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

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## SUMMARY

1. Paleolimnological techniques were used to reconstruct the trophic and sedimentation history of Little Comfort and Forest lakes in the Comfort Lake - Forest Lake Watershed District, Chisago and Washington Counties, MN. Both lakes are in the North Central Hardwood Forest ecoregion and defined as “deep” by the State of Minnesota. As such, the state nutrient standard that applies to them is 40 ppb total phosphorus (or 40 µg/l total phosphorus). Little Comfort Lake is listed on the state’s impaired waters list due to high nutrient levels; recent monitoring efforts show TP concentrations just above the state standard. TP concentrations in the three basins of Forest Lake are currently below the state standard, however, the District’s goal is to bring TP averages below 30 µg/l.
2. In Little Comfort Lake, a piston and overlapping Bolivia core were collected on April 16, 2021. Due to the complex nature of Forest Lake, separate cores were collected from the West, Central, and East basins. A single piston core was collected from the West basin and overlapping piston and Bolivia cores were collected from the Central and East basins; all Forest Lake cores were collected on July 29, 2021. Lead-210 activity was analyzed to develop a dating model for each lake (and basin) and determine the sediment accumulation rate over the past 150-200 years. Sediments were analyzed for inorganic, organic, and carbonate components using loss-on-ignition analysis; geochemical analyses also included sediment phosphorus and biogenic silica. Subfossil diatoms in the sediments were analyzed to reconstruct changes in lake ecology and trophic state. In addition to diatoms, algal pigments were measured to determine historical changes in other algal groups.
3. In Little Comfort Lake, multiple proxies showed a large shift in the 1940s, including a sharp rise in sedimentation rate. This coincides with the construction of the highway that was built between Little Comfort and Comfort Lakes. In addition to the increase in sedimentation rate, BSi flux, TP flux, and algal pigment concentrations all increased in the 1940s and have remained elevated since that time.
4. In all three basins of Forest Lake, sedimentation rates increased in the late 1800s/early 1900s, likely indicative of early land conversion in the watershed. Modern sedimentation rates in each basin are approximately double what they were prior to the 1890s.
5. In the West basin of Forest Lake, there was an increase in Fe-bound P in recent decades, coinciding with a spike in algal pigment concentration, and an increase in diatom-inferred TP.
6. In Forest Central and Forest West, there were significant peaks in P flux to the core sites in the late 1800s, and again in recent decades. The diatom community assemblages in both basins suggest some level of nutrient enrichment over the period of study.
7. Please see the Conclusions section for management recommendations for Little Comfort and Forest lakes.

## INTRODUCTION

Lakes are a valuable natural resource in the glaciated regions of the Upper Midwest. As land use has intensified in the recent past, activities such as logging, agriculture, and urban development have put pressure on these ecosystems and raised concerns about the current state of lakes and the best management strategies for the future. To develop an effective management plan, it is critical to understand the state of a particular lake prior to European settlement (when land use intensified), and the timing and magnitude of historical ecological changes.

A basic understanding of natural fluctuations within the system is important for any lake management plan; however, long-term data sets (on the order of 30-50 years) are rarely available. Paleolimnological analysis can fill this void by estimating past conditions, natural variability, and timing of changes. 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. This is the third phase of paleolimnological work in the Comfort Lake – Forest Lake Watershed District (CLFLWD or District). Phase I consisted of work on Shields, Moody, and Comfort Lakes (Ramstack Hobbs et al. 2017) and Phase II focused on Bone and School Lakes (Ramstack Hobbs et al. 2020). In this project, paleolimnological techniques were used to reconstruct the trophic (nutrient and algal condition) and sedimentation history of Little Comfort Lake and Forest Lake in the CLFLWD in Chisago and Washington Counties, MN.

The primary aim of this project was to use dated sediment cores from Little Comfort and Forest lakes to reconstruct the ecological history of the lakes since the mid- to late-1800s using geochemistry, sediment accumulation, diatom-inferred total phosphorus (DI-TP), diatom community composition, and algae pigments as historical geological and biological indicators. Analytical tools included radioisotopic dating of the cores to determine local sediment accumulation rates, geochemical analyses, and analysis of subfossil diatom and algae communities. Multivariate analyses, diatom-based transfer functions, and comparison of diatom assemblages with an 89 Minnesota lake data set were used to relate changes in nutrient conditions and diatom communities to land use impacts in the watershed.

Diatoms have been widely used to interpret environmental conditions in lakes (Dixit and Smol 1994). Many species are sensitive to specific water conditions and are useful as bioindicators. Over the past 30 years, statistical methods have been developed to estimate quantitative environmental parameters from diatom assemblages. These methods are statistically robust and ecologically sound (Birks 1998). They have been used successfully in reconstructing a wide variety of environmental parameters including pH, total phosphorus (TP), and salinity (e.g. Fritz et al. 1991, 1999; Hall and Smol 1992; Ramstack et al. 2003). In the state of Minnesota, diatom analysis has been used as one line of evidence for developing lake nutrient criteria (Heiskary and Wilson 2008) and lake-specific nutrient standards (Edlund and Ramstack 2007).

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

### *Study Area*

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

Monitoring and diagnostic surveys of lakes in the CLFLWD found evidence of borderline to elevated total phosphorus (TP) and chlorophyll concentrations and the presence of cyanobacterial blooms in several lakes. As such, many of the lakes are judged impaired by state of Minnesota water quality standards and require remediation and management plans. Little Comfort and Forest lakes are in the North Central Hardwood Forest ecoregion and defined as “deep” by the State of Minnesota. As such, the state nutrient standard that applies to them is 40 ppb total phosphorus (or 40 µg/l total phosphorus). Past monitoring efforts have shown Little Comfort Lake to be impaired for nutrients and it is listed on the state’s impaired waters list due to high nutrient levels. The District TP monitoring average in 2021 (June-Sept) was 43 µg/l, just above the state standard, and the long-term District goal is <30 µg/l TP (https://www.clflwd.org/documents/2021LittleComfortLakeMonitoringReport_000.pdf; retrieved October 12, 2022). In Forest Lake, June through September monitoring averages for 2021 range from 24 to 36 µg/l TP depending on the basin being sampled (https://www.clflwd.org/documents/2021ForestLakeMonitoringReport_000.pdf; retrieved October 12, 2022). Although these averages are below the 40 µg/l TP state standard, individual measurements in the Central and East basins did occasionally exceed the standard in 2021, and summer averages have exceeded the standard in these two basins at times over the past 10 years. And as with Little Comfort, the District’s goal is to bring TP averages below 30 µg/l TP throughout Forest Lake. Little is known of the long-term history of these lakes; the goal of this project is to determine the long-term nutrient and productivity of these systems.

Little Comfort Lake has a maximum depth of 17.1 m (56 feet) and a surface area of 37 acres. Little Comfort’s total watershed area is 10,009 acres, including eleven lakes; the lake receives drainage from School Lake, and then drains to Comfort Lake. The lake is currently on the state’s impaired waters list for nutrients. (https://www.clflwd.org/waterbody-little-comfort-lake.php; retrieved October 12, 2022) Water quality data from 2021 reported the following summer averages: total phosphorus 43 µg/l, Secchi depth 2.6 m (8.4 feet), and chlorophyll *a* 7.4 µg/l (https://www.clflwd.org/documents/2021LittleComfortLakeMonitoringReport_000.pdf; retrieved October 12, 2022).

Forest Lake is a large and complex basin with a surface area of 2,220 acres, a maximum depth of 11.3 m (37 feet), and three distinct basins (West, Central, and East). Due to the distinct nature of the basins, a separate sediment core was collected and analyzed from each. An area of 8,160 acres drains to Forest Lake, this includes Clear, Twin, Elwell, and Cranberry lakes. The Sunrise River flows out of Forest Lake on the northwest side and flows into Comfort Lake. Forest Lake has three public access sites, high recreational use, and several storm sewer outfalls. (https://www.clflwd.org/waterbody-forest-lake.php; retrieved October 12, 2022). Water quality data from 2021 reported the following summer averages for each basin: West basin, total phosphorus 24 µg/l, Secchi depth 2.3 m (7.4 feet), and chlorophyll *a* 6.2 µg/l; Central basin, total phosphorus 36 µg/l, Secchi depth 2.1 m (6.9 feet), and chlorophyll *a* 9.1 µg/l; East basin, total phosphorus 34 µg/l, Secchi depth 2.5 m (8.1 feet), and chlorophyll *a* 14.3 µg/l. (https://www.clflwd.org/documents/2021ForestLakeMonitoringReport_000.pdf; retrieved October 12, 2022).

## METHODS - SEDIMENT CORING

In Little Comfort Lake, a piston and overlapping Bolivia core were collected on April 16, 2021, reaching a sediment depth of 182 cm (Table 1). Cores were collected from each of the basins of Forest Lake on July 29, 2021. A single 105 cm-long piston core was collected from the West basin. Overlapping piston and Bolivia cores were collected from both the Central and East basins and reached a sediment depth of 199 cm and 191 cm, respectively. In each lake, the coring location represented a flat and deep area of the basin to avoid areas of high sedimentation and sediment slumping, and to provide a highly integrated sample of diatom community structure from the lake as a whole. All piston cores were collected using a drive-rod piston corer equipped with a 6.5 cm diameter polycarbonate barrel (Wright 1991). In the Forest West and Forest East piston cores, the sediment-water interface was stabilized using a gelling agent (Zorbitrol); in the Little Comfort and Forest Central piston cores, the top sediments were sectioned in the field. All cores were returned to the lab for further sectioning and processing, stored at 4°C, and sectioned in 2-cm increments.

Table 1 details the coring location, water depth, and recovery for each of the lakes. Figures 2 and 4 show the coring locations on Little Comfort Lake and Forest Lake, respectively.

## METHODS - AERIAL PHOTOS AND SURVEY MAPS

Aerial photos from the 1930s through the present were used to examine changes to each lake and its watershed, including variations in lake surface area, and land use changes. Available aerial photos were downloaded from the University of Minnesota John R. Borchert Map Library's Historical Aerial Photographs Online collection (https://www.lib.umn.edu/apps/mhapo/; October 2022). Modern-day aerial photos were obtained from Google Earth (https://www.google.com/earth/; October 2022).

Historic land survey maps from the 1800s were used to examine changes in the lake basins. Land survey maps were downloaded from the Minnesota Geospatial Information Office's website (http://www.mngeo.state.mn.us/chouse/GLO/; July 2022).

## METHODS – HIGH FREQUENCY WATER QUALITY MONITORING BUOYS

A buoyed thermistor/dissolved oxygen (DO) string was deployed in each basin of Forest Lake following ice-out in 2021. The buoy consisted of an anchor (35 lbs of cinder blocks), temperature logger (HOBO Temperature Pendants UA-002-64) attached at every meter of depth, a DO logger (HOBO DO Logger U26-001) placed 0.5 m off the bottom and 2.5 m below the surface. Temperature and DO loggers were set to take readings over 30 minutes to record full water column profiles of temperature and dissolved oxygen conditions to determine patterns of open-water seasonal stratification and hypolimnetic anoxia.

Loggers were deployed to better understand stratification patterns in Forest Lake. Given the bathymetry of Little Comfort Lake, it is likely that the lake holds its stratification all summer, so loggers were not deployed in Little Comfort.

Buoys and data loggers were collected at the end of the open water season, and all data were downloaded and post-processed in R. Unfortunately, the buoy from Forest East was lost and not recovered, so only data from Forest West and Forest Central are reported. In both Forest West and Forest Central, the top DO sensors were rendered useless due to zebra mussel infestation and the data could not be recovered. One of the temperature pendants on Forest West (3.5 m from the bottom) only recorded data for the first month; data for this depth was interpolated by averaging the two adjacent depths.

## METHODS - LEAD-210 DATING

Lead-210 was measured in all cores by lead-210 distillation and alpha spectrometry methods, and dates and sedimentation rates were determined according to the c.r.s. (constant rate of supply) model (Appleby and Oldfield 1978). Dating and sedimentation errors were determined by first-order propagation of counting uncertainty (Binford 1990). In each core, between 18 and 22 core sections were analyzed for lead-210 activity to determine age and sediment accumulation rate for the past 150 years.

## METHODS - GEOCHEMISTRY

*Loss on Ignition*
Weighed subsamples were taken from regular intervals throughout each core for loss-on-ignition (LOI) analysis to determine bulk and dry density and dry weight percent of organic, carbonate, and inorganic matter. Sediment subsamples were heated at 105°C to determine dry density, then sequentially heated at 550°C and 1000°C to determine organic and carbonate content from post-ignition weight loss, respectively (Dean 1974).

*Biogenic Silica*
Biogenic silica (BSi), a proxy for historical diatom and chrysophyte algal productivity, was measured using 14-15 weighed subsamples (30 mg) from each core, which were digested for BSi analysis using 40 ml of 1% (w/v) $Na_2CO_3$ solution heated at 85°C in a reciprocating water bath for five hours (DeMaster 1979, Conley and Schelske 2001). A 0.5 g aliquot of supernatant was removed from each sample at 3, 4, and 5 hr. After cooling and neutralization with 4.5 g of 0.021N HCl solution, dissolved silica was measured colorimetrically on a Unity Scientific SmartChem 170 discrete analyzer as molybdate reactive silica (SmartChem 2012). Silica concentrations are converted to percent BSi by weight of sediment (typically 1-6% in most cores) and converted to flux or accumulation of BSi (the amount of diatoms that accumulate through time in a core).

*Sediment Phosphorus*
Sediment phosphorus fractions were analyzed for 15 increments from each core following the sequential extraction procedures in Engstrom (2005), Engstrom and Wright (1984), Psenner and Puckso (1988), and Kopácek et al. (2005). Extracts were analyzed colorimetrically on a Seal AQ400 discrete analyzer using methods described by Seal Analytical. Measured sediment phosphorus (P) concentrations were also converted to flux using bulk sedimentation rates in each core. In addition to TP in cores, sediment fractions include the refractory forms *Mineral-bound P*, *Recalcitrant Organic-P*, *Al-bound P* and the labile or readily exchangeable forms of *Fe-bound*, *labile Organic-P*, and *loosely-bound P*.

## METHODS - DIATOM AND NUMERICAL ANALYSES

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

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

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

## METHODS - ALGAL PIGMENT ANALYSIS

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

## RESULTS AND DISCUSSION - AERIAL PHOTOS AND SURVEY MAPS

*Little Comfort Lake* – Historical aerial photos of Little Comfort Lake from 1936, 1953, and 1964 showed some small variations in lake level, but little change overall (Figure 2). However, significant alterations to the watershed were visible in the aerial photos. A highway was constructed between 1936 and 1953 between Little Comfort and Comfort Lakes. Between the 1964 photo and the Google Earth photo retrieved in 2022, the area around the lake became noticeably more residential.

In the historic 1848 survey map, Little Comfort Lake appears and is labeled as "pond" (Appendix A). Comfort Lake does not appear on the map as it is today, instead smaller waterbodies are mapped in the area of the Comfort basin.

*Forest Lake* – As with Little Comfort Lake, the Forest Lake aerial photographs from 1936, 1953, and 1964 showed only small variations in lake level (Figures 3 and 4). The largest changes were seen in continued residential growth around the lakeshore between each time interval. Highway development was evident to the west of the lake between 1936 and 1953. As seen with Little Comfort Lake, between the 1964 photo and the modern Google Earth photo, large areas of the watershed shifted from what appeared to be agricultural to residential.

Forest Lake is present on the 1849 survey map, with the contour of the shoreline and the three distinct basins looking very similar to present day (Appendix B).

## RESULTS AND DISCUSSION – HIGH FREQUENCY WATER QUALITY MONITORING BUOYS

*Forest West* – The thermistor and dissolved oxygen buoy data for Forest West showed that this shallow basin was polymictic from June through October (Figure 5a). There were several prolonged periods of hypoxia during June, July, and October.

*Forest Central* – This same dataset showed that the Central basin of Forest was stratified and anoxic for most of the season (Figure 5b). The stratification pattern first broke on October 13th, but the lake then restratified and rapidly went anoxic again; the stratification broke down for the final time of the season later in October. The early break in stratification could have had the potential to trigger an algal bloom by mixing nutrients into the upper layers of water.

## RESULTS AND DISCUSSION - DATING AND SEDIMENTATION

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

*Little Comfort Lake* – The unsupported lead-210 activity, the resulting lead-210 dating model, and the sediment accumulation rate for Little Comfort Lake are shown in Figure 6a-c. In Little Comfort Lake, the lead-210 activity declined throughout the core, reaching background levels at approximately 88 cm, corresponding to a date of 1858 (Figures 6a-b). Thirty centimeters downcore corresponds to approximately 1995, and 74 cm corresponds to 1909 (Figure 6b). The lead-210 record is contained in the top 88 cm of sediment; in this core 88 cm corresponds to approximately 1850 (Figure 6b). From the mid-1800s to the 1930s, the sedimentation rate fluctuated between 0.02 and 0.07 g/cm$^2$/yr (Figure 3c). There was a sharp rise in sedimentation rate in the 1940s, and the rate has remained elevated since that time, with sharp peaks at approximately 1946 and 1995 (0.14 and 0.15 g/cm$^2$/yr, respectively). The sedimentation rate at the core top is roughly double what it was in the late 1800s and early 1900s.

The sedimentation rate in Little Comfort showed a similar pattern to the rate in Comfort Lake (Ramstack Hobbs et al. 2017). Both lakes showed a sharp increase in the 1930s/40s, with peaks in sedimentation rates in the 1940s and 1990s. A trend showing a decrease in sedimentation rates occurred after the 1990s probably due, in grand part, to the more systematic implementation of watershed management practices and regulations.

*Forest West, Central, and East* – In the Forest West core, lead-210 activity reached background levels at approximately 84 cm (Figure 7a) corresponding to a date of 1826 (Figure 7b).

Sediments deposited 14 cm downcore are dated to 1993, and 62 cm represents 1899 (Figure 7b).

In the core from Forest Central, lead-210 activity reached background levels at approximately 161 cm (Figure 7d), corresponding to a date of 1831 (Figure 7e). A date of 1994 corresponds to about 42 cm sediment depth, and 1894 to 121 cm depth (Figure 7e).

Activity in the Forest East core reached background levels at approximately 176 cm (Figure 7g) corresponding to a date of 1848 (Figure 7h). Sediments deposited 38 cm downcore are dated to 1997, and 140 cm represents 1898 (Figure 7h).

Sedimentation rates for all three basins of Forest Lake showed some similarities; all basins showed increases in the sedimentation rate in the late 1800s/early 1900s, consistent with what has been shown around the CLFLWD basin (Figures 7c, f, i; Ramstack Hobbs et al. 2017 and 2020). The West basin had an average "background" (used here to represent pre-1890s) sedimentation rate of 0.03 g/cm$^2$/yr, the background rate in both the Central and East basins was twice as high (0.06 g/cm$^2$/yr). The West basin showed a steady rise from the late 1800s until a peak of 0.10 g/cm$^2$/yr in the 1960s. In the Central and East basins, there was some fluctuation in the late 1800s and early 1900s, and the steady rise began in the 1920s. After the sedimentation rate in the West basin peaked in the 1960s, there was a sharp decline to a rate of 0.04 g/cm$^2$/yr around 1980; since this time the rate has been steadily rising. Conversely, the Central and East basins have shown declines in sedimentation in recent decades, although cores from both basins suggest a reversal of that pattern in the most recent sample. Modern sedimentation rates in all three basins are roughly double background levels; averages from the 2000s are 0.07 g/cm$^2$/yr in the West basin, and 0.13 g/cm$^2$/yr in both the Central and East basins.

## RESULTS AND DISCUSSION - GEOCHEMISTRY

### *Loss on Ignition*

*Little Comfort Lake* – During the period covered by the lead-210 record (1850 to present, 88 cm sediment depth) there was very little change in the sediment composition in the Little Comfort Lake core (Figure 8). From the bottom of the lead-210 record at 88 cm (1850), up to about 24 cm (2001) the sediments were composed of, on average, 31% organic matter, 48% inorganic matter, and 20% carbonate. There was a slight shift from 24 cm (2001) to the core top, with a rise in relative amount of organic matter in the core; averages during this time were 39% organic matter, 47% inorganic matter, and 14% carbonate.

For each core in the study, 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 10 for Little Comfort Lake); sediment flux was calculated to the end of the lead-210 record for each core (88 cm in Little Comfort Lake). In Little Comfort Lake, this calculation demonstrated that organic material was the primary component of sediment flux to the core site over most of the record, including the times of peak sedimentation in the 1940s and 1990s (Figure 10). The peak in the 1940s could have been caused by erosion when the highway between Little Comfort and Comfort Lake was built. However, since an erosional pulse from the watershed may have shown an altered sediment composition, which was not seen here (Figure 8), it's possible that the peak may be indicative of sediment slumping or redistribution (especially if water level was lowered during road construction). Even though inorganic material made up the largest component of sediment flux to the core site over most of the record, the flux of organics has become a larger component in the past decade.

*Forest West, Central, and East* – In each of the Forest Lake cores, the largest shift in sediment composition was an increase in the relative amount of carbonate in the sediments around 1880-

1900 (66 cm in the West basin, 117 cm in Central, and 148 cm in East; Figure 9). This increase in carbonates likely indicates increased productivity in the lake.

