SEDIMENT CORE STUDY OF LITTLE ROCK LAKE, BENTON COUNTY, MINNESOTA

Paul J. Garrison and Gina D. LaLiberte

Wisconsin Department of Natural Resources,

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INTRODUCTION

Inquiries often arise concerning how a lake's water quality has changed through time as a result of watershed disturbances. In most cases there is little or no reliable long-term data. Questions often asked are if the condition of the lake has changed, when did this occur, what were the causes, and what was the historical condition of the lake? Paleoecology offers a way to address these issues. The paleoecological approach depends upon the fact that lakes act as partial sediment traps for particles that are created within the lake or delivered from the watershed. The sediments of the lake entomb a selection of fossil remains that are more or less resistant to bacterial decay or chemical dissolution. These remains include diatom frustules, cell walls of certain algal species, and subfossils from aquatic plants. The chemical composition of the sediments may indicate the composition of particles entering the lake as well as the past chemical environment of the lake itself. Using the fossil remains found in the sediment, one can reconstruct changes in the lake ecosystem over any period of time since the establishment of the lake.

Little Rock Lake, is a large shallow lake in Benton County, MN. The lake elevation is directly affected by the water level of the river because of a dam located at Sartell, downriver of the connection of Little Rock Lake with the river. The dam was first installed in 1911 and raised in 1934. At the present time, the lake experiences frequent noxious algal blooms for much of the summer. The purpose of this study was to determine the lake's sedimentation rate for the last 150 years and water quality changes that have occurred.

Figure 1. Location of the site for the sediment coring. The water depth was 11 feet.

METHODS

A sediment core was collected from Little Rock Lake, Benton County, MN from the deep area of the lake on 24 June 2008. The location of the coring site was 45.72682° north and 94.16515° west in 11 feet of water (Figure 1). A piston corer with an inside diameter of 8.8 cm was used to collect the 130 cm sediment core. The core was vertically extruded on the lakeshore and subsamples of 2 cm intervals were placed in plastic freezer bags.

In order to determine when the various sediment layers were deposited, the samples were analyzed for lead-210 (^{210}Pb). Lead-210 is a naturally occurring radionuclide. It is the result of natural decay of uranium-238 to radium-226 to radon-222.

Since radon-222 is a gas (and thus is sometimes found in high levels in basements) it moves into the atmosphere where it decays to lead-210. The ^{210}Pb is deposited on the lake during precipitation and with dust particles. After it enters the lake and is in the lake sediments, it slowly decays. The half-life of ^{210}Pb is 22.26 years (time it takes to lose one half of the concentration of ^{210}Pb) which means that it can be detected for about 130-150 years. This makes ^{210}Pb a good choice to determine the age of the sediment since European settlement began in the mid-1800s.

Cesium-137 (Cs^{137}) can be used to identify the period of maximum atmospheric nuclear testing (Appleby 2001). The peak testing occurred by the USSR in 1963 and thus the ^{137}Cs peak in the sediment core should represent a date of 1963. The United States began testing in 1952 with measurable fallout beginning in 1954, thus the rise in ^{137}Cs corresponds with this date.

Activities of ^{210}Pb, ^{226}Ra, and ^{137}Cs were determined on 15 freeze dried samples by measuring gamma spectrometry using an ultra low background intrinsic germanium semi-planer detector coupled to a multichannel analyzer (Schelske et al. 1994). Sediment ages for the various depths of sediment were determined by the constant rate of supply (CRS) model (Appleby and Oldfield 1978) and the piecewise CRS model of Appleby (1998, 2001). Bulk sediment accumulation rates (g cm^{-2} yr^{-1}) were calculated from output of the CRS model.

Sediment samples for dry bulk density and organic matter content determinations were dried at 105°C for 24 h. Dry bulk density was determined using a known volume of wet sediment (usually 1 mL) for determining water weight percent. Organic matter content was determined by weight loss after ashing (loss on ignition, or LOI) at 550°C for 1 hour (Dean 1974) and following the recommendation of Boyle (2004) for sediments with a large amount of organic matter following the recommendation of Henri et al. (2001) we used similar volumes of material for all of the samples.

