HISTORICAL WATER QUALITY AND ECOLOGICAL CHANGE IN ARCTIC LAKE

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SUMMARY

1. In this project, paleolimnological techniques were used to reconstruct the trophic and sedimentation history of Arctic Lake in Scott County, Minnesota.

2. A sediment core was collected from the lake, and lead-210 activity was analyzed to develop a dating model 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, and subfossil diatoms in the sediments were analyzed to reconstruct changes in lake ecology and trophic state.

3. The sedimentation rate in Arctic Lake spikes in 1939, and remains elevated into the present. From 1943 to 2010, the sediment accumulation rate is nearly ten times higher than the average rate from 1820 to 1931.

4. The spike in sedimentation rate in 1939 corresponds with an increase in the concentration of inorganic matter in the sediments, suggesting a large erosional pulse from the watershed.

5. Throughout the core the diatom community assemblage is dominated by planktonic species that are indicative of nutrient-rich conditions. The diatom assemblage, and resulting diatom-inferred TP reconstruction, suggest that in the early 1940s the lake changed from mesotrophic to eutrophic/hypereutrophic.

6. The algal pigments suggest that Arctic Lake has been a productive system since the early 1900s.

7. The oldest samples analyzed suggest that the lake may have been very different during the late 1700s. The bottommost diatom sample, dated at approximately 1774, shows the highest diatom-inferred TP concentrations in the core. These core sections also have the highest levels of organic matter in the core, suggesting that the lake may have been hypereutrophic at this time.

INTRODUCTION

Within the glaciated regions of the Upper Midwest, lakes feature prominently in the landscape and are a valued resource. Current and historical land and resource uses around the lakes in this region have raised concerns about the state of the lakes and how to best manage them in a future certain to bring change. To effectively develop management plans, knowledge of the natural state of a lake and an understanding of the timing and magnitude of historical ecological changes become critical components.

With any lake management plan it is important to have a basic understanding of natural fluctuations within the system. 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 type of 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 project, paleolimnological techniques were used to reconstruct the trophic and sedimentation history of Arctic Lake in Scott County, Minnesota. Results provide a management foundation through the determination of the natural or reference condition of this lake and the reconstruction of ecological changes that have occurred in the lake during the last 150-200 years.

Initial sediment core investigations of nearby Spring Lake, Scott County MN, found evidence of historically elevated TP concentrations and the presence of cyanobacterial blooms prior to settlement and development of the watershed (Hobbs 2013). This led to an interest in understanding the historical conditions of other lakes within the watershed. Arctic Lake flows into Upper Prior Lake, which then flows into Spring Lake. Arctic Lake currently has elevated nutrient levels; it supports large carp populations, which contribute to internal loading of phosphorus, and the lake likely goes anoxic each year (Nat Kale, personal communication).

The primary aim of this project was to use paleolimnological analysis of a dated sediment core from Arctic Lake to reconstruct its ecological history using geochemistry, sediment accumulation, diatom-inferred total phosphorus (DI-TP), and diatoms as biological indicators. Analytical tools included radioisotopic dating of the cores, geochemical analyses to determine local sediment accumulation rates, and analysis of subfossil algal communities. Multivariate analyses, diatom-based transfer functions, and comparison of algal assemblages with an 89 Minnesota lake data set were used to relate changes in trophic conditions and algal 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 20 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, changes in whole lake algal communities were also characterized through time. 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). 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 changes 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 blue-green algae.

METHODS - SEDIMENT CORING

A piston and overlapping Livingstone core were collected from Arctic Lake on May 16, 2013. The cores were collected from a deep, flat area of the basin to provide a highly integrated sample of diatom community structure from the lake as a whole. The piston core was taken using a drive-rod piston corer equipped with a 6.5 cm diameter polycarbonate barrel (Wright 1991). A Livingstone corer was used to collect a secondary core from sediment depths below that of the piston core, in case the sedimentation rate was too high to capture sediments dating prior to European settlement within the length of the piston core.

The coring location was at 44.71967N, 93.45673 °W, in 8.89 m of water. The piston core recovered 0.85 m of sediment; the Livingstone core recovered 1.00 m of sediment, with 0.10 m of overlap with the piston core. Cores were returned to the laboratory and stored at 4°C.

METHODS - GEOCHEMISTRY

Weighed subsamples were taken from regular intervals throughout the 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.

METHODS - LEAD-210 DATING

Twenty-one core sections were analyzed for lead-210 activity to determine age and sediment accumulation rate for the past 150-200 years. Lead-210 was measured 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).

Lead-210 dates prior to the mid-1800s were obtained by linear extrapolation of the model. These dates at the bottom of the core should be considered approximations, with large errors associated with the extrapolation.

METHODS - DIATOM AND NUMERICAL ANALYSES

Fourteen downcore samples were analyzed for diatoms. See Table 1 for a list of samples prepared for diatom analysis.

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 (full immersion optics of NA 1.4). 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 to achieve consistent taxonomy.

