

A PALEOLIMNOLOGICAL STUDY OF DEER YARD AND POPLAR LAKES IN COOK COUNTY, MINNESOTA

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SUMMARY

1. Paleolimnological techniques were used to reconstruct the trophic (nutrients and algae) and sedimentation history of Deer Yard and Poplar lakes in Cook County, MN.
2. Piston cores were collected from the two study lakes in October of 2016. Since the Poplar Lake basin is complex, two cores were collected to better understand the spatial differences in the lake history between the deep central basin and the marginal bays.
3. Lead-210 activity was analyzed to develop a dating model for each core and determine the sediment accumulation rate over the past 150-200 years. Sediments were analyzed for inorganic, organic, and carbonate components using loss-on-ignition analysis; geochemical analyses also included sediment phosphorus and biogenic silica. Subfossil diatoms in the sediments were analyzed to reconstruct changes in lake ecology and trophic state. In addition to diatoms, algal pigments were measured to determine historical changes in other algal groups.
4. All three cores showed a small increase in sedimentation concurrent with initial logging and Euroamerican settlement, and then an increase in sedimentation rate beginning in the in the 1980s and continuing into recent years. In each core, the modern-day sedimentation rate was two to three times higher than it was in the 1800s.
5. Phosphorus (P) concentrations in the sediment cores changed very little in the last 150-200 years suggesting no dramatic shifts in nutrient loading to the lake. The Deer Yard and shallow bay Poplar core did not show any increased concentration of P fractions near the core top that would indicate a high threat of internal loading. The deep Poplar core did have a peak in mobile P fractions, suggesting some threat of internal loading in Poplar's deep basins.
6. Diatom community assemblage in Deer Yard Lake showed a small shift in the 1950s, characterized by a decrease in planktonic species and an increase in tychoplanktonic species. The diatom communities in both cores from Poplar Lake showed very little change. Diatom-inferred total phosphorus reconstructions suggested that both lakes, and the deep and shallow regions within Poplar, have been mesotrophic since the 1800s.
7. Sediment pigments showed a slight increase in total algal production in all three cores in recent decades. Notably there was no strong evidence to suggest any historical increase or threat of cyanobacterial blooms in either lake.
8. Overall, neither of the lakes showed dramatic changes in nutrient condition or algal communities over the last 150-200 years. Management recommendations include continued monitoring, as well as efforts such as sound management of lakeshore properties, and preventing the introduction of aquatic invasive species, to maintain these lakes in their current condition.
9. The monitored trend of decreasing Secchi depth or decreasing clarity in Deer Yard and Poplar lakes indicates something is changing in these lakes. Three things can change to decrease water clarity: more algae growth in the water, more sediment in the water, or the color of the water. The cores suggest that neither algae communities nor sedimentation have dramatically changed, leaving color shifts due to "browning" of the lakes (transport of colored compounds called dissolved organic carbon, DOC) as a possible concern for the lakes. This is a global problem in northern lakes and monitoring for long-term changes in DOC should be encouraged.

INTRODUCTION

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

A basic understanding of natural fluctuations within the system is important for any lake management plan. Reliable long-term data sets, on the order of 30 - 50 years, are generally not available for most regions of the country. Through the use of paleolimnological techniques (reconstructing the history of a lake based on the sediments deposited in its basin) and quantitative environmental reconstruction, we can estimate past conditions, natural variability, timing of changes, and determine rates of change and recovery. This information allows managers and researchers to put present environmental stresses into perspective with the natural variability of the ecosystem. It can also be used to identify response to, and recovery from, short-term disturbances. In this project, paleolimnological techniques were used to reconstruct the trophic and sedimentation history of Deer Yard Lake and Poplar Lake, both located in Cook County in Minnesota's Arrowhead Region.

The primary aim of this project was to use dated sediment cores from each lake to reconstruct the ecological history using geochemistry, sediment accumulation, diatom-inferred total phosphorus (DI-TP), 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 are one group of microscopic algae that are characterized by having cell walls made of biologically produced glass. As a result, they are usually well preserved in lake sediments when they die and sink to the bottom of lakes. Diatoms have been widely used to interpret environmental conditions in lakes (Dixit and Smol 1994). Many species are sensitive to specific water conditions and are useful as bioindicators. Over the past 25 years, statistical methods have been developed to estimate quantitative environmental parameters from diatom assemblages. These methods are statistically robust and ecologically sound (Birks 1998). They have been used successfully in reconstructing a wide variety of environmental parameters including pH, total phosphorus (TP), and salinity (e.g. Fritz et al. 1991, 1999; Hall and Smol 1992; Ramstack et al. 2003). In the state of Minnesota, diatom analysis has been used as one line of evidence for developing lake nutrient criteria (Heiskary and Wilson 2008) and lake-specific nutrient standards (Edlund and Ramstack 2007).

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

Study Area

Deer Yard Lake and Poplar Lake are both located in Cook County in Minnesota's Arrowhead Region; however, the two lakes are quite different. Deer Yard Lake runs SW-NE for a length of about 2 miles and has a single basin that reaches approximately 6 m (20 feet) depth. In contrast, Poplar Lake runs for about 4 miles along the Gunflint Trail and has a very complex basin that includes numerous islands, at least two deep holes that reach 21 m (70 feet) deep, and several marginal bays that are commonly 9 m (30 feet) deep. The lakes also contrast in development, with the northern shore of Poplar home to several resorts, and Deer Yard with homes on the west and east shores and a few scattered homes on its north shore.

Concern for the lakes centers on their current trends of decreasing Secchi depths. Although both lakes still meet nutrient goals (Deer Yard 10-22 ppb total phosphorus (TP); Poplar 8-15 ppb TP), trends in Secchi depth may presage emerging issues with the state of the lakes. Changes in water clarity are generally caused by three things: increased algae growth in the water, increased loading of sediment (erosion) to the lake, or changes in lake color due to greater input of dissolved organic carbon (DOC, tannins) from the watershed. The latter, referred to as lake "browning" is a widely documented phenomenon that is accompanying global warming trends (Monteith et al. 2007; Solomon et al. 2015; Williamson et al. 2015). This has further led to questions whether the productivity of the lakes have changed over time, what the natural or historical condition of the lakes were, what the current trajectory of each lake is, and how to best set management goals.

METHODS - SEDIMENT CORING

A single sediment core (1.02 m or 40 inches long) was collected from Deer Yard Lake on October 26, 2016, and two sediment cores were collected from Poplar Lake on October 27, 2016. In Deer Yard Lake, the coring location represented a flat a deep area of the main basin (depth 6.17 m or 20.2 ft); in Deer Yard, this was sufficient to provide a highly integrated sample from the lake as a whole. Since the Poplar Lake basin is much more complex, two cores were collected to better understand the spatial differences in lake history between the deep central basins and the marginal bays. Poplar Lake core 1 (1.03 m or 40 inches long) was collected from a shallow bay on the west side of the lake (depth 9.36 m or 30.7 ft) and Poplar Lake core 2 (1.40 m or 55 inches long) was collected from a deep central basin (depth 21.16 m or 69.4 ft) on the east side of the lake (Figure 1). All cores were collected using a drive-rod piston corer equipped with a 6.5 cm diameter polycarbonate barrel (Wright 1991). All cores were sectioned in the field in 1-cm increments from 0-50 cm; cores were then returned to the laboratory and stored at 4°C, sectioning then continued in 2-cm increments below 50 cm to the core bottom.

Table 1 details the coring location, water depth, and recovery for each of the lakes. Figure 1 shows the coring locations on each of the lakes.

METHODS - AERIAL PHOTOS

Aerial photos from the 1930s and 1980s were used to examine changes to each lake and its watershed. Available historical aerial photos were downloaded from the University of Minnesota John R. Borchert Map Library's Historical Aerial Photographs Online collection (<https://www.lib.umn.edu/apps/mhapo/>; May 2018). Modern aerial photos were obtained from Google Earth (<https://earth.google.com/web/>; May 2018).

METHODS - LEAD-210 DATING

The first analysis done on a sediment core is radioisotopic dating to determine the relationship

between depth in the sediment and when that sediment was deposited. Lead-210 was measured in all cores by lead-210 distillation and alpha spectrometry methods, and dates and sedimentation rates were determined according to the c.r.s. (constant rate of supply) model (Appleby and Oldfield 1978). Dating and sedimentation errors were determined by first-order propagation of counting uncertainty (Binford 1990). In each core, between 15 and 19 core sections were analyzed for lead-210 activity to determine age and sediment accumulation rate for the past 150 years.

METHODS - GEOCHEMISTRY

Loss on Ignition

Loss-on-ignition determines the relative composition of lake sediment. Changes in the amounts of organic matter, carbonates, and inorganic matter are clues to how a lake has changed due to erosion, land use, depth changes, and algae and plant growth. Weighed subsamples were taken from regular intervals throughout each core for loss-on-ignition (LOI) analysis to determine bulk and dry density and dry weight percent of organic, carbonate, and inorganic matter. Sediment subsamples were heated at 105°C to determine dry density, then sequentially heated at 550°C and 1000°C to determine organic and carbonate content from post-ignition weight loss, respectively (Dean 1974).

Biogenic Silica

Biogenic silica (BSi) is a measure of historical diatom and chrysophyte algal productivity. Diatoms and chrysophytes are common types of microscopic algae that can produce biologically polymerized glass or biogenic silica. BSi was measured using 15 weighed subsamples (30 mg) from each core, which were digested for BSi analysis using 40 ml of 1% (w/v) Na₂CO₃ solution heated at 85°C in a reciprocating water bath for five hours (DeMaster 1979, Conley and Schelske 2001). A 0.5 g aliquot of supernatant was removed from each sample at 3, 4, and 5 hr. After cooling and neutralization with 4.5 g of 0.021N HCl solution, dissolved silica was measured colorimetrically on a Unity Scientific SmartChem 170 discrete analyzer as molybdate reactive silica (SmartChem 2012a). Measured BSi concentrations were also converted to flux using bulk sedimentation rates in each core.

Sediment Phosphorus

The growth of algae in most lakes in Minnesota is limited by the amount of phosphorus in the lake, meaning that phosphorus additions to a lake will lead to more algae growing along the shore and in the water. Phosphorus can get into a lake from multiple sources including runoff, land use change, poorly maintained septic systems, fertilizer runoff, and from point sources where water treatment or industry discharge directly to lakes. Phosphorus that gets into a lake can be easily cycled for a long time, moving from the sediments to the water and back to the sediments (called internal loading) before it either flows out of the lake or is permanently buried in the sediments. We analyzed the distribution of phosphorus fractions in the lake sediments to assess the risk and likelihood of high levels of internal loading, and to identify whether there have been lake-wide changes in historical nutrient loading to the lake.

Sediment phosphorus fractions were analyzed for 15-18 increments from each core following the sequential extraction procedures in Engstrom (2005), Engstrom and Wright (1984), Psenner and Puckso (2008), and Kopáček et al. (2005). Extracts were analyzed colorimetrically on a Unity Scientific SmartChem 170 discrete analyzer using methods described by SmartChem (2012b). Measured sediment phosphorus (P) concentrations were also converted to flux using bulk sedimentation rates in each core. In addition to total phosphorus (TP) in cores, sediment P fractions were measured, including the refractory forms *Mineral-bound P*, *Recalcitrant Organic-P*, *Al-bound P* and the labile or readily exchangeable forms of *Fe-bound*, *labile*

Organic-P, and *loosely-bound P*, which can lead to internal loading.

METHODS - DIATOM AND NUMERICAL ANALYSES

Fifteen samples from each core were analyzed for diatoms. Diatom and chrysophyte cysts were prepared by placing approximately 0.25 cm³ of homogenized sediment in a 50 cm³ 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 byproducts. Aliquots of the remaining material, containing the diatoms, were dried onto 22x22 mm #1 coverglasses, which were then permanently attached to microscope slides using Zrax mounting medium. Diatoms were identified along random transects to the lowest taxonomic level under 1250X magnification with oil immersion optics. A minimum of 400 valves was counted in each sample. Abundances are reported as percent abundance relative to total diatom counts. Identification of diatoms used regional floras (e.g. Patrick and Reimer 1966, 1975; Camburn and Charles 2000) and primary literature 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 Non-Metric Multidimensional Scaling (NMDS), 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 an NMDS biplot is that samples that plot closer to one another have more similar diatom assemblages. Diatom community relationships were also explored using a constrained cluster analysis, using the CONISS method with Euclidean distance, and Hellinger transformation of species. Significant breaks in the constrained cluster analysis were evaluated using a broken stick model.

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

METHODS - ALGAL PIGMENT ANALYSIS

The different groups of algae or photosynthetic bacteria each have unique pigment complements based on chlorophylls, accessory pigments, and breakdown products that are deposited in the sediments when the algae sink to the bottom and die. The types and quantities of the pigments provide a history of presence and quantity of each algal group.

Algal pigment analyses were performed by Dr. Peter Leavitt at the University of Regina.

Carotenoids, chlorophylls, and derivatives were extracted (4°C, dark, N₂) from freeze-dried sediments according to Leavitt et al. (1989), measured on a Hewlett-Packard model 1050 high performance liquid chromatography system, and are reported relative to total organic carbon (TOC; Hall et al. 1999).

RESULTS AND DISCUSSION - AERIAL PHOTOS

Deer Yard Lake and Poplar Lake – Aerial photos from 1934 and 1982 were examined for each of the lakes (Figures 2 and 3). In each case, the lakes showed very little change between these time periods. In Deer Yard Lake, the modern-day Google Earth aerial photo showed some homes or cottages along the northwestern shore that did not appear to be there in the 1982 photo (Figure 2). Similarly, in Poplar Lake, the Google Earth photo showed some increase in development along the northern shore (Figure 3).

RESULTS AND DISCUSSION - DATING AND SEDIMENTATION

Sedimentation rates vary naturally among lakes based on factors such as lake and watershed area, and surficial geology. For each of the study lakes, the sedimentation rate in the early to mid-1800s can be considered the background rate for the lake; this is the sedimentation rate prior to European settlement and significant disturbance to the watershed. This allows changes in each lake to be evaluated relative to the “natural” or pre-European conditions.

Deer Yard Lake – The unsupported lead-210 activity, the resulting lead-210 dating model, and the sediment accumulation rate for Deer Yard Lake are shown in Figure 4a-c. In Deer Yard Lake, the lead-210 activity declined throughout the core, reaching background levels at approximately 34 cm (Figure 4a). The period following Euro-american settlement in the region (late 1800s/early 1900s) is preserved in the upper 25 cm of core (about 10 inches). The sedimentation rate in Deer Yard Lake averaged 0.013 g/cm² yr during the early to mid-1800s; there was some fluctuation in the rate from the late 1800s through the 1970s, and it ranged from 0.013 g/cm² yr to 0.029 g/cm² yr during this period (Figure 4c). Beginning in the 1980s, the sedimentation rate in Deer Yard Lake began to steadily rise, with a peak of 0.045 g/cm² yr at the core top. The rate at the core top is about three times higher than the rate in the early to mid-1800s.

Poplar Lake Core 1 – Figure 5a-c illustrates the unsupported lead-210 activity, the resulting lead-210 dating model, and the sediment accumulation rate for Poplar Lake core 1. Lead-210 activity reached background levels by 25 cm in Poplar Lake core 1 (Figure 5a). The period following Euro-american settlement in the region (late 1800s/early 1900s) is preserved in the upper 20 cm of core (about 8 inches). From the early 1800s through the 1970s, the sedimentation rate in this shallow bay of Poplar Lake averaged 0.008 g/cm² yr (Figure 5c). Beginning in the 1980s, the sedimentation rate began to rise and peaked at 0.025 g/cm² yr in 2005. In the recent decade, the rate has been fairly steady and averaged 0.24 g/cm² yr; this is nearly three times higher than the average rate from the early 1800s through the 1970s.

Poplar Lake Core 2 – In core 2 from Poplar Lake, lead-210 activity reached background levels at 23 cm (Figure 5d). The period following Euro-american settlement in the region (late 1800s/early 1900s) is preserved in the upper 17-18 cm of core (only about 7 inches!). With the exception of one small increase in the 1920s (0.015 g/cm² yr), the sedimentation rate in the deep central basin of Poplar Lake was fairly constant and averaged 0.011 g/cm² yr from the mid-1800s to the 1970s (Figure 5f). The rate began a slow rise in the 1980s (although less pronounced than in core 1), and peaked at the core top at 0.021 g/cm² yr. The rate at the core top (2015) is almost two times higher than the average rate from the mid-1800s to the 1970s.

RESULTS AND DISCUSSION - GEOCHEMISTRY

Loss on Ignition

Deer Yard Lake – The sediment composition from Deer Yard Lake showed very little fluctuation throughout the core (Figure 6a). The sediments were predominantly composed of inorganic matter, which fluctuated between 60 and 69% over the length of the core; organic matter ranged from 26 to 35%, and carbonates from 4 to 6%. The sedimentation rate in Deer Yard Lake was low, the lead-210 record only extended to 34 cm depth, and there was surprisingly little variation in LOI within this most recent portion of the record, which is a good sign for the lake.