Two samples for top/bottom diatom analysis were cleaned with hydrogen peroxide and potassium dichromate (van der Werff, 1956). A portion of the diatom suspension was dried on a coverslip and samples were mounted with Naphrax®. Specimens were identified and counted under oil immersion objective (1400X) until 400 valves had been encountered. Diatoms were identified to species level wherever possible using references which included Patrick and Reimer (1966, 1975), Krammer and Lange-Bertalot (1986, 1988, 1991a,b), and Lange-Bertalot (2001).

Eighteen samples for blue-green and green algal fossils were processed using a modified method of Moore et al. (1991). Samples of a known weight were cleaned with hot 10% potassium hydroxide for 30 minutes. Cleaned samples were placed in a Palmer-Maloney chamber and a known area was counted. During counting, all fossils were enumerated at a magnification of 500X. Fossils encountered included blue-green algae, green algae, and diatoms.

RESULTS AND DISCUSSION

The total length of the sediment core extracted from the lake was 130 cm (4.3 ft). From 0-70 cm the sediment color was dark gray. From 70 to 130 cm the color was a lighter medium gray in color.

The specific activity of ^{210}Pb in the surface sediments of the core was 5.88 pCi cm^{-2}, which is somewhat lower than the regional average. The ^{210}Pb inventory was 22.73 cm^{-2} which is somewhat higher than the regional mean in Binford et al. (1993). The higher than normal inventory and lower specific activity probably reflects the likely accelerated sediment input from the largely agricultural landuse in the watershed. The mean ^{210}Pb flux was 0.71 pCi cm^{-2} yr^{-1}, which is within the normal ranges commonly found in the region (Binford et al. 1993). This implies that there is little sediment focusing occurring in the lake. Sediment focusing occurs when finer sediment particles accumulate at higher rates in the deepest part of the lake.

Total ^{210}Pb and ^{137}Cs activities vs. sediment depth are shown in Figure 2. The graph of ^{137}Cs appears to display the typical increase at 40 cm, which may indicate when the United States began atmospheric nuclear testing in the early 1950s. The peak in the activity is broad but the highest values are between 25-30 cm which may indicate the date of 1963. The flattening of the peak indicates there has been some migration of the cesium in the sediment profile. There likely has also been additional transport of ^{137}Cs from the watershed during erosional events. It is known that ^{137}Cs readily attaches to soil particles and can be transported to receiving waters.

If the sedimentation rate was unchanged during the last 150 years, the graph of ^{210}Pb activity vs. depth should be linear as the decay of ^{210}Pb is exponential. This is not the case as there is a flattening near the bottom and the top of the core. The flattening at the bottom may represent background concentrations, i.e. ^{210}Pb has decayed to undetectable levels which would be circa 150 years ago. For reasons discussed below this not believed to be the case.

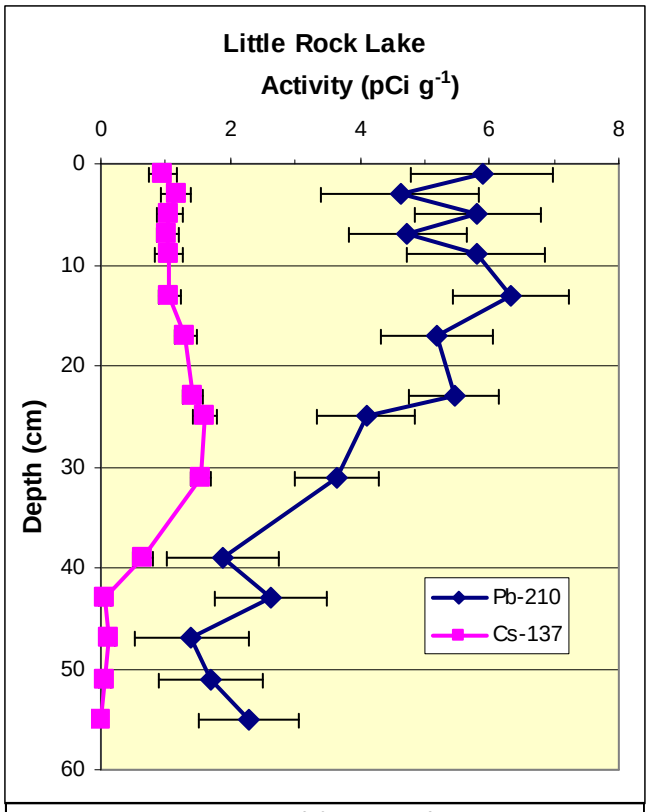

Figure 2. Radioisotope (^{210}Pb and ^{137}Cs) activities vs. sediment depth in the sediment core.

