SOME LIME-INDUCED CHANGES IN LAKE METABOLISM

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INTRODUCTION

Application of hydrated lime to bog and other dystrophic lakes is thought to stimulate production at several trophic levels. It enhances the medium for plant growth by increasing: the rate of remineralization of plant nutrients (Hasler and Einsele 1948); the depth of the euphotic zone (Hasler *et al.* 1951) and the supply of available carbon dioxide (Hasler *et al.* 1951, Waters 1957, Waters and Ball 1957). In addition, phosphate should be conserved in the trophogenic layer as a result of the removal of iron from suspension. The consequences of phosphate removal by ferric-iron complexes are discussed by Einsele (1938), Ohle (1937a) and Mortimer (1941, 1942).

Lakes treated with lime have not responded uniformly owing, perhaps, to the differences in the nature of the lakes and method of treatment. Hasler *et al.* (1951) and Johnson and Hasler (1954) have enlarged the euphotic zone in several instances although the latter workers and Waters (1957) were unable to clear some lakes. Large applications of hydrated lime result in plankton blooms and probably are induced by the momentary release of phosphorus (Waters). But whether the increase in plant production is transferred to all trophic levels is questionable. Johnson and Hasler report no increase in production of rainbow trout following an increase in standing crop of plankton. However, Waters and Ball show an increase in plankton and growth rate of yellow perch.

This paper considers some of the direct effects of lime on lake metabolism. A lake previously treated with apparent success was used to test the result of treatment on lake dystrophy and the distribution of iron and phosphorus. Because of its possible significance in achieving and maintaining desired results, a method of application was studied in two other lakes by measuring the efficiency of solution of lime and the degree of retention of the dissolved products. The effect of lime-treatment on the production of planktonic crustacea will be reported elsewhere.

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THE LAKES

Three lakes on the Wisconsin-Michigan border near Land O' Lakes, Wisconsin were selected for the studies. All are slightly acid and are stained with organic colloids. Bog plants grow on a portion of the shorelines, and peat-like organic materials are deposited on the bottoms, except in some of the shallow areas where wave action has exposed the underlying sand. The restricted drainage basin surrounding each lake has not permitted permanent tributaries to develop. George and Corrine lakes are slightly elongated; whereas, Peter-Paul Lake consists of two concentric basins which were connected by a narrow, shallow canal, in hourglass fashion. This lake was separated in 1951 by an earthen dam (Johnson and Hasler 1954). Peter Lake (treated portion) received treatment with hydrated lime beginning in 1951 and continuing until 1954. Paul Lake (untreated portion) was preserved for use as a natural reference. The area, volume, and maximum depth of each lake are given in Table 1.

APPARATUS AND PROCEDURE

To provide maximum homogeneity and uniform distribution, the lime was slurried and applied with the aid of a high speed centrifugal pump. The pump and lime receptacle were attached to a large boat