For all cores, 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 6b for Deer Yard Lake); sediment flux was calculated to the end of the lead-210 record for each core (34 cm in Deer Yard Lake). Since there was very little variation in the sediment composition in Deer Yard Lake over the course of the lead-210 record, the pattern of sediment flux to the core site showed the same pattern as the sediment accumulation rate. Peaks in inorganic accumulation in the 1870s and 1930s in Deer Yard may record early logging or fires that caused short periods of enhanced erosion.

Poplar Lake Core 1 – The sediment composition of core 1 from Poplar Lake was fairly uniform over the length of the core (Figure 7a). The sediments consisted of between 57 and 61% inorganic matter, 33 to 38% organic matter, and 4 to 7% carbonates. The sediment flux was calculated over the length of the lead-210 record (0-25 cm); this mimicked the pattern of overall sediment accumulation since there was very little variation in the sediment composition (Figure 7b). Again, small increases in sedimentation, and especially inorganic accumulation, from 1900-1930 may reflect effects of early logging in the watershed.

Poplar Lake Core 2 – The sediments from the deep basin of Poplar Lake were also fairly uniform throughout the length of the core (Figure 8a). The sediments were composed of between 61 and 67% inorganic matter, 26 to 32% organic matter, and 5 to 8% carbonates. The sediment flux was calculated over the length of the lead-210 record (0-23 cm); again, the pattern reflects the overall sediment accumulation rate (Figure 8b). The peak in inorganic flux in the 1920s could be the result of early logging in the basin.

All three cores had fairly uniform sediment composition profiles, and the percentages of inorganic, organic, and carbonate were fairly consistent between the two basins of Poplar Lake, and even between Poplar and Deer Yard lakes. This suggests that the sediment composition is reflecting the surficial geology of the region, and that neither of the lakes has experienced a significant change in the source of sediment to the lake. Although each of the cores showed an increase in sediment accumulation rate beginning in the 1980s, the sediment composition has not changed in recent decades in any of the cores.

Biogenic Silica and Sediment Phosphorus

Deer Yard Lake – The weight percent of BSi in the Deer Yard Lake core showed only slight variation and ranged from 32 to 40% from the mid-1800s to 2016; the weight percent was slightly higher from the mid-1800s to the 1940s (average of 39%) than it was from the 1950s to the core top (average 35%) (Figure 9a). Because of the very high BSi content of Deer Yard Lake (most Minnesota lakes have <2-10% BSi content), over half of the inorganic material in the core represents diatom algae.

For all cores, silica flux was calculated by multiplying the weight percent of BSi by the sedimentation rate at that interval (Figure 9b for Deer Yard Lake). As with the LOI profile, the pattern of silica flux reflects the overall sediment accumulation rate since there was little variation

in the weight percent of BSi throughout the core.

The concentration of phosphorus in the core showed a gradual overall rise from 0.8 mg P/g in the mid-1800s to just over 1.0 mg P/g at the core top (Figure 10a). The proportion of P fractions did not change drastically over the period of study; however, there was a slight increase in the proportion of labile organic P over time, which along with recalcitrant organics may have been the fractions that drove the TP increase (Figure 11). Because of the low and unchanging concentrations of Fe-bound P, there is little evidence to suggest enhanced or increasing threats of internal loading to Deer Yard Lake.

Poplar Lake Core 1 – There was very little fluctuation in the weight percent of BSi in the core from the shallow bay of Poplar Lake (Figure 12). The BSi in this core ranged from 30 to 34%; similar to Deer Yard Lake, the inorganic portion of Poplar Lake sediments is about half diatom algae remains. There is an increased accumulation rate of BSi in Poplar 1 after the 1970s that may be an indication of slightly higher diatom growth in the lake; however, we have to be cautious in interpreting upcore trends in low sedimentation rate lakes like Poplar.

The concentration of TP in the Poplar 1 core ranged from 1.9 to 2.2 mg P/g, and also showed little variation over time (Figure 13). Labile organic P, a readily exchangeable form of P, is the largest phosphorus fraction in this core (Figure 14). Consistent concentrations of Fe-bound P, especially upcore, suggest minimal threats of enhanced internal loading in the shallow bays of Poplar Lake.

Poplar Lake Core 2 – The weight percent of BSi in the core from the deep basin of Poplar Lake shows an overall decline over time (Figure 15a). The highest value was a weight percent of 37 in the early 1900s; this declined to 24% at the core top. The flux of silica to the core site was slightly higher in the late 1800s/early 1920s, then declined until beginning a slow rise in the 1980s (Figure 15b).

The concentration of TP in the core was slightly higher from the 1830s to the 1870s (average 2.5 mg P/g), then declined and remained steady through the 2010s (average 1.6 mg P/g) (Figure 16a). There is a spike in TP at the core top, reaching 3.6 mg P/g. The P flux to the core site is relatively constant with the exception of the sharp peak at the core top (Figure 16b). This spike at the core top may indicate greater potential for internal loading due to upcore mobility of phosphorus in the deep basin(s) of Poplar Lake. The increase at the core top was largely driven by increases in iron-(Fe-)bound P (readily exchangeable) and aluminum bound P (refractory) (Figure 17).

RESULTS AND DISCUSSION - DIATOM STRATIGRAPHY AND ORDINATION

Deer Yard Lake – The ordination biplot from the NMDS shows how the core samples clustered based on similarity of diatom assemblage (Figure 18). The samples from the 1846 to about 1950 clustered on one side of the biplot, then the community showed gradual change through the core top.

The stratigraphic diagram shows the predominant diatoms that were driving the shifts in the community assemblages, as well as the results of the constrained cluster analysis, and the percentage of plankton throughout the core (Figure 19). Throughout the Deer Yard Lake record, changes in the diatom community assemblage were subtle (Figure 20); the core was dominated by planktonic diatom species, including: *Asterionella formosa*, *Aulacoseira ambigua*, *Cyclotella* and *Discostella* species, *Fragilaria crotonensis*, *Stephanodiscus niagarae*, and *Tabellaria flocculosa* Strain IIIp (Figure 21). According to the constrained cluster analysis, the largest break in the samples occurred between 1950 and 1958, although when evaluated against a broken stick model, this was not shown to be a significant shift in the assemblage; there has been minimal change in the diatom community of Deer Yard Lake in the last 170 yrs. Around the 1950s there was a

decrease in the percentage of plankton (algae that live suspended in the water column) in the diatom community; the average percent plankton from 1846 to 1950 was 78% and the average dropped to 53% from 1958 to 2016. This change was driven by a decrease in the planktonic species *Fragilaria crotonensis*, *Stephanodiscus niagarae*, and *Tabellaria flocculosa* Strain IIIp and an increase in the tychoplanktonic species *Pseudostaurosira brevistriata* var. *inflata* and *Staurosira construens* var. *venter* (Figure 21). These tychoplanktonic species are primarily benthic or bottom-dwelling, but are often swept-up and suspended into the water column; many of these species are adapted to live on fine-grained sediments, such as those found in shallow lakes. This shift in the 1950s may have been indicative of a change in habitat in the lake.

Poplar Lake Core 1 – In the Poplar Lake core 1 NMDS biplot, there was no clear clustering of samples and no clear trajectory through time (with the possible exception of the three most recent samples plotting in the lower left region) (Figure 22). The gradients in this analysis were short, also indicating that there was little change in the diatom community throughout the core from this shallow bay.

The constrained cluster analysis, when evaluated against a broken stick model, showed no significant breaks. The largest break was between 1993 and 1999, although there were no obvious or large shifts in the community at this time (Figure 23). The diatom community averaged 71% plankton over the record; the most abundant planktonic species were *Asterionella formosa*, *Aulacoseira subarctica*, *Aulacoseria ambigua*, and *Tabellaria flocculosa* Strain IIIp.

Poplar Lake Core 2 – The NMDS biplot from the deep basin of Poplar Lake showed slightly more structure and change through time than core 1 (Figure 24). There was a division between the older samples (1871-1931) and the more recent samples (1949-2015).

The constrained cluster analysis showed the largest break at this same time (between 1931 and 1949), although this break was not significant when evaluated against a broken stick model (Figure 25). The diatom community in the deep basin was similar to that in the shallow bay. The deep basin was also dominated by plankton (ranged from 81 to 88% plankton throughout the core), and the predominant species were the same: *Asterionella formosa*, *Aulacoseira subarctica*, *Aulacoseira ambigua*, and *Tabellaria flocculosa* Strain IIIp. The community shift in the 1930s/40s was subtle, and included fluctuations in the relative abundance of the planktonic species, such as decreases in *Aulacoseira subarctica* and *Discostella stelligera*, and increases in *Cyclotella affinis*.

Overall, changes in diatom community assemblage in the Poplar Lake cores were minimal (Figure 26). Predominant species in the lake were mostly planktonic, but also included some tychoplanktonic and benthic species (Figure 27). The diatom *Tetracyclus glans* was found in Poplar Lake (Figure 27); this is only the second report of this diatom in Minnesota lakes, it is more commonly found in alpine lakes in the Rocky Mountains (Bright 1986).

RESULTS AND DISCUSSION - PHOSPHORUS RECONSTRUCTION

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

Another way to evaluate the reconstruction is to determine the amount of variance in the diatom

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

Deer Yard Lake – When passively plotted on the MN calibration set, the core sections show more movement along axis 2 than along the TP gradient (associated with axis 1) (Figure 28). This suggests that while nutrients may be driving some of the small changes in Deer Yard Lake diatoms, there are other drivers that are equally important in influencing diatom community turnover. Alternative drivers include: habitat alterations, changes in turbidity, 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.

In Deer Yard Lake, the fraction of the maximum explainable variation in the diatom data that can be explained by TP (λ_r/λ_p) was 0.48. This again suggests that TP may have played a role in diatom community change, but was not likely one of the most important drivers.

The TP reconstruction for Deer Yard Lake suggests that the lake has been mesotrophic since the mid-1800s (Figure 29). The reconstruction at the core top matches with modern measured values in the lake (diatom-inferred TP=23 $\mu\text{g/l}$, measured range=10-22 $\mu\text{g/l}$). These results suggest that the recent decreases in Secchi depth measurements in the lake have not been due to increases in TP.

Poplar Lake Core 1 - Passive plotting of the Poplar Lake core from the shallow bay on the MN calibration set showed some movement along the TP axis, but even more movement along axis 2 (Figure 30). Again, these results suggest that while nutrients may be driving some of the diatom turnover in the lake, there are other drivers (such as habitat alterations, or changes in turbidity) that are equally important in influencing diatom community turnover.

The fraction of the variation in the diatom data that can be explained by TP (λ_r/λ_p) was 0.73 for the shallow bay of Poplar Lake. Although this suggests that TP may have been a driver of change, it is also important to recognize that there was very little diatom change throughout the length of this core (Figures 22 and 23); therefore, the implication that TP is driving lake change should not be over interpreted.

The diatom-inferred TP (DI-TP) reconstruction for Poplar Lake core 1 showed that the lake has been mesotrophic since the mid-1800s (Figure 31). Diatom-inferred TP values at the core top (21 $\mu\text{g/l}$) are slightly higher than recent measured values (8-15 $\mu\text{g/l}$), although they both suggest that the lake is mesotrophic.

Poplar Lake Core 2 – When passively plotted on the MN calibration set, the core sections from the deep basin of Poplar Lake primarily show movement along axis 2 (Figure 32). The λ_r/λ_p score for this core was 0.48. Both of these results suggest that TP was likely not a primary driver of diatom community change.

The TP reconstruction for this deep central basin showed similar results to those from the shallow bay; again, suggesting that this part of the lake has been mesotrophic since the mid-1800s (Figure 33). There is a suggestion that there was a slight rise in DI-TP in the 1950s/60s. However, this is a very small increase that does not exceed the model error; in addition, the λ_r/λ_p score was low for this lake, which indicates that the DI-TP should be interpreted with caution. Therefore, this rise should not be over-interpreted, but should provide a note of caution that among the lakes

or lake areas studied here, the deep basin of Poplar is the only core that suggested any trend in increased nutrients.

As with the core 1 results, the DI-TP at the top of the core put the lake in the mesotrophic range, which was in line with modern TP measurements.

RESULTS AND DISCUSSION - HISTORICAL ALGAL COMMUNITIES

Deer Yard Lake – Total algal production, as measured by chlorophyll *a*, showed a rise beginning in the 1970s and continuing through 2014 (Figure 34). This rise appeared to be largely driven by increases in diatoms, as the concentration of other algal pigments remained mostly constant throughout the core.

Some types of cyanobacteria (blue-green algae) have been present in Deer Yard Lake since the 1800s. However, the cyanobacterial pigments have been lower in concentration than those from other algal groups, and their concentration has not changed dramatically over the record. Importantly, there was no indication in Deer Yard Lake of historical or current problems with noxious cyanobacterial blooms.

The pigment okenone, from purple sulfur bacteria, is an indication of anoxic and clear-water conditions; this pigment was not detected in any of the samples from Deer Yard Lake.

Poplar Lake Core 1 – In the core from the shallow bay of Poplar Lake there was a slight rise in overall algal abundance beginning in the 1970s and continuing through 2013 (Figure 35). As with Deer Yard Lake, the rise seemed to be driven by an increase in diatoms, and the pigment concentrations of most other algal groups remained relatively constant throughout the core.

The pigments of several types of cyanobacteria were present throughout the core, including a nitrogen-fixing form (canthaxanthin) and pigments from potentially toxic forms (myxoxanthophyll); however, these pigment concentrations were lower than those of other algal groups, and have remained constant since the 1800s. Their presence in Poplar Lake should be considered normal, but treated with a watchful eye in the future for any increased abundance of cyanobacteria.

Poplar Lake Core 2 – There was a rise in overall algal abundance in the most recent sample (2011) from the deep basin of Poplar Lake (Figure 36). In this core, there was a slight decrease in pigments exclusive to diatoms in the most recent decades, but other algal groups remained relatively constant since the mid-1800s.

The cyanobacterial groups showed the same pattern as in Poplar core 1. Pigments from nitrogen-fixing forms (canthaxanthin) and potentially toxic forms (myxoxanthophyll) were both present; however, the concentrations were lower than other algal groups, and they remained constant throughout the core.

CONCLUSIONS AND RECOMMENDATIONS

Sediment accumulates in the bottom of every lake; that mud preserves a history of how each lake has changed over time in response to what has happened in the lake, in the lake's watershed, and globally. We recovered 1-1.4 m long cores, one from Deer Yard Lake (near Lutsen, Cook County, MN) and two from separate locations in Poplar Lake (near Grand Marais, Cook County, MN) in October 2016. The cores were subjected to multiple chemical and biological analyses to better understand the last 150-200 years of history of these lakes. Overall, both lakes had very slow sedimentation rates, showed small impacts from initial logging in the region, showed

little landuse change in their forested watersheds in the last 80 years, and did not show dramatic changes in nutrient condition or algal communities over the last 150-200 years.

The monitored trend of decreasing Secchi depth, or decreasing clarity, in Deer Yard and Poplar lakes indicates something is changing in these lakes. Three things generally cause a decrease in water clarity: more algae growth in the water, more sediment in the water, or the color of the water. The cores suggest that algae communities nor sedimentation have dramatically changed, leaving color shifts due to browning of the lakes (transport of colored compounds called dissolved organic carbon, DOC) as a possible concern for the lakes. This is a global problem in northern lakes referred to as lake “browning” (Monteith et al. 2007; Solomon et al. 2015; Williamson et al. 2015) and monitoring for long-term changes in DOC should be encouraged.

Conclusions from the study, as well as management recommendations for each lake, are presented separately below:

Deer Yard Lake – Deer Yard Lake is a long shallow single basin lake with a “deep” hole of approximately 6 m or 20 ft depth. The lead-210 dating model showed that the top 10 inches (25 cm) of sediment from that hole preserve almost 140 years of lake history. Sedimentation rates showed two changes in the last 150 years. There were small increases in the 1870s and 1930s that were likely related to early fires or logging in the region. Sedimentation rate increased again after the 1980s to current levels that are 2-3 times pre-Euroamerican rates. Deer Yard sediments were primarily inorganic material (65%) and organics (35%), typical of many Minnesota lakes; however, there was little change in sediment character in the core, suggesting that sediment sources have not changed to the lake. Biogenic silica (BSi), a measure of diatom algae, represented 35-40% of sediment weight, over half of the inorganic material in the core; BSi concentration also changed little in the last 150 years suggesting that diatom production has not appreciably changed in Deer Yard. Diatom accumulation did increase slightly since the 1980s. Phosphorus concentration in the sediments increased slightly upcore due to increased labile organic P; however, the key types of P that drive internal loading did not increase upcore, indicating that there have not been large changes in the nutrient budget nor increased threat of internal loading. Throughout the 15 core sections analyzed for diatoms, 174 taxa were found. Historical diatom communities showed a small shift in the 1950s to fewer planktonic species. This shift was, however, not significant and suggests only minor habitat changes in the lakes (possibly related to forest regrowth or stronger periods of stratification). When diatom communities downcore were used to estimate historical TP levels in Deer Yard Lake, they showed no significant changes or trends in the last 150 years; Deer Yard has long been a mesotrophic lake with TP levels reaching the low 20 ppb range. Finally, fossil algal pigments confirmed the long-term stability of Deer Yard Lake, as pigment records did not show major changes in algal communities, and in particular did not show any evidence of increased cyanobacteria (blue-green algae) growth.