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 Detrended Correspondence Analysis (DCA), in the software package R (R Core Development Team 2012). 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 a DCA is that samples that plot closer to one another have more similar diatom assemblages.

Downcore diatom communities were also used to reconstruct historical epilimnetic 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 ANALYSES

Sediment pigment concentrations were quantified by Dr. Rolf Vinebrooke at the University of Alberta, Canada, using reverse-phase high-pressure liquid chromatography (HPLC) (Vinebrooke et al. 2002). Freeze-dried subsamples from the Arctic Lake core were stored in a freezer under nitrogen to prevent degradation of pigments prior to analysis.

Pigments were first extracted from freeze-dried sediments using an acetone:methanol solution. Extracts were then filtered (0.2-lm pore nylon), dried under N_2, and reconstituted using a precise volume of injection solution. Chromatographic separation was performed with an Agilent 1100 Series HPLC equipped with a Varian Microsorb 100A C18 column, and pigment detection using in-line diode array and fluorescence detectors. Pigment concentrations were quantified via calibration equations and an electronic spectral library constructed using standards purchased from DHI Water and Environment, Denmark. Jeffrey et al. (2005) was consulted as a key reference for taxonomically diagnostic pigments.

RESULTS AND DISCUSSION - GEOCHEMISTRY

The sediment composition in the piston and overlapping Livingston core from Arctic Lake shows some variation throughout the core; however, with the exception of the bottommost samples, inorganic material makes up the largest percentage of the sediment (Figure 1). Throughout the core, the amount of inorganic matter fluctuates between 39 and 88 percent, the amount of organic matter fluctuates between 8 and 51%, and carbonate between 4 and 36%. The most notable change in the sediment composition is the rise in organic matter at the bottom of the Livingston core, from about 149 cm to the core bottom; in the two lowest samples the amount of organic matter becomes higher than the amount of inorganic matter.

RESULTS AND DISCUSSION - DATING AND SEDIMENTATION

The unsupported lead-210 activity, the resulting lead-210 dating model, and the sediment accumulation rate for Arctic Lake are shown in Figure 2. The lead-210 activity shows a large decline at the core top and an overall decline throughout the rest of the core (Figure 2a). The sediment accumulation rate is low from the early 1800s until the early 1930s and ranges from 0.0092 to .0911 g/cm^2 yr (Figure 2c). The rate spikes to 0.7931 g/cm^2 yr in 1939; although the sediment accumulation rate drops back down in the early 1940s, it averages 0.39 g/cm^2 yr from 1943 to 2010, which is almost tenfold higher than the average from 1820 to 1931. The sedimentation rate drops in the topmost sample, although it still remains elevated over the pre-1930s samples.

The large peak in sedimentation rate in 1939 corresponds with one of the peaks in inorganic matter in the core from 131-133 cm (Figure 1), suggesting that there may have been a large erosional pulse of sediment from the watershed during this time.

RESULTS AND DISCUSSION - DIATOM STRATIGRAPHY AND ORDINATION

The ordination biplot from the detrended correspondence analysis (DCA) shows how the core samples cluster together based on similarity of diatom assemblage (Figure 3). The sample from 1774 is somewhat unique in its diatom community assemblage, and plots away from the other samples. The samples from 1789 to 1850 cluster closely together, with a shift in the community between 1850 and 1900. The samples from 1900 to the present show some variation, with no strong directional change over time.

The stratigraphic diagram shows the predominant diatoms whose abundances are driving the shifts in the community assemblage (Figure 4). All of the predominant diatoms in the Arctic Lake core are planktonic, and are indicative of some degree of nutrient enrichment in the lake. In 1774, *Aulacoseira granulata* makes up nearly 80% of the diatom assemblage, making this sample unique from the others analyzed in the Arctic Lake core. From the late 1700s through the mid-1900s, the diatom assemblage is a mix of planktonic eutrophic and mesotrophic indicators: *Stephanodiscus* species, *Cyclostephanos* species, *Asterionella formosa*, *Fragilaria* species, *Tabellaria quadriseptata*, and *Aulacoseira granulata*. From 1943 to the present, the assemblage is largely dominated by *Stephanodiscus* and *Cyclostephanos* species, suggesting a higher degree of nutrient enrichment than the previous time period. This coincides with the peak in sedimentation rate and increase in organic matter in the core, suggesting that this increase in sediment load to the lake may have delivered additional nutrients as well.

In addition to diatoms, another biological proxy that was examined in the cores was the abundance of chrysophyte cysts. Figure 5 shows the ratio of chrysophyte cysts to diatoms valves for each of the core sections. There is a dramatic shift in the relative abundance of chrysophyte cysts in this core, with extremely high abundances found from 1774 to 1850; the ratio of cysts to diatom valves then drops off from 1900 to the present. This change in the late 1800s is indicative of a shift in the ecology of Arctic Lake. The DCA biplot also shows a shift in the overall diatom community at this time, largely driven by a decrease in *Aulacoseira granulata* and an increase in *Asterionella formosa* and *Fragilaria crotonensis*.