The non-linearity of the lead-210 activity indicates that determining sediment ages may be problematic. This difficulty sometimes occurs in relatively large shallow lakes as well as lakes with significant changes in water levels and landuse activities in the watershed, as is the case with Little Rock Lake. The lake is located adjacent to the Mississippi River above Sartell. In 1911 a dam was placed across the river downstream from the outlet of the lake. This dam resulted in the water level of the lake being raised. The water level was further raised in 1934 when the dam height was raised. Prior to the installation of the dam, Little Rock Lake was a open water wetland. With the initial dam,

it became a deepwater marsh. The erection of the dam of 1934, further increased the height of the lake to its current level. The progression from marsh to open water lake had profound impact on the lake's biota. One of these impacts was on the deposition of organic matter in the sediments .

The loss on ignition, which indicates organic matter content, was higher at the bottom of the core than it was at the top (Figure 3). This reflects the fact that prior to 1911, the current Little Rock Lake was a marsh but now it is an open water lake. The peak between 40 and 55 cm may represent the time period soon after the installation of the first dam in 1911. The increased water level would have likely have flooded a substantial amount of vegetation and the deeper water may have retarded bacterial decomposition of this organic matter. This could have resulted in increased deposition of organic matter. The lower values in the upper 35 cm of the core reflect the reduced production of organic matter when the dam was raised in 1934. The conversion from a marsh to a lake meant that fewer vascular plants were found in the lake and much of the primary production consisted of algae. The diatom *Stephanodiscus niagarae* (Figure 4) is found floating in the open water of lakes and rivers. Its large increase at 40 cm signals the transition from a deep water marsh to an open lake. This likely occurred with the increased height of the dam in 1934.