In the West basin, inorganic material makes up the largest portion of the sediment composition throughout the core (Figure 9). From 66 cm (1887) to the core top, there is a gradual rise in inorganic material, from 47% to 60%.

In the Central basin, the sediment composition is relatively stable after the rise in carbonates that began around 117 cm (1900) and lasted until about 88 cm (1946) (Figure 9). From about 88 cm to the core top, inorganic material makes up the largest portion of the sediment composition (average 48%). There is a slight rise in the relative amount of organic material from 26 cm (2007) to the core top (from 27% to 38%).

In the East basin, inorganic material makes up the largest portion of the sediment after the rise in carbonates around 148 cm (1889), and averages 42% (Figure 9). As in the Central basin, there is a slight rise in organic matter in the East basin core from about 32 cm (2002) to the core top (from 27% to 42%).

In each of the three basins, inorganic material made up the largest component of sediment flux to the core site (Figure 11); as in Little Comfort, this may point to erosion in the watershed as a main source of sediment. In the West basin, the relative contribution of inorganic material was most pronounced, especially during the peaks in sedimentation in the 1960s, and in recent decades. There was a sharp decline in sedimentation in the West basin in the 1970s that was not seen in the other two basins (Figures 7 and 11). The aerial photos showed highway development to the west of the lake between the 1936 and 1953 photos; it is possible that development in this part of the watershed caused changes in sedimentation and hydrology in the West basin that did not affect the other basins. In the Central and East basins, there is a greater relative contribution of organic material and carbonate to the overall flux at the core site, especially in the most recent years, where the relative component of inorganic and organic material was nearly equal.

### *Biogenic Silica and Sediment Phosphorus*

*Little Comfort Lake* – The weight percent of biogenic silica (BSi) in the Little Comfort Lake core was relatively stable; there was a slight rise between the 1950s and 1960s, with slightly elevated percentages (average of 16%) through the early 2000s, before declining to 12-13% in recent decades (Figure 12a). Weight percent of BSi increases when the historical growth of diatoms (one group of algae) increases, often in response to greater access to nutrients in a lake. The slight increase in BSi from about 1960-2000 occurs at the time of high sediment load to the lake; this sediment load, composed largely of inorganic material, may have brought increased nutrients to Little Comfort.

For each core in the study, both silica and phosphorus flux were calculated by multiplying either the weight percent of BSi, or the concentration of each phosphorus fraction, by the sedimentation rate at that interval. Flux of silica to the Little Comfort Lake core site showed a rise in in the 1940s, with some decrease in elevated levels in recent decades (Figure 12b).

The concentration of phosphorus (P) in the Little Comfort Lake core showed an increase in the 1960s, and another large increase in the most recent decades (Figure 13a). As with BSi, these increases occur at a time of high sediment load to the lake. The average total phosphorus (TP) concentration in Little Comfort Lake from 1869-1951 (before the increase in the 1960s) was 3.2 mg P/g; the average TP concentration from 2008-2021 was 9.8 mg P/g. When converted to flux, the rise in TP begins a bit earlier (1940s); the current flux to the core site is 1.0 mg/cm$^2$/yr, which is about six times higher than the average flux from 1869-1931 (0.16 mg/cm$^2$/yr) (Figure 13b). In the Little Comfort Lake sediments, the two largest fractions of P were Fe-bound and Al-bound. Fe-bound P is a readily exchangeable form and is of concern in sediments because it represents one of the most easily available forms of P to a lake through internal loading. The average flux of Fe-bound P was 0.09 mg/cm$^2$/yr from 1869-1931, and 0.34 mg/cm$^2$ /yr from 2008-2021.

In Little Comfort Lake, both the BSi and P flux to the core site increased in the 1940s; this indicates that the rise in sedimentation at that time, possibly caused by the highway construction and hydrologic changes, brought nutrients to the lake and fueled diatom growth. The BSi flux in recent years is about the same as the rate in the 1940s, however, P flux has continued to steadily rise. The rise in P flux in the core could be a true representation of increased P deposition over time, it is also possible that it is a consequence of P diffusion upwards through the sediment pore waters. This potential for P to be mobile in sediments means that the profile may not always be true to when the P was deposited.

*Forest West* – In the core from the west basin of Forest Lake, both the weight percent of BSi and the flux to the core site show some fluctuations (with low points in the 1860s and 1930s) but very little directional change over time (Figure 14 a-b). Overall, the amount of silica in the Forest West core was low in comparison to the other cores in the study.

The concentration of P in the Forest West core increased from the 1980s to the core top (Figure 15a); as with Little Comfort, it is important to remember that some portion of this peak at the core top could have been due to upward diffusion of P in the core. When converted to P flux two peaks are seen, the first occurring in the 1940s-60s and the second in the most recent decade (Figure 15b). The average P flux to the core site was 0.3 mg/cm$^2$/yr in the 1800s and increased by more than threefold to 1.0 mg/cm$^2$ /yr in the last decade. The largest P fraction in the Forest West core consisted of recalcitrant organic-P, this is a refractory form that is not readily available for algal uptake. However, Fe-bound P was the second largest fraction in Forest West, and the flux of this labile form increased from an average of 0.003 mg/cm$^2$/yr in the 1800s to 0.02 mg/cm$^2$/yr in the last decade.

*Forest Central* – The weight percent of BSi in the Forest Central core showed little variation throughout the core, except for an increase in 2007 (Figure 16a). When converted to silica flux, there was a steady increase to the core site beginning in the 1930s; except for a spike in 2007, the flux has remained elevated but fairly constant from the 1950s to the core top (Figure 16b).

The concentration of P in the Forest Central core was highest in the 1800s (average of 2.28 mg P/g), with the labile form Fe-bound P making up the largest fraction (Figure 17a). The TP concentration decreased through the 1900s but spiked again in recent years (average of 2.18 mg P/g from 2015-2021); Fe-bound P was again the largest fraction in these core top samples. When converted to flux, the P flux at the core site was highest in recent years, however, there was a peak in the 1800s that was higher than the flux throughout the 1900s (Figure 17b). The average flux of Fe-bound P was 0.06 mg/cm$^2$/yr in the 1800s, 0.03 mg/cm$^2$/yr through the 1900s and early 2000s, and 0.12 mg/cm$^2$/yr from 2015-2021.

*Forest East* – Both the weight percent of BSi and the silica flux to the Forest East core site showed large fluctuations, but very little directional change over time (Figure 18 a-b). There were peaks in both concentration and flux in the early 1900s and again in the 1990s/early 2000s.

The P concentration in the Forest East core showed a similar pattern to Forest Central, with high TP concentrations in the 1800s, lower concentrations throughout the 1900s and early 2000s, and a peak in the most recent samples (Figure 19a). Again, Fe-bound P was the dominant fraction during both peaks. Converting to flux showed the highest P accumulation rates from the 1990s through to the core top; however, the accumulation rate in the 1800s was still higher than the rate during most of the 1900s (Figure 19b). The average flux of Fe-bound P was 0.08 mg/cm$^2$/yr from 1869-1904, 0.03 mg/cm$^2$/yr from 1912-1980, and 0.15 mg/cm$^2$/yr from 1992-2019.

## RESULTS AND DISCUSSION - DIATOM STRATIGRAPHY AND ORDINATION

*Little Comfort Lake* – The NMDS ordination biplot from Little Comfort Lake showed how core samples clustered based on similarity of diatom assemblage (Figure 20). Samples from the late 1800s to the 1940s clustered together on the right side of axis 1, indicating that the diatom assemblage was very similar during that period. From the 1950s to the core top, there were larger changes between the samples, primarily moving back and forth along axis 2.

The stratigraphic diagram showed the predominant diatoms that were driving the shifts in the community assemblages, as well as the results of the constrained cluster analysis, and the percentage of plankton throughout the core (Figure 21). According to the constrained cluster analysis, the largest break in the Little Comfort Lake samples occurred between 1942 and 1951, although when evaluated against a broken stick model, this was not shown to be a significant shift in the assemblage. This shift coincided with a large decrease in *Stephanodiscus parvus* and increases in *Asterionella formosa* and *Aulacoseira granulata*. *S. parvus* is indicative of nutrient enrichment, suggesting that nutrients were slightly elevated in Little Comfort Lake from the late 1800s to the 1940s. However, other mesotrophic to eutrophic indicators, such as *A. formosa*, *Fragilaria crotonensis*, and *Aulacoseira* species remained abundant from the 1950s through 2021; *A. formosa* and *F. crotonensis* can be indicative of nitrogen enrichment. Overall, plankton made up most of the diatom community assemblage over the period of study (between 73-95% throughout the core), and most of the predominant diatom species were mesotrophic or eutrophic indicators.

*Forest West* – In the Forest West NMDS biplot, the diatom community showed steady change over time, with no abrupt shifts (Figure 22). The pattern in the ordination suggests gradual changes in the community over time, this was also reflected in the fact that there were no significant breaks in the constrained cluster analysis when evaluated against a broken stick model (Figure 23). The largest break in the constrained cluster occurred between 1980 and 1993 and was characterized by an increase in the planktonic diatom *Lindavia ocellata* and decreases in several tychoplanktonic diatoms in the genera *Staurosira*, *Pseudostaurosira*, and *Staurosirella*. The second largest break in the assemblage was between 1933 and 1943. From 1867 to 1933 there were an abundance of *Aulacoseira ambigua* and *Aulacoseira granulata*, these taxa are indicative nutrient rich, turbid waters. This period was also characterized by the planktonic taxa *Lindavia lemanensis* and *Cyclotella michiganiana*, as well as several tychoplanktonic taxa in the genera *Staurosira*, *Pseudostaurosira*, and *Staurosirella*. From 1943 to 1980, the planktonic taxa drop to low abundances (between 9-18% total abundance), and the assemblages are dominated by tychoplankton. These tychoplanktonic species are primarily benthic but are often swept-up and suspended into the water column. Many of these species are adapted to live on fine-grained sediments, such as those found in shallow lakes. The shifts between plankton dominance and tychoplankton dominance in the Forest West record suggest habitat changes; it's possible there was more littoral habitat during the periods of highest tychoplankton dominance (the 1860s, and between 1943 and 1980).

*Forest Central* – The NMDS biplot from the Central basin of Forest Lake showed the samples from the 1800s (1831-1894) clustering tightly together in the upper right quadrant (Figure 24). The rest of the record showed more gradual changes through the 1900s and 2000s. The shift in assemblage between 1894 and 1916 was the largest break in the constrained cluster analysis, although it was not statistically significant; this change was characterized by a sharp decline in the tychoplanktonic diatom *Staurosirella pinnata* and increases in two species of *Aulacoseira* (Figure

25). The second largest shift was between 2007 and 2015. At this time there was large shift in the plankton, with an increase in *Lindavia ocellata* and corresponding deceases in *Aulacoseira ambigua* and *Fragilaria crotonensis*.

*Forest East* – Other than some difference in the uppermost (2020) and bottommost (1986) samples, there were no distinct breaks, or strong directional changes amongst the samples from Forest East (Figure 26). The stratigraphic diagram from Forest East also illustrates the subtle nature of the changes in the diatom community (Figure 27). The record from Forest East was dominated by *Aulacoseira ambigua*, *A. granulata*, and *Fragilaria crotonenis*. There was a small uptick in the planktonic diatoms *Lindavia ocellata* and *Fragilaria mesolepta* at the core top. The tychoplanktonic diatoms *Staurosira construens* var. *venter* and *Staurosirella pinnata* were more prevalent in the 1800s and early 1900s; the rest of the predominant taxa throughout the record were planktonic.

## RESULTS AND DISCUSSION - PHOSPHORUS RECONSTRUCTION

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 ($\lambda_r / \lambda_p$). A maximum $\lambda_r / \lambda_p$ value of 1.0 would mean that TP was the best explanatory variable of diatom community change (Juggins et al. 2013).

*Little Comfort Lake* – When passively plotted on the MN calibration set, the core sections from Little Comfort showed movement that was primarily along axis 2, and not directional over time (Figure 28). The lack of strong movement along the TP gradient suggests that changes in nutrient levels were not driving most of the turnover in the lake, and that other drivers, such as habitat alteration, changes in turbidity due to sediment load, or other stressors that were not measured in the calibration set (e.g., aquatic invasive species) may have played a larger role.

In Little Comfort Lake the fraction of the maximum explainable variation in the diatom data that could be explained by TP ($\lambda_r / \lambda_p$) was 0.40. This suggest that TP was not the main driver of diatom community change over the course of this record and therefore the quantitative TP reconstruction should be interpreted with caution.

The diatom-inferred (DI) TP reconstruction for Little Comfort Lake suggests that the lake has been in the eutrophic range since the late 1800s (Figure 29, Table 2). The average of the two most recent diatom-inferred TP values (2015 and 2021) was 37 μg/l, which is comparable to the five-year average of monitoring data from the District (44 μg/l) (https://www.clflwd.org/documents/2021LittleComfortLakeMonitoringReport_000.pdf; Retrieved October 20, 2022). Even though the diatom-inferred TP reconstruction should be interpreted with caution, the prevalence of a diatom community that was indicative of mesotrophic to eutrophic conditions supports the conclusion that Little Comfort has had elevated nutrient levels throughout the period of study and has remained at or near the state phosphorus standard of 40 ppb TP.

The largest break in the diatom community assemblage (between the 1940s and 1950s) occurred at the same time as the large rise in sedimentation rate in Little Comfort Lake; this was also a time of increase P flux to the core site. However, the shift in diatom species assemblage, and the resulting DI-TP reconstruction are not indicative of nutrient enrichment. This suggests that the diatom community was responding to a change in a different environmental factor at this time, such as habitat changes or possible shifts in the lake's hydrology with highway construction and development in the basin. The loss of *Stephanodiscus* species may reflect shorter spring mixing (best period of diatom growth) as the basin became reforested following highway construction and transitioned from agriculture to homes around the lake (Fig. 3). Monitoring data from 2021 (https://www.clflwd.org/documents/2021LittleComfortLakeMonitoringReport_000.pdf) clearly show that Little Comfort Lake remains stratified well into the fall effectively keeping nutrients released from sediments in the anoxic hypolimnion. Diatoms that increased after highway construction are forms more indicative of plankton and tychoplankton mixing from the shallower waters around the margins of Little Comfort.-

*Forest West* – Passive plotting of the Forest West core on the MN calibration set showed the samples primarily moving along axis 2 (Figure 30) with several periods of secondary movement along axis 1 (TP axis). The fraction of the maximum explainable variation in the diatom data that could be explained by TP ($\lambda_r / \lambda_p$) was 0.34. Both analyses, combined with the fact that the plankton/tychoplankton shifts suggest changes in habitat in this shallow basin, lead to the conclusion that TP was not the primary driver of diatom community change in the West basin. Therefore, the TP reconstruction should be interpreted with caution.

The TP reconstruction from the West basin suggests that the lake has been mesotrophic to slightly eutrophic since the late 1800s (Figure 31, Table 2) with periods in the 1920s and current period with slightly higher DI-TP compared to pre-settlement. The average of the two uppermost DI-TP values (2019 and 2012) was 33 µg/l; this is comparable to the District's five-year average of 27 µg/l (https://www.clflwd.org/documents/2021ForestLakeMonitoringReport_000.pdf; Retrieved October 20, 2022). The West basin does not show any periods of time in the record where DI-TP values exceed the state standard of 40 µg/L TP.

*Forest Central* – When passively plotted on the MN calibration set, the core sections from Forest Central primarily change along axis 2, again suggesting that TP is not the main driver of diatom community turnover in this basin (Figure 32). This conclusion is also supported by the $\lambda_r / \lambda_p$ score of 0.39.

In the Central basin, the TP reconstruction suggested that the lake has been mesotrophic to eutrophic throughout the period of study, with the highest DI-TP values (over 50 µg/l) in the 1980s and several other periods in the 1900s when DI-TP values exceeded the state standard of 40 µg/L TP (Figure 33, Table 2). The average DI-TP value at the core top (2015 and 2021) was 31 µg/l, similar to the District's 5-year average of 39 µg/l (https://www.clflwd.org/documents/2021ForestLakeMonitoringReport_000.pdf; Retrieved October 20, 2022).

*Forest East* – As with the other cores from Forest Lake, passive plotting of the Forest East core on the MN calibration set showed movement primarily along axis 2, orthogonal to the TP gradient (Figure 34). And, as with the other Forest Lake cores, the $\lambda_r / \lambda_p$ value was low (0.42).

The DI-TP reconstruction suggested that Forest East was in the eutrophic category over the period of study, with the highest TP levels in the 1980s and 1990s (Figure 35, Table 2), and a long history of DI-TP values at or near the state standard of 40 µg/L TP. The DI-TP average of the two uppermost samples was 38 µg/l, in line with the District's 5-year monitoring average of 41 µg/l (https://www.clflwd.org/documents/2021ForestLakeMonitoringReport_000.pdf; Retrieved

October 20, 2022).

## RESULTS AND DISCUSSION - HISTORICAL ALGAL COMMUNITIES

*Little Comfort Lake* – The pigment data from Little Comfort Lake showed that total algal production was highest in the 1940s and from 2011-2020 (Figure 36). The timing of the rise in the 1940s coincides with the initial increase in sedimentation and increased P flux. The highest concentrations of pigments were from the green algae, with diatoms and cryptophytes also abundant throughout the record. Cyanobacterial pigments were present throughout the core, but at lower concentrations. Pigments associated with cyanobacterial nitrogen-fixing forms (canthaxanthin and aphanizophyll), as well as pigments from potentially toxic forms (myxoxanthophyll) were present in relatively low concentrations throughout the core. Pigments of purple sulfur bacteria were absent in the Little Comfort Lake samples; these bacteria are indicative of anoxic conditions, but where light still penetrates the water.

*Forest West* – In the Forest West core, total algal production showed a dramatic increase in 2008 and again in 2015, driven largely by an increase in diatom pigments (Figure 37). Cyanobacterial pigments are present throughout the record, but at relatively low concentrations, and they showed little fluctuation throughout the samples analyzed. As in Little Comfort Lake, pigments associated with cyanobacterial nitrogen-fixing forms and potentially toxic forms were detected in relatively low concentrations throughout the core.

*Forest Central* – The pigment data from the Forest Central core showed that algal production was lower in the late 1800s, suggesting that the peak in P concentration and flux seen in the core in the late 1800s did not cause increased algal production (Figure 38). There was a rise in pigments associated with overall algal production in the early 1900s and again in recent decades. The rise in recent decades was reflected in multiple algal groups: diatoms, cryptophytes, cyanobacteria, green algae, and purple sulfur bacteria. Cyanobacterial pigments associated with a nitrogen-fixing form (canthaxanthin), as well as pigments from a potentially toxic form (myxoxanthophyll) were present throughout the core and showed a slight rise in recent decades.

*Forest East* – The pigment data from Forest East showed many similarities to the results from Forest Central (Figure 39). Overall algal production was lower in the late 1800s, again suggesting that the increase in P at that time did not fuel increased algal production. In Forest East there was a steady rise in total algal production over the course of the record, which was driven by small rises in multiple algal groups. As with Forest Central, cyanobacterial pigments associated with a nitrogen-fixing form (canthaxanthin) and a potentially toxic form (myxoxanthophyll) were present throughout the core; there was a slight rise in the potentially toxic form in recent decades.

## CONCLUSIONS

*Little Comfort Lake* – The sedimentation rate in Little Comfort Lake showed a sharp rise in the 1940s; although the current sedimentation rate in the lake has decreased from the peaks in the 1940s and 1990s, the rate remains about double what it was in the late 1800s and early 1900s. In Little Comfort Lake, inorganic material was the largest component of the sediment over most of the record, although organics made up an equal portion of the sediment in the most recent samples. The increased flux of organics at the core top may be indicative of greater in-lake productivity (e.g., algal growth), this conclusion is supported by an increase in pigments indicative of total algal production in the most recent samples.

Both the BSi and P flux to the core site increased in the 1940s; this indicates that the rise in sedimentation at that time (with inorganic material making up the largest component of the sediment, and possibly caused by highway construction) brought nutrients to the lake and fueled diatom growth. The BSi flux in recent years was about the same as the rate in the 1940s, however, P flux has continued to steadily rise. Fe-bound P makes up a large fraction of the P flux in Little Comfort Lake, this is of concern since this is one of the most easily available forms of P to a lake through internal loading. Fortunately, recent CLFLWD monitoring data show that Comfort Lake holds its stratification well into October. The algal pigment data showed that the P rise likely fueled growth of cryptophytes and green algae.

The diatom community in Little Comfort also recorded the largest shift in assemblage in the 1940s; however, the shift in taxa suggest the diatom community was responding to a stressor other than increased P. The rise of peaks of *Asterionella formosa* and *Fragilaria crotonensis* after the 1940s suggest that there may have been times of N enrichment in the lake. The increase in *Aulacoseira granulata* after the 1940s may indicate that the lake became more turbid and wind-swept with mixing from its shallower regions.

The largest shift in all proxies was seen in the 1940s, indicating this was a time of significant disturbance to the basin. This coincides with the construction of the highway between Little Comfort and Comfort Lakes, which likely brought sediment and additional nutrients to the lake. Aerial photos showed that the area around the lake has become increasingly residential between the 1960s and the present. This continued development of the watershed may account for the fact that the sedimentation rate, BSi flux, TP flux, and algal pigment concentration have all remained elevated since their initial rise in the 1940s.