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 in Arctic Lake 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). This analysis demonstrates that some of the change in the Arctic Lake core follows the TP gradient, which is closely correlated with Axis 1; however, the fact that the change only partially follows the TP gradient suggests that there are other drivers that may be strongly influencing diatom community turnover (Figure 6).

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 (Juggins et al. 2013). In Arctic Lake, this analysis shows that the fraction of the maximum explainable variation in the diatom data that can be explained by TP is 0.53. These evaluations suggest that it is plausible to reconstruct TP from the Arctic Lake diatom assemblage; however, the TP reconstruction should be interpreted with caution, since there appear to be factors beyond TP that are having a substantial influence on the diatom community change.

The total phosphorus (TP) reconstruction shows that Arctic Lake has fluctuated between mesotrophic and eutrophic/hypereutrophic conditions during the period analyzed (Figure 7). There is a spike in TP concentration in 1943, which corresponds with the peak in sedimentation rate and the high percentage of inorganic matter in the core.

The highest DI-TP concentration occurs in the bottommost sample, and is driven by the extremely high abundance of *Aulacoseira granulata*. This peak corresponds with the highest levels of organic matter found in the core, suggesting that the lake may have been nutrient-rich; the passive plot also indicates that the lake may have been very different during this time (Figure 6). The core section from 1774 plots near lakes from the Western Corn Belt Plains and Northern Great Plains ecoregions, while all of the other core sections plot near the Central Hardwood Forests ecoregion and the Twin Cities metropolitan region (Figure 6).

RESULTS AND DISCUSSION - HISTORICAL ALGAL COMMUNITIES AND PRODUCTION

Algal pigments were quantified in five core sections to give an idea of the historical concentration or production of different algal groups (Figure 8). Diatom carotenoid pigments were not recorded in measurable amounts, suggesting that they have not been an abundant algal group in the lake. The concentrations of beta-carotene and chlorophyll *a* represent total algal production, and suggest that production was high even in the early 1900s (Figure 8). The low concentration of overall algal production in the 1939 sample is likely due to the spike in sedimentation rate and influx of inorganic matter at that time.

The algal pigment results support the conclusion from the diatom community composition and diatom-inferred TP reconstruction, that the lake has been highly productive over the period of study. The high concentrations of cyanobacteria (blue-green algae) suggest that the lake has been relatively eutrophic since 1900 (Figure 8), because cyanobacteria tend to flourish in nutrient-rich waters. Pigments from the cyanobacteria could be further broken down into different types, and there is evidence that potentially toxic forms (myxoxanthophyll) are present in Arctic Lake, especially in the most recent sample. The high abundance of the cryptophyte pigment, alloxanthin, also suggests high levels of productivity, and that Arctic Lake has had its brown-colored stain over the period of study. High levels of bacteriochlorophyll (from photosynthetic bacteria) suggest that anoxia is common in Arctic Lake, at least in the deeper waters.

CONCLUSIONS

Over the past two hundred years the largest change to Arctic Lake occurred in the late 1930s/ early 1940s. At this time the sedimentation rate spiked, corresponding with an increase in organic matter concentration in the sediments, suggesting a large erosional pulse from the watershed. The diatom assemblage and TP reconstruction indicate that the lake changed from a mesotrophic to eutrophic/hypereutrophic system in the early 1940s. This suggests that the large inorganic sediment load to the lake was also a source of additional nutrients. The algal pigment results also suggest that Arctic Lake has been a productive system since the early 1900s.

There is a large shift in the ratio of chrysophyte cysts to diatoms between 1850 and 1900, suggesting a change in the ecology of the system. There is a slight shift in the diatom community during this time, but the change is subtle, and the timing does not correlate with any large fluctuations in the sedimentation rate or sediment geochemistry.

The histories of Spring Lake and Arctic Lake are similar in that the diatom communities indicate that both lakes have been meso- to eutrophic over the past two hundred years. However, the timing of major changes differs between the two lakes. In Spring Lake, the sedimentation rate increased in the early 1900s and peaked in the 1980s, and the major change in the diatom communities occurred in the mid 1980s (Hobbs 2013). Therefore, the two lakes do have a similar trophic history, but they seem to be responding to different stressors in their sub-watersheds.

In the bottommost core samples, dated in the 1770s, the sediment geochemistry and diatom community assemblage suggest that the lake may have looked very different. The diatom assemblage in 1774 is analogous to the shallow, wind-swept lakes of the Western Minnesota ecoregions (Figure 6). This coincides with the largest concentration of organic matter in the sediments; this, in conjunction with the diatom-inferred TP, suggests the lake was hypereutrophic at this time.

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Erin Mortenson, Shawn Schottler and Dan Engstrom (SCWRS) performed 210-Pb analysis. Erin Mittag (SCWRS) was responsible for diatom slide preparation. Algal pigments were analyzed by Rolf Vinebrook at the University of Alberta, Canada.

