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The Effects of Lime Application to Acid Bog Lakes
in Northern Michigan¹

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Abstract

To investigate the observed correlation between alkalinity and productivity of lake waters and to test the use of lime in bog lakes to increase biological productivity, lime application was made to two, acid, soft-water, colored bog lakes in the upper peninsula of Michigan. Lime application was made twice to each of the two lakes, once in the summer under thermally stratified conditions and once in the autumn under nearly homothermous conditions, by pumping a lime-water mixture into the surface waters. Total rate of lime application was 100 pounds per acre-foot in each lake.

The summer lime applications resulted in raising the pH and increasing alkalinity, total hardness and conductivity in the epilimnion only. The autumn application resulted in similar effects in the lower

hypolimnion, due to a fall of the lime solution to the bottom because of the greater density of the solution, which did not later mix with upper layers.

Lime application did not decrease the organic colloidal color.

Total phosphorus was greatly increased in the bottom waters of one treated lake which had had low original total phosphorus content but was not increased significantly in the bottom waters of the other treated lake where total phosphorus concentrations were originally high. Total phosphorus also increased temporarily in the epilimnion of one lake following the summer application.

A bloom of nanoplankton (Microcystis aeruginosa) was observed in one lake following the release of epilimnial phosphorus. Chemical data indicated that because of the presence of higher bicarbonate concentrations, the nanoplankton utilized carbon dioxide at a rate which may not have been possible without lime application. In both lakes the following summer, significantly higher standing crops of net phytoplankton were observed (principally due to Dinobryon sertularia). Increases in standing crop of zooplankton also occurred the year following lime application.

Introduction

A direct correlation between the biological productivity and alkalinity of lake waters has been observed and reported frequently (Ball, 1948; Moyle, 1949; and others). This correlation appears to hold generally true at the lower region of the range of alkalinity found in natural waters (lakes with soft to medium hardness), but at extremely high values

of alkalinity the correlation appears to be reversed with the result of "alkalitrophy" in hard-water lakes (Barrett, 1953).

In the upper peninsula of Michigan, despite the presence of calcareous glacial drift, many seepage lakes including colored bog lakes fall into the lower part of the alkalinity range; measurements reveal many waters of less than five p.p.m. total alkalinity. These lakes, for the most part, are characteristically of low productivity, as revealed by a paucity of plankton and bottom fauna, a scarcity of aquatic vegetation, and the slow growth of fish.

It was the purpose of the present experimental program to test the feasibility of increasing biological productivity of these waters by increasing the alkalinity through the application of hydrated lime. In Michigan the first attempt to alkalinize an acid lake was in 1943, when a small application of hydrated lime was made to a soft-water, non-bog lake by the Michigan Department of Conservation; the same lake was treated again in 1945, this time with limestone,² neither treatment

²Report on Stoner Lake, Alger-Delta County, Michigan by R. C. Ball, 1947. Unpublished report.

effecting any significant changes in alkalinity. In 1952, the same lake again was incorporated in an experimental alkalination program which continued through 1955 (Ms. in preparation). The use of lime in treating bog lakes was investigated in Wisconsin in 1948 by Hasler, Brynildson and Helm (1951). They offered several suggestions as to the mechanisms by which productivity might be increased by lime application in colored bog

lakes. The color—caused by humic colloids—would be flocculated and precipitated through combination with calcium, thus permitting deeper light penetration and increasing the volume of the trophogenic zone. Secondly, alkalization of the water would mobilize nutrients which are fixed in unavailable organic forms in the lake soils. Finally, a higher concentration of bicarbonates would result, offering available carbon dioxide to plants for photosynthesis in higher concentration. Following their experiment, they reported that the lime treatment resulted in clearing the color from the water and improving oxygen conditions for trout in the deeper, cooler levels of the lakes, but showed no striking differences in nutrient content of the water. It was later reported (Johnson and Hasler, 1954) that no apparent increase in production or carrying capacity resulted.

In the summer of 1953 the present research program was initiated upon two bog lakes in the upper peninsula of Michigan. Three postulates were made regarding the mechanisms by which biological productivity might be increased by the use of lime, and the sampling program was designed to test these postulates: (1) a greater concentration of bicarbonate alkalinity, offering more available carbon dioxide for photosynthesis, would result; (2) phosphorus would be released either by increased decomposition activities or through ion-exchange phenomena in the mud; and (3) the colloidal organic color would be decreased by flocculation and precipitation caused by combination with calcium.

The two bog lakes used in the experiment, Timijon and Starvation lakes, are both located in the Hiawatha National Forest, an area which contains many small bog lakes of the colored, acid, soft-water type.

Timijon Lake, T. 44 N., R. 18 W., Sec. 19, Schoolcraft County, was 2.0 acres in surface area with a maximum depth of 42 feet, and Starvation Lake, T. 44 N., R. 19 W., Sec. 1, Alger County, was 1.7 acres in surface area with a maximum depth of 42 feet. Both lakes were completely surrounded by an encroaching sphagnum-leatherleaf bog mat; the waters were acid (approximately pH 5), very soft (3 to 5 p.p.m. total hardness), and colored by humic colloids. The bottom types in both lakes were of brown fibrous peat near the mat and of a fine, gelatinous pulpy peat in the deepest regions of the lakes. Both lakes appeared to be meromictic.

Methods of lake sampling and lime application

A periodical sampling program was initiated in the summer of 1953 consisting of the chemical analysis of the water and the collection of two net plankton samples approximately every ten days from each of the following four levels: central epilimnion (always three feet), top of thermocline, central hypolimnion, and bottom waters (one foot above the mud-water interface). Chemical analysis consisted of the determination of dissolved oxygen, free carbon dioxide, pH, alkalinity, total hardness, conductivity, color, and total phosphorus. Air and water temperatures, weather data and light penetration (Secchi disk) were also recorded. The plankton from a ten-liter sample was collected with a Juday plankton trap and analyzed volumetrically by counting the organisms under a microscope in a Sedgewick-Rafter cell and determining average volumes of each species by measuring with a calibrated ocular micrometer.

