A PALEOLIMNOLOGICAL STUDY IN THE COMFORT LAKE - FOREST LAKE WATERSHED DISTRICT

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SUMMARY

1. Paleolimnological techniques were used to reconstruct the trophic and sedimentation history of Shields, Moody, and Comfort Lakes in the Comfort Lake - Forest Lake Watershed District, Chisago and Washington Counties, MN.

2. Piston and overlapping Bolivia or Livingstone cores were collected through the ice from the three study lakes on February 25, 2016. Lead-210 activity was analyzed to develop a dating model for each lake 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. All three lakes showed an increase in sedimentation rate in the early 1900s, although peaks in sedimentation varied temporally among lakes. All three lakes showed a decline in sedimentation rate in recent decades. In recent years the sedimentation rate in Moody Lake has decreased to what it was in the 1800s; sedimentation rates in Shields and Comfort Lakes remain elevated over the rates from the 1800s and early 1900s.

4. Diatom community assemblages and algal pigments showed that Shields and Comfort Lakes have been eutrophic since the 1800s; although diatom-inferred total phosphorus reconstructions suggested that Comfort Lake may have shifted into the mesotrophic category in recent decades. Diatom reconstructions showed that Moody Lake was likely mesotrophic until the 1960s, and is now eutrophic. Algal pigments showed that all three lakes have had cyanobacteria present over the period of study.

5. Shields and Comfort Lakes showed similar and synchronous changes in sediment composition. Both lakes showed a large flux of organics beginning in the 1930s or 40s and persisting through the early 2000s. Algal pigment analysis in each lake showed a dip in overall algal production during this time period, suggesting that the organic matter pulse was not from in-lake production, but likely came from a terrestrial source. The large-scale industrialization of agriculture occurred around this time, and it is possible that agricultural practices were affecting this western portion of the watershed. The Moody Lake sediments did not show this drastic shift in sediment composition.

6. Written historical records from the Forest Lake Golf Club described direct influences on Shields Lake. However, these events occurred during the same time as larger-scale changes in the watershed (affecting both Shields and Comfort Lakes), making it difficult to distinguish the impact of the golf course in the sediment record.

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 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 three lakes in the Comfort Lake - Forest Lake Watershed District in Chisago and Washington Counties, MN: Shields Lake, Moody Lake, and Comfort Lake.

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 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

The Comfort Lake - Forest Lake Watershed District (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 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. All three lakes in this study are on the state's impaired waters list due to high nutrient levels. Although currently impaired, little is known of the long-term history of these lakes; the goal of this project is to determine when and why they became impaired or if these lakes have long-been high nutrient and productivity systems.

Shields Lake is shallow, with a maximum depth of 7.8 m, and surface area of 30 acres. Rooted plants grow in 87% of its area and it is used mainly for fishing. The lake drains 538 acres, mostly from the south; Shields Lake drains to Forest Lake to the north. The lake borders the Forest Hills Golf Club, initial construction began in 1958 with an additional nine holes constructed in 1965 (the additional nine holes are those most directly adjacent to the lake); in the early 1980s a complete drainage system was installed on the course (http://www.foresthillsgc.com/aboutus/; July 21, 2017). In 2006, the lake was placed on MN's Impaired Waters List due to high nutrient levels, and monitoring has shown that through 2015 the water clarity has decreased. Management efforts on Shields Lake have included an alum treatment in ~1995 (EOR personal communication), aeration, and fish barrier installation; these treatments have failed to resolve nutrient issues, and summer average TP concentrations in the lake are currently near 200 $\mu g/l$. (http://www.clflwd.org/waterbody-shields-lake.php; March 27, 2017)

Moody Lake has a surface area of 34 acres and a maximum depth of 14.3 m. The Moody Lake 2,315 acre watershed is primarily agricultural and rural; there is no public boat launch, and the lake is used for watering livestock, and some fishing and non-motorized boating. Average summer TP in 2016 was 104 $\mu g/l$, and the district notes that TP levels have been improving. (http://www.clflwd.org/waterbody-moody-lake.php; July 21, 2017)

Comfort Lake has a surface area of 218 acres, making it the third largest lake in the CLFLWD. The lake is 13.7 m deep and the summer of 2016 average TP was 34 $\mu g/l$. The watershed district reports that even though total phosphorus levels have been improving, water clarity appears to be declining. Comfort Lake has a public boat launch and is heavily used for recreation. Comfort Lake is at the outlet of the CLFLWD, with the Sunrise River entering after discharging from Forest Lake and flowing through wetland, residential, and agricultural lands; the lake has a very large drainage area of nearly 25,000 acres. The Sunrise River flows out of Comfort Lake at the northwest end and discharges to the St. Croix River. (http://www.clflwd.org/waterbody-comfort-lake.php; July 21, 2017)

METHODS - SEDIMENT CORING

Sediment cores from each of the lakes were collected through the ice on February 25, 2016. In each lake, the coring location represented a flat and deep area of the basin, to provide a highly integrated sample of diatom community structure from the lake as a whole. A piston core was collected from each lake; in Comfort Lake an overlapping Livingstone core was collected, and in Shields and Moody Lakes overlapping Bolivia cores were collected. All piston cores were collected using a drive-rod piston corer equipped with a 6.5 cm diameter polycarbonate barrel (Wright 1991).

Table 1 details the coring location, water depth, and recovery for each of the lakes. Cores were returned to the laboratory and stored at 4°C and sectioned in 2-cm increments.

METHODS - AERIAL PHOTOS

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/; July 2017). Aerial photos from 2015 and 2016 were obtained from Google Earth.

METHODS - MAGNETIC SUSCEPTIBILITY

Magnetic susceptibility provides a non-destructive measure of relative quantity and size of ferro-magnetic minerals. Increases in magnetic susceptibility signatures may be correlated with land use changes including land clearance, increased terrestrial-derived sediments, and paleosols. Decreases in magnetic susceptibility often accompany increased carbonate and organic fluxes to the sediments from increased in-lake productivity.

A Geotek Standard MSCL with an automated trackfeed was used for magnetic susceptibility logging. Susceptibility measures were taken at 1-cm intervals, which integrate a signal over a 5-10-cm length of core. Following magnetics logging, cores were returned to storage at 4°C. Magnetic susceptibility logging was performed at the Limnological Research Center's core lab facility at the University of Minnesota.

METHODS - 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 21 and 30 core sections were analyzed for lead-210 activity to determine age and sediment accumulation rate for the past 150 years.

As a further check of dates on the Comfort Lake core, cesium-137 was also quantified in nine core sections. Cesium-137 is an isotopic product of atmospheric nuclear bomb testing; its presence indicates sediments deposited after 1950 and its peak concentration occurs in 1963 when atmospheric testing was banned.

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 15-16 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 2012a).

Sediment Phosphorus
Sediment phosphorus fractions were analyzed for fifteen or sixteen increments from each core following the sequential extraction procedures in Engstrom (2005), Engstrom and Wright (1984), Psenner and Puckso (2008), and Kopácek 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 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 to sixteen 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 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. 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 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

Shields Lake - The aerial photos of Shields Lake showed that water levels were slightly higher in the 2015 photo; it also appeared that the marginal peatlands that surrounded the lake through the 1960s were lost by 2016 (Figure 2). During the 1964 photo, the golf course was only partially constructed (to the northwest of the lake). In the 2015 photo, the course is a much more prominent feature on the landscape, directly on the north shore and northwest of Shields Lake.

Moody Lake - Aerial photographs showed that the water level of Moody Lake was lower in 1938 than in was 1953. Even though the lake level in 1953 came up from where it was in 1938, it still appeared to be a bit lower than in 2015 (Figure 3).

Comfort Lake - Aerial photos of Comfort Lake from 1936, 1938, 1953, and 1964 showed some slight variations in lake level, but overall the lake level showed very little change (Figure 4). However, the aerial photos did show significant alterations to the watershed. There was a highway constructed between 1936 and 1953; and prior to the 2016 photo the land surrounding the lake appeared largely agricultural, while in 2016 it had become noticeably more residential.

RESULTS AND DISCUSSION - DATING AND SEDIMENTATION

Shields Lake - The unsupported lead-210 activity, the resulting lead-210 dating model, and the sediment accumulation rate for Shields Lake are shown in Figure 5a-c. In Shields Lake, the lead-210 activity declined throughout the core, reaching background levels at approximately 266 cm (Figure 5a). The sedimentation rate in Shields Lake was low in the early 1800s (average of 0.05 g/cm^2 yr), and then began a slow but steady increase from the late 1800s through the 1960s, reaching 0.44 g/cm^2 yr in 1963 (Figure 5c). The sedimentation rate reached a peak of 0.85 g/cm^2 yr in 1986, and has been on a downward trajectory since that time. Even though the sedimentation rate has declined in recent decades in Shields Lake, the rate at the core top (0.26 g/cm^2 yr) remains about five times higher than was in the 1800s, and is comparable to the sedimentation rate in the 1930s and 1940s.

Moody Lake - Figure 5d-f illustrates the unsupported lead-210 activity, the resulting lead-210 dating model, and the sediment accumulation rate for Moody Lake. Lead-210 activity reached background levels by 314 cm in the Moody Lake core (Figure 5d). From 1840 to 2016, the sedimentation rate at the core site fluctuated between 0.07 and 0.33 g/cm^2 yr (Figure 5f). The sedimentation rate was low in the 1800s (average of 0.09 g/cm^2 yr), then rose to a peak of 0.22 g/cm^2 yr in 1911; the rate then declined again before peaking at 0.33 g/cm^2 yr in 1991. There has been a steady decline in the rate since the 1984 peak, and the sedimentation rate at the core top (0.09 g/cm^2 yr) is similar to the rate in the mid-1800s.

Comfort Lake - In the Comfort Lake core, lead-210 activity reached background levels at 147 cm (Figure 6a). As a further check on the dating model, cesium-137 activity was measured in nine intervals in the core (Figure 6b). The cesium-137 peak at 58 cm (representing 1963; Figure 6b) aligns with the lead-210 date at this interval (Figure 6c), which lends support to the lead-210 dating model. The sediment accumulation rate at the Comfort Lake core site was low from the mid-1800s through the early 1920s, with an average rate of 0.13 g/cm^2 yr (Figure 6d). The sedimentation rate increased in the 1930s, and peaked at 0.59 g/cm^2 yr in 1990. The rate has been decreasing since the 1990s, however the sedimentation rate at the core top (0.40 g/cm^2 yr) remains about three times higher than it was in the 1800s and early 1900s.

RESULTS AND DISCUSSION - MAGNETIC SUSCEPTIBILITY AND GEOCHEMISTRY

Magnetic Susceptibility

Shields Lake - The most significant feature in the magnetic susceptibility profile from Shields Lake was a sharp decrease between 142 and 146 cm (early to mid-1940s) (Figure 7a). Decreases in magnetic susceptibility can result from increased productivity, for example from lake eutrophication, or a change in sediment source. There was also a decline in magnetics that peaked at 198 cm (1913).

Moody Lake - Overall, there was very little change in the magnetic susceptibility profile from Moody Lake, although there was a slight increase at approximately 280 cm (pre-1800) (Figure 8a), this could be due to an increase in terrestrially derived sediments.