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Table 1. Samples prepped for diatom analysis.

Depth (cm)	Lead-210 Date
0.5	2013
24.5	2003
40.5	1995
60.5	1983
76.5	1975
96.5	1967
117.5	1955
127.5	1943
135.5	1931
143.5	1900
147.5	1850
149.5	1820
151.5	1789
152.5	1774

Figure 1. Percent dry weight of organic, $CaCO_3$, and inorganic matter in the Arctic Lake piston and Livingstone core plotted against core depth.

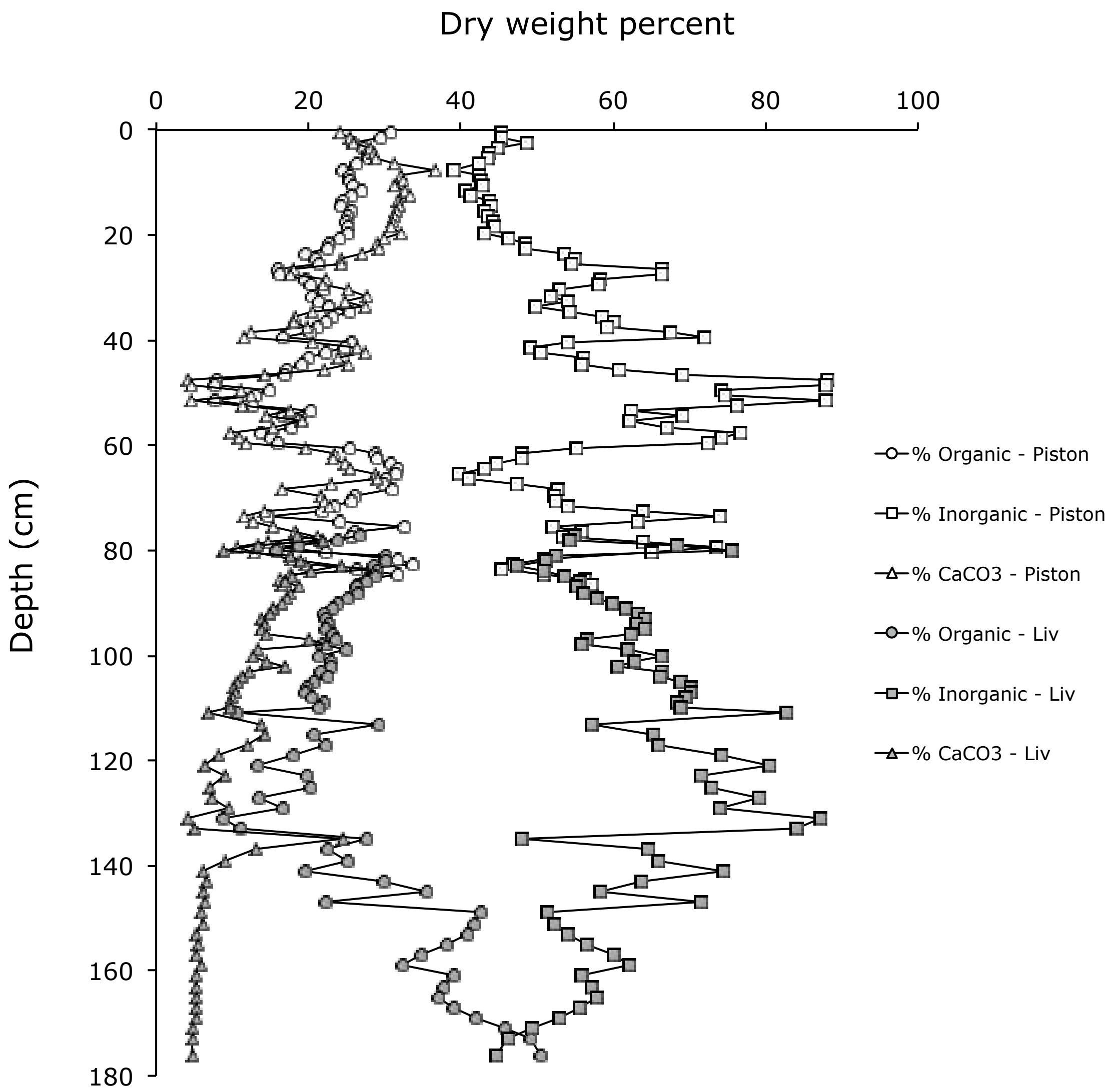

Figure 2. Unsupported lead-210 activity (a), lead-210 dating model (b), and sediment accumulation rate (c) for Arctic Lake.