Lime applications were made twice to each lake during 1954, the first during the summer under conditions of thermal stratification and the

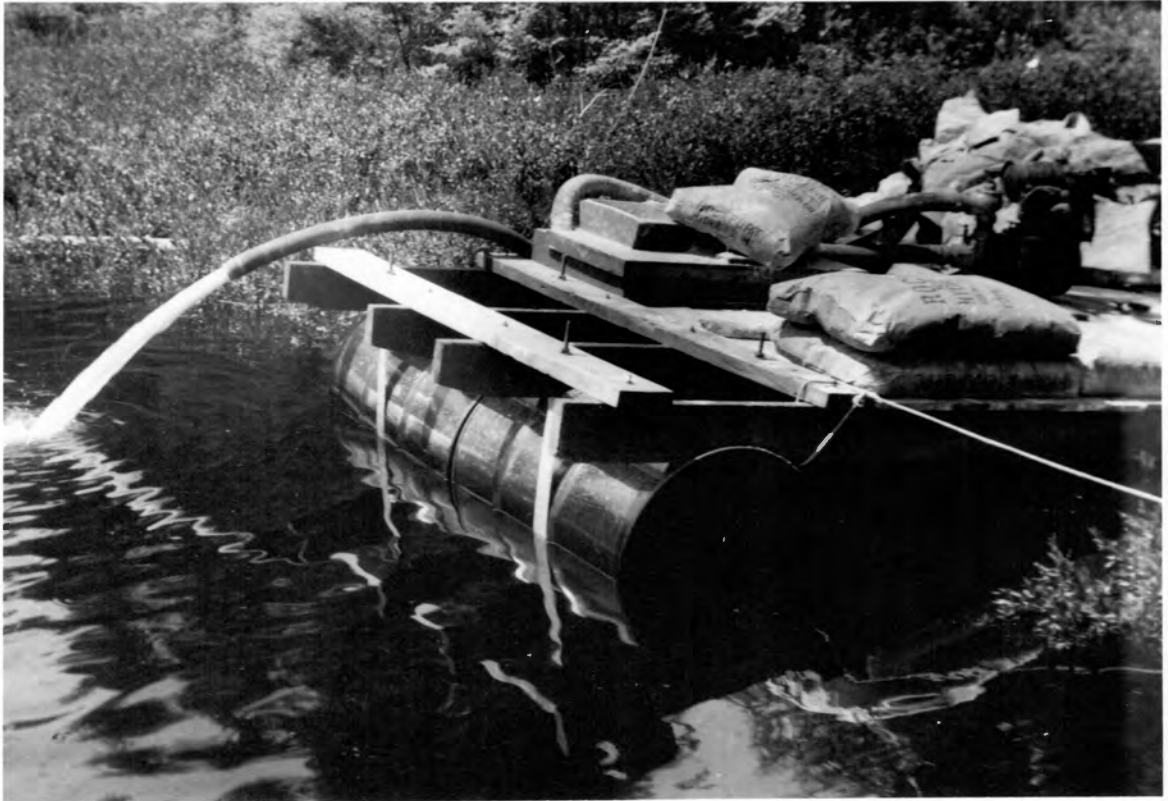
second in the fall when the lake waters were nearly homothermous. For all applications, a raft-and-pump system was employed which mixed the lime with water and discharged the mixture into the surface waters. The apparatus consisted of a raft ten feet long and six feet wide, supported in back by the edge of the bog mat and in front by two floating 50-gallon drums. Through a rectangular hole in the raft was lowered a plywood mixing tank which allowed the intake of water at the bottom of the front side of the tank; a hopper was constructed at the top of the mixing tank through which the lime was introduced. The intake hose of the pump was placed in the mixing tank, where both lime and water were taken up, carried through the mechanism of the pump and through the exhaust hose of the pump, to be finally discharged into the lake (Figure 1). A total rate of application of 100 pounds hydrated lime per acre-foot was applied in this manner to each of the two lakes, half this amount being applied at each of the summer and fall applications. The summer application in Starvation Lake was made as rapidly as possible, and when the apparent destruction of the plankton resulted from the precipitous chemical changes the subsequent summer application to Timijon Lake was made at a more gradual rate through most of the summer; the discharge point for the summer application to both lakes was immediately in front of the raft. Both fall applications were made rapidly, with the discharge point being near the center of the lake.

Immediate effects of lime application

Because of the strong thermal stratification present during the summer applications, the immediate effects of the lime were felt only in the epilimnion and no chemical changes were observed below the thermocline.

Figure 1.—Summer lime application to Starvation Lake,
showing raft-and-pump system.

Figure 1.



The chemical effects in the epilimnion, however, were abrupt and large. Figure 2 shows the changes in pH and alkalinity in the central epilimnion of Starvation Lake, where the application was made rapidly, while Figure 3 shows the pH and alkalinity in the central epilimnion of Timijon Lake where lime applications were made throughout the summer.

At the fall application when the lake waters were nearly homothermous, almost the entire application of lime fell to the bottom, apparently because of the greater density of the lime solution, with little mixing in the upper levels of the lakes. Because of the meromictic character of the lakes the lime solution remained at the bottom and did not later circulate through the upper levels. In the bottom waters of Starvation Lake, the pH rose from about 6 to 11, while total alkalinity increased from 17 to 128 p.p.m. In Timijon Lake, at the same level, pH values also rose from about 6 to 11, and total alkalinity increased from 13 to 175 p.p.m.

Changes in total hardness and conductivity, in both the epilimnion and hypolimnion, in both lakes, generally followed those of total alkalinity. No decrease in color was observed following the lime applications in either lake.

Release of phosphorus from lake soils

Preliminary laboratory experiments.—To obtain some information upon the possibility of a release of phosphorus from the lake soils upon lime application, the following experiments were carried out in the laboratory prior to the field experiments involving lime application to the lake. The general pattern of these experiments was to add hydrated lime at known rates of application to bottles containing water and mud from the lakes

Figure 2.—pH and alkalinity in the central epilimnion,
Starvation Lake.

Figure 2.