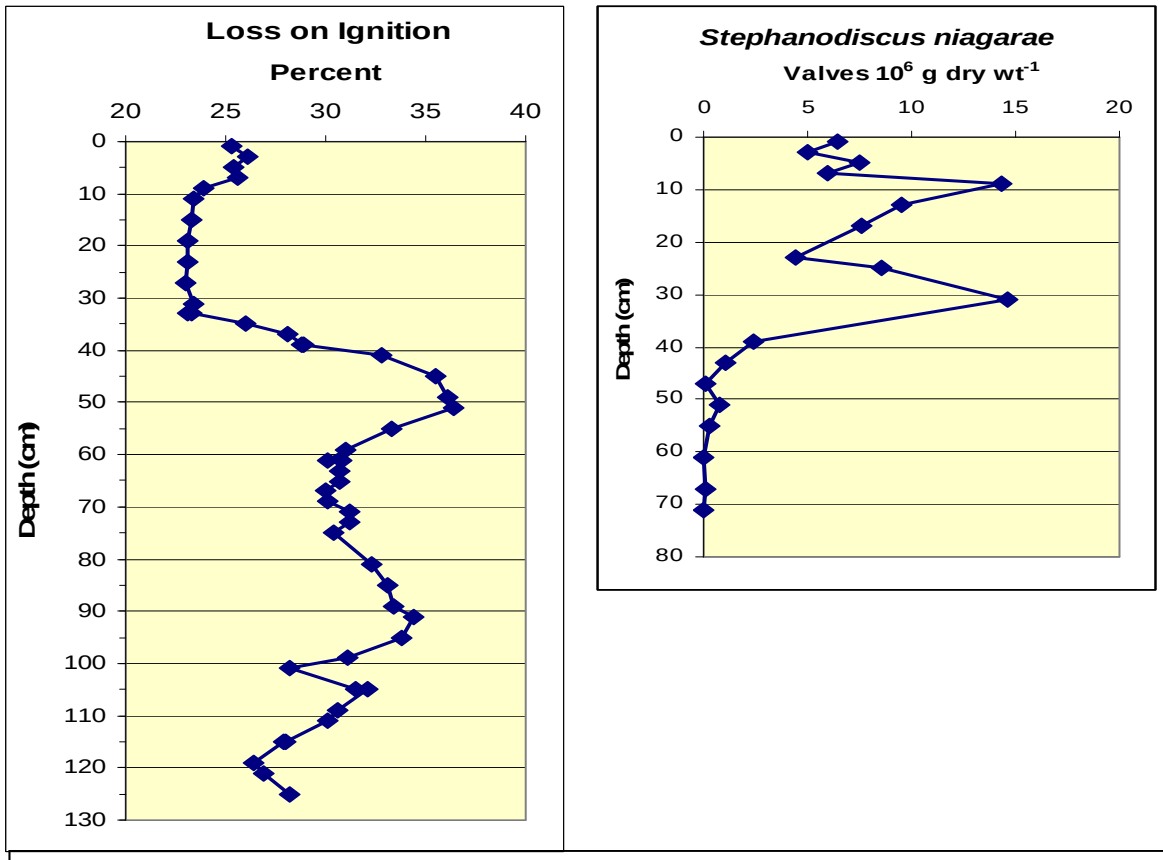

Figure 3. Profiles of loss on ignition (organic matter) and the diatom *Stephanodiscus niagarae*. Changes in both of these parameters reflects water level changes in the lake during the last century.

Figure 4. Photomicrograph of the diatom *Stephanodiscus niagarae*. Changes in its abundance at 30-32 cm in the core was used to construct one of the dating models.

The sediment age for the various depths of sediment were initially determined by the CRS model. Using this method, the estimated dates for the ^{137}Cs peak was around 1970, the increased abundance of the diatom *S. niagarae* was 1961 and the increase in loss on ignition was 1883. The date for the cesium peak is reasonable with the likely migration of the cesium that may have occurred. The date for the increase in *S. niagarae* is more recent and the increase in LOI is earlier, implying non-steady-state ^{210}Pb supply rates during the time period represented by the core. Appleby (2000) found this type of discontinuity in a number of cores in European mountain lakes and used a piecewise CRS method to correct for this. This model assumes that the ^{210}Pb supply is uniform only within each distinct zone in the core. A similar piecewise CRS method was used with a core from a shallow bay in Lac Courte Oreilles, WI (Garrison and Fitzgerald 2005).

Two different piecewise models were employed for the Little Rock Lake core. One model assumed the ^{137}Cs peak at 30-32 cm represented a date of 1963 and that the increase of LOI at 54-56 cm represented a date of 1911. This model ignored the rise of *S. niagarae* at the same time as the ^{137}Cs peak. The other piecewise model assumed that the ^{137}Cs peak at 30-32 cm was incorrect and that the rise of *S. niagarae* peak represented a date of 1934 while the increase of LOI at 54-56 cm represented a date of 1911. Using the three models: (1) CRS, (2) CRS adjusted for ^{137}Cs and LOI (CRS-Cs adj), and (3) CRS adjusted for *S. niagarae* and LOI (CRS-Steph adj) sediment dates and the mass sedi-

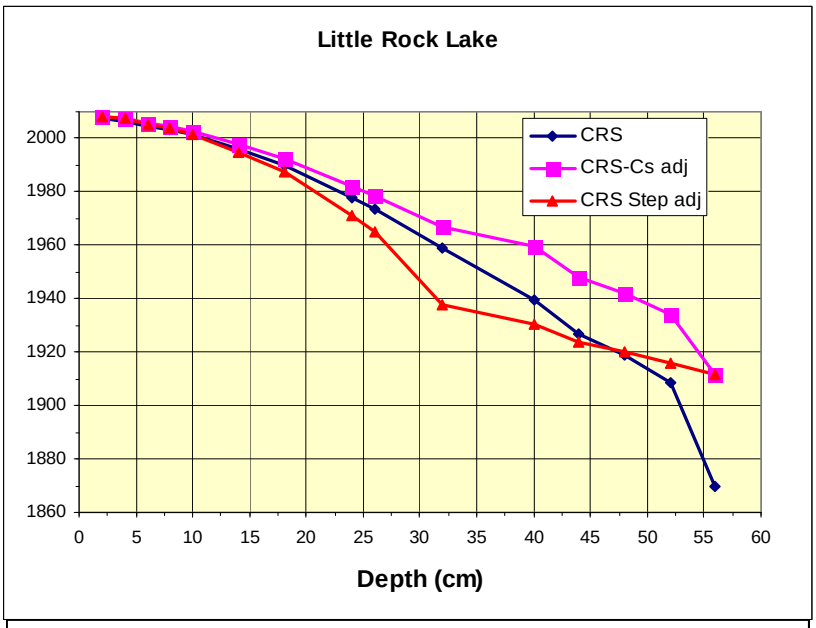

Figure 5. Sediment depth vs. dates calculated from the 3 dating models. The CRS model assumes the changes in water levels in the lake have not affected the ^{210}Pb supply rates to the lake. The other 2 models assume the rise in LOI at 55 cm indicates the installation of the dam in 1911. The CRS-Cs adj model assumes the peak ^{137}Cs at 30 cm represents a date of 1963. The CRS-Steph adj model assumes the rise in abundance of *S. niagarae* at 30 cm represents a date of 1934.