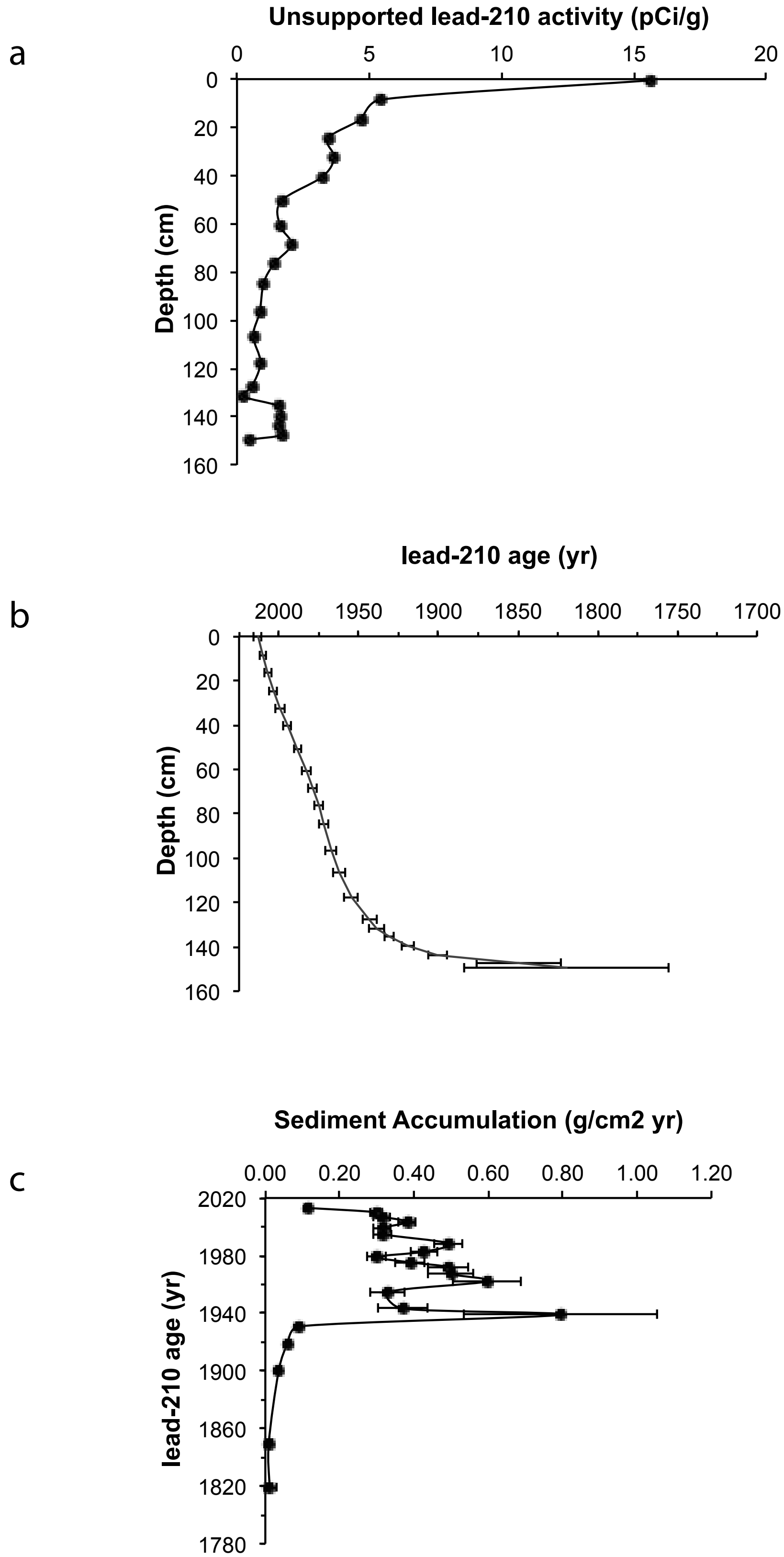

Figure 3. Detrended correspondence analysis (DCA) of diatom communities from Arctic Lake.