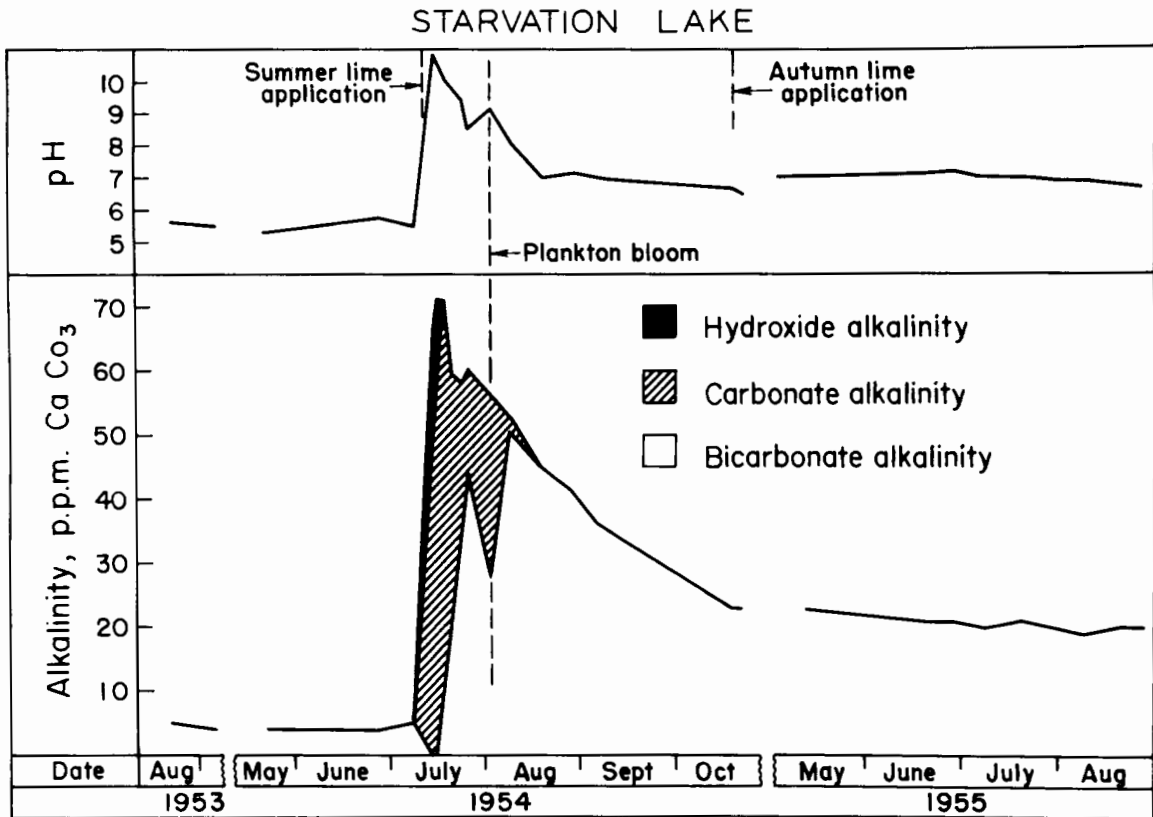
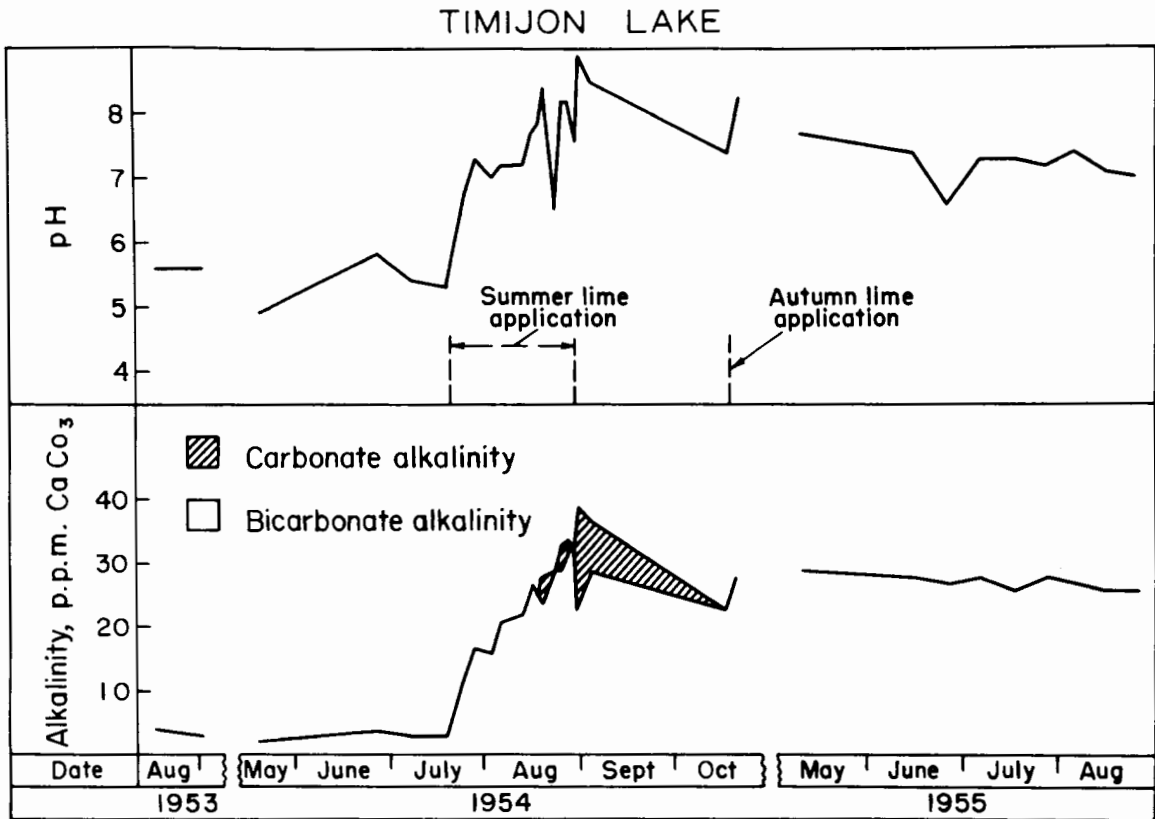


Figure 3.—pH and alkalinity in the central epilimnion,
Timijon Lake.

Figure 3.



and subsequently to analyze the water for dissolved phosphorus. Three mud-water combinations from each of the two bog lakes were treated with lime: (1) surface water with mud, (2) bottom water with mud, and (3) surface water without mud (control). Six different rates of lime application were used: 0 (control), 25, 50, 100, 150, and 200 pounds per acre-foot. The experimental unit consisted of a two-quart jar containing 50 milliliters of mud, taken from the mud-water interface, and one liter of water. The lime was added by dissolving weighed amounts of lime with water from the experimental bottles and adding the solution to the bottle. Water samples were extracted for analysis by pipette three days after the lime addition.

The results are shown in Figure 4, where it can be seen that dissolved phosphorus concentrations were higher at the higher rates of lime application; this was true in all series containing mud except that series including Starvation Lake bottom water, where the dissolved phosphorus concentration was originally high. In both control series (no mud) there were no increases in dissolved phosphorus concentrations with lime application, indicating that the higher phosphorus concentrations observed in the other series resulted from the presence of mud.

