PALEOLIMNOLOGICAL ANALYSIS OF SILVER LAKE, HENNEPIN COUNTY, MINNESOTA

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SUMMARY

1. Paleolimnological techniques were used to reconstruct the trophic and sedimentation history of Silver Lake in Hennepin County, Minnesota.

2. Two overlapping sediment cores were collected from the lake. 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. Subfossil diatoms in the sediments were analyzed to reconstruct changes in lake ecology and trophic state.

3. The sedimentation rate began to rise in the 1940s and continued to a peak in 2002. There was a decline in the sedimentation rate in the most recent samples, however the rate still remains approximately three times higher than it was in pre-settlement times.

4. The sediments were composed of primarily organic and inorganic material; the amount of carbonate was low throughout the core. The peak in sedimentation in the late 1990s/ early 2000s was driven largely by organic matter.

5. The diatom assemblage throughout the core was dominated by small *Fragilaria* species, which are well adapted to the habitats of shallow lakes. Other predominant species throughout the core suggest nutrient enrichment. The largest shift in the diatom community assemblage occurred in the 1920s; the change at this time corresponds with a period of drought in Minnesota, and the change in the diatom community could be related to lake level changes. A shift in the assemblage at the top of the core suggests increased nutrient enrichment in recent decades.

6. Analysis of the diatom community changes in conjunction with the MN diatom calibration set suggest that total phosphorus (TP) may be an important driver of change in the diatom community in Silver Lake. The TP reconstruction shows that the lake has been eutrophic over the past 200 years, with a slight rise in TP concentration in recent years.

7. Overall, Silver Lake seems to have been a eutrophic system over the past 200 years. The lake has a very high sedimentation rate; at its peak, the rate was four to six times higher than the pre-European settlement rate.

INTRODUCTION

Lakes are a prominent feature within the landscape of the glaciated regions of the Upper Midwest, 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.

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 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 Silver Lake in Hennepin 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.

Silver lake is near the town of Chanhassen in Hennepin County, MN; the lake is within the Riley Purgatory Bluff Creek Watershed District and one of the origins of Purgatory Creek. Silver Lake is shallow and eutrophic, with a small watershed. The region has a long history of changes to the landscape including post-settlement agriculture and transition to suburban development. Silver Lake is currently impaired for total phosphorus (TP) levels and does not meet state standards for shallow lakes in the NCHF ecoregion. The 2014 growing-season mean TP measurement in Silver Lake was 110 µg/l (http://www.rpbcwd.org/files/3814/2963/4179/Silver_Lake_Fact_Sheet_2014.pdf; December 11, 2015), well above the state standard of 60 µg/l for lakes in the North Central Hardwood Forest ecoregion. This impairment has led to questions about whether the productivity of the lake has changed over time, and how best to set management goals.

The primary aim of this project was to use paleolimnological analysis of a dated sediment core from Silver 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 to determine local sediment accumulation rates, geochemical analyses, and analysis of subfossil diatom 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 trophic 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).

METHODS - SEDIMENT CORING

A piston core was collected from Silver Lake on May 15, 2015. Upon initial lead-210 dating it was found that the core was not long enough to recover sediments from pre-settlement times. Therefore, on July 15, 2015 a second, longer, piston core was collected from the lake. Both cores were collected from the same area of the lake; the coring location represented a flat and one of the deeper areas of the basin, to provide a highly integrated sample of diatom community structure from the lake as a whole. Each piston core was taken using a drive-rod piston corer equipped with a 6.5 cm diameter polycarbonate barrel (Wright 1991).

The coring locations were at 44° 53.809' N, 93° 31.939' W, in 2.87 m of water and 44° 53.840' N, 93° 31.933' W, in 3.02 m, for the May and July cores respectively. The piston core collected in May recovered 1.8 m of sediment, and the July core recovered 2.07 m and in part overlapped the depth of the first core, for a total sediment depth of 3.37 cm. Each core was 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 (Dean 1974).

METHODS - LEAD-210 DATING

Twenty-six core sections were analyzed for lead-210 activity to determine age and sediment accumulation rate for the past 150 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).

METHODS - DIATOM AND NUMERICAL ANALYSES

Fifteen 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.

