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R. W. Adams and H. C. Duthie

Department of Biology, University of Waterloo, Waterloo, Ontario

Relationships Between Sediment Chemistry and Postglacial Production Rates in a Small Canadian Lake

Abstract

In a chemical investigation of the sediments of a small meromictic lake in southwestern Ontario, Canada, the hypolimnion had evidently become increasingly reductive over most of the postglacial as the lake gradually filled in. The ratio of phosphorus to organic matter tended to fall, suggesting that an increasing proportion of precipitated phosphorus had become mobile and re-available to the lake's ecosystem. Productivity, as inferred from fossil pigment analysis, tended to increase over the postglacial, and there is no evidence for a prolonged period of trophic equilibrium. Maximum production rates were correlated with efficient phosphorus diagenesis. The lake evidently became meromictic around 900 BP (before present) and this was associated with a sulphide producing monimolimnion and decreased productivity. Cultural practices in the watershed around 140 BP increased inorganic sedimentation and further reduced productivity.

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I. Introduction

It has been questioned recently whether any natural process in a lake can be termed natural eutrophication in the sense of a steady increase of productivity resulting from a steadily increasing nutrient supply to the lake (Bortleson 1971, Beeton and Edmondson 1972). In the developmental history of glacially formed lakes the filling in of a lake basin may be attributable to the normal process of ecological succession; for natural eutrophication to occur there would have to be a steadily increasing supply of nutrients from the surrounding drainage area. Once a soil profile is established it is difficult to imagine a mechanism that could allow such a process to occur, though there may be long- or short-term variations with changing climate or drainage. In the developmental history of Linsley Pond, Connecticut, HUTCHINSON and WOLLACK (1940) concluded that the lake rapidly increased in productivity after deglaciation reaching a state of trophic equilibrium with its environment, which was maintained over most of the postglacial. This concept of trophic equilibrium under relatively constant climatic conditions has been generally confirmed (HUTCHINSON 1969) from other studies.

It is widely recognised that three sets of factors control the productivity of a lake: edaphic, or nutrient input from the watershed; climatic and hydrographic; and morphometric, which largely concerns oxygen supply in the hypolimnion. In the case of glacially formed lakes both edaphic and morphometric factors contribute to increasing nutrient supply in the initial stages of development, but once trophic equilibrium is established only the morphometric factor progressively changes as the lake gradually fills in (excluding, of course, human influence). From a knowledge of the sediment stratigraphy at various points in Linsley Pond and the present use of oxygen in the hypolimnion, DEEVEY (1955) was able to calculate the postglacial hypolimnetic volumes and oxygen relations. He concluded that the obliteration of the hypolimnion, or morphometric eutrophication, was not so important during the growth of the lake biocoenosis as edaphic eutrophication. Only in some small lakes is morphometric eutrophication likely to be of major significance.

Interest in Sunfish Lake, a small meromictic lake in southwestern Ontario, was stimulated when an analysis of diatom stratigraphy in a sediment core (SREENIVASA and DUTHIE 1973) revealed increasing deposition of frustules and a succession of species suggestive of gradually increasing productivity throughout the postglacial. Sunfish Lake had evidently not reached a state of trophic equilibrium with its environment early in the postglacial. This was largely due to progressive changes in morphometry as indicated by estimations of postglacial hypolimnetic volumes. It was found that the hypolimnion had been obliterated by about 41%, and that the present hypolimnion comprised only 33% of the volume of the lake. It was therefore decided to investigate by chemical analysis of the sediments the obliteration of the hypolimnion and its progressive anaerobiosis and to infer the developmental history of the lake from its inception to the present, particularly with regard to changes in postglacial production rates. Another objective was to determine the origin and possible causes of meromixis in Sunfish Lake.

Sunfish Lake is a small kettle surrounded by sandy kames and till. It has a small watershed of about 2.25 km^2 composed mostly of mixed deciduous woodland and farmland. The morphometry is as follows: total area 8.3 ha, maximum depth 20.0 m, mean depth 10.4 m, and volume development ratio 1.56. The lake is moderately alkaline (100–150 mg/l $CaCO_3$), and the pH of the epilimnion is 8.0–8.5. In midsummer the thermocline lies at about 8 m and the chemocline at about 13 m. The monimolimnion is generally anaerobic and contains up to 40 mg/l sulphide. The lake bottom is covered by a black sulphide sapropel. Further data on the limnology of Sunfish Lake are given in DUTHIE and CARTER (1970).

II. Material and Methods

All the analyses in this study were performed on a 460 cm long continuous section, designated core SL-6, collected by means of a piston corer under 17.4 m water. Coring procedures were identical to those described in SREENIVASA and DUTHIE (1973). Pollen enumeration and all chemical analyses were performed on samples taken every 10 cm along the length of the core.

Moisture content was determined by drying fresh samples at 105 °C for 24 hr. Ash-free dry weight (organic matter) was determined after heating at 550 °C and sedimentary carbonates after heating at 950 °C.

Samples for all other analyses were prepared in such a way as to enable results to be expressed as sedimentation intensity, concentration per cm^2 per unit time, as well as the more usual concentration per g dry weight sediment. This was achieved by preparing extracts from samples of known volume and density.

Phosphorus was determined in three extractions: 1) distilled water extraction, 2) 0.1 N HCl and 3) HF followed by $HClO_4 + NHO_3$ digestion ("total" phosphorus). Concentrations in all extractions were estimated spectrophotometrically by ATKINS' modification of DENIGE's method (MACKERETH, 1963).

