HISTORICAL WATER QUALITY, ECOLOGICAL CHANGE, AND SEDIMENTATION IN DEAN LAKE

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SUMMARY

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

2. Examination of aerial photos and a historic plat map shows that Dean Lake mostly dried out during the 1930s drought, but has otherwise retained nearly the same shoreline throughout the period of study.

3. Five sediment cores were collected from the lake, and lead-210 activity was analyzed to develop dating models for two of the cores. Sediments from all five cores were analyzed for inorganic, organic, and carbonate components using loss-on-ignition analysis. Subfossil diatoms and algal pigments were analyzed in sediments from the primary core to reconstruct changes in lake ecology and trophic state.

4. The sedimentation rate at the primary core site (core 5) shows two periods of increase, one in the early 1900s (driven by carbonates), and another from the 1970s/1980s to the present (driven by inorganic matter). The lead-210 activity profile from the secondary core (core 2) had a hiatus during the drought years of the 1930; it was possible to model dates from the 1940s to the present in this core, assuming a constant sedimentation rate.

5. Synchronous changes in LOI and magnetics profiles allowed the dating model from core 5 to be applied to core 4 (eastern basin) and the model from core 2 to be applied to cores 1 and 3 (western basin). Rough calculations of sediment load to Dean Lake were made over three time periods (1945-1985, 1985-2000, and 2001-2014) that were chosen to examine changes after major hydrologic alterations to the watershed. These calculations show that the average annual sediment load to Dean Lake has increased over each of these time periods.

6. The largest change to the diatom community assemblage occurred in the early 1900s, and coincided with the increase in carbonate flux. Diatom-inferred reconstructions suggest the shift was associated with an increase in TP and pH.

7. Overall algal production started to increase around the 1930s, and continued to increase to the present, with a large spike in production in top most sediment dated to 2014.

8. Overall, it appears that the hydrologic alterations to the Dean Lake watershed in the 1980s are correlated with an increased sediment load and increases in algal production. It does not appear that measures put in place in 2000 to ease the sediment load to Dean Lake are slowing these trends, although it is possible that it’s too soon to see the effects.

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 Dean 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.

Dean Lake has had substantial hydrologic alterations over the past century. Aerial photos suggest that the lake nearly dried out during the 1930s (Appendix A), but appears to have recovered with a similar shoreline since the 1940s (Appendix B). In the 1980s, an outlet system from the downstream watershed of Prior Lake was constructed; this connected Dean Lake and greatly increased the surface water inputs to the lake (Paul Nelson, personal communication). In the 2000s, a bypass was constructed, routing some of the flow around Dean Lake (Paul Nelson, personal communication). These hydrologic alterations have led to questions about whether the biological, specifically the algal, communities have been affected by these changes. Moreover, how has the productivity of the lake changed over this time period?

Dean Lake is currently impaired for total phosphorus (TP); the average of the past 10 years of summer samples analyzed for Total Phosphorus (TP) is 298 μg/l, well above the state standard of 60 μg/l for shallow lakes in the North Central Hardwood Forest ecoregion (http://cf.pca.state.mn.us/water/watershedweb/wdip/waterunit.cfm?wid=70-0074-00; December 1, 2014). 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 multiple sediment cores from Dean Lake to reconstruct its ecological and sedimentation history. Analytical tools included radioisotopic dating of the cores, geochemical analyses to determine local sediment accumulation rates, analysis of subfossil diatom communities, and quantification of algal pigments. 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 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. cyanobacteria or 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.

In order to assess more accurately the whole basin accumulation of sediment and how this may have changed over the period of hydrologic alteration, five sediment cores were collected from Dean Lake. In complex lake basins such as Dean, previous studies have shown that relying on a single sediment core for inferences of sediment loading can be problematic (Engstrom and Rose 2013). Therefore, the additional sediment cores in this study provide a more complete picture of sediment accumulation in Dean Lake.

METHODS - STUDY SITE AND SEDIMENT CORING

Examination of historical aerial photos suggests that Dean Lake dried out in the 1930s (Appendix A) and that the basin had refilled to its present-day shoreline by the 1940s (Appendix B). The plat map from 1855 shows Dean Lake with a similar shoreline to the present day (Appendix C). Therefore, the assumption was made that the drying event was limited to the drought years of the 1930s, and that the lake basin has been approximately that of the present day throughout the rest of the period of study.

Five piston cores were collected from Dean Lake on May 2, 2014 using a drive-rod piston corer equipped with a 6.5 cm diameter polycarbonate barrel (Wright 1991). The cores were collected along a transect from the northwest to southeast end of the basin (Figure 1). The location of each core, the water depth at the coring sites, and the amount of sediment recovered are provided in Table 1. Immediately following collection, the upper flocculent sediments and core-water interface were stabilized using Zorbitrol, a gelling agent (Tomkins et al. 2008). All cores were returned to the laboratory and stored at 4°C.

Core 5 was collected from a deep, flat area of the basin. It was determined that this core would be the most representative of the basin as a whole, and would provided a highly integrated sample of algal abundance. Therefore, Core 5 was designated as the primary core in this study, it was lead-210 dated, and all diatom samples were taken from this core; algal pigments were analyzed from Core 4, which was well aligned by magnetics and geochemistry with Core 5, because fresh material was needed for pigments and had been exhausted from the supply of Core 5 material. Core 2 was selected as the second core for lead-210 dating.

METHODS - MAGNETIC SUSCEPTIBILITY LOGGING

Magnetic susceptibility provides a non-destructive measure of relative quantity and size of ferro-magnetic minerals. Increases in magnetic susceptibility signatures may be correlated with land use changes including land clearance, increased terrestrial-derived sediments, and paleosols.

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. 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 - GEOCHEMISTRY

Weighed subsamples were taken from regular intervals throughout each of the five cores 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

Sixteen sections from the primary sediment core (core 5) and ten sections from the secondary core (core 2) 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 (Appleby and Oldfield 1978); dating and sedimentation errors were determined by first-order propagation of counting uncertainty (Binford 1990). Profiles of unsupported lead-210 activity were examined in the two cores (Figures 2a and 3a), and led to different models being chosen to determine the sedimentation rate and age in each core.

Core 2 appears to have a hiatus in the lead-210 profile at approximately 40 cm, below which there is a sharp drop in activity to background (supported lead-210) levels. This hiatus violates the assumption of the frequently used c.r.s. (constant rate of supply) model by not having a constant rate of supply of lead-210 to the coring site. The interruption in sedimentation is presumably due to the drying of the lake during the 1930s. The activity profile for the upper part of core 2 (0-40 cm) is exponential, indicating fairly constant sediment accumulation during this part of the record (Figure 2a). This allowed the cf:cs (constant flux: constant sedimentation) model to be applied to the upper portion of core 2, and dates were not able to be obtained for the lower portion of this core (Appleby and Oldfield 1983).

The hiatus in activity seen in core 2 was not found in core 5, and core 5 appears to have a near-complete lead-210 profile (Figure 3a). This indicates that Dean Lake did retain some wet areas (e.g. core site 5) during the 1930s drought. The c.r.s. model was therefore applied to core 5 to determine age and sedimentation rates for the length of the core (Appleby and Oldfield 1978). Lead-210 dates prior to the early 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.

As a further check of dates in core 5, cesium-137 was also quantified in seven core sections. Cesium-137 is an isotopic product of atmospheric nuclear bomb testing; its presence indicates sediments deposited after 1950 and its peak concentration occurs in 1963 when atmospheric testing was banned. In core 5, the cesium-137 peak occurs at 29 cm; this fits almost perfectly with the lead-210 date at this interval (1966; Figure 3b), which lends support to the c.r.s. model being applied to core 5.

METHODS - DIATOM AND NUMERICAL ANALYSES

Fifteen samples from the primary sediment core (core 5) were analyzed for diatoms. See Table 2 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.

Diatom community turnover was closely aligned with the pH axis in the MN calibration set; therefore, a pH transfer function was also applied. The pH model was evaluated in the same way as the logTP model (r^2=0.77, RMSE=0.278, RMSEP=0.337).

METHODS - ANALYSIS OF ALGAL PIGMENTS

Ten samples from Core 4 were analyzed for fossil pigments; fresh and frozen sediment stored under N_2 is needed for pigment analysis and all material from Core 5 had been freeze-dried for other analyses. Approximate dates of sediment sections in Core 4 were estimated using alignment with the magnetic and geochemical profiles from Core 5. Carotenoids, chlorophylls, and derivatives were extracted (4°C, dark, N_2) following freeze-drying according to Leavitt et al.

(1989), measured on a Hewlett-Packard model 1050 high performance liquid chromatography system, and are reported relative to TOC (Hall et al. 1999).