RESULTS AND DISCUSSION - GEOCHEMISTRY

The composition of the sediments from Silver Lake showed some fluctuations over the 300 cm length of the overlapping piston cores (Figure 1). The amount of carbonate in the core remained relatively constant, between 3 and 10%, with a slight rise in the bottom 10-15 cm of the core where it peaked at 20%. The largest fluctuations in the sediment composition were between the relative amounts of organic versus inorganic matter. At the core top, the sediments consisted of just over 30% inorganic matter and nearly 60% organic matter; moving downcore, the relative amount of inorganic matter increased and organic matter decreased, until they both reached about 46% at 108 cm. From 108 cm until about 258 cm, the predominant component of the sediment fluctuated back and forth between inorganic and organic matter. At the bottom of the core (258-300 cm), the composition of the sediments were similar to those at the core top, consisting of approximately 30% inorganic matter and about 60% organic matter.

RESULTS AND DISCUSSION - DATING AND SEDIMENTATION

The unsupported lead-210 activity, the resulting lead-210 dating model, and the sediment accumulation rate for Silver Lake are shown in Figure 2. The lead-210 activity showed a large decline at the core top and an overall decline throughout the rest of the core (Figure 2a). The sediment accumulation rate was lowest from the early 1800s until the 1940s, ranging from 0.03 to 0.06 g/cm^2 yr (Figure 2c). The rate steadily increased from the late 1940s until the early 2000s, with a peak sedimentation rate of 0.26 g/cm^2 yr in 2002; this peak sedimentation rate was four to six times higher than the rate prior to European settlement. In the most recent samples, the sedimentation rate declined from the peak in 2002, however the rate was approximately 0.19 g/cm^2 yr, which was still much higher than the pre-settlement rate.

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 3); sediment flux was calculated to the end of the lead-210 record (approximately 246 cm). This showed that the rise in sedimentation rate that began in the 1940s was driven by an increase in both organic and inorganic matter. The peak in sedimentation in the early 2000s was driven largely by organic material.

RESULTS AND DISCUSSION - DIATOM STRATIGRAPHY AND ORDINATION

The ordination biplot from the detrended correspondence analysis (DCA) show how the core samples cluster together based on similarity of diatom assemblage (Figure 4). With the exception of the sample from 1928, the diatom samples from the early 1800s through the 1990s clustered together. The samples from the 1990s through 2007 showed that there has been change in the diatom communities in recent decades. However, the largest change in species composition in the core was in the sample from 1928.

The stratigraphic diagram shows the predominant diatoms that were driving the shifts in the community assemblages (Figure 5). From the early 1800s through 1990, with the exception of the 1928 sample, the diatom assemblage was dominated by *Fragilaria lapponica* and other small *Fragilaria* species (*F. construens*, *F. construens* var. *venter*, *F. brevistriata* var. *inflata*, and *F. pinnata*). These species of *Fragilaria* are primarily benthic, but often suspended into the water column; many of these species are adapted to live on fine-grained sediments, such as those found in shallow lakes. The assemblage was also characterized by the planktonic diatoms *Aulacoseira granulata* and *Cyclostephanos tholiformis*, which are both indicative of nutrient enrichment.

In the 1928 sample there was a marked decline in the small *Fragilaria* species, and an increase in the benthic species *Nitzschia amphibia* and *Achnanthes minutissima*, as well as *Fragilaria capucina* var. *mesolepta*. In a large dataset of MN shallow lakes we found that all three of these species were associated with clear-water, macrophyte-dominated conditions (Ramstack Hobbs, unpublished data), so it is possible that there was an increase in macrophyte abundance in Silver Lake at this time. The timing of this change corresponds with a time of drought conditions in MN; the lower lake level during this time may have allowed for increased macrophyte growth.

In the most recent samples (1990s to 2015) there was an increase in the planktonic *Stephanodiscus minutulus* and *Cyclostephanos* species (Figure 5); in our dataset of MN shallow lakes, these species were associated with turbid, phytoplankton-dominated conditions (Ramstack Hobbs, unpublished data). There were also slight increases in other planktonic species at the core top, such as *Fragilaria crotonensis* and *Aulacoseira ambigua*, which are also associated with nutrient-rich conditions.

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 Silver 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 showed that for Silver Lake, there was change along the TP gradient (associated with axis 1), however, there was about the same amount of movement along axis 2 (Figure 6). This suggests that while nutrients may be driving some of the change in Silver Lake, there are other drivers that are equally important in influencing diatom community turnover. Alternative drivers include: habitat alterations, changes in turbidity due to sediment load, or other stressors that were not measured in the calibration set. It is possible that the drivers of ecological shifts change over time, meaning that TP may have been a more important variable during certain periods and less important during others.

