A PALEOLIMNOLOGICAL STUDY IN THE COMFORT LAKE - FOREST LAKE WATERSHED DISTRICT: PHASE II

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SUMMARY

1. Paleolimnological techniques were used to reconstruct the trophic and sedimentation history of Bone and School Lakes in the Comfort Lake - Forest Lake Watershed District, Chisago and Washington Counties, MN. Both lakes are located in the North Central Hardwood Forest ecoregion and defined as "deep" by the State of Minnesota. As such, the state nutrient standard that applies to them is 40 ppb total phosphorus (or 40 µg/l total phosphorus). Past monitoring efforts have shown both lakes to be impaired for nutrients.

2. In Bone Lake, a piston and an overlapping Bolivia core were collected through the ice on March 7, 2019. A single piston core was collected from School Lake on June 12, 2019. Lead-210 activity was analyzed to develop a dating model for each lake and determine the sediment accumulation rate over the past 150-200 years. Sediments were analyzed for inorganic, organic, and carbonate components using loss-on-ignition analysis; geochemical analyses also included sediment phosphorus and biogenic silica. Subfossil diatoms in the sediments were analyzed to reconstruct changes in lake ecology and trophic state. In addition to diatoms, algal pigments were measured to determine historical changes in other algal groups.

3. Both Bone and School Lakes showed an increase in sedimentation rate in the early 1900s. Our previous work showed that Shields, Moody, and Comfort Lakes also recorded increases in sedimentation in the early 1900s. Although there was some variation in the timing in peaks among lakes, this nearly synchronous pattern across the region suggests that this was due to initial land clearance. The sedimentation rate in Bone and School Lakes remains approximately three times higher at the core top compared to the rate in the early to mid-1800s.

4. Multiple proxies suggest that there was a large change in Bone Lake in the 1940s/50s. Following the increase in sedimentation rate in the early 1900s, there was a large increase in the phosphorus concentration in the sediments (peaking in the 1950s). This was largely driven by Fe-bound P, a readily exchangeable form. In the early 1940s the composition of the sediments changed, there was a sharp rise in inorganic matter and relative decrease in organic matter. The algal community also recorded a shift in the 1940s/50s: algal abundance showed a sharp increase over multiple groups, there was an increase in BSi in the sediments, and diatoms began to preserve in the core.

5. In School Lake, the sedimentation rate continued an overall rise to the core top following the initial increase between 1917 and 1938. Following the initial rise in sedimentation rate in the early 1900s, there were increases in TP concentration and flux (primarily Fe-bound P). The diatom community was characterized by indicators of eutrophic conditions throughout the period of record. Algal productivity has been high since the 1880s, with a slight decline in recent decades.

6. Please see the Conclusions section for management recommendations for Bone and School Lakes.

INTRODUCTION

Lakes are a prominent feature and a valued resource within the landscape of the glaciated regions of the Upper Midwest. Land and resource use in the watersheds over the past several hundred years, including logging, agriculture, and urban development, have raised concerns over the current state of lakes in this region as well as the best management strategy for the future. Knowledge of the state of a particular lake prior to European settlement, as well as an understanding of the timing and magnitude of historical ecological changes, are critical components of an effective management plan.

A basic understanding of natural fluctuations within the system is important for any lake management plan. Reliable long-term data sets, on the order of 30 - 50 years, are generally not available for most regions of the country. Through the use of paleolimnological techniques and quantitative environmental reconstruction, we can estimate past conditions, natural variability, timing of changes, and determine rates of change and recovery. This information allows managers and researchers to put present environmental stresses into perspective with the natural variability of the ecosystem. It can also be used to identify response to, and recovery from, short-term disturbances. In this phase of the project, paleolimnological techniques were used to reconstruct the trophic (nutrient and algae condition) and sedimentation history of two lakes in the Comfort Lake - Forest Lake Watershed District in Chisago and Washington Counties, MN: Bone Lake, and School Lake.

The primary aim of this project was to use dated sediment cores from each lake to reconstruct the ecological history using geochemistry, sediment accumulation, diatom-inferred total phosphorus (DI-TP), diatom community composition, and algae pigments as historical geological and biological indicators. Analytical tools included radioisotopic dating of the cores to determine local sediment accumulation rates, geochemical analyses, and analysis of subfossil diatom and algae communities. Multivariate analyses, diatom-based transfer functions, and comparison of diatom assemblages with an 89 Minnesota lake data set were used to relate changes in nutrient conditions and diatom communities to land use impacts in the watershed.

Diatoms have been widely used to interpret environmental conditions in lakes (Dixit and Smol 1994). Many species are sensitive to specific water conditions and are useful as bioindicators. Over the past 25 years, statistical methods have been developed to estimate quantitative environmental parameters from diatom assemblages. These methods are statistically robust and ecologically sound (Birks 1998). They have been used successfully in reconstructing a wide variety of environmental parameters including pH, total phosphorus (TP), and salinity (e.g. Fritz et al. 1991, 1999; Hall and Smol 1992; Ramstack et al. 2003). In the state of Minnesota, diatom analysis has been used as one line of evidence for developing lake nutrient criteria (Heiskary and Wilson 2008) and lake-specific nutrient standards (Edlund and Ramstack 2007).

In addition to diatoms, historical changes in whole lake algal communities were characterized. While diatoms are an important component of the lake algae, other groups of algae can be ecologically important in eutrophic lakes (e.g. blue-green algae or cyanobacteria). The primary pigments (chlorophylls, carotenoids, and their derivatives) of lake algae are often reliably preserved in lake sediments over time (Leavitt and Hodgson 2001). The concentration of these pigments is directly proportional to the abundance of each algal group. Whereas the relative percent change in diatom communities is an effective measure of water quality over time, whole lake algal changes can inform us about the absolute changes in algal production and the historical presence of nuisance algae, such as cyanobacteria.

Study Area

The Comfort Lake - Forest Lake Watershed District (CLFLWD or District) is northeast of the Twin Cities metropolitan area; it spans northern Washington County and southern Chisago County, and covers approximately 47 square miles (Figure 1). The main outlet for the watershed is the Sunrise River in the northwest; the Sunrise flows out of Comfort Lake and discharges into the St. Croix River. The CLFLWD falls within the North Central Hardwood Forests Ecoregion, which is characterized by a wide range of land uses and water quality.

Monitoring and diagnostic surveys of lakes in the CLFLWD found evidence of borderline to elevated total phosphorus (TP) and chlorophyll concentrations and the presence of cyanobacterial blooms in several lakes. As such, many of the lakes are judged impaired by state of Minnesota water quality standards and require remediation and management plans. Bone and School lakes are located in the North Central Hardwood Forest ecoregion and defined as "deep" by the State of Minnesota. As such, the state nutrient standard that applies to them is 40 ppb total phosphorus (or 40 µg/l total phosphorus). Past monitoring efforts have shown both lakes to be impaired for nutrients and they are listed on the state's impaired waters list due to high nutrient levels. Recent monitoring trends in Bone Lake suggest somewhat improving nutrient conditions while the shorter monitoring record for School Lake shows continued impairment (https://www.clflwd.org/data.php#Data_School; September 16, 2020). Although both lakes are currently listed as impaired, little is known of the long-term history of these lakes; the goal of this project is to determine when and why they became impaired or if these lakes have long-been high nutrient and high productivity systems.

Bone Lake has a surface area of 221 acres, making it the second largest lake in the District. The lake has a public boat landing and is used for swimming, fishing and motorized and non-motorized boating. An area of 5,586 acres drains to Bone Lake, this includes Moody and Third Lakes. The lakes in this study are hydrologically connected in that the main outlet from Bone Lake is a stream that flows northwest to Birch, School, and Little Comfort Lakes. With a maximum depth of 9.8 m (32 feet), Bone Lake is considered a deep lake; however, 58% of the lake area is in the littoral zone. Bone Lake was placed on the impaired waters list in 2004, due to high nutrient levels. Water quality data from 2018 reported the following summer averages: total phosphorus 21 µg/l, Secchi depth 1.82 m (5.97 feet), and chlorophyll *a* 7.8 µg/l). Monitoring data from the 1980s through 2011 suggest that the water quality of Bone Lake was fairly consistent over that time period. (https://www.clflwd.org/waterbody-bone-lake.php; September 16, 2020)

School Lake is smaller than Bone Lake, with a surface area of 49 acres. However, the total watershed area is larger; an area of 8,272 acres drain to School Lake, this includes 10 lakes. Inputs to the lake include drainage from Birch Lake and from the northern portion of the watershed. There is an outlet on the northwest side of the lake that drains to Little Comfort Lake. School Lake is considered a deep lake, with a maximum depth over 25 feet. In contrast to Bone Lake, School Lake does not have public boat access and is used for passive recreational activities, such as non-motorized boating, fishing, and wildlife viewing. School lake is on the impaired waters list for high nutrient levels. Water quality data from 2018 reported the following summer averages: total phosphorus 53 µg/l, Secchi depth 0.76 m (2.49 feet), and chlorophyll *a* 50.4 µg/l). (https://www.clflwd.org/waterbody-school-lake.php; September 16, 2020)

METHODS - SEDIMENT CORING

In Bone Lake, a piston core and overlapping Bolivia core were collected through the ice on March 7, 2019 to reach a sediment depth of 237 cm. A single 135 cm-long piston core was collected from School Lake on June 12, 2019 (Table 1). In each lake, the coring location represented a flat and deep area of the basin to avoid areas of high sedimentation and sediment slumping, and to provide a highly integrated sample of diatom community structure from the lake as a whole. All piston cores were collected using a drive-rod piston corer equipped with a 6.5 cm diameter polycarbonate barrel (Wright 1991). The sediment-water interface was stabilized using a gelling agent (Zorbitrol); all cores were returned to the lab for sectioning and processing, stored at 4°C, and sectioned in 2-cm increments.

Table 1 details the coring location, water depth, and recovery for each of the lakes. Figures 2 and 3 show the coring locations on Bone Lake and School Lake, respectively.

METHODS - AERIAL PHOTOS AND SURVEY MAPS

Aerial photos from the 1930s through the present were used to examine changes to each lake and its watershed, including variations in lake surface area, and land use changes. Available aerial photos were downloaded from the University of Minnesota John R. Borchert Map Library's Historical Aerial Photographs Online collection (https://www.lib.umn.edu/apps/mhapo/; August 2020). Modern-day aerial photos were obtained from Google Earth (https://www.google.com/earth/; September 2020).

Historic land survey maps from the 1800s were used to examine changes in the lake basins. Land survey maps were downloaded from the Minnesota Geospatial Information Office's website (http://www.mngeo.state.mn.us/chouse/GLO/; August 2020).

METHODS - MAGNETIC SUSCEPTIBILITY

Magnetic susceptibility provides a non-destructive measure of relative quantity and size of ferro-magnetic minerals. The analysis measures the magnetic strength of the sediment in the presence of a small magnetic field. Increases in magnetic susceptibility signatures may be correlated with land use changes including land clearance, increased terrestrial-derived sediments, and paleosols (fossil soils). Decreases in magnetic susceptibility often accompany increased carbonate and organic fluxes to the sediments from increased in-lake productivity.

A Geotek Standard MSCL with an automated trackfeed was used for magnetic susceptibility logging. Susceptibility measures were taken at 1-cm intervals, which integrate a signal over a 5-10 cm length of core. In the Bone Lake core, magnetic susceptibility logging was run on the Bolivia core only. In School Lake, magnetics was run on the piston core, minus the top portion of the core that was sectioned in the field (0-37 cm). Following magnetics logging, cores were returned to storage at 4°C. Magnetic susceptibility logging was performed at the Limnological Research Center's core lab facility at the University of Minnesota.

METHODS - LEAD-210 DATING

Lead-210 was measured in all cores by lead-210 distillation and alpha spectrometry methods, and dates and sedimentation rates were determined according to the c.r.s. (constant rate of supply) model (Appleby and Oldfield 1978). Dating and sedimentation errors were determined by first-order propagation of counting uncertainty (Binford 1990). In each core, 20 core sections were analyzed for lead-210 activity to determine age and sediment accumulation rate for the past 150 years.

METHODS - GEOCHEMISTRY

Loss on Ignition

Weighed subsamples were taken from regular intervals throughout each core for loss-on-ignition

(LOI) analysis to determine bulk and dry density and dry weight percent of organic, carbonate, and inorganic matter. Sediment subsamples were heated at 105°C to determine dry density, then sequentially heated at 550°C and 1000°C to determine organic and carbonate content from post-ignition weight loss, respectively (Dean 1974).

Biogenic Silica
Biogenic silica (BSi), a proxy for historical diatom and chrysophyte algal productivity, was measured using 15 weighed subsamples (30 mg) from each core, which were digested for BSi analysis using 40 ml of 1% (w/v) Na_2CO_3 solution heated at 85°C in a reciprocating water bath for five hours (DeMaster 1979, Conley and Schelske 2001). A 0.5 g aliquot of supernatant was removed from each sample at 3, 4, and 5 hr. After cooling and neutralization with 4.5 g of 0.021N HCl solution, dissolved silica was measured colorimetrically on a Unity Scientific SmartChem 170 discrete analyzer as molybdate reactive silica (SmartChem 2012a). Silica concentrations are converted to percent BSi by weight of sediment (typically 1-6% in most cores), and converted to flux or accumulation of BSi (the amount of diatoms that accumulate through time in a core).

Sediment Phosphorus
Sediment phosphorus fractions were analyzed for 15 increments from each core following the sequential extraction procedures in Engstrom (2005), Engstrom and Wright (1984), Psenner and Puckso (1988), and Kopácek et al. (2005). Extracts were analyzed colorimetrically on a Unity Scientific SmartChem 170 discrete analyzer using methods described by SmartChem (2012b). Measured sediment phosphorus (P) concentrations were also converted to flux using bulk sedimentation rates in each core. In addition to TP in cores, sediment fractions include the refractory forms *Mineral-bound P*, *Recalcitrant Organic-P*, *Al-bound P* and the labile or readily exchangeable forms of *Fe-bound*, *labile Organic-P*, and *loosely-bound P*.

METHODS - DIATOM AND NUMERICAL ANALYSES

Fifteen samples from each core were analyzed for diatoms. Diatom and chrysophyte cysts were prepared by placing approximately 0.25 cm^3 of homogenized sediment in a 50 cm^3 polycarbonate centrifuge tube, and adding 2-5 drops of 10% v/v HCl solution to dissolve carbonates. Organic material was subsequently oxidized by adding 10 ml of 30% hydrogen peroxide and heating for 3 hours in an 85°C water bath. After cooling, the samples were rinsed with distilled deionized water to remove oxidation biproducts. Aliquots of the remaining material, containing the diatoms, were dried onto 22x22 mm #1 coverglasses, which were then permanently attached to microscope slides using Zrax mounting medium. Diatoms were identified along random transects to the lowest taxonomic level under 1250X magnification with oil immersion optics. A minimum of 400 valves was counted in each sample. Abundances are reported as percent abundance relative to total diatom counts. Identification of diatoms used regional floras (e.g. Patrick and Reimer 1966, 1975; Camburn and Charles 2000) and primary literature (diatoms.org, Spaulding et al. 2020) to achieve consistent taxonomy.

In the Bone Lake core, diatom valves were scarce in the lowermost samples. Scarcity of diatoms is uncommon in lake sediments but can occur based on elevated salinity, elevated alkalinity, high pH, extreme erosional events, drying of the lake, and silica-limited waters. Samples from this part of the core were prepared for diatoms and scanned under the microscope, however insufficient valves were found to include these sections in the analyses. Therefore, analyses on the Bone Lake core are based on samples from 2-94 cm (2018-1942).