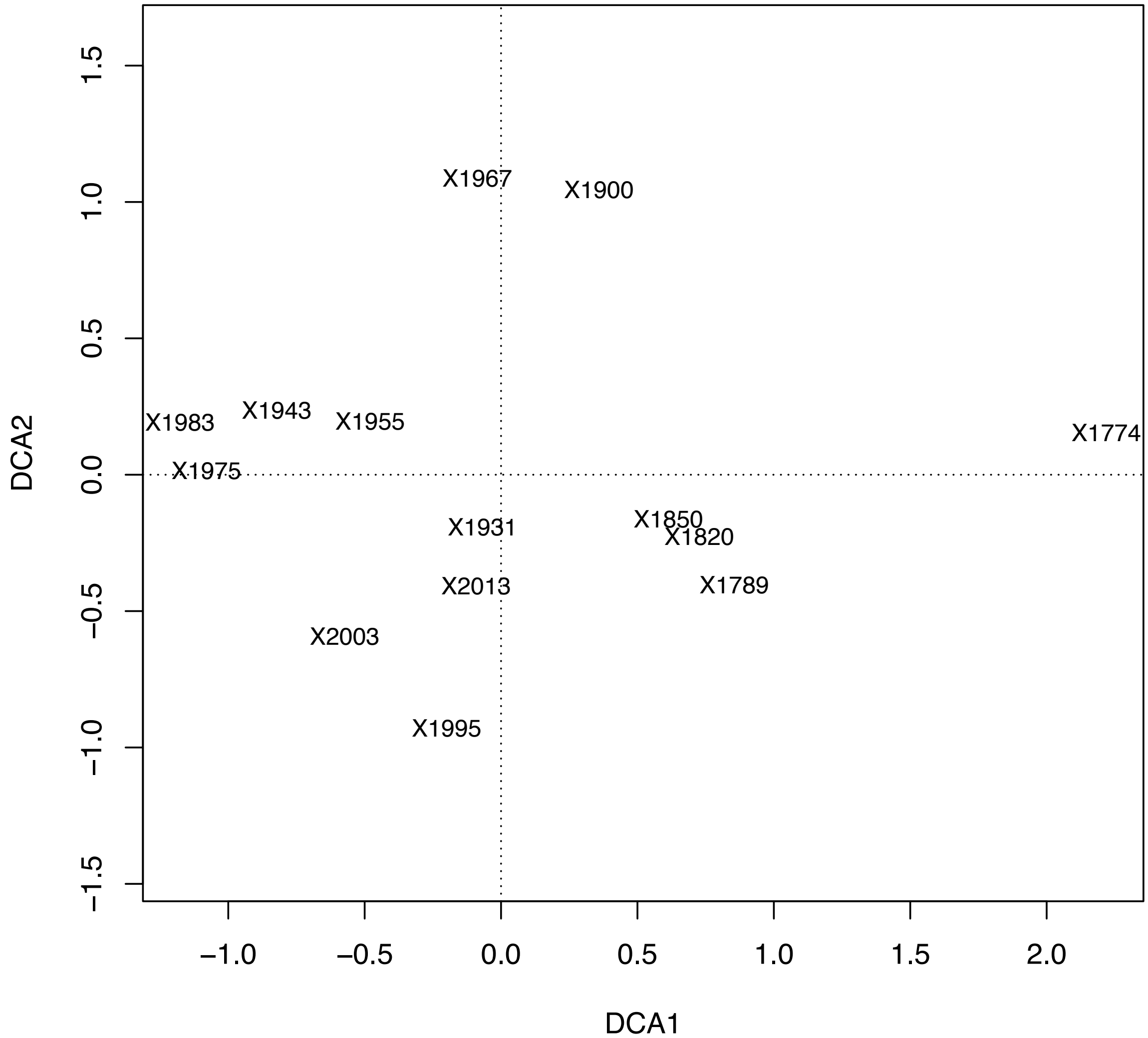

Figure 4. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance) in Arctic Lake (1774-2013).

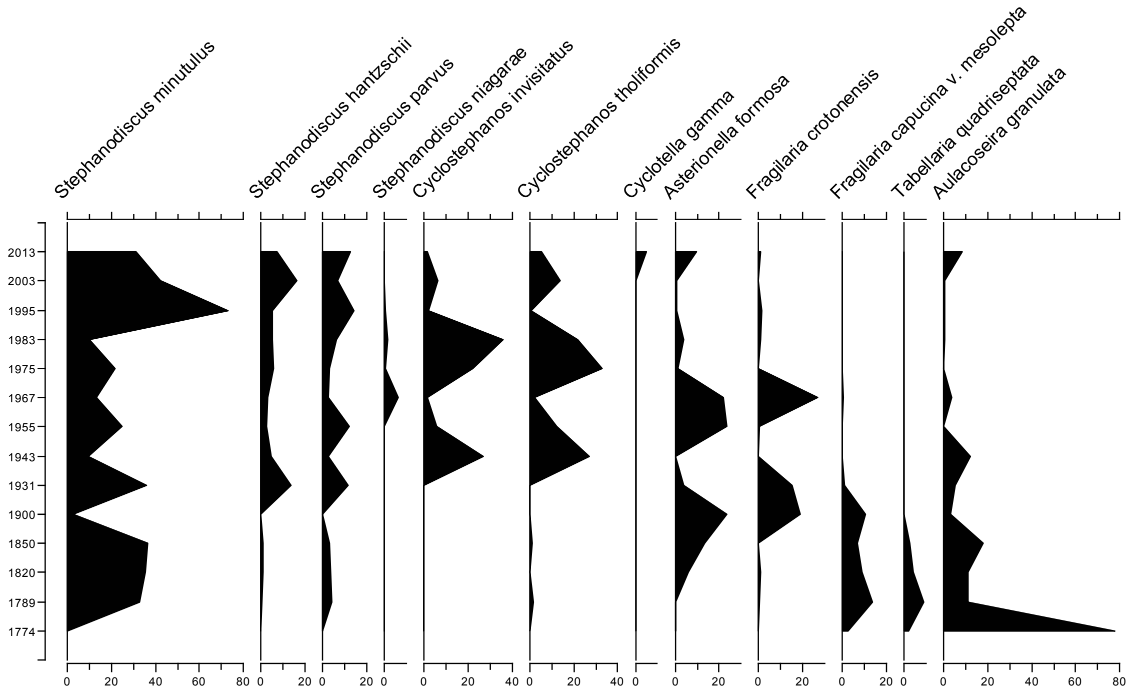

Figure 5. Ratio of chrysophyte cysts to diatom valves in the Arctic Lake core.