RESULTS AND DISCUSSION - MAGNETIC SUSCEPTIBILITY LOGGING

All five of the cores show a steady decline in magnetic susceptibility from 20-30 cm to the core top (Figure 4). Decreases in magnetic susceptibility can result from increased autochthonous productivity, for example from lake eutrophication. Cores 4 and 5 both have a peak in magnetic susceptibility at approximately 45 cm; the increase from the core bottom to the peak could be due to increases in terrestrial derived sediments. The relatively similar magnetics profiles in cores 4 and 5 also indicate that sedimentation patterns may be uniform in this eastern portion of the basin.

RESULTS AND DISCUSSION - GEOCHEMISTRY

The loss on ignition profile in each of the five cores shows that the sediment composition was similar across the basin in the earliest part of the record (prior to approximately 20 cm in cores 1, 2 and 3 and approximately 30 cm in cores 4 and 5) (Figure 5).

As seen in the magnetics profiles, there again appears to be synchronicity in the loss on ignition profiles in the eastern portion of the basin (cores 4 and 5; Figure 5). Both of these cores show that below 30 cm the sediment composition was dominated by carbonates. The timing of decrease in carbonates differs slightly between cores 4 and 5, although both record a significant change in sediment composition at approximately 30 cm. From 30 cm to the core top, inorganic matter becomes the primary component (near 40%) of the sediment composition in these two cores.

Cores in the western portion of the basin (cores 1, 2 and 3; Figure 5) also consist primarily of carbonates in the lower portions of the core. These cores also show a dramatic change in sediment composition, with a sharp decline in the relative amount of carbonate; however, in this western portion of the basin that change occurs between 15-20 cm, as opposed to 30 cm in the eastern basin. The other difference between the two basins is that after the sharp decline in carbonates, the relative amount of carbonate increases again in cores 2 and 3. In core 1, organic matter predominates at the core top, as opposed to inorganic matter in the eastern basin cores.

RESULTS AND DISCUSSION - DATING AND SEDIMENTATION

Primary Core (Core 5)

For core 5, the unsupported lead-210 activity, lead-210 dating model, and sediment accumulation rate from the c.r.s model are shown in Figure 3. The sedimentation rate in core 5 is low through the 1800s, averaging 0.03 g/cm^2 yr (Figure 3c). The rate begins to rise in the early 1900s, and averages 0.08 g/cm^2 yr from the 1920s through the 1960s. In the 1970s there is another increase in the sedimentation rate, and this steady rise continues to a peak of 0.14 g/cm^2 yr in the sample dated at 2011. The most recent sample (2014), suggests that the rate may be tapering off at 0.14 g/cm^2 yr; but with just one sample it can't be discerned if this is a true change in the upward trend.

The flux of sediment to core 5 was calculated by multiplying the fraction of each component of the sediment (organic, carbonate, inorganic) by the sedimentation rate at that interval (Figure 6). This shows that the initial rise in sedimentation rate in the early 1900s was driven primarily by an increase in carbonates, and the more recent rise in sedimentation rate (1970s-2010s) was driven primarily by inorganic material.

The increase in carbonates in the early 1900s could have been washed in from the watershed, or formed within the lake. The mechanism for in-lake production of carbonates can be related to algal productivity and lake temperature.

The timing of the rise in sedimentation rate in the 1970s, which was driven by inorganic (mineral) material, is likely the result of the hydrologic changes put into place in the 1980s when the outlet system from Prior Lake was constructed, increasing the surface water inputs to Dean Lake. There is a slight discrepancy in the timeline from the known changes in the 1980s and changes in the core dating in the 1970s; however, this small offset may be due to errors associated with modeling the core dates. The indication that the sedimentation rate may be leveling off at the core top, instead of continuing to increase, suggests that the bypass constructed in 2000 to route some of the flow around Dean Lake could be having an effect. However, with only one sample it is not possible to determine if the trend toward increased sedimentation is truly reversing.

Secondary Core (Core 2)

The unsupported lead-210 activity, and resulting dating model for core 2 are shown in Figure 2. The cf:cs (constant flux: constant sedimentation) model used for core 2 assumes a constant sedimentation rate, which was calculated to be 0.13 g/cm^2 yr for 1943 to 2014 (0-40 cm).

Entire Basin

Due to synchronous changes in LOI and magnetics profiles, the dates and sedimentation rates calculated for core 2 were applied to core 1 and core 3 (the western portion of the basin), and dates and sedimentation rates calculated for core 5 were applied to core 4 (the eastern portion of the basin). Extrapolating the dating models in this way allows for rough calculations on sedimentation patterns throughout the basin.

Sedimentation rates throughout the basin were evaluated over three time periods, to correspond with major hydrologic alterations in the watershed. The first time period, 1945-1985, represents conditions in the lake after refilling from the 1930s drought and before any major hydrologic changes; the second time period, 1985-2000, represents the period after the outlet system from Prior Lake was constructed, during a period of increased surface water inputs to the Dean Lake; the third time period (2000-2014) represents the time period after the bypass was constructed, which routed some of the flow around Dean Lake. Google Earth Pro was used to determine the surface area of each basin (outlined in Figure 1; Table 3). The bathymetry of Dean Lake is unknown (Paul Nelson, personal communication), therefore a “bathtub” basin shape was assumed for these rough calculations of sediment accumulation. Because these are rough calculations, errors associated with each measurement have not been quantified; therefore, it is important to focus on overall trends.

An examination of sedimentation patterns at each of the five cores sites shows that the largest volume of sediment per year is accumulating in the basin associated with core site 4, which does have the largest surface area of any of the sub-basins (Figures 1 and 7a). In basins 4 and 5, the average amount of sediment accumulating per year has increased over each of the time periods. This suggests that the hydrologic alterations in the 1980s have affected the sediment load to Dean Lake, and that the bypass constructed in 2000 has not reversed the increasing trend, although it could be too soon to see the effects. The cf:cs dating model that was used for core 2 (and applied to cores 1 and 3) assumes a constant sedimentation rate over time; this is why there is no time trend for the core sites in the western portion of the basin. If the assumption of a constant sedimentation rate since the 1940s in the western portion of the basin is true (inferred from the nearly exponential decline of supported lead-210), it means that the hydrologic alterations have primarily affected the sediment load in the eastern portion of the basin. This conclusion is also supported by the sediment composition (Figure 5). In the western basin cores, the most recent sediments are primarily composed of organic material or carbonates, suggesting a predominance of in-lake production. The sediments in the eastern basin are primarily composed of inorganic (mineral) material, suggesting that allochthonous inputs are contributing to the bulk of the sediment load.

Combining the sediment accumulation from sites 1, 2, and 3 and sites 4 and 5, reveals differences in patterns between the western and eastern sides of the basin. The western and eastern portions of the basin are roughly equal in surface area (western = 46% of the surface area, eastern = 54%). Figure 7b shows that prior to hydrologic alterations (1945-1985), sediment accumulation was greater in the western basin; this trend reversed after 1985, and the sediment load has continued to increase from 2000-2014. Figure 7c shows the Dean Lake basin as a whole, with the sediment load steadily increasing over the three time periods, from an average of 382 metric tons per year during the period before hydrologic alterations, to 495 metric tons per year during the most recent time period (2000-2014). This upward trend suggests that the hydrologic alterations made in the mid-1980s have increased the sediment load in Dean Lake, and the efforts to divert surface flow from Dean Lake in the early 2000s do not appear to have decreased the sediment load to the lake.

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 8). The largest change in the community assemblage occurs between the 1912 and 1926 samples. This change corresponds with an increase in sedimentation rate in the primary core, which was largely driven by an increase in carbonates (Figures 3c and 6). The changes on the DCA show a progression of the diatom community throughout the core; however, the largest change does not correspond with the hydrologic alterations in the watershed.

The stratigraphic diagram shows the predominant diatoms whose abundances are driving the shifts in the community assemblage (Figure 9). From the late 1700s until the early 1900s, the diatom community assemblage was dominated benthic species and tychoplanktonic species (those that can be swept into the plankton by chance events, such as turbulence). The species that are predominant in this lower portion of the core include *Nitzschia amphibia*, *Navicula minima*, *Fragilaria pinnata*, *Fragilaria construens*, and *Fragilaria brevistriata* variety *inflata*. The largest shift in the diatom community assemblage occurs in the 1920s, when planktonic diatoms such as *Aulacoseira* species and *Fragilaria capucina* variety *mesolepta* rise in abundance. There is also a continuous rise in the abundance of *Cocconeis* species, which are associated with aquatic plants.

RESULTS AND DISCUSSION - PHOSPHORUS and pH RECONSTRUCTIONS

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 Dean 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 shows that there is change along the TP axis (closely correlated with Axis 1) in the calibration set (Figure 10). It's also clear that there are other factors affecting changes in the diatom community assemblage; much of the change is correlated with the pH axis, suggesting pH changes as a possible driver. In addition, changes may be due to habitat alterations or other stressors that were not measured in the calibration set.