A stratigraphy of predominant diatoms (species with greater than or equal to 5% relative abundance in one or more core depths) was plotted against core date. Relationships among diatom communities within the sediment core were explored using the unconstrained ordination method of Non-Metric Multidimensional Scaling (NMDS), in the software package R (R Core Team 2019). Core depths/dates were plotted in ordinate space and their relationships and variability used to identify periods of change, sample groups, and ecological variability among core samples. A general rule for interpreting an NMDS biplot is that samples that plot closer to one another have more similar diatom assemblages. Diatom community relationships were also explored using a constrained cluster analysis, using the CONISS method with Euclidean distance. Significant breaks in the constrained cluster analysis were evaluated using a broken stick model.

Downcore diatom communities were also used to reconstruct historical epilimnetic total phosphorus levels. A transfer function for reconstructing historical logTP was developed earlier based on the relationship between modern diatom communities and modern environmental variables in 89 Minnesota lakes (Ramstack et al. 2003, Edlund and Ramstack 2006) using weighted averaging (WA) regression with inverse deshrinking and bootstrap error estimation (C2 software; Juggins 2003). The strength of the transfer function was evaluated by calculating the squared correlation coefficient (r^2=0.83) and the root mean square error (RMSE=0.181) between the observed logTP with the model estimates of logTP for all samples. Bootstrapping was used in model validation to provide a more realistic error estimate (RMSEP, the root mean square error of prediction=0.208) because the same data are used to both generate and test the WA model (Fritz et al. 1999). Reconstructed estimates of logTP (diatom-inferred TP, or DI-TP) for each downcore sample were determined by taking the logTP optimum of each species, weighting it by its abundance in that sample, and determining the average of the combined weighted species optima. Data are presented as both logTP values and as backtransformed values, to TP in μg/l.

METHODS - ALGAL PIGMENT ANALYSIS

Algal pigment analyses were performed by Dr. Peter Leavitt at the University of Regina. Carotenoids, chlorophylls, and derivatives were extracted (4°C, dark, N_2) from ten freeze-dried sediment subsamples according to Leavitt et al. (1989), measured on a Hewlett-Packard model 1050 high performance liquid chromatography system, and are reported relative to total organic carbon (TOC; Hall et al. 1999).

RESULTS AND DISCUSSION - AERIAL PHOTOS AND SURVEY MAPS

Bone Lake – Historical aerial photographs from 1938, 1957, and 1964 showed that the water level and shoreline of Bone Lake were relatively unchanged during these times (Figure 2). Between 1957 and 1964 there was a notable increase in homes along the shoreline of the lake, especially along the western and southern shores. From 1964 to the present, there appears to have been residential development along the eastern shore.

Bone Lake was present on the survey map from 1848 (Appendix A). In this map the shoreline of the lake appeared similar to present day, and the outlet in the northwest portion of the lake was recorded on the map.

School Lake – The aerial photographs from 1938, 1953, and 1964 showed the shoreline of School Lake relatively unchanged; however, the water level in 1938 may have been slightly lower (most pronounced in the northwest portion of the lake) (Figure 3). The most recent Google Earth image showed a land clearing to the south of the lake, which is an open pit gravel quarry. A review of recent satellite photos in Google Earth showed that the pit appeared between 1991 and 2003.

The survey map from 1849 did not show School Lake with a recognizable shoreline; however it was likely the "pond" referred to on the bottom right portion of the map (on the line between Sections 35 and 36) (Appendix B).

RESULTS AND DISCUSSION - DATING AND SEDIMENTATION

Sedimentation rates naturally vary among lakes based on factors such as lake and watershed area, lake bathymetry (depth), surficial geology, and in-lake productivity. For example, a steep-sided lake basin will accumulate sediment (the sedimentation rate) more quickly because any sediment that reaches the bottom is more quickly focused or winnowed and buried in a steep-sided lake. A lake with a broad deeper area will accumulate sediments more slowly. For each of the study lakes, the sedimentation rate in the early to mid-1800s can be considered the background rate for the lake; this was the sedimentation rate prior to European settlement and significant disturbance to the watershed. This allows changes in each lake to be evaluated relative to the "natural" or pre-European conditions.

Bone Lake – The unsupported lead-210 activity, the resulting lead-210 dating model, and the sediment accumulation rate for Bone Lake are shown in Figure 3a-c. In Bone Lake, the lead-210 activity declined throughout the core, reaching background levels at approximately 205 cm, which corresponds to a date of 1806 AD (Figure 3a). Thirty centimeters downcore corresponds to approximately 1999, one meter downcore corresponds to the late 1930s, and 167 cm downcore corresponds to 1880, the approximate period of European settlement (Figure 3b). From the early 1800s to the early 1900s, the sedimentation rate in Bone Lake fluctuated between 0.04 and 0.08 g/cm^2 yr; there was a sharp rise in the rate between the early 1900s and the 1920s, with a peak in the core of 0.27 g/cm^2 yr in 1927 (Figure 3c). After the peak in 1927 the rate declined to 0.11 g/cm^2 yr in the early 1950s, before rising again. From the mid-1970s to 1990, the rate was fairly steady at approximately 0.20 g/cm^2 yr. There has been an overall decline in recent decades, however the rate at the core top (0.17 g/cm^2 yr) remains about three times higher than the average rate during the early to mid-1800s. Therefore, Bone Lake is still accumulating sediment three times faster than in the 1800s. If we convert this to rate to sediment thickness added per year, Bone Lake accumulated sediment at about 6 mm (0.25 in) per year (2.5 in per decade) before 1900; in recent decades, Bone Lake is accumulating sediment at around 15 mm (0.6 in) per year– that's 6 inches of sediment accumulated per decade.

School Lake – In the School Lake core, lead-210 activity reached background levels at approximately 56 cm (Figure 4a) corresponding to a date of 1829 AD. Sediments deposited 20 cm downcore are dated to 1995, 42 cm represents the late 1930s, and sediments deposited in the 1880s during European settlement are located 51 cm downcore (Figure 4b). From the 1820s to the 1910s, the average sedimentation rate was 0.03 g/cm^2 yr (Figure 4c). After 1917, the sedimentation rate showed an overall increase through time, with a large increase between 1917 and 1938. The rate of 0.10 g/cm^2 yr at the core top represents a more than threefold increase over conditions in the early to mid-1800s; therefore, School Lake is accumulating sediment three times more quickly than before. If we convert that to thickness of sediment that is accumulating, School Lake accumulated about 1.5 mm of sediment per year (or 0.6 in per decade) before 1900, but now accumulates about 7 mm per year or 2.7 inches per decade. It is possible that operations at the quarry just south of the lake have contributed to the increased sedimentation rate in recent decades.

RESULTS AND DISCUSSION - MAGNETIC SUSCEPTIBILITY AND GEOCHEMISTRY

Magnetic Susceptibility

Bone Lake – Magnetic susceptibility logging was performed only on the Bolivia core for Bone Lake (Figure 5a). From the core bottom (235 cm, 1741 AD), up to about 182 cm (1855 AD) there was a slight overall rise in magnetics, this could have been due to an increase in terrestrially derived sediments. From 180 cm to the top of the Bolivia core (122 cm, 1929 AD) there was very little directional change in magnetic susceptibility.

School Lake – From the bottom of the School Lake core up to about 107 cm (1460 AD), there was an overall decline in magnetic susceptibility (Figure 6a). Decreases in magnetic susceptibility can result from increased productivity, for example from lake eutrophication, or from changes in the watershed, such as hydrologic changes causing sediment to wash in from a different source. The magnetic susceptibility showed a rise again from 107 cm to 102 cm (1505 AD), then stayed relatively stable from about 102 to 79 cm (1656 AD), at which point there was another decline. There was very little directional change between the decline at 77-79 cm and the uppermost measurement (39 cm, 1945 AD). Lead-210 background was reached at 56 cm, therefore, the largest shifts in the magnetics profile in School Lake predate the lead-210 record and may reflect earlier periods of climate variation (e.g. Little Ice Age). All dates that predate the lead-210 record are provided as rough approximations and are based on linear extrapolation of the downcore lead-210 dates.

Loss on Ignition

Bone Lake – There were several shifts in the composition of the sediment throughout the piston and Bolivia cores from Bone Lake (Figure 5b). From the bottom of the Bolivia core (236 cm, 1741AD) up to about 182 cm (1855 AD), the sediments from Bone Lake were composed of, on average, 58% organic matter, 39% inorganic matter, and 3% carbonate. There was a shift beginning around 180 cm where the relative amount of inorganic matter increased, and organic matter decreased. This roughly corresponded to a slight rise in magnetic susceptibility in the Bolivia core, again suggesting that there may have been a rise in terrestrially derived sediment at this time. The shift around 180 cm dates to the mid-1800s, so the shift that occurred here predated European settlement, or may have represented the earliest onset of settlement.

From 180 cm until approximately 94 cm there were fluctuations between inorganic and organic matter, with carbonates staying stable. At 94 cm (1940s) there was a rise in inorganic matter and a decrease in organic matter that held through the top of the core. Carbonates showed an increase beginning at 72 cm (1960s) and continued to show an overall rise to the top of the core.

For each lake, the flux of sediment to the core was calculated by multiplying the fraction of each component of the sediment (organic, carbonate, inorganic) by the sedimentation rate at that interval (Figure 7 for Bone Lake); sediment flux was calculated to the end of the lead-210 record for each core (205 cm in Bone Lake). In Bone Lake, this calculation demonstrated that from the early 1800s until about 1940 (including the peak in sedimentation in the 1920s), the sedimentation rate was driven nearly equally by organic and inorganic material. This changed in the 1940s; from that point on, the sediment accumulation at the core site was driven primarily by inorganic material.

School Lake – The largest shift in sediment composition in the School Lake core occurred at about 78 cm (late 1600s; Figure 6b). Prior to this (from 136 to 78 cm), the sediments were composed of, on average, 62% inorganic matter, 27% organic matter, and 11% carbonate. At about 80 cm there was a shift in the relative amount of inorganic matter and carbonate in the core. After this shift (from about 80 cm to the core top), the average sediment content was 45% inorganic, 24% organic, and 31% carbonate. The shift around 80 cm corresponds with a decline in magnetics; the decrease in magnetics and increase in carbonates both suggest an increase in productivity at this time. Background levels of lead-210 were reached at 56 cm (1829 AD), so the early shift in sediment composition in the School Lake core predated the early 1800s.

The flux of sediment to the School Lake core site was driven primarily by inorganic matter throughout the entire section of the core within the lead-210 record (Figure 8), which is often a reflection of new watershed (erosion) sources. The one exception was a small rise in the relative contribution of carbonates during the 1980s.

Biogenic Silica and Sediment Phosphorus

Bone Lake – The weight percent of biogenic silica (BSi) in the Bone Lake core showed an upward trend throughout the core, with an overall rise from 1.8% at the core bottom to 5.9% at the top (Figure 9a). Weight percent of BSi increases when the historical growth of diatoms (one group of algae) increases, often in response to greater access to nutrients in a lake.

For each lake, both silica and phosphorus flux were calculated by multiplying either the weight percent of BSi, or the concentration of each phosphorus fraction, by the sedimentation rate at that interval. Flux of silica to the Bone Lake core site also showed an overall rise over time, with a peak of 10.7 mg/cm^2 yr in the early 1990s, and a slight decline in recent decades (Figure 9b).

The concentration of phosphorus (P) in the Bone Lake core was high in 1870, lower in the late 1800s and early 1900s, began to rise again in the 1930s, and peaked at 4.0 mg P/g in 1953 (Figure 10a). The peaks in concentration in 1870, the 1930s, and the 1950s were largely due to increases in the Fe-bound P fraction.

When converted to flux, the P flux to the core site was lowest in the late 1800s and early 1900s (average of 0.16 mg/cm^2 yr), and then peaked at a rate of 0.59 mg/cm^2 yr in the 1933 section (Figure 10b). After the peak in the 1930s, the P flux decreased and remained fairly steady, with a rate of 0.42 mg/cm^2 yr at the core top. From the 1930s to 2018, Fe-bound P, a readily exchangeable form, comprised the largest fraction of the P flux to the core site. High levels of Fe-bound P in sediment is of concern because it represents one of the most easily available forms of P to a lake through internal loading.

School Lake – In the School Lake core there was a slow rise in the weight percent of BSi in the sediments from 11% in the 1870s to a peak of 21% in 1939 (Figure 11a). After the 1939 peak there was a decrease, and BSi remained at an average of 15% from the 1940s through 2010. There was a slight drop to 12% in the most recent sample (2019). The flux of silica to the core site showed an overall increase through time (Figure 11b). The average silica flux in the 2010s (13.2 mg/cm^2 yr) was almost four times higher than the average flux in the 1800s (3.5 mg/cm^2 yr).

The P concentration in the School Lake sediments rose over time, with peak concentrations exceeding 6.0 mg P/g in 1945 and 1973 (Figure 12a). The flux of P to the core site also increased over time; the rate at the core top (0.54 mg/cm^2 yr) was almost six times higher than the average rate in the 1800s (0.09 mg/cm^2 yr) (Figure 12b). As such, School Lake has also been burying P at a much greater rate since the 1920s. However, throughout the majority of the record, Fe-bound P represented the largest fraction in terms of both concentration and flux (Figure 12a and b), which can contribute to internal loading of P to School Lake. The only exception was the uppermost sample (2019) where the concentration and flux of Al-bound P, a refractory form, was more abundant.

RESULTS AND DISCUSSION - DIATOM STRATIGRAPHY AND ORDINATION

Bone Lake – In Bone Lake, diatom valves were scarce in the lowermost samples; all of these samples were removed from the analysis. Therefore, all diatom analyses were based on nine core sections (1942 through 2018), which contained abundant, well-preserved diatom valves.

The ordination biplot from the NMDS showed how the core samples clustered based on similarity of diatom assemblage (Figure 13). The biggest break along axis 1 was between the three uppermost samples (2002-2018) and the lower sections of the core (1942-1991). These lower sections also showed directional change along axis 2 (the 1940s-50s in the lower right quadrant, moving to the upper right quadrant over time). This suggests a driver of diatom community change that differed from the driver between 1991 and 2002.

The stratigraphic diagram showed the predominant diatoms that were driving the shifts in the community assemblages, as well as the results of the constrained cluster analysis, and the percentage of plankton throughout the core (Figure 14). According to the constrained cluster analysis, the largest break in the samples occurred between 1991 and 2002, although when evaluated against a broken stick model, this was not shown to be a significant shift in the assemblage. This shift coincided with an decrease in small *Stephanodiscus* species (*S. minutulus* and *S. parvus*). These small *Stephanodiscus* species are indicative of nutrient enrichment, so there may have been some decline in nutrient levels in recent decades. However, other eutrophic indicators, such as *Aulacoseira* species and *Fragilaria crotonensis*, remained abundant in these upper core sections.

Overall, the shifts in the diatom community assemblage in Bone Lake were subtle, and plankton made up the majority of the assemblage over the period of study (1942-2018); the percent plankton ranged from 55% to 79% over this time period. The predominant species (those occurring at 5% or greater in any core section) were either planktonic or tychoplanktonic. The tychoplanktonic species in the Bone Lake core were *Pseudostaurosira brevistriata* var. *inflata*, *Staurosira construens*, *Staurosira construens* var. *venter*, and *Staurosirella pinnata*. Even though there were some minor fluctuations in the percent abundance of each of these individual taxa, there was no strong temporal shift in the group as a whole. These tychoplanktonic species are primarily benthic, but are often swept-up and suspended into the water column. Many of these species are adapted to live on fine-grained sediments, such as those found in shallow lakes and are likely abundant in Bone Lake due to the large littoral area.

Although there were not enough diatom valves in the lower core sections to confidently analyze the community composition, the valves that were found suggest that the diatom assemblage from 1870-1933 may have been similar to the assemblage from 1942-2018.