Comfort Lake - There was an offset between the overlapping piston and Livingstone core from Comfort Lake; this was due to the smaller diameter of the Livingstone core (Figure 9a). The most noteworthy feature in the magnetic susceptibility profile from Comfort Lake was the slow decline that began at 131 cm (1880s) and ended at approximately 110 cm (1920). The decrease could have been due to lake eutrophication or a change in sediment source.

Loss on Ignition

Shields Lake - The overlapping piston and Bolivia cores from Shields Lake recorded a large shift in sediment composition beginning at 142 cm until 26 cm (Figure 7b). From the core bottom up to 144 cm, the sediments consisted of an average of 48% organic matter and 46% inorganic matter. The large shift began at 142 cm and continued to 26 cm; during this time the sediments consisted of an average of 75% organic matter and 21% inorganic matter. From 24 cm to the core top, the sediment composition was similar to the core bottom, with an average of 52% organic matter and 41% inorganic matter. Carbonates were low throughout the length of the Shields Lake core (between 1% and 9%).

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 10 for Shields Lake); sediment flux was calculated to the end of the lead-210 record for each core (272 cm in Shields Lake). In Shields Lake, this flux calculation showed that the large shift in sediment composition began in the 1940s, and was driven by an increase in the flux of organic matter at the core site. Beginning in 2009, the flux of organic matter at the core site began to decrease, and by 2011 the sediment flux at the Shields Lake core site resembled the flux prior to 1940.

The timing of the rise in organic matter flux coincided with the sharp decrease in magnetics. Both of these changes predate the golf course, which began construction in 1958.

Moody Lake - The sediments from Moody Lake did not show drastic changes in composition throughout the length of the core (Figure 8b). Carbonates were low throughout the core, and averaged about 4% of the sediment composition. Organic matter averaged 53% and inorganic matter 43%. The biggest change in the proportion of organic versus inorganic matter was at the core bottom; from 350 cm to 270 cm, organic matter averaged 65% and inorganic matter 32%. This rise in inorganic matter corresponds with the rise in magnetics at 280 cm, suggesting an increase in terrestrially derived inorganics at this time; these changes occurred during the 1850s and could be due to initial settlement and land clearance in the area.

The flux of sediment to the Moody Lake core site was driven nearly equally by organic and inorganic matter (Figure 11). The flux of inorganic material was slightly higher during the peak in sedimentation rate during the 1980s/early 1990s.

Comfort Lake - From the core bottom up to 102 cm, the sediments were composed of an average of 59% inorganic material, 25% organic matter, and 16% carbonates (Figure 9b). A large shift in sediment composition occurred at 100 cm depth, characterized by a sharp increase in the proportion of organic matter; from 100 cm to 26 cm, the sediments were composed of an average of 56% organic material, 25% inorganic matter, and 19% carbonates. From 24 cm to the core top, the sediment composition was similar to the core bottom, with inorganic matter comprising the largest proportion of the sediments (average of 49% inorganics, 24% organics, and 27% carbonates).

When the sedimentation rate increased in Comfort Lake in the 1930s, it was largely driven by an increased flux of organic matter to the core site (Figure 12). During the most recent decades, as the sedimentation rate has shown a small decline, the flux is no longer driven by organics and instead is primarily composed of inorganic material, as it was prior to 1930. This change in sediment composition and flux is very similar to the change that occurred in Shields Lake at approximately the same time (1932-2005 in Comfort Lake, 1946-2010 in Shields Lake), suggesting that there were large-scale changes in the watershed during this period.

Biogenic Silica and Sediment Phosphorus

Shields Lake - For all cores, silica flux was calculated by multiplying the weight percent of BSi by the sedimentation rate at that interval (Figure 13b for Shields Lake). The weight percent of biogenic silica (BSi) in the Shields Lake core showed a notable increase between the 1940s and 1950s (Figure 13a). From the early 1800s through the early 1940s, the biogenic silica in the core averaged 3.9% by weight; from the mid 1950s through 2016, the average increased to 10.4% by weight. The flux of BSi at the core site started to increase in the 1940s/50s, peaked in the 1990s, and has been declining in recent decades (Figure 13b). This suggests that diatom/chrysophyte algal productivity increased during the time of increased organic matter flux.

The concentration of phosphorus (P) in the core, and P flux to the core site both showed a peak in 1918 (Figure 14a and b). The P flux also showed a secondary peak in the early 1990s, with a decrease in recent decades. From the early to mid-1990s (including the 1918 peak), the flux of P largely consisted of iron-bound P, which is readily exchangeable (Figure 14b). From the mid-1900s to the core top, the P flux was more of a mix of readily exchangeable and refractory forms, particularly recalcitrant organic P.

There is a slight dip in both the P concentration and flux during the late 1990s/early 2000s (Figures 14a and b); this may be a reflection of the alum treatment on Shields Lake that occurred in ~1995. These results suggest that the alum treatment had only a small effect on the sediment

P, and the iron-bound P fraction has increased again in recent years.

Moody Lake - There was a sharp decrease in the weight percent of BSi in the Moody Lake core between the mid-1920s and 1940 (Figure 15a). The amount of BSi in the core was relatively constant from the 1940s to the core top and averaged 7.5% by weight. The peak in BSi flux to the core site occurred in 1984, and has been steadily declining since (Figure 15b). This peak and subsequent decline correspond with the flux of organic matter to the core, suggesting that diatom and chrysophyte algae productivity were contributing to this organic matter flux.

There was an increase in sediment P at the top of the Moody Lake core, with a large spike in the uppermost sample; the rest of the core showed almost no change in sediment P concentration (Figure 16a). This spike at the core top may indicate greater potential for internal loading due to upcore mobility of phosphorus. The P flux showed a steady increase in P flux to the core site with a rapid increase between ~1960-1980 (Figure 16b). From the 1990s to 2016, the majority of the P is in readily exchangeable forms (iron-bound P and labile organic P); again suggesting that internal loading of P is an issue in the lake.

Comfort Lake - There were few notable changes in the weight percent of BSi in the Comfort Lake core (Figure 17a). The large increase in the flux of BSi to the core site in the 1930s, and slight decrease in recent decades (Figure 17b), coincided with the large increase in organic matter flux at that time, again suggesting that diatom and chrysophyte algal productivity increased during the increased flux of organic matter.

The TP concentration in the sediments of the Comfort Lake core showed an overall decline over time, with the highest concentrations in the 1800s (Figure 18a). The TP flux showed that when sedimentation rate at the core site was accounted for, there has been a steady rise in TP flux in Comfort Lake since the early 1900s (Figure 18b); it's possible that the flux of organic matter to the lake provided increased nutrients.

RESULTS AND DISCUSSION - DIATOM STRATIGRAPHY AND ORDINATION

Shields Lake - In Shields Lake the diatom preservation was poor, and diatom valves were scarce in the lowermost samples. Therefore, all diatom analyses were based on twelve core sections, from 1918 through 2012.

The ordination biplot from the NMDS showed how the core samples clustered based on similarity of diatom assemblage (Figure 19). The four oldest samples (1918-1955) clustered together in the bottom left quadrant of the NMDS biplot. The three samples from 1967-1986 formed a cluster, and those from 1992-2004 another. The two most recent samples, 2012 and 2016, did not cluster closely with any of the other downcore samples.

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 20). Planktonic diatom species dominated the Shields Lake core, the most common taxa were: *Aulacoseira* species, *Cyclostephanos* species, and small *Stephanodiscus* species, which are all indicative of nutrient enrichment. Other predominant taxa included the mesotrohic indicator *Fragilaria mesolepta*, and *Asterionella formosa*, which can be indicative of nitrogen enrichment. The sample from 1941 showed a dip to 70% plankton, all other samples ranged from 84-97% plankton. According to the constrained cluster analysis, the largest break in the samples occurs between 1955 and 1967, although when evaluated against a broken stick model, this was not shown to be a significant shift in the assemblage. This shift coincides with an increase in small *Stephanodiscus* species and *Cyclostephanos* species from the 1960s to the core top.

The largest shift in the diatom community assemblage occured in the late 1950s/1960s, which is later than the large shift in geochemistry seen in the Shields Lake core. Instead, this change in the diatom community coincides with the construction of the golf course.

Moody Lake - In the Moody Lake NMDS biplot, the oldest samples (1849-1905) clustered together on the right side of the plot (Figure 21). Samples from 1927 to the core top were on the left side of the plot, and there was a strong trend in this group of samples along axis 2.

The constrained cluster analysis showed that the largest break in the diatom community assemblage was between 1905 and 1917; this break was significant when evaluated against a broken stick model (Figure 22). This break coincided with an increase in percent plankton from 23% in the 1905 sample to 61% in the sample from 1917 (Figure 22).

The diatom flora from Moody Lake showed high diversity (Figure 22). From 1849 to 1905, the predominant diatoms in the lake were the tychoplanktonic species *Pseudostaurosira brevistriata* var. *inflata* and *Staurosira construens* var. *venter*. These 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. *Gomphonema gracile*, a species associated with aquatic plants, was also predominant at this time. The sample from 1917, which plotted between the two groups on the NMDS (Figure 21), was characterized by the planktonic diatom *Tabellaria flocculosa* Strain 3p. In the samples from 1927-2016, the flora remained diverse, but there was a rise in eutrophic indicators such as *Aulacoseira ambigua*, *A. granulata*, *Cyclostephanos invisitatus*, *Fragilaria crotonensis*, and small *Stephanodiscus* species.

Comfort Lake - The samples from 1830 to 1981 cluster together on the NMDS biplot, suggesting that there was little change in the diatom community assemblage during that time (Figure 23). Samples from 1990 to 2016 show change along axis 1.

The constrained cluster analysis for Comfort Lake showed one significant break in the community assemblage, occurring between 1990 and 2001 (Figure 24). The break corresponded with a decrease in the percent plankton; plankton in the core dropped from 82% in the early 1980s, to 54% in the early 2000s (Figure 24).

The diatom flora from the 1830s to the 1990s was largely dominated by *Aulacoseira ambigua* and *A. granulata* (Figure 24); these species are characteristic of nutrient-rich and turbid, wind-swept conditions. There are other eutrophic indicators during this time period, such as small *Stephanodiscus* species and *Fragilaria crotonensis*. During the 2000s the abundance of *Aulacoseira* species sharply declines. *Fragilaria crotonensis* increases in abundance during the 2000s, and there is a distinct rise in the tychoplanktonic *Staurosira* and *Pseudostaurosira* species. These tychoplanktonic species are primarily benthic, but often suspended into the water column; many of these species are adapted to live on fine-grained sediments, such as those found in shallow lakes

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).

Shields Lake - When passively plotted on the MN calibration set, the core sections show movement along the TP gradient (associated with axis 1); however there was more movement along axis 2 (Figure 25). This suggests that while nutrients may be driving some of the change in Shields Lake, there are other drivers that are equally important in influencing diatom community turnover. Alternative drivers include: habitat alterations, changes in turbidity due to sediment load, or other stressors that were not measured in the calibration set. It is possible that the drivers of ecological shifts change over time, meaning that TP may have been a more important variable during certain periods and less important during others. In Shields Lake, changes in depth, hydrology and sediment source may have created habitat changes that influenced the diatom community assemblage.