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 (a maximum value of 1.0 would mean that TP was the best explanatory variable of diatom community change) (Juggins et al. 2013). In Silver Lake the fraction of the maximum explainable variation in the diatom data that can be explained by TP was 0.55. This again suggests that TP was playing a role in the diatom community change, but that other factors were important as well.

The TP reconstruction for Silver Lake suggested that it has been eutrophic throughout the period of study (Figure 7 and Table 2). The lowest TP concentrations (approximately 30 µg/l) were in the period from 1928-1949. The highest TP concentrations were at the core top (2007 and 2015 samples), although the concentrations are only slightly higher than at other times. The TP reconstruction at the core top was 65 µg/l, which is considerably lower than the modern measured value of 110 µg/l. The small *Fragilaria* species that dominate the Silver Lake core are often better indicators of habitat changes in lakes than nutrient level changes; therefore, the quantitative TP reconstruction should be interpreted with caution.

CONCLUSIONS

Based on the diatom ecology and sediment history of the past 200 years, the paleolimnology of Silver Lake can be described by four time periods:

Early 1800s to the 1920s

During this time period the sedimentation rate in Silver Lake was low and the diatom community assemblage was stable. The diatom assemblage suggests that the lake was eutrophic during this time, and contained species that we have found to be associated with turbid, phytoplankton-dominated conditions in MN shallow lakes.

1920s/1930s

In the late 1920s, the diatom community assemblage recorded a large shift, and became dominated by species that we associate with clear-water, macrophyte-dominated conditions in shallow lakes. The timing of this shift in the diatom ecology corresponds with a time of drought MN; it is possible that a lowering of the lake level during this time led to an establishment of macrophytes. The sedimentation rate remained low during this time period.

1940s to 1980s

During the 1940s the sediment accumulation rate began to increase dramatically and continued to rise throughout this time period. The diatom community assemblage reverted back to a very similar assemblage to the one that characterized the period from the early 1800s to the 1920s.

1990s to 2015

The sedimentation rate continued to rise during the 1990s, and in 2002 peaked at a rate that was four to six times higher than pre-settlement times. The sedimentation rate showed a decline in recent decades, but remained about three times higher than it was in the past. Beginning in the 1990s, the sediment flux to the core site changed from being driven equally by inorganic and organic matter, to more predominantly organic matter; this suggests a change in sediment source during these recent decades. During this time, there is a pronounced rise in diatom species that are indicative of nutrient enrichment.

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Table 1. Samples prepped for diatom analysis.

Depth (cm)	Lead-210 Date
2	2015
38	2007
76	1997
92	1991
110	1982
126	1971
136	1963
148	1955
156	1949
164	1941
172	1928
186	1906
200	1888
226	1860
246	1823

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

Lead-210 Date	Diatom-Inferred Total Phosphorus (μg/l)
2015	65
2007	73
1997	45
1991	64
1982	55
1971	47
1963	48
1955	47
1949	29
1941	33
1928	33
1906	43
1888	51
1860	58
1823	38

Figure 1. Percent dry weight of organic matter, inorganic matter, and carbonate (CaCO3) in the Silver Lake core plotted against core depth. Note that each fraction of the sediment is plotted for the two overlapping cores (Core1 = 0-176 cm; Core2 = 132-300 cm).