Table 1. Dates calculated with the three models. The CRS-Steph adjusted model is assumed to be the most accurate.

Interval (cm)	CRS	CRS-Cs adjusted	CRS-Steph adjusted
0-2	2007.5	2008.1	2008.0
2-4	2006.5	2007.5	2007.3
4-6	2004.7	2005.9	2005.3
6-8	2003.3	2004.7	2003.7
8-10	2001.3	2002.8	2001.4
12-14	1996.0	1997.9	1995.0
16-18	1990.1	1992.6	1987.7
22-24	1978.0	1982.1	1971.3
24-26	1973.7	1978.5	1965.0
30-32	1958.8	1966.7	1937.7
38-40	1939.6	1959.3	1930.3
42-44	1926.6	1948.2	1923.5
46-48	1918.7	1941.9	1919.9
50-52	1908.5	1934.2	1916.1
54-56	1869.5	1911.3	1911.3

mentation rate were calculated for each depth. The calculated dates using each model are shown in Table 1 and Figure 5.

All of the models give similar dates from the top of the core until 18 cm (circa 1990). The dates for the CRS-Steph adj model diverge more between 22 and 40 cm. The two adjusted models estimate more recent dates at the bottom of the core because of the date forcing factor in their models.

Although it is not possible to know with certainty which model is the most accurate, We believe that the model using the diatom *S. niagarae* and rise in LOI to adjust the CRS calculations (CRS-Steph adj) is the most accurate. We reject the CRS and CRS-Cs adj models because they estimate the rise of *S. niagarae* at a dates that are too recent. While it is not possible to know for sure when the increased abundance of the diatom *S. niagarae* occurred, it seems reasonable that this happened soon after the initial dam was built (1911) or when the water level was further raised in 1934. It is more problematic that the LOI rise at 55 cm represents the date of 1911 but two models do not estimate either event accurately. While ^{137}Cs is known to be mobile and the supply rate of ^{210}Pb could change as a result of large water level changes and agricultural activity in the watershed, it is unlikely that the diatom would migrate significantly once deposited. It is also very reasonable that this diatom

would only be present after the lake had transitioned from a marsh to a lake since it is commonly found as a planktonic diatom in lakes.

The flattening of the ^{210}Pb activity at the top of the core could be either: (1) the result of accelerated sedimentation which diluted the more recently deposited ^{210}Pb or (2) mixing by physical processes or biological activity. Since there is a sharp rise in both the ^{137}Cs profile between 30-40 cm as well as a sharp rise in abundance of the diatom *S. niagarae*, the flattening is more consistent with an increase in the sedimentation rate. It is very likely that some of the flattening is the result of mixing but it is felt most of the flattening is the result of increased sedimentation. A similar flattening of the lead activity curve was found in a lake in Slovenia (Appleby 1998), in White Lough in Northern Ireland (Appleby 2001), and Musky Bay in Lac Courte Oreilles, WI (Garrison and Fitzgerald 2005) which was attributed to an increase in the mass sedimentation rate. Binford and Brenner (1986) also found decreased concentrations of ^{210}Pb in surficial sediments in Florida lakes with accelerated eutrophication similar that likely to have occurred in Little Rock Lake. In contrast to these lakes, the flattening of the lead activity in Upper Klamath Lake, Oregon, USA was attributed primarily to physical mixing (Colman et al. 2004). This lake is much larger than Little Rock Lake (31, 000 vs. 595 ha) and Upper Klamath Lake is more susceptible to high winds.