In Shields Lake the fraction of the maximum explainable variation in the diatom data that can be explained by TP (λ_r / λ_p) was 0.60. This again suggests that TP was playing a role in the diatom community change, but that other factors were important as well.

The TP reconstruction for Shields Lake suggests that the lake has been eutrophic from the 1920s to the time of study (Figure 26; Table 2). One core section (2012) gave a reconstructed value of 95 µg/l of TP; however, the rest of the core showed diatom-inferred TP values ranging between 56-75 µg/l.

The diatom-inferred TP (DI-TP) values are lower than some of the recently measured TP values in Shields Lake (near 200 µg/l), although the DI-TP results did show that the lake is in the eutrophic to nearly hypereutrophic range. The evaluation of the TP reconstruction (λ_r / λ_p = 0.60) showed that there were other factors beyond TP that were influencing diatom community turnover, and therefore the quantitative TP reconstruction should be interpreted with caution.

The sediment P results showed a slight dip in P after the alum treatment in Shields Lake in ~1995 (Figures 14a and b). However, this slight reduction did not significantly impact the diatom community assemblage, and was not reflected in the diatom-inferred TP (Figure 26).

Moody Lake - Passive plotting of the Moody Lake core on the MN calibration set showed that there has been a great deal of change in the diatom community assemblage (Figure 27). As in the Shields Lake core, there was some movement along the TP gradient, however there was more movement along axis 2. Again suggesting 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. Aerial photos from Moody Lake showed that the lake level was lower in the past, so alterations to the hydrology and lake level may have caused habitat changes in the lake that affected the diatom community.

The fraction of the variation in the diatom data that can be explained by TP (λ_r / λ_p) was 0.63 for Moody Lake. Again suggesting that TP was influencing the diatom community change, but that other factors were important as well.

The TP reconstruction for Moody Lake showed that from the mid-1800s to the 1950s, the lake was in the mesotrophic range (Figure 28; Table 2). TP increased in the 1960s, and from then until the early 2000s, the diatom-inferred TP suggested that the lake would have been classified as slightly eutrophic. The core top sample (2016) showed a large increase in diatom-inferred TP; this reconstruction of 81 µg/l of TP was due to the rise of *Aulacoseira ambigua*, *A. granulata*, *Cyclostephanos invisitatus* in the uppermost sample.

In Moody Lake, the DI-TP reconstructed value of 81 µg/l in 2016 is close to the measured TP average of 104 µg/l in that year. However, as in Shields Lake, the intermediate λ_r / λ_p value of 0.63 showed that other factors were influencing the diatom community turnover, and therefore the quantitative TP reconstruction should be interpreted with caution.

Comfort Lake - When passively plotted on the MN calibration set, the Comfort Lake samples clustered relatively close to each other (Figure 29). The most notable movement was that the three samples from the 2000s moved to the right along the TP gradient.

In Comfort Lake the fraction of the maximum explainable variation in the diatom data that can be explained by TP (λ_r / λ_p) was 0.92. This suggests that TP was an important driver of change in the diatom community in Comfort Lake.

The diatom-inferred TP reconstruction showed that Comfort Lake was eutrophic from the 1830s to the 1980s, with TP values ranging from 47-67 µg/l during this period (Figure 30; Table 2). The sample from the 1990s suggested the lake was slightly eutrophic during this time (36 µg/l). The samples from the 2000s continued to show a decline in diatom-inferred TP, and suggested that the lake has moved into the mesotrophic range.

These results match up with current measured TP in the lake; summer of 2016 average measured TP was 34 µg/l, very close to the DI-TP reconstructed value of 26 µg/l at the core top. The watershed district has reported that TP levels have been improving in recent years, and the DI-TP results showed the same trend.

RESULTS AND DISCUSSION - HISTORICAL ALGAL COMMUNITIES

Shields Lake - Total algal production, as measured by beta-carotene and chlorophyll *a*, showed that overall production was highest in recent samples (2002 and 2014) and in samples older than 1950; there is a distinct decrease in algal abundance beginning in the late 1930s through the 1980s (Figure 31). This time of decline in algal abundance corresponds with the highest sedimentation rates and the sharp increase in the proportion of organic matter in the core; the diatom community assemblage also showed little change during this time period. These results suggest that the increase in organic flux was not due to algal production; instead it was likely a terrestrial flux of organic material from erosional inputs. It is also possible that during this time period erosional inputs from the onset of the construction of the golf course played a role in the continual terrestrial flux of organic matter to the lake.

The pigments that are unique to diatoms decreased to very low levels prior to 1900. This suggests that the low abundance of diatoms found in the samples at the core bottom was not an issue of dissolution of the valves, but simply a very low abundance of diatoms in the lake. The high concentrations of purple sulfur bacteria in the 1800s also indicate that conditions in Shields Lake were very different during this time. Purple sulfur bacteria are indicative of anoxic conditions, so it's likely that Shields Lake was not well mixed during this time, the lake may have been very shallow with frequent anoxic conditions under the ice, or the lake may have had very thick macrophyte beds.

Cyanobacteria (blue-green algae) have been present in Shields Lake since the early 1800s. Pigments associated with nitrogen-fixing forms (canthaxanthin and aphanizophyll) have been present since the early 1800s, while pigments from potentially toxic forms (myxoxanthophyll) first appeared in the late 1930s, at the time of the large influx of organics, and have persisted since that time.

Many of the algal pigments show a rise in concentration in the early 1900s into the 1920s. This corresponds with a sharp rise in TP concentration and flux in the Shields Lake sediments (Figure 14).

Moody Lake - Pigments from Moody Lake showed that overall algal production was the lowest during the 1950s and 1960s, and highest in most recent years; this pattern is pronounced in the cyanobacteria, with a marked drop in the 1950s/60s (Figure 32). Cyanobacterial pigments have been present in the lake since the 1920s, and pigments associated with potentially toxic forms (myxoxanthophyll) have been present since the 1940s.

Comfort Lake - The pigment data from Comfort Lake showed that overall algal production was highest from the 1990s to the present, and from the 1800s into the 1920s; there was a decline in production between these two periods (from the 1940s through the 1980s) (Figure 33). This is similar to the decline seen in Shields Lake, again suggesting that the pulse of organic matter during this time was not due to algal production, but must have been terrestrially derived.

Pigments of purple sulfur bacteria were present in more than half of the samples analyzed, and were spread throughout the core, suggesting that Comfort Lake has undergone periods of anoxia since the early 1800s.

Cyanobacteria have been present since the 1830s, and their abundance follows the pattern of total algal abundance. There has been a marked increase in cyanobacteria in the two uppermost samples (2010 and 2014), and pigments associated with potentially toxic forms (myxoxanthophyll) have increased in recent years.

CONCLUSIONS

Sedimentation rates in all three lakes showed an increase in the early 1900s, although timing of the increase and peaks varied among lakes. Each lake showed some decline in the sedimentation rate in recent decades; the rate in Moody decreased to what it was in the 1800s, rates in Shields and Comfort still remain elevated over rates from the 1800s and early 1900s.

Downcore diatom communities and algal pigments suggest that Shields Lake was eutrophic since the early 1900s. Due to the lack of diatoms at the bottom of the Shields Lake core, full analysis of pre-European settlement trophic state was not possible, however algal pigments suggest that total algal production was high in the 1800s. Diatom communities and algal pigments suggest that Comfort Lake was also eutrophic since the 1800s, although DI-TP suggests that the lake has become mesotrophic in recent decades. Diatom reconstructions showed that Moody was likely mesotrophic until the 1960s, and is now eutrophic. Algal pigments showed that all three lakes have had cyanobacteria present over the period of study.

Shields and Comfort Lakes had similar and synchronous changes in sediment composition. Both showed a large flux of organics, likely terrestrially derived, beginning in the 1930s or 40s and persisting through the early 2000s. The large-scale industrialization of agriculture occurred around this time, so it could be that changing agricultural practices were affecting this western potion of the watershed.

Shields Lake - From the early 1820s through the late 1800s, algal pigments showed that the lake experienced anoxic conditions; there was also very little diatom preservation during this time.

Beginning in the 1940s and lasting until about 2010, there was likely a large change in watershed hydrology and sediment source. This period was characterized by a large flux of organic matter to the core site; algal pigments showed a dip in total algal production during this time, meaning that the organic matter was likely from a terrestrially derived source and was diluting the algal flux to the core site. This terrestrial source of organics could have been due to the industrialization of agriculture and subsequent alterations to the drainage of the landscape. During the post-World War II era, agricultural practices shifted in many areas to include tile drainage and increased fertilizer use; the pulse of organic matter from the landscape may be the result of these practices in the watershed.

Golf course construction began almost two decades after the onset of this large change; therefore it is difficult to discern possible erosional inputs from the golf course from large hydrological/watershed changes that predate the construction. The fact that a similar and synchronous change (large organics pulse that was not from algal production) occurred in Comfort Lake points to larger-scale changes in the watershed, which made it difficult to discern the effects of more localized signals, such as the golf course. The golf course has certainly had an influence on the lake. For example, the written history of the club from the Forest Hills Golf Club website (http://www.foresthillsgc.com/aboutus/; August 3, 2017), describes the installation of a complete drainage system, as well as other changes to the hydrology, and erosional issues:

> "During the winter of 1991-1992, an 82-foot bridge was installed over the small arm of Shields Lake to the right of the 14th green, in order to carry cart traffic away from the green. In the process of driving pilings to support the abutments, we drove through more than 70 feet of peat without reaching bedrock. We also installed a C-loc retaining wall around the perimeter of the bay and around the small pond to the left of the green to control erosion. Finally, we replaced the culvert connecting the pond and the lake."

> "In 1992-1993, we undertook the complete reconstruction of the 15th hole. Fifteen curls around the northern shore of Shields Lake. Over the years, the hole sank slowly, as the peat soil underlying it squeezed into the lake. In addition, we were steadily losing ground to erosion. The reclamation project included installation of a retaining wall along the shore from tee to green, installation of a fabric barrier beneath the entire fairway, covering the fabric with up to three feet of soil, and complete replacement of tees and green. Subsequently, we took additional actions to protect the hole from recent high water in the lake."

Both quotes from the golf course history describe peat soils that have become part of the golf course, and according to aerial photos were previously marginal peatlands around the lakeshore. Unfortunately, the large changes seen in the western portion of the watershed (synchronous in both Shields and Comfort Lakes) made it difficult to discern these golf club issues, and control measures, from the larger changes in the watershed. The largest shift in the diatom community occurred between the 1950s and 1960s, which does correspond to golf course construction. This shift coincided with an increase in nutrient-loving small *Stephanodiscus* species and *Cyclostephanos* species from the 1960s to the core top.