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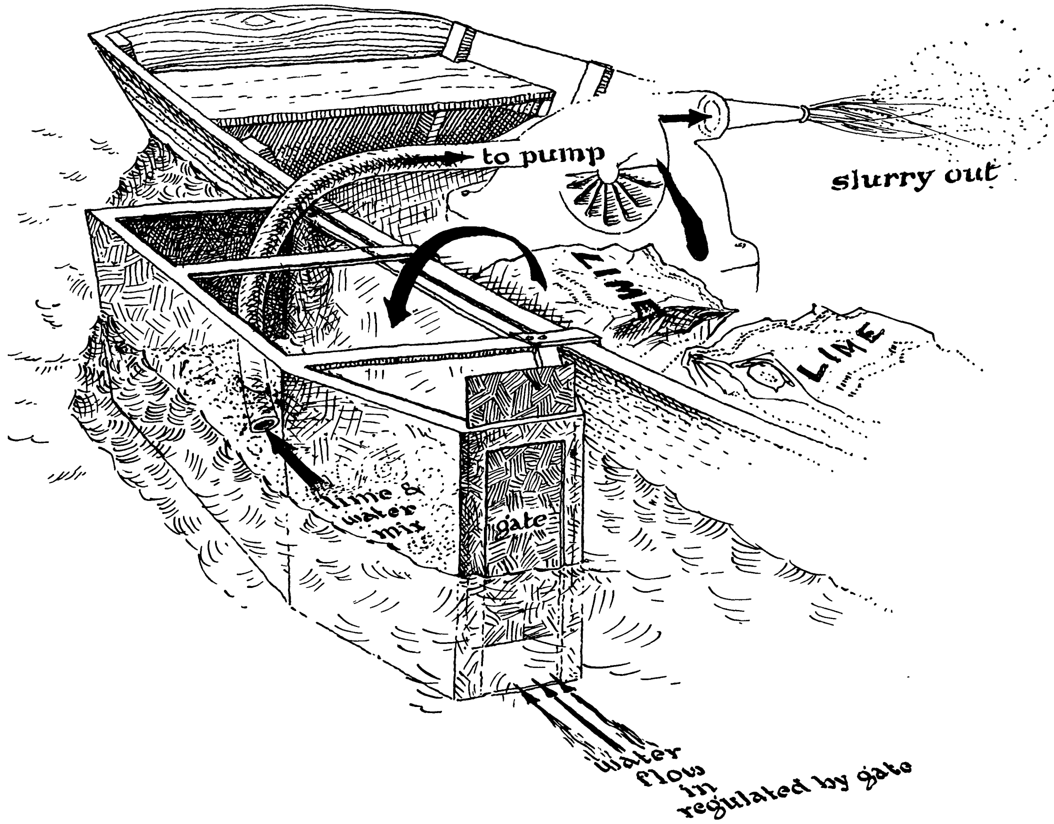

FIG. 1. Apparatus used for application of lime.

capable of transporting the apparatus and a supply of lime about the lake (Fig. 1). When the water level was adjusted correctly, the addition of lime to the receptacle was an almost continuous operation.

Temperature and light measurements were obtained with Whitney instruments from a station in the center of each lake as were samples of water for chemical analyses. Water samples were filtered within a few hours through fine-porosity-glass filters to separate "soluble" and "particulate" fractions.

Calcium, magnesium, sodium and potassium were measured by flame photometry in a Beckman D.U. spectophotometer after the water sample had been concentrated to ⅕ of its initial volume. Total phosphorus was measured by the molybdate-blue procedure (Truog and Meyer 1929) in samples concentrated to 1/10 of their initial volume. Total iron was determined by an orthophenanthroline technique as used by Neess (personal communication) which consisted of complete oxidation to ferric iron followed by reduction with hydroxylamine hydro-

TABLE 1. *Morphometric features of the lakes*

Lake	Area (Acres)	Area (ha)	Max. Depth (m)	Volume (m^3)	Axis
George	42.8	17.3	14.0	778,000	WSW–ENE
Corrine	36.1	14.6	5.2	350,000	N–S
Peter (treated)	6.0	2.4	19.0	436,000	neutral
Paul (untreated)	3.0	1.2	12.0	134,000	neutral

chloride. Bicarbonate was calculated from the milliequivalents of acid required to bring a sample to a methyl-orange endpoint and was expressed as bicarbonate; calculations were made only when the pH of the sample indicated carbonate to be insignificant (Hutchinson 1957). Measurements of pH were made with a Beckman G pH meter.

Hydrated lime with an average content of 30.5% calcium and 17.0% magnesium, and an hydroxide equivalent of 96.5% was used throughout the study. These values were used to calculate theoretical amounts in each application. Only calcium and magnesium were considered in calculating efficiencies of solution, and their hydroxides were assumed to dissolve in equal molar quantities. Other cations in the lime were assumed to compensate for introduced "non-carbonate" salts.

RESULTS

Efficient solution of lime

Two treatments with hydrated lime were made in George and Corrine lakes in the summers of 1956 and 1957, respectively. Each treatment added a calculated 5.8 mg/L of lime to George Lake and 12.9 mg/L to Corrine Lake. A difference in the time-interval and quantity of each application provided an indication of the effect of available carbon dioxide on the efficiency of solution. In George Lake a six-week period separated the two additions during which time the pH of the epilimnion returned from a post-treatment value of 9.4 to 7.2. The second application to Corrine Lake followed five days after the first and at a time when most of the lake was still at a post-treatment pH of 9.7.