Field experiments.—Immediately following the rapid lime application during the summer in Starvation Lake total phosphorus increased from approximately 15 p.p.b. before application to a high of about 70 p.p.b. in the central epilimnion, as shown in Figure 5. A similar increase to about 60 p.p.b. occurred at the top of the thermocline level. The high values decreased soon after to values near those existing before lime application. It is suggested that the source of released phosphorus was

Figure 4.—Dissolved phosphorus in experimental bottles of lake
water and mud treated with lime.

Figure 4.

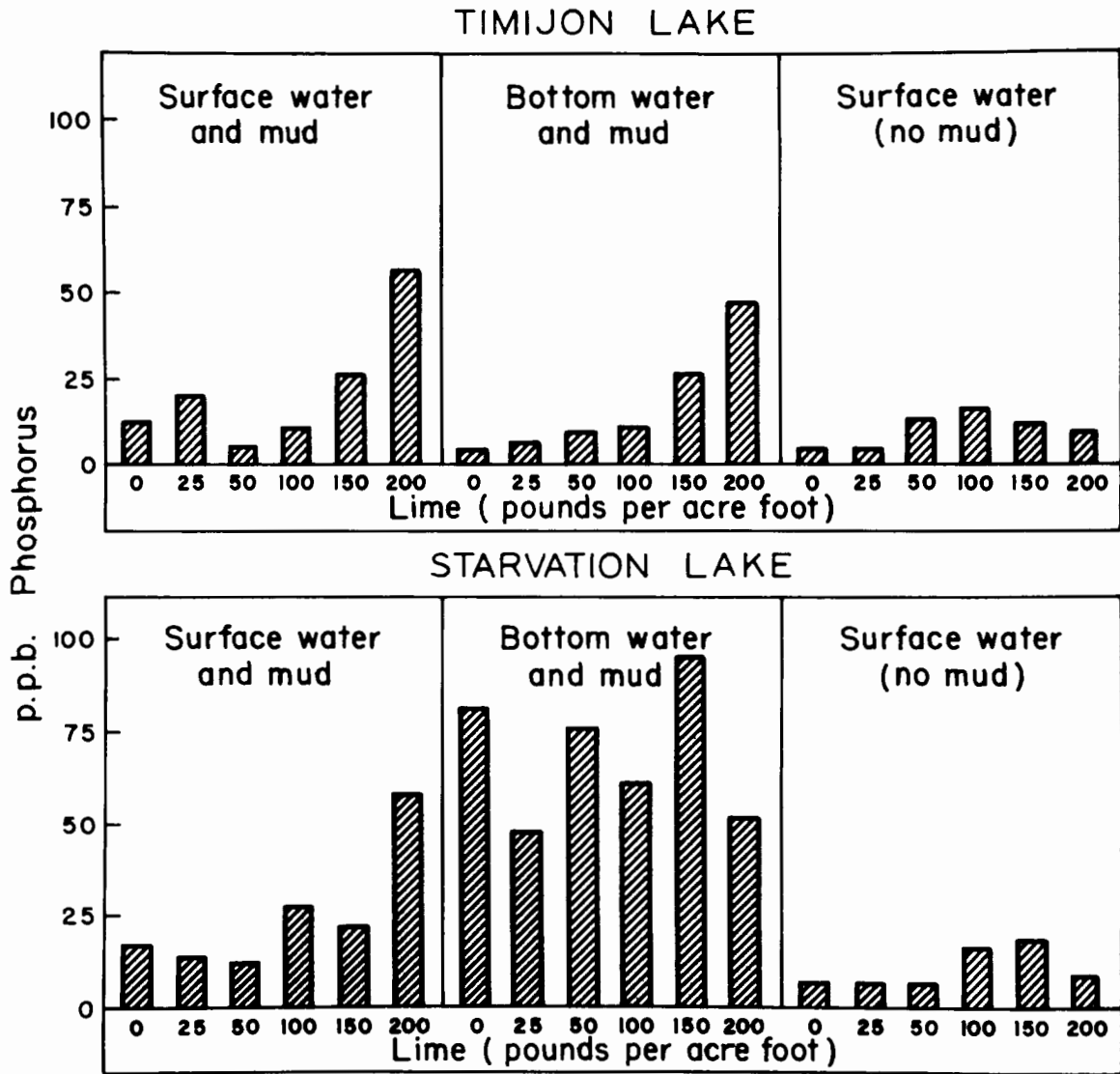
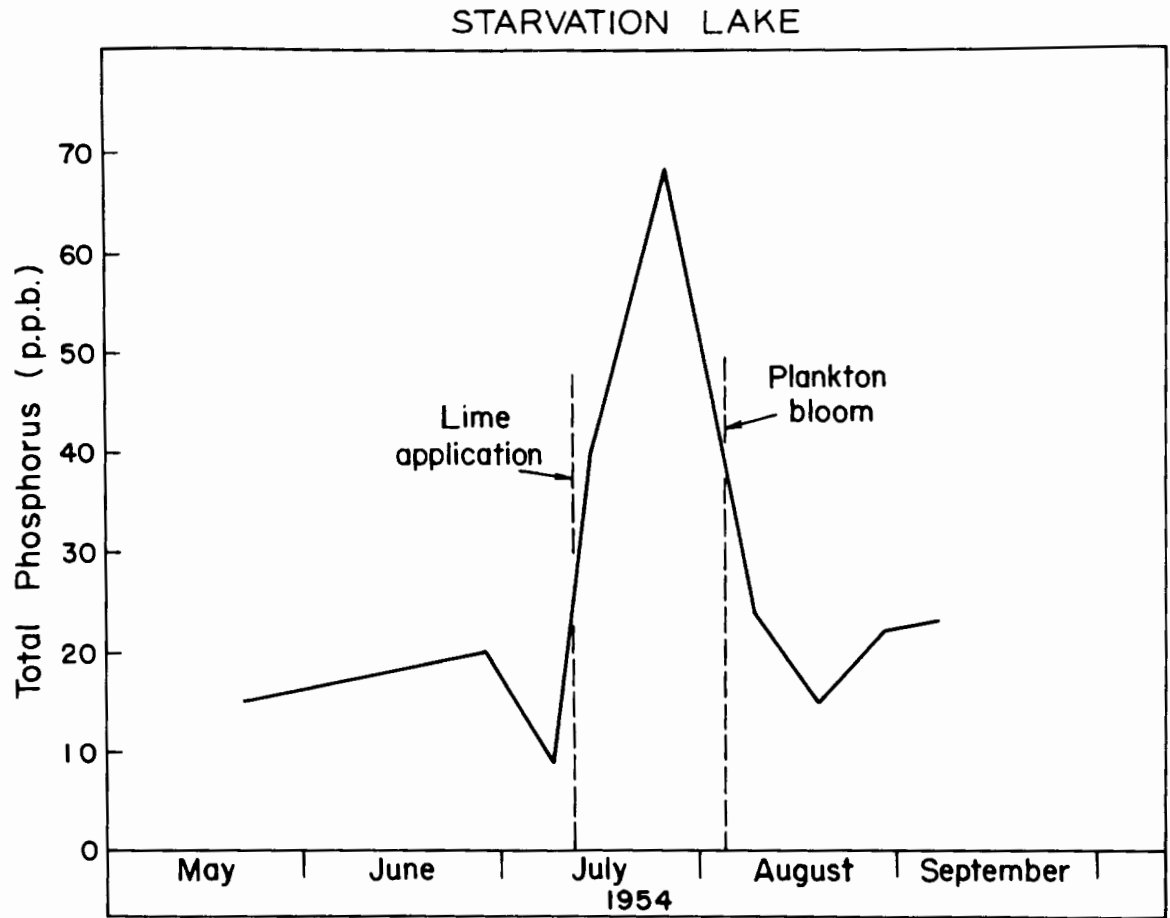