*Forest Lake* – Across the three basins of Forest Lake, sedimentation rates increased in the late 1800s/early 1900s; this is consistent with other lakes in the CLFLWD and is likely indicative of early land conversion. Although the overall sedimentation rate in the West basin was lower than the other two basins over the course of the record, modern sedimentation rates in all three basins are roughly double what they were prior to the 1890s. In each of the basins, inorganic material was the largest component of the sediment flux at the core site. In the Central and East basins, there was a greater relative contribution of organic material and carbonate to the overall flux at the core site, especially in the most recent decade, suggesting greater in-lake productivity.

P flux in the West basin peaked in the 1940s to 1960s, and again in the most recent decade. Fe-bound P was the second largest fraction in Forest West, and the flux of this labile form increased about sixfold over the course of the record; the buoy data showed this basin is polymictic, meaning this easily available form for algal uptake has the potential to be continually mixed into the water column. There was a spike in pigment concentration representing total algal production in recent decades (driven primarily by diatoms), as well as a coincident rise in DI-TP, both suggesting that this rise in labile P is currently fueling algal growth in the West basin. Even though the Fe- bound P fraction showed this increase at the core top, the peak in the 1940s-60s consisted of primarily refractory forms of P. The algal pigment data showed a decrease in overall algal production during this period, and DI-TP was also lower during this time, both suggesting that the 1940s-60s peak in P did not promote algal growth.

Forest Central and Forest East had similar P profiles, both with a significant peak in P concentration and flux in the late 1800s around the time of initial land clearance, and sharp peaks in recent decades. Labile Fe-bound P constituted the largest fraction during both peaks in both basins, a testament to its mobility in cores and its continued threat as an internal loading source. The diatom species assemblage showed some shifts that coincided with the P peak in the late 1800s, characterized by increases in the tychoplanktonic genera *Staurosirella* and *Staurosira* (most pronounced in the Central basin). Both proxies suggest some change to the basin and watershed during the late 1800s. Even though the 1848 Plat Map showed the outline of Forest

Lake to be similar to present day, there were perhaps water level differences at this time leading to a larger littoral area and greater habitat for tychoplanktonic diatom taxa. Overall, the diatom community assemblage in Forest East and Central suggests that there has been some level of nutrient enrichment in each basin over the period of study. Most shifts in the community assemblage in these basins are indicative of shifts in habitat, as opposed to large shifts in nutrient availability. Some interesting recent increases in abundance of diatoms indicative of nitrogen enrichment (*Fragilaria crotonensis, Asterionella formosa*) coupled with appearances of diatoms indicative of possible shifts in spring mixing and thermocline stability (*Lindavia ocellata* can maintain itself in an enriched low light environment like a thermocline) may be a bellwether of future shifts in Forest Lake's mixing environment as we face changes in ice duration and weather patterns due to climate change.

Based on monitoring and the historical records recovered from the sediments, both Little Comfort and Forest lakes have long been meso- to more eutrophic systems that remain at risk for deterioration of water quality without continued nutrient management efforts and vigilance. Little Comfort has long toed the line of Minnesota's nutrient standards and may be a challenge to bring down to 30 ppb TP to meet District goals. Continued monitoring, especially of the strength of stratification, would be encouraged to detect possible late summer/early fall destratification as well as encouraging nutrient management in the watershed. Forest Lake similarly has a long history of nutrient levels at or near the state standard, with some historical periods, especially in the Central and East basins, when nutrient levels exceeded state standards. Management efforts in the Forest basins are more likely to bring the lake in alignment with District nutrient goals and should include continuing the excellent district monitoring program, curlyleaf pondweed (CLP) controls to prevent post stratification nutrient loading, maintaining shoreline and submerged beds, and continuing to work with shoreline and watershed stakeholders to encourage nutrient control.

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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) |
|---|---|---|---|---|---|
| Little Comfort | 45.31350 | 92.93692 | Piston | 15.82 | 1.05 |
| Little Comfort | 45.31350 | 92.93692 | Bolivia | 15.82 | 1.15 |
| Forest West | 45.28633 | 92.96429 | Piston | 5.10 | 1.05 |
| Forest Central | 45.26746 | 92.94928 | Piston | 9.59 | 1.08 |
| Forest Central | 45.26746 | 92.94928 | Bolivia | 9.59 | 1.16 |
| Forest East | 45.26123 | 92.92350 | Piston | 10.72 | 0.95 |
| Forest East | 45.26123 | 92.92350 | Bolivia | 10.72 | 1.21 |

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

| Lake_Lead-210 Date | Diatom-Inferred TP µg/l | Lake_Lead-210 Date | Diatom-Inferred TP µg/l |
|---|---|---|---|
| Little Comfort 2021 | 29 | Forest Central 2021 | 34 |
| Little Comfort 2015 | 45 | Forest Central 2015 | 29 |
| Little Comfort 2011 | 43 | Forest Central 2007 | 37 |
| Little Comfort 2001 | 28 | Forest Central 1994 | 38 |
| Little Comfort 1992 | 48 | Forest Central 1986 | 51 |
| Little Comfort 1981 | 34 | Forest Central 1978 | 36 |
| Little Comfort 1971 | 51 | Forest Central 1968 | 28 |
| Little Comfort 1960 | 35 | Forest Central 1960 | 41 |
| Little Comfort 1951 | 48 | Forest Central 1951 | 42 |
| Little Comfort 1942 | 45 | Forest Central 1938 | 49 |
| Little Comfort 1931 | 44 | Forest Central 1924 | 36 |
| Little Comfort 1916 | 41 | Forest Central 1916 | 48 |
| Little Comfort 1902 | 45 | Forest Central 1894 | 34 |
| Little Comfort 1889 | 47 | Forest Central 1866 | 33 |
| Little Comfort 1869 | 49 | Forest Central 1831 | 32 |
| | | | |
| Forest West 2019 | 31 | Forest East 2020 | 38 |
| Forest West 2012 | 35 | Forest East 2012 | 37 |
| Forest West 2003 | 31 | Forest East 2003 | 41 |
| Forest West 1993 | 26 | Forest East 1992 | 51 |
| Forest West 1980 | 22 | Forest East 1980 | 48 |
| Forest West 1971 | 19 | Forest East 1970 | 33 |
| Forest West 1962 | 21 | Forest East 1960 | 44 |
| Forest West 1953 | 23 | Forest East 1950 | 37 |
| Forest West 1943 | 23 | Forest East 1941 | 43 |
| Forest West 1933 | 32 | Forest East 1932 | 44 |
| Forest West 1921 | 36 | Forest East 1922 | 37 |
| Forest West 1913 | 30 | Forest East 1912 | 41 |
| Forest West 1904 | 27 | Forest East 1904 | 39 |
| Forest West 1887 | 27 | Forest East 1889 | 47 |
| Forest West 1867 | 19 | Forest East 1869 | 39 |

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

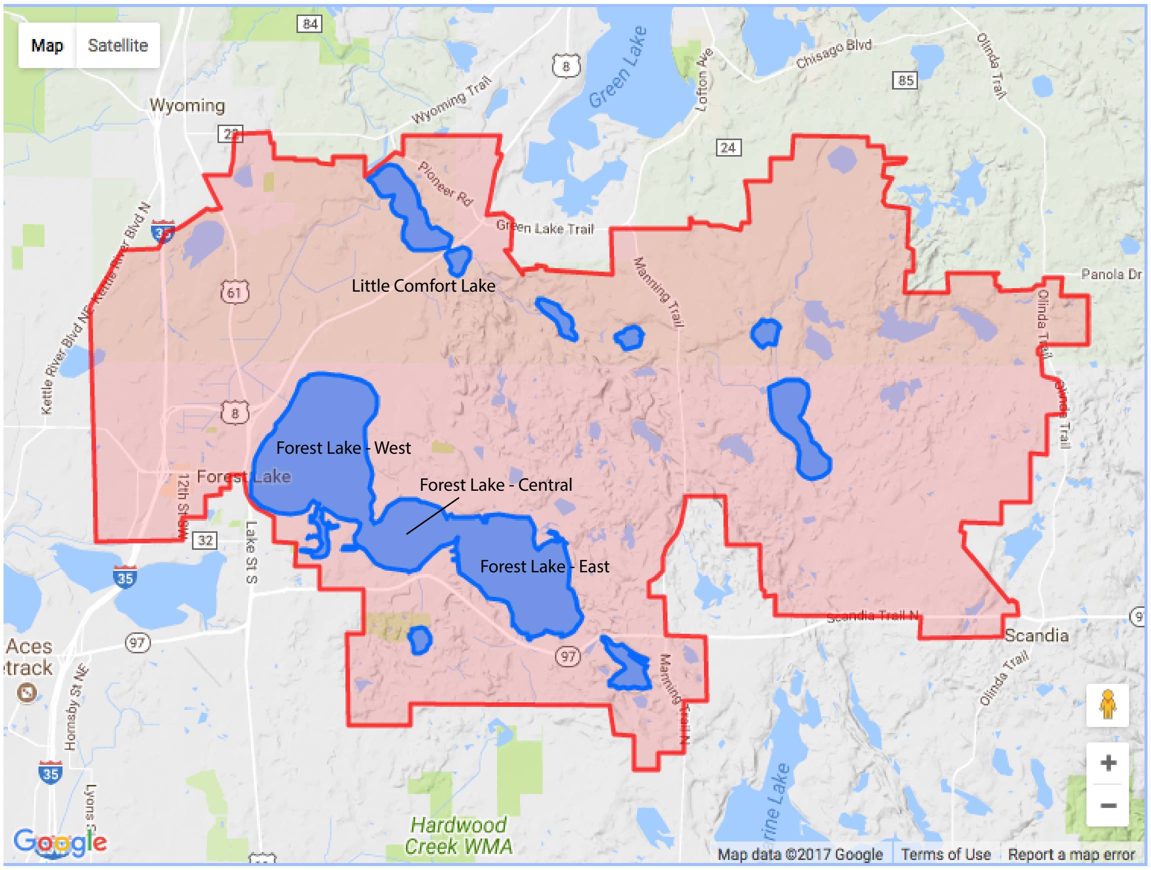
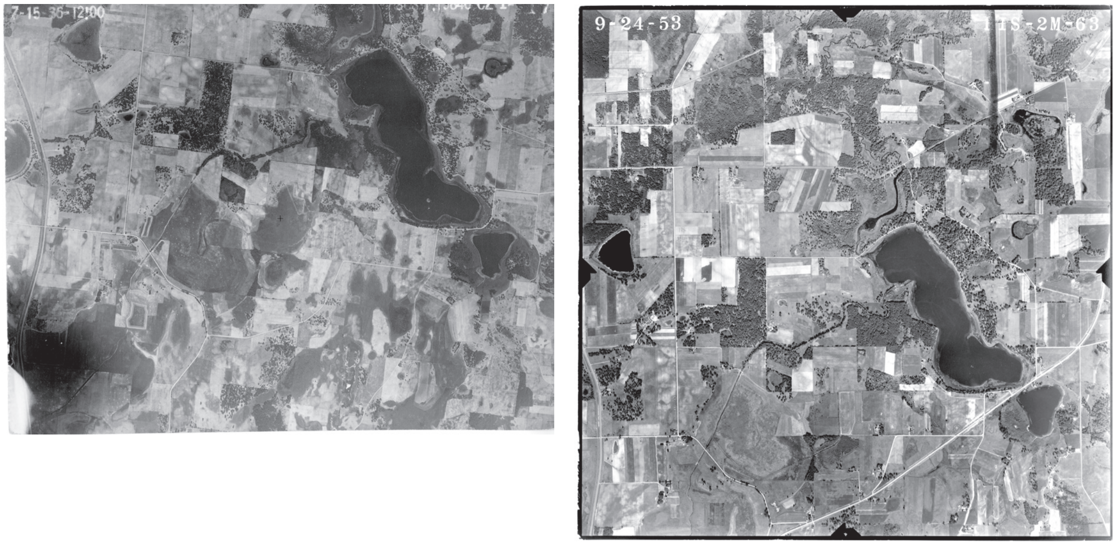


Figure 2. Aerial photographs of Little Comfort Lake. The red marker in the modern (Google Earth) photo denotes the coring location.



1936

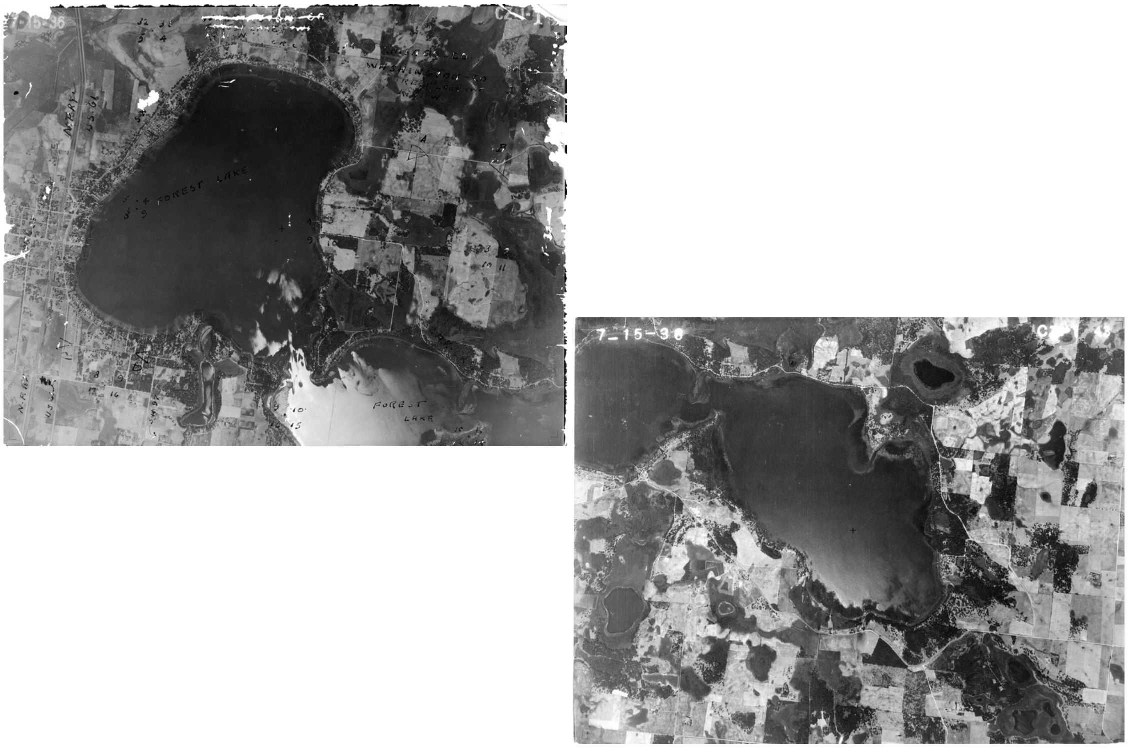
1953

1964

Google Earth (retrieved Oct 2022)

Figure 3. Aerial photographs of Forest Lake from 1936 and 1953. The red markers in the modern (Google Earth) photo denote the coring locations.

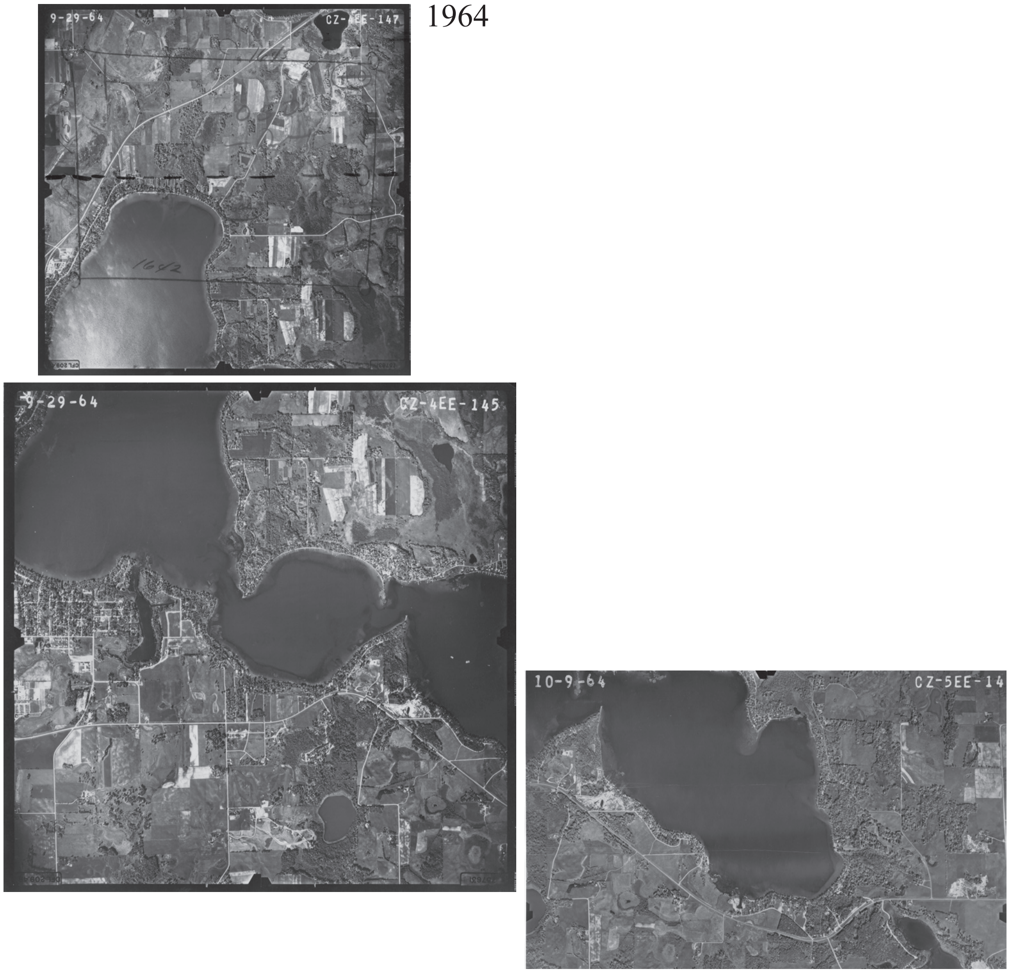
1936



1953

Figure 4. Aerial photographs of Forest Lake from 1964 and a recent Google Earth image. The yellow markers in the Google Earth photo denote the coring locations in each basin.