School Lake – In the School Lake NMDS biplot, the diatom community assemblage showed change along axes 1 and 2, although the trajectory over time was not completely in one direction along either axis (Figure 15). The pattern in the ordination suggests that there were no abrupt, directional shifts, but rather gradual changes in the community over time. This was also reflected in the fact that there were no significant breaks in the constrained cluster analysis when evaluated against a broken stick model (Figure 16). The largest break in the constrained cluster occurred between 1952 and 1962 and was characterized by a decrease in *Aulacoseira ambigua*, a planktonic diatom characteristic of nutrient-rich and turbid, wind-swept conditions. At this time there was also a slight increase in the tychoplanktonic diatom *Pseudostaurosira brevistriata* var. *inflata*. The School Lake diatom assemblage was dominated by plankton throughout the core; however the average percent plankton was 92% from 1874-1952 and dropped slightly to 83% from 1962-2019, which can result from greater plant growth in the lake or changes in water level.

As with the Bone Lake core, the shifts in the diatom assemblage over time were subtle. Overall, the core was dominated by taxa that are indicative of nutrient enrichment, such as *Asterionella formosa* (can be an indicator of N enrichment), *Fragilaria crotonensis*, small *Stephanodiscus* species, and *Aulacoseira* species.

RESULTS AND DISCUSSION - PHOSPHORUS RECONSTRUCTION

In order for a diatom-inferred total phosphorus (TP) reconstruction to be meaningful, changes in the diatom community assemblage over time must be primarily driven by changes in TP concentrations, as opposed to other factors that could drive community change such as pH, light penetration, and habitat availability. One way to evaluate TP as a driver of change is to project the core sections on the MN calibration set (the model used to reconstruct TP) to determine if changes in the diatom assemblage in the core correlate with the TP gradient in the model (Juggins et al. 2013).

Another way to evaluate the reconstruction is to determine the amount of variance in the diatom data that can be accounted for by the TP reconstruction. This can be calculated by the variance explained by the first axis of an ordination of the sediment assemblages constrained to diatom-inferred TP, divided by the variation explained by an unconstrained ordination of the sediment assemblages (λ_r / λ_p). A maximum λ_r / λ_p value of 1.0 would mean that TP was the best explanatory variable of diatom community change (Juggins et al. 2013).

Bone Lake – When passively plotted on the MN calibration set, the core sections showed small amounts of movement along axis 1, with the exception of the sections from 1981 and 1991, which plotted much lower on axis 2 (Figure 17). In Bone Lake the fraction of the maximum explainable variation in the diatom data that could be explained by TP (λ_r / λ_p) was 0.81. This suggests that a large amount of the variation in the core can be explained by TP. However, the changes in the 1981 and 1991 core sections suggest an alternate driver during that time period. Alternative drivers include: habitat alterations, changes in turbidity due to sediment load, or other stressors (e.g. aquatic invasive species) that were not measured in the calibration set.

The TP reconstruction for Bone Lake suggests that the lake has been in the eutrophic category since the 1940s (Figure 18; Table 2), with the lowest values in the most recent decade (38 µg/l in 2011 and 40 µg/l in 2018). These diatom-inferred TP (DI-TP) values also suggest that TP was slightly elevated in the 1960s-80s, and has since declined so that TP values in recent decades were similar to that of the 1940s. The DI-TP value at the core top 40 µg/l is higher than the 2018 measured summer average of 21 µg/l (https://www.clflwd.org/waterbody-bone-lake.php; September 16, 2020). However, 21µg/l TP is the lowest measured summer average of the past decade, and values were close to or exceeding 40 µg/l TP in 2014, 2015, and 2016 (https://www.clflwd.org/documents/BoneLake_000.pdf; October 16, 2020).

School Lake – Passive plotting of the School Lake core on the MN calibration set showed movement along both axes 1 and 2 (Figure 19). The fraction of the variation in the diatom data that can be explained by TP (λ_r / λ_p) was 0.72 for School Lake. Again suggesting that a large amount of variation in the core could be explained by TP.

The TP reconstruction from School Lake suggests that the lake has been eutrophic since the 1870s (Figure 20; Table 2). According to the DI-TP, phosphorus levels were highest in School Lake from the late 1930s through the 1950s (over 60 µg/l TP); this was driven by a higher percentage of *Aulacoseira ambigua* during those years. The DI-TP value in the most recent sample (2019) was 44 µg/l; this is comparable to the 2018 measured summer average of 53 µg/l TP (https://www.clflwd.org/waterbody-school-lake.php; September 16, 2020).

RESULTS AND DISCUSSION - HISTORICAL ALGAL COMMUNITIES

Bone Lake – The pigment data from Bone Lake showed that there was a large increase in algal productivity between 1936 and 1953 (Figure 21). This increase was reflected in total algal production, green algae, diatoms, cryptophytes, and cyanobacteria. This shift was also seen in a rise in BSi concentration in the sediments between 1942 and 1953 (Figure 9a).

Cyanobacterial pigments were present in the Bone Lake core in the late 1800s and early 1900s, but in much lower concentrations than the 1950s-2018. Pigments associated with nitrogen-fixing forms (canthaxanthin and aphanizophyll), as well as pigments from potentially toxic forms (myxoxanthophyll), increased in concentration in the 1950s, and persist through to the core top.

Pigments of purple sulfur bacteria increased in the uppermost sample (2017). Purple sulfur bacteria are indicative of anoxic conditions, but where light still penetrates the water; in Bone Lake it's possible that these conditions have occurred in thick macrophyte beds in the large littoral zone

School Lake – Algal pigments from School Lake showed that overall algal production has not changed drastically since the late 1800s, although measures of total algal abundance have declined slightly from the mid-1990s to 2017 (Figure 22). This decline in recent decades was driven primarily by decreases in diatoms and green algae.

Cyanobacteria have been present in the lake since the late 1880s. Pigments associated with nitrogen-fixing forms (canthaxanthin and aphanizophyll) remained largely steady in their abundance over the period of record, with the exception of a high concentration of aphanizophyll in the 1870s. The pigment myxoxanthophyll, which comes from potentially toxic forms of cyanobacteria, showed higher concentrations from the 1870s to the 1920s, and decreased concentrations from the 1940s to 2017.

Okenone, a pigment from purple sulfur bacteria, was present throughout the record. This suggests that School Lake has undergone periods of anoxia since the late 1800s. The anoxic conditions could be due to poor mixing, or thick macrophyte beds.

CONCLUSIONS

Bone and School Lakes showed some similarities in their sediment records. Both lakes had about a threefold increase in sedimentation rate at the core top compared to the rate in the early to mid-1800s; increased sediment accumulation in lakes typically reflects a combination of new sources of sediment delivered to a lake (e.g., erosion) and greater productivity (e.g., algae growth). In Bone Lake, the sharp increase in the sedimentation rate occurred between 1907 and 1927, and in School Lake there was a distinct rise between 1917 and 1938. Our previous work in the watershed district showed a large rise in sedimentation rate in Comfort Lake between 1918 and 1936, and a smaller increases in Moody and Shields Lakes in the early 1900s (Ramstack Hobbs et al. 2017). Even though the timing of the increase showed some variation in individual sub-watersheds, this nearly synchronous pattern among the lakes suggests that this increase in sedimentation in the early 1900s was due to initial land conversion in the basin.

Bone Lake – Multiple lines of evidence suggest that there was a large change in Bone Lake in the 1940s/50s. Beginning in the early 1930s (just after the spike in sedimentation rate), and coming to a peak in the 1950s, there was a large increase in phosphorus concentration in the Bone Lake sediments. This rise was primarily driven by an increase in iron bound phosphorus, a readily exchangeable form. After the sedimentation rate in Bone Lake peaked in 1927, the rate showed a steep decline and remained low for the next several decades. This suggests that the TP increase may have been initially driven by external inputs, but since it continued for decades after the sedimentation rate decreased, this continuation was likely due to internal loading and continually elevated watershed sources.

Beginning in the early 1940s, there was a change in the composition of the sediments, with a sharp rise in inorganic matter and relative decrease in organic matter. When converted to flux, the record showed that from the early 1800s until the 1940s, changes in sedimentation had been driven in nearly equal parts by inorganic and organic material. In the 1940s this changed, and from the 1940s to the core top changes in sedimentation were largely controlled by changes in inorganic matter.

This change was reflected in the algal communities in several ways. There was an increase in overall algal abundance; this was driven my multiple algal groups, including green algae, diatoms, cryptophytes, and cyanobacteria. This increase was also reflected in an increase in BSi concentration in the sediments. Since diatoms did not preserve in the core prior to the 1940s, the effect on the diatom community composition across this boundary is unknown. However, the fact that preservation in the sediments changed at this time suggests a possible change in water chemistry. The BSi data suggest that preservation was not due to a lack of silica prior to the 1940s; it's possible that there was a change in the alkalinity in the lake at this time, allowing for better preservation. Since the 1940s/50s, overall algal production has remained high across all groups. There was a slight decrease in DI-TP from 2002-2018, driven by a declining number of small *Stephanodiscus* species; however, the diatom community assemblage remained dominated by other species indicative of eutrophic conditions.

This change in Bone Lake in the 1940s/50s could have been due to land use changes that altered the hydrology of the Bone Lake watershed. There were no striking differences between the 1938 and 1957 aerial photos; however, the spike in sedimentation between 1907 and 1927 that likely initiated these changes predates the aerial photos.

In summary, our historical evidence suggests that Bone Lake had poorer water quality in the 1940s-1990s, a period of both agricultural intensification and shoreline development; however, several lines of evidence (including sedimentation rate and diatom-inferred TP) show an overall trend of improvement since that time. Recent diatom inferred total phosphorus measures since 2000 show that Bone Lake is poised at or near the Minnesota nutrient standard of 40 ppb TP. Although we do not have diatom evidence from before 1940, other types of evidence in the core (sedimentation rate, P burial, algal pigments) suggest that the lake underwent changes at that time to a more productive system that has been maintained due to watershed modification and likely enhanced internal loading. At this time, efforts to continue curbing nutrient loading to the lake should be encouraged, as outlined in the TMDL, with the goal of maintaining the recent trend of improving water quality in Bone Lake, keeping the lake below the state standards, and potentially reaching the District goal of 30 ppb TP.

School Lake – In School Lake, the sedimentation rate showed an overall steady rise from the initial increase in the early 1900s through to 2018. This was in contrast to Bone Lake where there were larger scale fluctuations in the sedimentation rate throughout the 1900s and 2000s. School Lake showed a rise in TP concentration and flux following the rise in the sedimentation rate in the early 1900s. As in Bone Lake, this increase in TP was largely driven by the Fe-bound fraction. However, in School Lake there was no notable change in the composition of the sediments during the period covered by the lead-210 record. Inorganic material was the largest contributor to the flux to the core site since the early to mid-1800s.

The diatom community in School Lake was relatively stable from the late 1800s through 2018. The most notable change was a steady decline in the relative abundance of *Aulacoseira ambigua* since the 1960s, however, the diatom community remained dominated by other eutrophic indicators. Algal productivity has been high in School Lake since the 1800s. Measures of total algal abundance have shown slight declines from the mid-1990s to 2017. This decline was driven by decreases in diatoms and green algae.

Although School Lake has been declared impaired for nutrients and maintains elevated total phosphorus levels, management response to our multiple lines of historical evidence suggest that School Lake has long-been a eutrophic and productive lake. Sediment evidence shows that the lake was even more nutrient-rich in the 1940s and 50s, likely in response to broad scale agricultural intensification, but that the lake has shown a recovery trend since the 1960s to diatom-inferred total phosphorus values of 40-50 ppb TP. Two things about this pattern are especially important. First, School Lake has shown recovery from a greater impairment. It is important to continue all reasonable nutrient control measures to prevent a return to those 1940s and 50s conditions. Second, the improvement has brought School Lake back to nutrient levels that are similar to what we estimated from before the 1920s. As such, it is equally important to understand that School Lake may have difficulty in reaching nutrient levels that are consistently below state nutrient standards; the watershed district may want to consider working with the MPCA to pursue a site-specific standard for School Lake.

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REFERENCES

Appleby, P.G., and F. Oldfield. 1978. The calculation of lead-210 dates assuming a constant rate of supply of the unsupported lead-210 to the sediment. Catena 5:1-8.

Binford, M.W. 1990. Calculation and uncertainty analysis of 210-Pb dates for PIRLA project lake sediment cores. Journal of Paleolimnology. 3:253-267.

Birks, H.J.B. 1998. D.G. Frey & E.S. Deevey Review #1, Numerical tools in palaeolimnology – Progress, potentialities, and problems. Journal of Paleolimnology 20:307-332.

Camburn, K.E., and D.F. Charles. 2000. Diatoms of Low-Alkalinity Lakes in the Northeastern United States. Academy of Natural Sciences of Philadelphia Special Publication 18:152 pp.

Conley, D.J. and C.L. Schelske. 2001. Biogenic silica. In Smol, J.P., H.J.B. Birks, and W.M. Last, (eds.), Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestrial, Algal, Siliceous Indicators. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp 281-293.

Dean, W.E. 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. Journal of Sedimentary Research 44: 242-248.

DeMaster D.J. 1979. The marine budgets of silica and ^{32}Si. Ph.D. Dissertation, Yale University.

Dixit, S. S. and J.P. Smol. 1994. Diatoms as indicators in the Environmental Monitoring and Assessment Program-Surface Waters (EMAP-SW). Environmental Monitoring and Assessment 31:275-306.

Edlund, M.B. and J.M. Ramstack. 2006. Diatom-Inferred TP in MCWD Lakes. Final Report to Minnehaha Creek Watershed District, Work Order #116-04, 33 pp.

Edlund, M.B., and J.M. Ramstack. 2007. Historical water quality and biological change in Peltier Lake, Anoka Co., MN. Final report submitted to Emmons and Olivier Resources, Inc. and the Rice Creek Watershed District, 19 pp.

Engstrom, D.R. 2005. Long-term changes in iron and phosphorus sedimentation in Vadnais Lake, Minnesota, resulting from ferric chloride addition and hypolimnetic aeration. Lake and Reservoir Management 21:95-105.

Engstrom, D.R. and H.E. Wright, Jr. 1984. Chemical stratigraphy of lake sediments as a record of environmental change. In E.Y. Haworth (Ed.), Lake sediments and environmental history. Leicester University Press: 11-67.

Fritz, S.C., S. Juggins, R.W. Battarbee, and D.R. Engstrom. 1991. Reconstruction of past changes in salinity and climate using a diatom-based transfer function. Nature 352:706-708.

Fritz, S.C., B.F. Cumming, F. Gasse, and K. Laird. 1999. Diatoms as indicators of hydrologic and climatic change in saline lakes. In Stoermer, E.F. and J.P. Smol, (Eds.), The Diatoms: Applications for the Environmental and Earth Sciences. Cambridge University Press, Cambridge & New York, pp 41-72.

Hall, R.I and J.P. Smol. 1992. A weighted-averaging regression and calibration model for inferring total phosphorus concentration from diatoms in British Columbia (Canada) lakes. Freshwater Biology 27: 417-434.

Hall, R.I., P.R. Leavitt, R. Quinlan, A.S. Dixit, and J.P. Smol. 1999. Effects of agriculture, urbanization, climate on water quality in the northern Great Plains. Limnology and Oceanography 44:739-756.

Heiskary, S.A., and C.B. Wilson. 2008. Minnesota's approach to lake nutrient criteria development. Lake and Reservoir Management 24:282-297.

Juggins, S. 2003. C2 version 1.3, Software for ecological and palaeoecological data analysis and visualization. University of Newcastle, Newcastle upon Tyne, NE17RU, United Kingdom.