Figure 5.—Total phosphorus in central epilimnion, Starvation
Lake, 1954.

Figure 5.



in the bottom mud in those shallower areas of the lake where epilimnial waters, originally containing low concentrations of phosphorus, came into contact with the bottom. These conditions are essentially those produced in the bottle experiments with "mud and surface water," where the release of dissolved phosphorus was observed. (The possibility of the increased phosphorus being due to its presence in the liming material was eliminated after analysis of the lime showed no significant amounts of soluble phosphorus.) In Timijon Lake, where the summer lime application was made gradually through the summer, no significant increases in total phosphorus were observed in the epilimnion.

Following the fall lime application to Timijon Lake, which fell almost entirely to the bottom, a large increase in total phosphorus was observed in the bottom waters. This increase was from a mean of 23 p.p.b. before the fall application (1954) to a mean of 156 p.p.b. after the fall application (1955); a t-test showed the difference to be highly significant. This result was essentially the same as obtained in the laboratory bottle experiments with "mud and bottom water," where the release of dissolved phosphorus was observed. In Starvation Lake, where the bottom waters originally contained high concentrations of total phosphorus, no significant increase in total phosphorus occurred following the fall application; this result was similar to that observed in the bottle experiments with Starvation Lake "bottom water and mud."

The release of phosphorus upon alkalization may be accomplished by one or both of two mechanisms. The first is by mineralization of organic phosphorus through decomposition. Acid conditions, such as are found in bog lake waters and muds, have inhibitory effects upon the micro-organisms

responsible for decomposition of organic matter and the subsequent mineralization of nutrients. It is well established that the addition of liming materials, where such acid conditions exist in soils, improves conditions for decomposition of micro-organisms and, therefore, hastens decomposition (for general discussion see Lyon, Buckman, and Brady, 1953, p. 139, and Waksman, 1938, p. 349). Secondly, phosphate ions may be released through anion exchange; in the case of the addition of lime, an anion exchange between phosphate and the introduced hydroxide radicals is probably the reaction involved. Anion exchange involving phosphorus in soils may concern phosphate adsorbed to clay minerals, organic colloids, and hydrated aluminum and iron oxides. It is not likely that clay minerals will be found in a bog lake, so the sources of exchangeable phosphate are most likely to be colloidal hydroxides and organic matter. In a general discussion of anion exchange in soils, Wiklander (1955) describes anion exchange mechanisms in clay minerals and hydrous oxides, and says, "Humic acids take part in anion exchange, as evidenced by their power of releasing adsorbed phosphate, but the exact mechanism is not known." Where releases of phosphorus were observed in the present study no data were collected to suggest which of the above two mechanisms, i.e., increased decomposition or anion exchange, were in operation.

From the practical standpoint, the release of phosphorus due to increased decomposition would have greater importance than that due to anionic exchange. In the former mechanism, the source of phosphorus to be mineralized is in almost inexhaustible supply and might be incorporated in a more balanced organic matter cycle, while in the latter

mechanism, the supply of exchangeable adsorbed phosphate ions may soon become exhausted, a phenomenon which has been observed in the use of lime to release nutrients in European carp ponds (Neess, 1949).

The value of applying lime to increase phosphorus concentrations in hypolimnial waters, such as occurred in Timijon Lake, when such waters appear never to enter into circulation with upper waters, may be questioned when such methods are applied in lake management. The bottom water of Starvation Lake contained original high concentrations of phosphorus; yet biological productivity in this lake (as measured by standing crop of plankton) was no greater than in other bog lakes lacking such high concentrations of phosphorus in the hypolimnion. Such phosphorus release can probably best be utilized in lakes which stratify yet still are holomictic; in these lakes phosphorus, released in the hypolimnion under deoxygenated conditions during the summer stratification period, would be transported to the upper trophogenic zone during fall and spring circulation periods.

Effects of alkalization upon plankton production

The immediate effects of the rapid summer lime application to Starvation Lake apparently resulted in a partial destruction of the plankton. The subsequent lime application to Timijon Lake was made gradually throughout the summer; however, the gradual application also appeared to destroy much of the plankton. Whipple (1948, p. 405) discusses the use of hydrated lime as an algicide and says that lethal effects are probably due to the loss of carbon dioxide available for photosynthesis or to changes in hydrogen ion concentration.

In Starvation Lake, after the pH in the central epilimnion had decreased from its high of near pH 11 following the summer lime application to about pH 8 (the point near which free carbon dioxide should appear), a definite plankton bloom of Microcystis aeruginosa Kuetz. was observed. This organism is a member of the Cyanophyta (blue-green algae); it was not observed prior to lime application nor were any other members of the blue-green group ever observed in either lake. The bloom did not appear among the quantitative data secured from the plankton samples collected because the organism was apparently too small to be retained by the plankton net (silk bolting cloth number 20). The bloom was, however, obvious to the eye; it gave a definite green color to the water and collected in windrows of "scum" along the lee shores of the lake at the edge of the bog mat. The date when it was most strikingly observed was August 2, 1954, and chemical data for this same date reflected the effects of the bloom. Dissolved oxygen increased markedly from the previous sampling date, from 2.8 to 10.5 p.p.m.; a rise in pH was observed with a corresponding shift in the form of alkalinity from the bicarbonate form to the normal carbonate form, these being the results of carbon dioxide extraction from the bicarbonates (see Figure 2). The Secchi disk reading was decreased markedly. The bloom occurred while the phosphorus content of the epilimnion was high (after the release of phosphorus in the epilimnion) which decreased after the beginning of the bloom (see Figure 5).