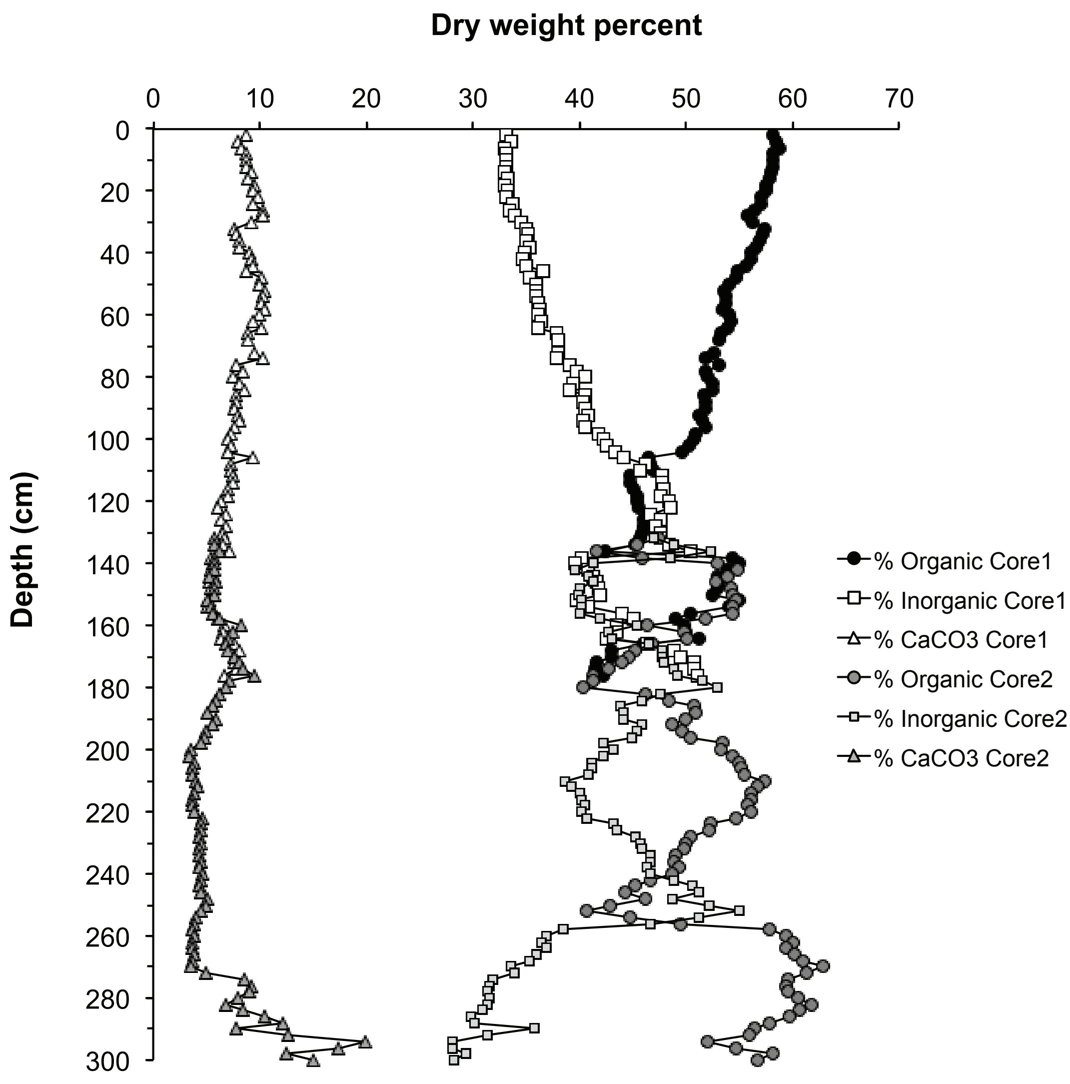

Figure 2. Unsupported lead-210 activity (a), lead-210 dating model (b), and sediment accumulation rate (c) for Silver Lake.