1964



Google Earth (retrieved Sept 2020)

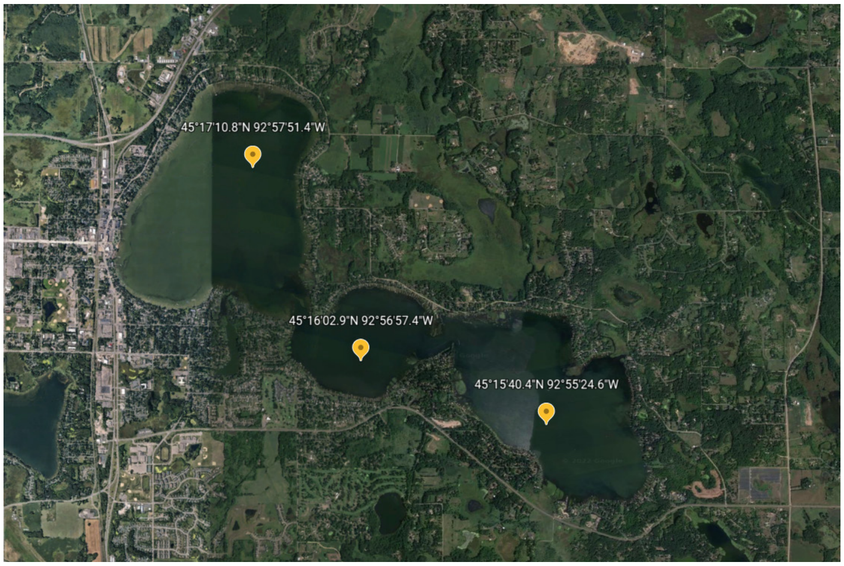
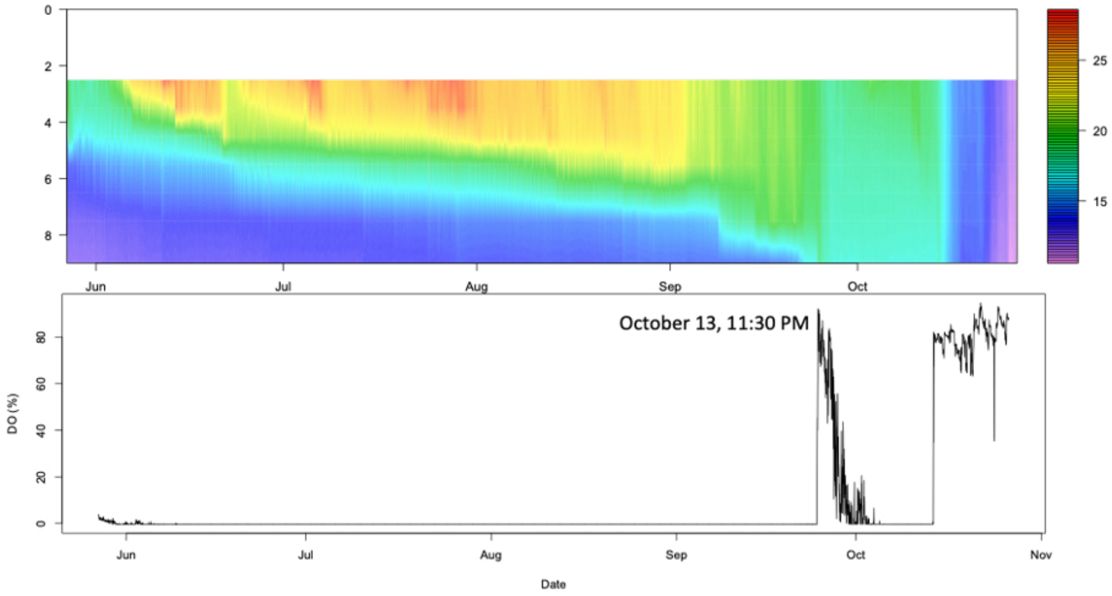


Figure 5. Temperature and DO results from buoyed thermister/dissolved oxygen strings in Forest Central (a) and Forest West (b).

a) Forest Central


October 13, 11:30 PM

b) Forest West

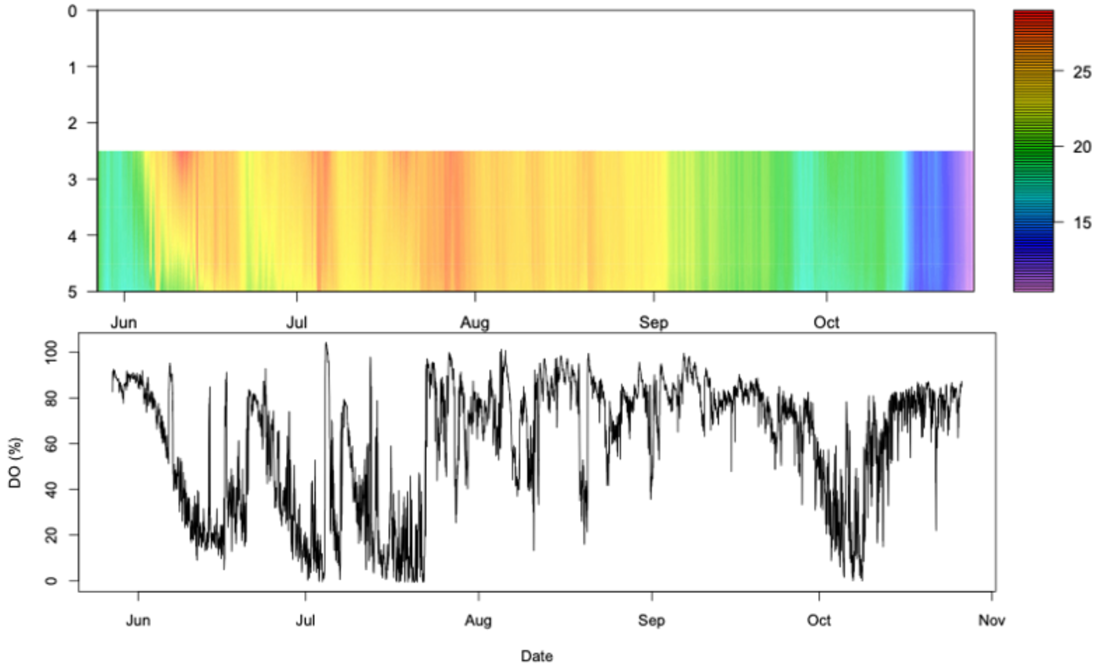


Figure 6. Unsupported lead-210 activity (a), lead-210 dating model (b), and sediment accumulation rate (c) for Little Comfort Lake.

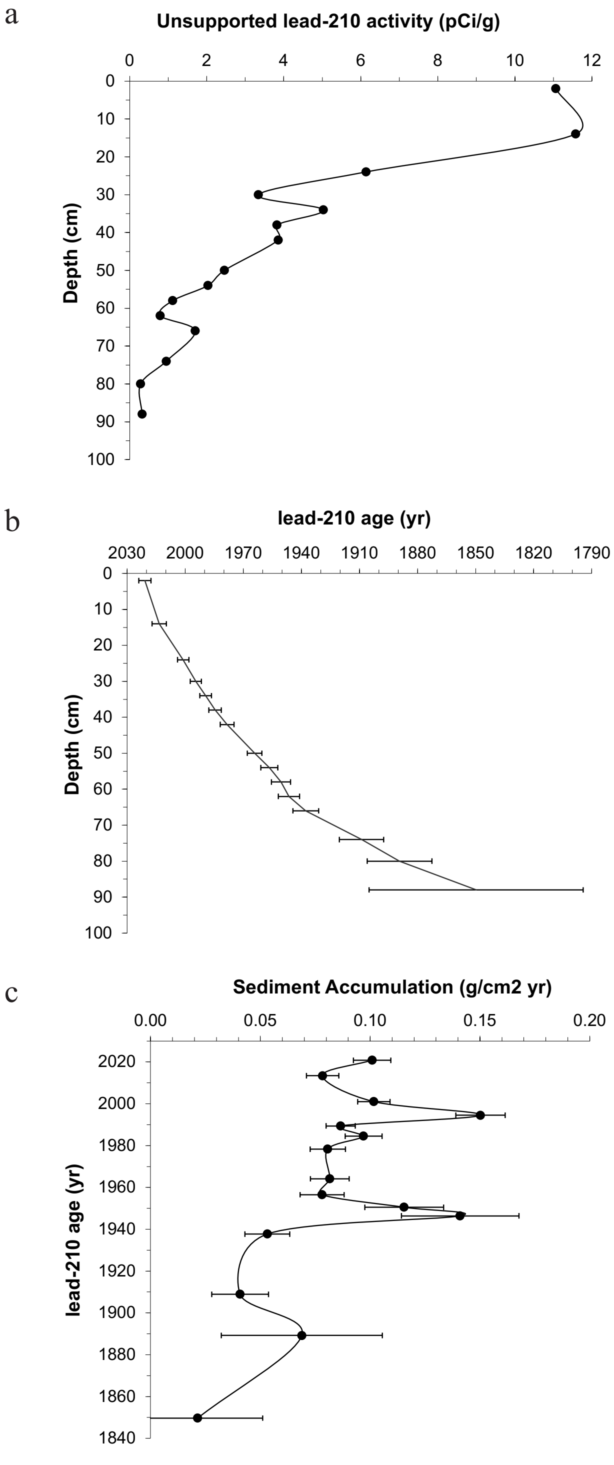


Figure 7. Unsupported lead-210 activity (a), lead-210 dating model (b), and sediment accumulation rate (c) for Forest West; d-f, the same results for Forest Central; g-i, Forest East.

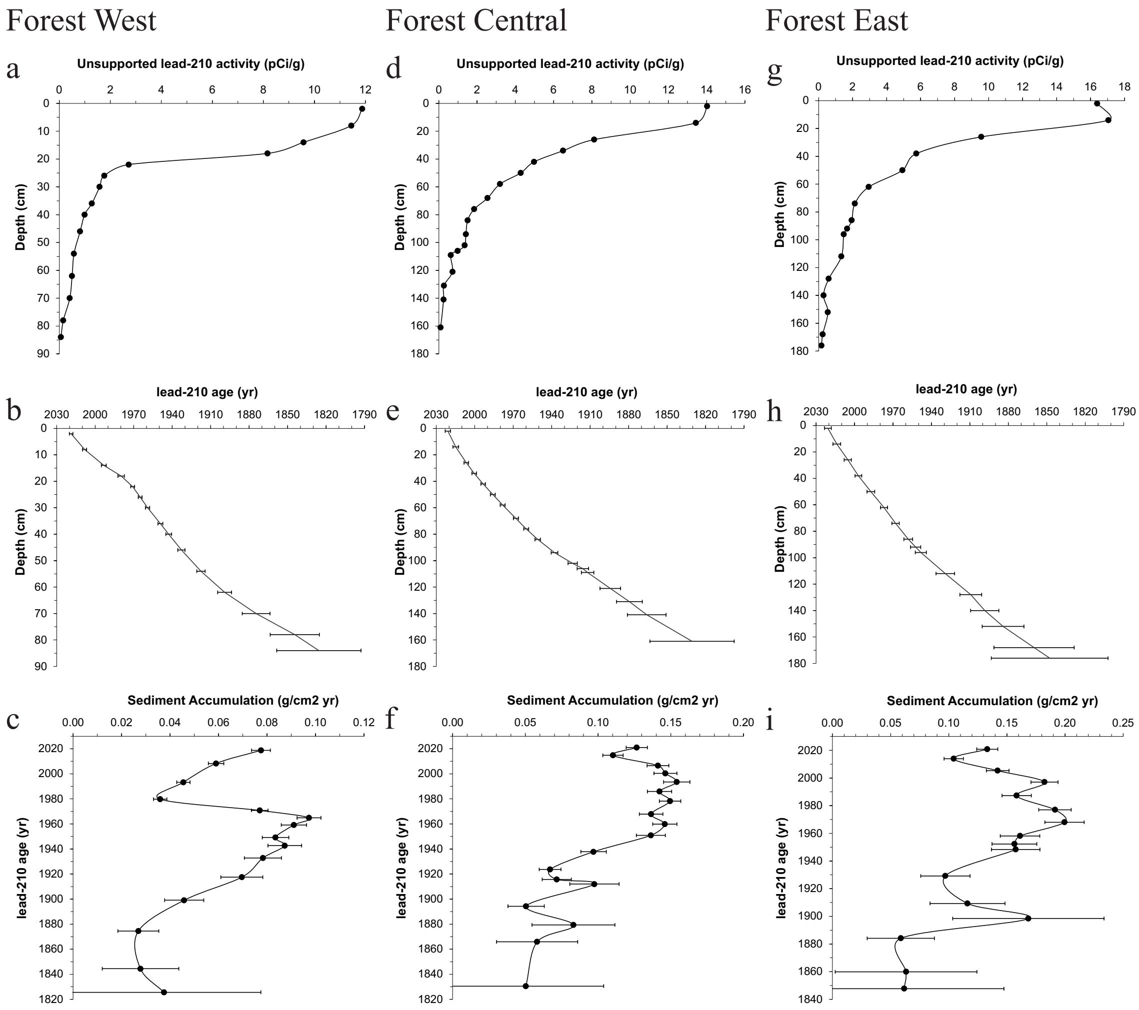


Figure 8. Percent dry weight of organic matter, inorganic matter, and carbonate (CaCO3) in the overlapping piston and Bolivia cores from Little Comfort Lake plotted against depth in the sediment.

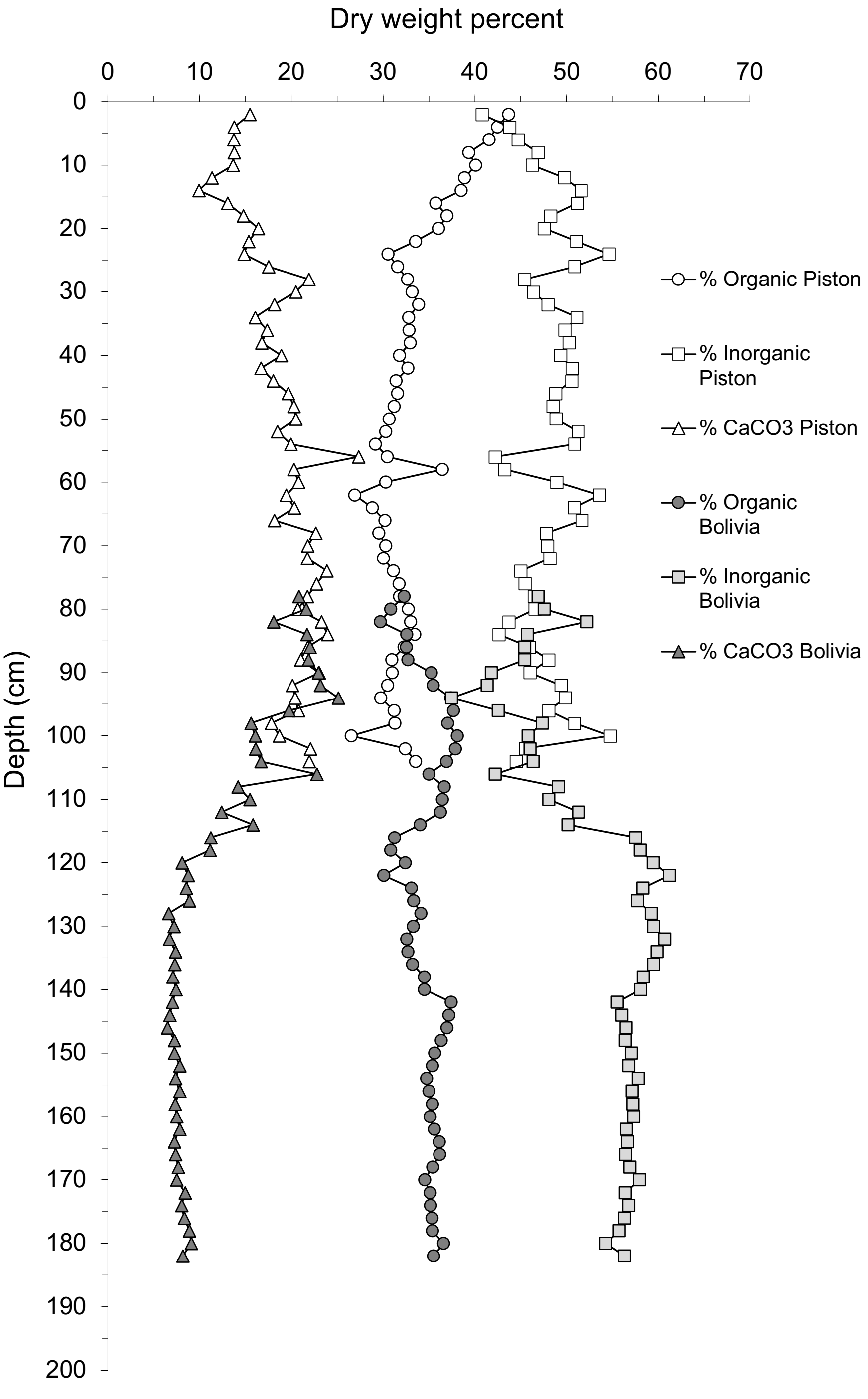


Figure 9. Percent dry weight of organic matter, inorganic matter, and carbonate (CaCO3) in the piston and Bolivia cores from the three basins of Forest Lake plotted against depth in the sediment.

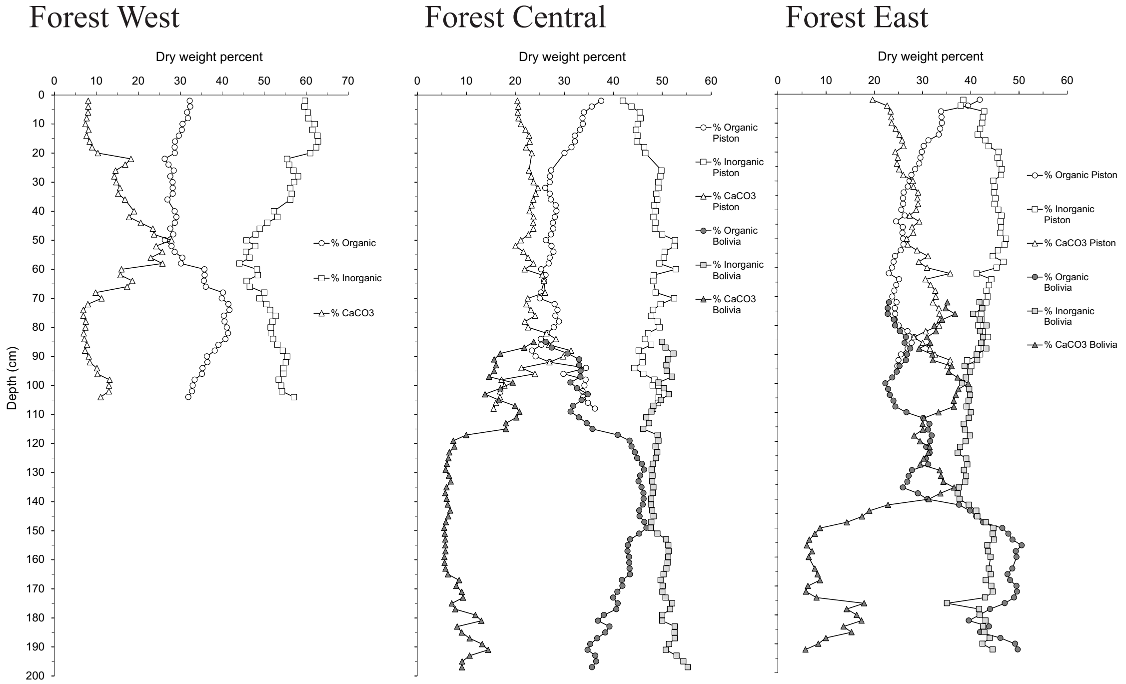


Figure 10. Sediment flux of organic matter, inorganic matter, and carbonate (CaCO3) to the Little Comfort Lake core. Flux was only calculated for the length of the core within the lead-210 record (0-88 cm).

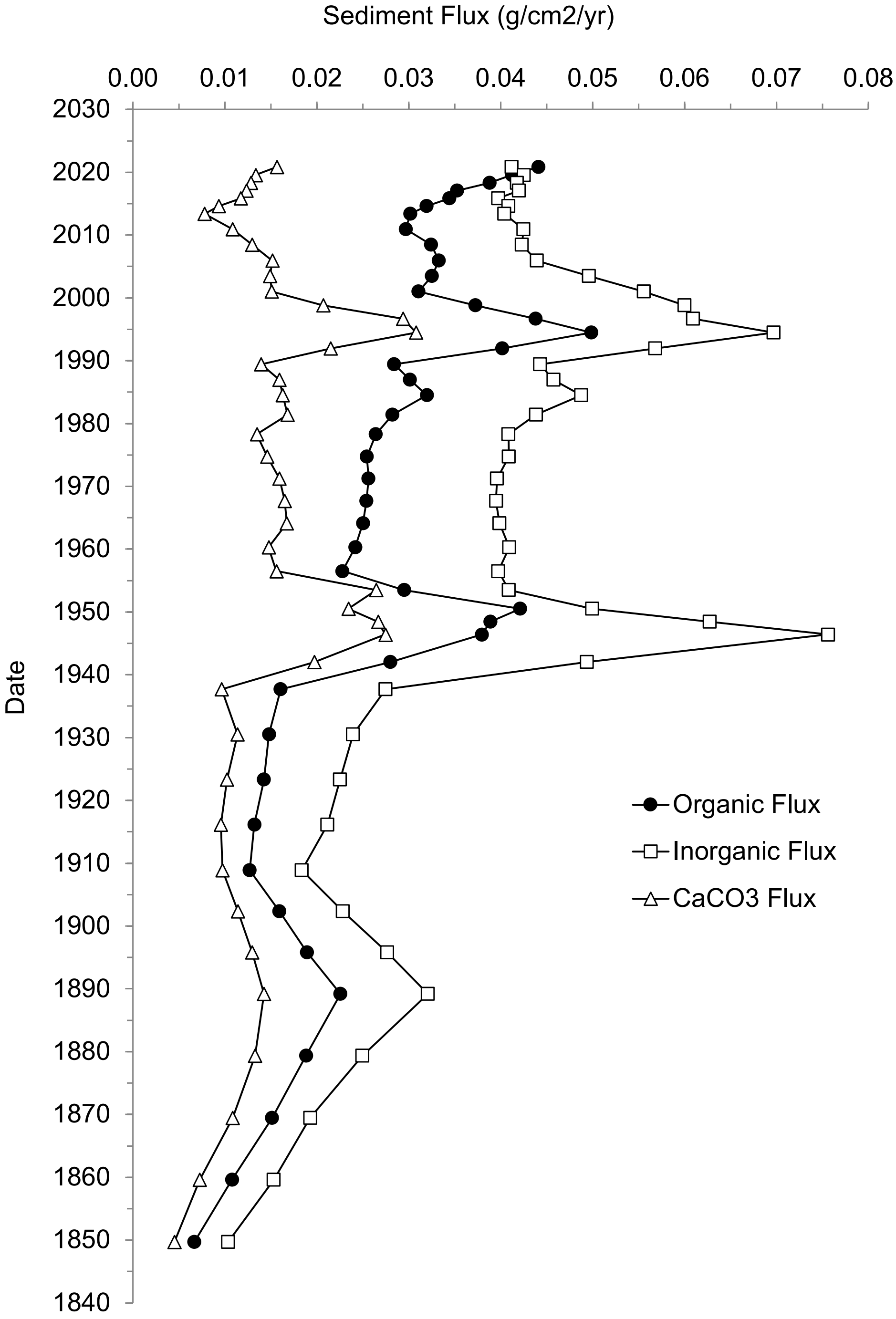


Figure 11. Sediment flux of organic matter, inorganic matter, and carbonate (CaCO3) to the three cores from Forest Lake. Flux was only calculated for the length of the core within the lead-210 record (Forest West, 0-84 cm; Forest Central, 0-161 cm; Forest East, 0-176 cm).