The digest prepared for total phosphorus was also used to determine total Ca, Mg, K, Na, Fe, Mn, Cu, SO_4^{--}, and Cl^-. All analyses except SO_4^{--} and Cl^{--} were performed on a Perkin-Elmer model 303 atomic absorption spectrophotometer using the manufacturer's recommended procedures and instrument settings. Sulphate was determined using the titrametric method of TRAVERSEY (1971) and chloride by argentometric titration.

Sedimentary pigments were determined in acetone-dimethylaniline extracts using the methods of VALLENTYNE (1955) as modified by WETZEL (1970). Sedimentary pigment degradation units (SPDU) were calculated per g dry weight, per g organic matter, and as sedimentation intensity.

III. Sedimentology and Correlation

A description of core SL-6 is given in Fig. 1. The stratigraphy and pollen sequence was practically identical to that of core SL-4 described by SREENIVASA and DUTHIE (1973) and hence their dates derived by radiocarbon dating and pollen chronology for SL-4 have been directly applied to SL-6. A further date of 13,200 BP has been added as an approximate date of final deglaciation, which is consistent with the interpretations of ANDERSON (1971) from other sites in the region. A description of the pollen sequence and major climatic inferences is given in SREENIVASA and DUTHIE (1973). The *Ambrosia* pollen horizon, interpreted as indicating forest clearance and settlement, is at 25 cm in core SL-6 and is dated at approximately 140 BP.

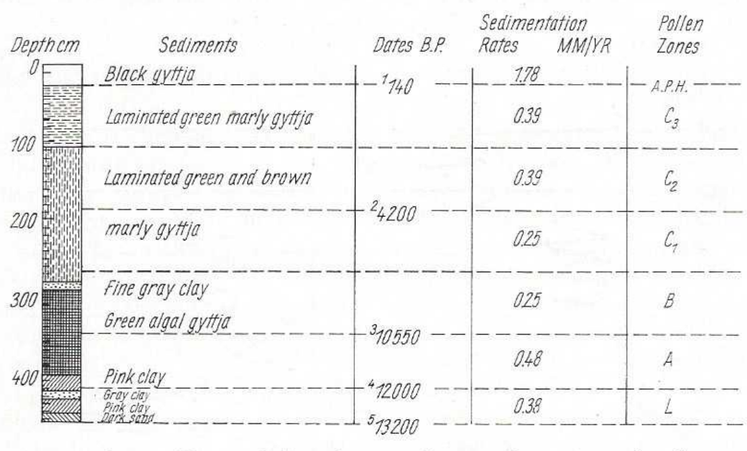

Fig. 1. Description of core SL-6 including dates, sedimentation rates and pollen zones. Zone L: herbaceous tundra with some *Picea*. Zone A: *Picea* with some *Pinus* and *Abies*. Zone B: *Picea* declines, increase in *Pinus* and several deciduous trees. Zone C_1: *Pinus* declines, replaced by *Tsuga*, *Quercus* and *Fagus*. Zone C_2: *Tsuga* declines, *Carya* and *Quercus* increase. Zone C_3: *Carya* and *Quercus* decline, *Tsuga* and *Fagus* increase. A.P.H., *Ambrosia* pollen horizon. Dates: 1, historic, 2, 4, and 5, pollen chronology and 3, radiocarbon dating.

IV. Physical and Chemical Analyses

1. Moisture content, density and carbonates (Fig. 2)

The moisture content generally increases from the older to the younger sediments; minima at 330 cm and 280 cm correspond to sand and clay layers. Density varies inversely with the moisture content, increasing from 1.01 g/cm^3 at the top of the core to 1.82 g/cm^3 near the bottom. The older sediments are generally more compact and contain less organic matter (Fig. 3).

Sedimentary carbonate ranges between 8% at the very top of the core to 32% in C_2 and shows no distinct trends over the postglacial. A little loss (2–3%) at 950 °C

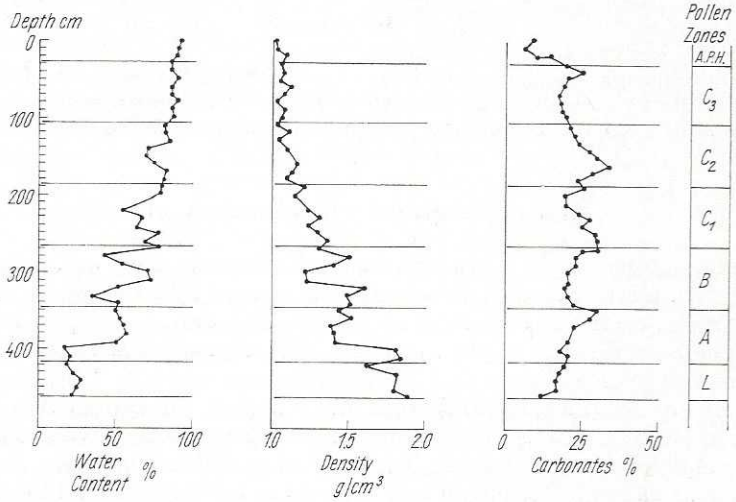

Fig. 2. Water content as percent fresh weight, density, and carbonates as percent dry weight of core SL-6.