The two applications to George Lake increased bicarbonate by 85 and 101% of the theoretical value. In Corrine Lake the increase was only 54%. Because the actual change was comparable in the two lakes, the lower efficiency obtained in Corrine Lake probably was the result of larger application of lime and smaller interval between treatment. Thus, efficiency of solution seemed to be dependent mainly on the amount of carbon dioxide immediately available for reaction with the hydroxides.

In George Lake the distribution of lime, as indicated by change in bicarbonate, was uniform with the exception of a region in the lower part of the thermocline (Fig. 2). Because the stratum was well beneath the zone where precipitation could occur as a result of photosynthesis, it is suggested that one size-group of particles dissolved in the epilimnion and another sank into the hypolimnion before dissolving. On the other hand, lime was distributed exclusive of the hypolimnion in Corrine Lake. Apparently, most of the undissolved lime was lost to the littoral region, and that which dissolved in the narrow stratum at the bottom was subsequently adsorbed by the sediments. Evidence for the entrance of lime into this stratum is presented below.

Calcium and magnesium

Direct determinations of calcium and magnesium in Corrine Lake permitted a measure of their retention and distribution. Table 2 gives the initial concentration, the amount added and the fraction of each which remained in the water column. The subsequent decline in the amount of calcium suggested that all may not have been in solution, although the formation of bicarbonate was sufficiently large to account for the maximum listed values of calcium and magnesium. Conceivably, calcium dissolved to the same extent after each application, as indicated by the amount present one week after application, but was subsequently lost from solution.

Magnesium salts were less soluble at the time of the second application and, presumably, less soluble than were the calcium salts. This may be expected since a water pH of 9.7 indicated an absence of free carbon dioxide, in which case calcium hydroxide should have been the more soluble. The net increase in calcium and magnesium, as measured four weeks after the second addition, was 38% of the theoretical value with magnesium comprising ⅔ of the total.

The smaller efficiency for solution of cations can be accounted for only if calcium

TABLE 2. *Amount of calcium and magnesium in solution and retained following application of hydrated lime to Corrine Lake*

	Calcium			Magnesium		
Day	Added (Kg)	Retained (Kg)	(%)	Added (Kg)	Retained (Kg)	(%)
0	1383	—	—	771	—	—
7	—	615	44	—	546	71
7	1383	—	—	771	—	—
9	—	857*	62	—	340*	44
14	—	580	42	—	300	39
34	—	139	10	—	345	44
Net increase		754	27		891	58

* Increase over and above that measured on day 7.

was adsorbed and precipitated by colloids in suspension and on the bottom (Ohle 1937b, 1955). This was indicated because of its continually declining concentration. Calcium also failed to accumulate in the 1-meter stratum near the bottom while magnesium increased sevenfold. Assuming only calcium was involved, approximately 16% was adsorbed after it dissolved.

The adsorption of calcium was also indicated in Peter-Paul Lake (Table 3). Despite the probability of an unrecorded application, the assumption regarding differential adsorption should remain the same. To satisfy the excess bicarbonate, which existed after several years, would require 24% more calcium than existed in solution. The apparently efficient solution of lime in this lake, although applied as a powder, was thought to be due to modest additions and depth of the lake.

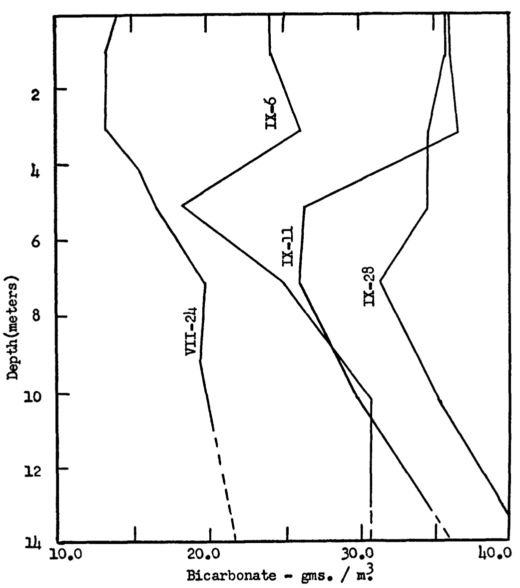

FIG. 2. Vertical distribution of bicarbonate in George Lake. Applications of hydrated lime were made on July 24 and September 6, 1956.