Management recommendations for Deer Yard Lake include participation in citizen monitoring programs to help detect any trends in lake condition, continued sound management of lakeshore properties including regular septic maintenance, maintaining shoreline buffers, minimizing use of chemical in lawns, driveways, and roads, cautious new development or landuse in the watershed, and preventing introduction of aquatic invasive species. It would be valuable to get Deer Yard on a regular monitoring schedule so that full water quality can be measured every 4-6 years, including starting to monitor DOC concentrations in the lake. The lake is currently being maintained in a condition where it has been for the last 150 years, and the goal is to keep it on that trajectory.

Poplar Lake – Poplar Lake is a large multibasin lake characterized by several deep central

basins (>60 ft or 20 m) and many shallower embayments (<30 ft or 10 m). Two cores recovered from Poplar helped to differentiate the environmental histories of the deeper basins from the shallower embayments. Both cores from Poplar Lake had very slow sedimentation rates, with the shallow Core 1 having the last 140 years of sediment accumulation in the top 20 cm (8 inches), and deep Core 2 having that same time period in only 18 cm (7 inches). Many lakes in the urban and agricultural regions across Minnesota have accumulated 4-6 feet of sediment in that same timeframe. Even in the Northern Lakes and Forests ecoregion, there is a range of sediment accumulation rates. For example, Net Lake (Carlton/Pine Co.) and LacLaBelle (Carlton Co.) had 22 cm and 57 cm in the last 150 years, respectively. The low sedimentation rate seen in the lakes in this study is the combined effect of 1) minimal erosion, 2) relatively low lake productivity, and 3) the depositional areas of the lake that accumulate sediment are very large (i.e. sediment accumulates in a large area across the basin rather than a narrow deep trench). Sedimentation rates in both the shallow and deep core showed small increases during the time of Euroamerican settlement and logging, a common watershed response in northern Minnesota lakes, and further increases in sedimentation rates after the 1980s. Regardless of core location, Poplar Lake sediment was primarily inorganic, 55-60% in shallow regions, 60-65% inorganic in deeper regions. Organics made up the next dominant fraction with the shallow core having slightly more content (35%) compared to the deep site (25-30%). Importantly neither core showed dramatic changes in sediment character, indicating that sources of sediment to the lake remain unchanged. Both cores had approximately 30% biogenic silica (BSi) so that over half of their inorganic matter was diatom algae produced in the lake. BSi concentration showed minimal trend in either core, although there was a slight increase in BSi accumulation after the 1980s in both cores from increased diatom growth. Total phosphorus concentrations differed between cores. The shallow core showed no change in TP concentration and especially no upcore increase in P fractions involved in internal nutrient loading. In contrast, the deep core showed a spike in P concentration at the sediment surface including increased concentration of Fe-bound P that may help fuel internal loading. In the core from the deep basin of Poplar Lake, 178 diatom taxa were found throughout the 15 core sections analyzed, and 222 taxa were found throughout the shallow core. Diatom communities in both cores were dominated by planktonic forms during the last 200 years. The most notable characteristic of the two cores was that the diatom communities showed very minimal change. This is rarely encountered in Minnesota lakes; rather the diatoms frequently show dramatic changes in response to lake and watershed perturbations. When the diatom communities in the cores were used to estimate historical levels of TP, both cores showed that Poplar Lake has long been a mesotrophic system, with TP levels reaching the high teens to low 20s ppb TP. The deep Poplar core showed a slight increase in TP after the 1960s; however, the increase was not greater than model error. Algal pigment records preserved in the cores similarly showed minimal change in Poplar's algal communities. While there was evidence of the long-term presence of potential bloom-forming cyanobacteria, their levels did not indicate any historic or recent threat of noxious cyanobacterial blooms.

Management recommendations for Poplar Lake are to proceed with vigilance. Continue citizen and agency monitoring programs so that changes in water quality trends can be detected and responded to. Agency monitoring should include DOC to better understand potential changes in lake color due to browning. Lakeshore owners should continue to be excellent stewards of the lake by controlling runoff, minimizing use of fertilizers and chemicals, maintaining excellent septic systems, approaching development and landuse with caution, and keeping shoreline buffers intact. Wilderness users should follow backcountry guidelines for protecting the lake. Lake users should be made aware of the threat of aquatic invasives, and all efforts should be made to prevent their introduction to Poplar Lake. The lake currently is a high value resource and shows minimal change in water quality, sedimentation, and algae communities in the last 150 years. Do everything to keep it that way.

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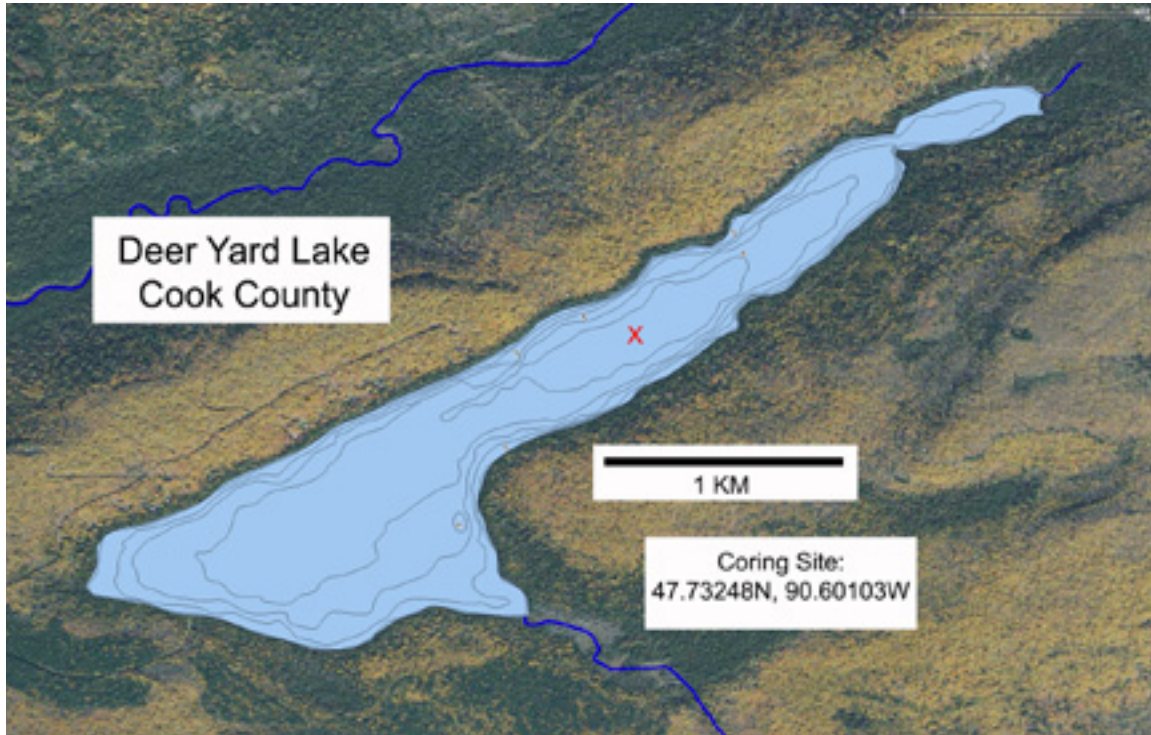
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Table 1. Location of each core collected, core type, water depth at core site, and sediment recovered.

Lake	Lat (N)	Long (W)	Core Type	Water Depth (m)	Recovery (m)
Deer Yard	47.73251	90.60109	Piston	6.17	1.02
Poplar (Core 1)	48.05287	90.53488	Piston	9.36	1.03
Poplar (Core 2)	48.04571	90.49409	Piston	21.16	1.40

Figure 1. Bathymetric maps of a) Deer Yard Lake and b) Poplar Lake; coring sites are denoted with a red "X". In Poplar Lake, core site 1 is on the west side of the lake, and core site 2 on the east.

a)



b)

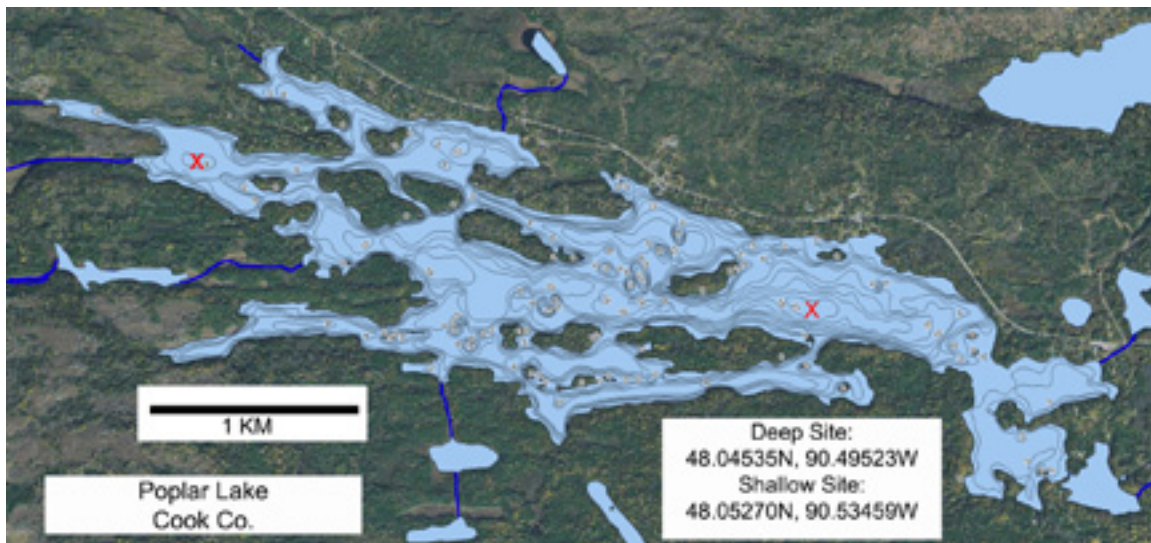


Figure 2. Aerial photographs of Deer Yard Lake from 1934 and 1982. Google Earth image of modern day Deer Yard Lake.

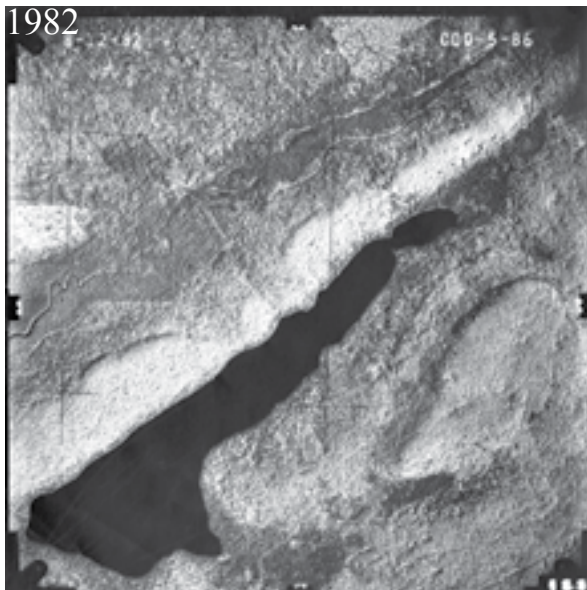
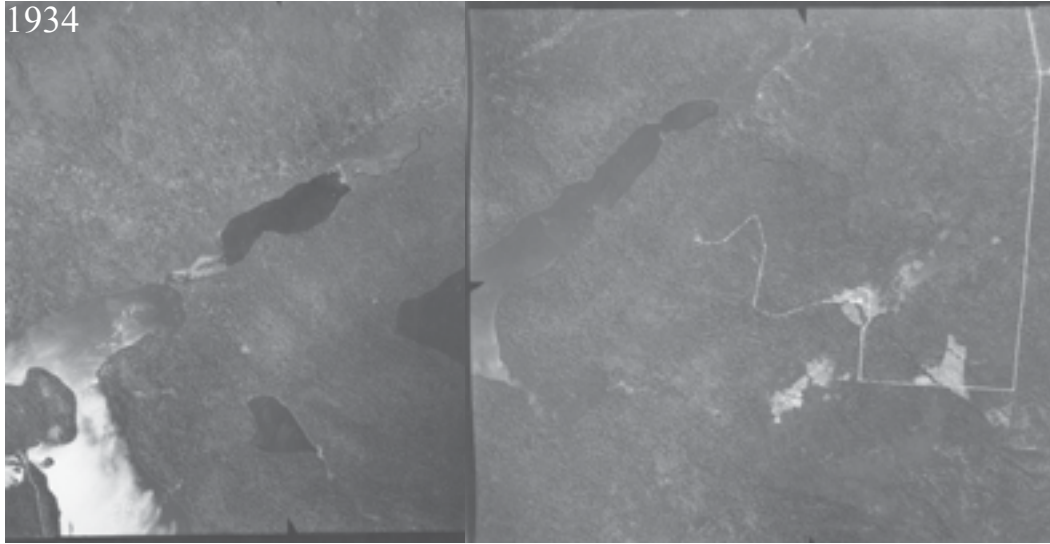


Figure 3. Aerial photographs of Poplar Lake from 1934 and 1982. Google Earth image of modern day Poplar Lake.

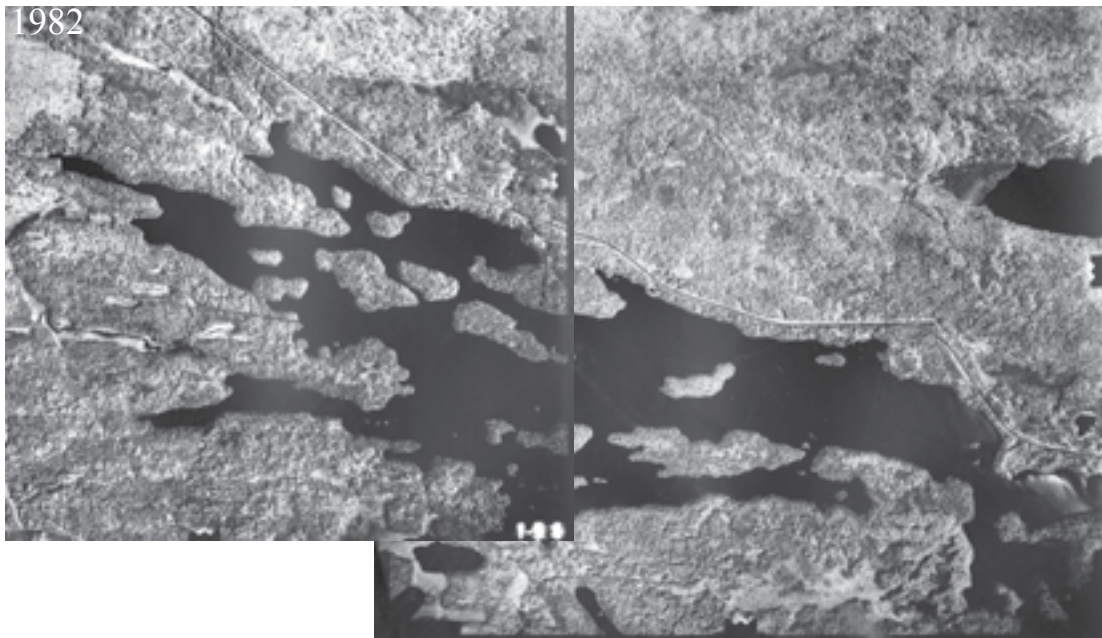
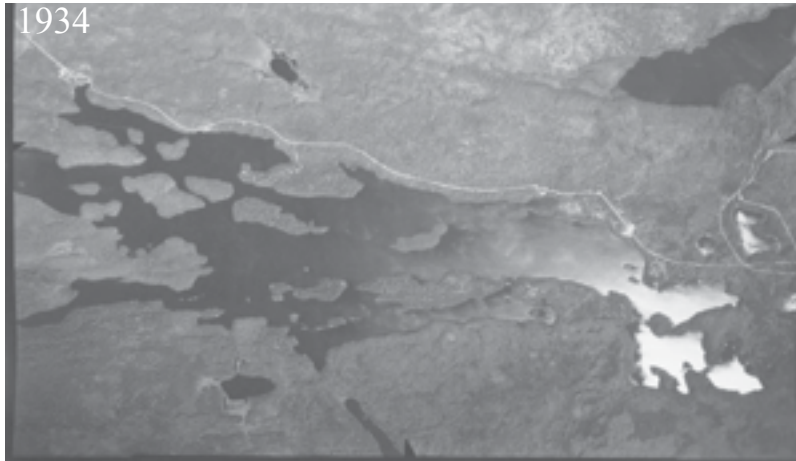


Figure 4. Unsupported lead-210 activity (a), lead-210 dating model (b), and sediment accumulation rate (c) for Deer Yard Lake.