During the summer of the following year (1955) the standing crops of both phytoplankton and zooplankton were observed to reach much higher levels than before lime application in both lakes, as shown in Figures

6 and 7. The organism principally comprising these large standing crops of net phytoplankton in both lakes was Dinobryon sertularia Ehrenberg, a member of the Chrysophyta (yellow-green algae) which had not been observed in either lake prior to lime application. There were no changes in pH or in the form of alkalinity attributed to these large standing crops of phytoplankton in 1955, giving no indication of carbon dioxide extraction from the bicarbonates. Figures 6 and 7 exclude data concerning one species of algae, Peridinium limbatum (Stokes) Lemmermann; this organism was omitted from the net plankton volume analyses because of the extreme variation it caused as a result of its relatively large size and scattered occurrence in the cell counts.

In considering the question of whether a causal relationship exists between alkalinity and productivity, differentiation should be clearly made between fertilization and lime application. In the former, the effects are principally direct ones; i.e., nutrients are supplied to the lake waters which are utilized directly by producing plants. The latter procedure is more a case of chemical modification and the effects are principally indirect: (1) nutrient availability is improved due to more optimum reactions (pH) and ion concentrations, and (2) a greater concentration of immediately available carbon dioxide results.

The events which occurred in Starvation Lake in 1954 soon after the summer lime application provided the necessary data to calculate the rate of carbon dioxide production by the lake and also the rate of its utilization under conditions of a plankton bloom, for the central epilimnion level. In Figure 2, the graph for bicarbonate alkalinity shows a linear increase between the dates of July 15, 1954, and July 25,

Figure 6.—Average volume of wet phytoplankton
in cubic millimeters per liter in central epilimnion,
Timijon and Starvation lakes.

Figure 6.

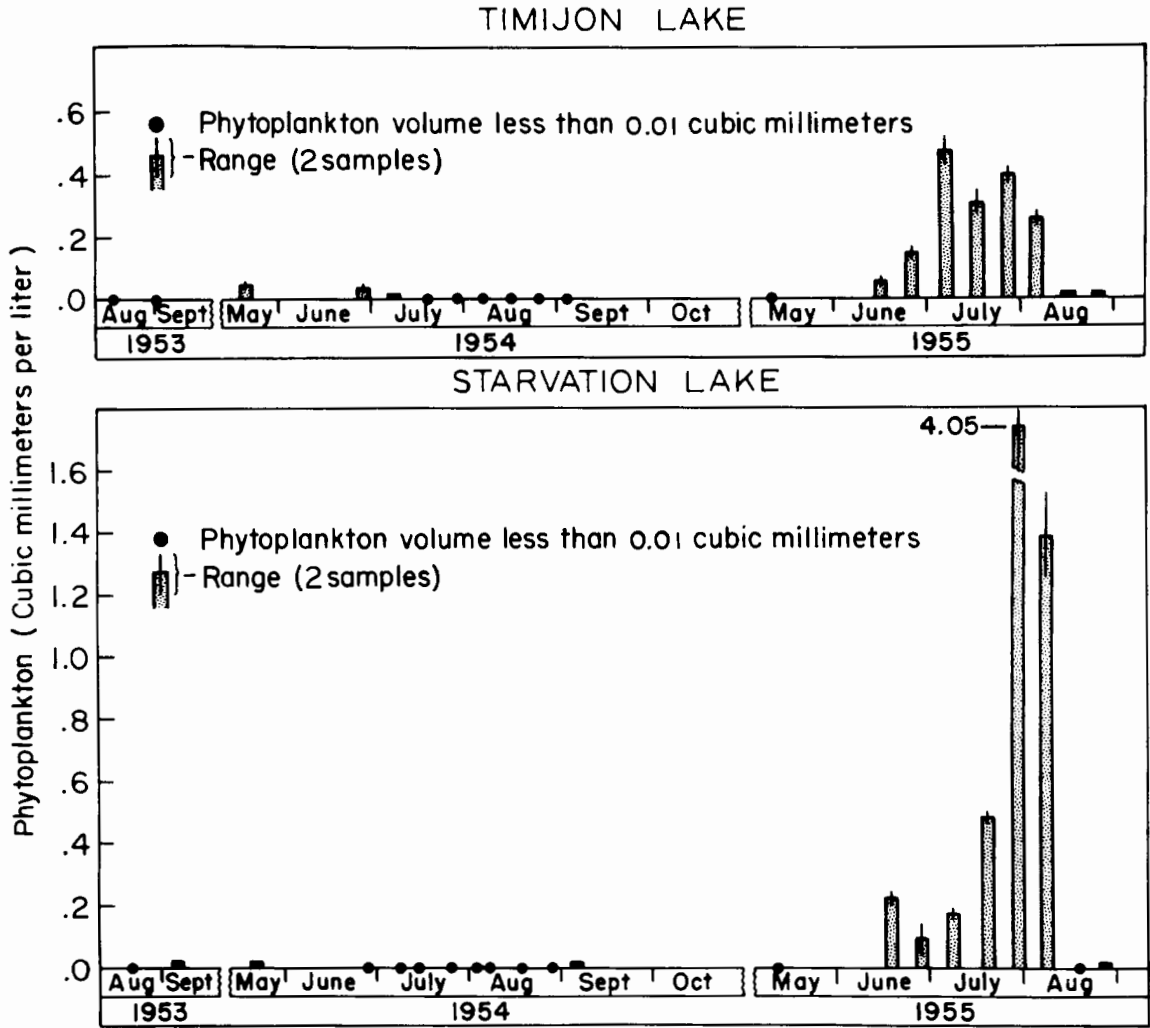
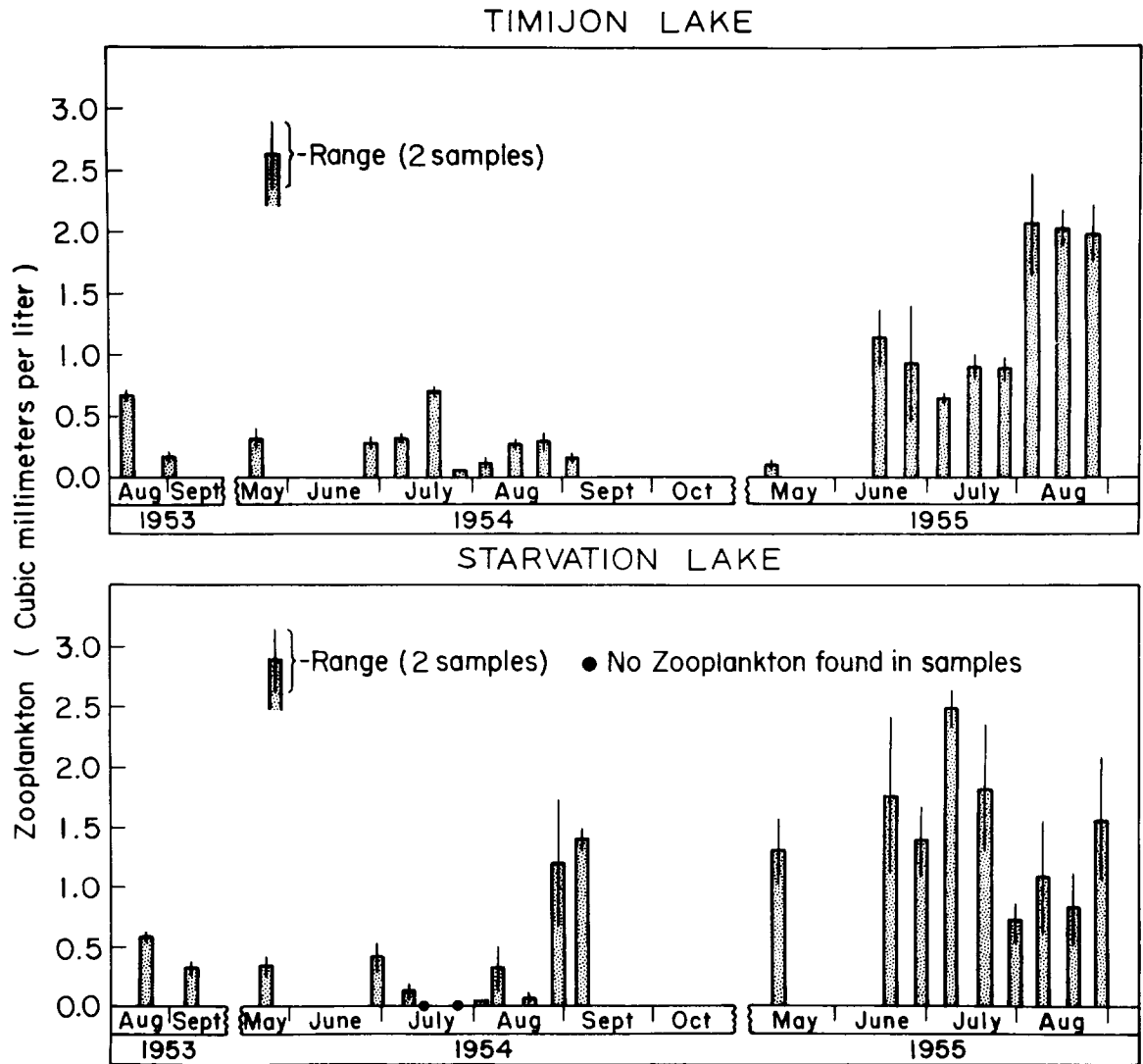