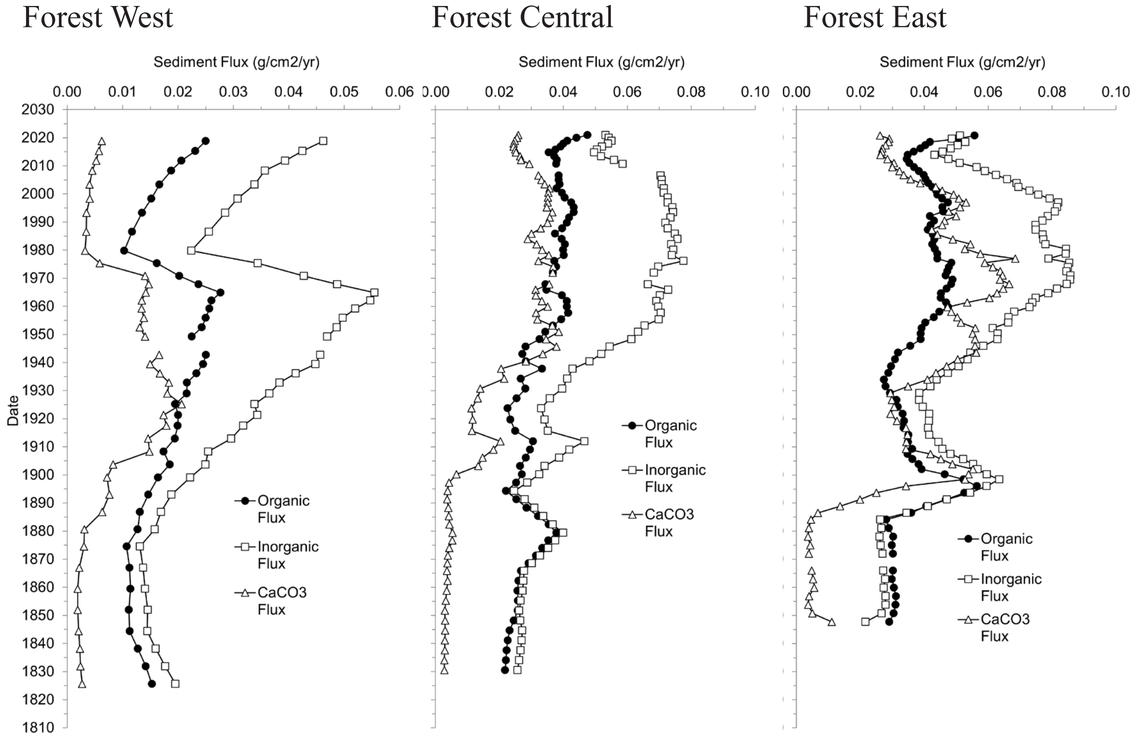


Figure 12. Weight percent of biogenic silica (BSi) (a) and SiO2 flux (b) in the Little Comfort Lake core, plotted against lead-210 date.

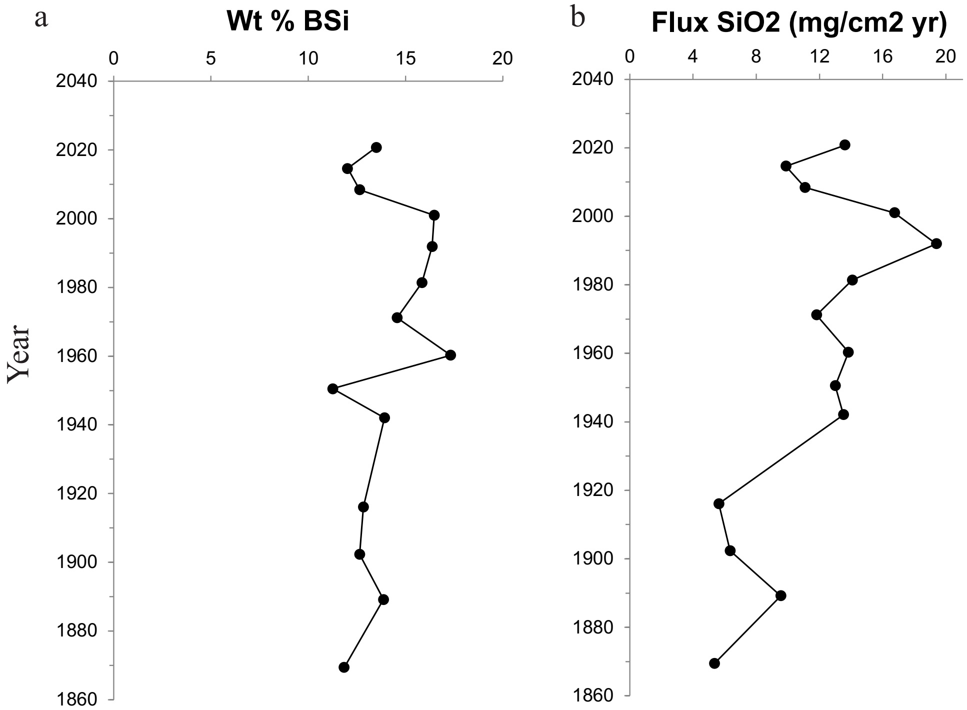


Figure 13. Concentration (a) and flux (b) of phosphorus fractions in the Little Comfort Lake core.

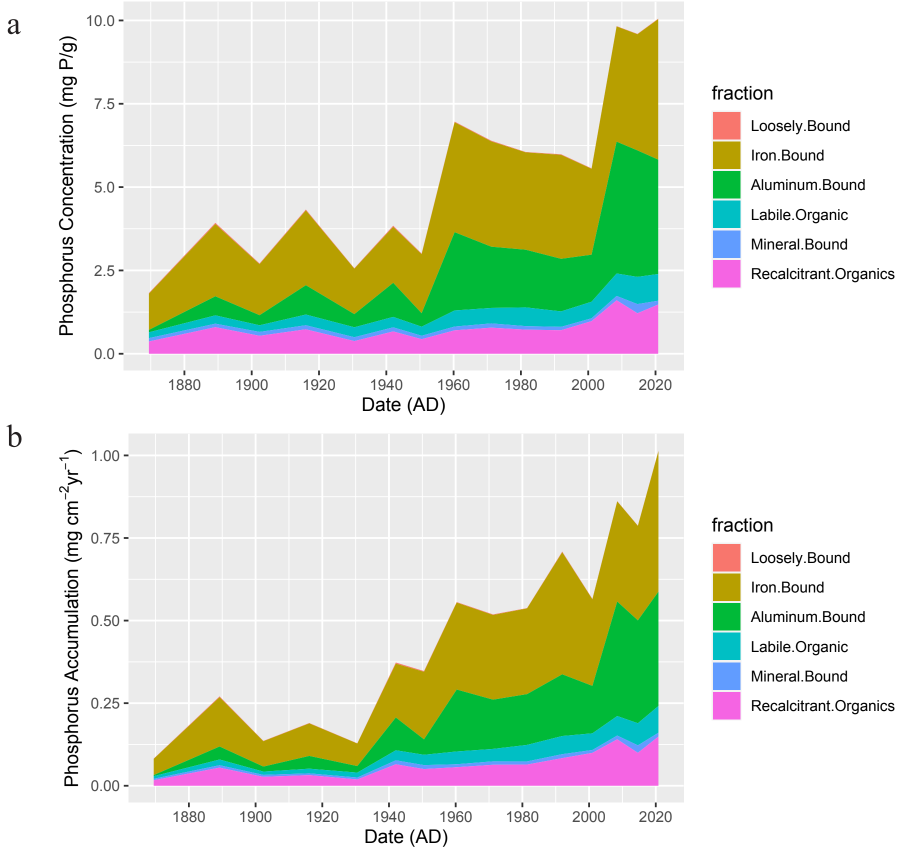


Figure 14. Weight percent of biogenic silica (BSi) (a) and flux (b) in the core from Forest West, plotted against lead-210 date.

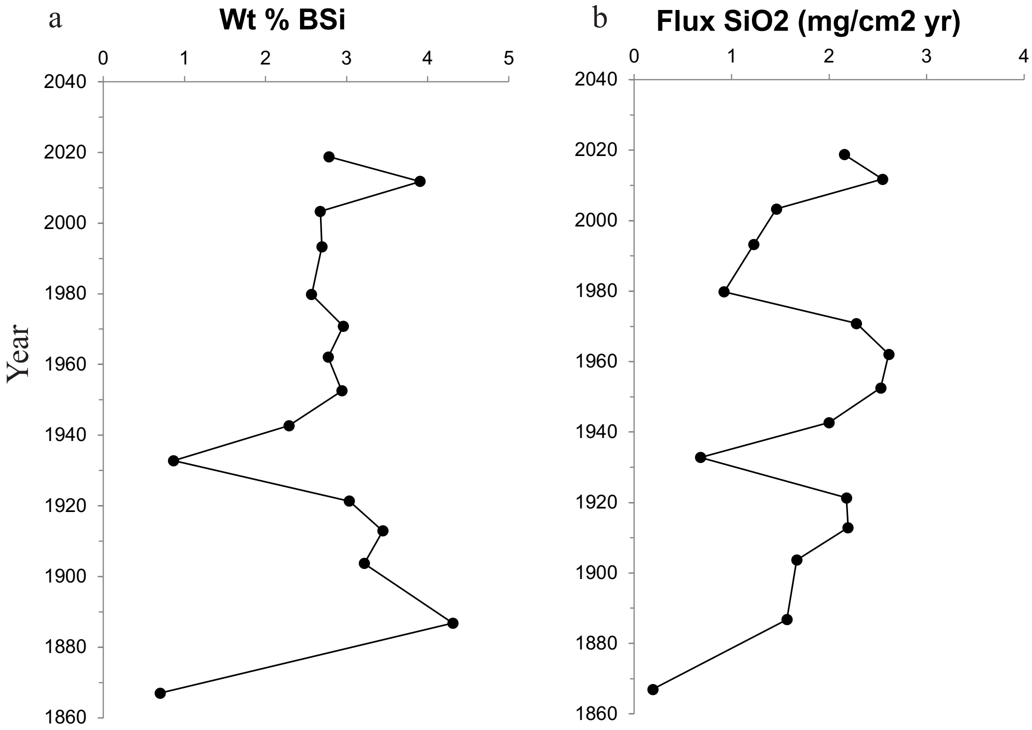


Figure 15. Concentration (a) and flux (b) of phosphorus fractions in the Forest West core.

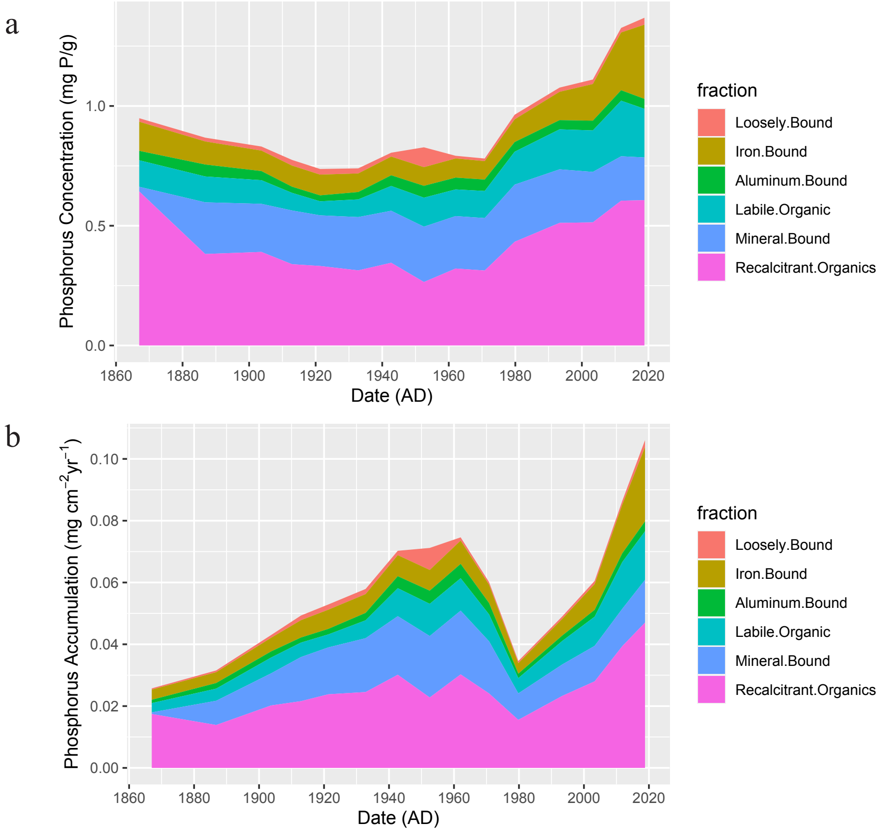


Figure 16. Weight percent of biogenic silica (BSi) (a) and flux (b) in the core from Forest Central, plotted against lead-210 date.

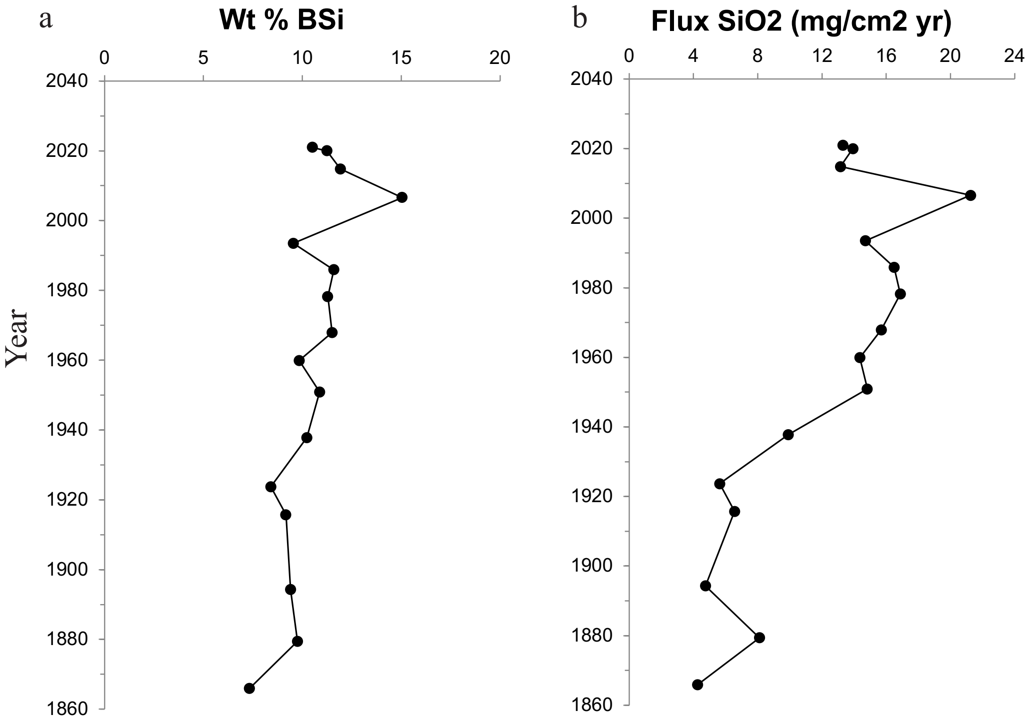


Figure 17. Concentration (a) and flux (b) of phosphorus fractions in the Forest Central core.

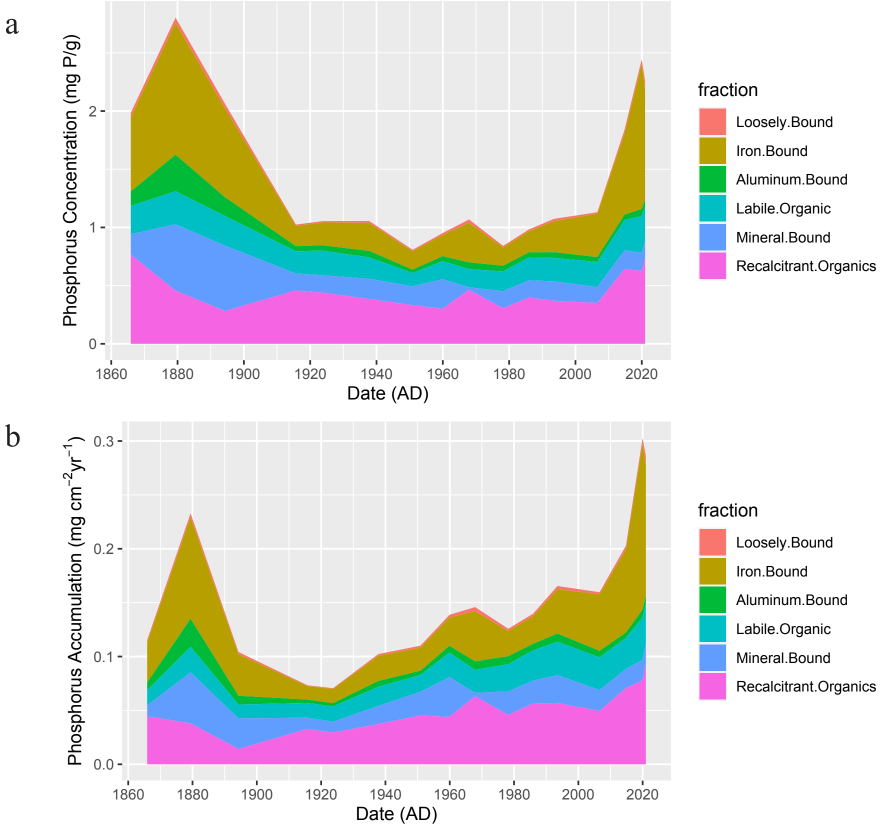


Figure 18. Weight percent of biogenic silica (BSi) (a) and flux (b) in the core from Forest East, plotted against lead-210 date.

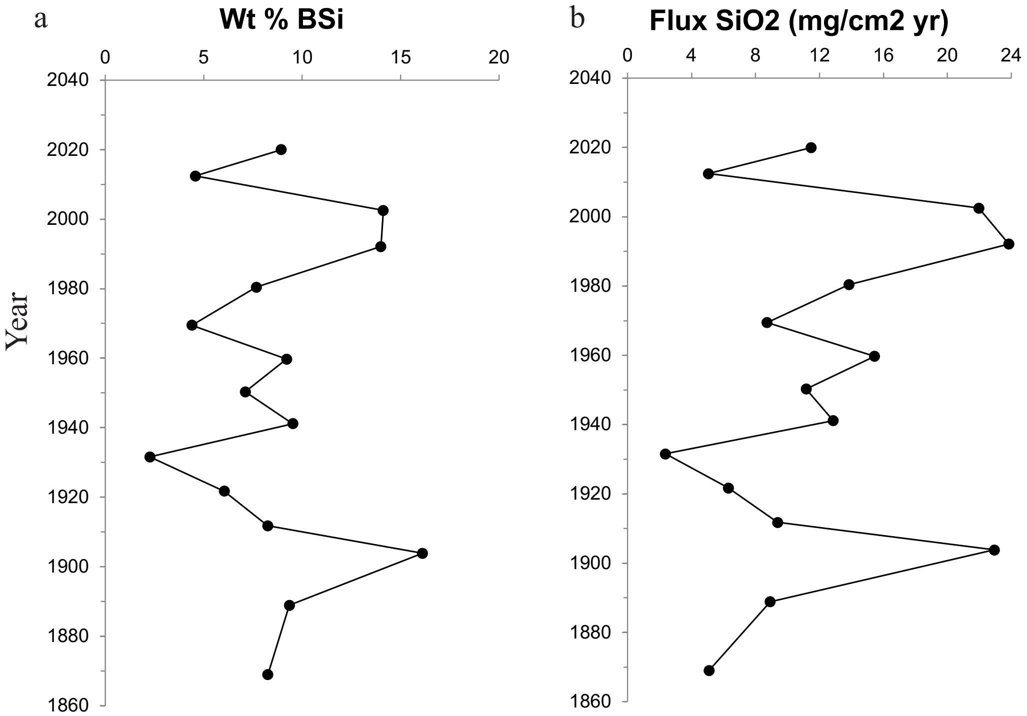


Figure 19. Concentration (a) and flux (b) of phosphorus fractions in the Forest East core.

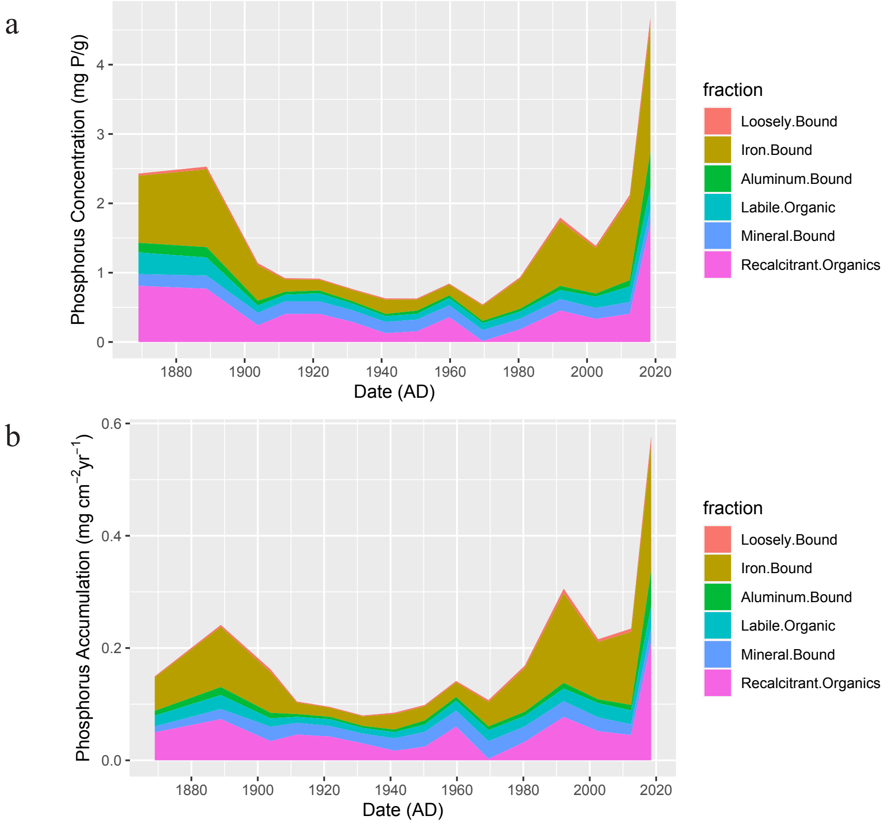


Figure 20. Non-Metric Multidimensional Scaling (NMDS) biplot of diatom communities from Little Comfort Lake (1869-2021).

