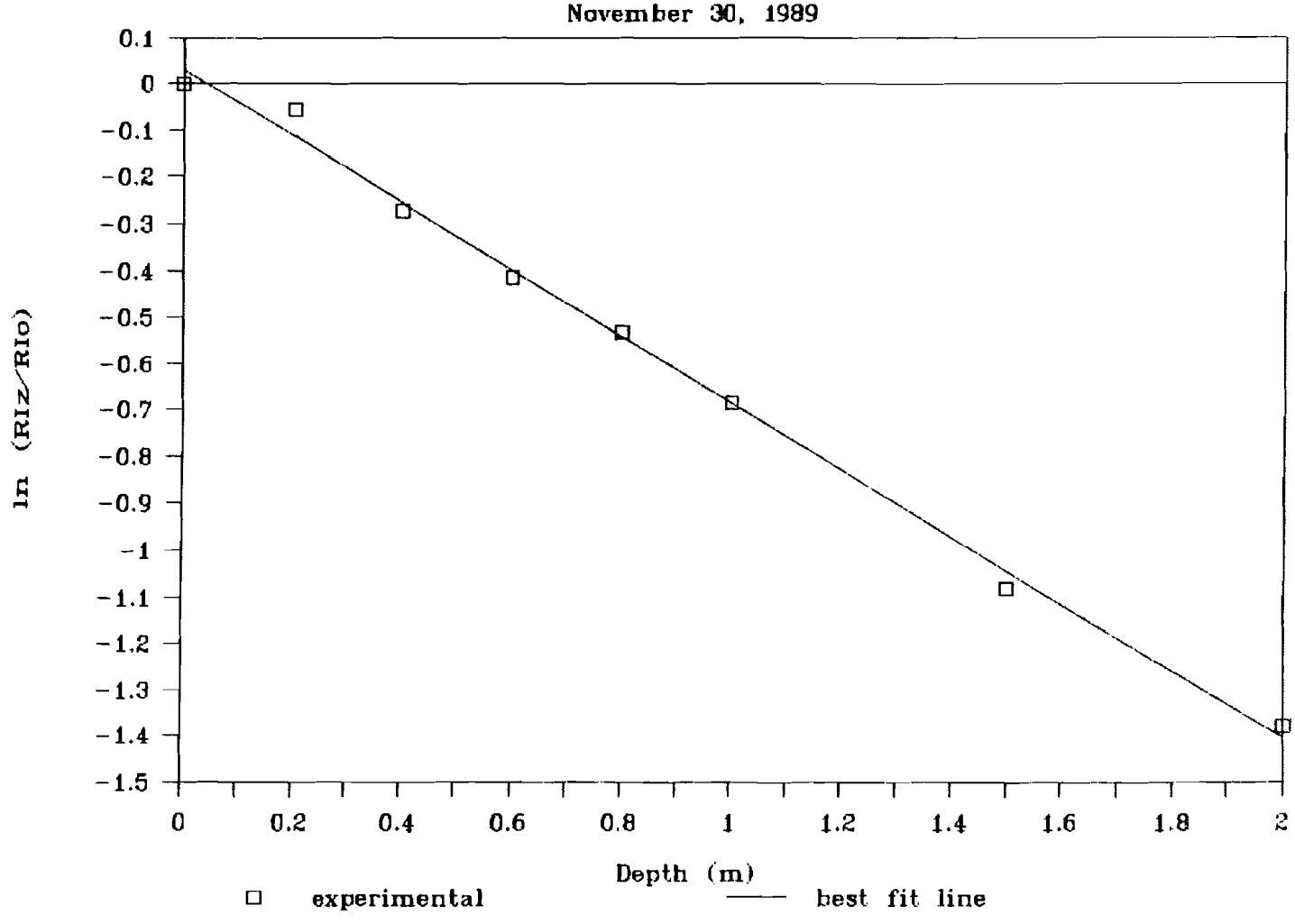
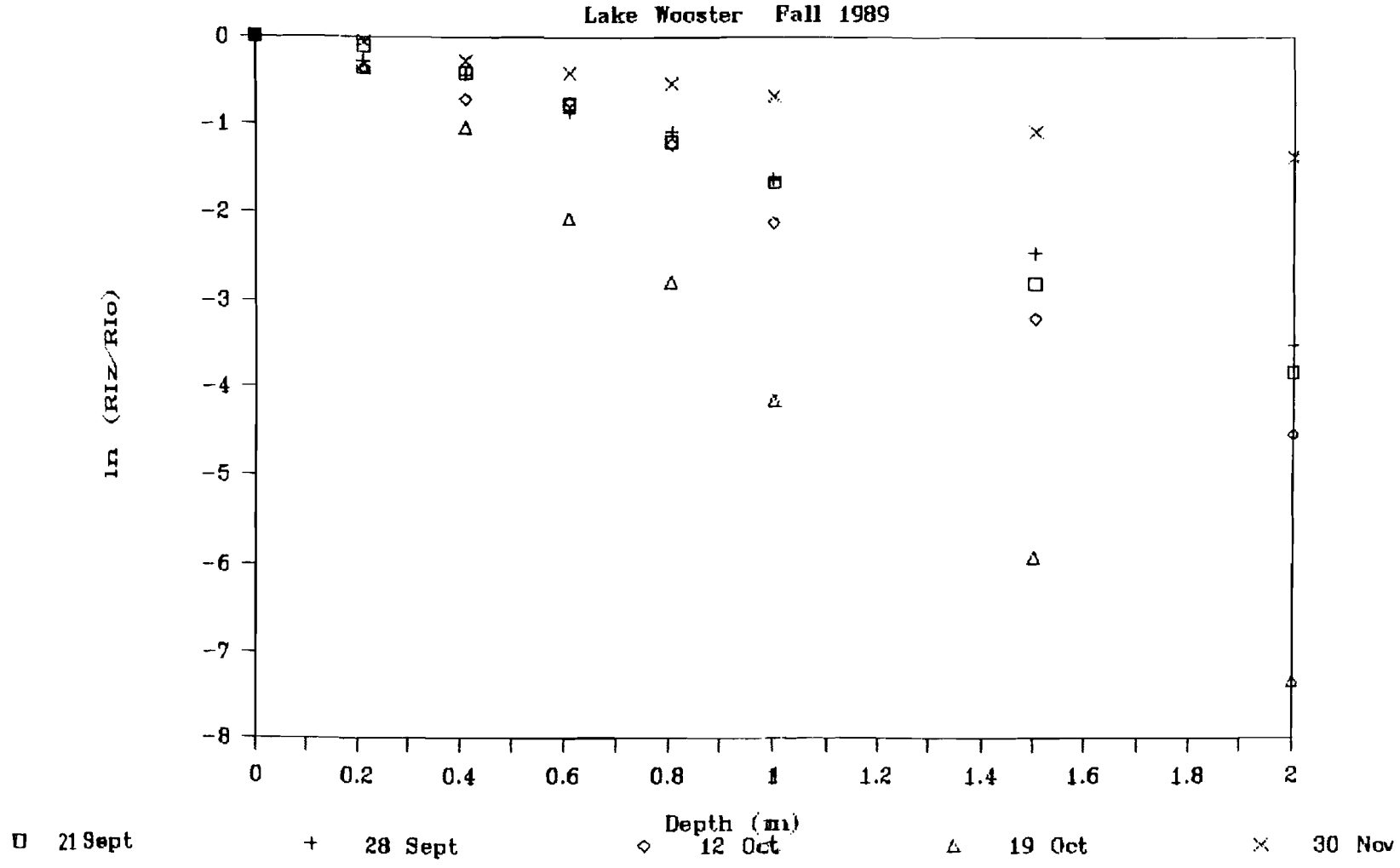


Fig. 23 Light penetration during bloom



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Signature of Author

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Date

The Role of Light and Nutrients in the Phytoplankton Productivity of Lake Wooster
Title of Thesis

Jacki Tolbert
Signature of Graduate Office Staff Member

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