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 Dean Lake, this analysis shows that the fraction of the maximum explainable variation in the diatom data that can be explained by TP is 0.65. Although the diatom-inferred TP values at the core top place Dean Lake within the eutrophic range (Figure 11), they are well below the modern measured average of 298 ug/l. TP reconstructions can be problematic in shallow lakes as other drivers, such as habitat change, often play a large role in diatom community change. Statistical evaluation of the results, in conjunction with what is known about the ecology of the lake and the species present, suggest that it is plausible to reconstruct TP from the Dean Lake diatom assemblage; however, the TP reconstruction should be interpreted with caution, since there appear to be factors other than TP that are having an influence on changes in the diatom community assemblage.

The TP reconstruction indicates that Dean Lake was in the mesotrophic to slightly eutrophic range from the late 1700s through the early 1900s (Figure 11). TP levels began to rise in the 1920s, coinciding with the increase in sedimentation rate at this time. The TP concentration peaks in the early 1980s, and then levels off (and even shows signs of slightly declining) through the present. This suggests that the hydrologic alterations beginning in the 1980s were not the initial driver of the rise in TP in Dean Lake.

Since diatom community turnover in the Dean Lake core was closely aligned with the pH axis in the calibration set (Figure 10), a pH transfer function was also applied to the core. The pH reconstruction was evaluated in the same manner as the logTP reconstruction, and it was found that the fraction of the maximum explainable variation in the diatom data that can be explained by pH is 0.81. Note that the fractions of maximum explainable variation for logTP and pH total greater than 1.0 due to interactive effects of the two variables. Present day monitoring of Dean Lake has not included pH measurements, but the abundance of *Nitzschia amphibia* in the record supports the finding that the alkalinity of the lake has been high throughout the record.

When the pH reconstruction is plotted alongside carbonate flux, there appear to be temporal similarities in the profiles (Figure 10). There are increases in diatom-inferred pH in the 1930s and 1940s, and again from the 1970s to the present, both corresponding with increases in carbonate flux. The correlation of these two variables lends support to the conclusion that the carbonate flux in Dean Lake is primarily a product of in-lake production. The mechanism being that primary production (photosynthesis) increases, likely from nutrient inputs (diatom-inferred logTP shows an increase in the 1920s/1930s), in alkaline systems the increase in production consumes $CO_{2[aq]}$, and inorganic carbon becomes predominately bicarbonate (HCO_3^-) or carbonate (CO_3^{2-}) along with an increase in pH. Under these conditions carbonates can readily combine with Ca^{2+} to form $CaCO_3$ or calcite; in warm summer lake water the solubility of calcite decreases, leading to a solid calcite crystal in the water that is then deposited on the lake bottom. Calcite is more than likely the type of carbonate deposit found in Dean Lake. During significant peaks in productivity CaCO3 can be visible in the water column, giving these events the name “whiting events.”

RESULTS AND DISCUSSION - HISTORICAL ALGAL COMMUNITIES AND PRODUCTION

Algal pigments were quantified in ten Core 4 sections to give an idea of the historical concentration or production of different algal groups (Figure 13). The concentrations of beta-carotene and chlorophyll *a* represent total algal production, and suggest that production was low until the early- to mid-1900s, at this time there was a steady increase in production, with a spike in the most recent decade. This same pattern is reflected in each of the algal groups analyzed (cyanobacteria, cryptophytes, and diatoms). The potentially toxic form of cyanobacteria (myxoxanthophyll) was not detected in the Dean Lake sediments. The nitrogen-fixing form of cyanobacteria (aphanizophyll) followed a slightly different pattern than the other algal groups, with its peak concentration occurring in the 1990s, and no detection in recent samples.

The algal pigment data show that there have been rises in algal production since the time of hydrologic alterations in the Dean Lake watershed. However, the initial increases in pigment concentration predated these alterations, and more closely coincides with the increases in diatom-inferred TP.

CONCLUSIONS

The first large change in Dean Lake occurred in the early 1900s (1920s-1930s). At this time, the sedimentation rate increased at the primary core site primarily driven by an increase in carbonates, which was likely due to an increase in in-lake production. The largest shift in the diatom community assemblage also occurred at this time; diatom-inferred reconstructions suggest this shift may be associated with increases in both total phosphorus and pH. Algal pigment data show that this time period marked the beginning of a slow, steady increase in algal production.

The next big increase in the sedimentation rate began in the 1970s/1980s and continues to the present day; during this time the increase was driven by mineral material (inorganic matter), suggesting an allochthonous source, especially in the eastern portion of the basin. This increase in sedimentation rate at core site 5 is likely due to hydrologic alterations in the watershed that began in the 1980s; average annual sediment load to the basin increased in the period from 1985-2000 and again from 2000 to the present. Overall algal production goes up at this time, as does the concentration of aphanizophyll, a pigment found in nitrogen-fixing and bloom-forming cyanobacteria.

Overall, it appears that the hydrologic alterations to the Dean Lake watershed in the 1980s are correlated with an increased sediment load and increases in algal production. It does not appear that measures put in place in 2000 to ease the sediment load to Dean Lake are slowing these trends, although it is possible that it’s too soon to see the effects; average annual sediment load to the lake continued to increase over the period from 2000-2014, and total algal production reached its highest level in 2014.

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Table 1. Core locations, water depth at core site, and sediment recovery for each of the five cores.

Core	Latitude (N); Longitude (W)	Water Depth at Core Site (m)	Sediment Recovery (m)
Dean Lake - 1	44°46.649'; 93°27.142'	1.07	0.96
Dean Lake - 2	44°46.550'; 93°26.963'	1.15	0.77
Dean Lake - 3	44°46.487'; 93°26.776'	1.00	0.97
Dean Lake - 4	44°46.421'; 93°26.531'	1.45	0.99
Dean Lake - 5*	44°46.351'; 93°26.350'	1.33	1.05

*Core 5 was designated as the primary core in this study.

Table 2. Samples prepped for diatom analysis (from core 5).

Depth (cm)	Lead-210 Date
0	2014
5	2011
15	2000
20	1991
25	1979
27	1973
32	1954
36	1940
40	1926
43	1912
46	1889
48	1869
50	1847
54	1800
56	1777

Table 3. Sediment accumulation in each sub-basin over designated time intervals (1945-1985, 1985-2000, and 2000-2014).

	Basin 1	**Basin 2**	**Basin 3**	**Basin 4**	**Basin 5**
Area (m^2)	40,747	52,508	75,322	111,782	88,898
Average Sedimentation Rate ($g/cm^2/yr$):					
2000- 2014	0.1256	0.1256	0.1256	0.1360	0.1360
1985-2000	0.1256	0.1256	0.1256	0.1167	0.1167
1945-1985	0.1256	0.1256	0.1256	0.0846	0.0846
Sediment Accumulation (metric tons/yr):					
2000- 2014	51	66	95	152	121
1985-2000	51	66	95	130	104
1945-1985	51	66	95	95	75
	West Basin			**East Basin**	
Area (m^2)	168,577			200,680	
Sediment Accumulation (metric tons/yr):					
2000- 2014	212			273	
1985-2000	212			234	
1945-1985	212			170	
	Entire Basin				
Area (m^2)	369,257				
Sediment Accumulation (metric tons/yr):					
2000- 2014	485				
1985-2000	446				
1945-1985	382				

Figure 1. Google Earth map of Dean Lake, with each of the five coring locations. Sub-basins used for sediment accumulation calculations are delineated.