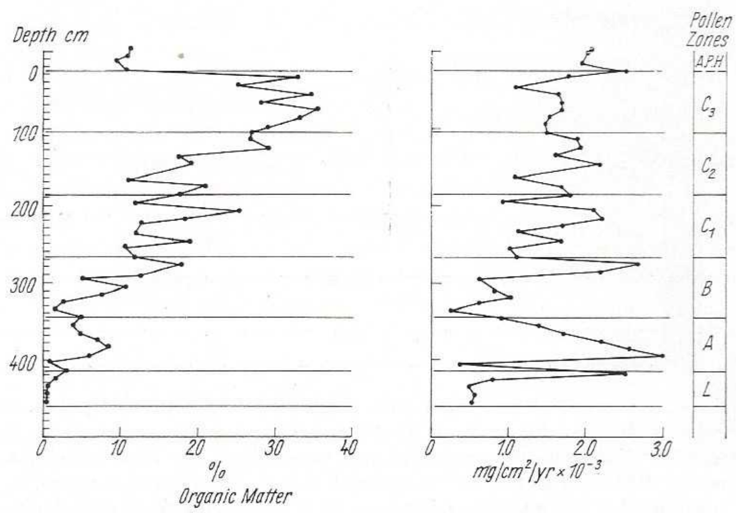

Fig. 3. Percent dry weight and sedimentation intensity of organic matter in core SL-6.

is probably not carbonate (Wetzel 1970). The decrease in carbonate in recent sediments is partially due to increased inorganic sedimentation. ,Carbonate deposition may also be related to fluctuations in primary productivity, although bacterial activity, biological respiration and chemical oxidation serve to decrease $CaCO_3$ precipitation and obscure any long-term relationship.

2. Organic matter (Fig. 3)

This generally increases but with many fluctuations, from less than 4% in the oldest sediments to 32% in C_3 before declining to 10% at the surface. The postglacial profile of organic matter in Sunfish Lake is dissimilar to that in several North American lakes (Hutchinson and Wollack 1940, Wetzel 1970) and English lakes (Mackereth 1966) which in general show a rapid rise in the early postglacial followed by a long period of equilibrium. Stratigraphic variations in organic matter reflect changes in any or all of the following: amount of autochthonous biological production, amount of allochthonous organic matter reaching the sediments, the degree of preservation of organic matter, and variations in deposition rate of the whole sediments. Except for the oldest and youngest sediments the postglacial deposition rate is fairly constant, and, as will be shown later in discussing sedimentary pigments, the amount of allochthonous organic matter appears minimal and the preservation of autochthonous material good. There is thus reason to believe that sedimentary organic matter in Sunfish Lake reflects autochthonous biological production. If this is so, then productivity has evidently increased over the postglacial. This is in agreement with the conclusions reached using sedimentary diatom analysis (Sreenivasa and Duthie 1973).

When organic matter is expressed as sedimentation intensity (mg/cm²/year) the postglacial increase is not so clear and is obscured by several large maxima particularly in zones A and B. These may be due to brief periods of high productivity or errors in calculating sedimentation intensity due to insufficient dating of the older sediments.

3. *Potassium, magnesium, sodium,* and *inorganic sedimentation (Fig. 4)*

The nutrient influx into a lake is influenced qualitatively and quantitatively by erosion and leaching processes in the watershed. In English lakes Mackereth (1966) claimed that potassium, magnesium, and sodium, were mainly associated with the mineral fraction of the sediment rather than the organic material. High sedimentary potassium and magnesium indicate more intensive erosion as opposed to leaching of the soil, and conversely, low potassium and magnesium indicate more leaching. In Sunfish Lake there is some indication of a relationship between potassium, magnesium and inorganic sedimentation intensity. Profiles of all three show maximum value in the L and early A zones. The decrease in the A zone is concomitant with the establishment of a spruce forest about 12,000 BP. Relationships in the B zone are less clear; potassium and magnesium have a series of maxima while the inorganic sedimentation rate evidently declines. The relationship is reestablished at 30 cm where the increase in inorganic sedimentation may be related to increased erosion with the onset of cultural practices such as forest clearance and agriculture in the watershed. Interpretation of the sodium profile with respect to erosion is not clear. It appears as if some of the sodium is associated with the organic material, especially in the younger sediments.

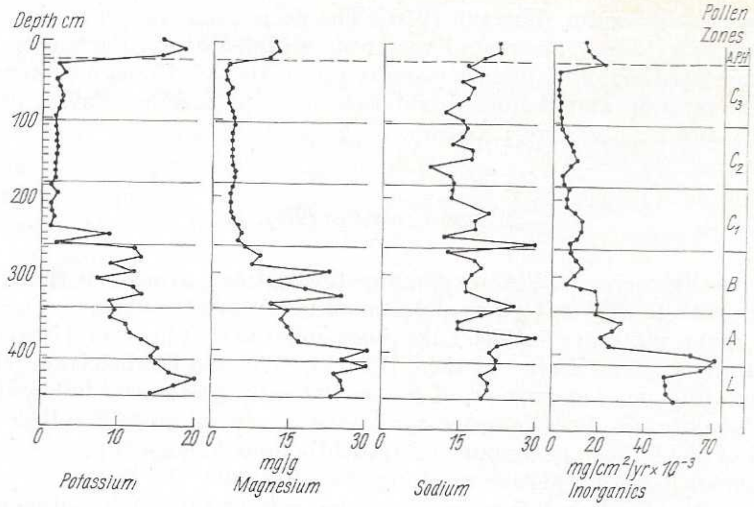

Fig. 4. Mg/g dry weight potassium, magnesium and sodium, and inorganic sedimentation intensity in core SL-6.

4. Calcium (Fig. 5)

Calcium is more readily leached from a soil profile then either potassium or magnesium (Likens and Borman 1972), and its presence in lake sediments has been associated with the products of leaching rather than erosion activity in the watershed (Mackereth 1966). The postglacial profile of calcium in Sunfish Lake evidently supports this hypothesis with low values in the L and A zones and in the top 30 cm. Furthermore, calcium minima in the B zone correspond to a series of potassium and magnesium maxima, suggesting periods of erosion during the pine forest period, 8–10,000 BP. Inexplicably this does not correspond with maxima in inorganic sedimentation (Fig. 4). Biological precipitation may also have influenced the postglacial profile of calcium.