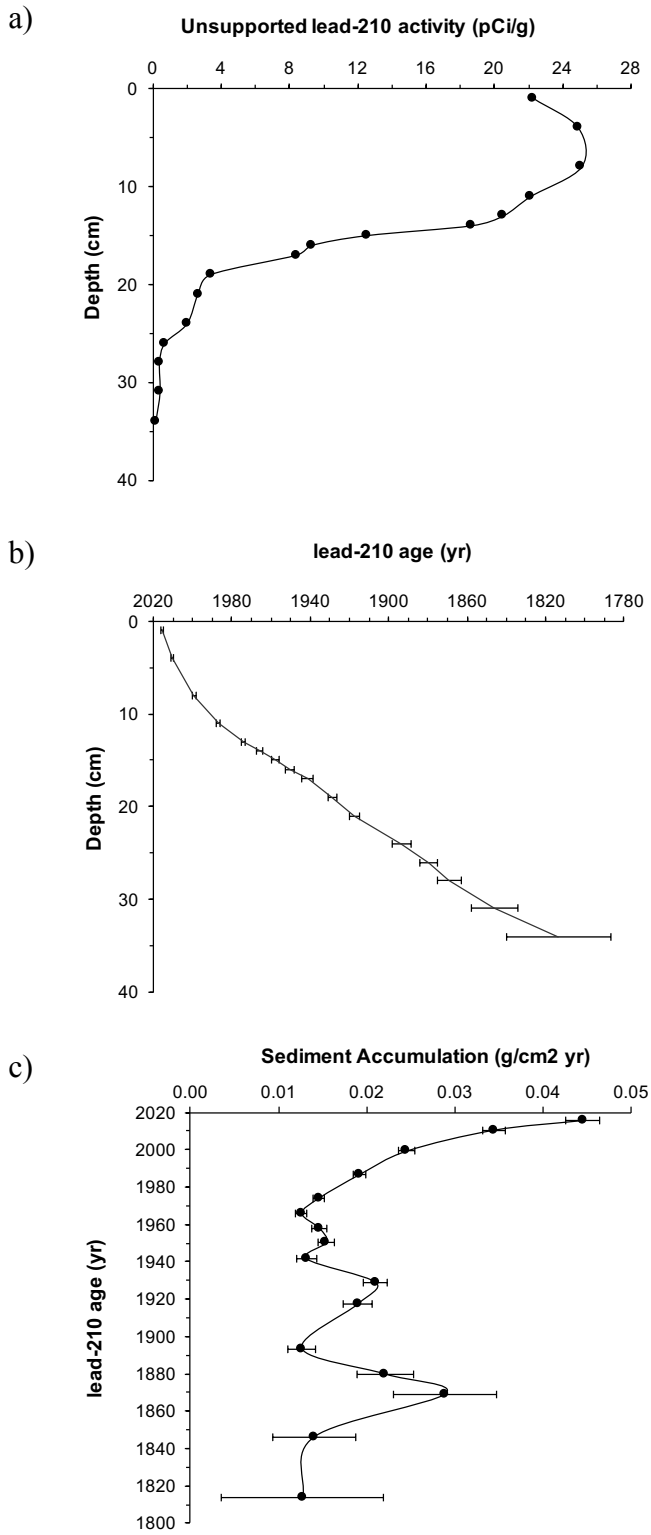


Figure 5. Unsupported lead-210 activity (a), lead-210 dating model (b), and sediment accumulation rate (c) for Poplar Lake core 1; d-f, the same results for Poplar Lake core 2.

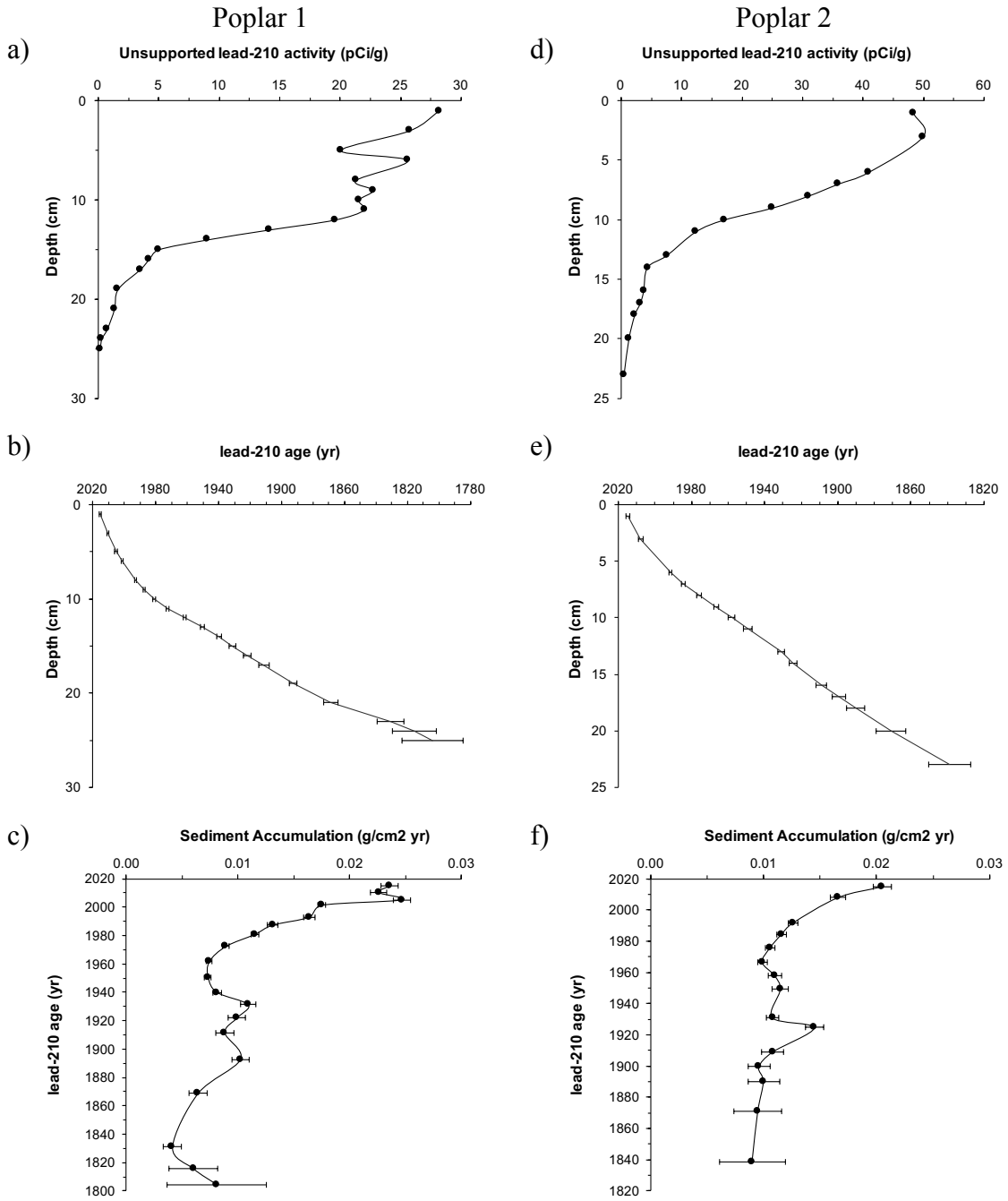


Figure 6. a) Percent dry weight of organic matter, inorganic matter, and carbonate (CaCO₃) in the Deer Yard Lake core plotted against depth in the sediment. b) Sediment flux of organic matter, inorganic matter, and carbonate (CaCO₃) to the Deer Yard Lake core. Flux was only calculated for the length of the core within the lead-210 record (0-34 cm).

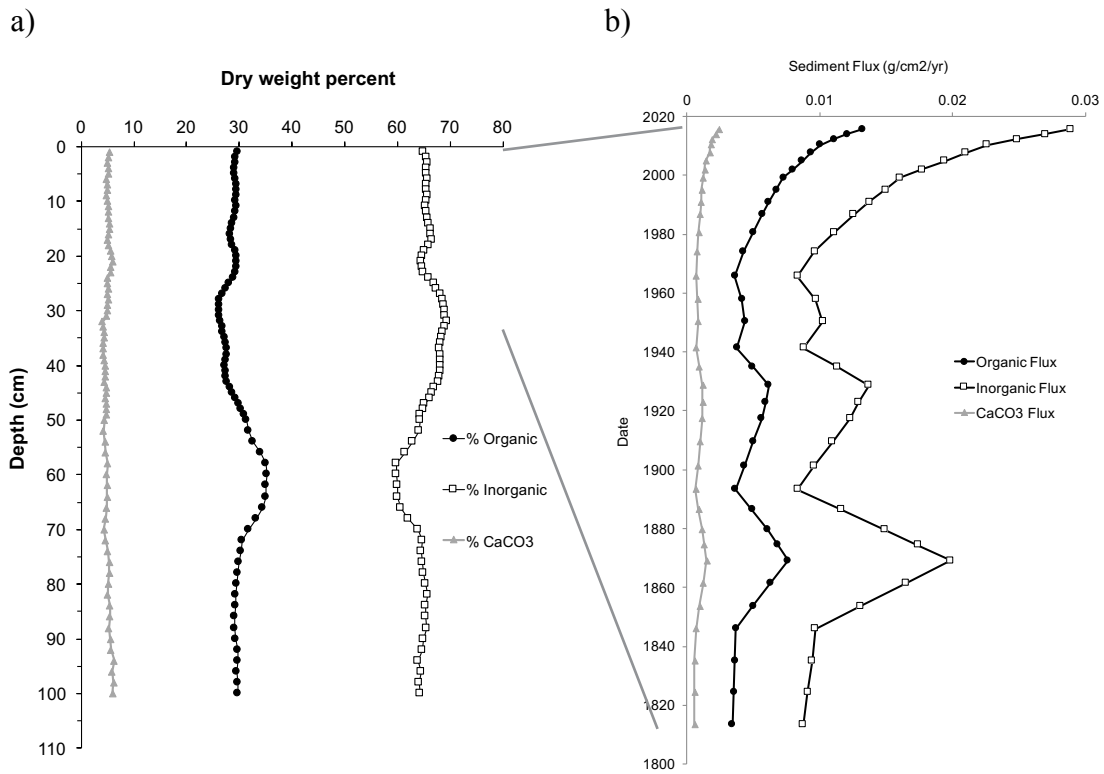


Figure 7. a) Percent dry weight of organic matter, inorganic matter, and carbonate (CaCO₃) in core 1 from Poplar Lake plotted against depth in the sediment. b) Sediment flux of organic matter, inorganic matter, and carbonate (CaCO₃) to core 1 from Poplar Lake. Flux was only calculated for the length of the core within the lead-210 record (0-25 cm).

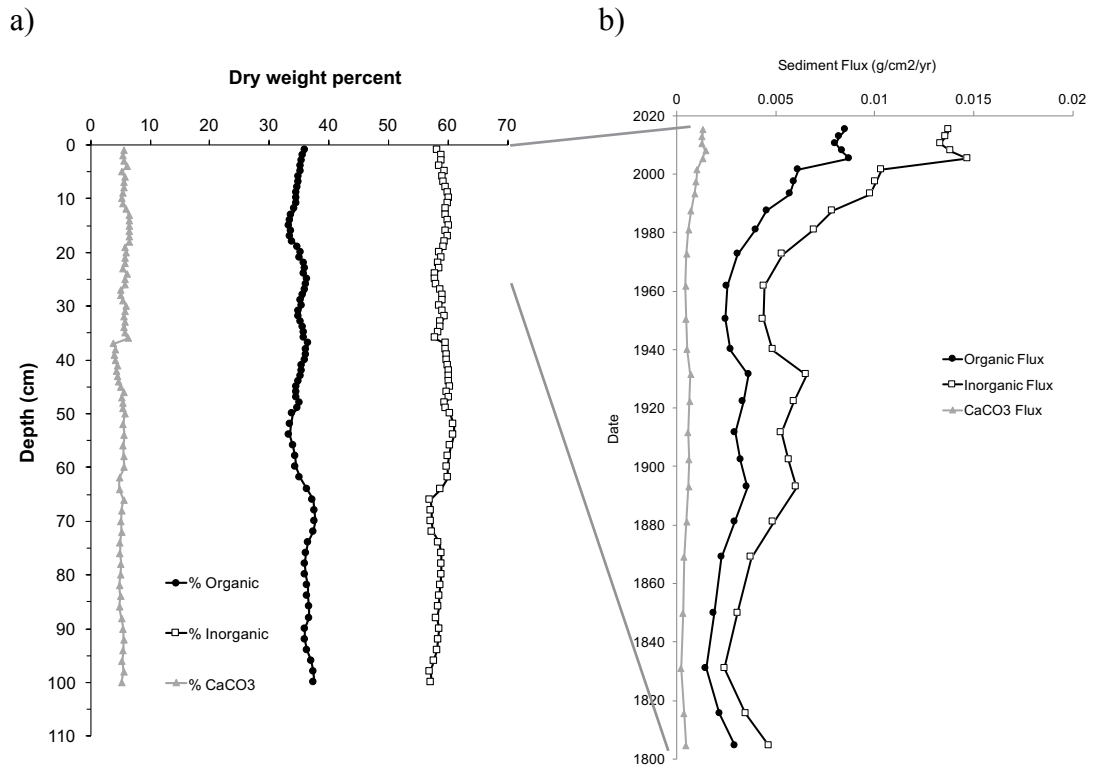


Figure 8. a) Percent dry weight of organic matter, inorganic matter, and carbonate (CaCO₃) in core 2 from Poplar Lake plotted against depth in the sediment. b) Sediment flux of organic matter, inorganic matter, and carbonate (CaCO₃) to core 2 from Poplar Lake. Flux was only calculated for the length of the core within the lead-210 record (0-23 cm).

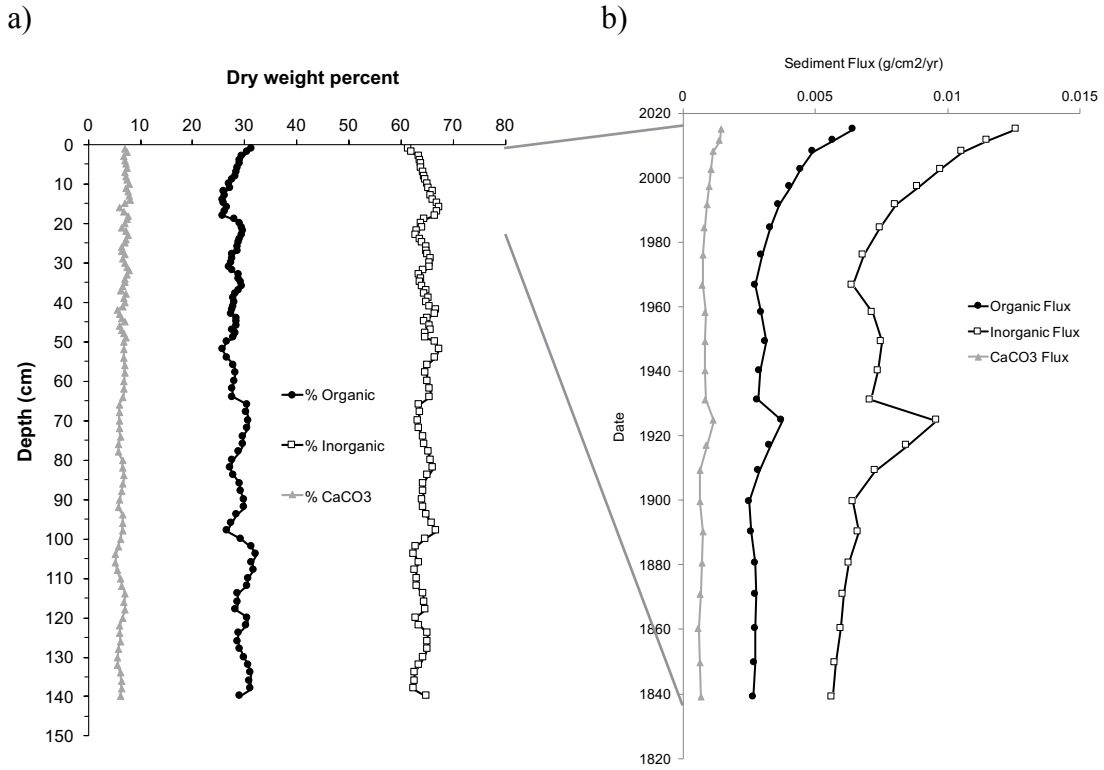


Figure 9. Weight percent of biogenic silica (BSi) (a) and SiO₂ flux (b) in the Deer Yard Lake core.