Juggins, S., N.J. Anderson, J.M. Ramstack Hobbs, and A. Heathcote. 2013. Reconstructing epilimnetic total phosphorus using diatoms: statistical and ecological constraints. Journal of Paleolimnology. DOI 10.1007/s10933-013-9678-x.

Kopácek, J., J. Borovec, J. Hejzlar, K.U. Ulrich, S.A. Norton, and A. Amirbahman. 2005. Aluminum control of phosphorus sorption by lake sediments. Environmental Science & Technology 39:8784-8789.

Leavitt, P.R., S.R. Carpenter, and J.F. Kitchell. 1989. Whole-lake experiments: The annual record of fossil pigments and zooplankton. Limnology and Oceanography 34:400-717.

Leavitt, P.R. and D.A. Hodgson. 2001. Sedimentary pigments. In: Smol JP, Birks HJB, Last WM (eds) Tracking environmental change using lake sediments. Terrestrial, algal, and siliceous indicators, vol 3. Kluwer, Dortrecht, pp 155–202.

Patrick, R. and C.W. Reimer. 1966. The diatoms of the United States, exclusive of Alaska and Hawaii, Volume 1-Fragilariaceae, Eunotiaceae, Achnanthaceae, Naviculaceae. Academy of Natural Sciences of Philadelphia Monograph No. 13, 699 pp.

Patrick, R. and C.W. Reimer. 1975. The diatoms of the United States, exclusive of Alaska and Hawaii, Volume 2, Part 1-Entomoneidaceae, Cymbellaceae, Gomphonemaceae, Epithemaceae. Academy of Natural Sciences of Philadelphia Monograph No. 13, 213 pp.

Psenner, R. and R. Puckso. 1988. Phosphorus fractionation: Advantages and limits of the method for the study of sediment P origins and interactions. Archiv für Hydrobiologie 30:43-59.

R Core Team. 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

Ramstack, J.M., S.C. Fritz, D.R. Engstrom, and S.A. Heiskary. 2003. The application of a diatom-based transfer function to evaluate regional water-quality trends in Minnesota since 1970. Journal of Paleolimnology 29:79-94.

Ramstack Hobbs, J.M., M.B. Edlund, K.M. Theissen, S.P. Duncanson, and G.R. Houle. 2017. A paleolimnological study in the Comfort Lake Forest Lake Watershed District. Final report submitted to Comfort Lake Forest Lake Watershed District. St. Croix Watershed Research Station, Science Museum of Minnesota, Marine on St. Croix, Minnesota, 55047.

SmartChem. 2012a. SmartChem 170 Method SIL-001-A (Rev: May 2012). Silica in Water, Waste Water and Soil Extracts and Other Aqueous Samples, 0.1-20 mg SiO_2/L. Unity Scientific, 1117 Old State Road, Brookfield, CT 06804.

SmartChem. 2012b. SmartChem 170 & SmartChem 200 Method PHO-001-A (Rev: May 2012). Phosphorus, All Forms, Orthophosphate, Hydrolyzable, and Total in Water, Waste Water and Soil Extracts and Other Aqueous Samples. Unity Scientific, 1117 Old State Road, Brookfield, CT 06804.

Spaulding, S.A., I.W. Bishop, M.B. Edlund, S. Lee, P. Furey, E. Jovanovska, and M. Potapova. 2020. Diatoms of North America. https://diatoms.org/

Wright, H.E., Jr. 1991. Coring tips. Journal of Paleolimnology 6:37-49.

Table 1. Location of each core collected, core type, water depth at core site, and sediment recovered.

Lake	Lat (N)	Long (W)	Core Type	Water Depth (m)	Recovery (m)
Bone	45.28912	92.86217	Piston	7.67	1.51
Bone	45.28912	92.86217	Bolivia	7.67	1.16
School	45.30455	92.91492	Piston	7.96	1.35

Table 2. Diatom-inferred total phosphorus values for each core section.

Lake_Lead-210 Date	Diatom-Inferred TP µg/l
Bone 2018	40
Bone 2011	38
Bone 2002	45
Bone 1991	53
Bone 1981	62
Bone 1972	61
Bone 1962	67
Bone 1953	55
Bone 1942	47
School 2019	44
School 2010	38
School 2002	54
School 1991	43
School 1983	41
School 1973	51
School 1962	56
School 1952	71
School 1945	71
School 1939	63
School 1928	47
School 1917	53
School 1905	53
School 1893	55
School 1874	56

Figure 1. Map of the Comfort Lake - Forest Lake Watershed District (modified from www.clflwd.org/district-waterbody-php).

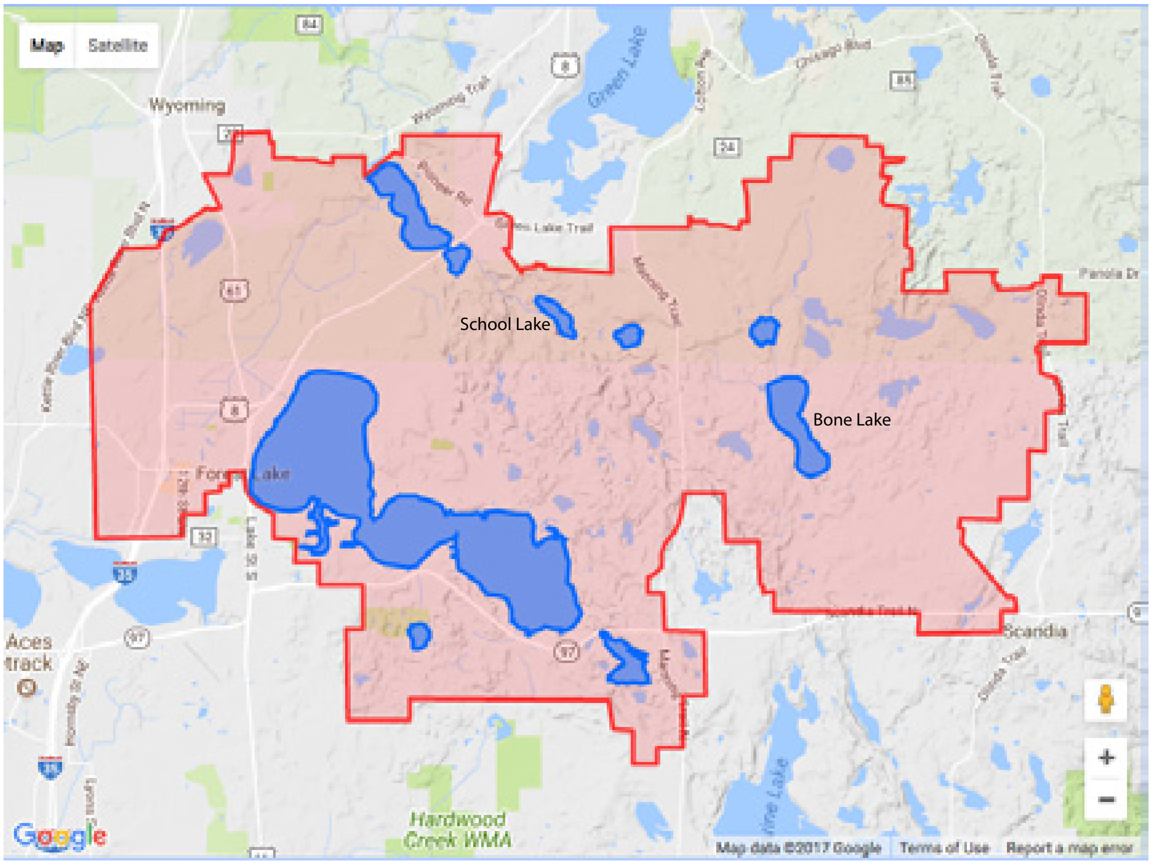
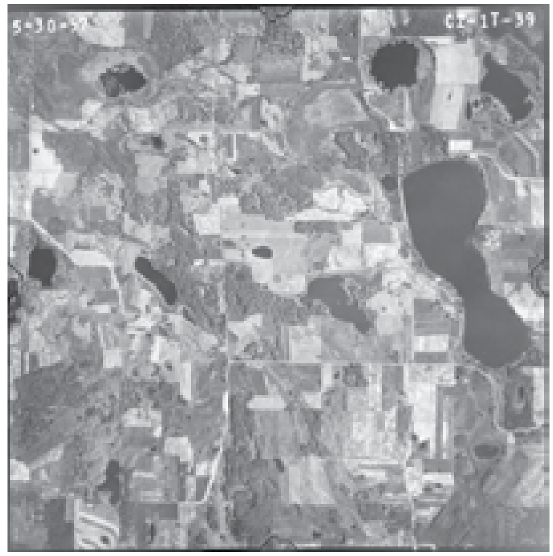


Figure 2. Aerial photographs of Bone Lake. The red marker in the modern (Google Earth) photo denotes the coring location.

1938

1957



1964

Google Earth (retrieved Sept 2020)

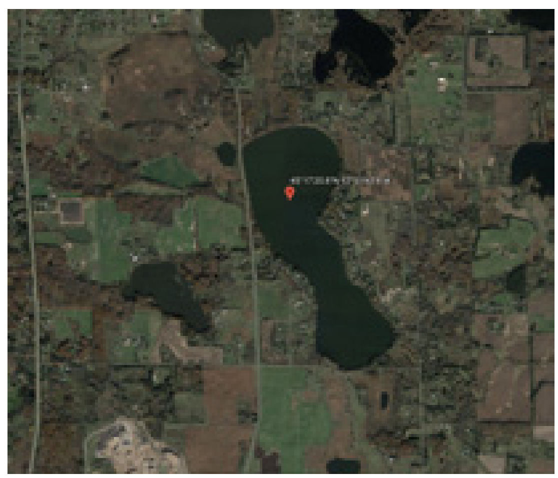
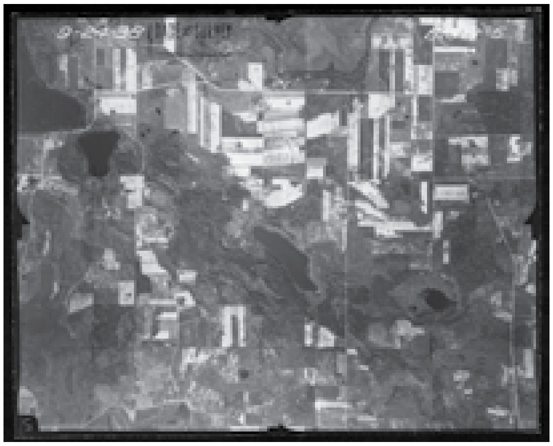
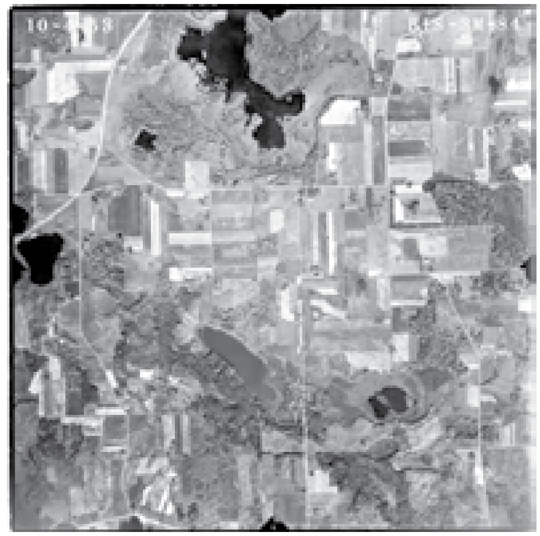


Figure 3. Aerial photographs of School Lake. The red marker in the modern (Google Earth) photo denotes the coring location.

1938



1953



1964

Google Earth (retrieved Sept 2020)

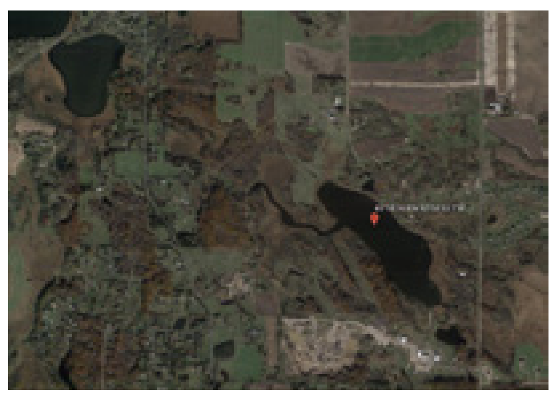


Figure 4. Unsupported lead-210 activity (a), lead-210 dating model (b), and sediment accumulation rate (c) for Bone Lake; d-f, the same results for School Lake.

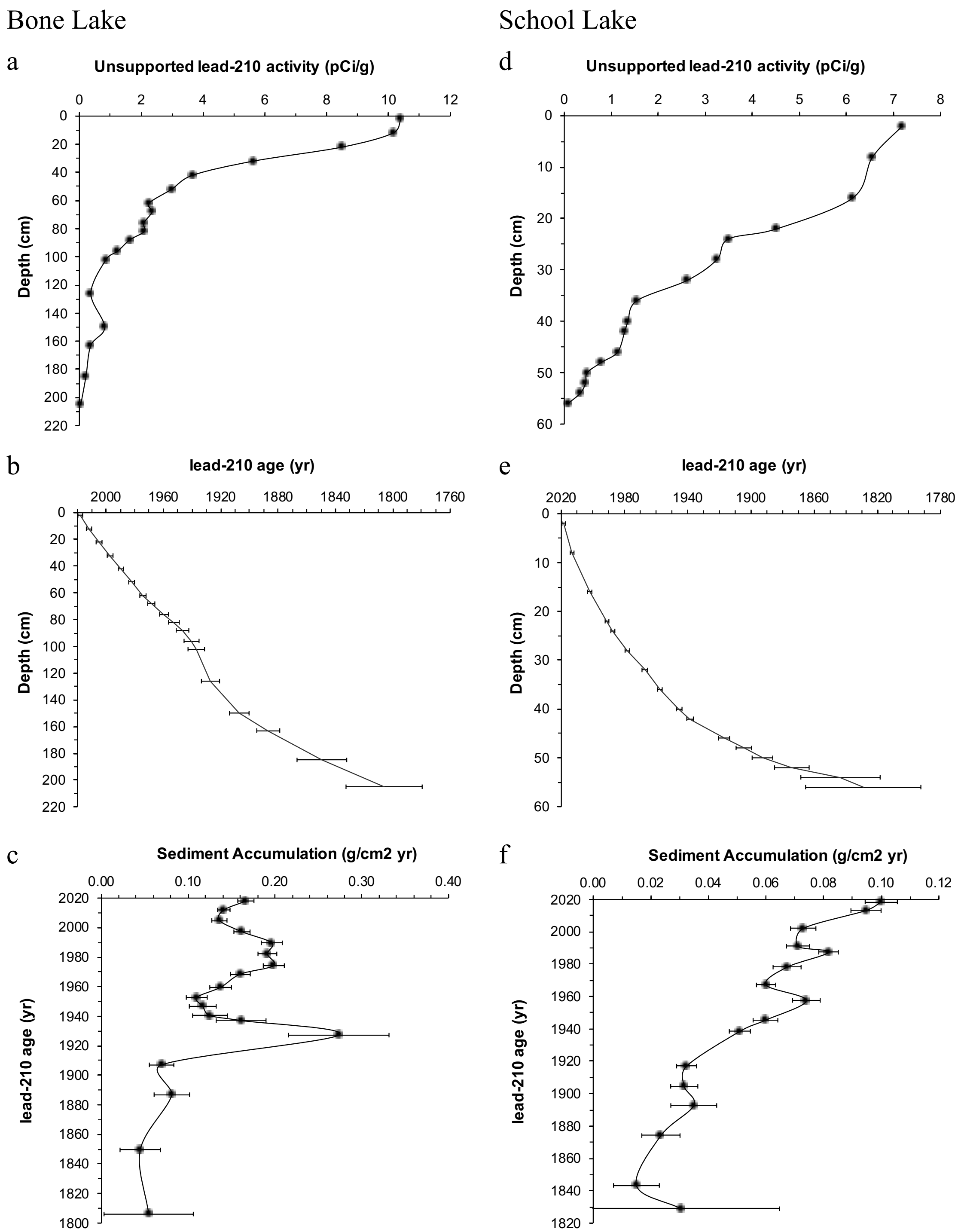


Figure 5. a) Magnetic susceptibility profile for the Bolivia core from Bone Lake plotted against depth in the sediment. b) Percent dry weight of organic matter, inorganic matter, and carbonate (CaCO3) in the overlapping piston and Bolivia cores from Bone Lake plotted against depth in the sediment. The horizontal black line at 205 cm shows where lead-210 activities reached background levels.