In terms of the trophic history of Shields Lake, the diatom assemblage suggested that the lake has been eutrophic since the early 1900s. From about 2012 to 2016, there was a large decrease in the sedimentation rate, and the pulse of terrestrially derived organics ended. However, diatom community assemblage and algal pigments suggest that TP levels and cyanobacterial abundance remain high. The alum treatment on Shields Lake in ~1995 may have had an effect on sediment P concentration, as it showed a small dip around that time; however, the effect appeared to be small and there was no significant change to the diatom community assemblage, and DI-TP reconstruction, during that time.

Moody Lake - The sedimentation rate began a slow rise in the late 1800s and peaked in the early 1900s and again in the 1990s. The rate has decreased in recent decades and the rate at the core top was comparable to the rate in the 1800s. There was a rise in inorganic matter in the core, and a subsequent rise in magnetics, in the 1850s; these changes may have been due to initial settlement and land clearance in the watershed. There were no drastic changes in sediment composition in the core in the 1900s or 2000s, suggesting that the Moody watershed did not experience the same change in hydrology/sediment source that Shields and Comfort Lake watersheds did.

The diatom community assemblage had one significant shift between 1905 and 1917; prior to this time, diatoms which are often associated with shallow lakes, and a few that are associated with aquatic plants, were present in significant abundance, meaning that the lake may have been shallower with more macrophytes. The oldest available aerial photo is from 1938, but the photos do suggest that the lake level in Moody has been rising since that time. An increase in the percent of planktonic diatoms began in 1917, and by the 1960s DI-TP indicated the lake had shifted into the eutrophic range; there was also an increase in the P flux to the sediments at this time. The P concentration shows a sharp spike at the core top, with the majority of the P in readily exchangeable forms (iron-bound P and labile organic P); suggesting that internal loading of P is an issue in the lake.

Comfort Lake - Aerial photos showed very little change to the lake basin from the 1930s to the present. The large change in Comfort Lake geochemistry is similar and synchronous to that of Shields Lake. There is a large increase in terrestrially derived organic matter beginning in the early 1930s and persisting through 2005, indicating a large change in watershed hydrology and sediment source during this time. Just as in Shields Lake, there was a dip in total algal production during this time period, suggesting that the organics pulse was coming from a terrestrially derived source and diluting the algal flux to the core site. Again, this flux of organics could be due to the industrialization of agriculture, increased fertilizer use, and alterations to the drainage of the landscape.

There is a suggestion that Comfort Lake has been improving in recent decades, although issues with the lake remain. The sedimentation rate has been declining, although it still remains elevated well over the rate in the late 1800s and early 1900s. There was a significant shift in the diatom community around the 1990s, which translated to a decline in DI-TP. However, algal pigments showed that overall algal abundance has sharply increased in recent years. This includes cyanobacterial groups, including those that have the potential to cause toxic blooms. The presence of purple sulfur bacteria off an on throughout the core, and as recent as 2010, suggests that the lake regularly experiences anoxia.

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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)
Shields	45.25312	92.94446	Piston	7.47	1.38
Shields	45.25312	92.94446	Bolivia	7.47	1.66
Moody	45.30083	92.86768	Piston	12.37	2.06
Moody	45.30083	92.86768	Bolivia	12.37	1.75
Comfort	45.32493	92.95025	Piston	12.44	1.43
Comfort	45.32493	92.95025	Livingstone	12.44	1.00

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

Lake_Lead-210 Date	Diatom-Inferred TP µg/l
Shields_2016	68
Shields_2012	96
Shields_2004	74
Shields_1999	66
Shields_1992	64
Shields_1986	56
Shields_1977	67
Shields_1967	72
Shields_1955	70
Shields_1941	75
Shields_1930	74
Shields_1918	61
Moody_2016	81
Moody_2009	38
Moody_1998	37
Moody_1991	31
Moody_1984	45
Moody_1972	31
Moody_1962	39
Moody_1952	20
Moody_1940	22
Moody_1927	21
Moody_1917	20
Moody_1905	22
Moody_1882	27
Moody_1866	20
Moody_1849	17
Comfort_2016	26
Comfort_2010	22
Comfort_2001	29
Comfort_1990	36
Comfort_1981	53
Comfort_1971	47
Comfort_1960	55
Comfort_1942	56
Comfort_1932	57
Comfort_1920	65
Comfort_1906	67
Comfort_1892	59
Comfort_1872	56
Comfort_1849	66
Comfort_1830	51

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

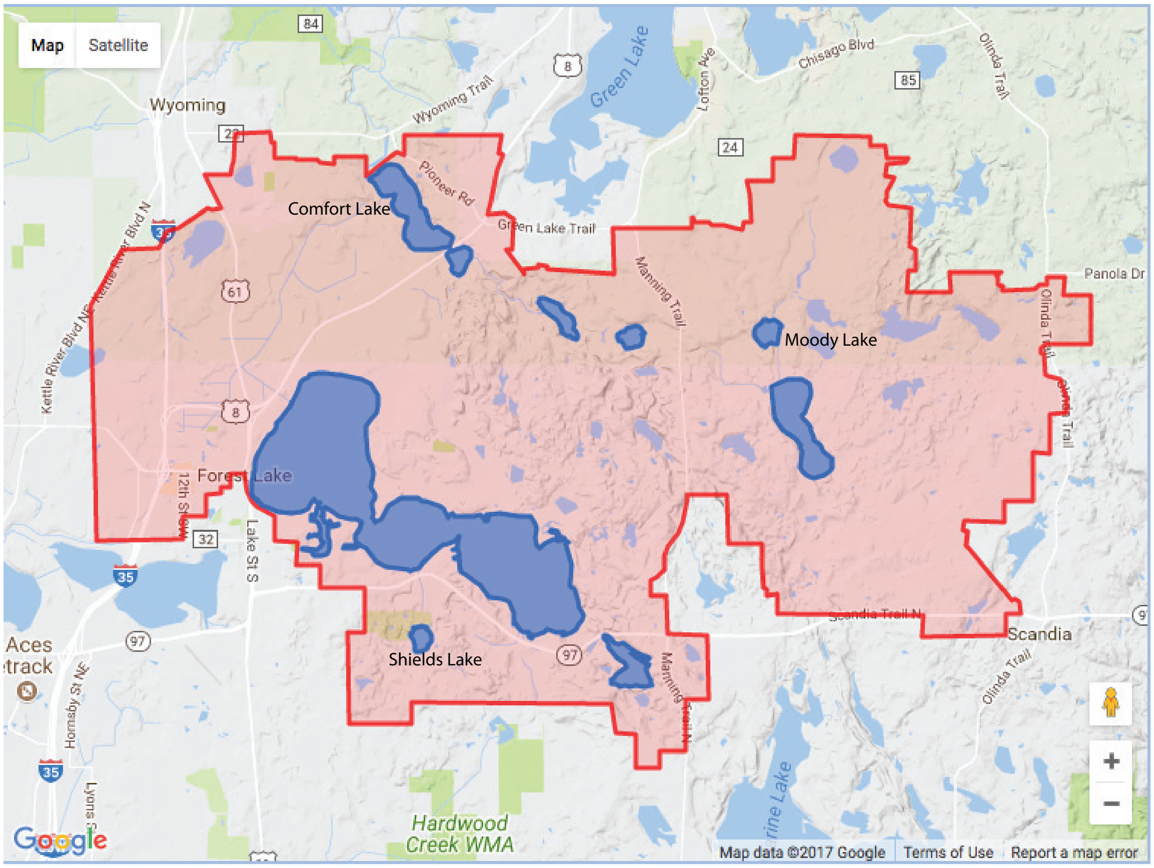


Figure 2. Aerial photographs of Shields Lake.

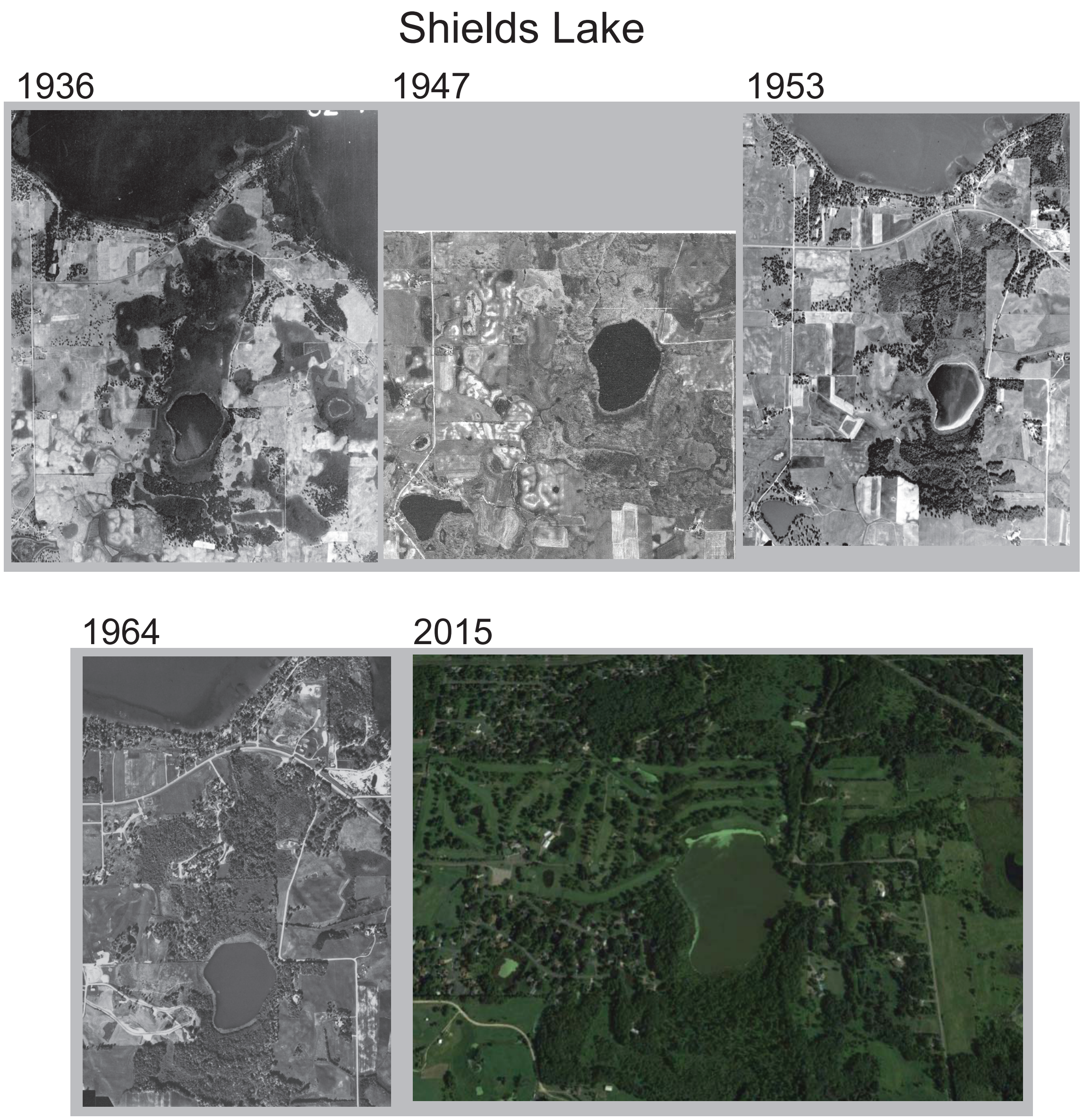


Figure 3. Aerial photographs of Moody Lake.