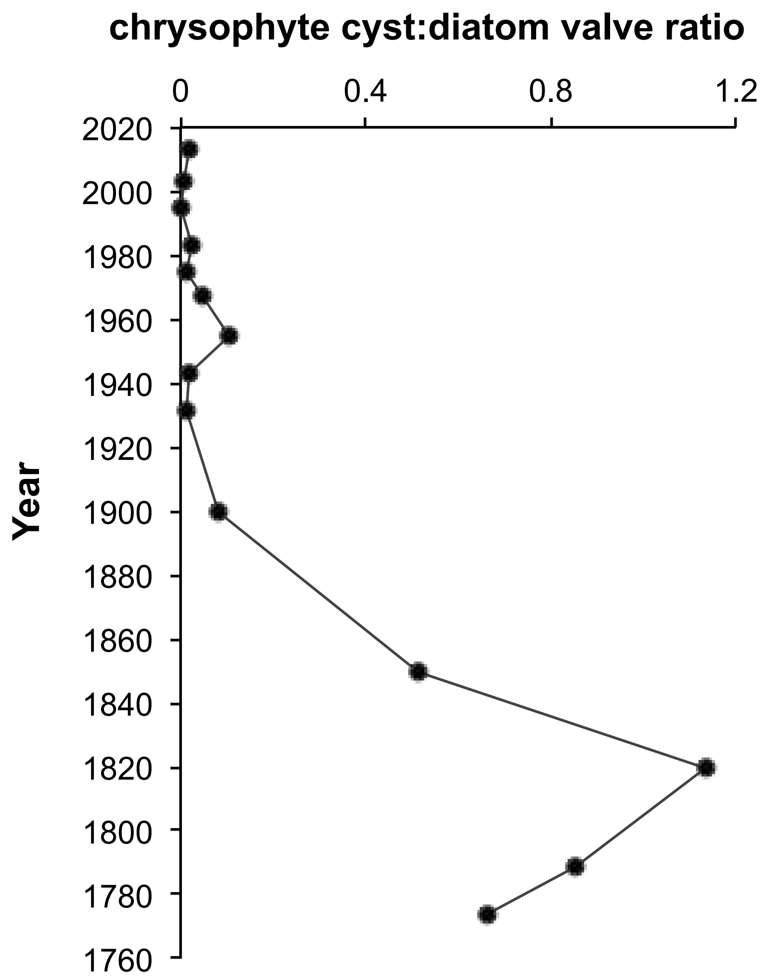

Figure 6. The core sections from Arctic Lake projected onto the MN calibration set. Symbols represent the 89 MN lakes in the calibration set, environmental vectors are shown on the inset plot. Note that logTP is strongly correlated with Axis 1.