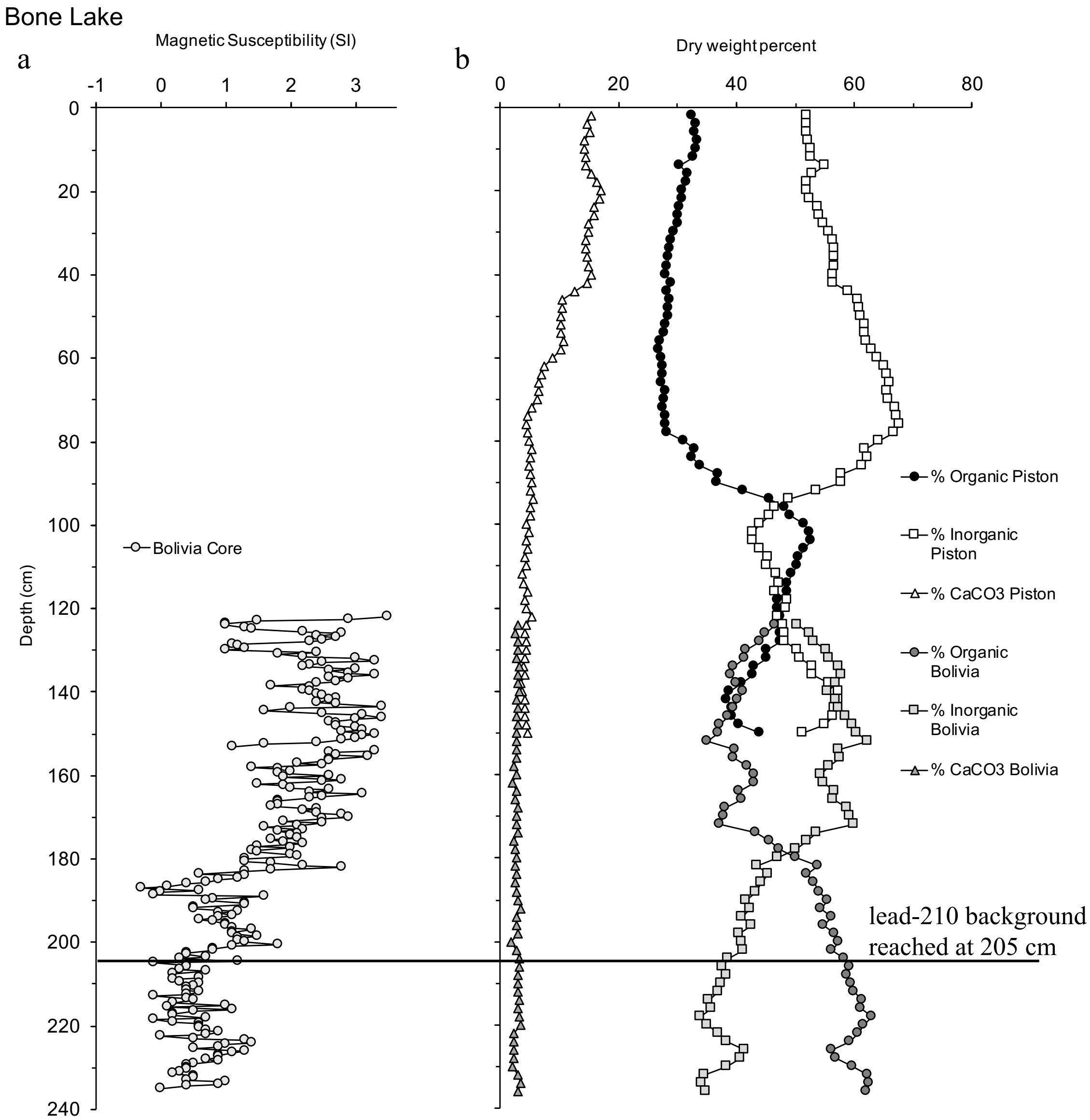


Figure 6. a) Magnetic susceptibility profile for the piston core from School Lake plotted against depth in the sediment; magnetics was not run on the top portion of the core that was sectioned in the field (0-37 cm). b) Percent dry weight of organic matter, inorganic matter, and carbonate (CaCO3) in the piston core from School Lake plotted against depth in the sediment. The horizontal black line at 56 cm shows where lead-210 activities reached background levels.

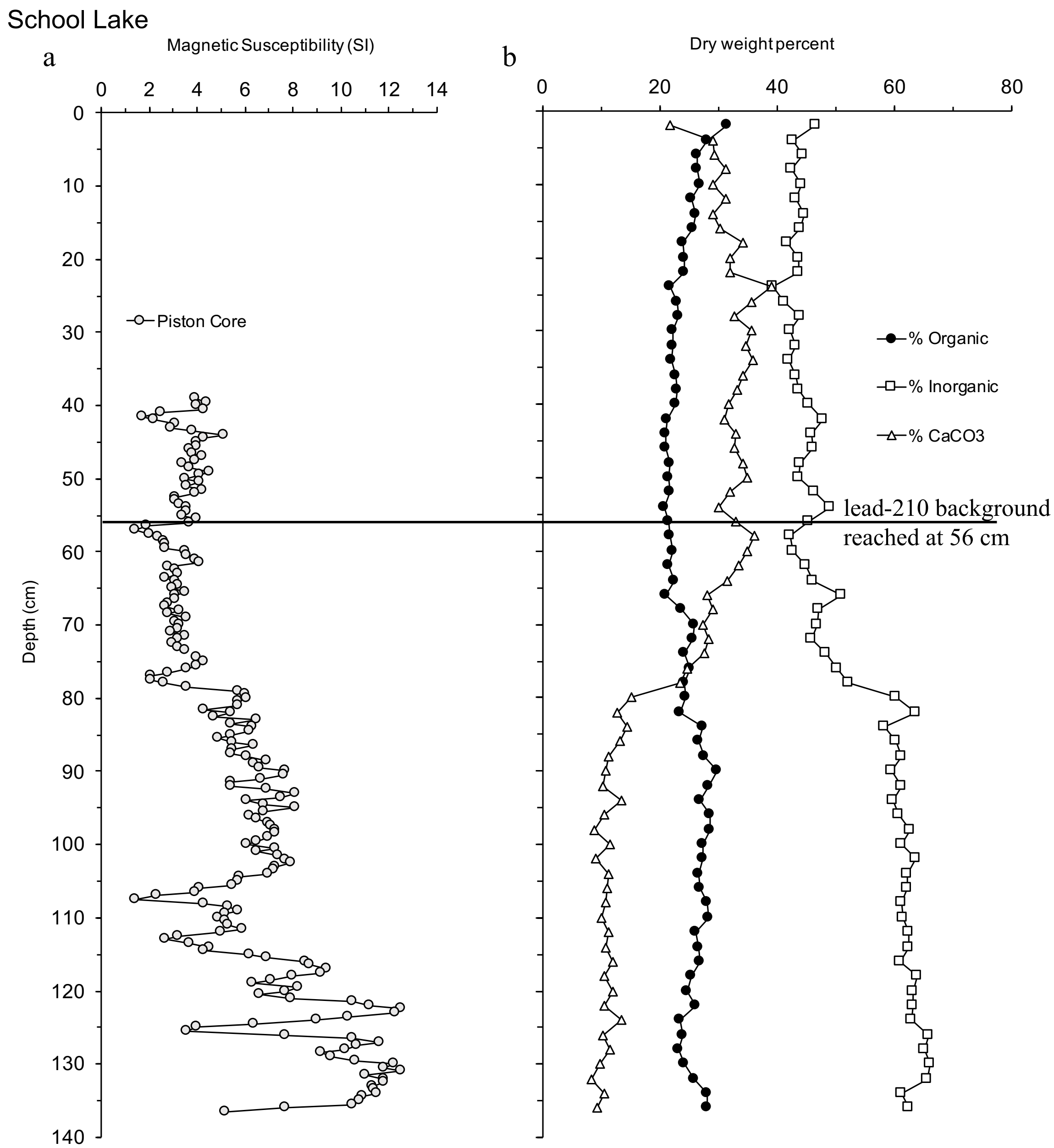


Figure 7. Sediment flux of organic matter, inorganic matter, and carbonate (CaCO3) to the Bone Lake core. Flux was only calculated for the length of the core within the lead-210 record (0-205 cm).

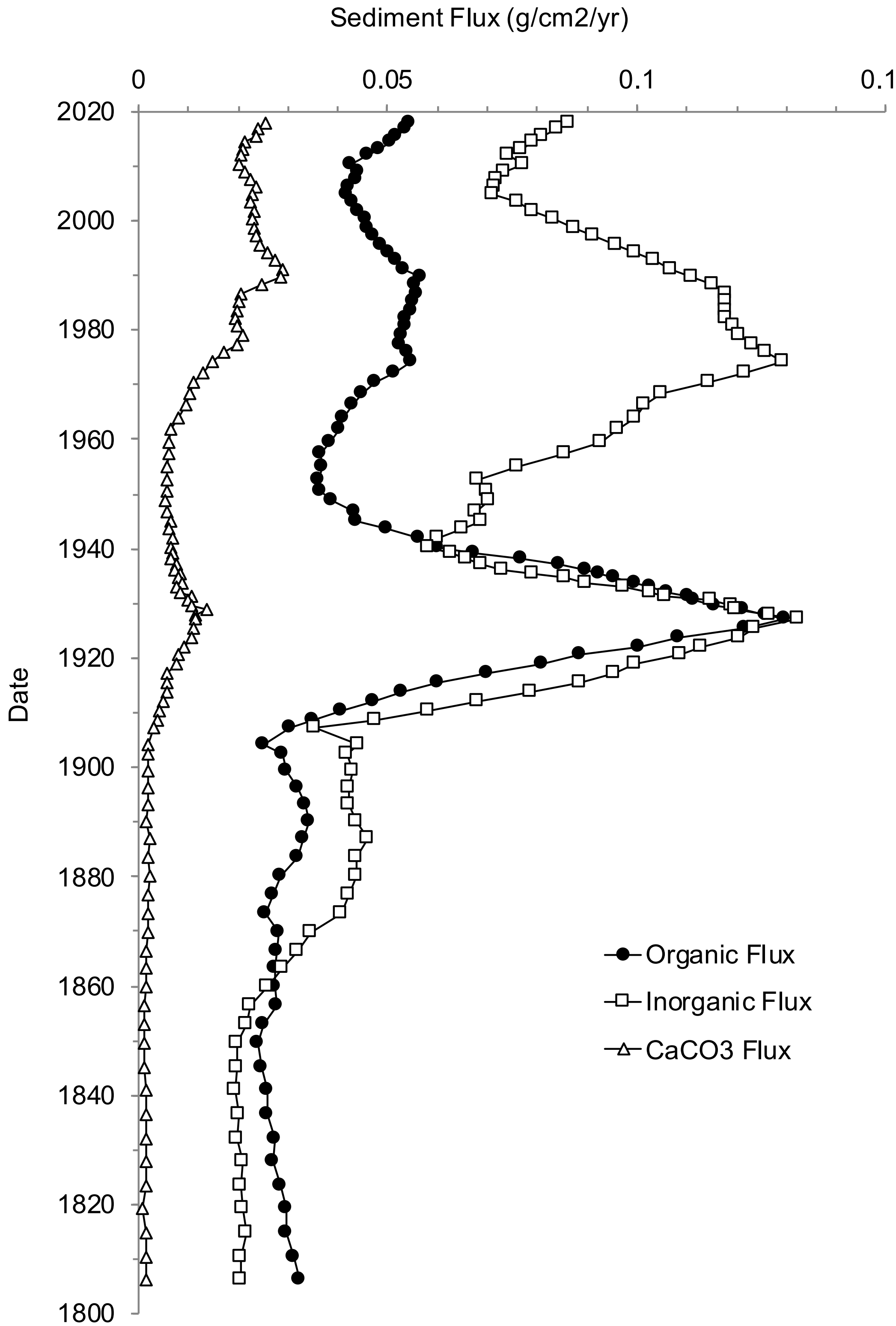


Figure 8. Sediment flux of organic matter, inorganic matter, and carbonate (CaCO3) to the School Lake core. Flux was only calculated for the length of the core within the lead-210 record (0-56 cm).

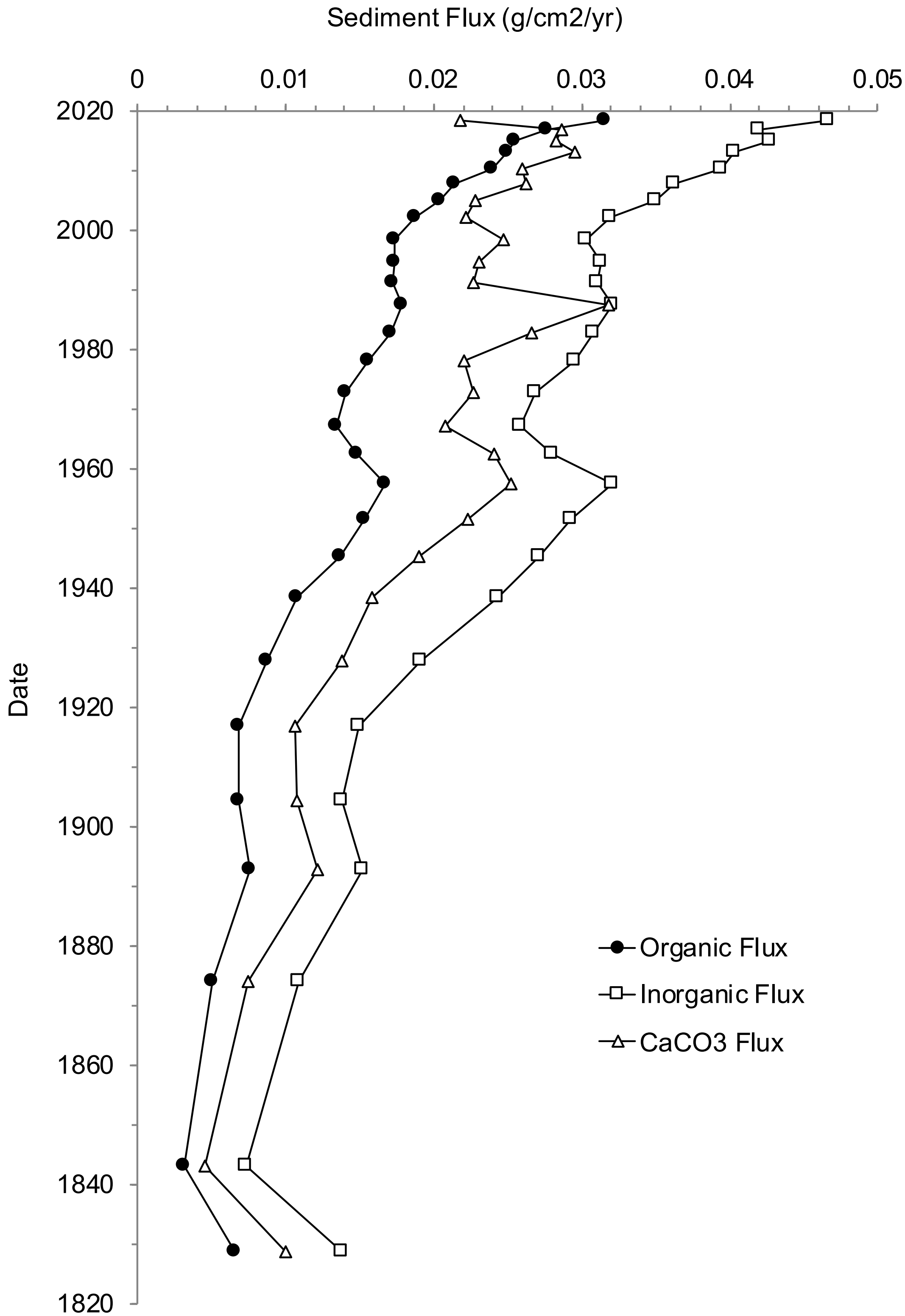


Figure 9. Weight percent of biogenic silica (BSi) (a) and SiO2 flux (b) in the Bone Lake core, plotted against lead-210 date.