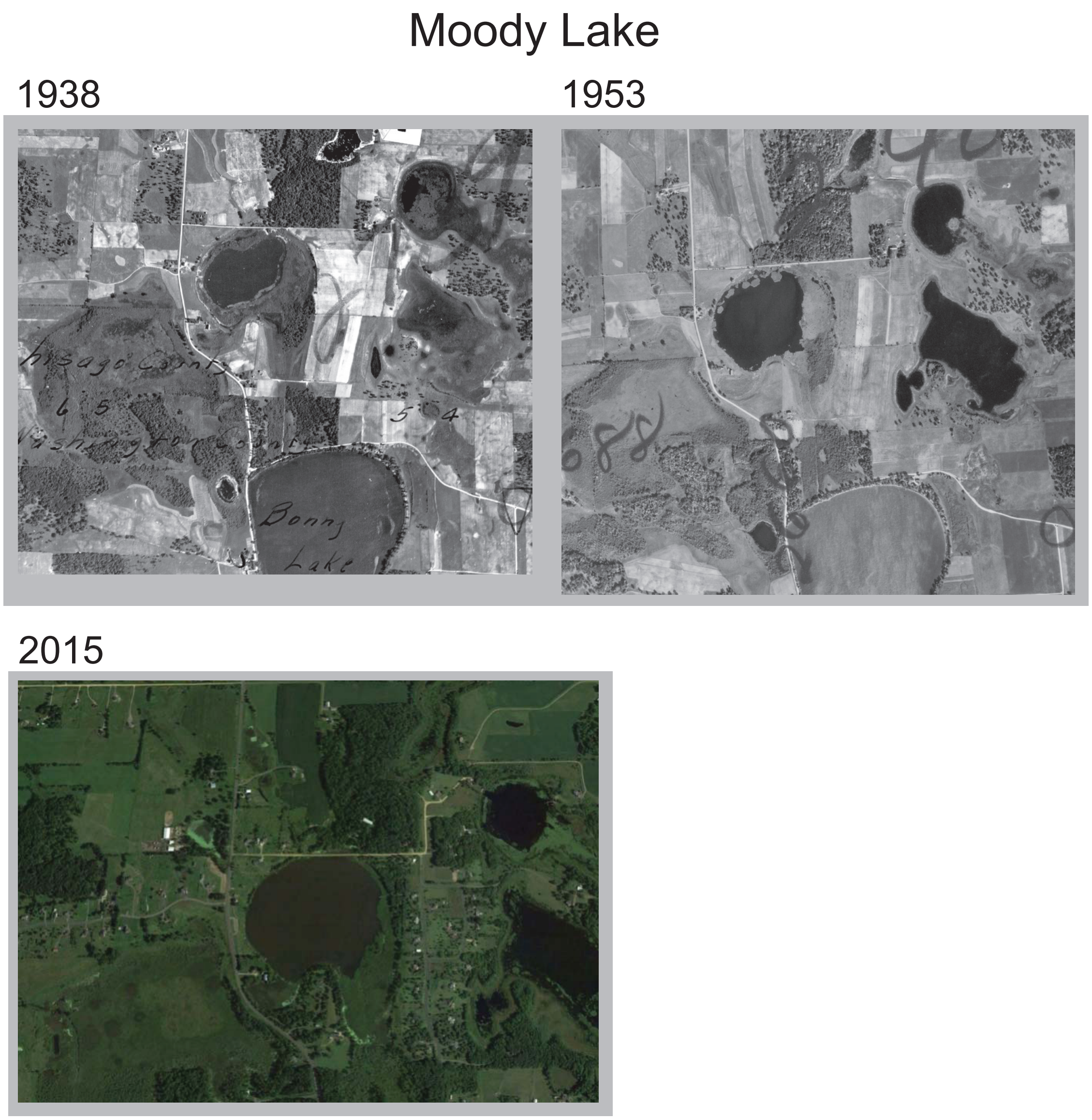


Figure 4. Aerial photographs of Comfort Lake.

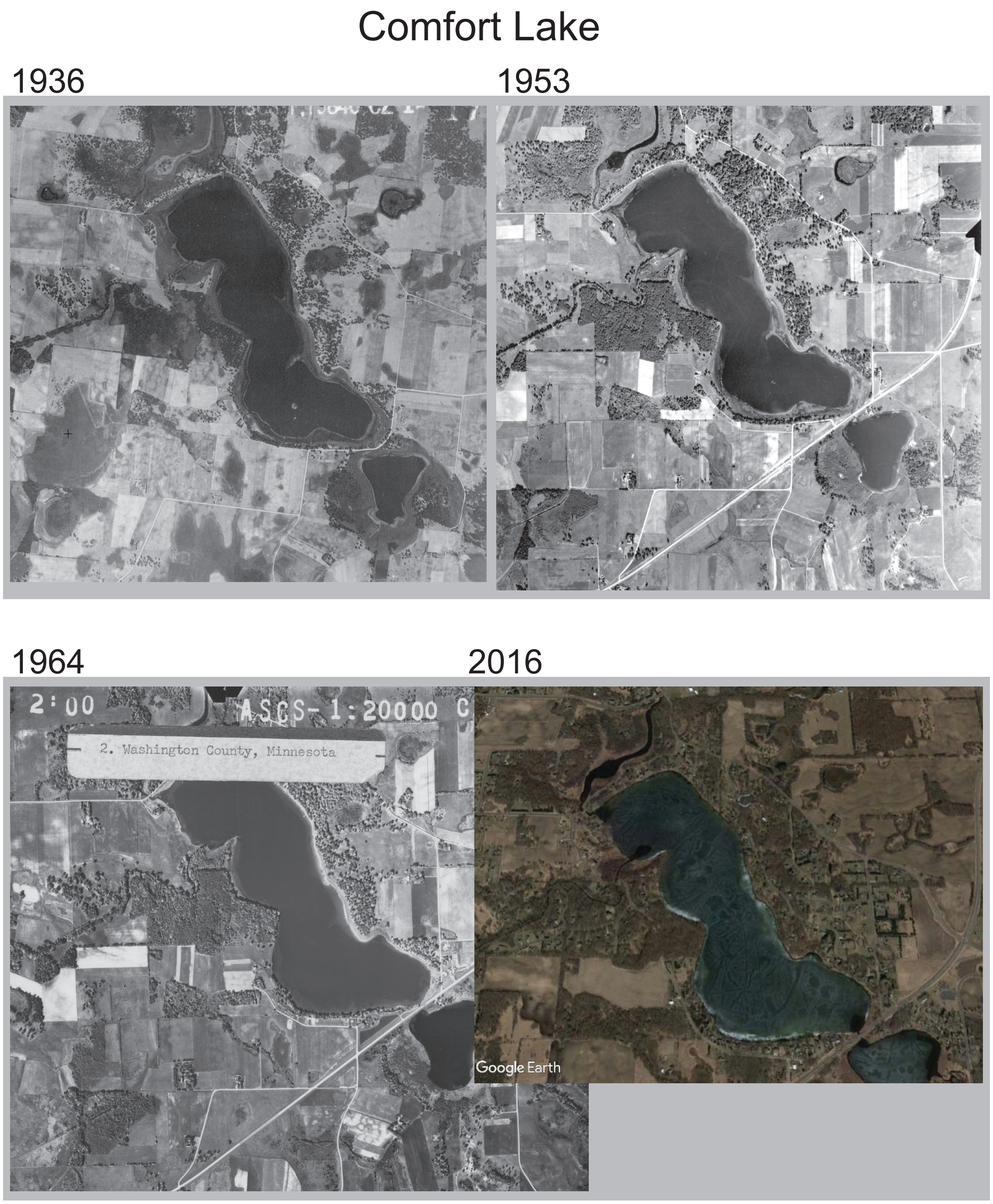


Figure 5. Unsupported lead-210 activity (a), lead-210 dating model (b), and sediment accumulation rate (c) for Shields Lake; d-f, the same results for Moody Lake.

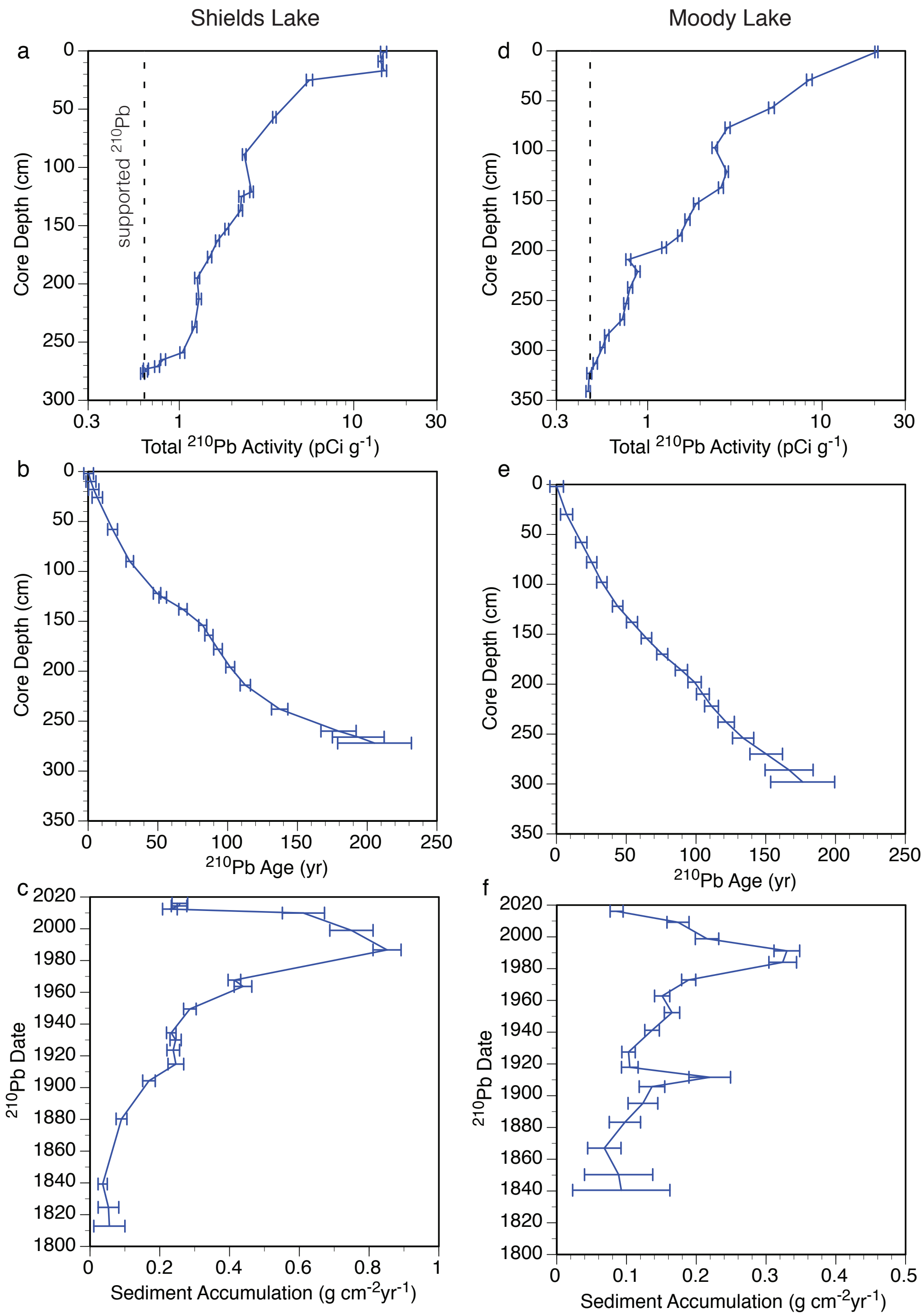


Figure 6. Unsupported lead-210 activity (a), cesium-137 activity (b), lead-210 dating model with cesium-137 peak shown for reference (c), and sediment accumulation rate (d) for Comfort Lake.