Figure 7.—Average volume of zooplankton in central epilimnion,
Starvation and Timijon lakes.

Figure 7.



1954, covering a period of 10 days which included five sampling dates; during this period of time the bicarbonate concentration was increasing due to the reaction of normal carbonates with the carbon dioxide being produced by the lake's respiratory activities (respiration, decomposition, and atmospheric absorption). The slope of the graph represents the rate of increase of bicarbonate, and, proportionally, the rate of carbon dioxide production. This rate, calculated by means of ratios of molecular weights of the compounds involved, was 1.94 p.p.m. carbon dioxide per day.

On August 2, 1954, the phytoplankton bloom of Microcystis aeruginosa was observed. Since carbon dioxide was extracted from the bicarbonates, it can be concluded that for the eight-day period from July 25 to August 2, or for an unknown shorter period of time, the phytoplankton utilized carbon dioxide at a rate more rapid than the rate of supply from the lake's respiratory activities. Table 1 shows the "balance sheet" for carbon dioxide for the eight-day period of plankton bloom. Section A is the carbon dioxide available over the eight-day period, being equal to the sum of that present at the beginning of the eight-day period plus the carbon dioxide production for the eight days, or a total of 34.9 p.p.m. carbon dioxide. The carbon dioxide utilized by the phytoplankton over the eight-day period, Section B, is equal to that available (Section A) minus that remaining at the end of the period, or 22.6 p.p.m. carbon dioxide. In Section C, the carbon dioxide available under conditions of no lime application is calculated to be 20.3 p.p.m. carbon dioxide, using the production rate computed above and the free carbon dioxide and bicarbonate concentrations found before lime application. The portion of that carbon dioxide utilized which was the result of lime application

Table 1.—Carbon dioxide utilized by phytoplankton after lime application compared to carbon dioxide available without lime application, Starvation Lake (as p.p.m. carbon dioxide).

A. CO ₂ available over 8-day period	34.9
Present at beginning of period,	
Free CO ₂	0.0
Half-bound CO ₂ (bicarbonate)	19.4
Production in 8-day period.	<u>15.5</u>
	34.9
B. CO ₂ utilized over 8-day period.	22.6
Available over period (Section A)	34.9
Less CO ₂ present at end of period,	
Free CO ₂	0.0
Half-bound CO ₂ (bicarbonate)	<u>12.3</u>
	22.6
C. CO ₂ available without lime application.	20.3
Present at beginning of period,	
Free CO ₂	3.0
Half-bound CO ₂	1.8
Production in 8-day period.	<u>15.5</u>
	20.3
D. Portion of CO ₂ utilized that was result of lime	2.3
CO ₂ utilized (Section B).	22.6
Less CO ₂ available without	
lime application (Section C)	<u>20.3</u>
	2.3

(i.e., the difference between the carbon dioxide utilized during the eight-day period and that which would have been available without lime application) is calculated in Section D. It is one measure of the effect of lime application upon phytoplankton production. It should be pointed out that it would not be necessary to know the carbon dioxide production rate in order to calculate the figure in Section D, for it would cancel out in the final subtraction.