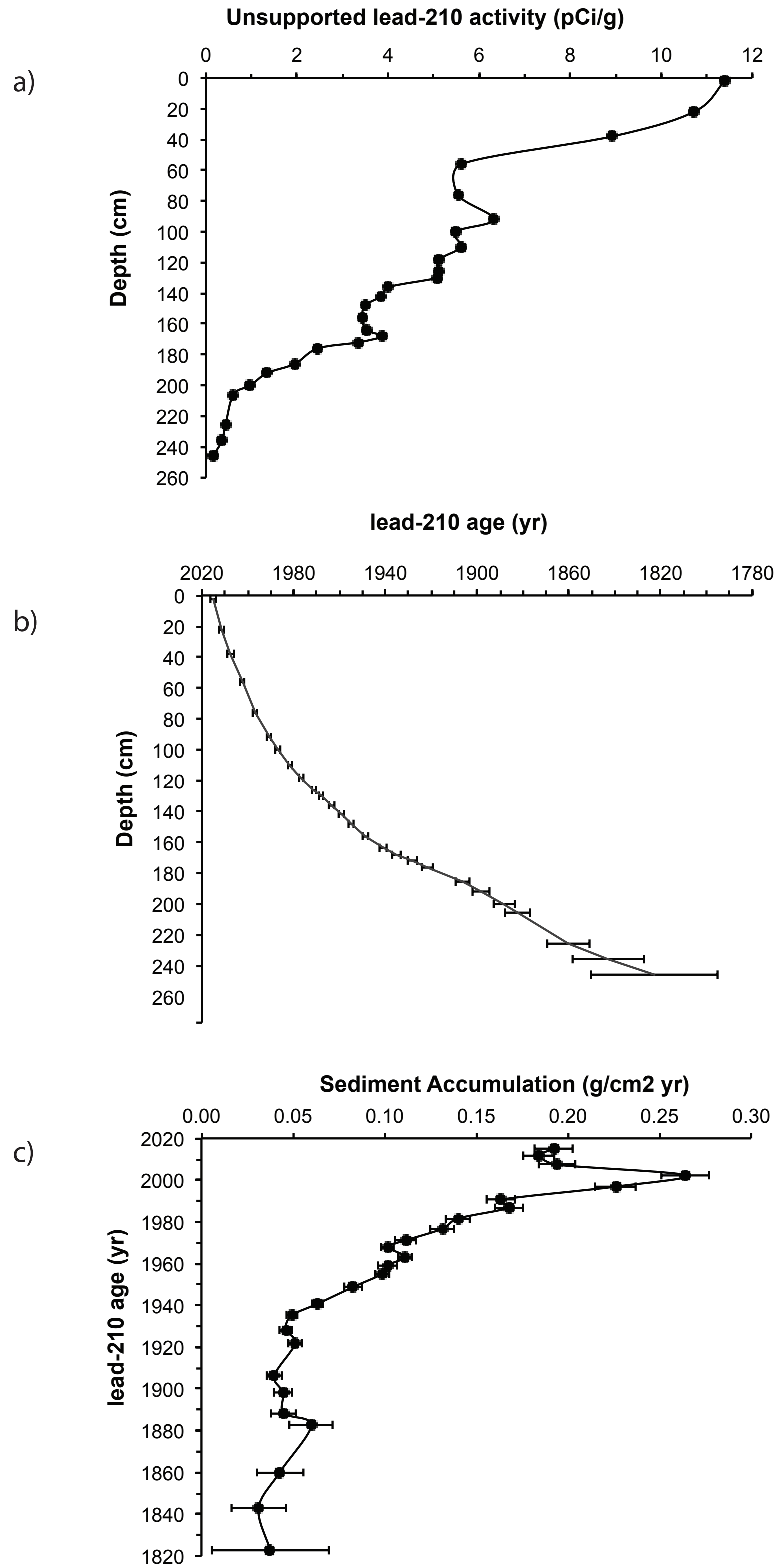

Figure 3. Sediment flux of organic matter, inorganic matter, and carbonate (CaCO3) to the Silver Lake core. Flux was only calculated for the length of core within the lead-210 record (0-246 cm).