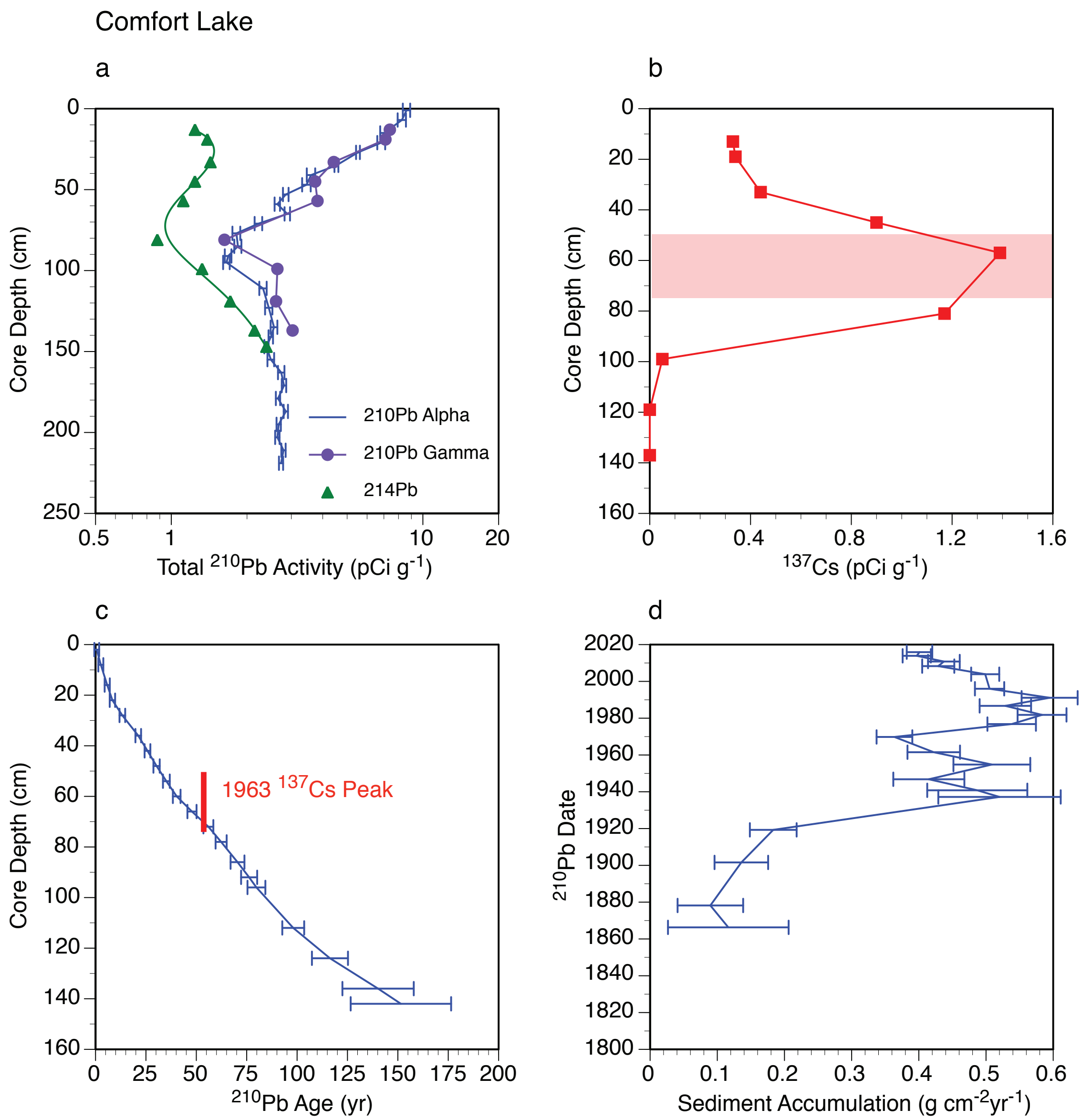


Figure 7. a) Magnetic susceptibility profile for the overlapping piston and Bolivia cores from Shields Lake plotted against depth in the sediment. b) Percent dry weight of organic matter, inorganic matter, and carbonate (CaCO3) in the overlapping piston and Bolivia cores from Shields Lake plotted against depth in the sediment. Lead-210 dates have been provided for important transitions in the core.

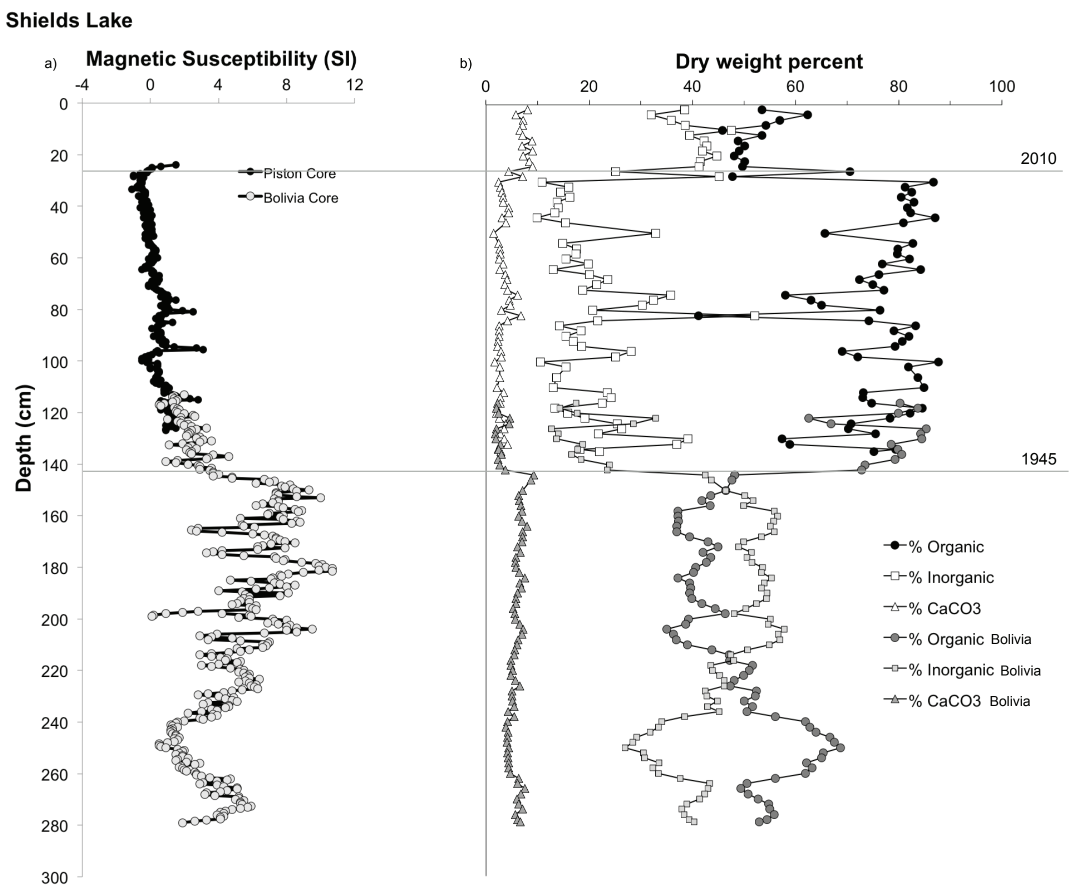


Figure 8. a) Magnetic susceptibility profile for the overlapping piston and Bolivia cores from Moody Lake plotted against depth in the sediment. b) Percent dry weight of organic matter, inorganic matter, and carbonate (CaCO3) in the overlapping piston and Bolivia cores from Moody Lake plotted against depth in the sediment. Lead-210 dates have been provided for important transitions in the core.

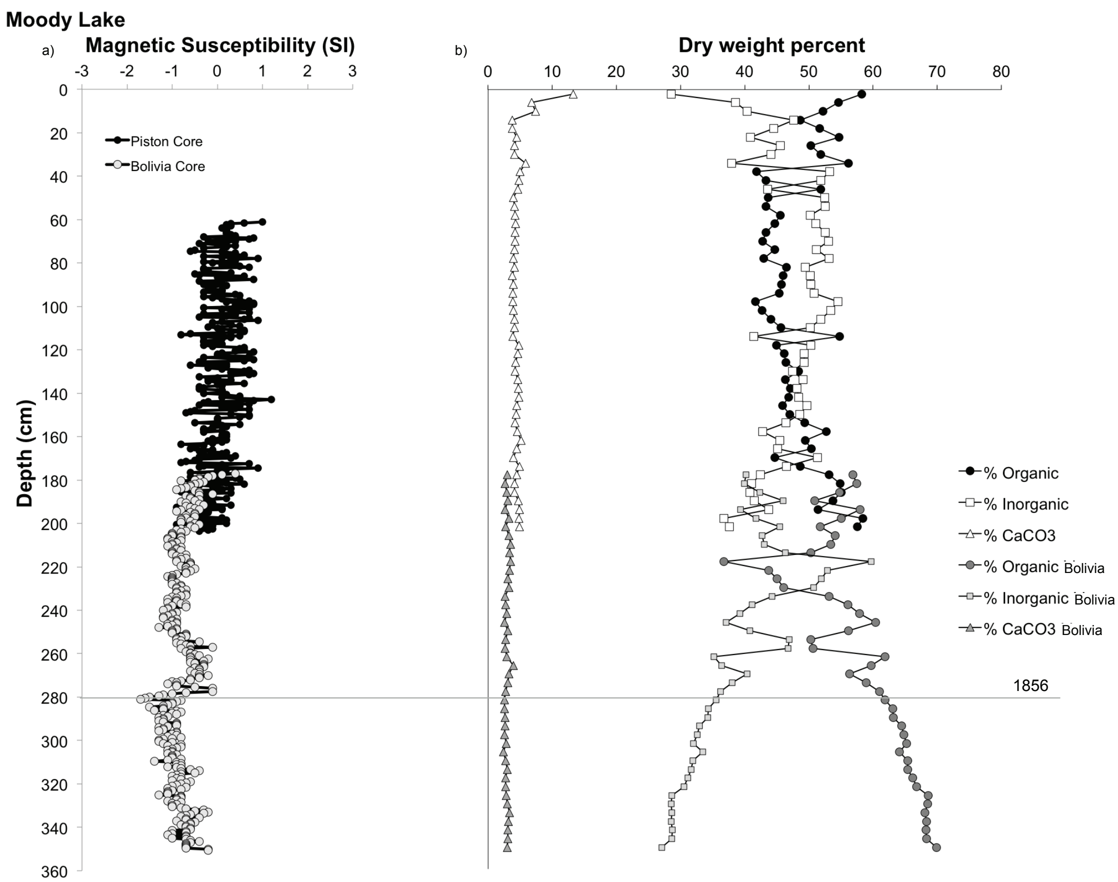


Figure 9. a) Magnetic susceptibility profile for the overlapping piston and Livingstone cores from Comfort Lake plotted against depth in the sediment. b) Percent dry weight of organic matter, inorganic matter, and carbonate (CaCO3) in the overlapping piston and Livingstone cores from Comfort Lake plotted against depth in the sediment. Lead-210 dates have been provided for important transitions in the core.