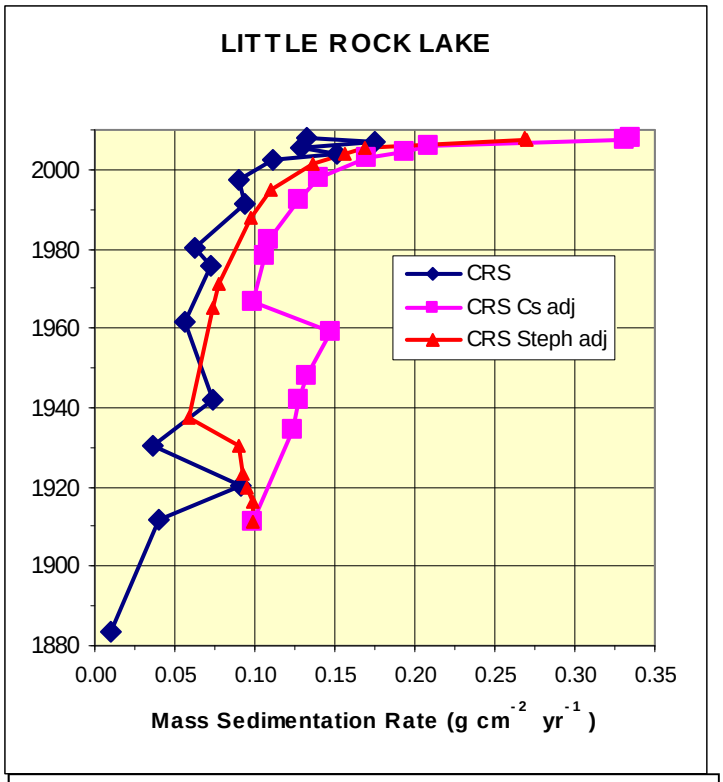

Figure 6. Mass sedimentation rate calculated from the 3 dating models. The CRS model assumes the changes in water levels in the lake have not affected the ^{210}Pb supply rates to the lake. The other 2 models assume the rise in LOI at 55 cm indicates the installation of the dam in 1911. The CRS-Cs adj model assumes the peak ^{137}Cs at 30 cm represents a date of 1963. The CRS-Steph adj model assumes the rise in abundance of *S. niagarae* at 30 cm represents a date of 1934.

The sedimentation rate was estimated using the three models (Figure 6). The mass sedimentation rates for each interval where it was measured is given in Table 2. All of the models indicate increased sedimentation rates in the last decade, although the two adjusted models estimate a much higher rate at the top of the core. The adjusted models will have overall higher rates since they use the same total ^{210}Pb inventory but apportion it over a shorter time period and sediment depth. All of the models assume there is negligible mixing of the surface sediments.

Table 2. Mass sedimentation rates calculated with the three models. The CRS-Steph adjusted model is assumed to be the most accurate.

Interval (cm)	CRS	CRS-Cs adjusted	CRS-Steph adjusted
0-2	0.133	0.335	0.268
2-4	0.175	0.332	0.270
4-6	0.129	0.208	0.169
6-8	0.151	0.194	0.156
8-10	0.112	0.170	0.136
12-14	0.090	0.140	0.110
16-18	0.094	0.128	0.097
22-24	0.063	0.109	0.078
24-26	0.072	0.107	0.073
30-32	0.056	0.099	0.058
38-40	0.073	0.147	0.090
42-44	0.036	0.133	0.092
46-48	0.091	0.128	0.095
50-52	0.040	0.124	0.099
54-56	0.010	0.099	0.099

The profiles of the algal fossils reflect the historic water level increases in the lake (Figure 7). For much of the bottom of the core the dominant fossils are the blue-green algae *Aphanizomenon, Anabaena*, and *Gloetrichia* and the green alga *Pediastrum*. The three blue-green taxa are the only common genera of this algae that leave fossils. While these algae are often found in lakes, they can also be common in wetlands with areas of open water. All of these species decline at about the time that the diatom *S. niagarae* begins to increase. This transition likely signals the rise in water level when dam was first installed at Sartell in 1911 and raised in 1934. When *S. niagarae* is common in the core, presumably after 1934, the blue-greens and green alga are only found in low abundance. While the higher water levels probably are the reason for the decline in *Pediastrum*, it is not directly the reason for the decline in blue-greens. This decline probably signals an increase in nutrients. Blue-green algae are very common for much of the summer at the present time in Little Rock Lake. This algae is likely to be the species *Microcystis* which can form large blooms but does not leave fossils. Both *Aphanizomenon* and *Anabaena* are reported to be more competitive under lower phosphorus levels than *Microcystis* (van Geel et al. 1994).