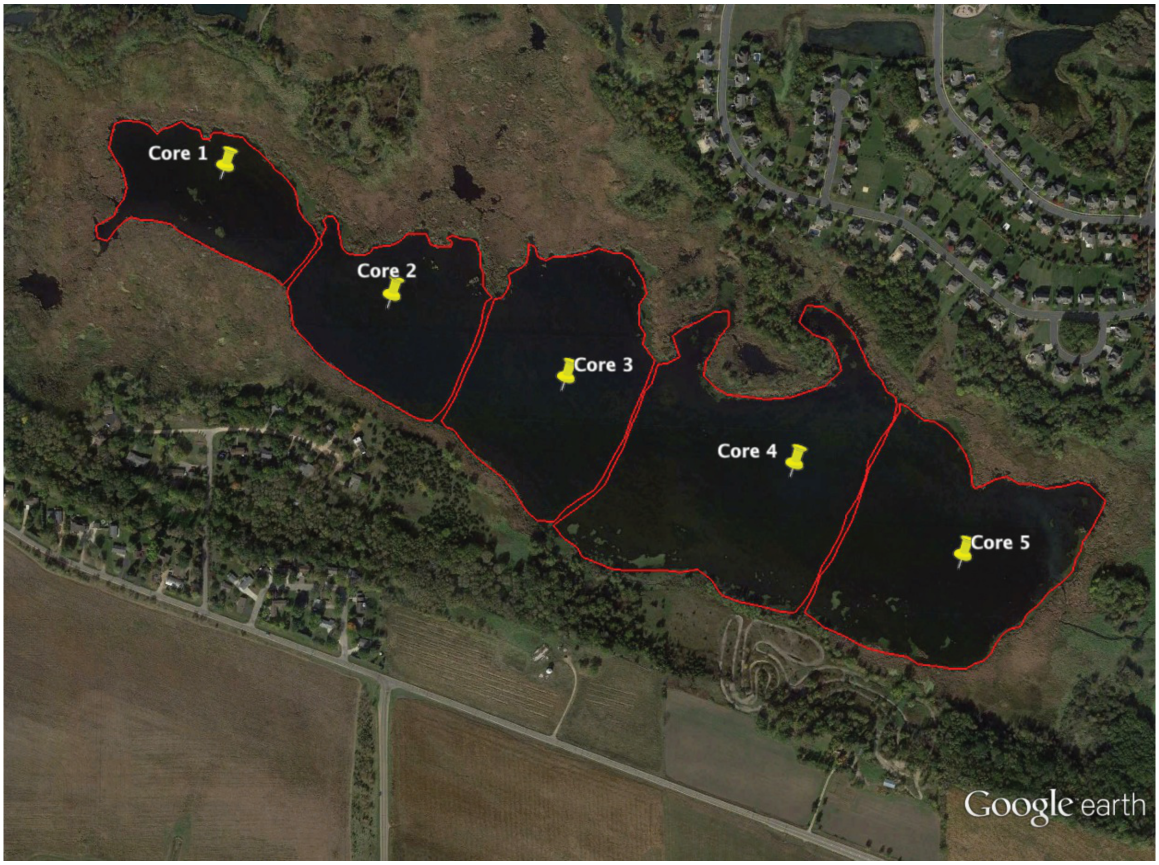


Figure 2. Unsupported lead-210 activity (a), and lead-210 dating model (b) for the secondary core (core 2) in Dean Lake. Note that the cf:cs model was applied to this core, assuming a constant sedimentation rate of 0.13 g/cm2 yr. Due to a hiatus in sedimentation, the dating model for this core only extends back to 1943.

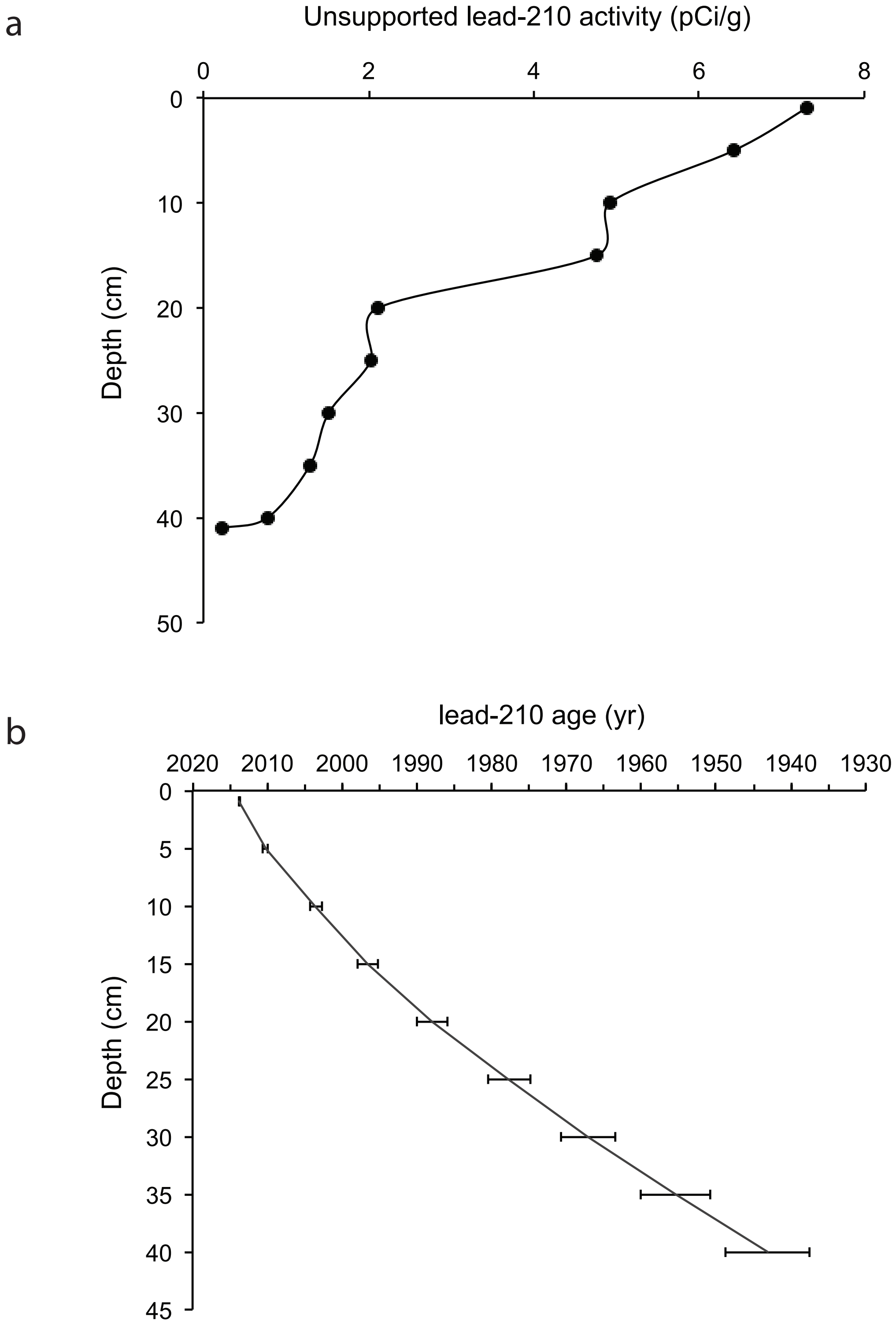


Figure 3. Unsupported lead-210 activity (a), lead-210 dating model (b), and sediment accumulation rate (c) for the primary core (core 5) in Dean Lake.

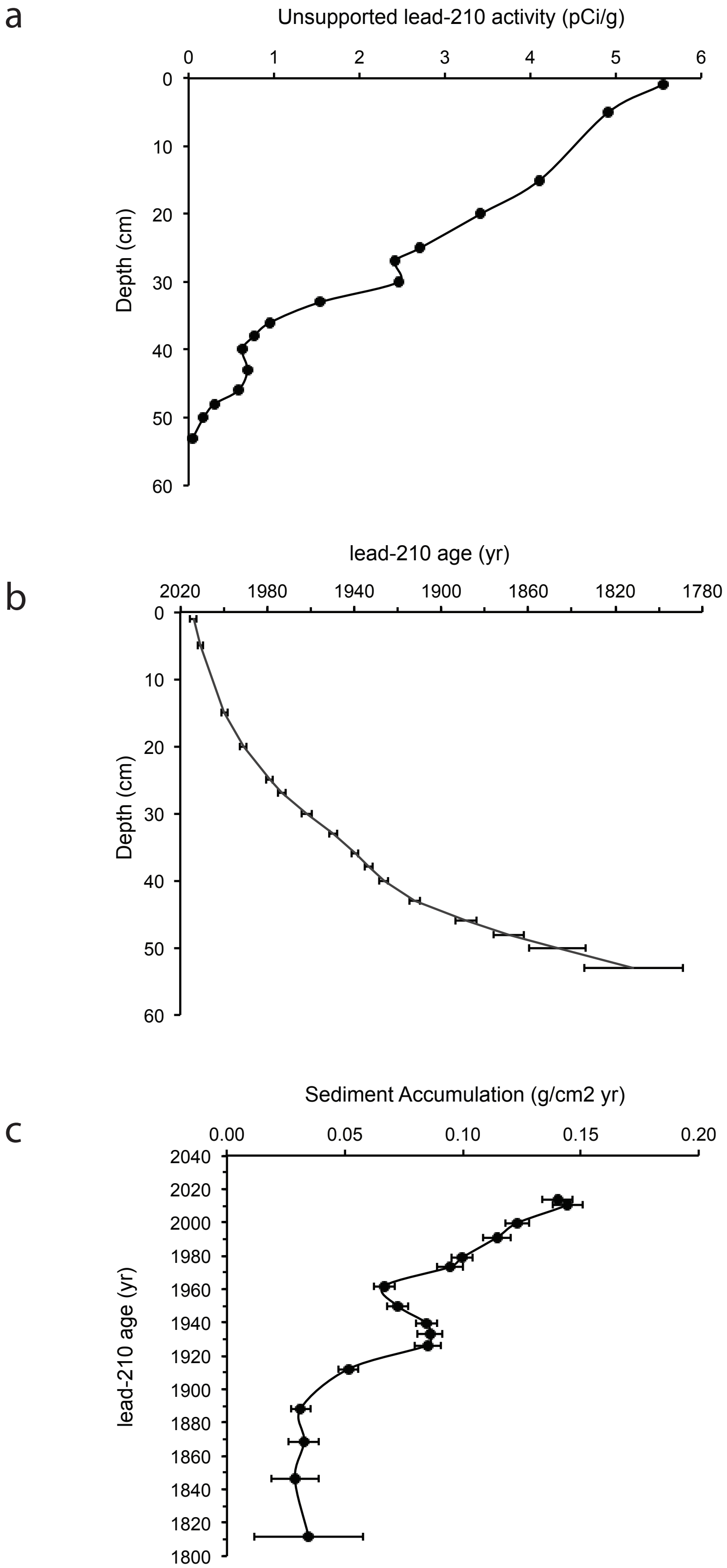


Figure 4. Magnetic susceptibility profiles for each of the five cores from Dean Lake. Note that magnetic susceptibility is not measured on the upper levels of each core where zorbitrol was added.