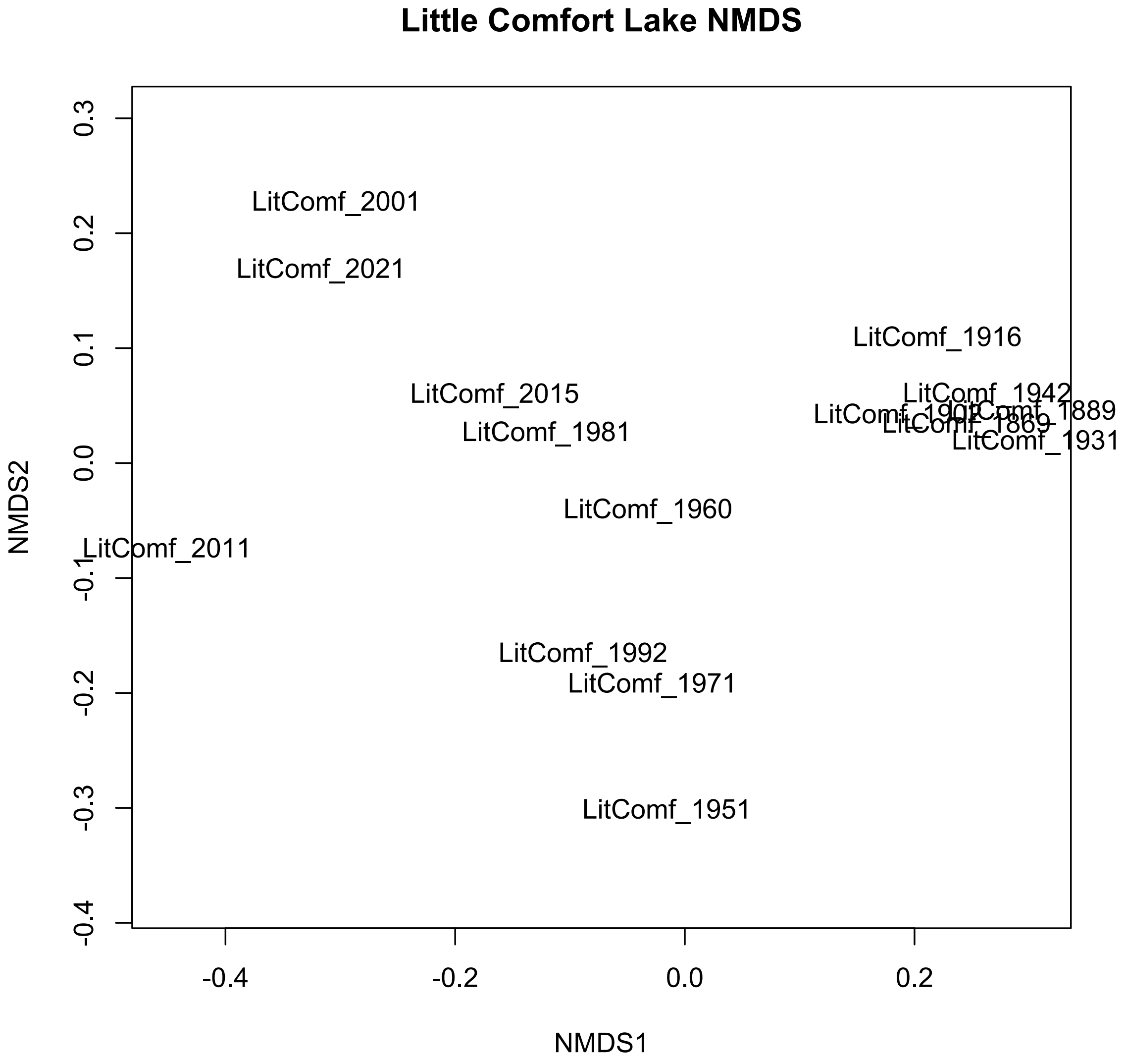


Figure 21. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance), results of a constrained cluster analysis, and percent plankton in Little Comfort Lake (1869-2021).

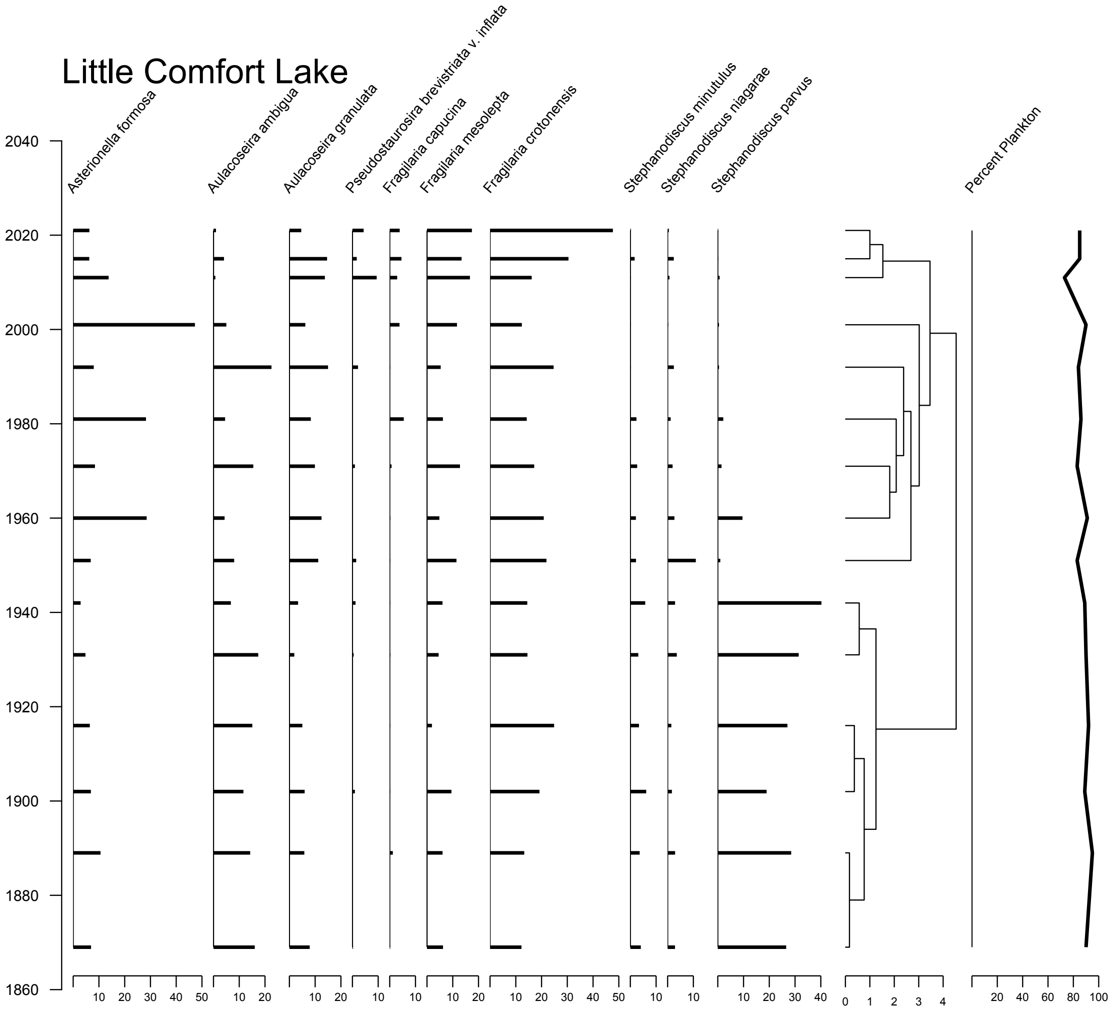


Figure 22. Non-Metric Multidimensional Scaling (NMDS) biplot of diatom communities from Forest West (1867-2019).

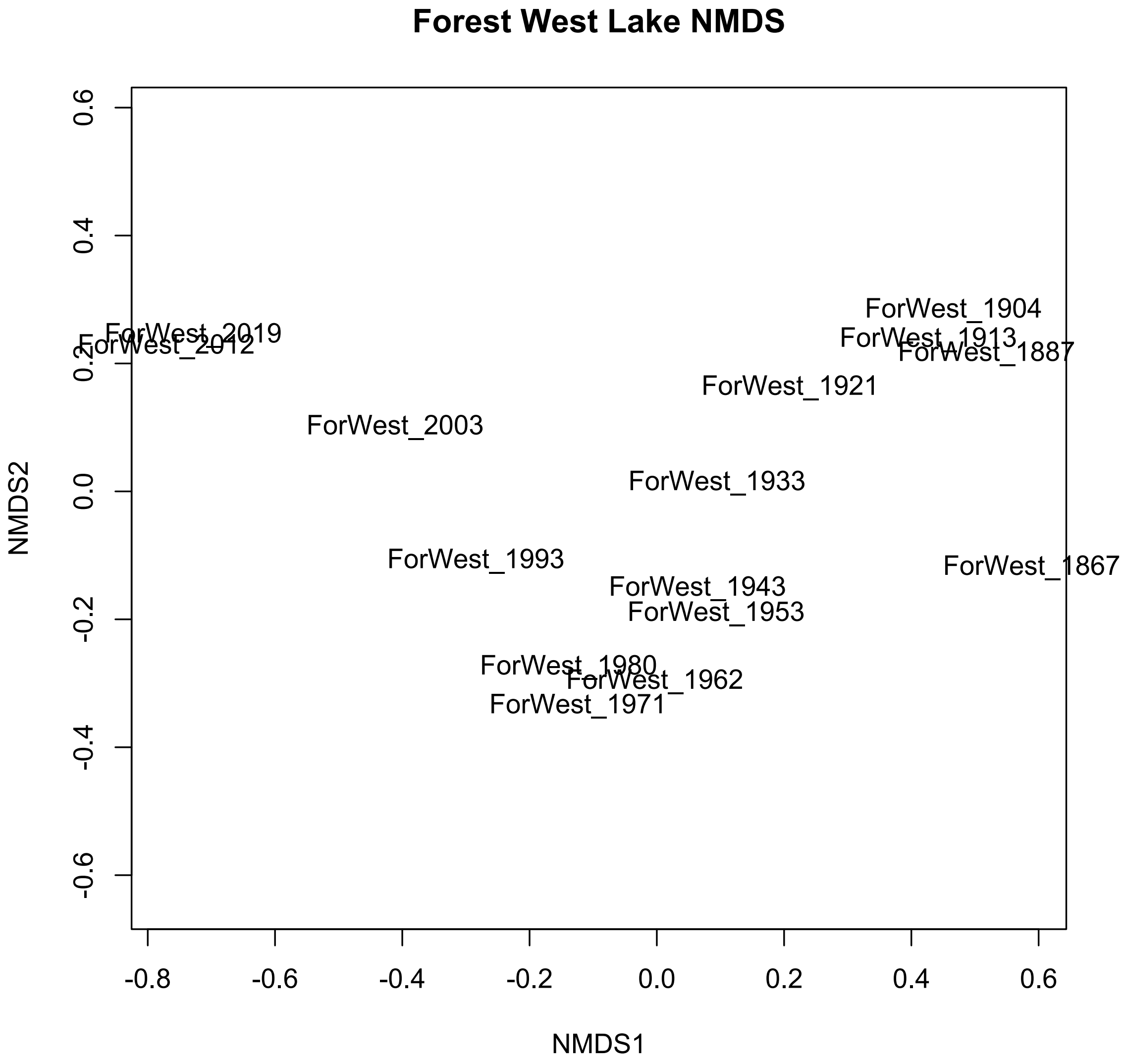


Figure 23. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance), results of a constrained cluster analysis, and percent plankton in Forest West (1867-2019).

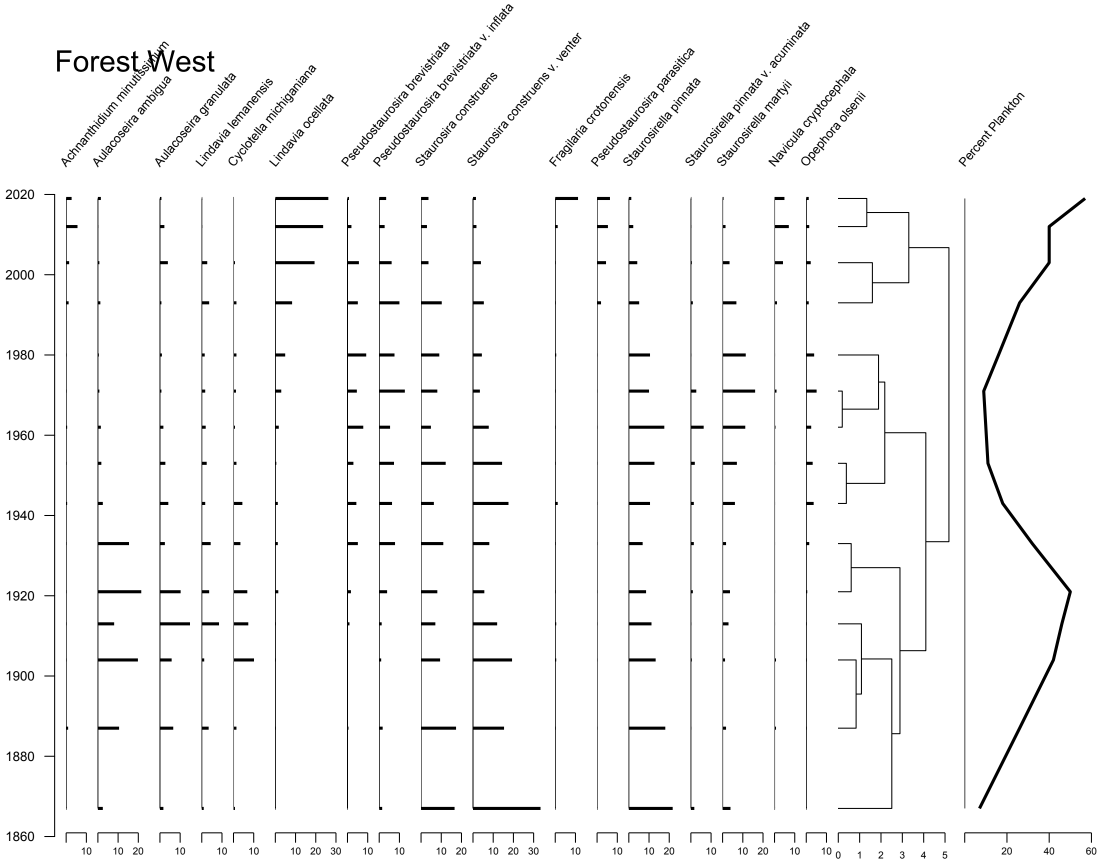


Figure 24. Non-Metric Multidimensional Scaling (NMDS) biplot of diatom communities from Forest Central (1831-2021).

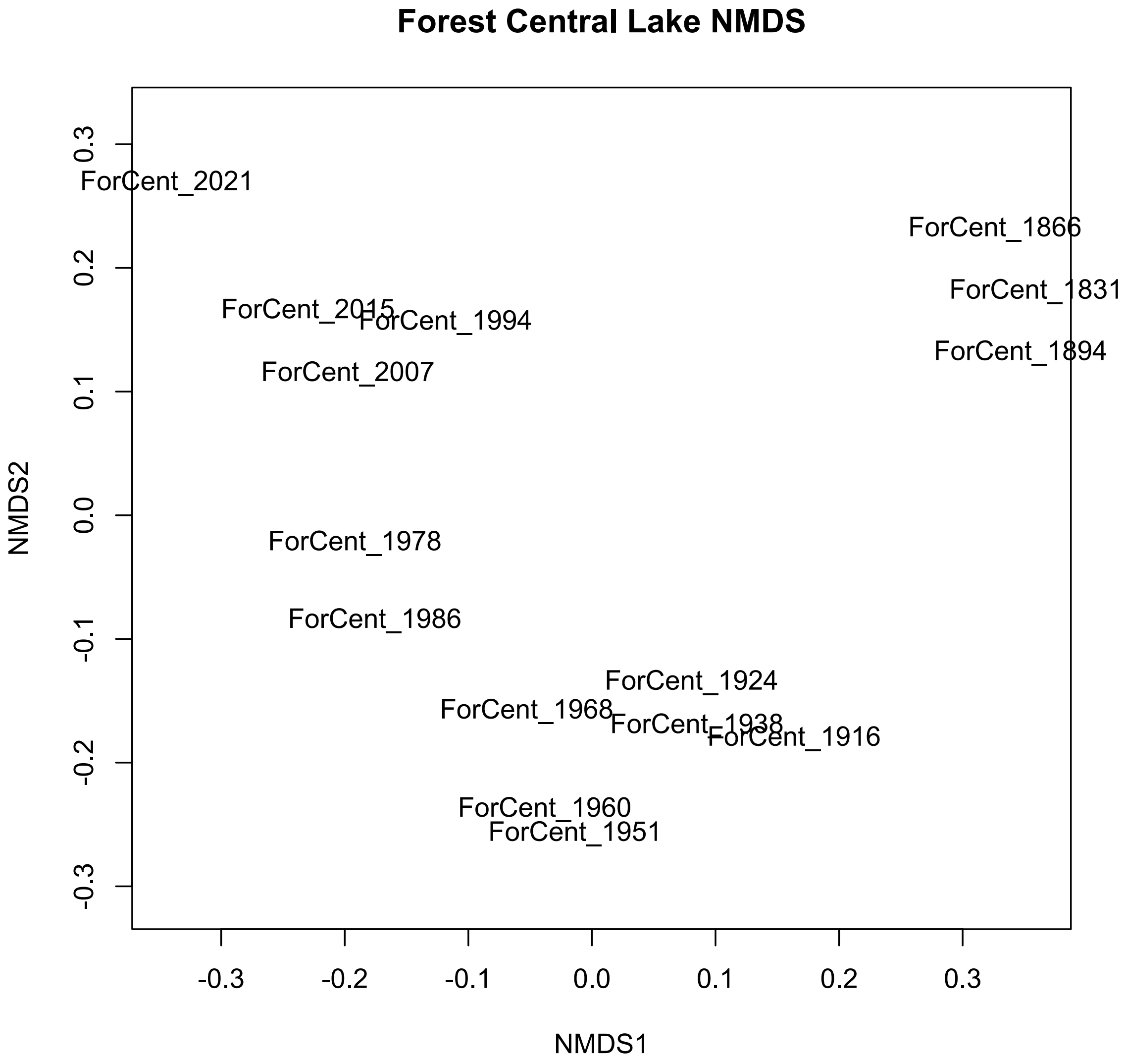


Figure 25. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance), results of a constrained cluster analysis, and percent plankton in Forest Central (1831-2021).