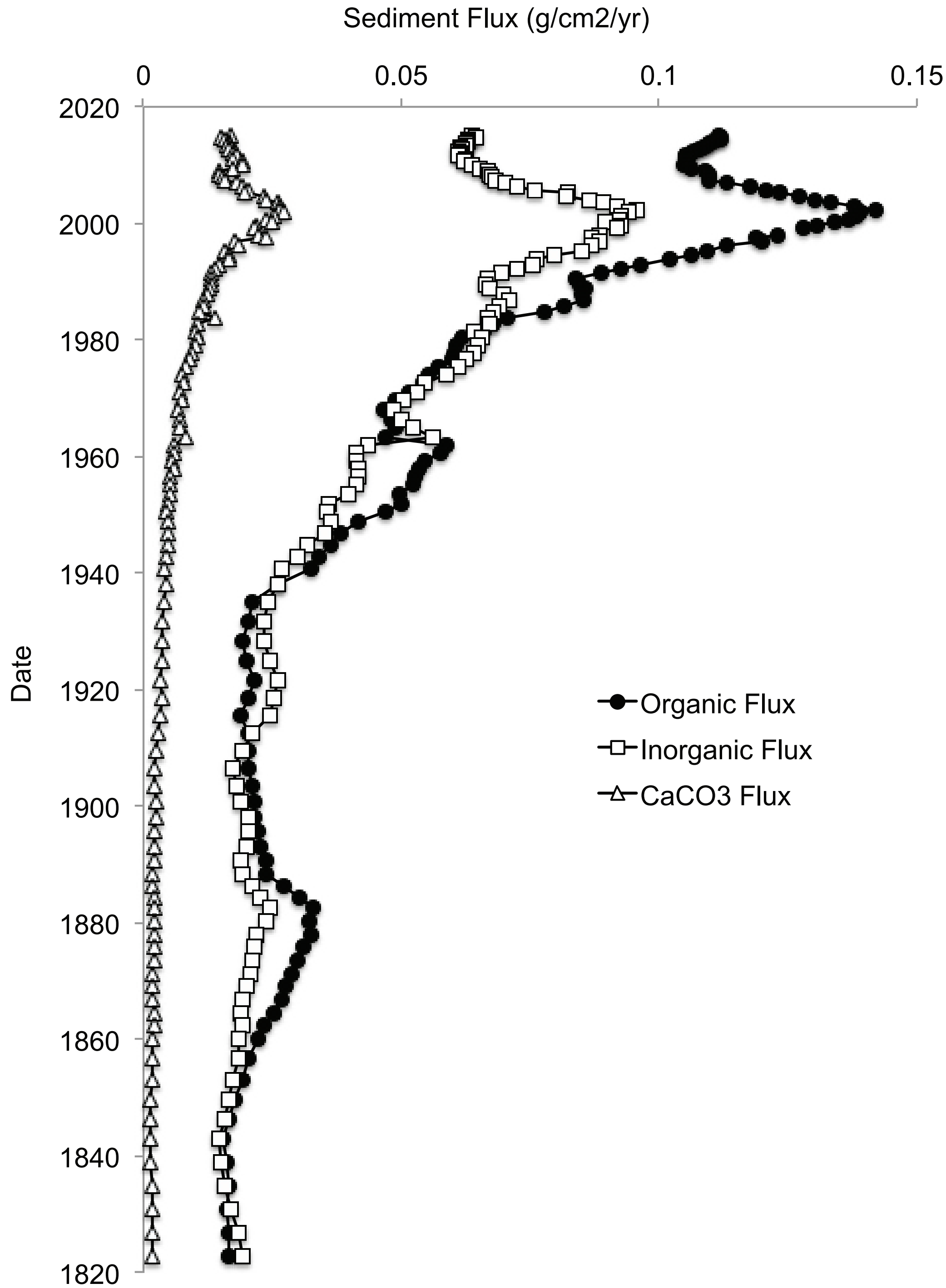

Figure 4. Detrended correspondence analysis (DCA) of diatom communities from Silver Lake.