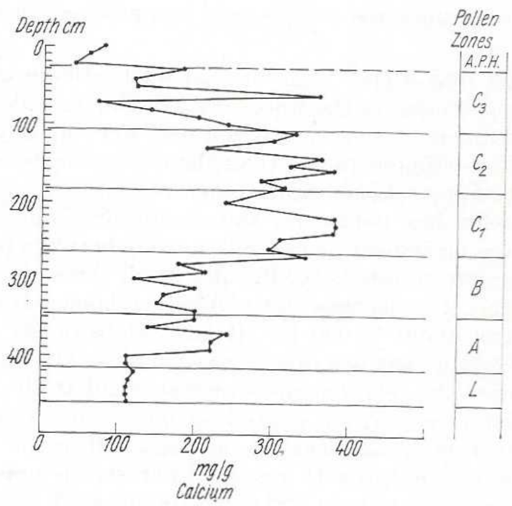

Fig. 5. Mg/g dry weight of calcium in core SL-6

5. Iron and manganese (Fig. 6)

The distribution of iron and manganese in sediments depends primarily on (1) the supply of particulate and dissolved iron and manganese, (2) the migration of iron and manganese as influenced by redox, and (3) the rate of accumulation of the whole sediment.

In the Sunfish Lake drainage basin erosional transport would not be expected to bring about any separation of iron and manganese, so that under purely erosional conditions their ratio should remain that of the lithosphere. However, the increase in manganese in the A zone probably coincides with the development of a soil profile and may indicate some preferential leaching of manganese over iron. Presumably this would continue more or less consistently over the remainder of the postglacial. Once these elements are precipitated into the sediments, transport by reduction to the mobile manganous and ferrous forms occurs. Since manganese is more readily reduced than iron, a change in the Fe:Mn ratio results. MACKERETH (1966) used the increase in the Fe:Mn ratio as an index to show the progression from oxidizing to reducing conditions in hypolimnia. In a very reductive hypolimnion iron also migrates and the ratio falls again.

In Sunfish Lake the Fe:Mn ratio on the whole increases from the A-B horizon to a maximum in mid C_3 (Fig. 6). Since there is no evidence for an increase in the rate of supply of iron over manganese this may be attributed to a progressively reductive hypolimnion. Presumably before the A-B horizon the hypolimnion was well-oxygenated. In zone B the ratio begins to increase presumably as a result of migration of manganese from the sediments accompanying a reduction in the amount of oxygen in the hypolimnion. In zone C_1 the ratio increases sharply. In zone C_2 the ratio begins to fluctuate; there is a further reduction in manganese content but also a reduction in iron, which indicates that iron is now starting to migrate out of the sediments. Above 70 cm there is a sharp decrease in the ratio together with an increase in both iron and manganese; the hypolimnion was probably sufficiently reducing to produce some sulphide thereby precipitating iron and manganese. The upper 25–30 cm of sediment are completely black with sulphide, probably concomitant with meromixis.

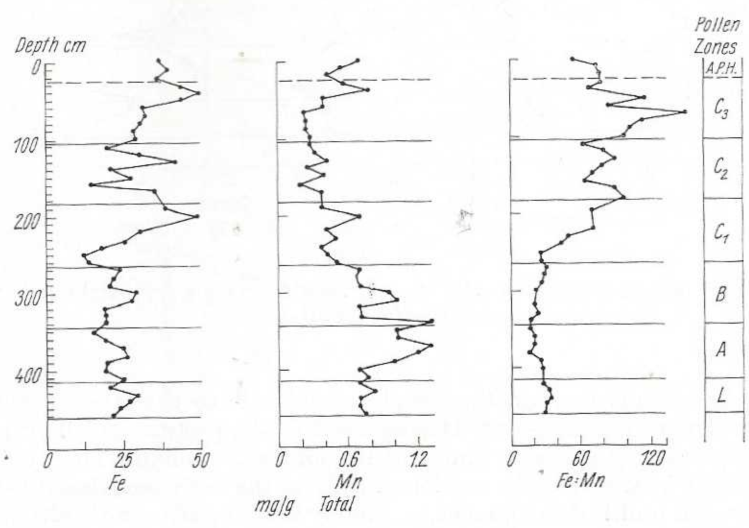

Fig. 6. Mg/g dry weight total iron and manganese, and iron: manganese ratio in core SL-6.

6. Copper (Fig. 7)

Concentrations of copper vary between 0.02 and 0.05 mg/g over most of the cor except in the top 25 cm, where it reaches a maximum of 0.1 mg/g, probably reflectin precipitation of copper as insoluble sulphide.

7. Sulphate and chloride (Fig. 7)

The precipitation of sulphate into lake sediments is probably largely biological an primarily with algal material. Bacteria at the mudwater interface have the abilit to reduce the sulphate to sulphide under sufficiently reducing conditions, in whic case sulphur would be held in the sediments as iron and manganese sulphides. Excep in the upper part there appears to be a resemblance between the profiles of sulphat and organic matter in the core. Toward the surface the falling concentration o sulphate probably corresponds to conversion to sulphide.