Light penetration

The depth of the euphotic zone increased by 22% in George and 40% in Corrine Lake following lime treatment. In George Lake clearing followed only the first application; the second, made near the time of the fall overturn, merely counteracted the normal resuspension of materials which usually narrowed the euphotic zone during the overturn of lakes in the area. Johnson and Hasler (1954) reported a 60% increase in the treated portion of Peter-Paul Lake. Readings taken two years later showed a total increase of 160%, a change from 2.7 to 7.0 m. The significance of the additional change was reduced by a proportional in-

TABLE 3. *Amount of calcium and magnesium retained in solution and the formation of bicarbonate from hydrated lime added over a 3-year period to the treated portion of Peter-Paul Lake. Measurements were made five years after the beginning of treatment.*

	Addition (mg/L)	Retained in solution (mg/L)	Efficiency (%)
Ca	4.35	2.17	50
Mg	2.47	2.38	96
HCO_3	25.6	20.8	81

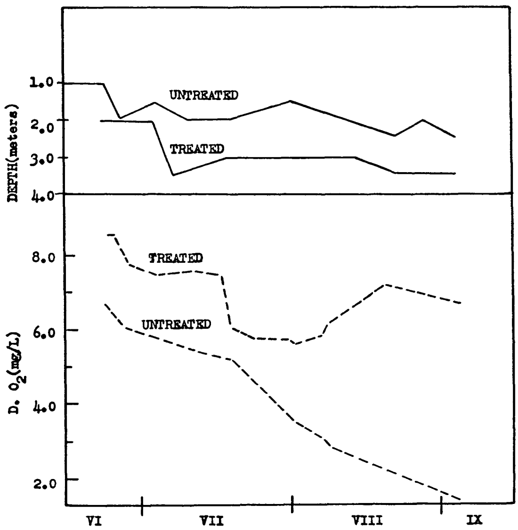

FIG. 3. Depth of the epilimnion in treated and untreated portion of Peter-Paul Lake and the changes in concentration of dissolved oxygen in each portion during the summer of 1956.

crease in depth of the euphotic zone in the untreated portion.

Lake dystrophy

Hasler *et al.* (1951) attributed the slower decline in concentration of dissolved oxygen in the thermocline of lime-treated lakes to the dual action of increased photosynthesis and decreased oxygen consumption, which result from deeper penetration of light and removal of organic suspensoids, respectively. To determine the relative importance of the two, a series of 8 light and dark bottle measurements were carried out at equal light intensities in the thermoclines of the treated and untreated portion. Because the thermoclines are located at different depths (Fig. 3) as a result of deeper light penetration in the treated portion (Stross 1958), equivalent light intensities occurred at 5.0 m in the treated and 3.0 m in the untreated portion. Light values at these depths ranged from 3.0 to 6.0% of surface radiation during the test period. The bottles were incubated for 8 hr. The change in amount of dissolved oxygen was measured by the unmodified Winkler technique.

The decline in concentration of dissolved oxygen in the upper thermocline of the untreated portion was due mainly to a high rate of respiration. A faster rate of consumption in this portion was readily apparent (Fig. 3). Presumably, no excess oxygen was produced during the daylight period because both production and consumption of oxygen were 28.5 μg/L/hr. In the treated portion, however, the values were 38.7 and 12.2 μg/L/hr., respectively, an oxygen demand of only 32% of that produced.

Iron and phosphorus

Peter-Paul Lake was selected for evaluating the effect of hydrated lime on the distribution of iron and phosphorus. Because application was stopped when this study began, the conditions present in the lake two years later were thought to represent a persistent influence of treatment on the two elements. Existing concentrations and distributions in the untreated portion at the time of measurement were considered representative of those in the treated portion before the initial application.