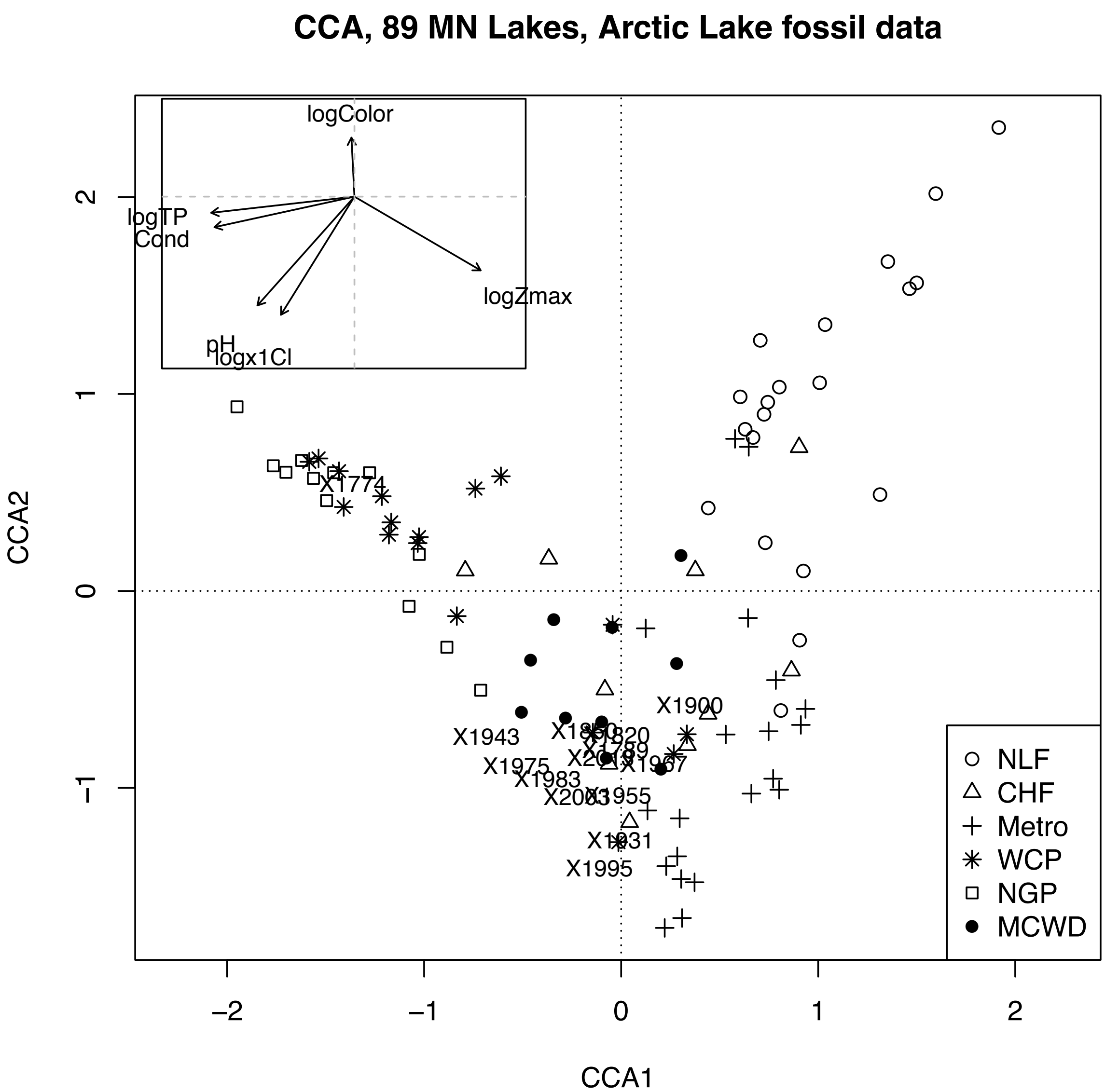

Figure 7. Diatom-inferred total phosphorus (TP) reconstruction for Arctic Lake. Reconstruction is shown as log TP (left panel) and as backtransformed values in micrograms per liter (right panel). Error estimates on log TP are plus and minus the root mean square error of prediction from the TP transfer function.

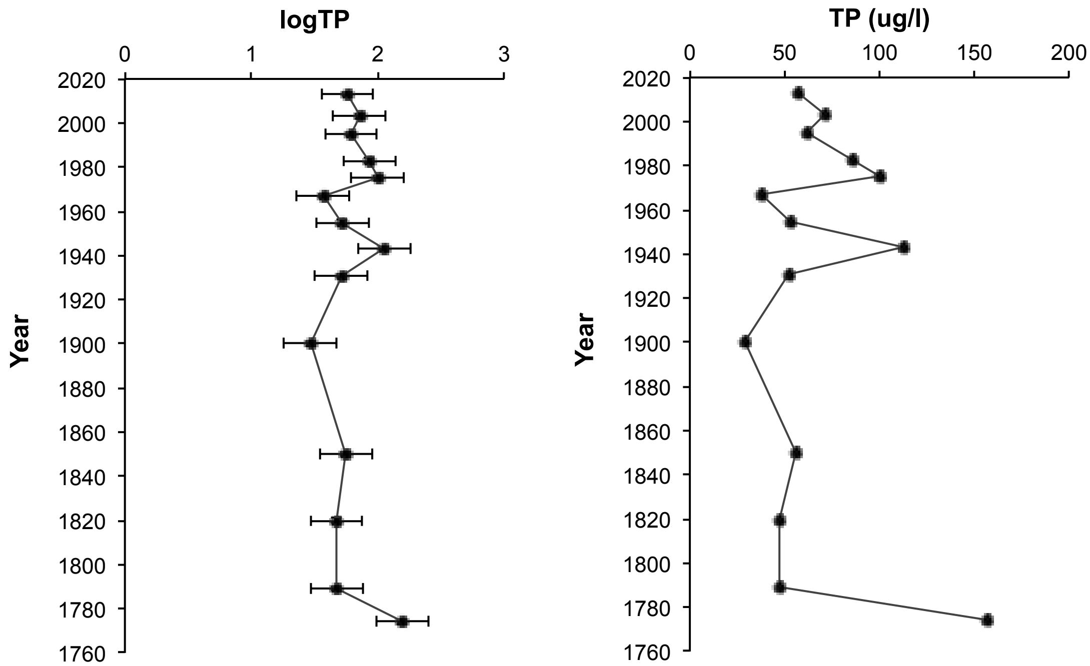

Figure 8. The sediment algal pigments quantified in five core sections from Arctic Lake. The group of algae associated with each pigment is shown along the x-axis. Pigment concentrations are reported as ug per g organic matter.