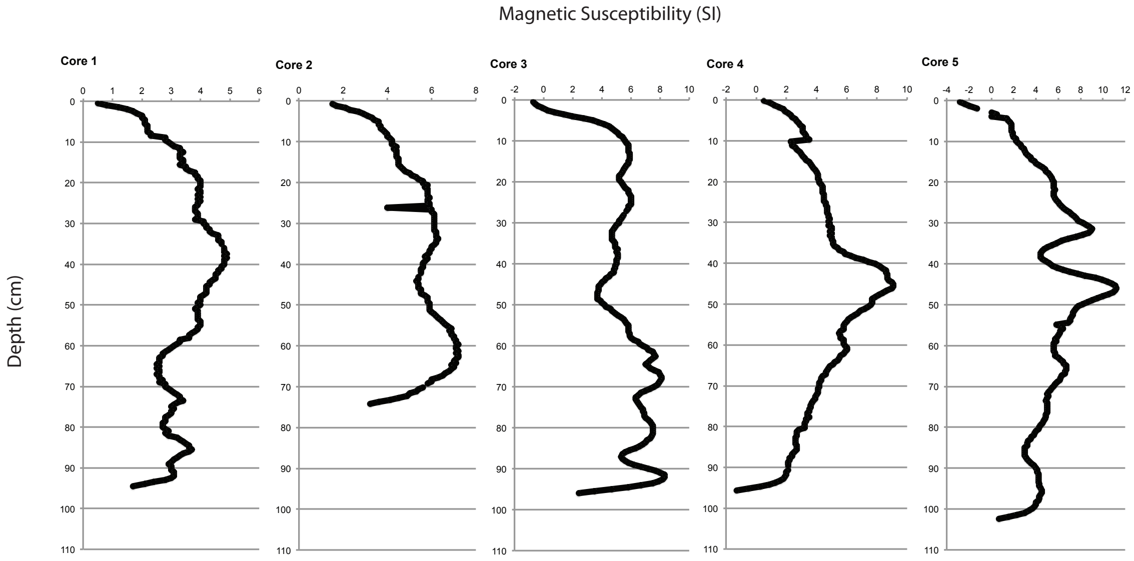


Figure 5. Percent dry weight of organic, $CaCO_3$, and inorganic matter in each of the five Dean Lake cores plotted against core depth.

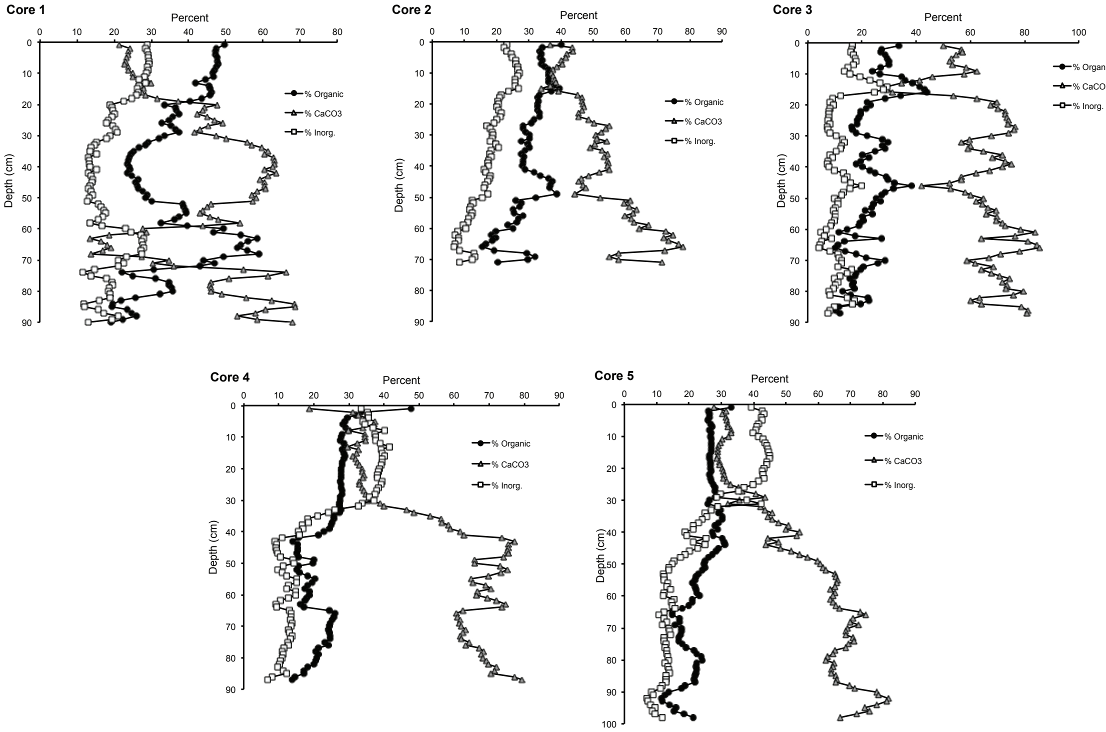


Figure 6. Sediment flux of organic matter, carbonate, and inorganic matter in the primary core (core 5).

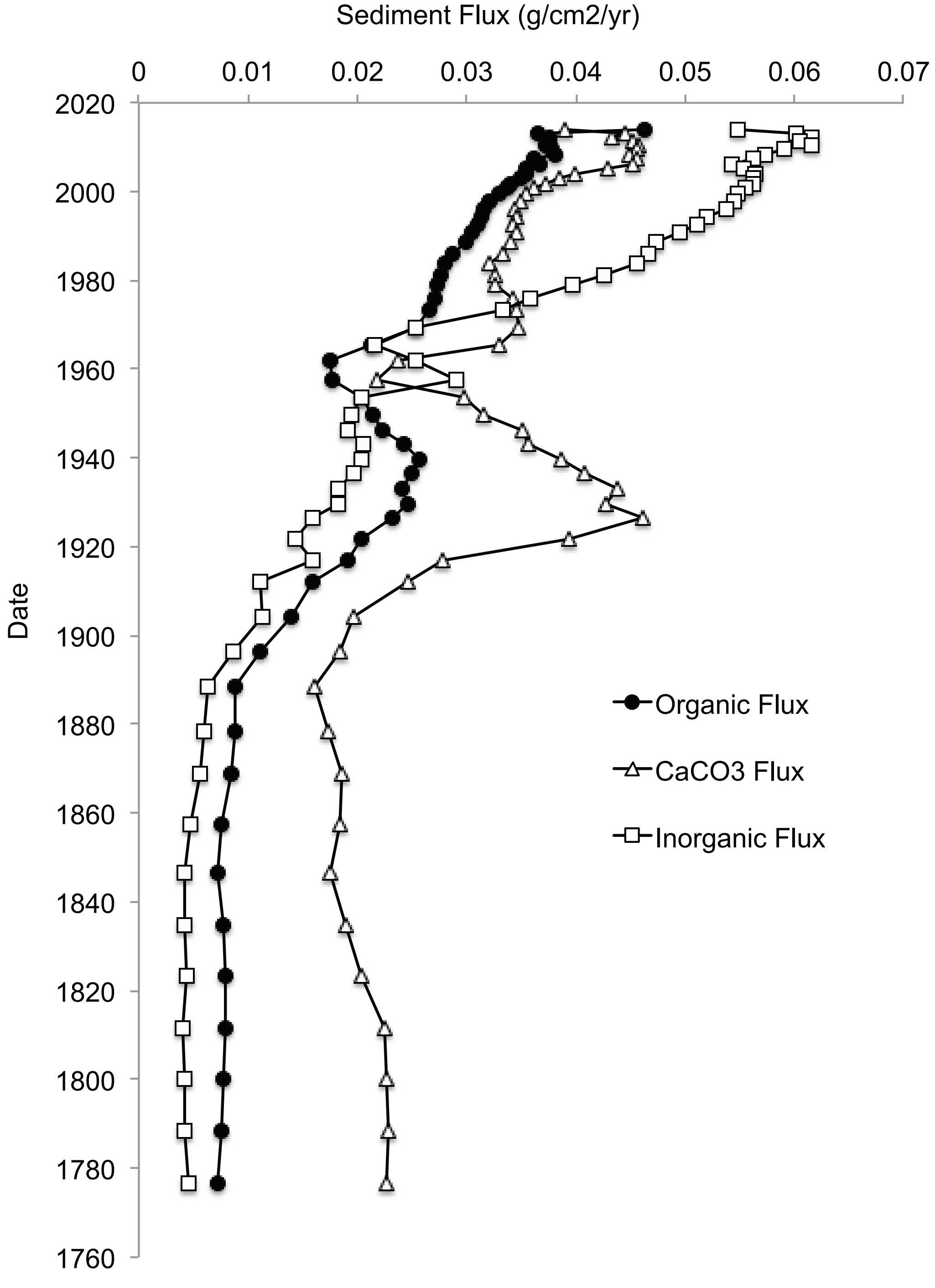


Figure 7. Mass of sediment accumulating per year in Dean Lake by core basin (a) western and eastern sides of the basin (b) and throughout the entire lake (c).