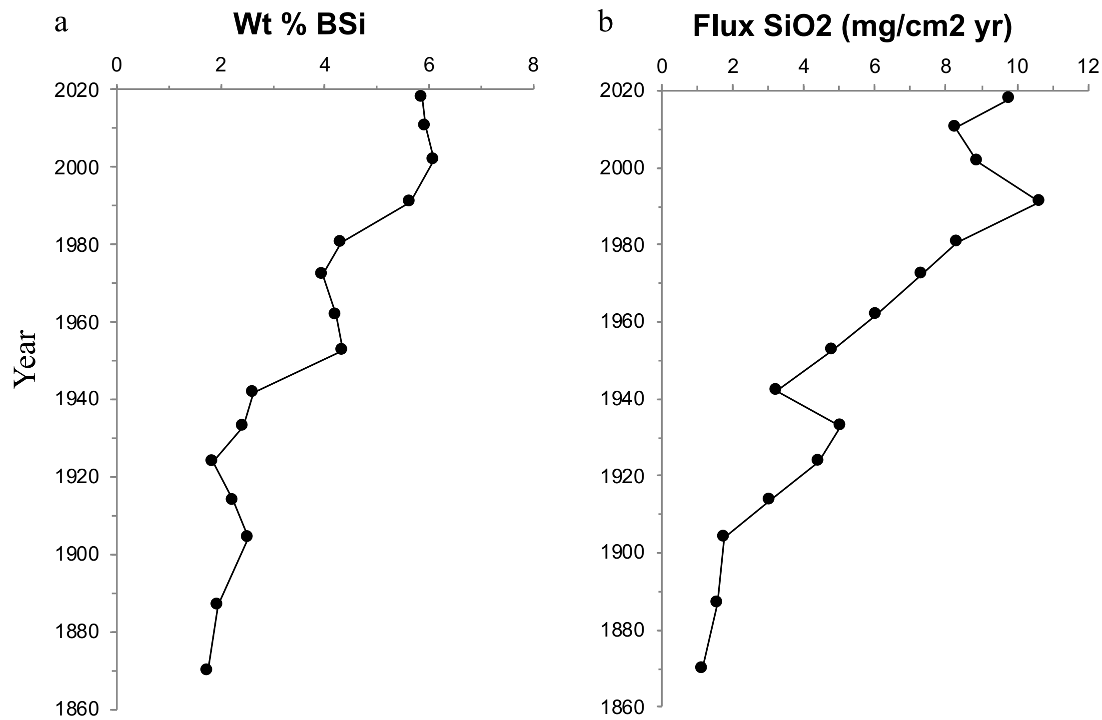


Figure 10. Concentration (a) and flux (b) of phosphorus fractions in the Bone Lake core.

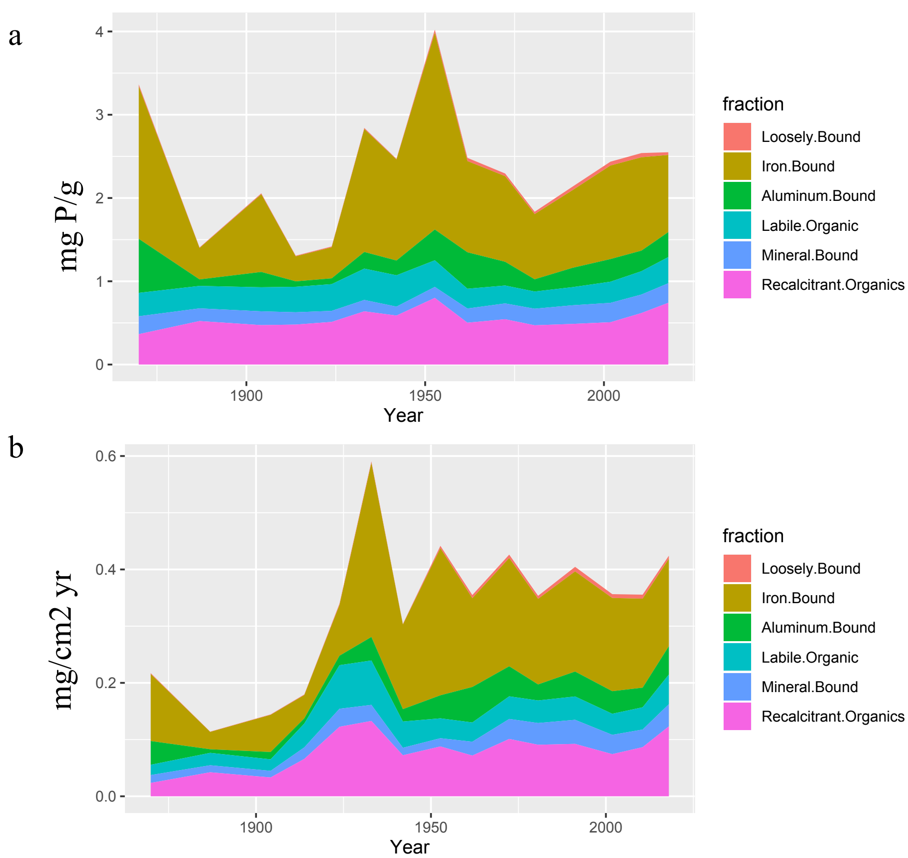


Figure 11. Weight percent of biogenic silica (BSi) (a) and flux (b) in the School Lake core, plotted against lead-210 date.

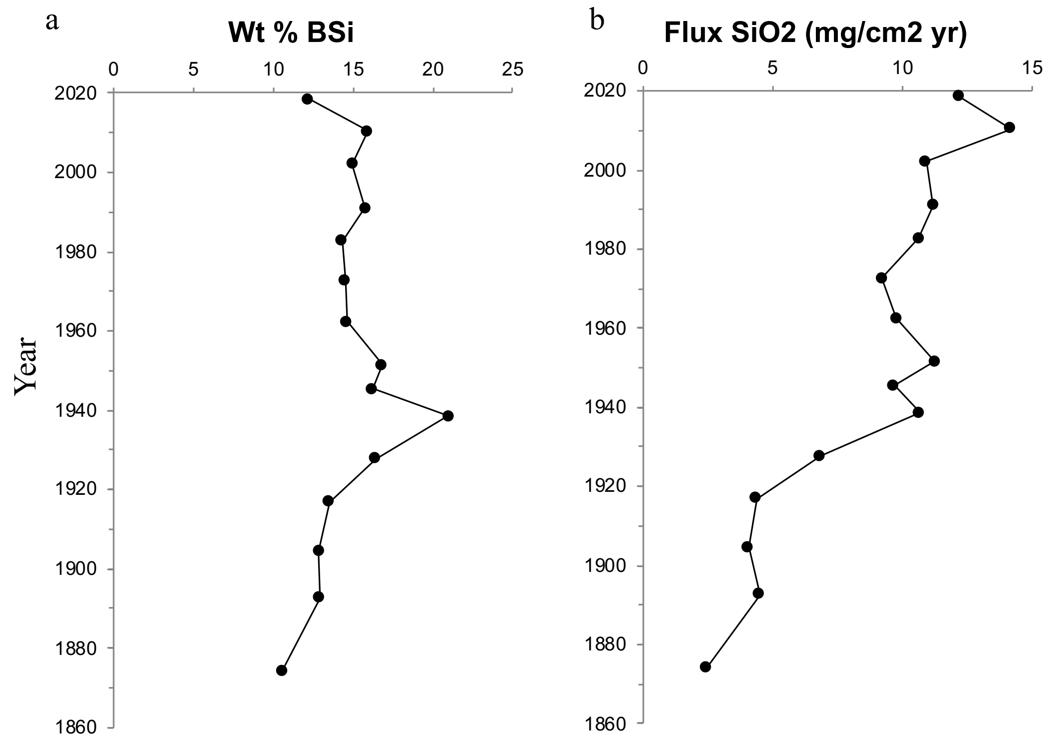


Figure 12. Concentration (a) and flux (b) of phosphorus fractions in the School Lake core.

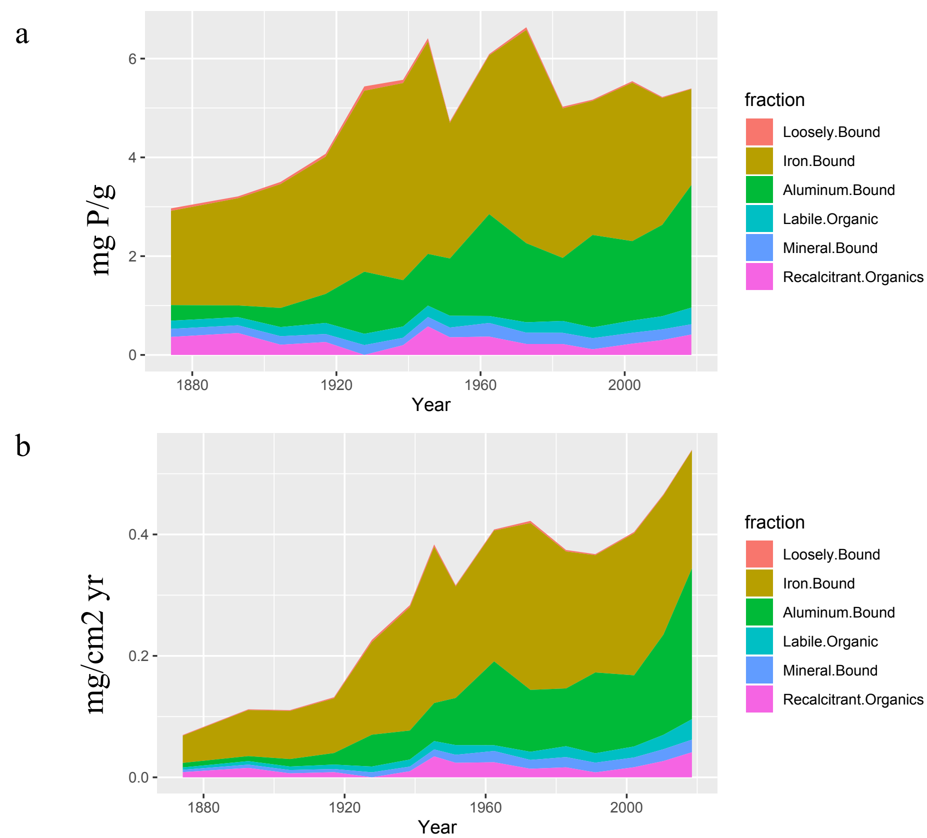


Figure 13. Non-Metric Multidimensional Scaling (NMDS) biplot of diatom communities from Bone Lake (1942-2018). Samples from 1870-1933 were not included in the analysis due to low diatom abundance.

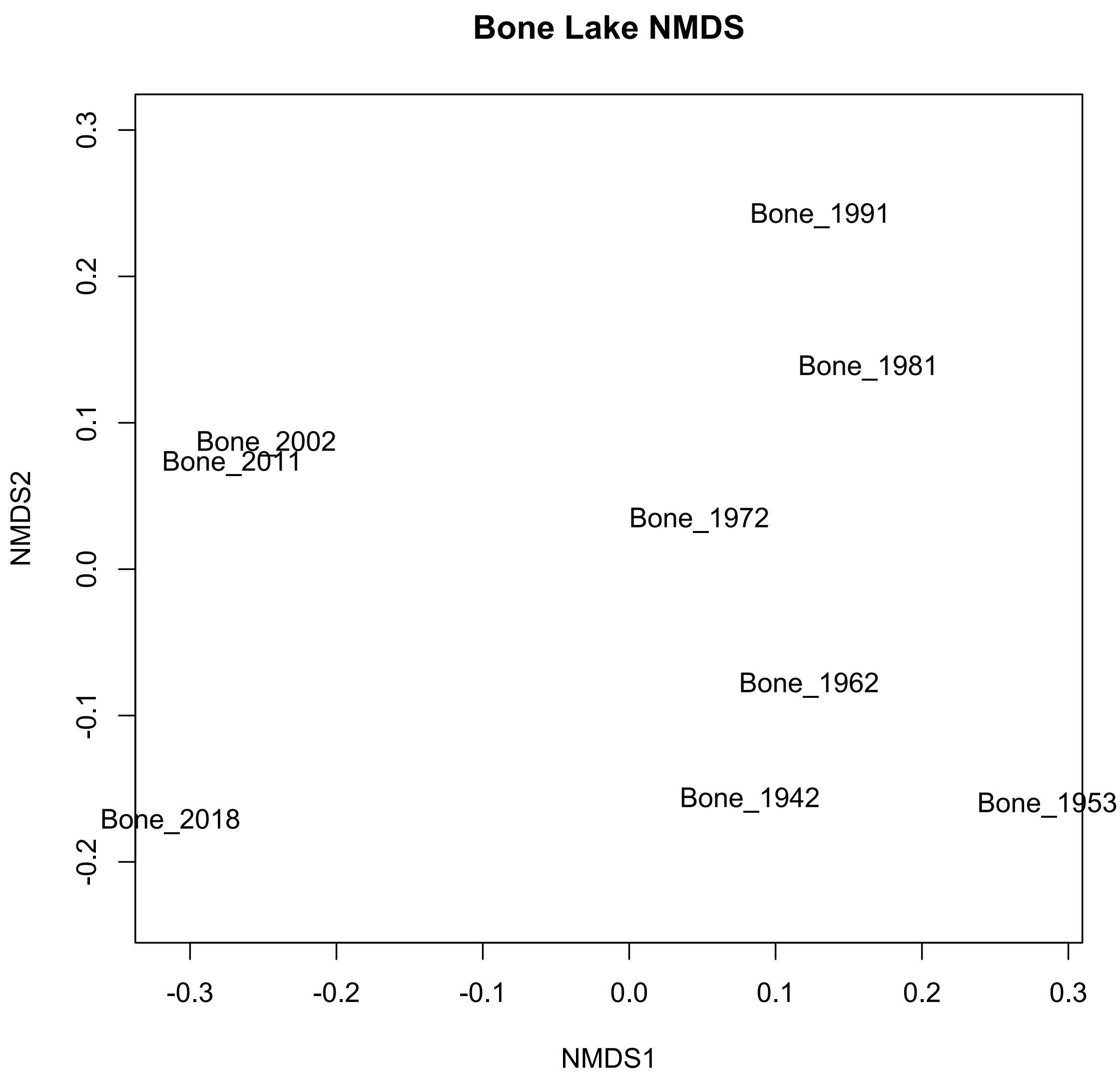


Figure 14. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance), results of a constrained cluster analysis, and percent plankton in Bone Lake (1942-2018). Samples from 1870-1933 were not included due to low diatom abundance.