Diatom assemblages historically have been used as indicators of trophic changes in a qualitative way (Bradbury 1975, Anderson et al. 1990, Carney 1982). In recent years, ecologically relevant statistical methods have been developed to infer environmental conditions from diatom assemblages. These methods are based on multivariate ordination and weighted averaging regression and calibra-

tion (Birks et al. 1990). Ecological preferences of diatom species are determined by relating modern limnological variables to surface sediment diatom assemblages. The species-environment relationships are then used to infer environmental conditions from fossil diatom assemblages found in the sediment core.

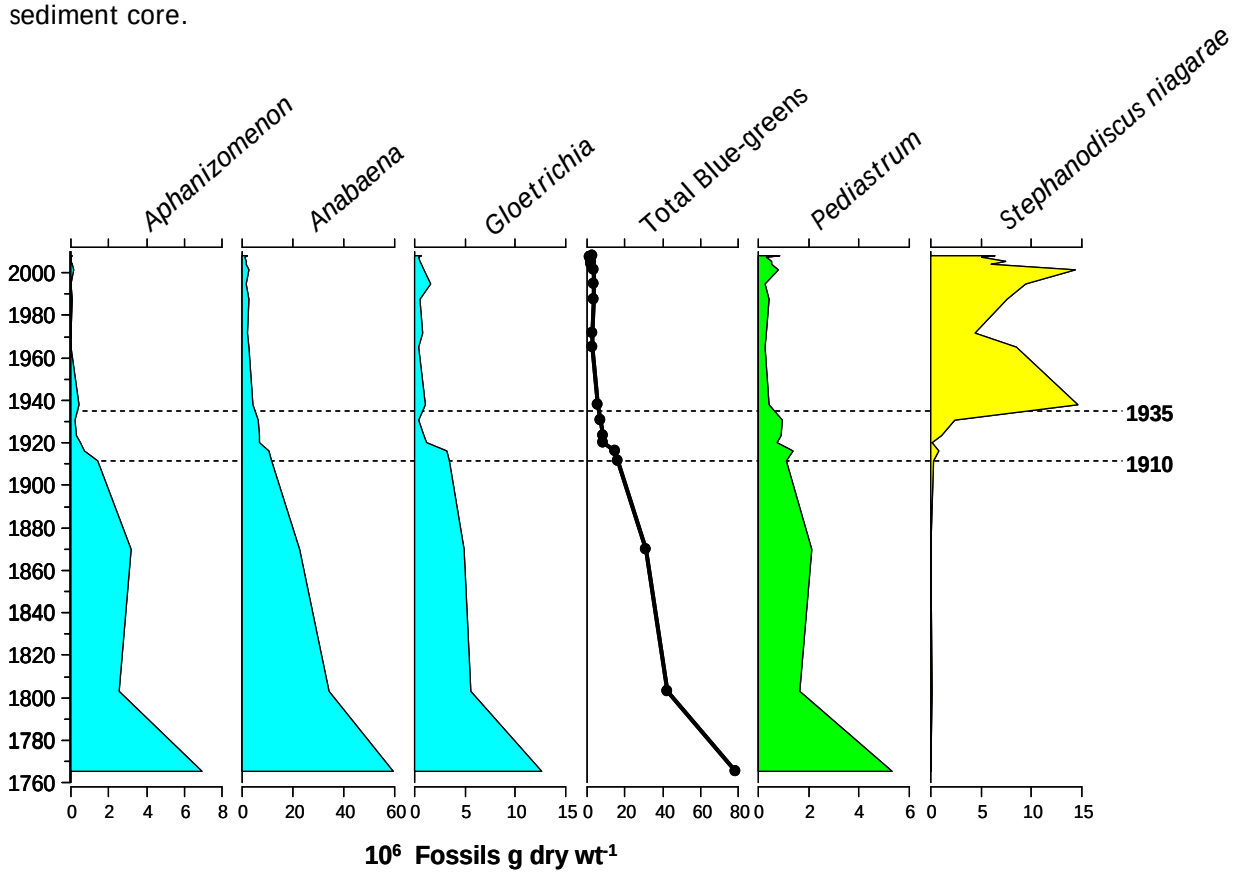

Figure 7. Profiles of selected algal fossils. The blue shaded graphs are blue-green algae. *Microcystis*, which is a common blue-green alga, does not produce fossils. It is likely that this species is the dominant blue-green alga after 1935. *Pediastrum* is a green alga and *S. niagarae* is a large free floating diatom pictured in Figure 4.