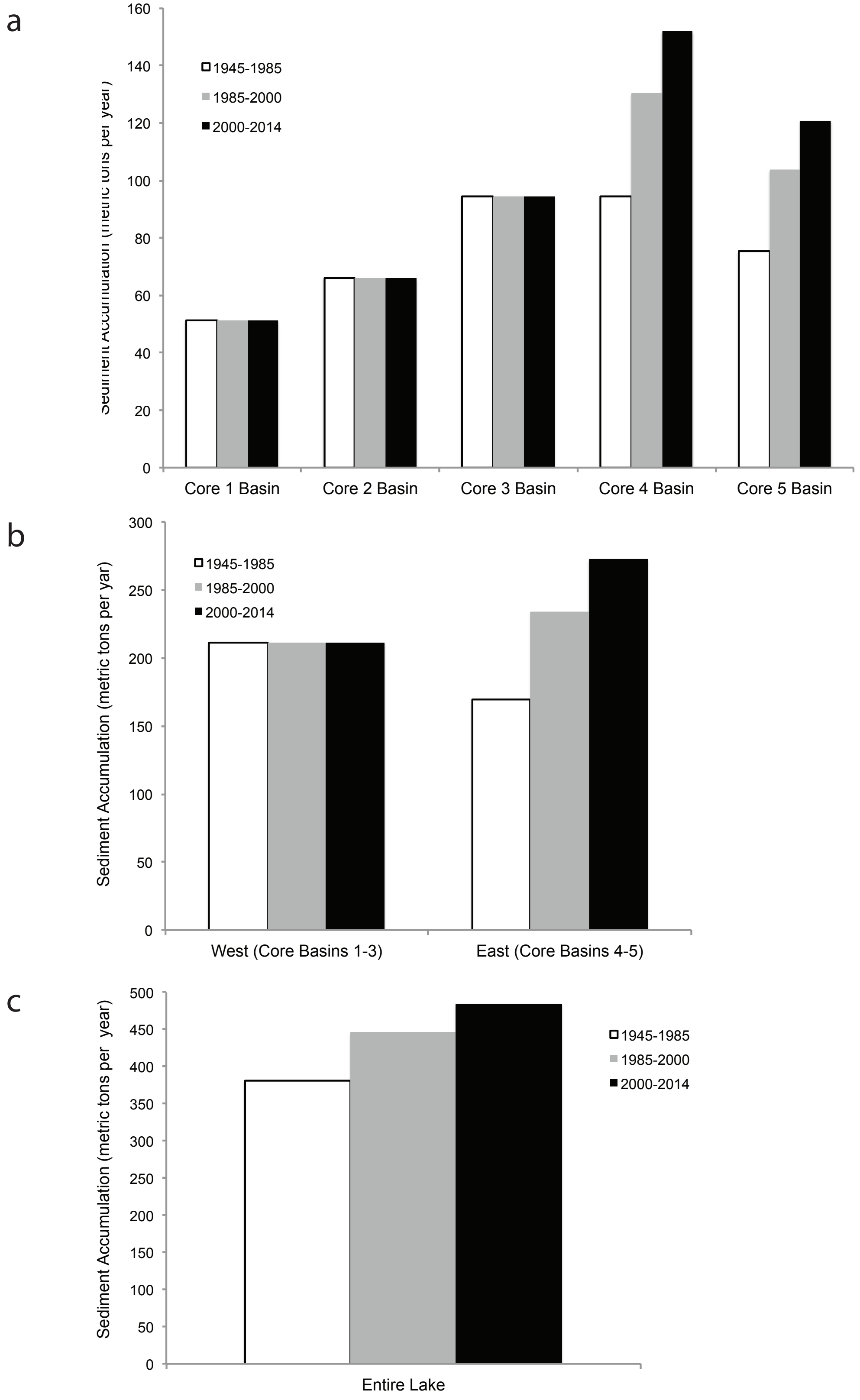


Figure 8. Detrended correspondence analysis (DCA) of diatom communities from Dean Lake.

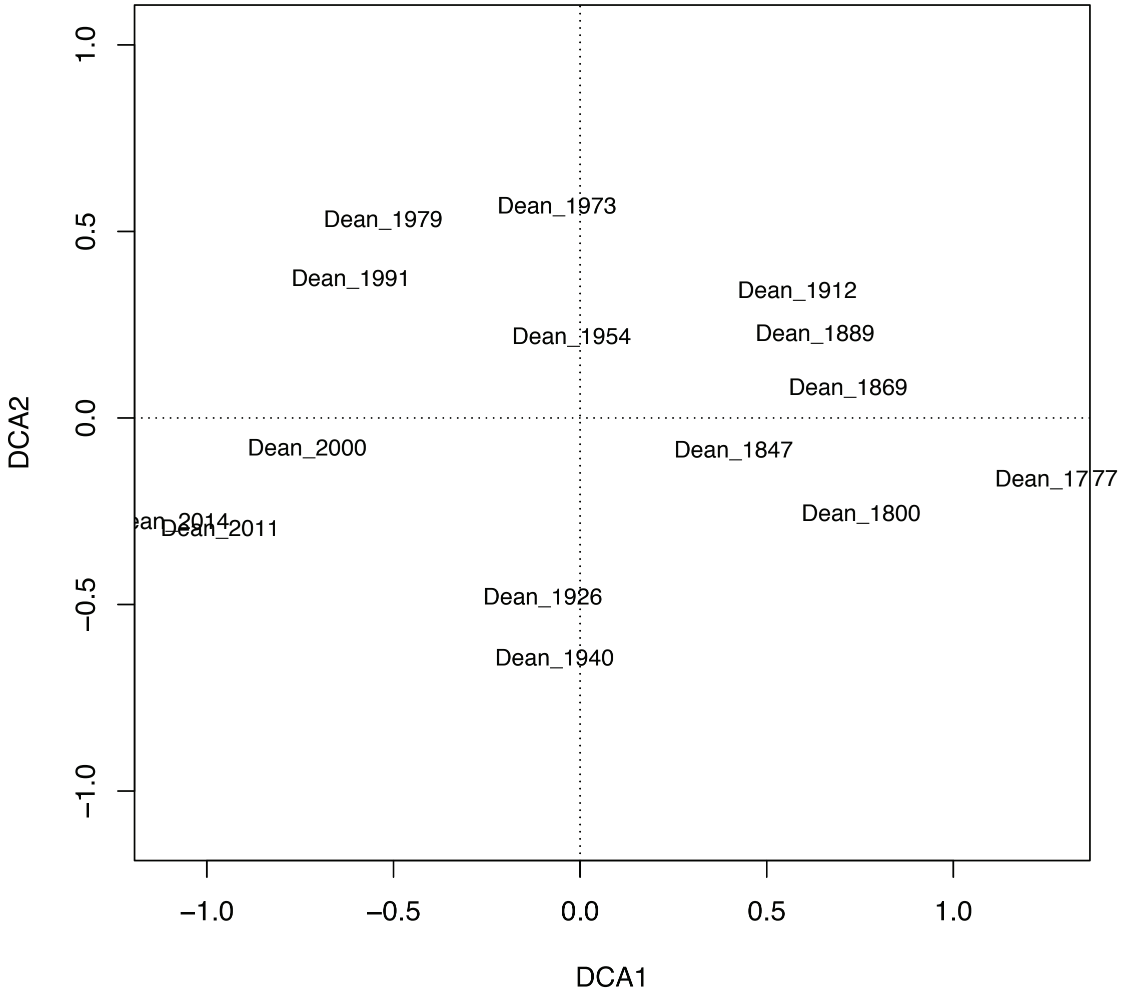


Figure 9. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance) in Dean Lake (1777-2014). The primary core (core 5) was used for all diatom analyses.