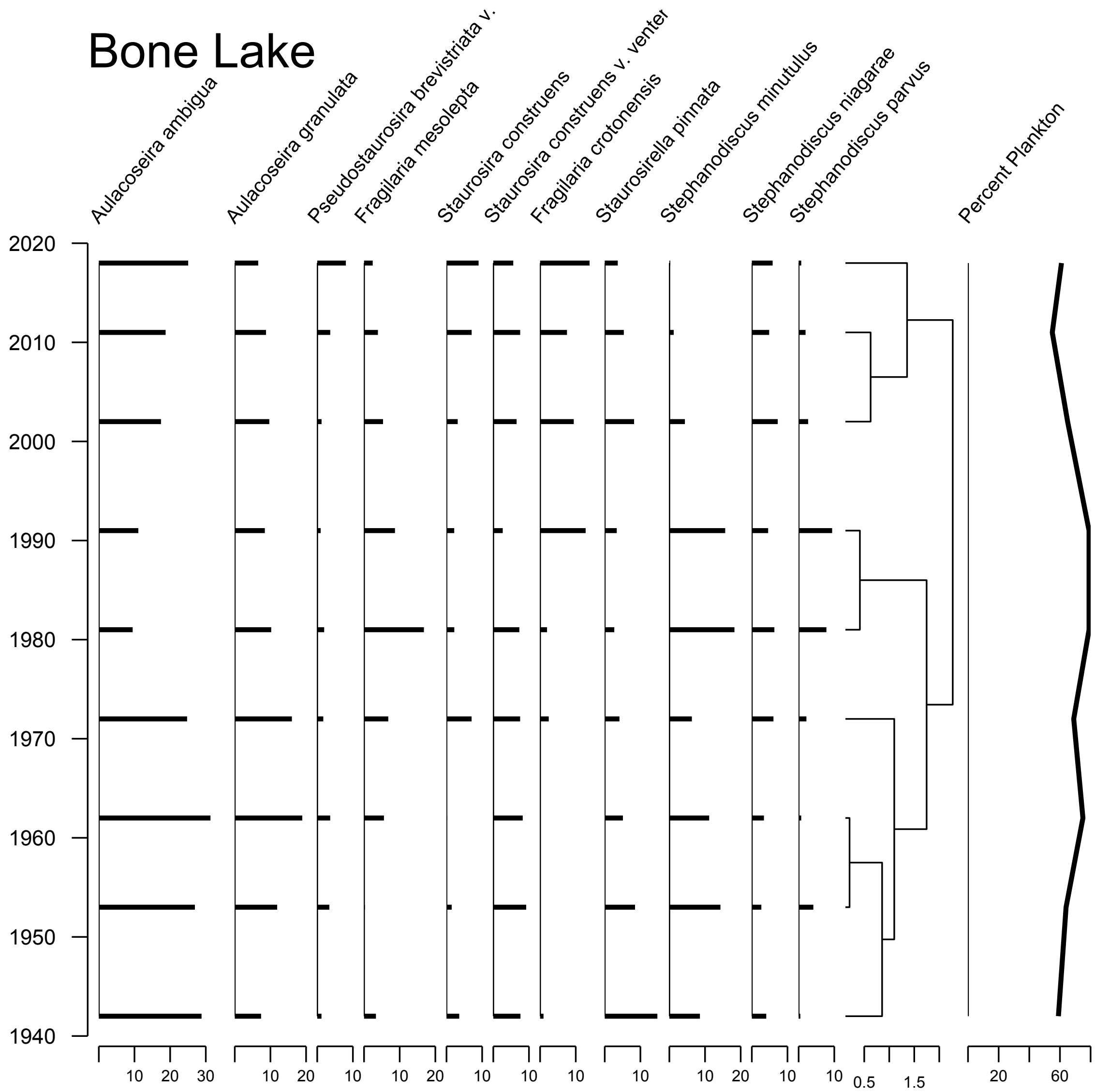


Figure 15. Non-Metric Multidimensional Scaling (NMDS) biplot of diatom communities from School Lake (1874-2019).

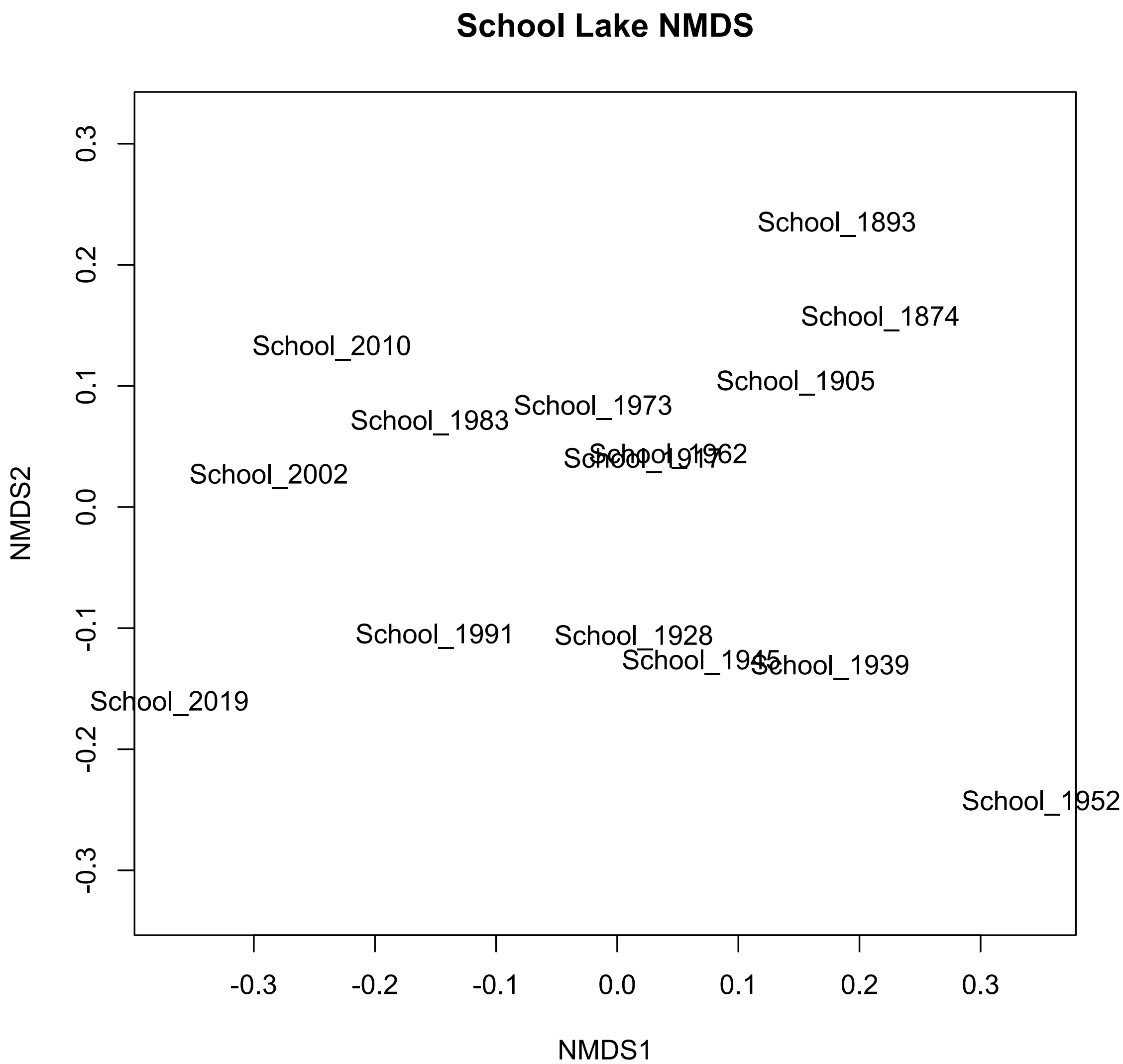


Figure 16. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance), results of a constrained cluster analysis, and percent plankton in School Lake (1874-2019).

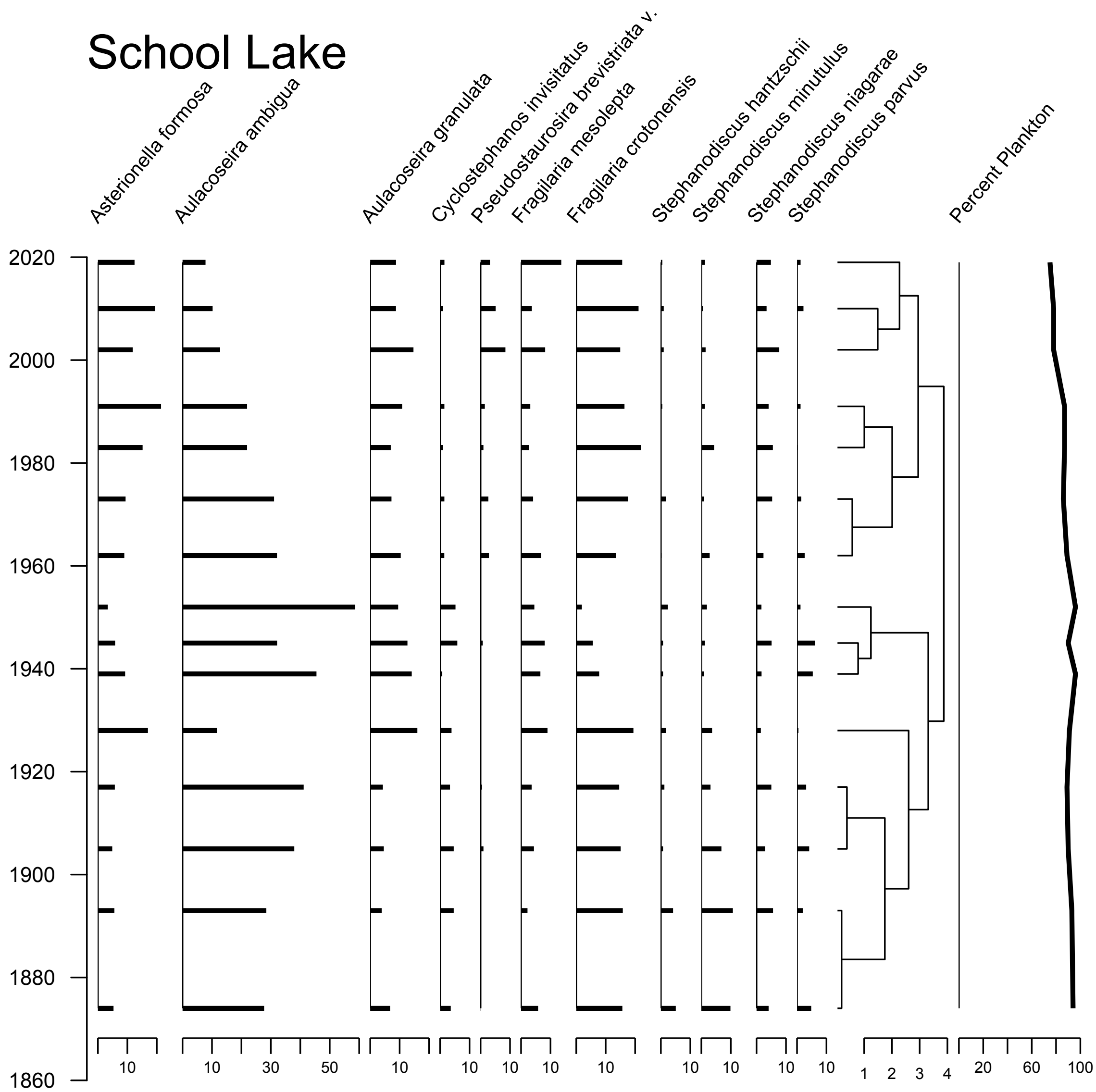


Figure 17. The core sections from Bone Lake projected onto the MN calibration set (denoted as "X core date"). Symbols represent the 89 MN lakes in the calibration set, coded by region; NLF=Northern Lakes and Forests, CHF=Central Hardwood Forests, Metro=Twin Cities Metropolitan Area, WCP=Western Corn Belt Plains, NGP=Northern Great Plains, and MCWD=Minnehaha Creek Watershed Distric. Environmental vectors are shown on the inset plot. Note that logTP is strongly correlated with Axis 1.

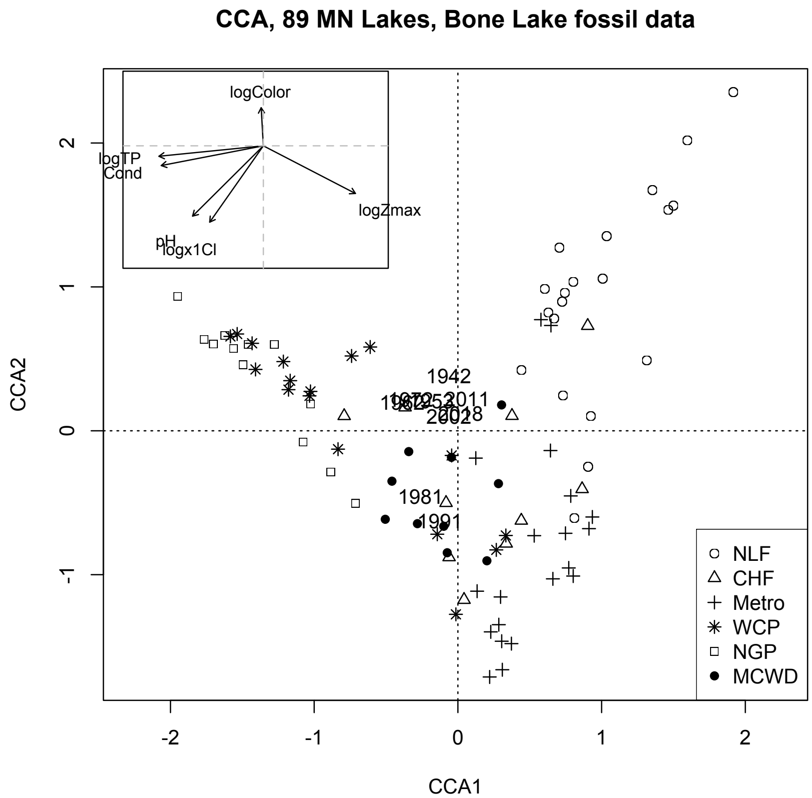


Figure 18. Diatom-inferred total phosphorus (TP) reconstruction for Bone Lake. Reconstruction is shown as log TP (left panel) and as backtransformed values in micrograms per liter (right panel). Error estimates on log TP are plus and minus the root mean square error of prediction from the TP transfer function.