The postglacial profile of chloride, expressed as mg/g, shows no resemblance t that of organic matter, although chloride is associated with the organic fraction. If however, chloride is plotted per unit weight of organic matter, so that variations du to varying amounts of organic matter are eliminated, the profile resembles that o inorganic sedimentation intensity (Fig. 4). Thus it would appear that although sedi

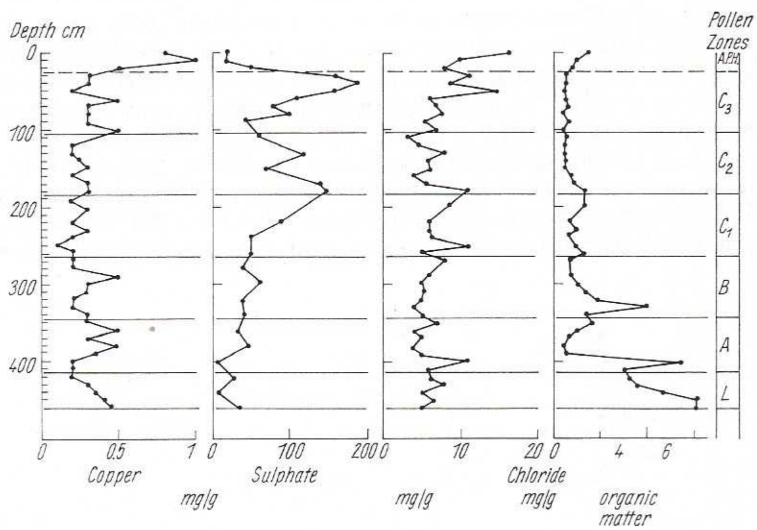

Fig. 7. Mg/g dry weight copper and sulphate, and chloride as mg/g dry weight and mg/g organi matter in core SL-6.

mented in the organic fraction the supply of chloride to the lake is controlled b erosion intensity in the watershed. During much of the postglacial, chloride in atmo spheric precipitation (the major source of the ion) was probably largely held in th soil profile, or at least its supply regulated. Only in the early postglacial before fores cover and, or, soil profile development, and lately with the advent of cultural practice in the watershed, has appreciably more chloride reached the lake.

8. Phosphorus (Figs. 8, 9, 10)

Both water extractable and 0.1 NHCl extractable phosphorus had their lowest concentrations near the bottom of the core and tended to increase very gradually toward the surface. Concentrations in the perchloric acid extract (total phosphorus) were always very much higher and showed very wide fluctuations, particularly in the upper half of the core. The .1 N HCl extract, and to a lesser extent the water extract, includes loosely bound sorbed phosphorus and some organic forms; the perchloric acid extract includes in addition tightly bound organic phosphorus and much of the inorganic fraction (WENTZ 1969). The interpretation of phosphorus in core SL-6 is not readily apparent; the final concentration in any given sample is the result of four major processes (cf. MACKERETH 1966): (1) the rate of supply of organic and inorganic phosphorus to Sunfish Lake, (2) the rate of precipitation of phosphorus onto the sediment, (3) the rate of release and migration of phosphorus from the sediments, and, (4) the rate of accumulation of the whole sediment.

In order better to separate the rate of supply of loosely-bound from tightly-bound and inorganic phosphorus to the sediments and to allow for differential rates of sedimentation over the postglacial all three extractions were re-plotted as sedi-

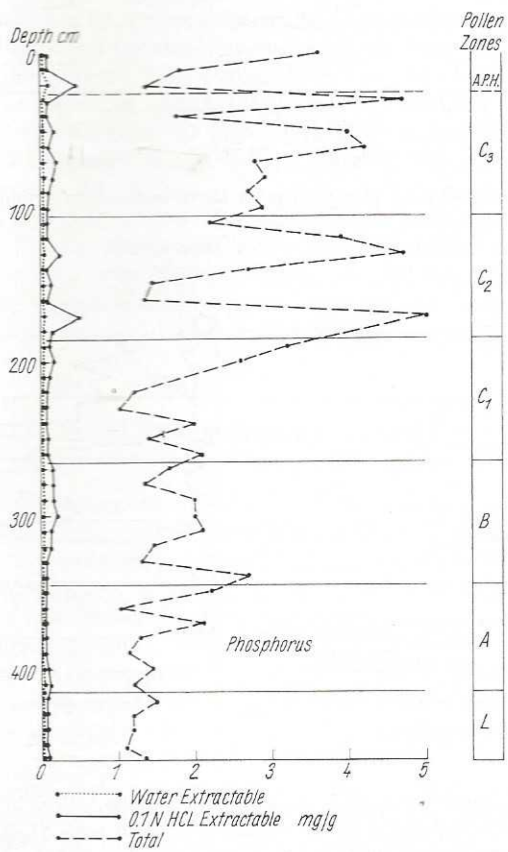

Fig. 8. Mg/g dry weight phosphorus in three extraction procedures from core SL-6.

mentation intensity (Fig. 9). The high sedimentation intensity of total phosphorus in zones L, A and lower B can best be attributed to the inorganic fraction (cf. LIVINGSTONE and BOYKIN 1962). All three extractions show a major maximum at 20 cm, just above the *Ambrosia* pollen horizon. Since there is no evidence for high erosional activity between the early B zone and the 20 cm sample presumably most of the phosphorus in these sediments was biologically precipitated as tightly or loosely bound organic phosphorus. The ratio between total phosphorus and organic matter (Fig. 10) tends to fall, though with wide fluctuations, throughout the postglacial. The main

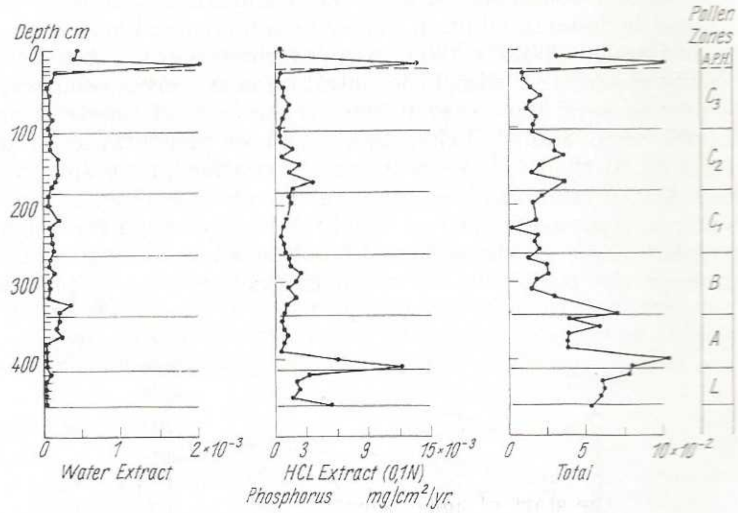

Fig. 9. Sedimentation intensity of phosphorus in three extraction procedures from core SL-6.