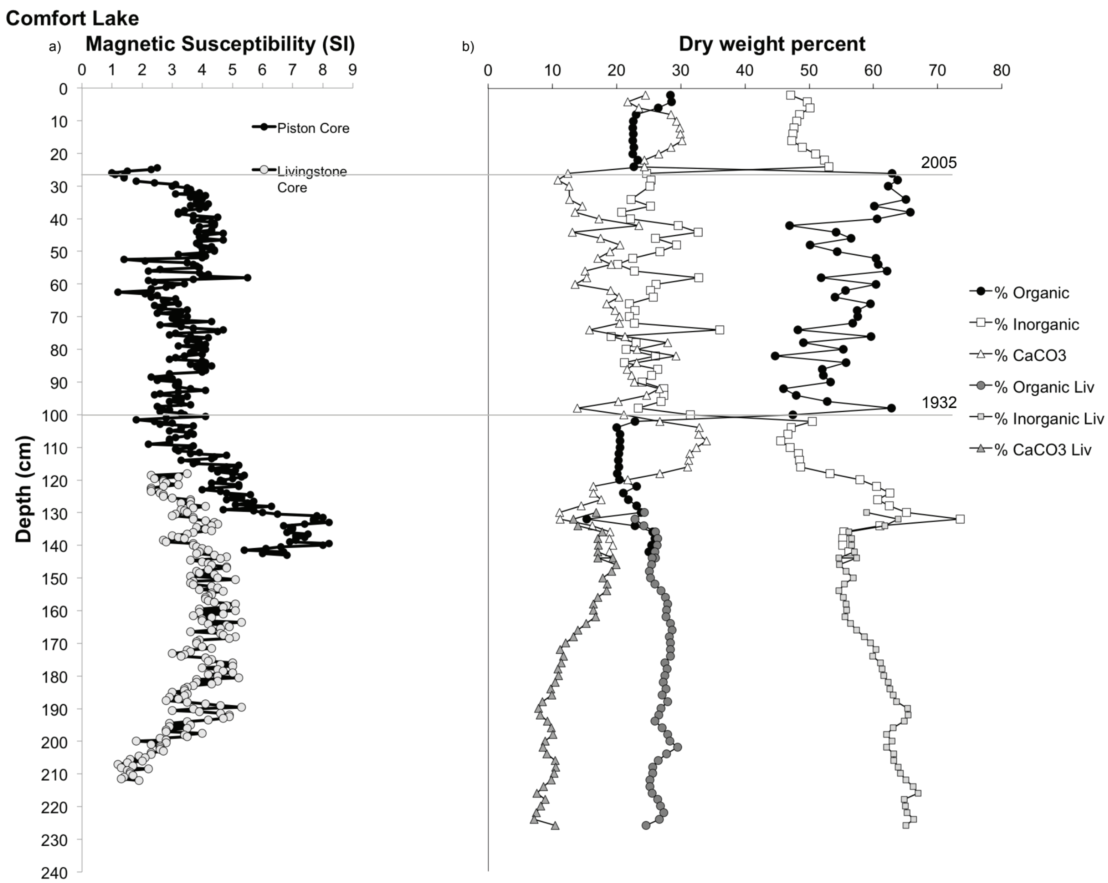


Figure 10. Sediment flux of organic matter, inorganic matter, and carbonate (CaCO3) to the Shields Lake core. Flux was only calculated for the length of the core within the lead-210 record (0-272 cm).

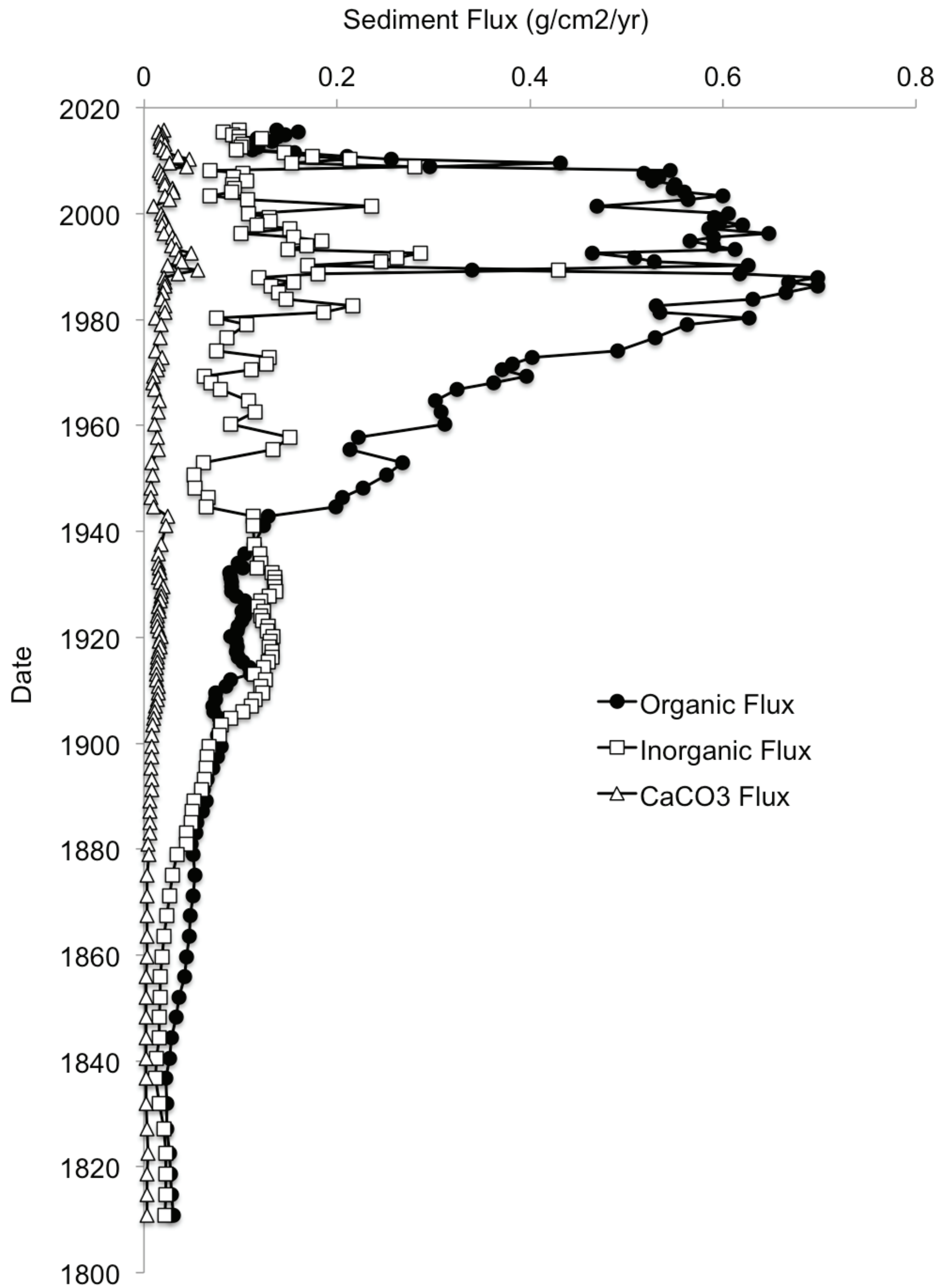


Figure 11. Sediment flux of organic matter, inorganic matter, and carbonate (CaCO3) to the Moody Lake core. Flux was only calculated for the length of the core within the lead-210 record (0-298 cm).

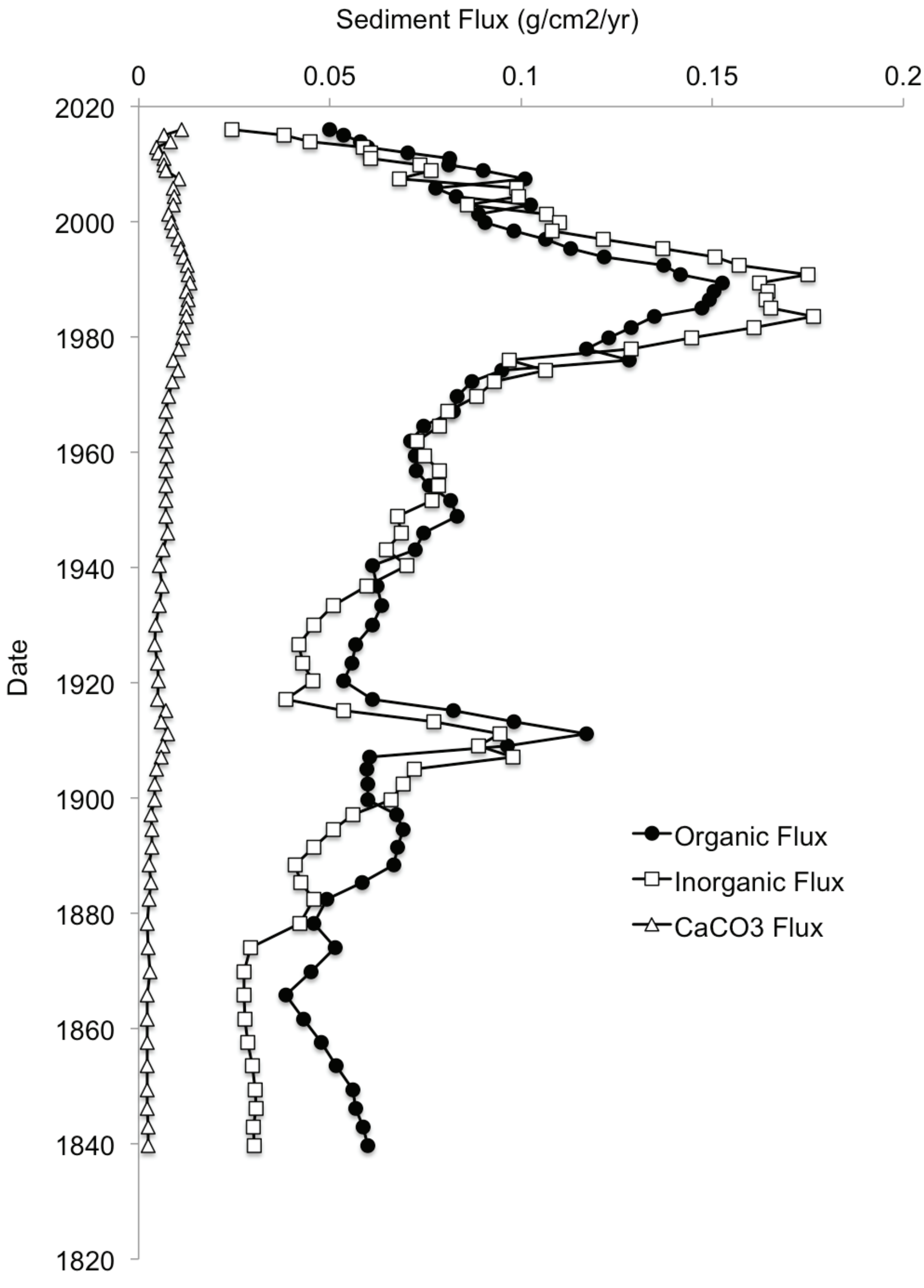


Figure 12. Sediment flux of organic matter, inorganic matter, and carbonate (CaCO3) to the Comfort Lake core. Flux was only calculated for the length of the core within the lead-210 record (0-142 cm).