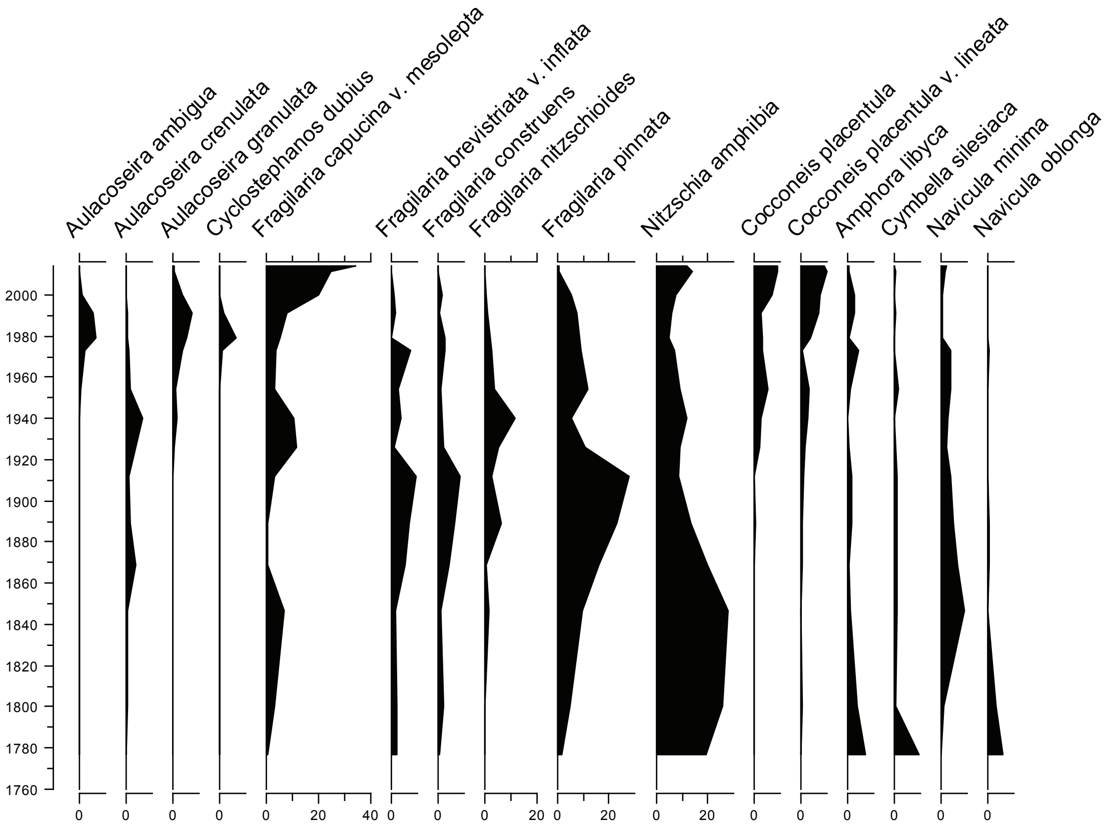


Figure 10. The core sections from the Dean Lake diatom analysis projected onto the MN calibration set (denoted as Dean_core date). Symbols represent the 89 MN lakes in the calibration set, coded by region; NLF=Northern Lakes and Forests, CHF=Central Hardwood Forests, Metro=Twin Cities Metropolitan Area, WCP=Western Corn Belt Plains, NGP=Northern Great Plains, and MCWD=Minnehaha Creek Watershed District. Environmental vectors are shown on the inset plot. Note that logTP is strongly correlated with Axis 1.

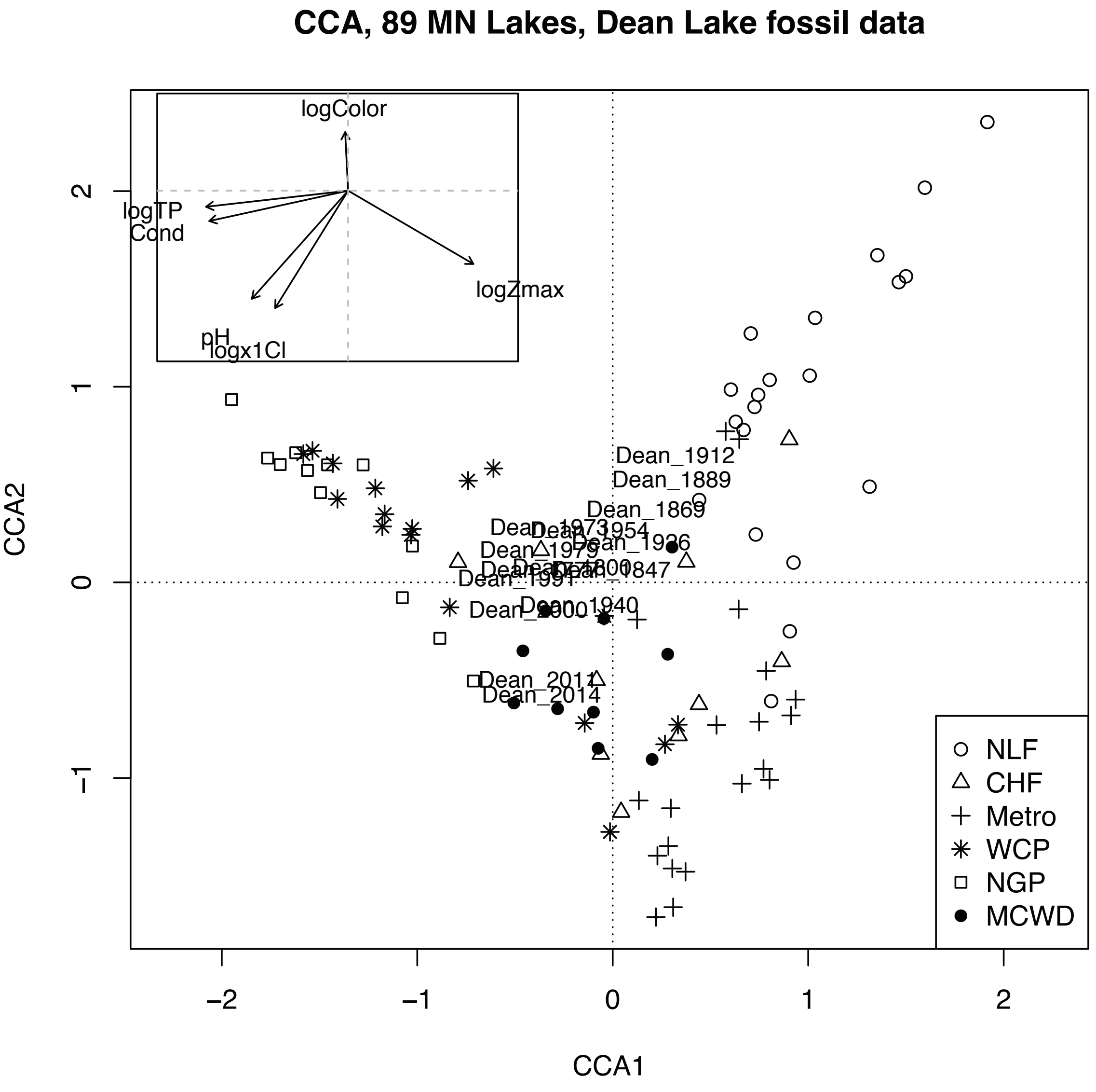


Figure 11. Diatom-inferred total phosphorus (TP) reconstruction for Dean Lake. Reconstruction is shown as log TP (left panel) and as backtransformed values in micrograms per liter (right panel). Error estimates on log TP are plus and minus the root mean square error of prediction from the TP transfer function.

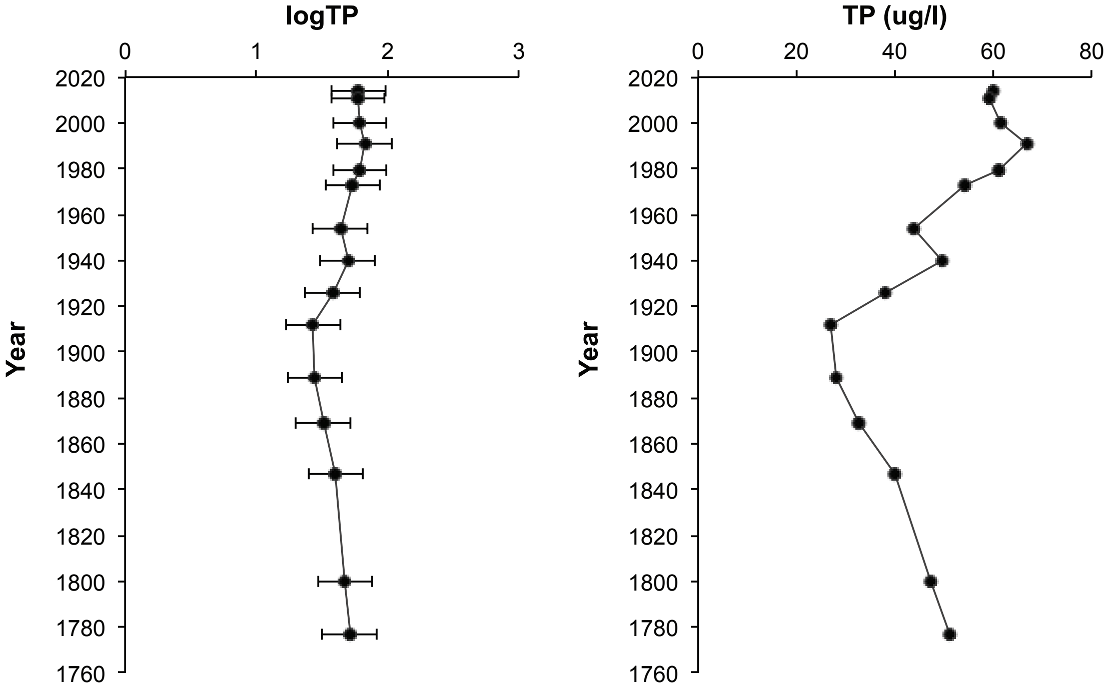


Figure 12. Diatom-inferred pH reconstruction for Dean Lake plotted alongside carbonate flux to the primary core (core 5). Error estimates on diatom-inferred pH are plus and minus the root mean square error of prediction from the pH transfer function.