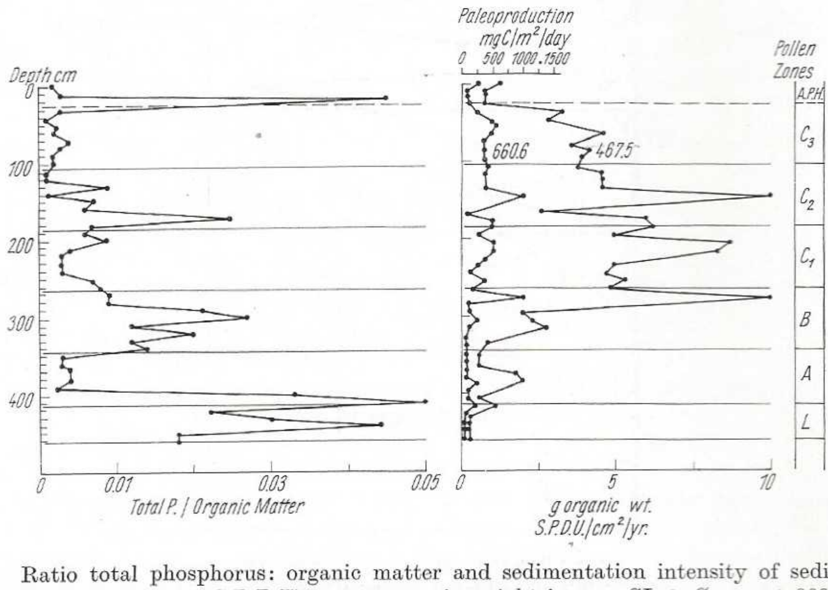

Fig. 10. Ratio total phosphorus: organic matter and sedimentation intensity of sedimentary pigment degradation units (S.P.D.U.) per g organic weight in core SL-6. Curve at 660.6 nm is mainly chlorophyll degradation products and 467.5 nm mainly carotenoid degradation products. Estimated paleoproduction (see text) refers only to curve at 660.6 nm.

reason for this is an increasing amount of organic matter in the sediments. Evidently over most of the postglacial an increasing proportion of the precipitated phosphorus became mobile and re-available to the lake's ecosystem. This is compatible with the hypothesis of an increasingly reductive hypolimnion. However, the pattern of maxima and minima in the phosphorus: organic matter ratio indicates that the process was neither regular nor continuous. Assuming a more or less consistent precipitating efficiency returning phosphorus to the sediments, the maxima and minima could be attributed to lower and higher diagenetic efficiency respectively. This may be tested by a comparison with the Fe:Mn ratio.

The high phosphorus: organic matter ratio in zone L is attributable to the low sedimentary organic matter. There is a general increase in the ratio from 350 cm to a maximum at 300 cm concurrent with a low and little changing Fe:Mn ratio. This was the period of decreasing mineral sedimentation. The hypolimnion was evidently well-oxygenated allowing little reduction and mobility of organically precipitated phosphorus. Between 300 and 180 cm the phosphorus: organic matter ratio falls and remains low. This correlates with a generally increasing Fe:Mn ratio indicating increased mobility of phosphorus from an increasingly reductive hypolimnion. The single maximum in the phosphorus: organic matter ratio at 170 cm and the decline in the Fe:Mn ratio between 180 cm and 160 cm indicates an apparent disturbance or pause in this process. There is another, lesser, disturbance at 130 cm, but the general trend between 160 cm and the *Ambrosia* pollen horizon is an increasingly reductive hypolimnion and a decreasing or low phosphorus: organic matter ratio. The presence of sulphide precipitating both iron and manganese would have the the effect of liberating previously bound phosphorus. This evidently is the case between 70 cm and 40 cm, and possibly also between 250 cm and 200 cm. The isolated maximum in the phosphorus: organic matter ratio at 20 cm is probably a consequence or erosion from forest clearance and the start of agriculture. Most of the watershed is used now for grazing or has regenerated to forest.

In conclusion, there is evidently a relationship in the sediments between phosphorus, organic matter and the Fe:Mn ratio. Trends compare better than individual minima or maxima. Variations in precipitating efficiency and reactions of phosphorus with iron and manganese complicate the system and are at least partially the cause of the minor irregularities in the phosphorus profiles.

V. Fossil Pigments and Paleoproductivity

Acetone extracts of sediments in core SL-6 showed two major absorption peaks. The major absorption maximum in the red at a mean of 660.6 nm (range 658.0–665.0 nm) is largely a measure of chlorophyll degradation products, primarily phaeophytin *a*. Intense absorption maxima in the blue at a mean of 467.5 nm (range 466.0–475.0 nm) are due to carotenoid degradation products with some influence by phaeophytin *a* (Wetzel 1970).

The profiles of S.P.D.U. per gram dry weight show a general increase throughout the postglacial sediments up to 60 cm (Fig. 11). Both chlorophyll and carotenoid curves show a series of maxima but the latter are most pronounced and amount to wide oscillations.