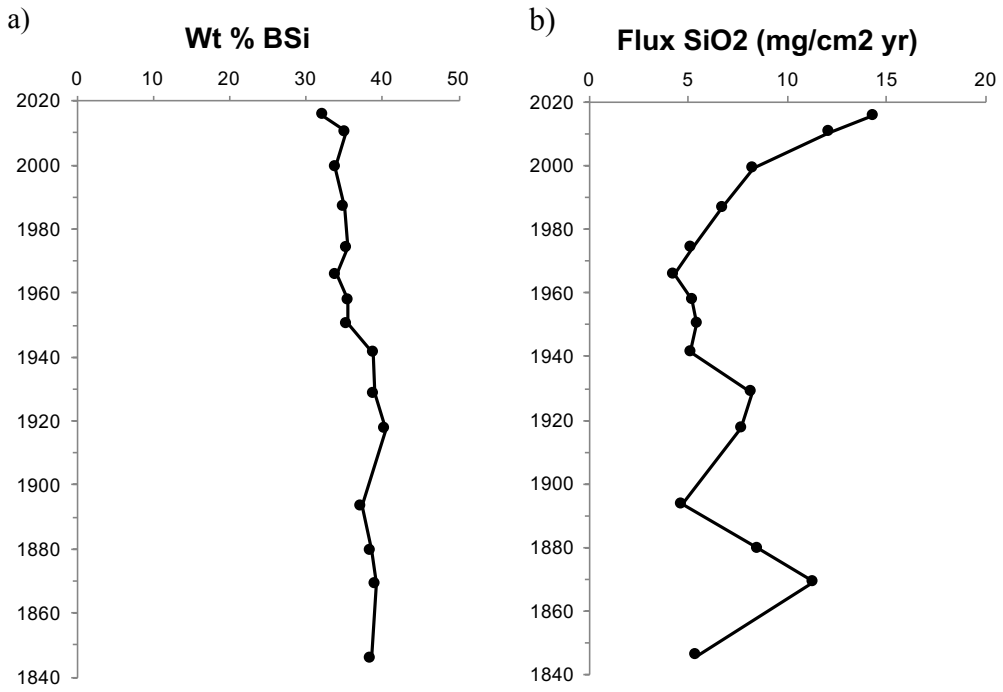


Figure 10. Concentration (a) and flux (b) of total phosphorus in the Deer Yard Lake core.

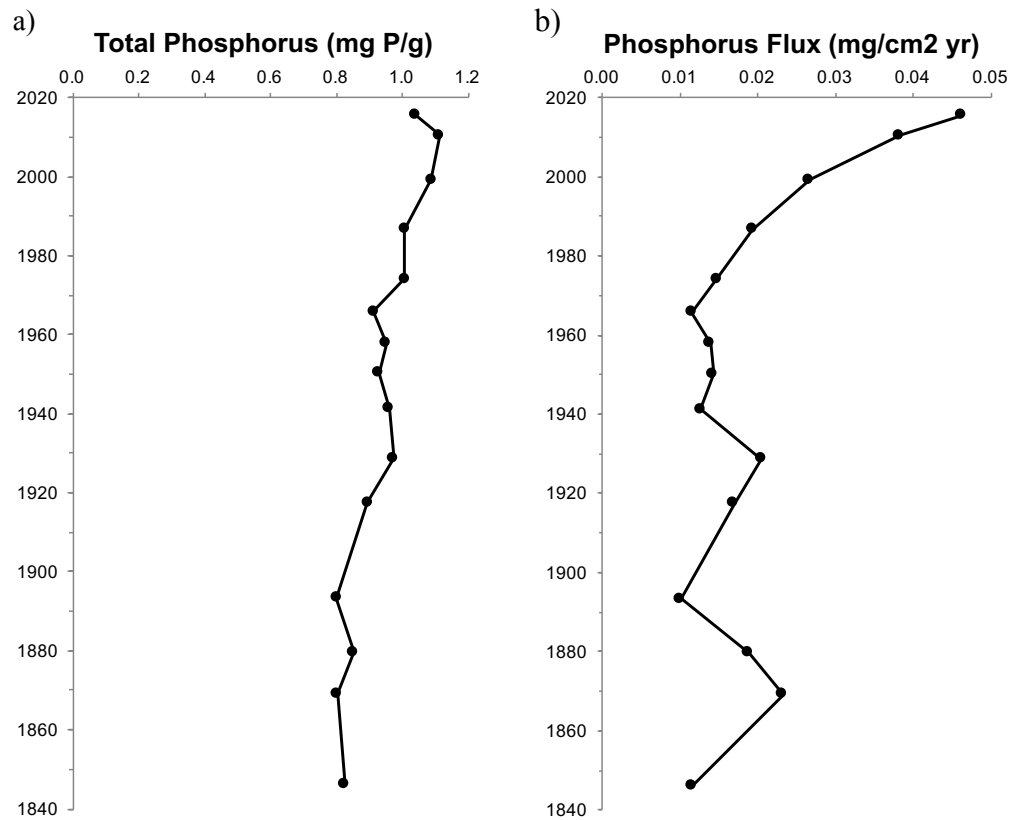


Figure 11. Concentration (a) and flux (b) of phosphorus fractions in the Deer Yard Lake core.

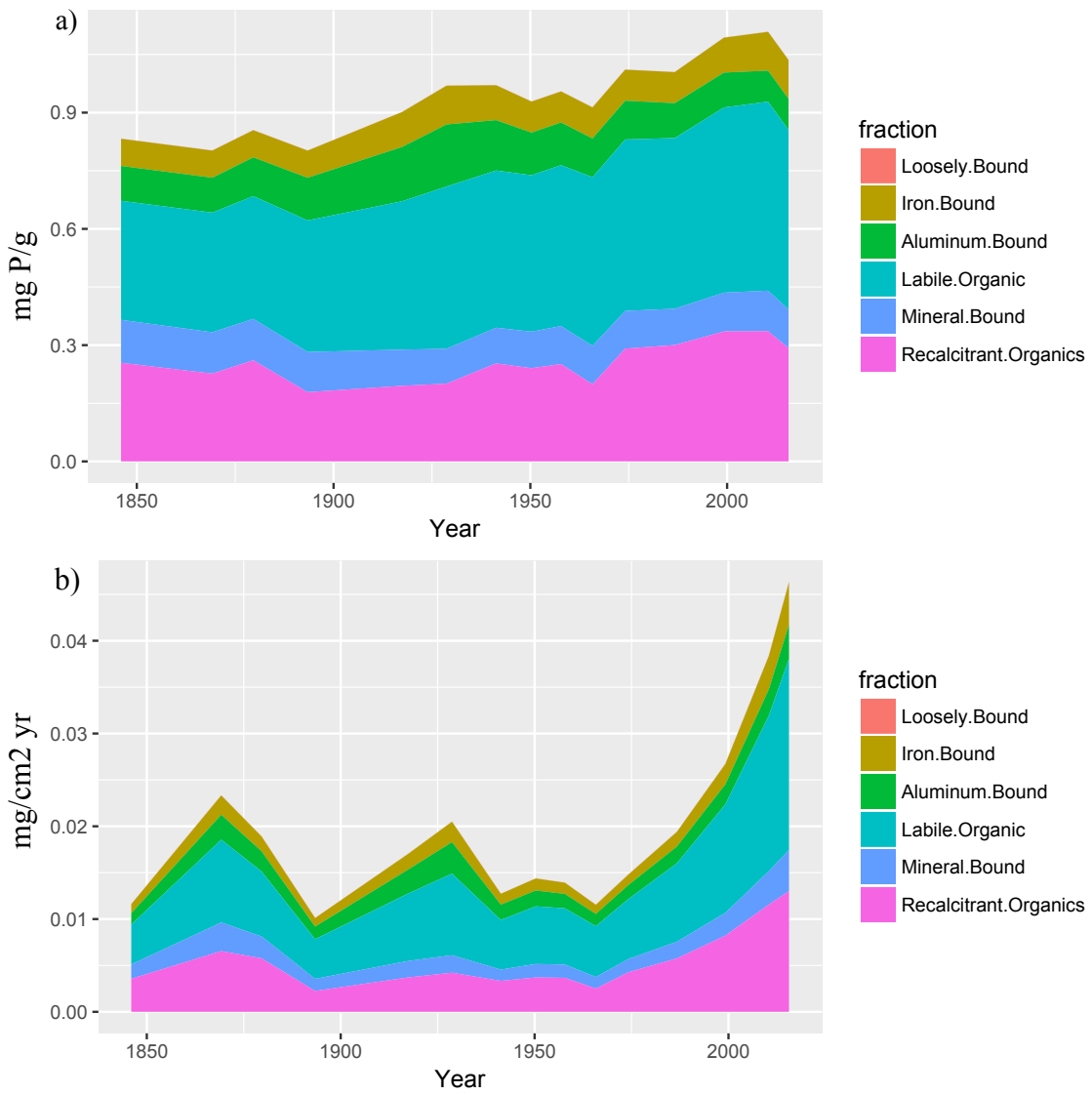


Figure 12. Weight percent of biogenic silica (BSi) (a) and SiO₂ flux (b) in Poplar Lake core 1.

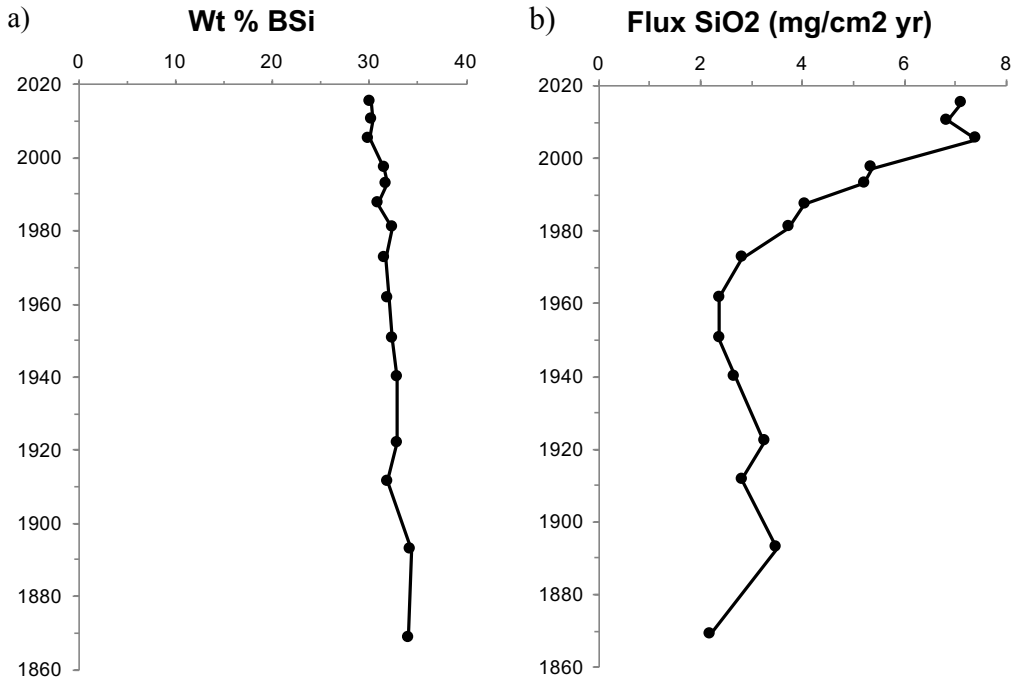


Figure 13. Concentration (a) and flux (b) of total phosphorus in Poplar Lake core 1.

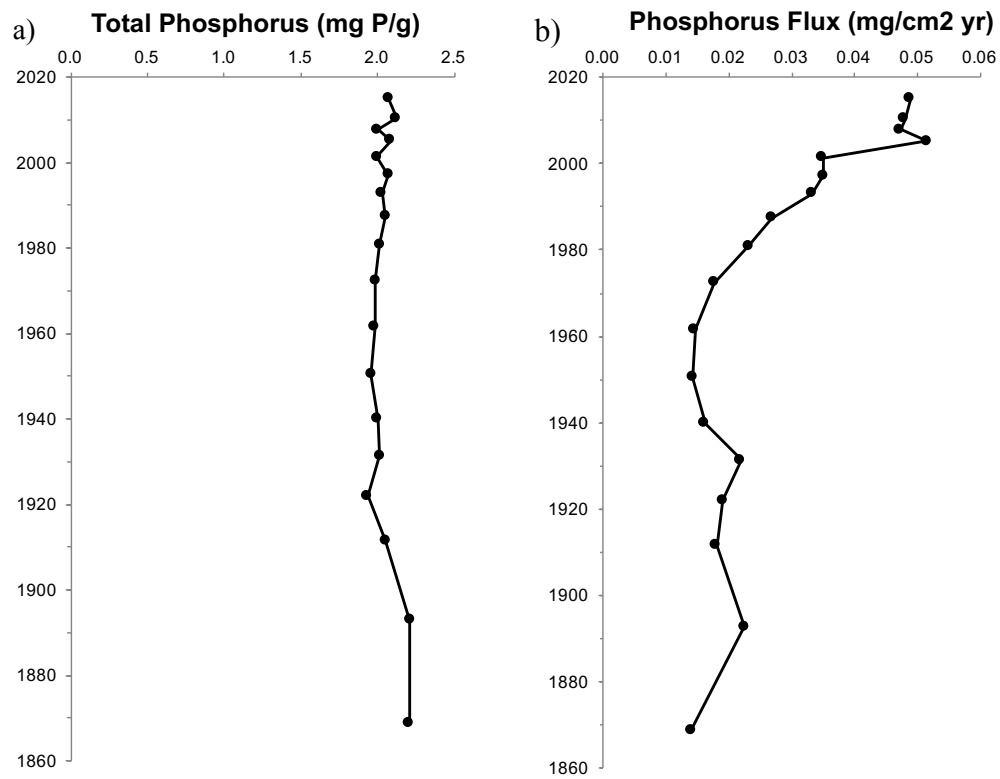


Figure 14. Concentration (a) and flux (b) of phosphorus fractions in Poplar Lake core 1.

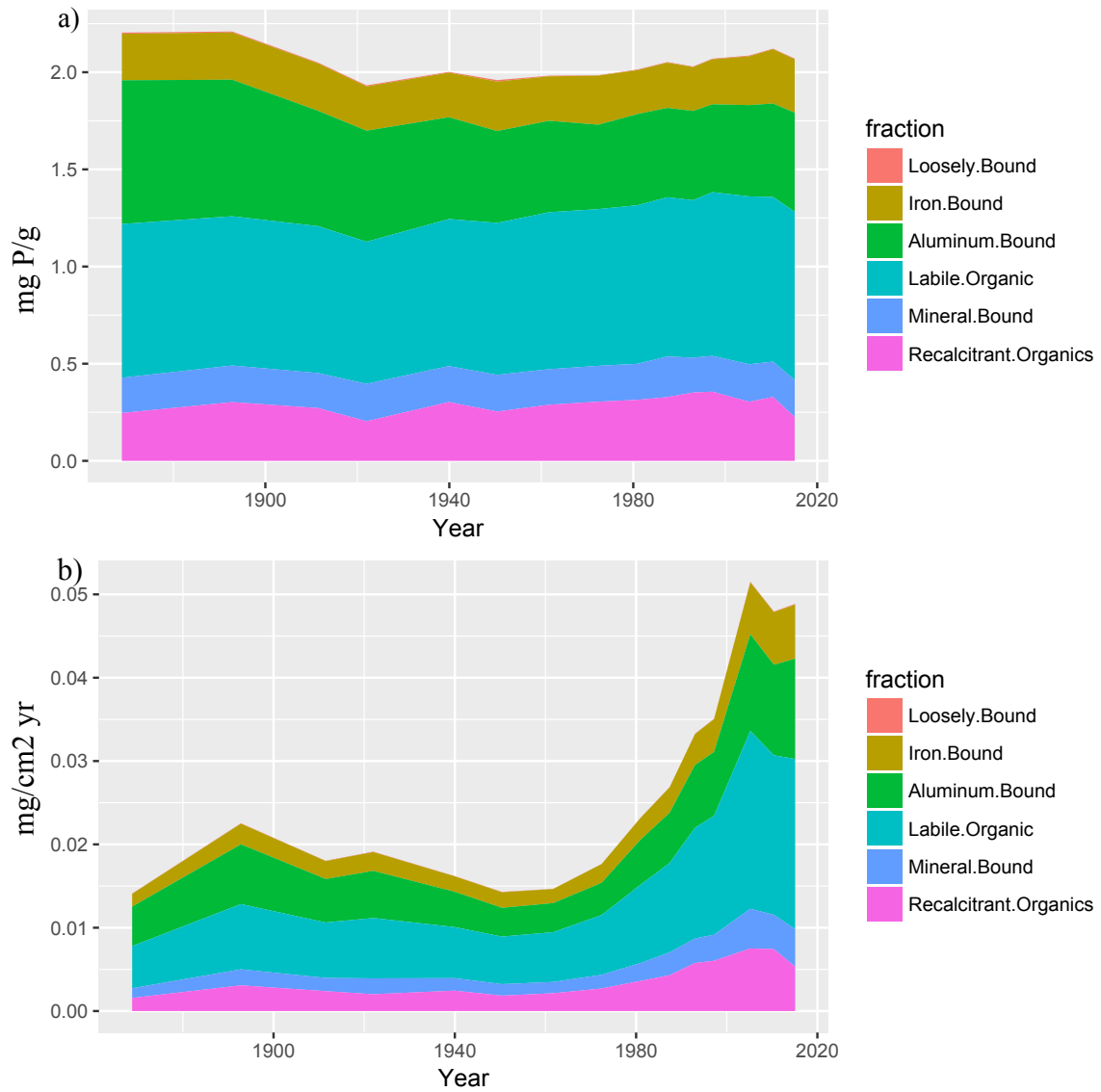


Figure 15. Weight percent of biogenic silica (BSi) (a) and SiO₂ flux (b) in Poplar Lake core 2.