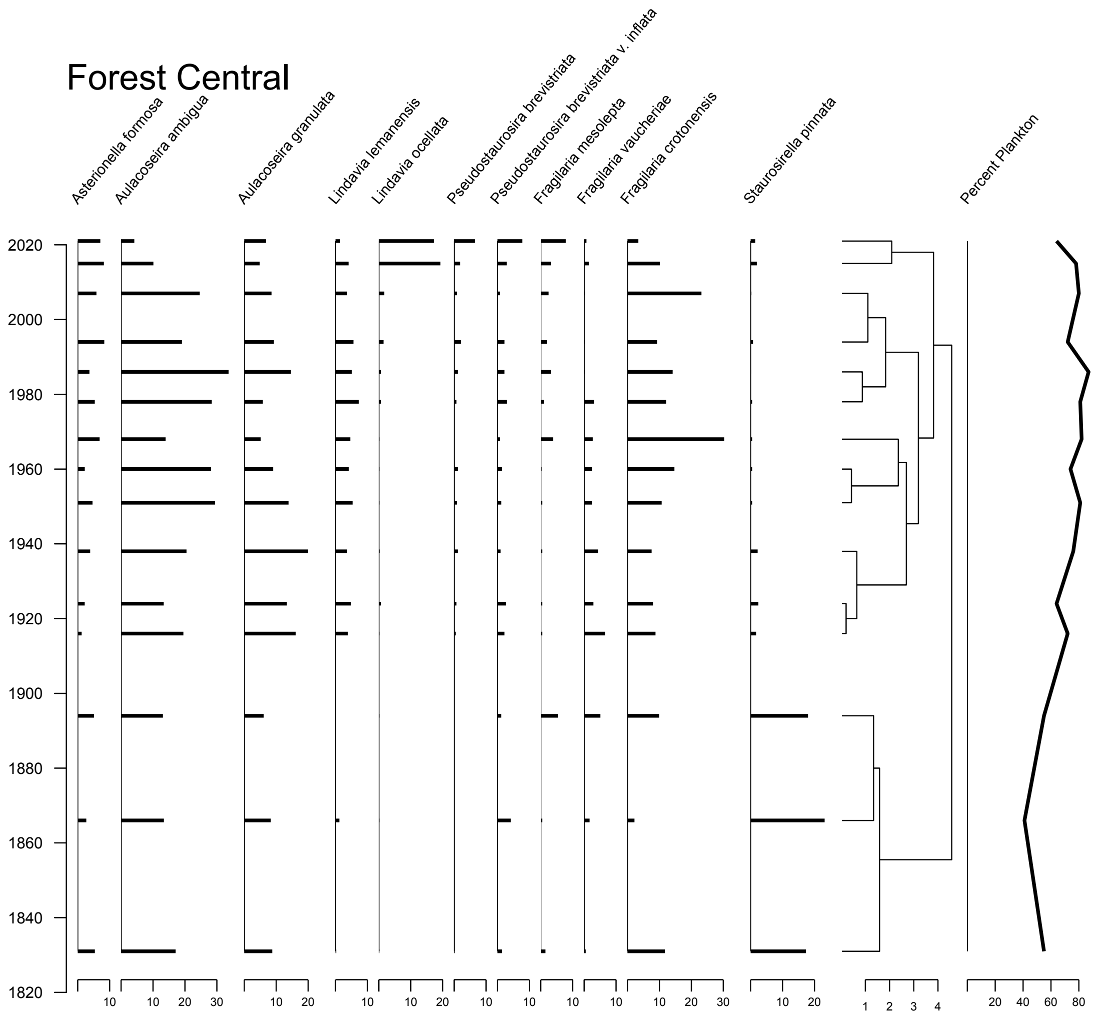


Figure 26. Non-Metric Multidimensional Scaling (NMDS) biplot of diatom communities from Forest East (1869-2020).

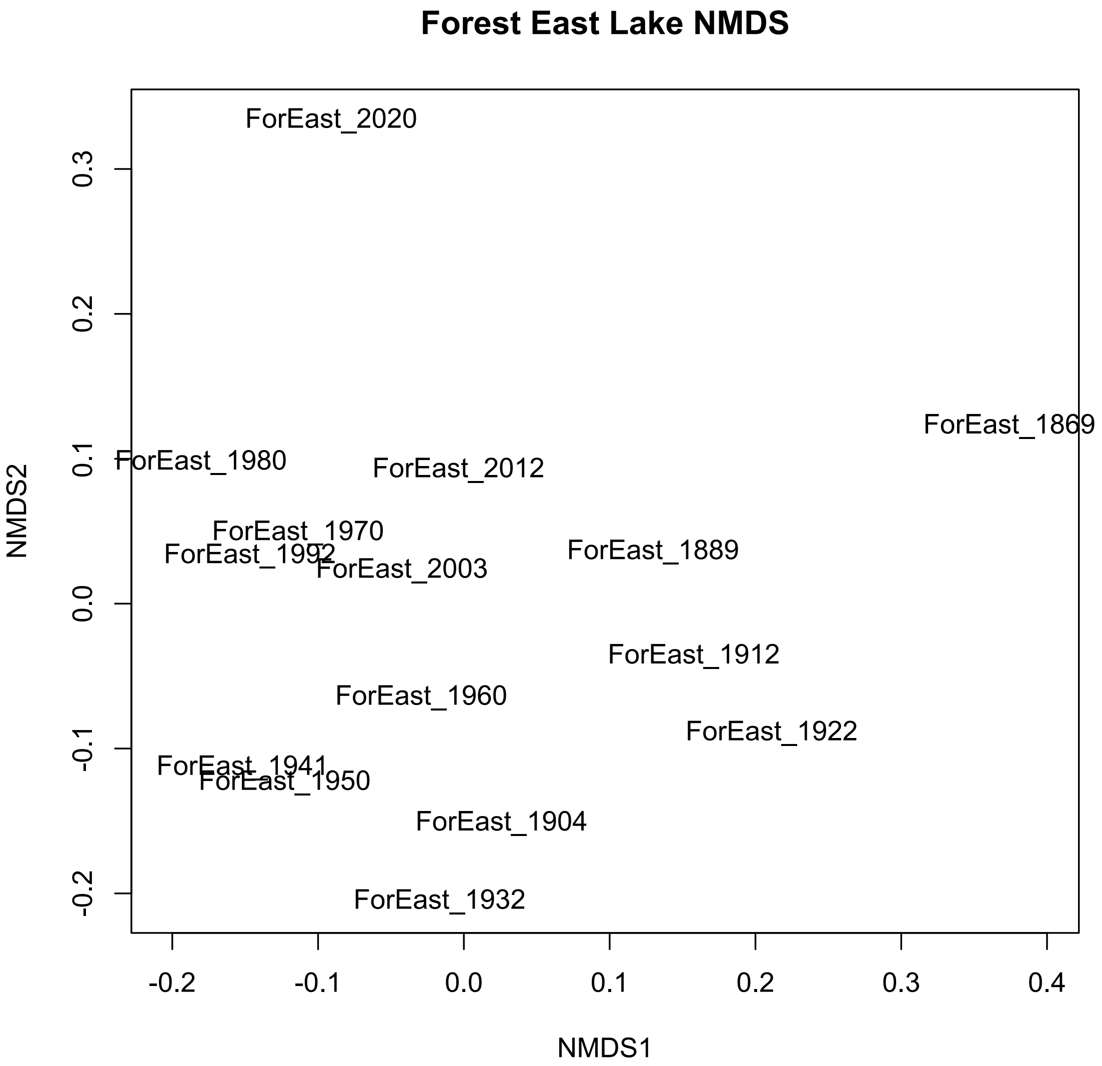


Figure 27. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance), results of a constrained cluster analysis, and percent plankton in Forest East (1869-2020).

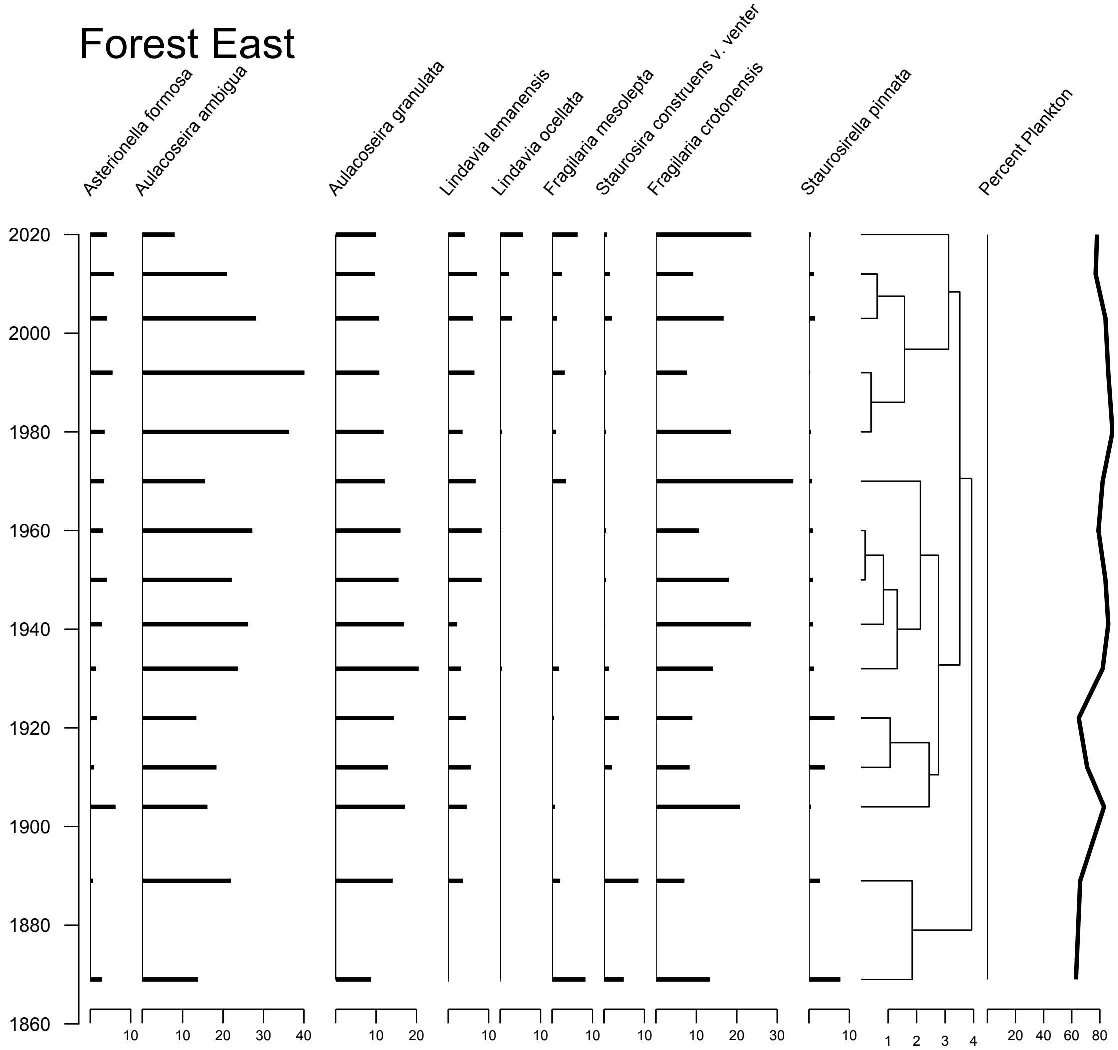


Figure 28. The core sections from Little Comfort Lake projected onto the MN calibration set (denoted as core date). Symbols represent the 89 MN lakes in the calibration set, coded by region; NLF=Northern Lakes and Forests, CHF=Central Hardwood Forests, Metro=Twin Cities Metropolitan Area, WCP=Western Corn Belt Plains, NGP=Northern Great Plains, and MCWD=Minnehaha Creek Watershed Distric. Environmental vectors are shown on the inset plot. Note that logTP is strongly correlated with Axis 1.

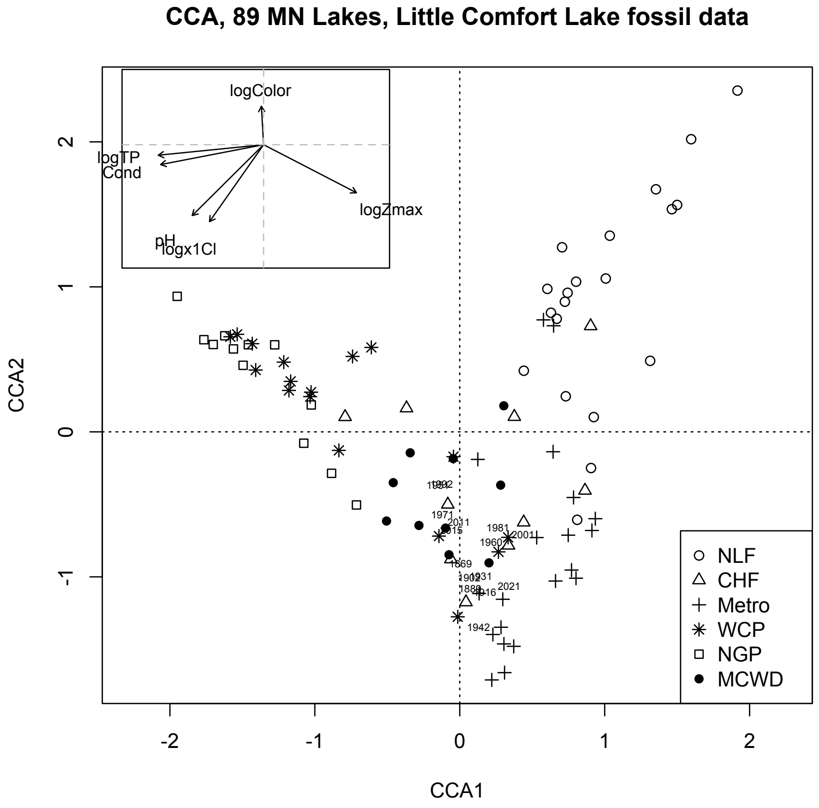


Figure 29. Diatom-inferred total phosphorus (TP) reconstruction for Little Comfort Lake. Reconstruction is shown as log TP (left panel) and as backtransformed values in micrograms per liter (right panel). Error estimates on log TP are plus and minus the root mean square error of prediction from the TP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

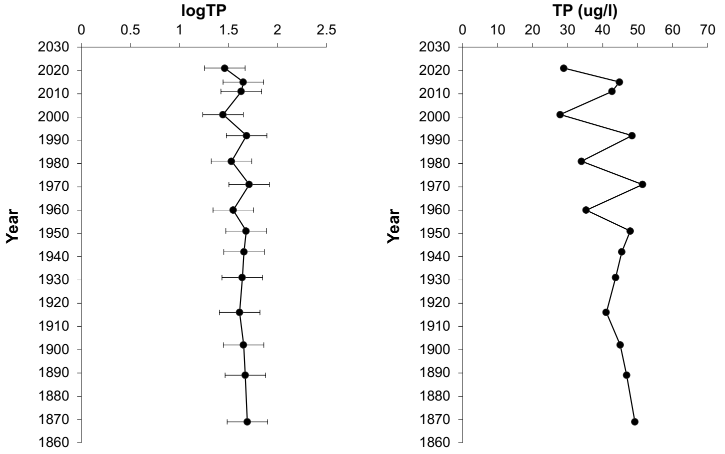


Figure 30. The core sections from Forest West projected onto the MN calibration set (denoted as core date). Symbols represent the 89 MN lakes in the calibration set, coded by region; NLF=Northern Lakes and Forests, CHF=Central Hardwood Forests, Metro=Twin Cities Metropolitan Area, WCP=Western Corn Belt Plains, NGP=Northern Great Plains, and MCWD=Minnehaha Creek Watershed Distric. Environmental vectors are shown on the inset plot. Note that logTP is strongly correlated with Axis 1.

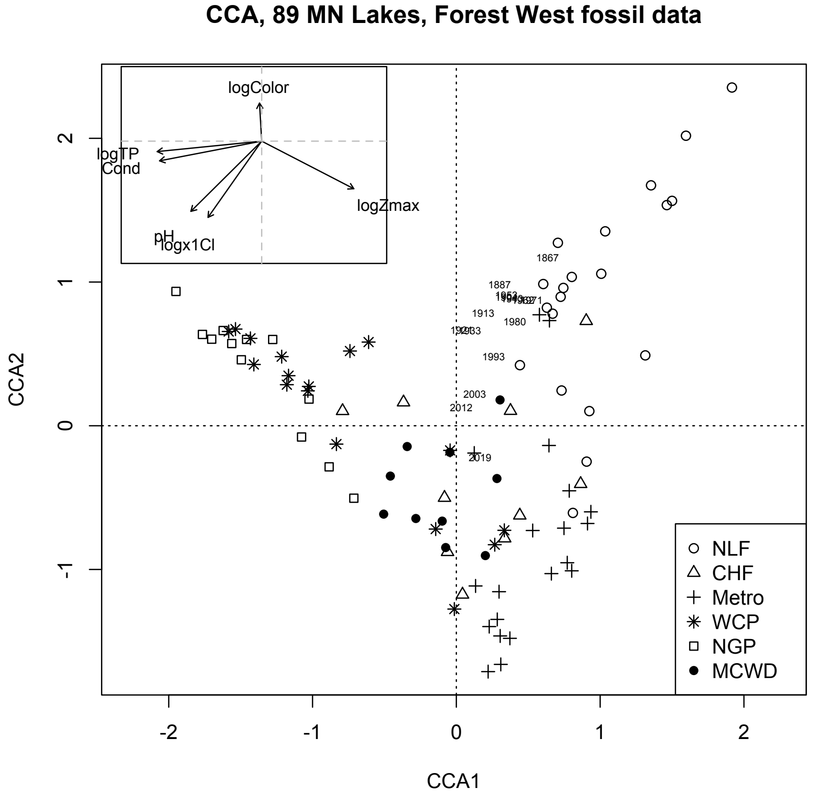


Figure 31. Diatom-inferred total phosphorus (TP) reconstruction for Forest West. Reconstruction is shown as log TP (left panel) and as backtransformed values in micrograms per liter (right panel). Error estimates on log TP are plus and minus the root mean square error of prediction from the TP transfer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

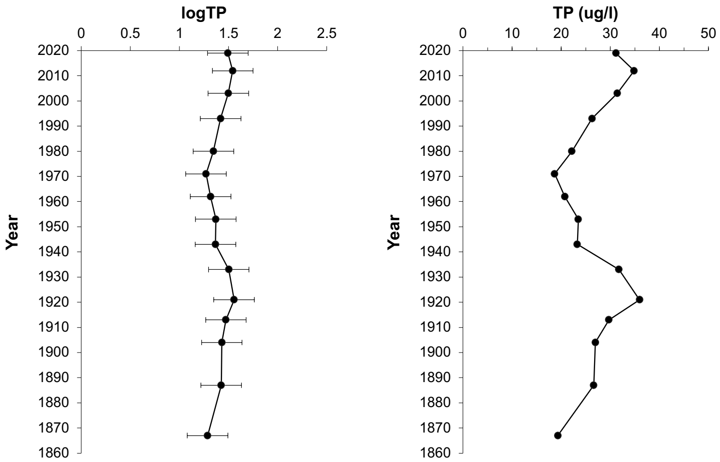


Figure 32. The core sections from Forest Central projected onto the MN calibration set (denoted as core date). Symbols represent the 89 MN lakes in the calibration set, coded by region; NLF=Northern Lakes and Forests, CHF=Central Hardwood Forests, Metro=Twin Cities Metropolitan Area, WCP=Western Corn Belt Plains, NGP=Northern Great Plains, and MCWD=Minnehaha Creek Watershed Distric. Environmental vectors are shown on the inset plot. Note that logTP is strongly correlated with Axis 1.

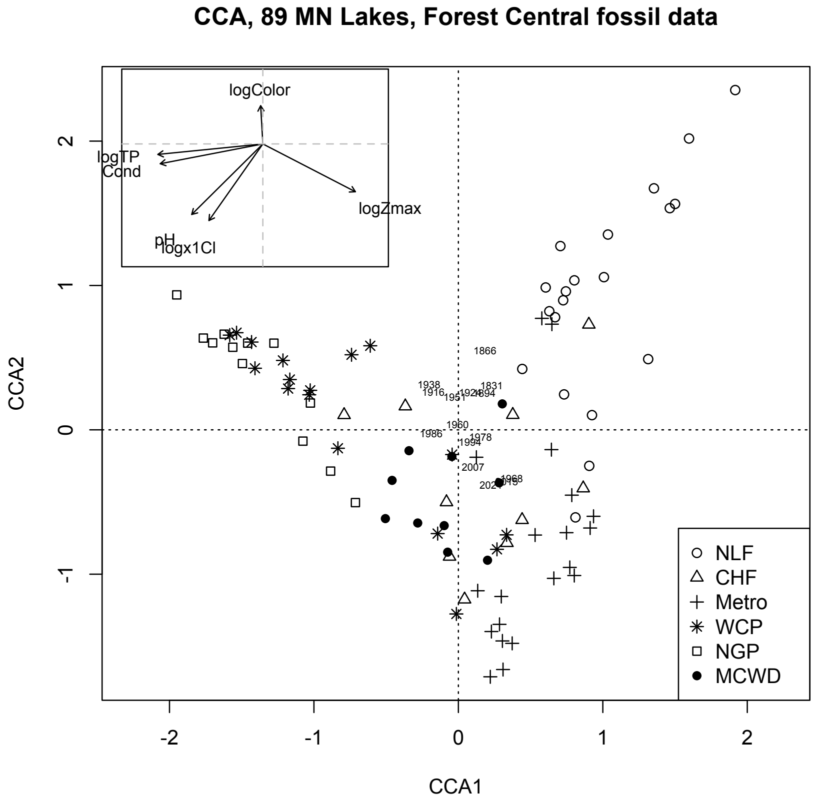


Figure 33. Diatom-inferred total phosphorus (TP) reconstruction for Forest Central. Reconstruction is shown as log TP (left panel) and as backtransformed values in micrograms per liter (right panel). Error estimates on log TP are plus and minus the root mean square error of prediction from the TP transfer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

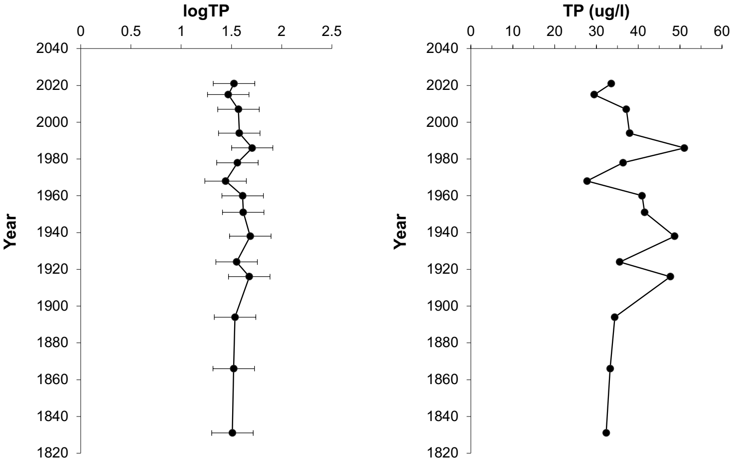


Figure 34. The core sections from Forest East projected onto the MN calibration set (denoted as core date). Symbols represent the 89 MN lakes in the calibration set, coded by region; NLF=Northern Lakes and Forests, CHF=Central Hardwood Forests, Metro=Twin Cities Metropolitan Area, WCP=Western Corn Belt Plains, NGP=Northern Great Plains, and MCWD=Minnehaha Creek Watershed Distric. Environmental vectors are shown on the inset plot. Note that logTP is strongly correlated with Axis 1.