The seasonal distribution of iron conformed with that summarized by Hutchinson (1957). Because the lakes circulated completely in autumn only, iron was homogeneously distributed at that time, but only for a brief period which preceded a rapid loss from suspension (Fig. 4). At overturn the concentration was 0.20 mg/L in the treated and 0.65 mg/L in the untreated portion. The ability of lime to remove iron permanently from circulation was therefore suggested; presumably, lime eliminated 70% of the iron.

Particulate iron comprised 30% of the total amount in each lake. There was, however, considerable variation, particularly at the time of overturn (Fig. 4). A greater proportion became particulate at the spring overturn, but because circulation was incomplete, the precipitating iron redissolved in the anaerobic stratum near the bottom. The greater accumulation occurred in the hypolimnion of the untreated lake, being 4.3 mg/L as compared to 1.8 mg/L in the treated portion.

Because ferric iron precipitates phosphorus from the euphotic zone of lakes, it

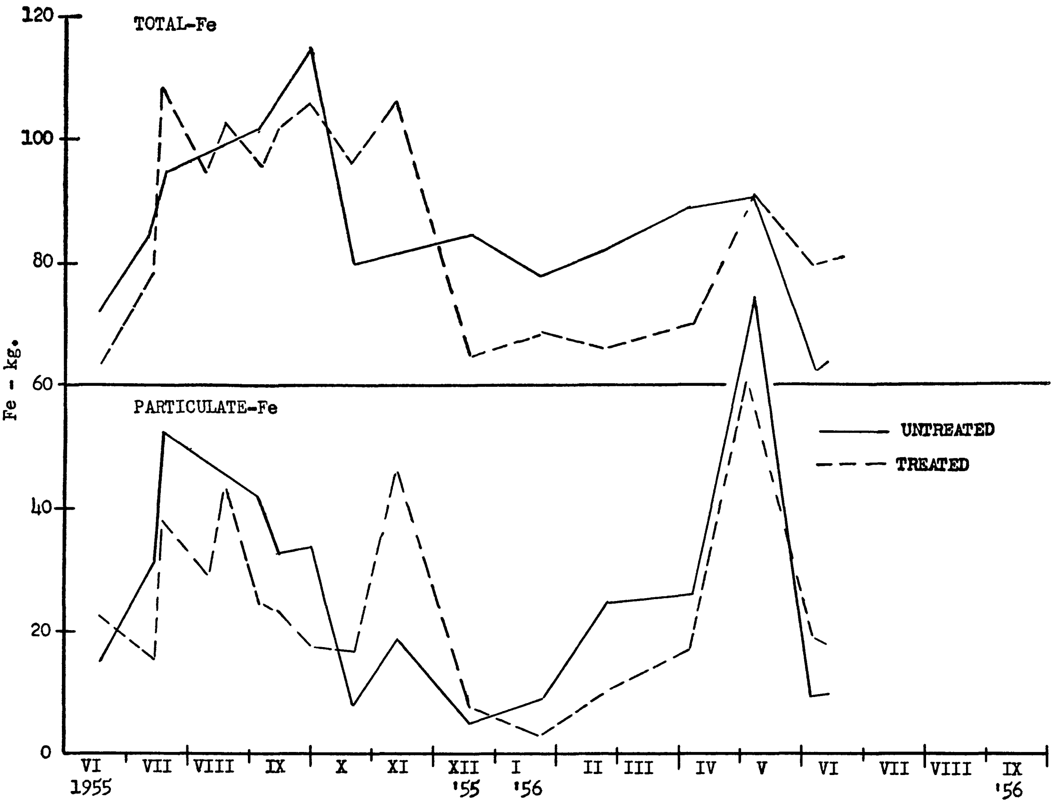

FIG. 4. Concentrations of total and non-filterable iron in the two portions of Peter-Paul Lake. The volume of the untreated portion is 30% of the other.

was of interest to determine if the distribution of phosphorus was affected by the partial removal of iron. A set of six measurements taken during the winter-to-spring period suggested the partial removal did not inhibit normal precipitation (Fig. 5). Instead, loss of phosphorus in the treated portion seemed to occur more rapidly and resulted in an average concentration of 22.0 μg/L as compared to 28.0 μg/L in the untreated part of Peter-Paul Lake. A nonbiological precipitation was thought to be the major cause for the loss because the plankton was extremely sparse during the period. The major difference in distribution was the appearance of a large concentration of phosphorus in the surface waters of the treated portion. A maximum was first noted in early February at a depth of one meter. This layer moved downward slowly and arrived at the bottom in late April. There seemed to be, however, no apparent correlation with the downward movement of iron.