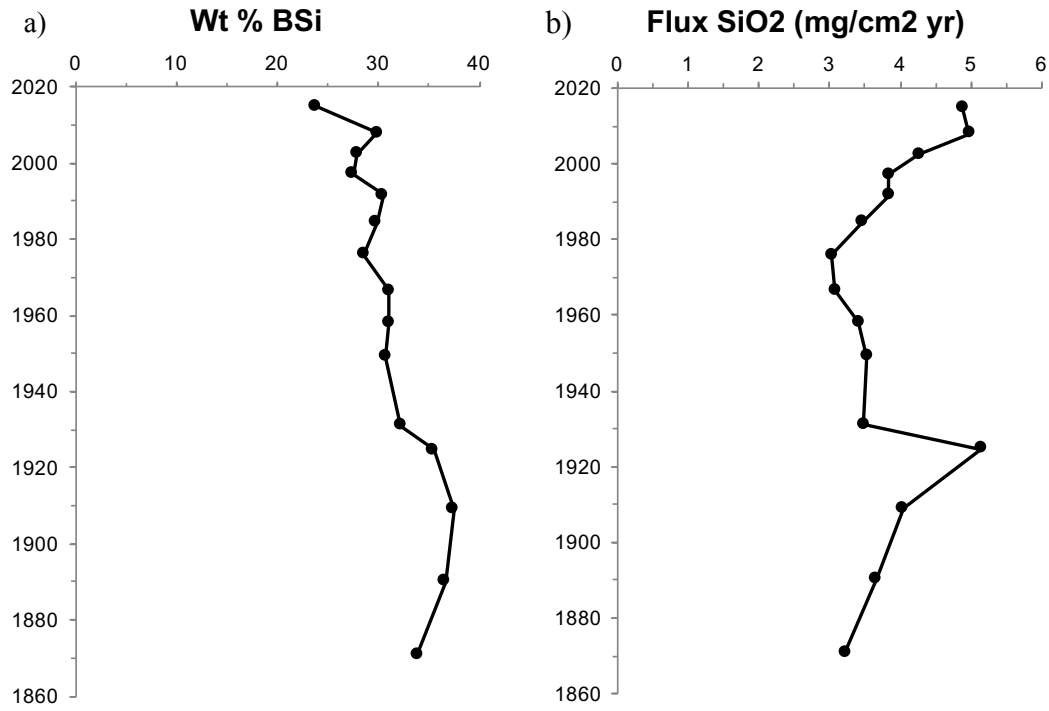


Figure 16. Concentration (a) and flux (b) of total phosphorus in Poplar Lake core 2.

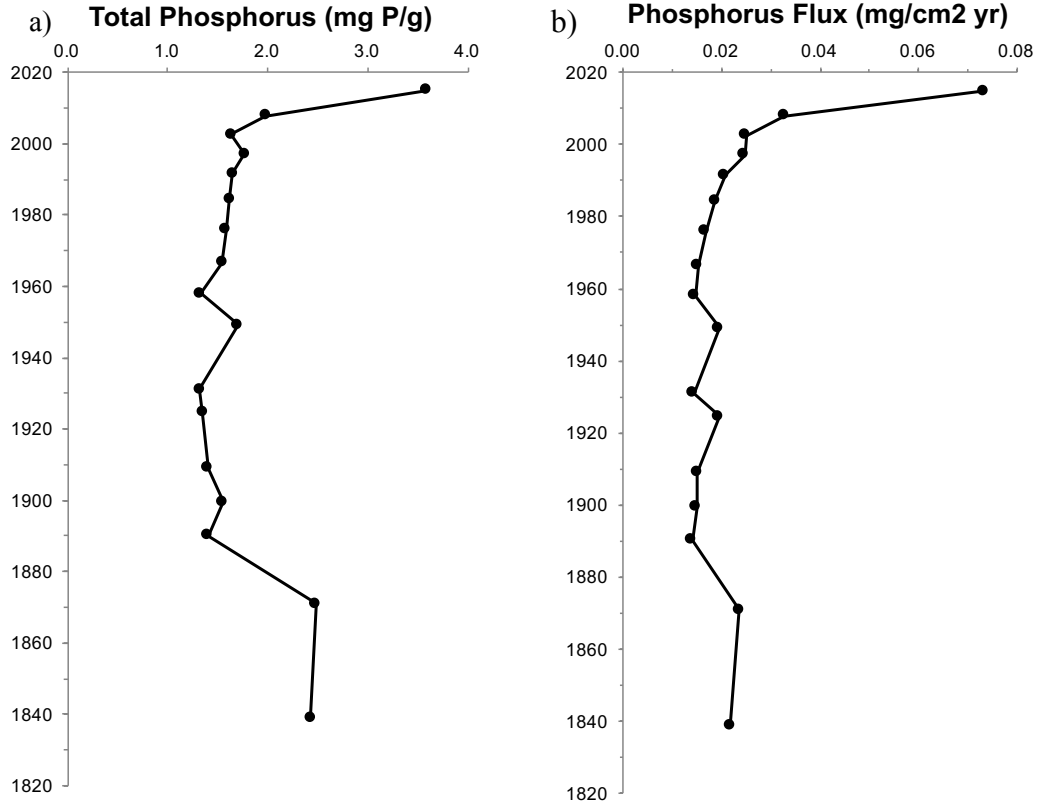


Figure 17. Concentration (a) and flux (b) of phosphorus fractions in Poplar Lake core 2.

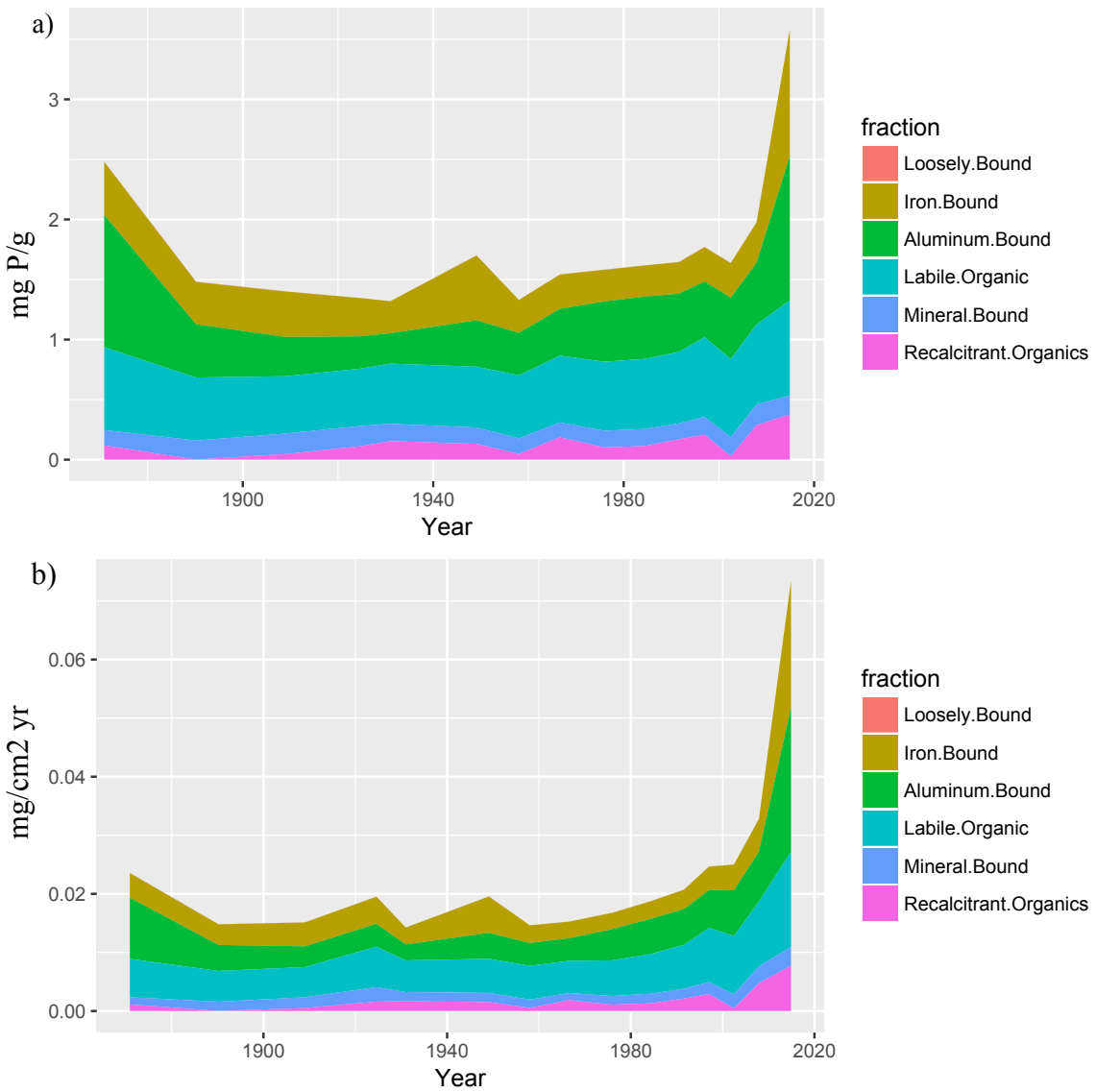


Figure 18. Non-Metric Multidimensional Scaling (NMDS) biplot of diatom communities from Deer Yard Lake (1846-2016) (k=2, stress=0.0639).

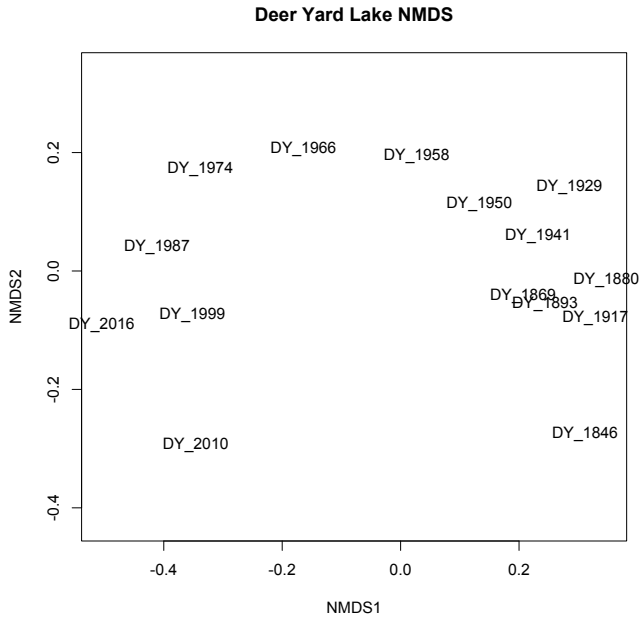


Figure 19. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance), results of a constrained cluster analysis, and percent plankton in Deer Yard Lake (1846-2016).

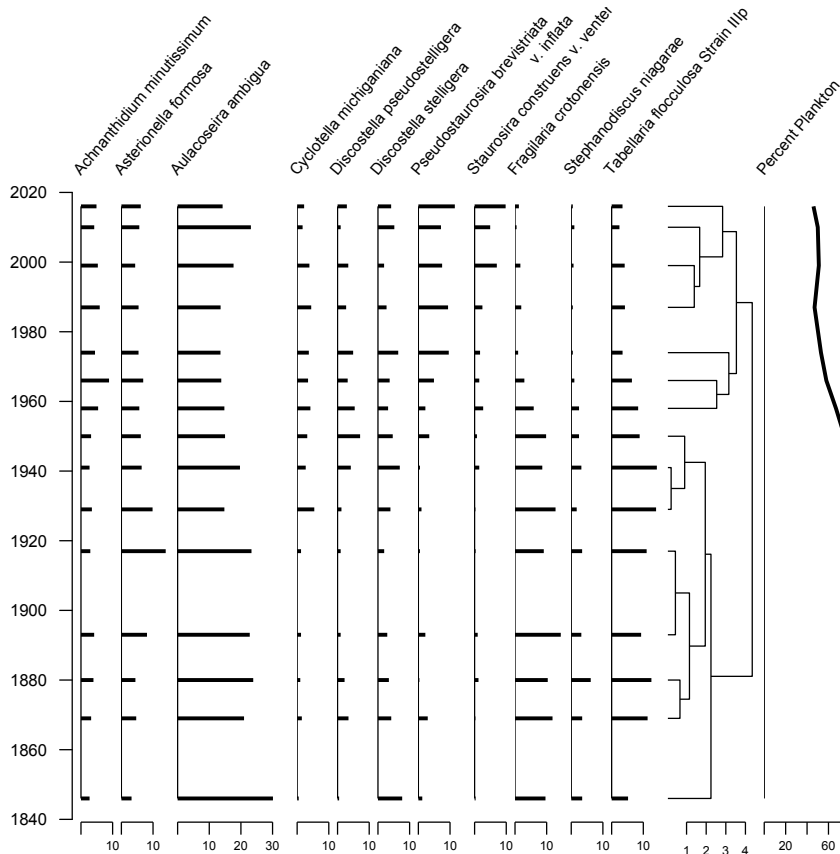


Figure 20. Changes in Deer Yard diatom communities are subtle between the late 1800s (left) and the 2000s (right).

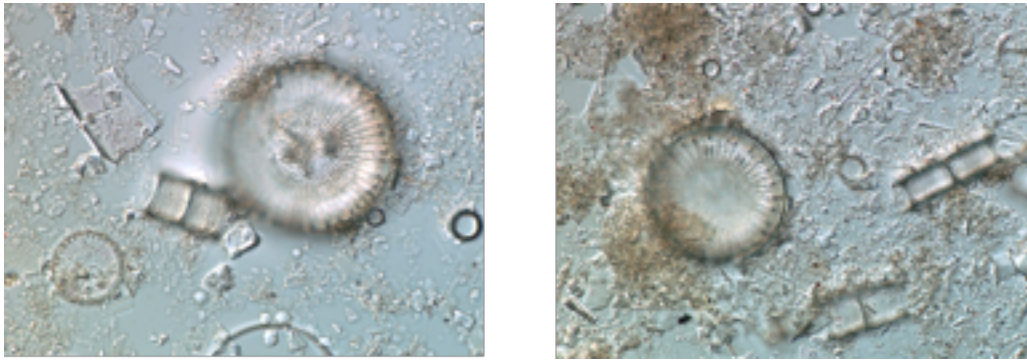


Figure 21. Predominant diatoms in Deer Yard Lake include *Aulacoseira ambigua* (A, F), *Asterionella formosa* (J), *Achnanthydium minutissimum* (C), *Discostella stelligera* (B), *Pseudostaurosira brevistriata* v. *inflata* (G), *Fragilaria crotonensis* (H), *Tabellaria flocculosa* IIIp (I), and *Staurosira venter* (D, E).