The validity of using sedimentary pigment degradation products as an index of past production rates depends mainly on the preservation of the pigments, the extent of differential degradation during and after sedimentation, and the extent of allochthonous sources of sedimentary pigment products. Preservation appears to have

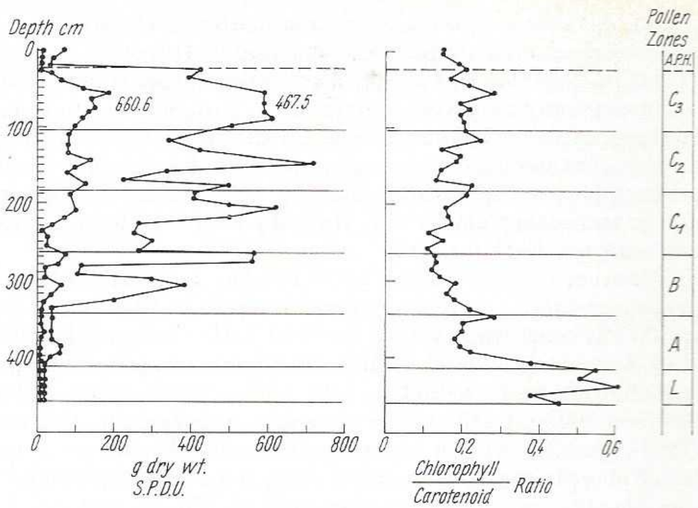

Fig. 11. Sedimentary pigment degradation units (S.P.D.U.) per g dry weight at 660.6 nm (Chlorophyll degradation products) and at 467.5 nm (carotenoid degradation products) in core SL-6, and the chlorophyll: carotenoid ratio.

been good in Sunfish Lake. The S.P.D.U. curves are similar to organic matter (Fig. 3). Also, Fogg and Belcher (1961) and Moss (1968) have shown that the ratio of chlorophyll degradation products to carotenoid degradation products decreases with increasing lake fertility and decreasing hypolimnetic oxygen. Moss further showed that the preservation of carotenoids increases with decreasing oxygen availability. The large amounts of carotenoids in the postglacial sediments of Sunfish Lake and the anoxia of the monimolimnion favours good preservation. The chlorophyll: carotenoid ratio (Fig. 11) decreases rapidly between zones L and A then varies about a mean over the remainder of the postglacial indicating at least a consistent preservation of both products. The low ratio and the similarity in chlorophyll and carotenoid curves also indicates little allochthonous input (Sanger and Gorham 1972). This is in harmony with the small watershed and narrow littoral of Sunfish Lake.

If, then, the assumption is made that fossil pigment biomass is generally on a long term basis directly proportional to past rates of production, then extrapolation throughout the postglacial is possible. In situ rates of primary production, as measured by the radiocarbon technique, show an integrated annual mean of 270 mg C/m^2/day (Waite and Duthie 1974). This was taken as time zero and extended on an appropriate relative basis through the postglacial using the sedimentation intensity of chlorophyll S.P.D.U. per g organic wt. (S.P.D.U./cm^2/year) for the extrapolation (Fig. 10). Production estimates are low in zones L and A but rise to a maximum of over 1000 mg C/m^2/day at 275 cm in zone B. Further large maxima are evident at 210–230 cm and 145 cm in zones C_1 and C_2 respectively. Following a smaller maximum at 55 cm in zone C_3 production rates decline toward the surface.

Assuming consistent preservation of pigments and a more or less consistent supply of nutrients from the watershed, the variations in production rates can best be attributed to internal factors in the lake. Evidence has been given above that the ratio of phosphorus to organic matter is related to the mobility of phosphorus from the sediments. The profiles of phosphorus: organic matter and sedimentation intensity of S.P.D.U. are compared in Fig. 10. It is apparent that there is an inverse relationship between the two, both in the general post-glacial trend and in individual maxima and minima. For example, S.P.D.U. (production) maxima correspond to phosphorus: organic matter minima (indicating efficient phosphorus migration from the sediments) at the following depths: 415–420 cm, 390 cm, 310 cm, 275 cm, 210–230 cm, 180–190 cm, 140–145 cm, and 55–65 cm. Conversly, the major phosphorus: organic matter maxima (inefficient phosphorus migration) at 490 cm, 410 cm, 300 cm, 170 cm, and 20 cm, correspond to production minima.

Thus there is evidence that the post-glacial production rates in Sunfish Lake have been influenced by the release and migration of phosphorus from the sediments. However, a closer comparison of the two curves reveals several discrepancies suggesting the presence of other complicating factors. The system may perhaps be better understood and possibly quantified by a more intensive analysis at closer intervals in the core. Recently, Bortleson and Lee (1974) have shown that iron and manganese deposition is closely related to phosphorus deposition in short cores from Wisconsin lakes.

VI. A Reinterpretation of the Postglacial History of Sunfish Lake

Sreenivasa and Duthie (1973) described the postglacial history of Sunfish Lake based mainly on diatom stratigraphy. This history should now be revised and elaborated upon in the light of the present investigation.

Zone L

Although inorganic sedimentation is high, the moderate rate of accumulation of the entire sediment discounts high erosion in this zone. Furthermore, the date of 13,200 BP for final deglaciation is probably conservative (P. F. Karrow[1], personal communication); an older date would further reduce the rate of accumulation. The high amounts of potassium and magnesium are probably due to loss from an undeveloped soil profile or associated with fine clay particles. Production rates are low but increase to a small maximum at the end of the zone. The absence of diatoms in the sediments may indicate poor preservation or possibly that other algal groups were predominant. The hypolimnion was well oxygenated. Pollen records indicate a tundra or spruce parkland vegetation in a climate colder than present.