Weighted averaging regression and calibration were performed using WACALIB version 3.3 (Line et al. 1993) with 999 bootstrap cycles. This procedure produced a diatom transfer function for summer mean phosphorus that was applied to the diatom assemblages in the sediment core samples. The calibration dataset was based upon the surface diatom community from 57 shallow Wisconsin lakes. The root mean squared error of prediction (RMSEP) was 0.28 log (P) µg L^{-1} (r^2 = 0.76).

Diatom slides from the 0-2 cm and 50-52 cm samples were prepared and counted as part of the weighted averaging regression to estimate phosphorus concentration. The diatom community enumerated with the algal fossil analysis was not used since it was not possible to examine diatoms in the Palmer-Maloney chamber at a high enough magnification to accurately identify small taxa. Typically, a top/bottom analysis of the diatom community is used to estimate changes in phosphorus levels from pre-settlement (bottom) time to the present (top). In Little Rock Lake this is problematic because of

the transition from a deep water marsh to a lake. Instead of representing pre-settlement time, the bottom sample represents the phosphorus concentrations when the lake was likely a deep water marsh.

The estimated mean summer phosphorus concentration at the 50-52 cm depth was 109 µg L^{-1} and it was 163 µg L^{-1} in the top sample (0-2 cm). The model underestimates the present phosphorus concentration, most likely because the calibration dataset does not include lakes with phosphorus concentrations as high as Little Rock Lake. What the model does indicate is that phosphorus levels at the present time are substantially higher than they were historically. The increased phosphorus levels at the present time are supported by the other algal fossils. Aphanizomenon and Anabaena dominated blue-green algal blooms when phosphorus levels were lower, and blooms likely have shifted to Microcystis as phosphorus levels have increased.

Table 3. Diatom inferred mean summer phosphorus concentrations from the top/ bottom samples.

	CRS-Steph adj date	Total Phosphorus (µg L^{-1})
Top (0-2 cm)	2008	163
Bottom (50-52 cm)	1916	109

In summary:

- It was difficult to estimate sediment dates in the core from Little Rock Lake because of changing rates of ^{210}Pb supply during the last century. This was caused by large water level changes as well as modification of landuse in the lake's watershed. These problems were compounded by the shallow depth of the lake.

- The blue-green algal fossils suggest the change in phosphorus concentrations during the last century and the diatom *Stephanodiscus niagarae* gives a good idea of past water level changes.

- The top\bottom diatom analysis indicates that the current phosphorus concentration is significantly higher than historic levels. Phosphorus levels at the time the lake transitioned from a deep water marsh to a lake were high, placing the lake in the hypereutrophic category.

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APPENDIX A

Radiochemical concentrations for the 15 depths analyzed in the sediment core.

Little Rock Lake
Benton County, MN

CORE: LRL-1

DEPTH INTERVAL (cm)	TOTAL Pb-210 ACTIVITY ($pCi\ g^{-1}$)	TOTAL Ra-226 ACTIVITY ($pCi\ g^{-1}$)	TOTAL Cs-137 ACTIVITY ($pCi\ g^{-1}$)	BULK DENSITY ($g\ cm^{-3}$)
0-2	5.8847	0.6365	0.9664	0.0671
2-4	4.6237	0.7677	1.1663	0.0877
4-6	5.8202	0.7955	1.0645	0.1143
6-8	4.7383	0.6667	1.0282	0.1017
8-10	5.8003	0.5676	1.0606	0.1129
12-14	6.3467	0.7392	1.0607	0.1305
16-18	5.1886	0.7328	1.3049	0.1401
22-24	5.4600	0.7777	1.4261	0.1484
24-26	4.0944	0.5457	1.6023	0.1537
30-32	3.6450	0.6997	1.5425	0.1504
38-40	1.8930	0.6789	0.6401	0.1569
42-44	2.6123	0.8674	0.0730	0.1337
46-48	1.3961	0.8974	0.1126	0.1269
50-52	1.7002	0.8339	0.0478	0.1222
54-56	2.2887	0.6776	0.0000	0.1275

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