DISCUSSION AND CONCLUSIONS

Complete solution of hydrated lime may be obtained if the addition does not greatly exceed the reservoir of free carbon dioxide. The importance of carbon dioxide is illustrated by the comparable amounts of lime which dissolved in George and Corrine lakes, although dosages were 6.0 and about 26.0 mg/L respectively. Although dosage and efficiency were not exactly proportional, the low efficiencies obtained by other investigators probably occurred because of the extremely high concentrations applied by them (Waters 1957; Waters and Ball 1957).

Odum (1956) suggests the degree of dystrophy is equivalent to the extent that

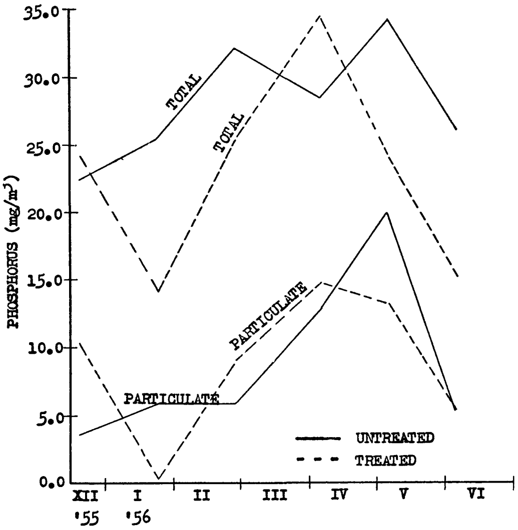

FIG. 5. Total and particulate phosphorus in the two portions of Peter-Paul Lake.

respiration exceeds photosynthesis. Because lime does not remove all organic colloids equally well, values of light penetration alone after treatment, may not measure adequately the change in degree of dystrophy. That the nature of the colloids is peculiar to lake-type is supported circumstantially by the fact that lakes which fail to clear following lime treatment are similar in being completely surrounded by a bog mat. Such lakes will respond, however. One such lake was maintained in a surprisingly clear state by temporary acidification with sulfuric acid to pH 4.0 (Zicker 1955). This variability of response suggests a difference in physical properties of the colloids. It may also imply variable stability to chemical oxidation. Conceivably, lime may precipitate efficiently only the more unstable colloids, in which case the rate of oxygen consumption may be decreased without changing the clarity of the water to any measurable extent. That some of the limnohumic acids are stable to oxidation was demonstrated by Shapiro (1957).

The normal precipitation of phosphorus by iron seemed unaffected by the addition of lime to Peter-Paul Lake. This occurred despite removal of nearly ¾ of the iron from suspension. At the autumnal overturn there was an iron to phosphorus ratio of approximately 3:1 which, according to Mortimer (1941), would seem to be sufficiently small to permit greater retention of phosphorus. However, a removal of colloids, which was indicated by the increase in clarity of the water, may have partially eliminated a mechanism for keeping phosphorus in suspension (Ohle 1937b) and thus, may account for the efficiency with which the iron remaining can act as a precipitating agent for phosphorus.

In a recent paper MacPherson *et al.* (1958) demonstrate that the release and uptake of phosphorus from reconstituted lake muds is dependent upon pH. Alkalization enhances release. A similar result was observed after the addition of lime to lakes by Waters (1957) and may also be inferred in other studies from the blooms of phytoplankton which followed the addition. Mimimal releases of phosphorus occur at a pH range of 5.5–6.5. Because pH in the three lakes of this study returned to 6.0–7.2, depending on depth, within a few weeks after treatment, the initial rate of flow from the muds probably was greatly slowed. This of course does not imply a lack of change in availability in subsequent years. In Peter-Paul Lake for example it is possible that as a result of treatment with lime a larger proportion of phosphorus was precipitated on the littoral sediments. Treatment may or may not have facilitated the release of phosphorus upon the necessary appearance of a reduced microzone at the mud-water interface.

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