In making the above calculations several assumptions were necessary; they were: (1) the carbon dioxide production observed for the 10-day period of increasing bicarbonate concentration (July 15 to July 25) was not higher, due to a more alkaline reaction and increased decomposition, than for a similar period of time without lime application; (2) there occurred no loss of carbon dioxide to the atmosphere during the 10-day period nor during the 8-day period of the plankton bloom (which is probably a valid assumption since normal carbonates were available during both periods for combination with carbon dioxide); (3) the increased standing crop of phytoplankton did not raise the rate of carbon dioxide production because of the algae's respiration, and (4) the period of plankton production and intense carbon dioxide utilization was not less than eight days. If any of the above assumptions were invalid, the figure calculated in Section D would either be greater or remain the same; the figure calculated, then, is a minimum value. Furthermore, it would not be expected that the phytoplankton would extract the carbon dioxide from all bicarbonate present; in the eight-day period of plankton bloom, 65 percent of the available carbon dioxide was utilized. If, in Section D of the table, 65 percent of the carbon dioxide available under conditions of no

lime application were subtracted from the carbon dioxide utilized, the figure in Section D would be even larger (calculated under these conditions to be 9.4 p.p.m. carbon dioxide).

The possibility exists, however, that in the absence of high bicarbonate concentrations but in the presence of other optimum conditions favorable to the occurrence of a plankton bloom, the rate of carbon dioxide supply from the lake sources (respiration, decomposition, and atmospheric absorption) may be increased to such a rate that would supply the demands of photosynthesis. This possibility would depend upon a physical-chemical demand produced by the removal of carbon dioxide by the algae from existing chemical systems in equilibrium; but the presence of carbonates also produces a demand upon carbon dioxide and changes the normal carbon dioxide relationships. The question, then, remains: Can intense photosynthetic demand for carbon dioxide increase the carbon dioxide production from the lake's respiratory activities (respiration, decomposition, and atmospheric absorption) above that rate supplied to react with carbonate? The ability of some algae, at least, to extract carbon dioxide from carbonates as well as bicarbonates (Ruttner, 1953, p. 63) would seem to indicate so. Further research into this question is indicated.

It was tentatively concluded that a causal relationship existed between the level of bicarbonate alkalinity and the phytoplankton production during the eight-day period of plankton bloom; in other words, bicarbonate alkalinity provided a reservoir of immediately available carbon dioxide which was utilized under conditions of intense photosynthetic activity (plankton bloom) after free carbon dioxide had been exhausted and the further production of carbon dioxide by the lake was insufficient to

provide for the phytoplankton's photosynthesis under the high rate of utilization existing at the time of bloom.

The higher levels of phosphorus concentration in the central epilimnion of Starvation Lake (see Figure 5) found soon after lime application may have been responsible for stimulating the Microcystis bloom. The reservoir of carbon dioxide in the bicarbonates might then have been responsible for permitting the bloom by furnishing carbon dioxide in excess of that produced by the lake. After the beginning of the bloom total phosphorus concentrations decreased, probably because of the fall of the plankton bodies out of the epilimnion after utilizing the phosphorus.

The effects of alkalinity upon phytoplankton production may be summarized in the following hypotheses which received support from the present study. (1) In soft-water lakes the bicarbonate alkalinity (or "reservoir" of immediately available carbon dioxide) may limit the rate of carbon dioxide utilization and thus the rate of phytoplankton production, but apparently does not limit the level to which the standing crop of phytoplankton may reach providing the rate of carbon dioxide production by the lake is equal to or greater than the rate of carbon dioxide utilization. (2) Under optimum conditions of alkalinity the availability of nutrients such as phosphorus is improved, and the availability of such nutrients probably limits the level of standing crop.

It appears possible now to summarize the reasons for observed differences in production in lakes with different conditions of alkalinity. (1) Hard-water, or alkalitrophic, lakes appear to suffer poor productivity because of the adverse effects of excess calcium upon the availability of nutrients (Barrett, 1953). (2) Medium-hard lakes with optimum conditions of alkalinity provide large reservoirs of immediately available carbon

dioxide in the form of bicarbonates and permit phytoplankton "blooms." These lakes may also provide optimum nutrient availability. (3) Soft-water lakes, such as acid bog lakes, may not permit as intense plankton blooms because of the lack of high concentrations of immediately available carbon dioxide in the bicarbonate form and also limit total production because of poor availability of nutrients.

Acknowledgments

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Literature Cited

Ball, Robert C.

1948. A summary of experiments in Michigan lakes on the elimination of fish populations with rotenone, 1934-1942. Trans. Am. Fish. Soc., Vol. 75 (1945), pp. 139-146.

Barrett, Paul H.

1953. Relationships between alkalinity and adsorption and regeneration of added phosphorus in fertilized trout lakes. Trans. Am. Fish. Soc., Vol. 82 (1952), pp. 78-90.

Hasler, Arthur D., G. M. Brynildson, and William T. Helm

1951. Improving conditions for fish in brown-water bog lakes by alkalization. Jour. Wildlife Man., Vol. 15, No. 4, pp. 347-352.

Johnson, Waldo B. and Arthur D. Hasler

1954. Rainbow trout production in dystrophic lakes. Jour. Wildlife Man., Vol. 18, No. 1, pp. 113-134.

Lyon, T. Lyttleton, Harry C. Buckman, and Nyle C. Brady

1953. The nature and properties of soils. Fifth Edition, Macmillan Co., New York, XVII + 591 pp.

Moyle, John B.

1949. Some indices of lake productivity. Trans. Am. Fish. Soc., Vol. 76 (1946), pp. 322-334.

Neess, John C.

1949. Development and status of pond fertilization in central Europe. Trans. Am. Fish. Soc., Vol. 76 (1946), pp. 335-358.

Ruttner, Franz

1953. Fundamentals of limnology. English translation by D. G. Frey and F. E. J. Fry. Univ. Toronto Press, Toronto, XI + 242 pp. (Original German edition published by Walter de Gruyter & Co., Berlin, 1952.)

Waksman, Selman A.

1938. Humus. Second Edition, Williams & Wilkins Co., Baltimore.

Whipple, G. C.

1948. The microscopy of drinking water. Fourth Edition, John Wiley & Sons., Inc., New York, XIX + 586 pp.

Wiklander, Lambert

1955. Cation and anion exchange phenomena. In: Chemistry of the soil. Edited by Firman E. Bear, Reinhold Publ. Corp., New York, X + 373 pp.

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