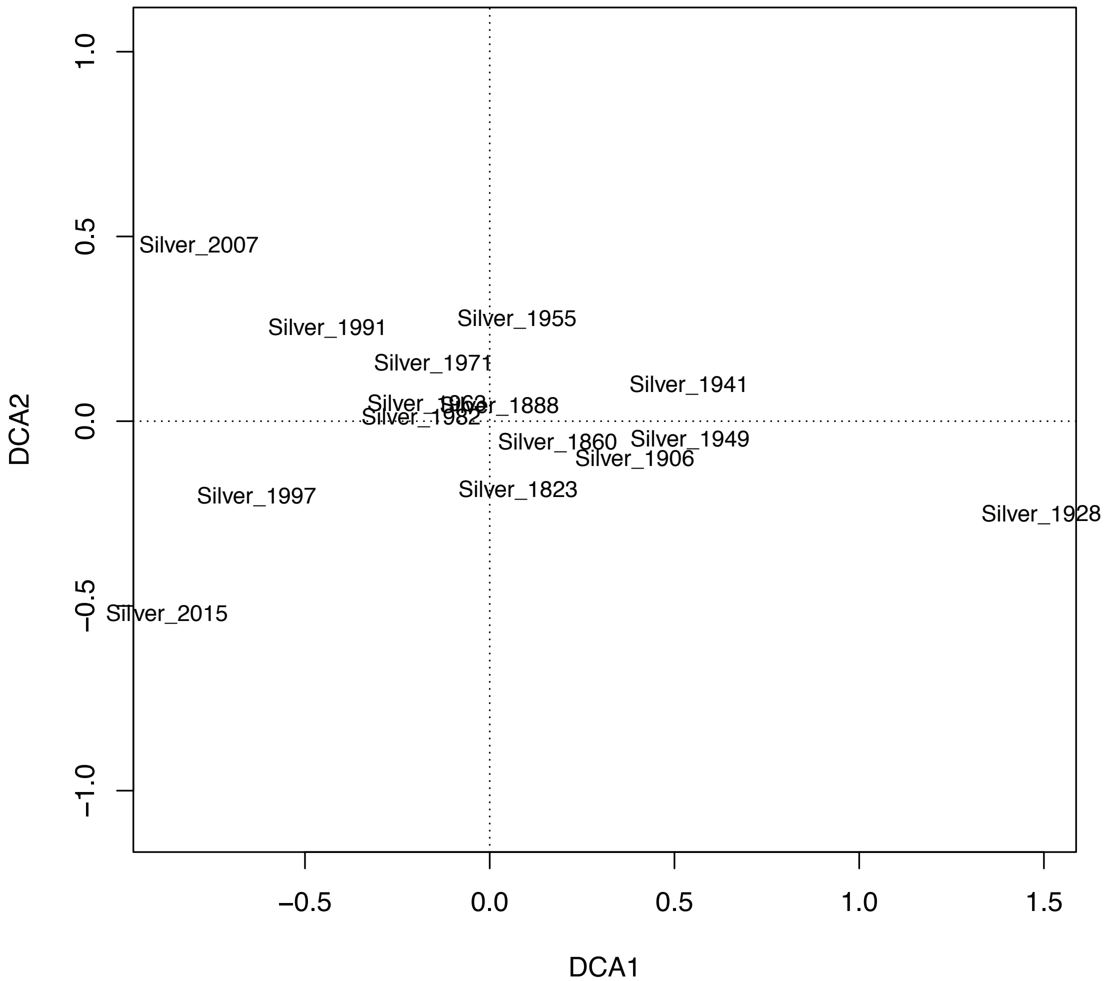

Figure 5. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance) in Silver Lake (1823-2015).

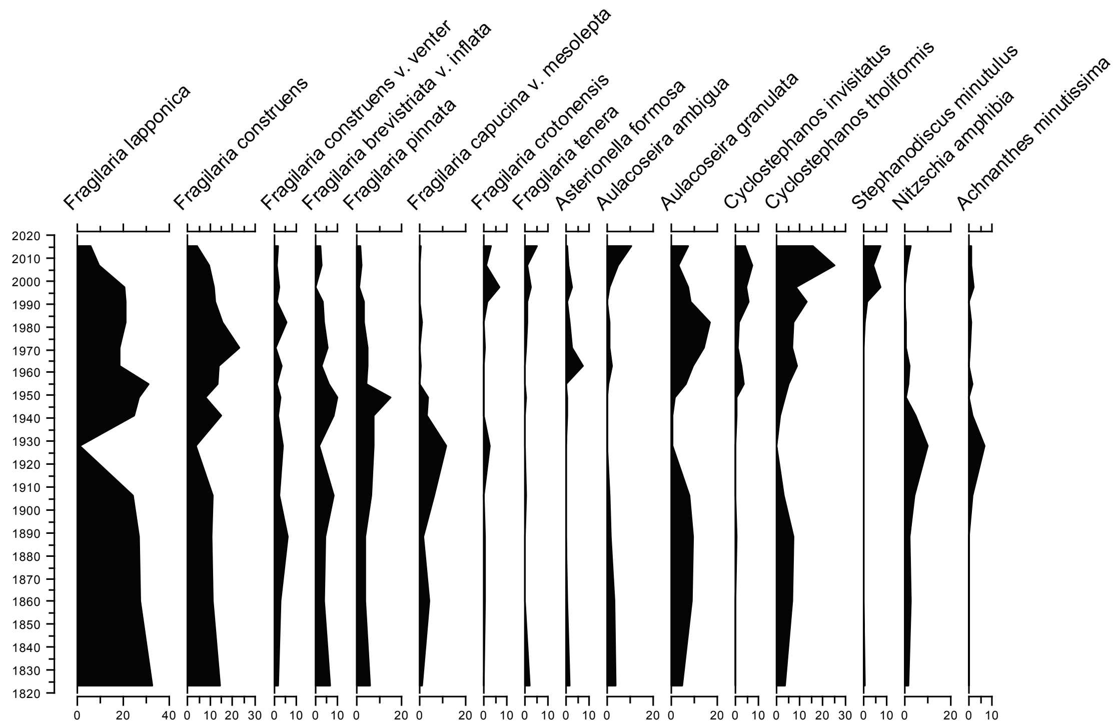

Figure 6. The core sections from Silver Lake projected onto the MN calibration set (denoted as Silver_core date). Symbols represent the 89 MN lakes in the calibration set, coded by region; NLF=Northern Lakes and Forests, CHF=Central Hardwood Forests, Metro=Twin Cities Metropolitan Area, WCP=Western Corn 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.