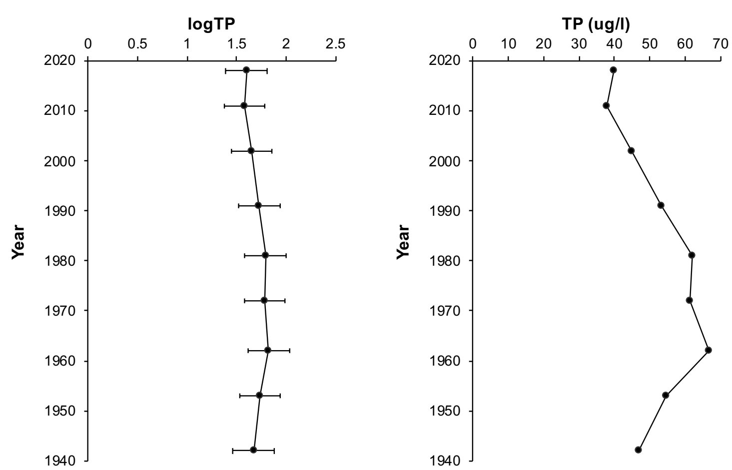


Figure 19. The core sections from School Lake projected onto the MN calibration set (denoted as “X core date”). Symbols represent the 89 MN lakes in the calibration set, coded by region; NLF=Northern Lakes and Forests, CHF=Central Hardwood Forests, Metro=Twin Cities Metropolitan Area, WCP=Western Corn Belt Plains, NGP=Northern Great Plains, and MCWD=Minnehaha Creek Watershed Distric. Environmental vectors are shown on the inset plot. Note that logTP is strongly correlated with Axis 1.

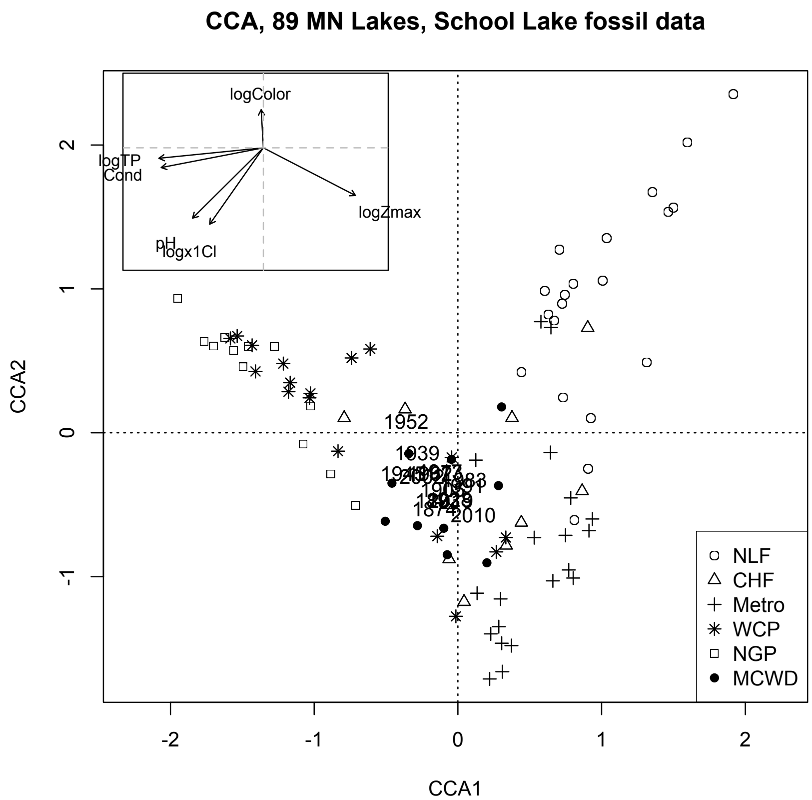


Figure 20. Diatom-inferred total phosphorus (TP) reconstruction for School Lake. Reconstruction is shown as log TP (left panel) and as backtransformed values in micrograms per liter (right panel). Error estimates on log TP are plus and minus the root mean square error of prediction from the TP transfer function.

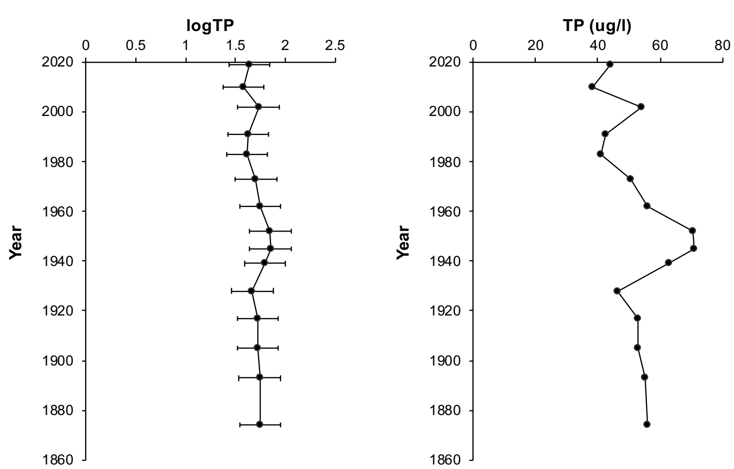


Figure 21. Sediment algal pigments quantified in ten core sections from Bone Lake. The group of algae associated with each pigment is shown along the x-axis.

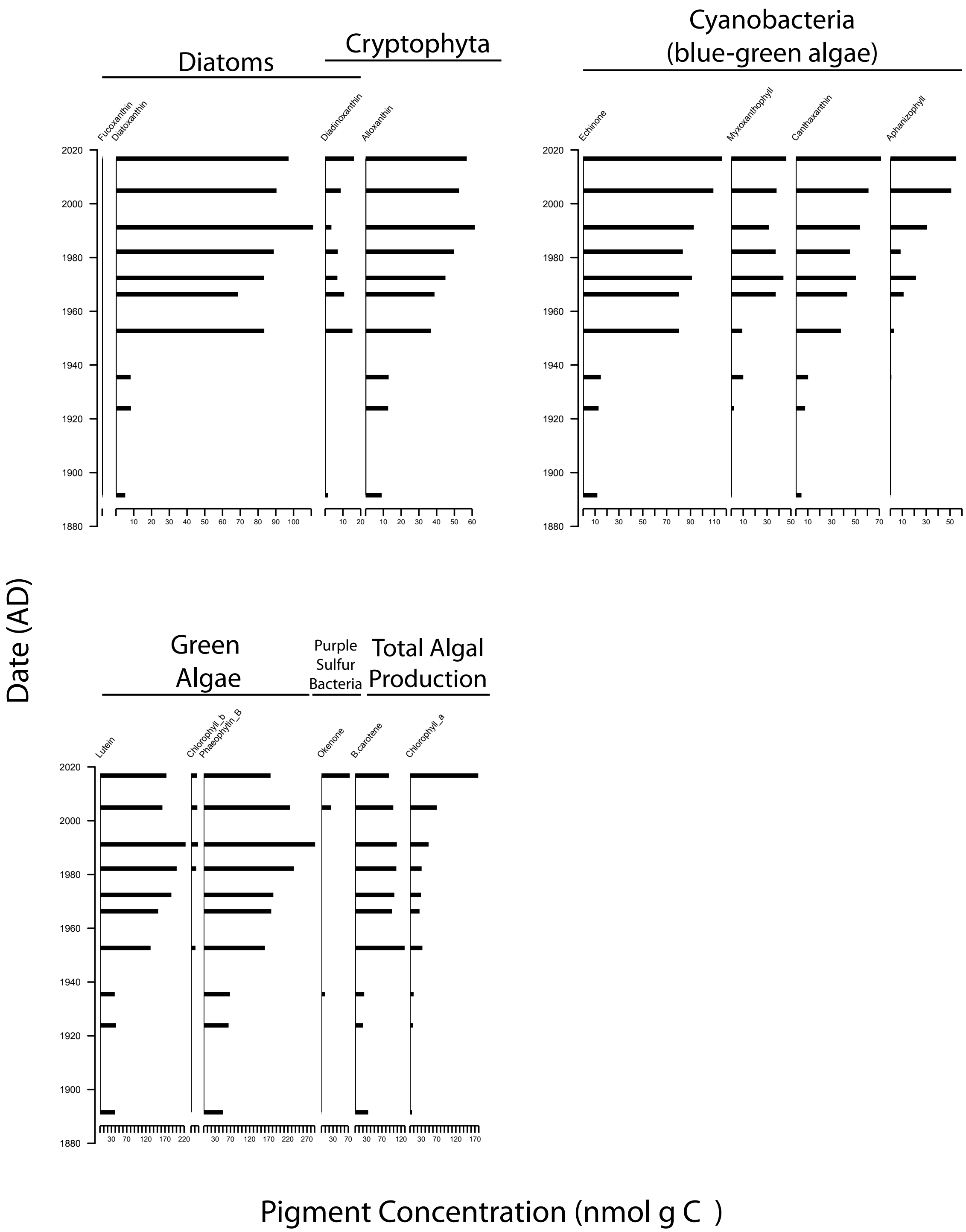
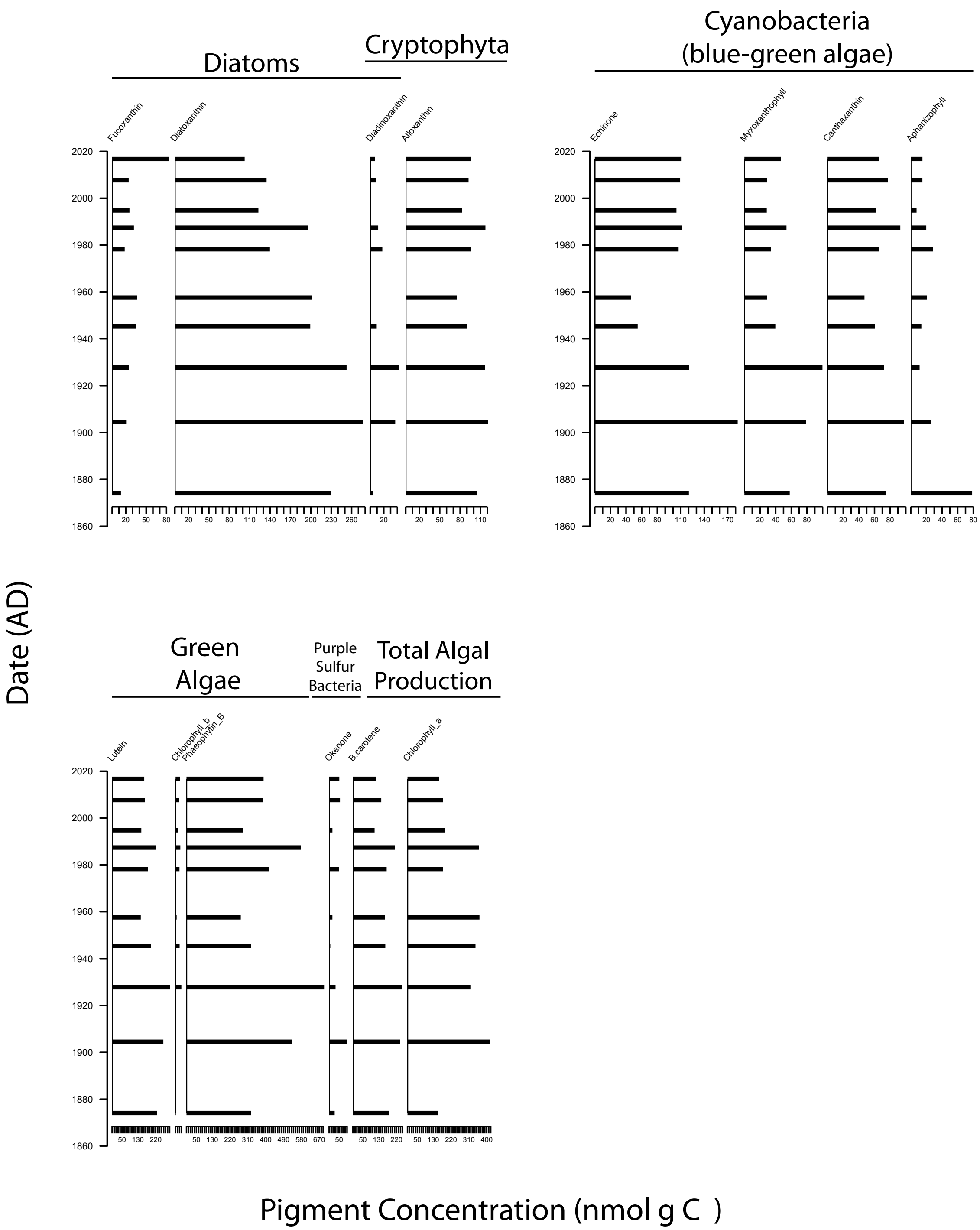
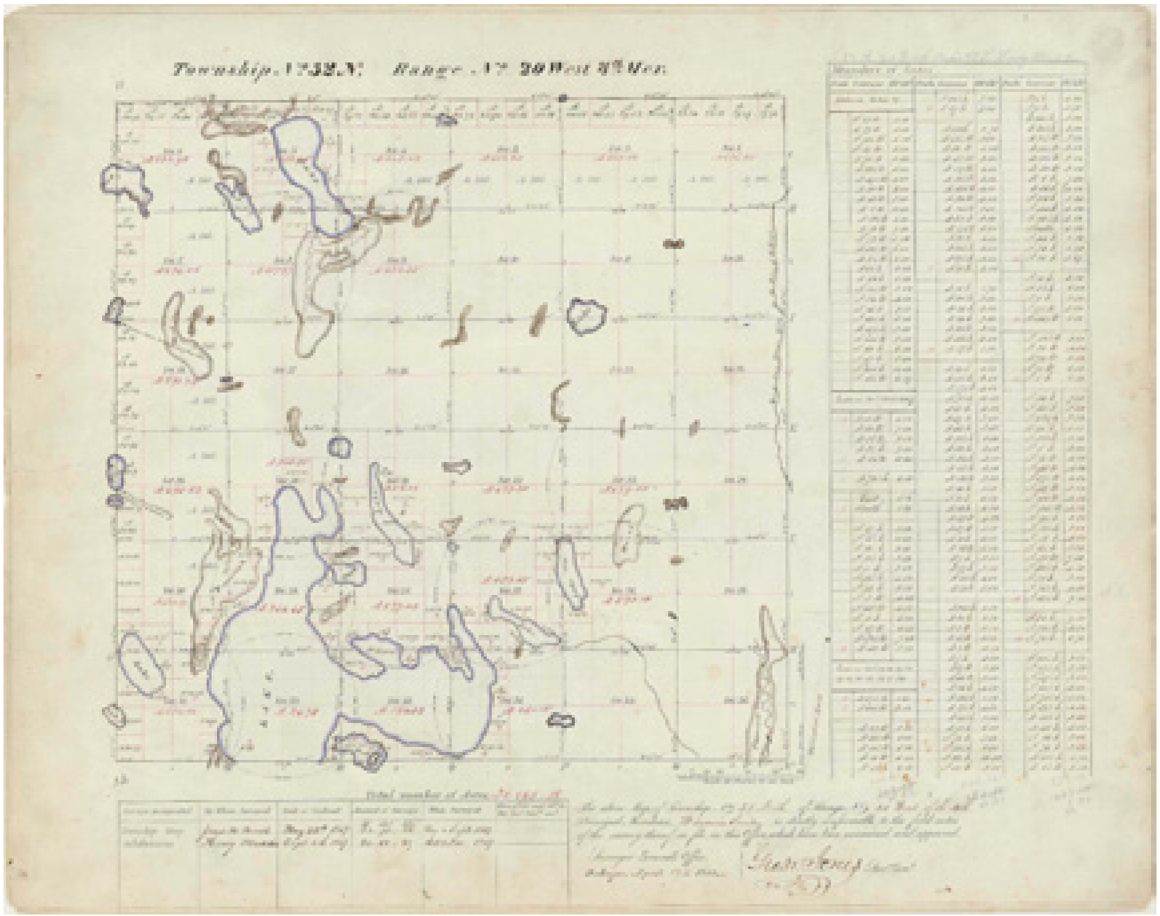


Figure 22. Sediment algal pigments quantified in ten core sections from School Lake. The group of algae associated with each pigment is shown along the x-axis.



Appendix A. Historic survey map from 1848, showing Bone Lake and the surrounding area.



Appendix B. Historic survey map from 1849, showing showing the area where School Lake presently is.