Zone A

This zone is typified by a spruce forest vegetation in a climate still colder than present. Inorganic sedimentation decreases rapidly during the first part of the zone. Production at first low later rises to rates at least as high as the present. The hypolimnion was not very reducing but the increased preservation of carotenoids may indicate some oxygen reduction during summer or winter stagnation, and possibly the reduction and migration of some sedimentary phosphorus. Near the end of the zone a temporary increase in inorganic sedimentation and a trend to lower production rates and a more oxidising hypolimnion may indicate a brief climatic deterioration. Diatoms are first found in the middle of this zone and are non-planktonic cold water stenotherms.

Zone B

This pollen zone marks the establishment (about 10,500 BP) of a forest dominated by pine but with some spruce and hardwoods in a climate a little cooler than present. The trend to lower production rates continues in the part of the zone. In the middle

[1] Department of Earth Sciences, University of Waterloo.

of the zone inorganic sedimentation declines to a minimum, and production rates increase together with a slightly more reducing hypolimnion and evidence for some mobility of precipitated phosphorus. Following a temporary pause, productivity rises to a maximum near the end of the zone The hypolimnion becomes more reducing with increased mobility of phosphorus. Diatoms become more abundant in the sediments.

Zone C_1

The zone is characterised by an increasingly reductive hypolimnion and high phosphorus diagenetic efficiency. Productivity reaches a large maximum near the end of the zone; the lake was evidently considerably more productive than present. Diatom frustules also reach maximal numbers in the sediments. The low mineral sedimentation implies a fully developed soil profile with attendant leaching of available nutrients. Pollen analyses show a forest of hemlock, oak and beech in a climate warmer and probably wetter than zone B.

Near the end of the zone a series of changes is evident possibly associated with a change to a dryer climate. Production rates decline, the hypolimnion becomes less reducing and phosphorus less mobile.

Zone C_2

Productivity declines in the first quarter of the zone, evidently to rates considerably less than present, and the number of diatom frustules in the sediments declines. The hypolimnion is less reducing and sedimentary phosphorus less mobile. The fossil diatom flora contains a higher proportion of littoral and attached forms and euplankters decline in importance, suggesting lower water levels. This is in harmony with the evidence from the pollen record suggesting a warm, dry, climate with hickory and oak predominant.

The minimum is short-lived, for by the middle of the zone productivity evidently rises to the postglacial maximum associated with a return to a very reducing hypolimnion and efficient phosphorus diagenesis. This maximum is not shown in the diatom record, possibly much of the productivity was realised by other algae. At the end of the zone productivity declines.

Zone C_3

This zone is marked by a decline in hickory and oak and an increase in hemlock and beech interpreted as a change to a modern climate, cooler and wetter than C_2. Productivity increases to a maximum at 60 cm in the core (estimated at 850–900 BP) then declines toward the surface. The hypolimnion is very reductive, with evidence for the production of sulphide precipitating iron and manganese above 70 cm. This would have the effect of releasing phosphorus previously bound to iron or manganese. Sreenivasa and Duthie (1973) interpreted a major change in the fossil diatom assemblage at the same horizon in core SL-4 as evidence for the lake becoming eutrophic. However, this is not borne out by the pigment analysis; it seems far more likely that the lake became meromictic around this time, considerably prior to the onset of cultural practices in the watershed. The main evidence is that although the hypolimnion is very reducing with high diagenetic efficiency of phosphorus, production rates evidently decline above 60 cm, implying noncirculation. In all other instances in the core high diagenetic efficiency of phosphorus is accompanied by high productivity ruling out prior establishment of meromixis. The exact sequence of events around 60 cm could be determined better by closer sampling intervals.

The impact of forest clearance and agriculture is well marked on the top of 20 cm of the core. There is a large increase in the rate of accumulation of the whole sediment including inorganic sedimentation. The hypolimnion remains very reducing and production rates low.

VII. Summary and Conclusions

The gradual obliteration of the hypolimnion has had a profound effect on the postglacial history of Sunfish Lake. The chief consequence has been an increasingly reductive hypolimnion which has resulted in an increasingly efficient diagenesis of phosphorus and possibly other nutrients. The manifestation of this in the sediments is a general increase through the postglacial in organic matter, fossil pigments and diatom frustules. However, the process has been neither regular nor progressive; there have evidently been several large fluctuations in productivity in the lake's history though the minima have tended to become less as the lake filled in. The maxima are correlated with efficient phosphorus diagenesis, though the factors controlling this diagenesis can only be speculated upon. Precipitation reactions with iron and manganese may be involved but resolution of this would require a more detailed analysis.

Postglacial climatic changes only agree in a very general way with past production rates. Changes in production rates appear to occur long before climatic changes are indicated by the pollen record. Changes in the forest composition appear to be a very conservative indicator of climatic change.

The present work shows the conclusions drawn from diatom analysis alone are hazardous. There are at least two periods in the history of Sunfish Lake where high production rates evidenced by pigments are not apparent in diatom counts; presumably other algae were predominant. The lake is now dominated by bluegreen algae. On the other hand the composition of the fossil diatom flora appear to be a good indicator of the relative importance of various habitats in the lake.

Without a finer resolution of events around the 60–70 cm levels in core SL-6 it is difficult to determine the exact sequence of events leading to meromixis, though it is undoubtedly biogenic in origin. The present meromixis is maintained by high concentrations in the monimolimnion of bicarbonates, sulphates and sulphides (Duthie and Carter 1970).

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Mr. R. W. ADAMS
Department of Biology
University of Waterloo
Waterloo, Ontario
Canada N2L 3G1

Dr. H. C. DUTHIE
Associate Professor
Department of Biology
University of Waterloo
Waterloo, Ontario
Canada N2L 3G1

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