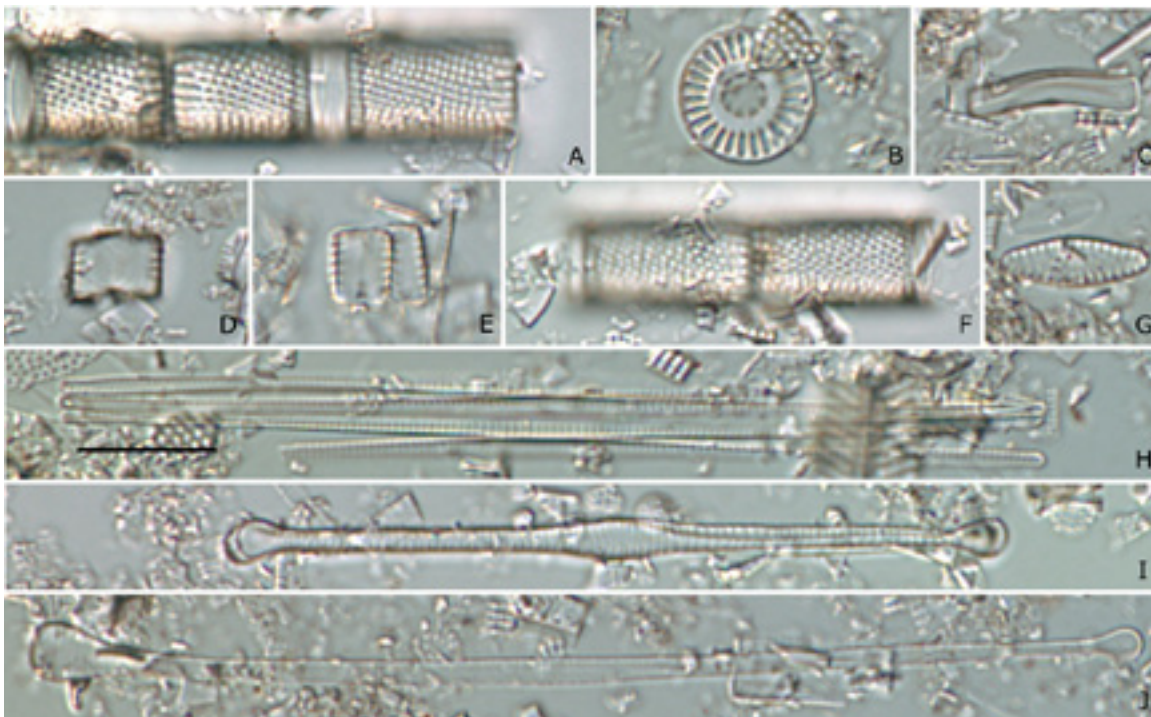


Figure 22. Non-Metric Multidimensional Scaling (NMDS) biplot of diatom communities from Poplar Lake core 1 (1869-2015) (k=2, stress=0.1823).

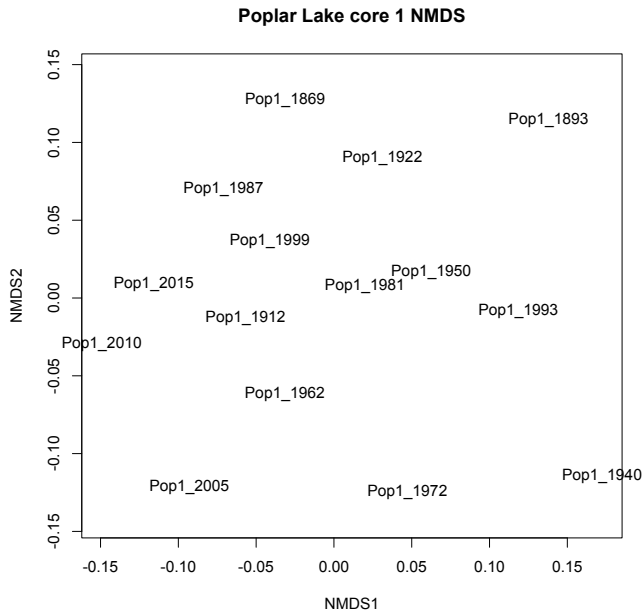


Figure 23. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance), results of a constrained cluster analysis, and percent plankton in Poplar Lake core 1 (1869-2015).

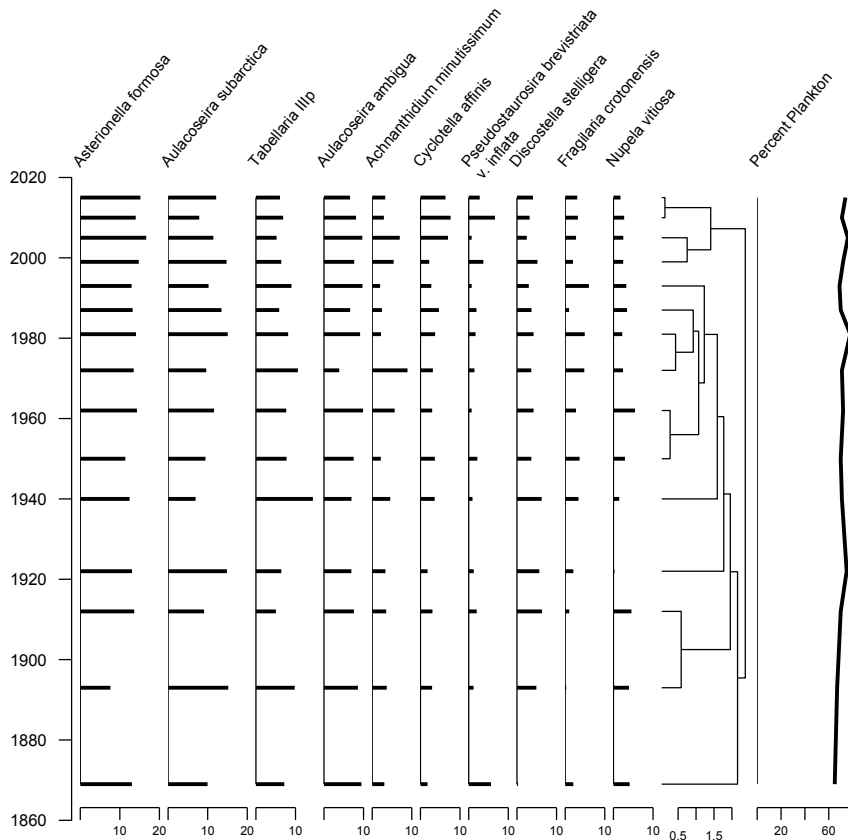


Figure 24. Non-Metric Multidimensional Scaling (NMDS) biplot of diatom communities from Poplar Lake core 2 (1871-2015) (k=2, stress=0.1034).

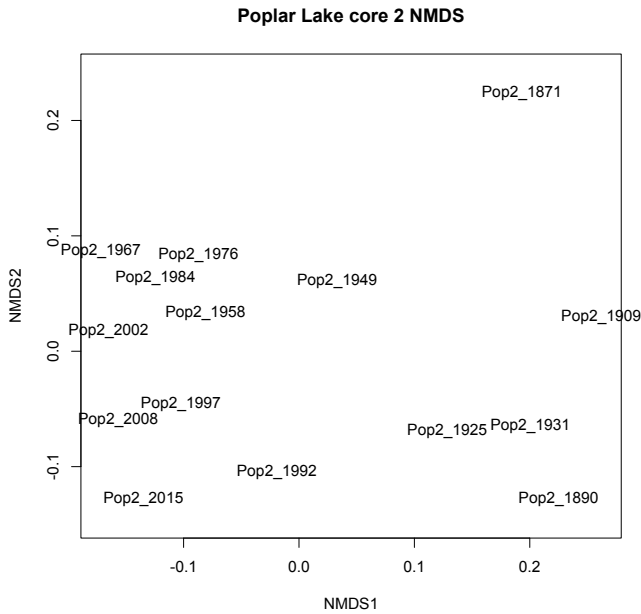


Figure 25. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance), results of a constrained cluster analysis, and percent plankton in Poplar Lake core 2 (1871-2015).

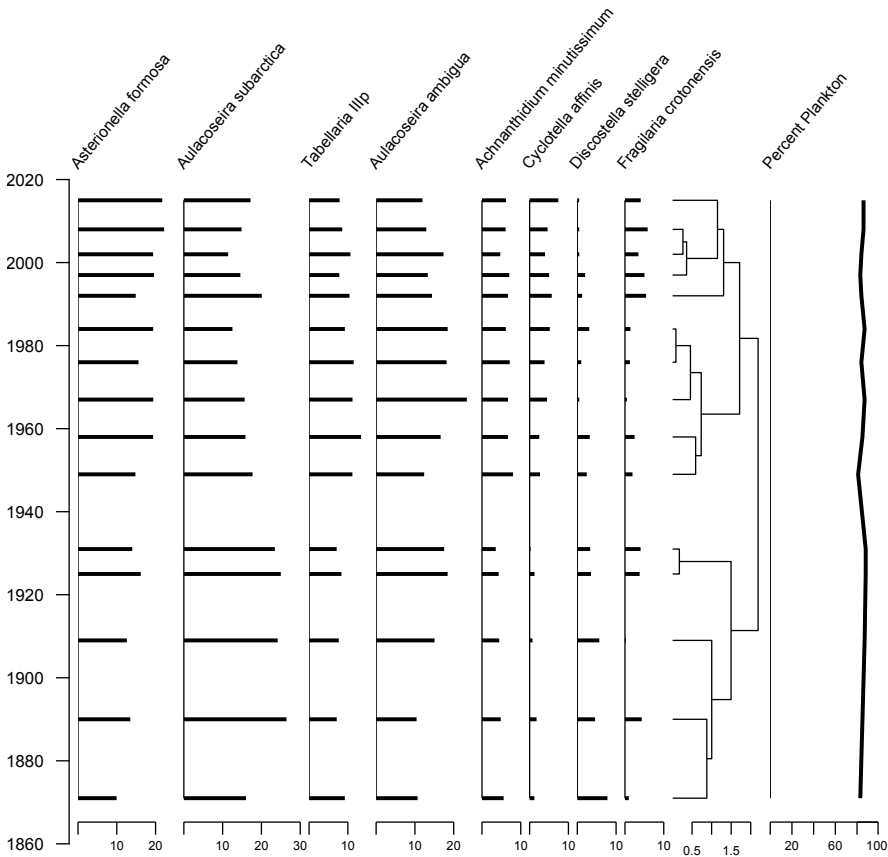


Figure 26. Changes in Poplar Lake diatom communities are minimal between the late 1800s (left) and the 2000s (right).

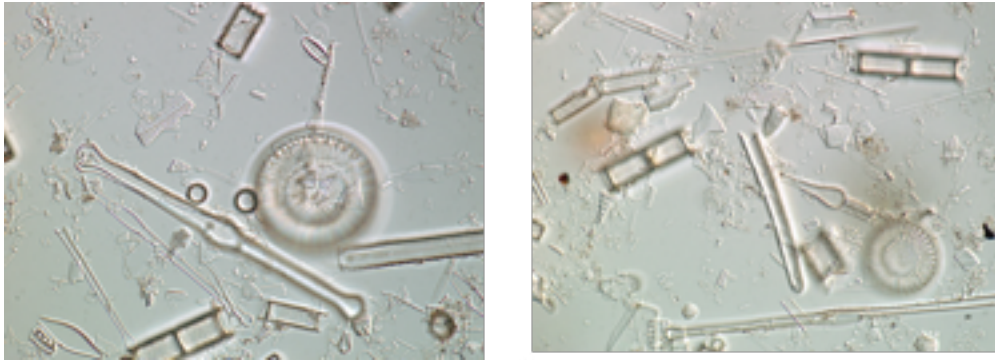


Figure 27. Predominant diatoms in Poplar Lake include *Aulacoseira subarctica* (C), *A. ambigua* (B), *Tabellaria flocculosa* IIIp (H), *Asterionella formosa* (I), *Achnanthydium minutissimum* (F), *Cyclotella affinis* (A), *Pseudostaurosira brevistriata* v. *inflata* (D, E), *Discostella stelligera* (G), and *Fragilaria crotonensis* (J). The diatom *Tetracyclus glans* (K) was very interesting to find in Poplar Lake, and appears to be only the second report of it from Minnesota lakes (also reported in Cook County’s Trout Lake (Bright 1968). It is more commonly found in alpine lakes in the Rocky Mountains.

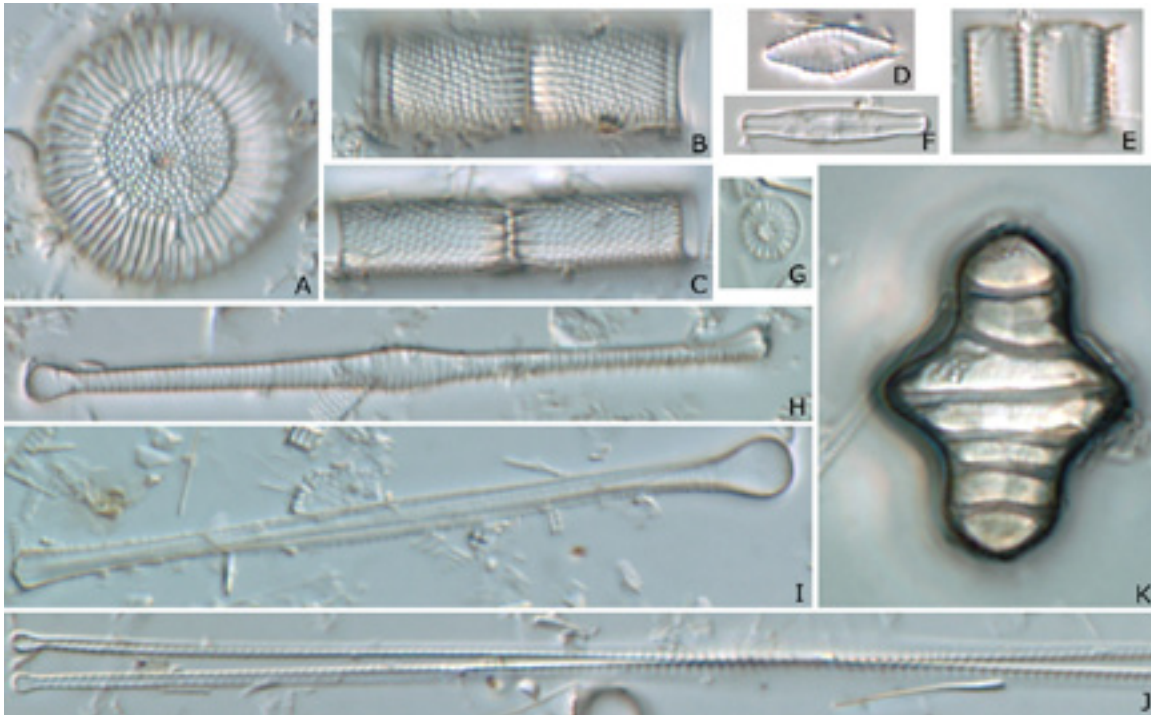


Figure 28. The core sections from Deer Yard Lake projected onto the MN calibration set. Symbols represent the 89 MN lakes in the calibration set, coded by region; NLF=Northern Lakes and Forests, CHF=Central Hardwood Forests, Metro=Twin Cities Metropolitan Area, WCP=Western Corn Belt Plains, NGP=Northern 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.

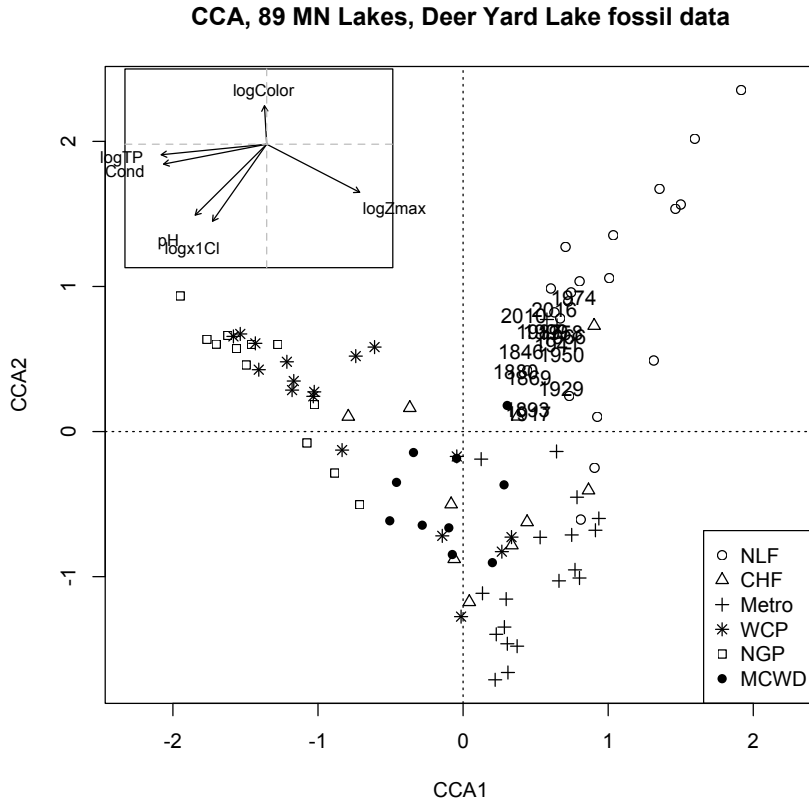


Figure 29. Diatom-inferred total phosphorus (TP) reconstruction for Deer Yard Lake. Reconstruction is shown as log TP (left panel) and as backtransformed values in micrograms per liter (right panel). Error estimates on log TP are plus and minus the root mean square error of prediction from the TP transfer function.