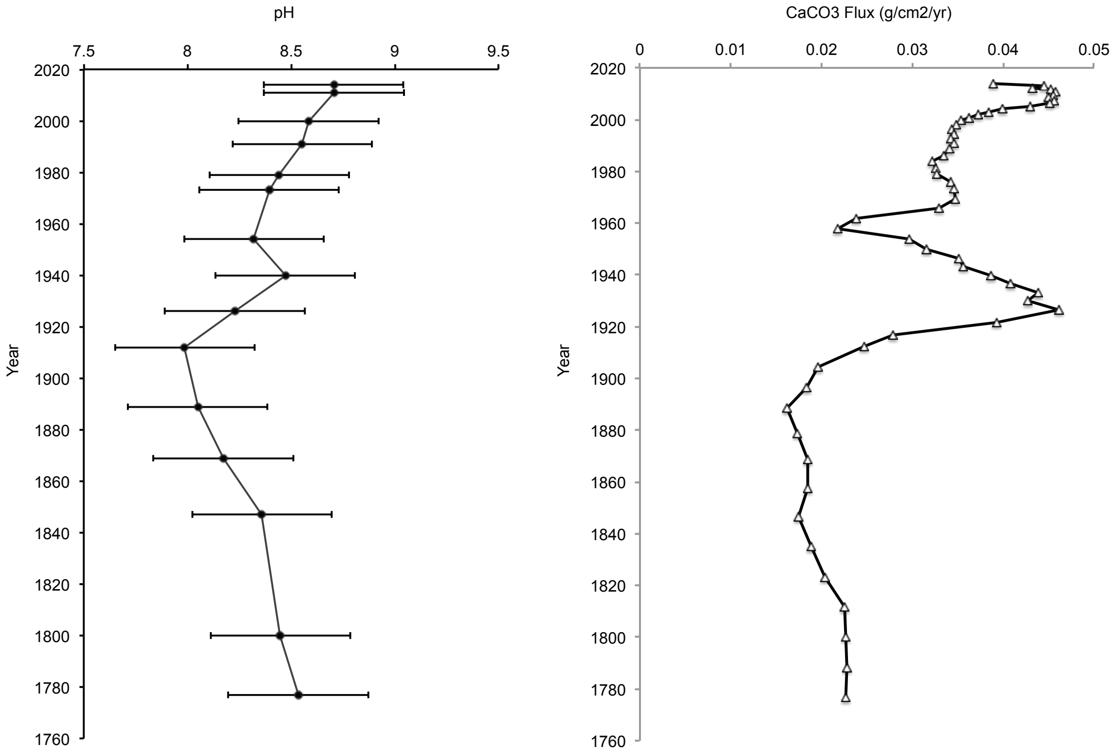
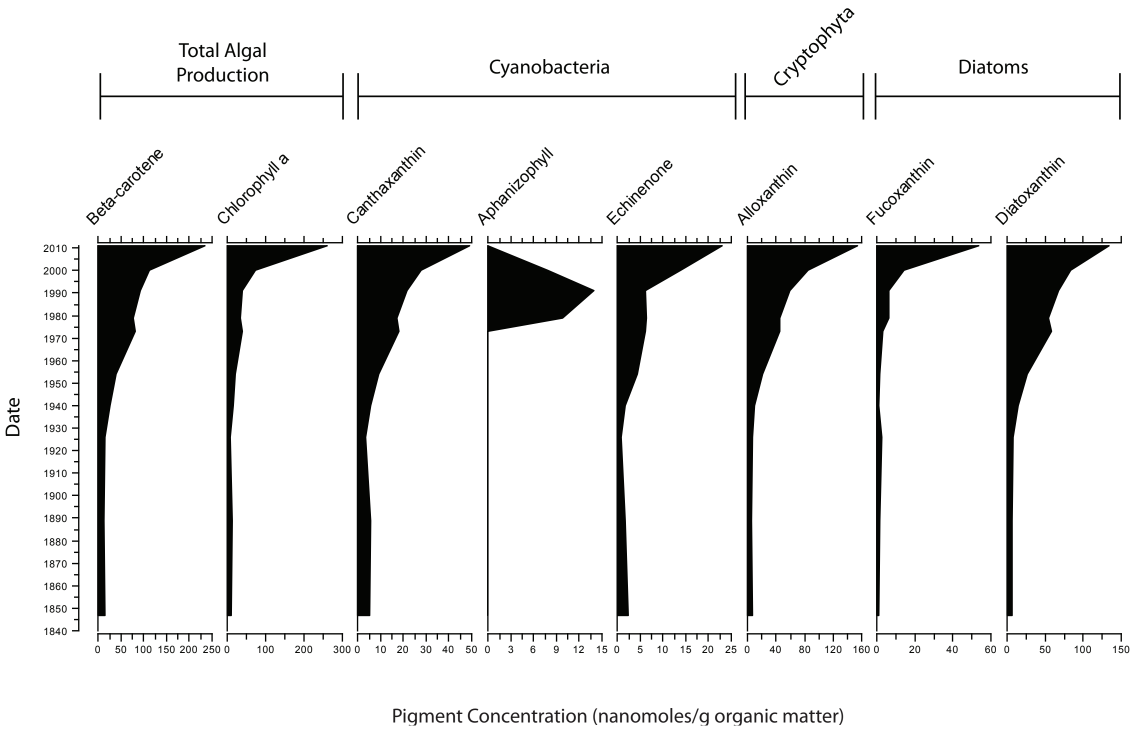
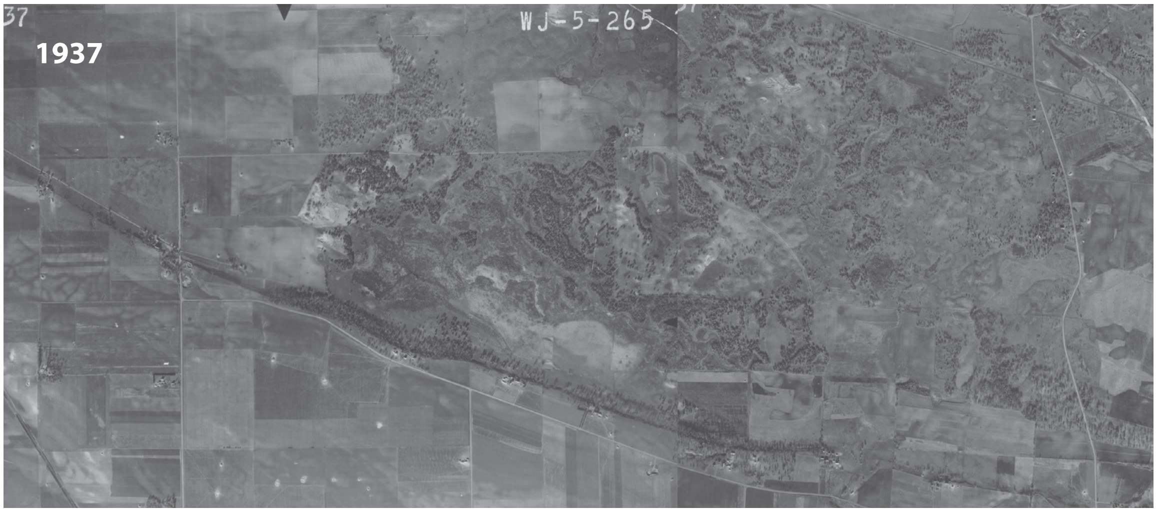


Figure 13. Sediment algal pigments quantified in ten core sections from the primary core (core 5) in Dean Lake. The group of algae associated with each pigment is shown along the x-axis. Pigment concentrations are reported as nanomoles per g organic matter.



Appendix A. 1937 aerial photo of Dean Lake, showing the lake basin mostly dry. Image obtained from the University of Minnesota John R. Borchert Map Library (https://www.lib.umn.edu/apps/mhapo/).



Appendix B. 1947 aerial photo of Dean Lake, showing the lake refilled after the 1930s drought. Image obtained from the University of Minnesota John R. Borchert Map Library (https://www.lib.umn.edu/apps/mhapo/).

Appendix C. 1855 Plat Map, showing Dean Lake with roughly the same shoreline as present day. Map obtained from the General Land Office Historic Plat Map website (http://www.mngeo.state.mn.us/glo/Index.htm).