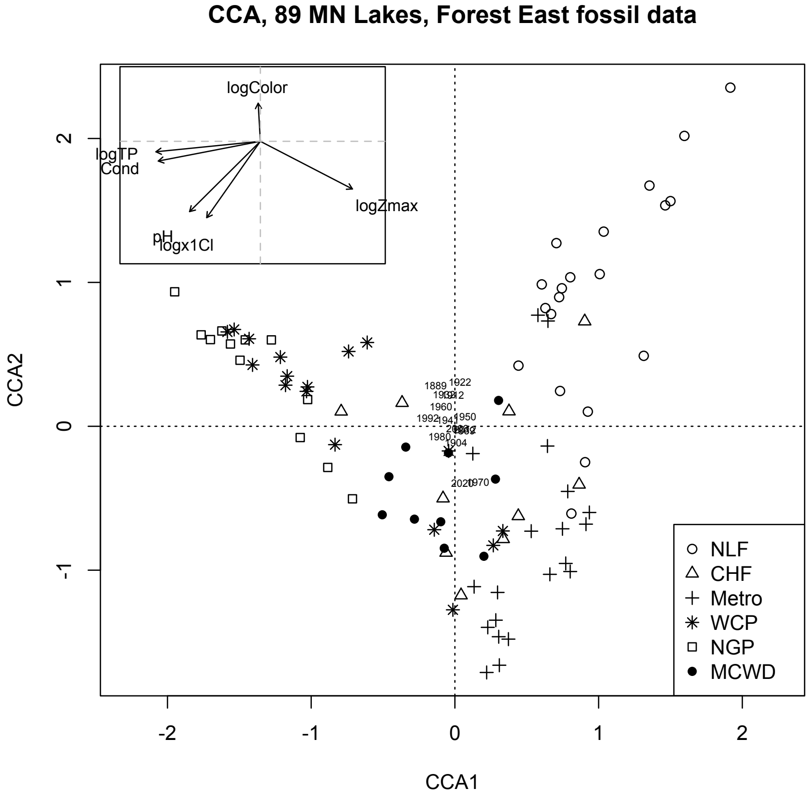


Figure 35. Diatom-inferred total phosphorus (TP) reconstruction for Forest East. Reconstruction is shown as log TP (left panel) and as backtransformed values in micrograms per liter (right panel). Error estimates on log TP are plus and minus the root mean square error of prediction from the TP transfer function.

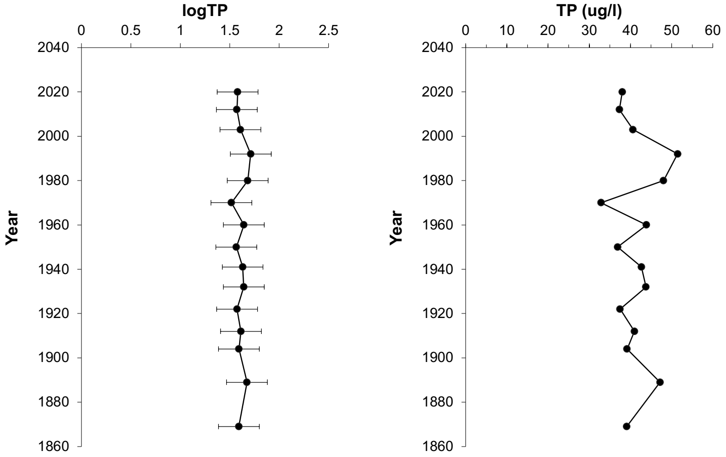


Figure 36. Sediment algal pigments quantified in ten core sections from Little Comfort Lake. The group of algae associated with each pigment is shown along the x-axis.

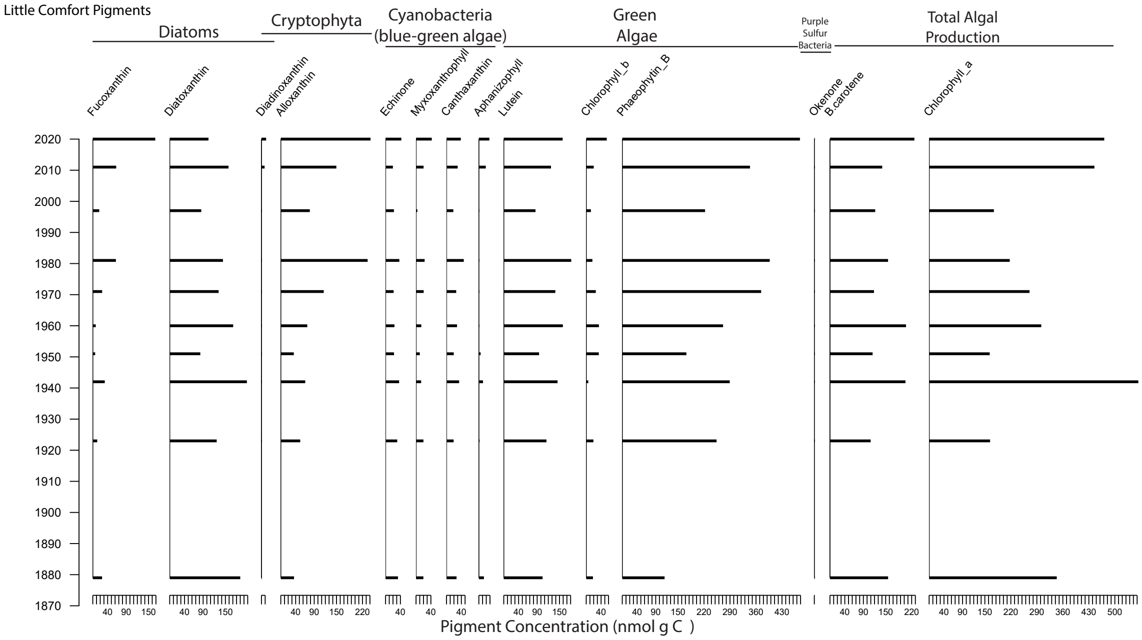


Figure 37. Sediment algal pigments quantified in ten core sections from Forest West. The group of algae associated with each pigment is shown along the x-axis.

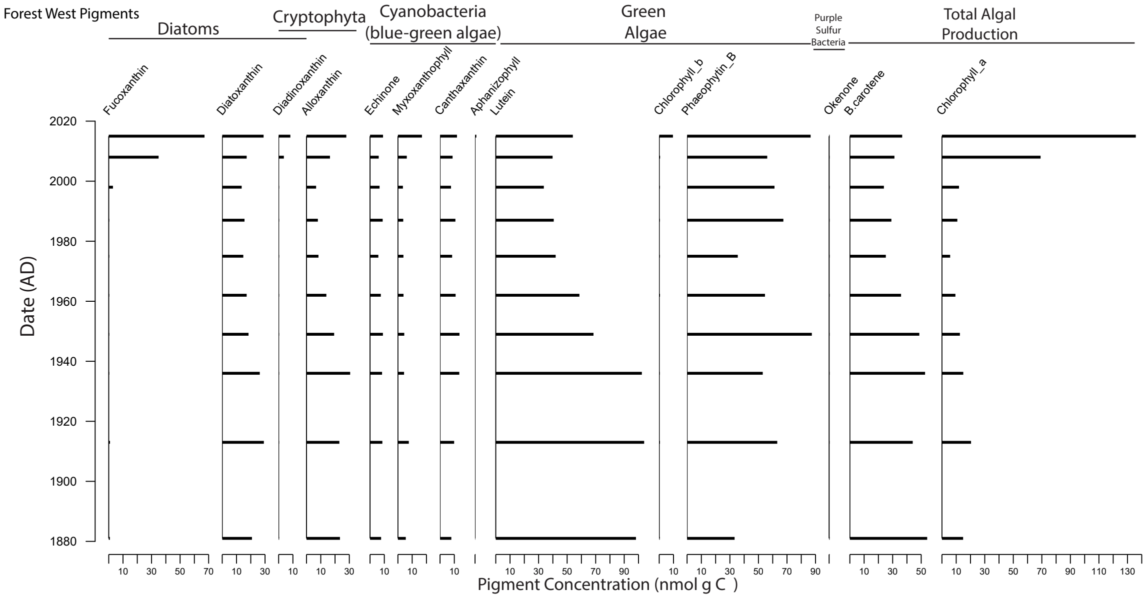


Figure 38. Sediment algal pigments quantified in ten core sections from Forest Central. The group of algae associated with each pigment is shown along the x-axis.

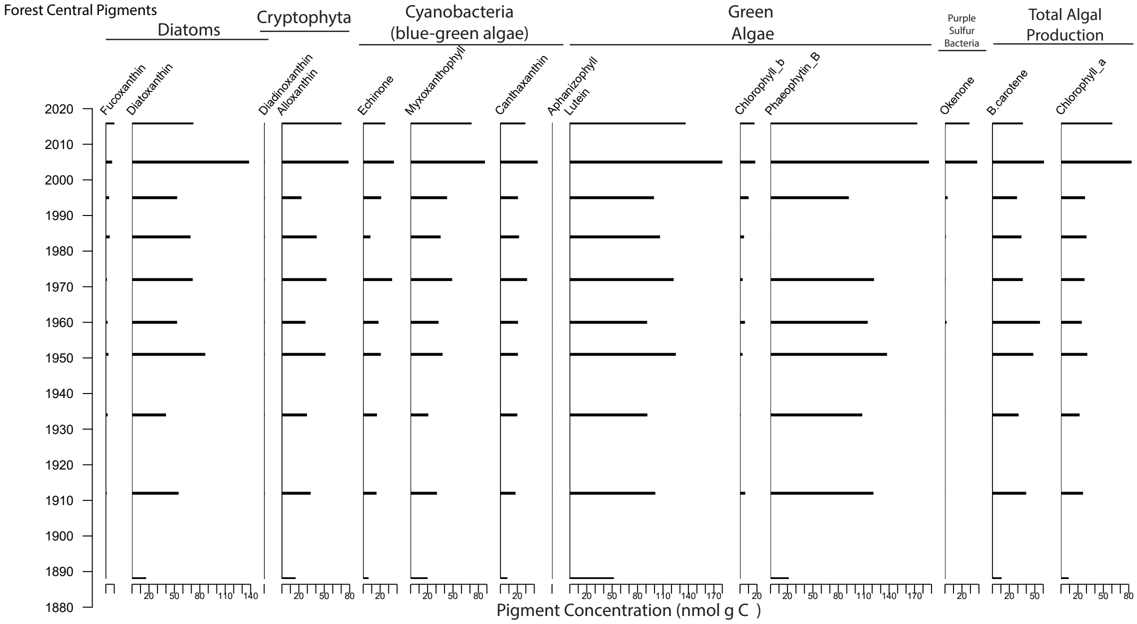
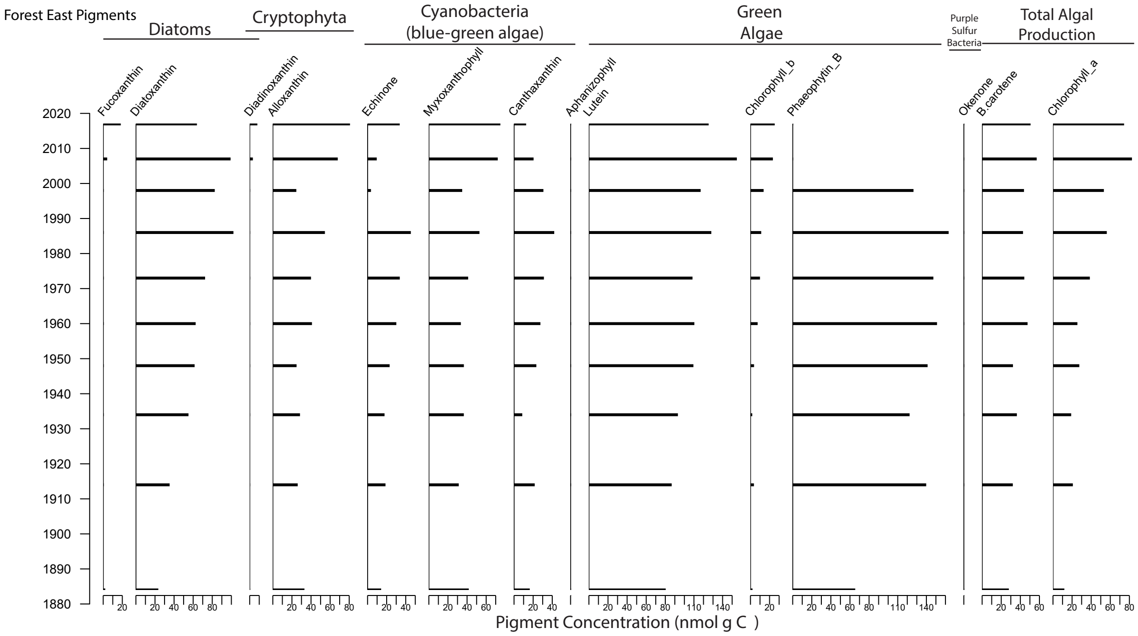
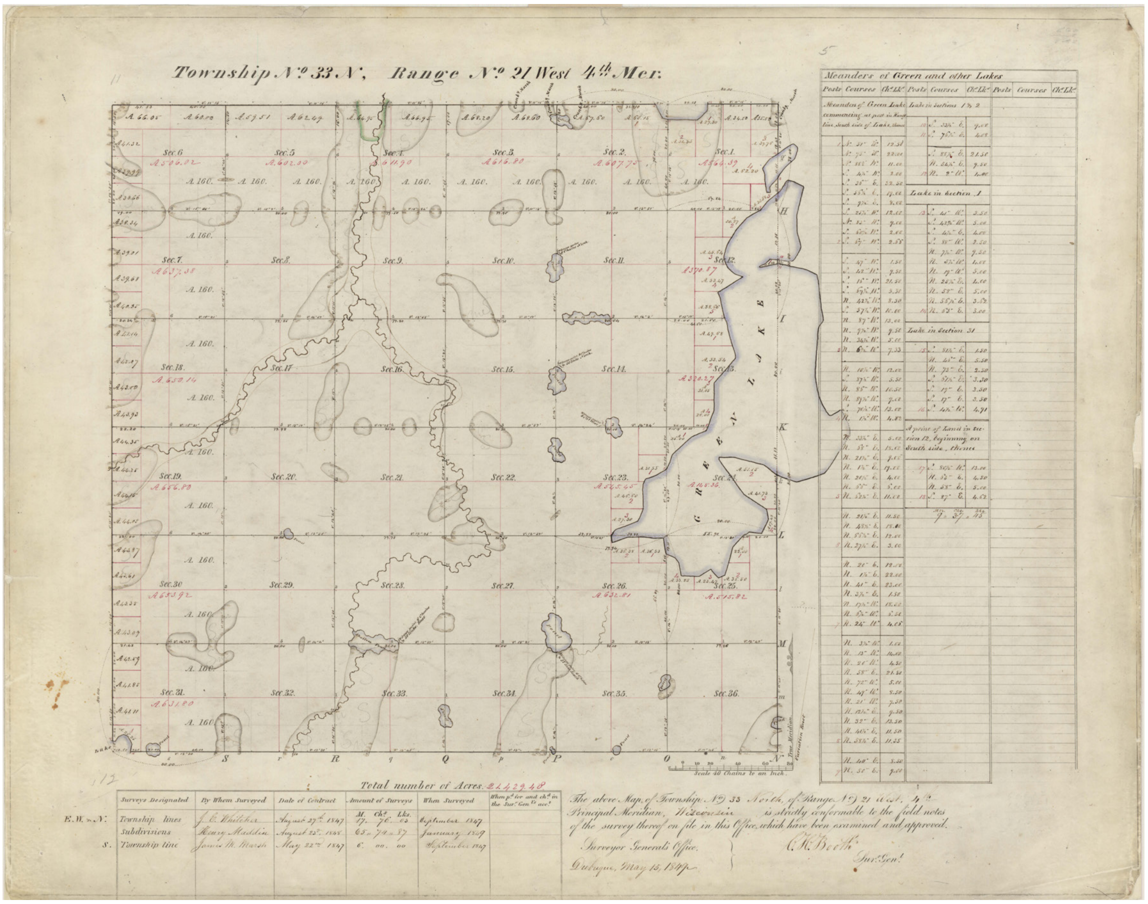


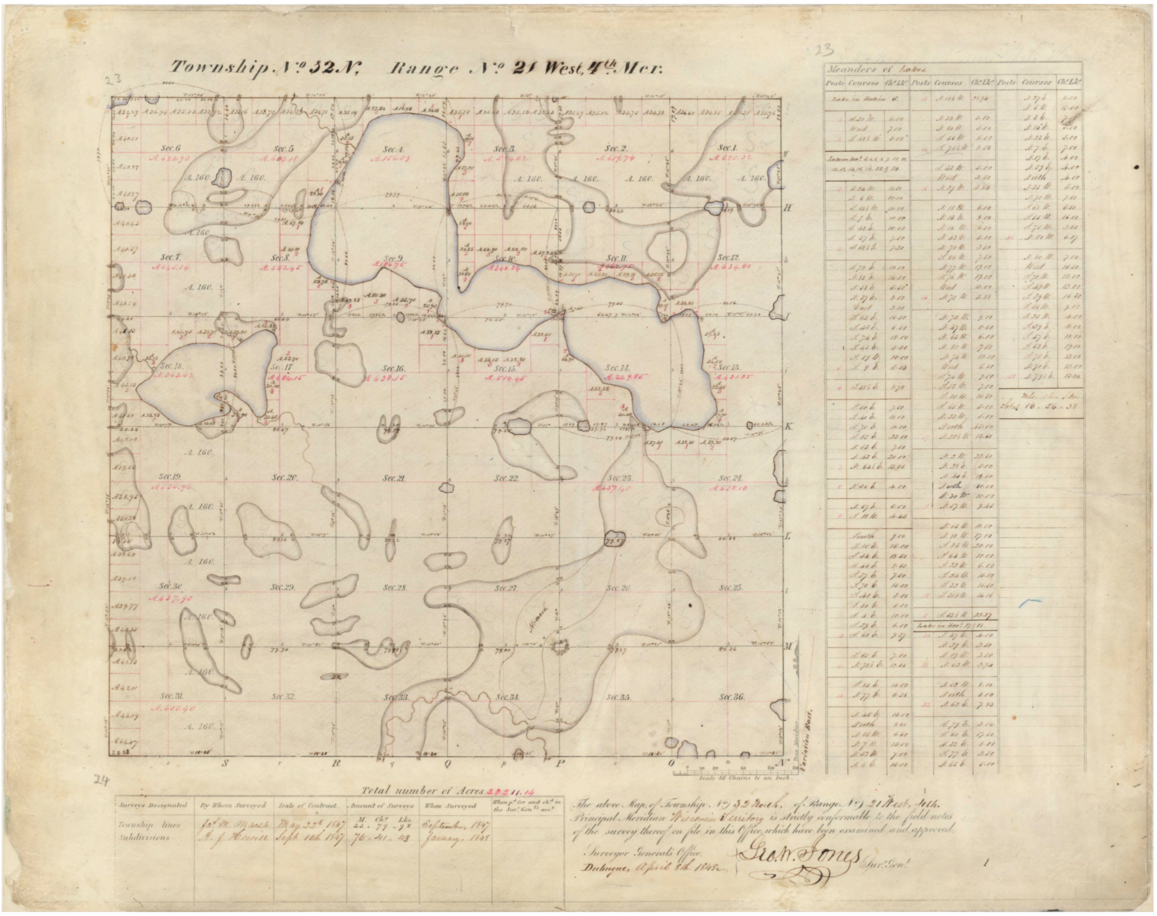
Figure 39. Sediment algal pigments quantified in ten core sections from Forest East. The group of algae associated with each pigment is shown along the x-axis.



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



Appendix B. Historic survey map from 1849, showing Forest Lake and the surrounding area.



Total number of Acres 20211.14

| Surveys Designated | By Whom Surveyed | Date of Contract | Amount of Surveys M. Chs. Lks. | When Surveyed | When pd. for and chd. in the Sur. Genls. acct. |
|---|---|---|---|---|---|
| Township lines | Jas. M. Marsh | May 22d 1847 | 23 . 79 - 98 | September, 1847 | |
| Subdivisions | A. J. Hewitt | Sept. 10th 1847 | 76 . 41 . 43 | January, 1848 | |

The above Map of Township No 32 North. of Range No 21 West, 4th. Principal Meridian Wisconsin Territory is strictly conformable to the field notes of the survey thereof on file in this Office which have been examined and approved.

Surveyor General's Office,
Dubuque, April 8th. 1848. Geo. W. Jones Sur. Genl.