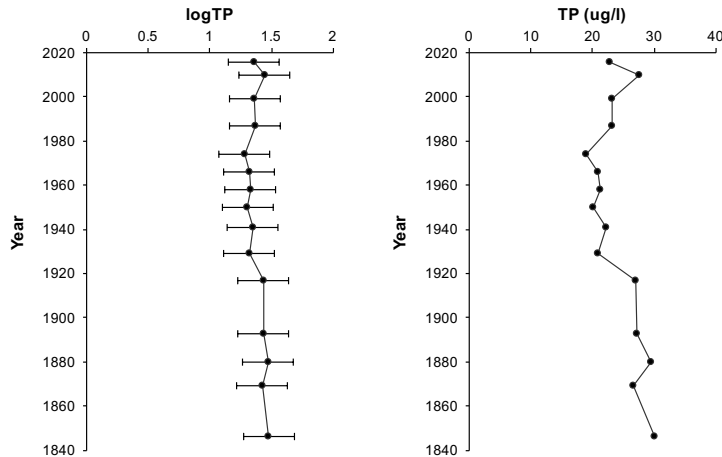


Figure 30. The core sections from Poplar Lake core 1 projected onto the MN calibration set. Symbols represent the 89 MN lakes in the calibration set, coded by region; NLF=Northern Lakes and Forests, CHF=Central Hardwood Forests, Metro=Twin Cities Metropolitan Area, WCP=Western Corn Belt Plains, NGP=Northern 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.

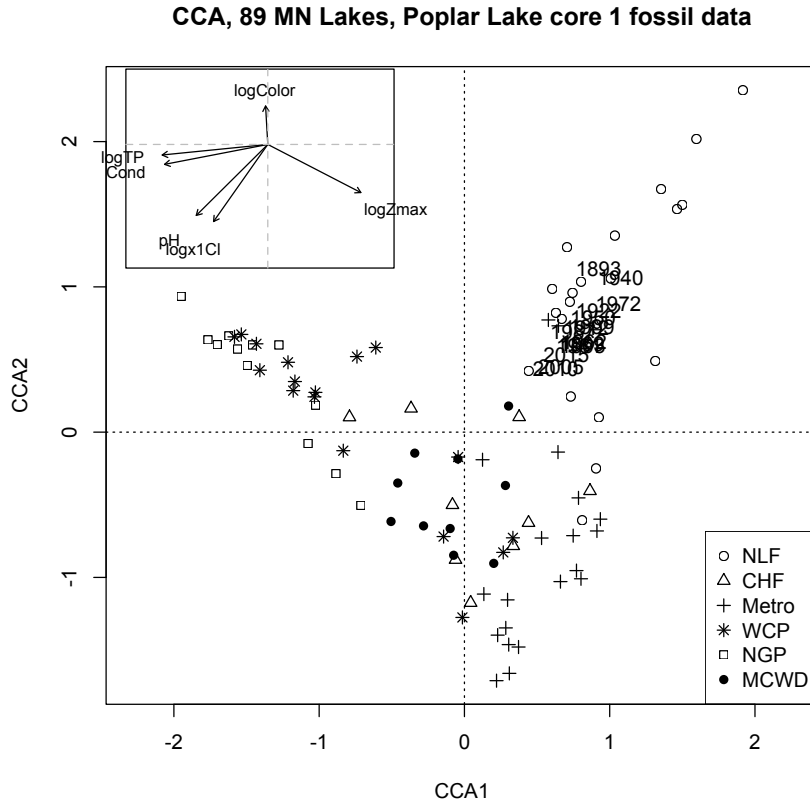


Figure 31. Diatom-inferred total phosphorus (TP) reconstruction for Poplar Lake core 1. Reconstruction is shown as log TP (left panel) and as backtransformed values in micrograms per liter (right panel). Error estimates on log TP are plus and minus the root mean square error of prediction from the TP transfer function.

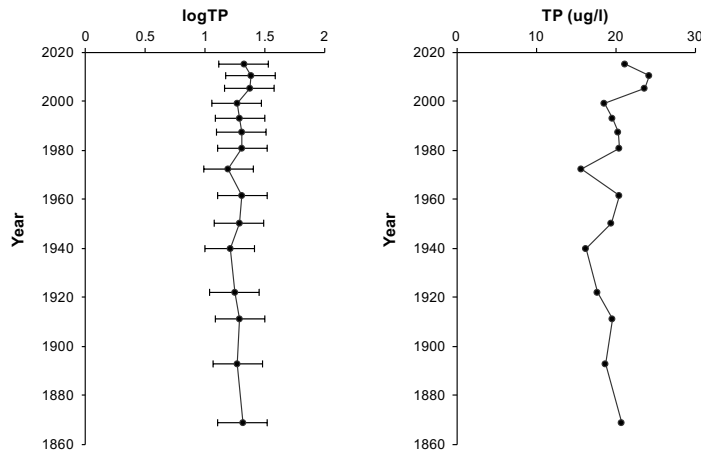


Figure 32. The core sections from Poplar Lake core 2 projected onto the MN calibration set. Symbols represent the 89 MN lakes in the calibration set, coded by region; NLF=Northern Lakes and Forests, CHF=Central Hardwood Forests, Metro=Twin Cities Metropolitan Area, WCP=Western Corn Belt Plains, NGP=Northern 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.

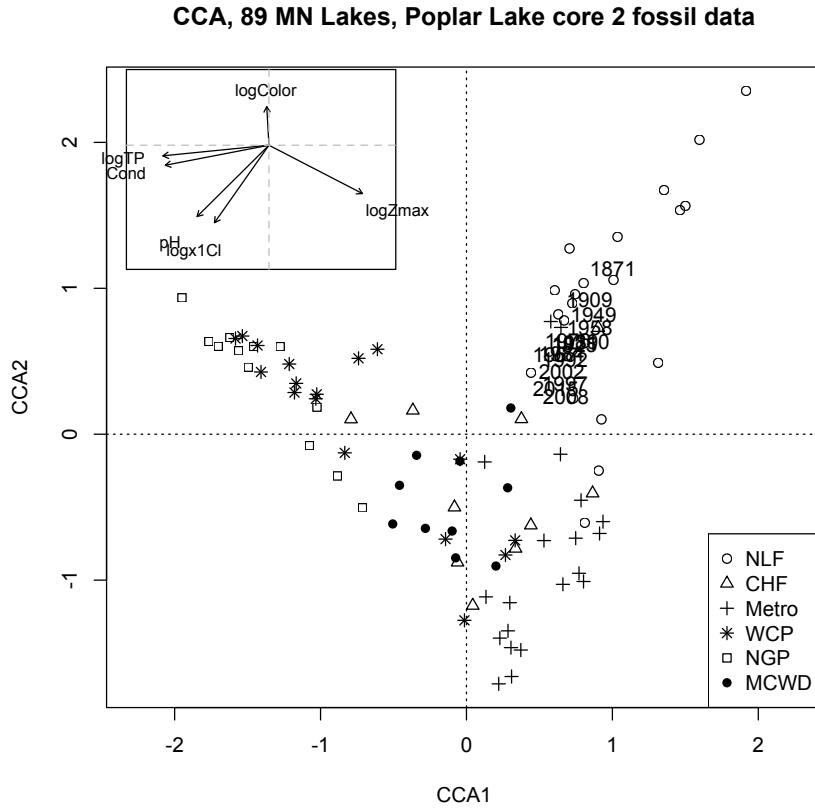


Figure 33. Diatom-inferred total phosphorus (TP) reconstruction for Poplar Lake core 2. Reconstruction is shown as log TP (left panel) and as backtransformed values in micrograms per liter (right panel). Error estimates on log TP are plus and minus the root mean square error of prediction from the TP transfer function.

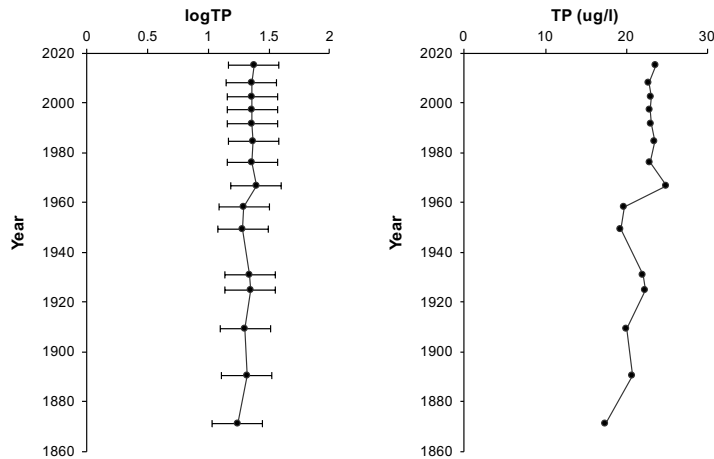


Figure 34. Sediment algal pigments quantified in ten core sections from Deer Yard Lake. The group of algae associated with each pigment is shown along the x-axis.

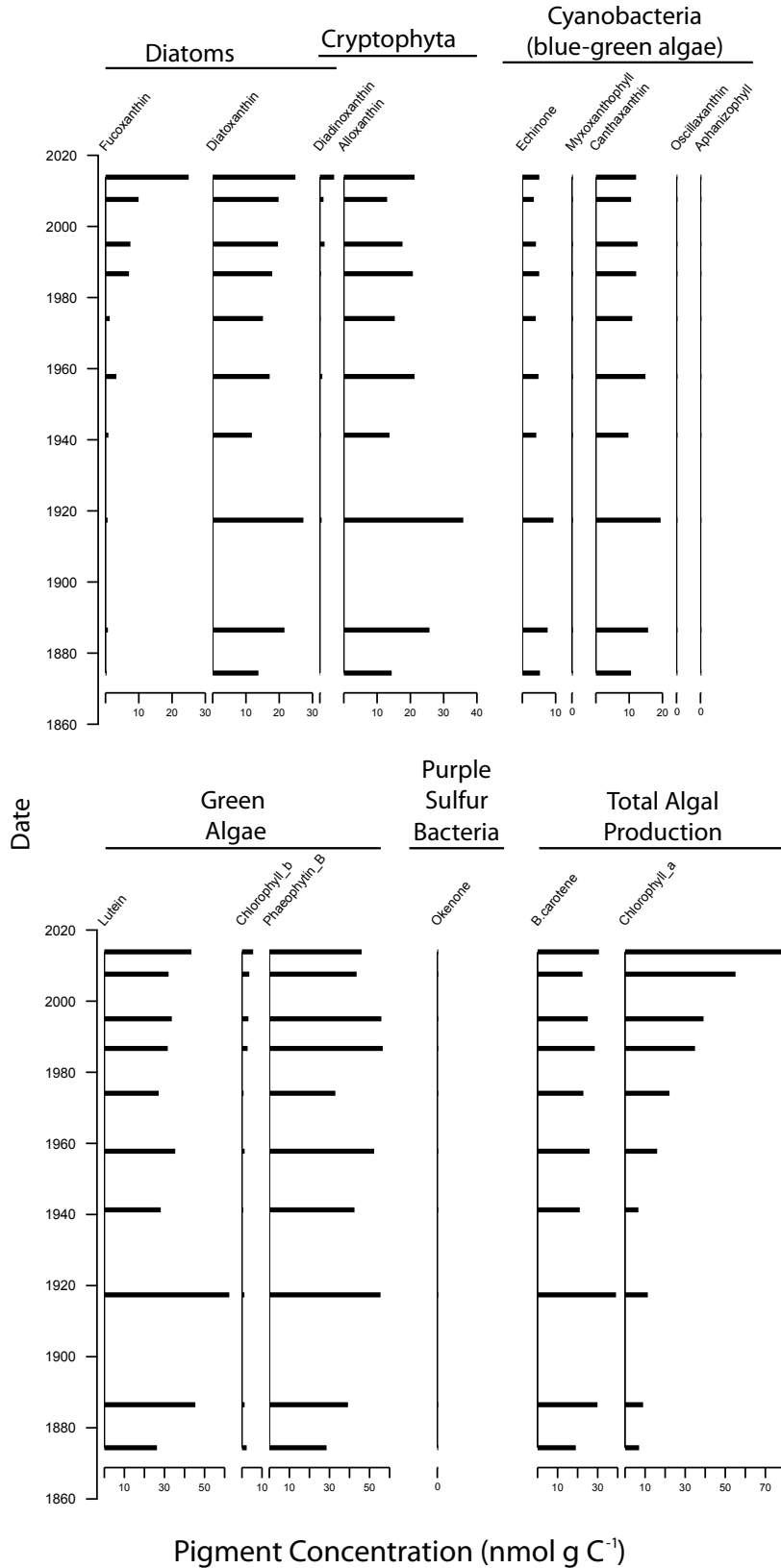


Figure 35. Sediment algal pigments quantified in ten core sections from Poplar Lake core 1. The group of algae associated with each pigment is shown along the x-axis.

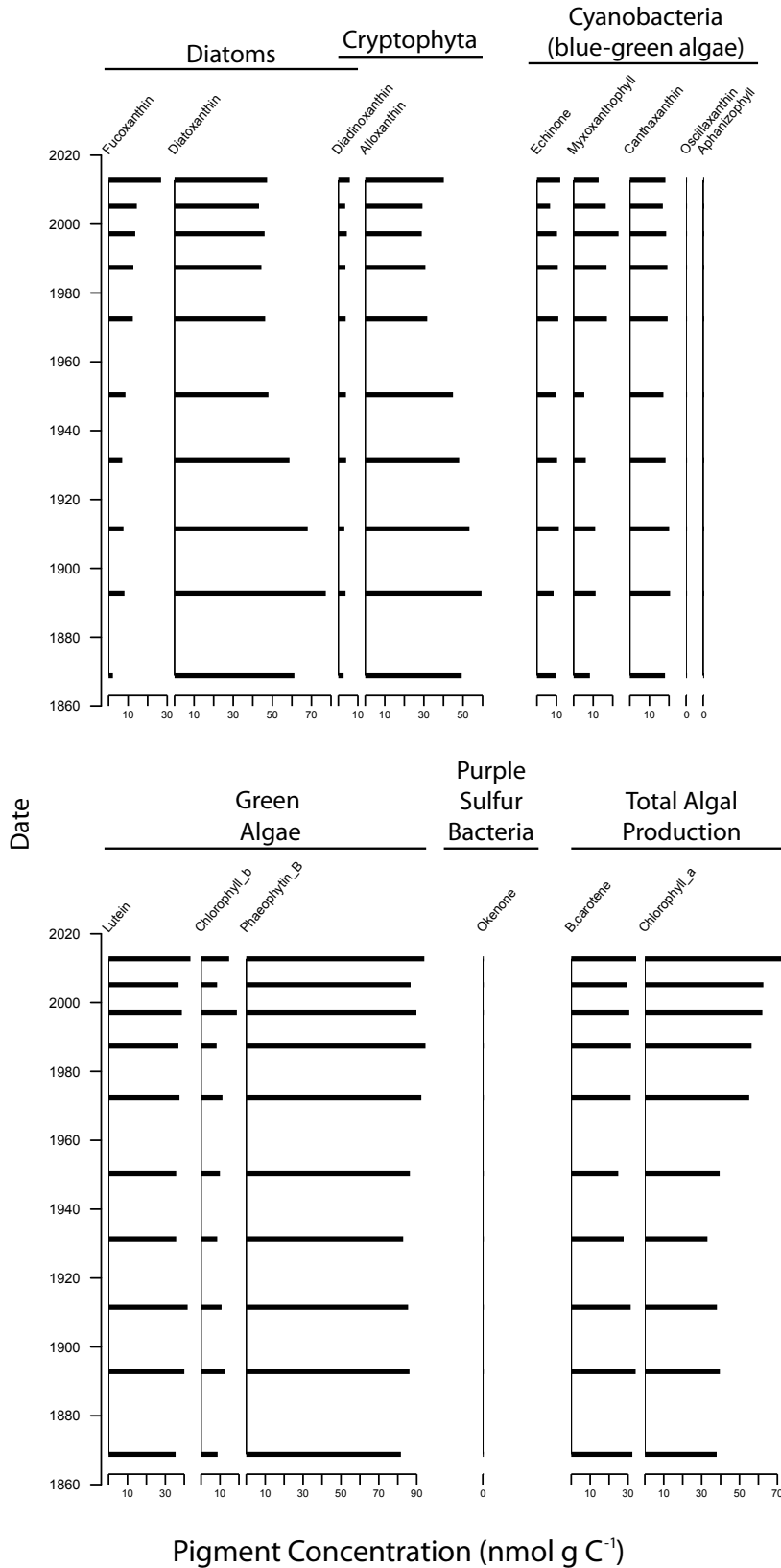


Figure 36. Sediment algal pigments quantified in ten core sections from Poplar Lake core 2. The group of algae associated with each pigment is shown along the x-axis.