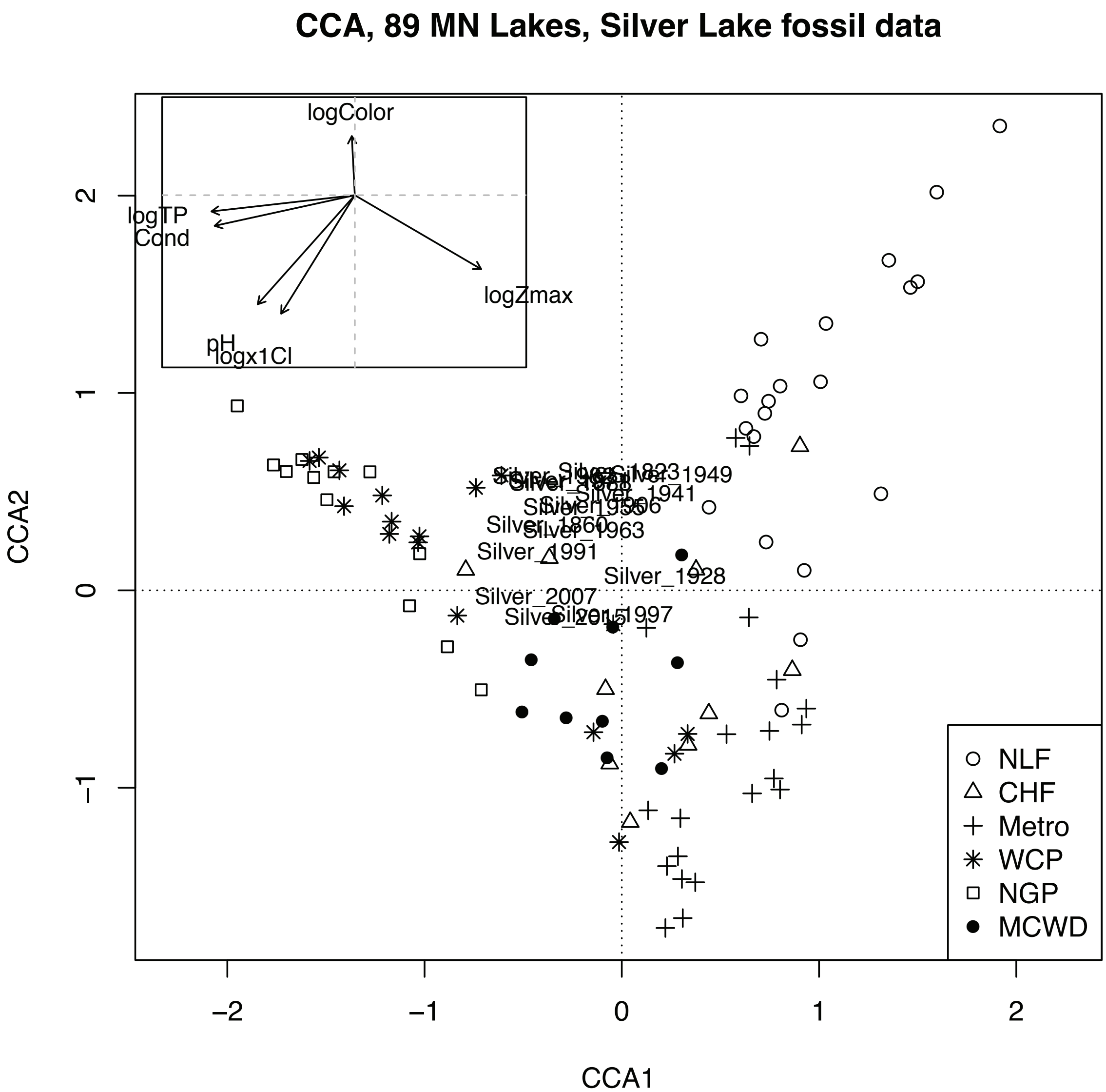

Figure 7. Diatom-inferred total phosphorus (TP) reconstruction for Silver Lake. Reconstruction is shown as log TP (left panel) and as backtransformed values in micrograms per liter (right panel). Error estimates on log TP are plus and minus the root mean square error of prediction from the TP transfer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