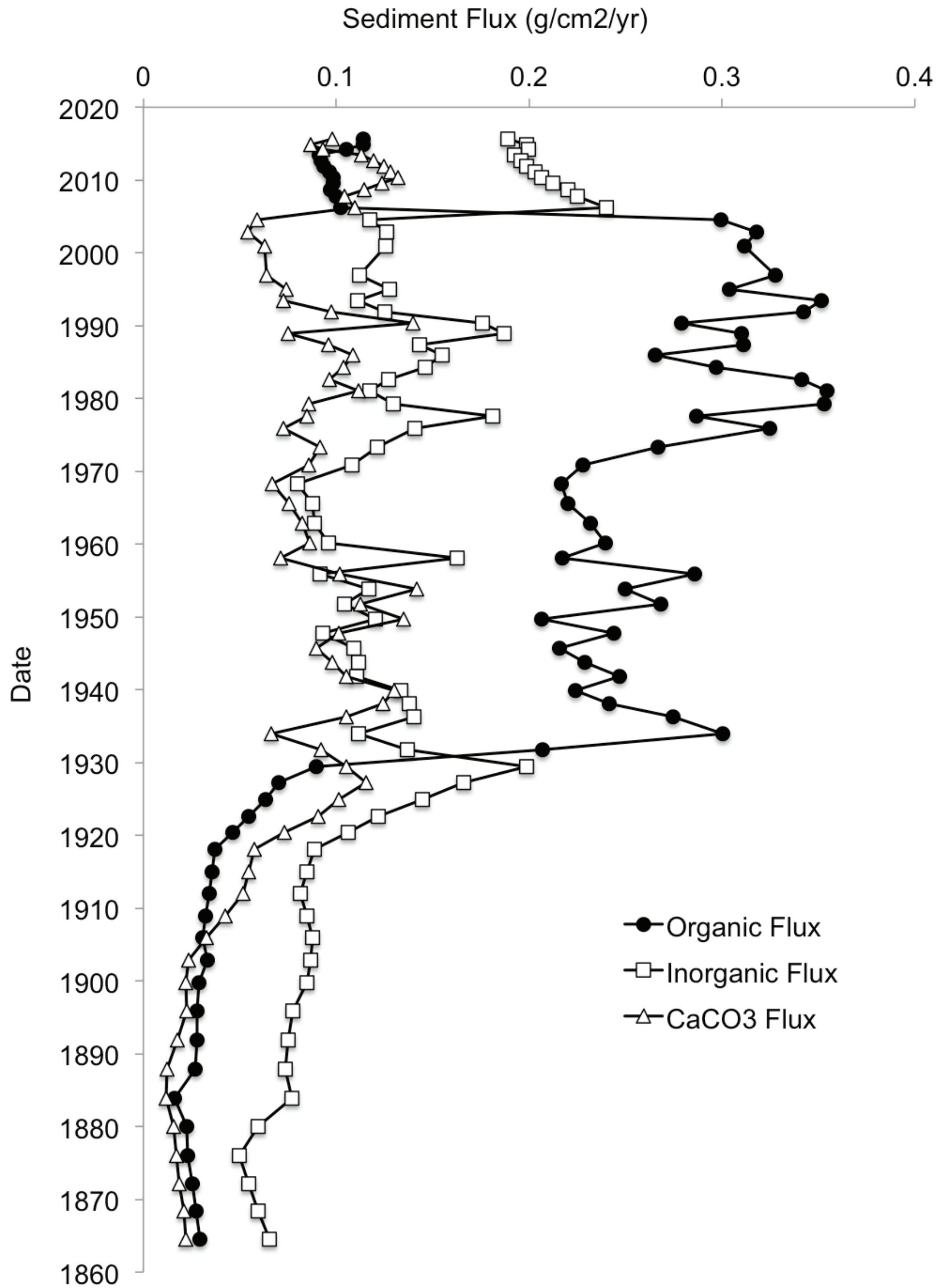
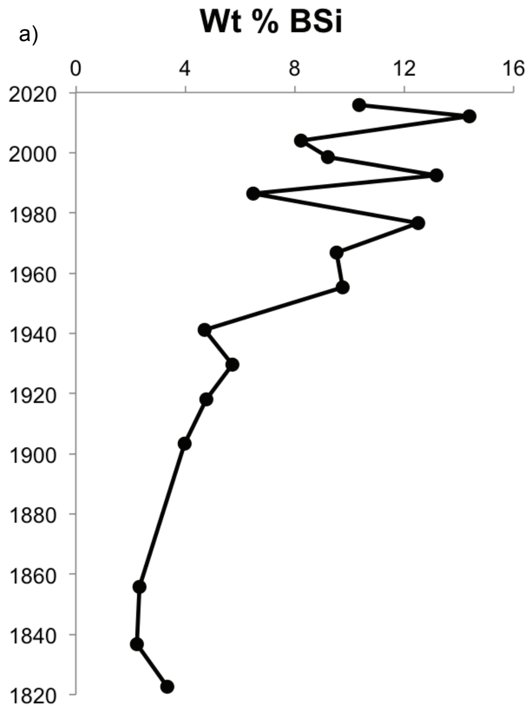


Figure 13. Weight percent of biogenic silica (BSi) (a) and SiO2 flux (b) in the Shields Lake core, plotted against lead-210 date.



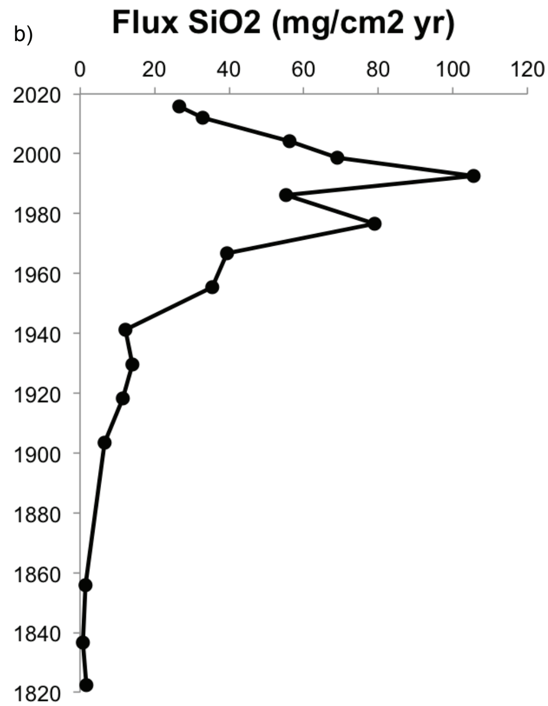
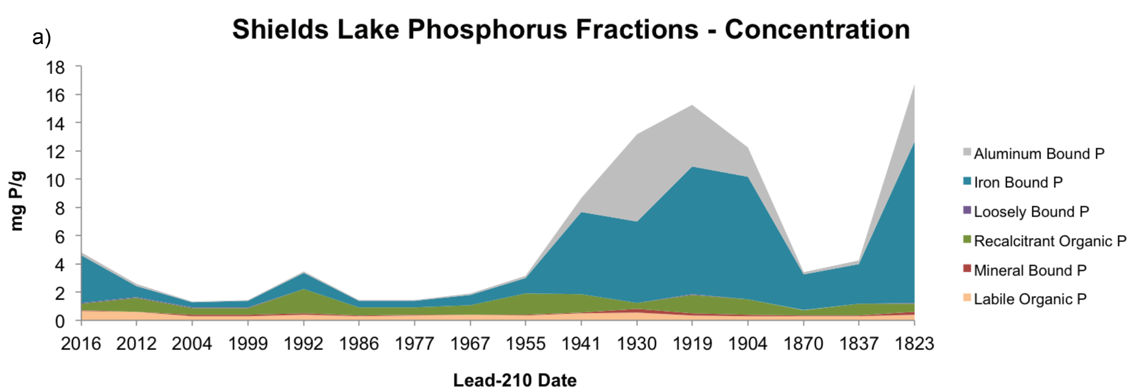


Figure 14. Concentration (a) and flux (b) of total phosphorus in the Shields Lake core, plotted against lead-210 depth.



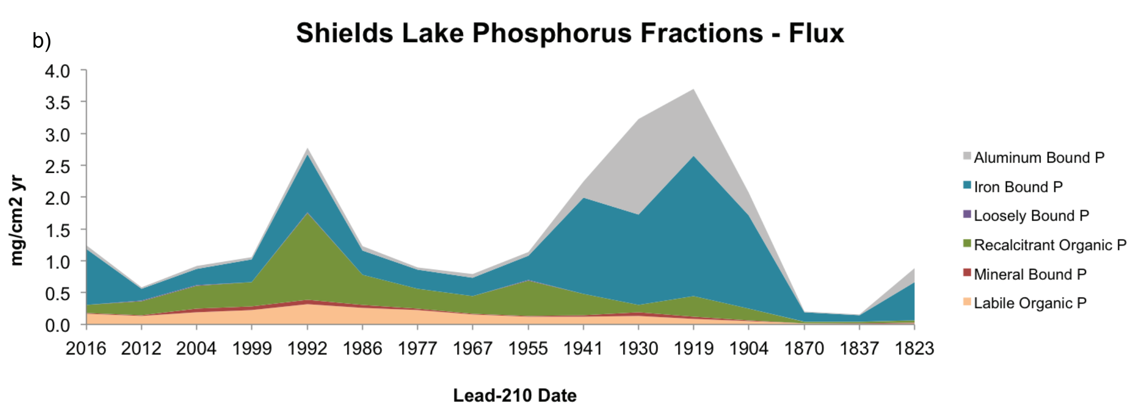


Figure 15. Weight percent of biogenic silica (BSi) (a) and flux (b) in the Moody Lake core, plotted against lead-210 date.

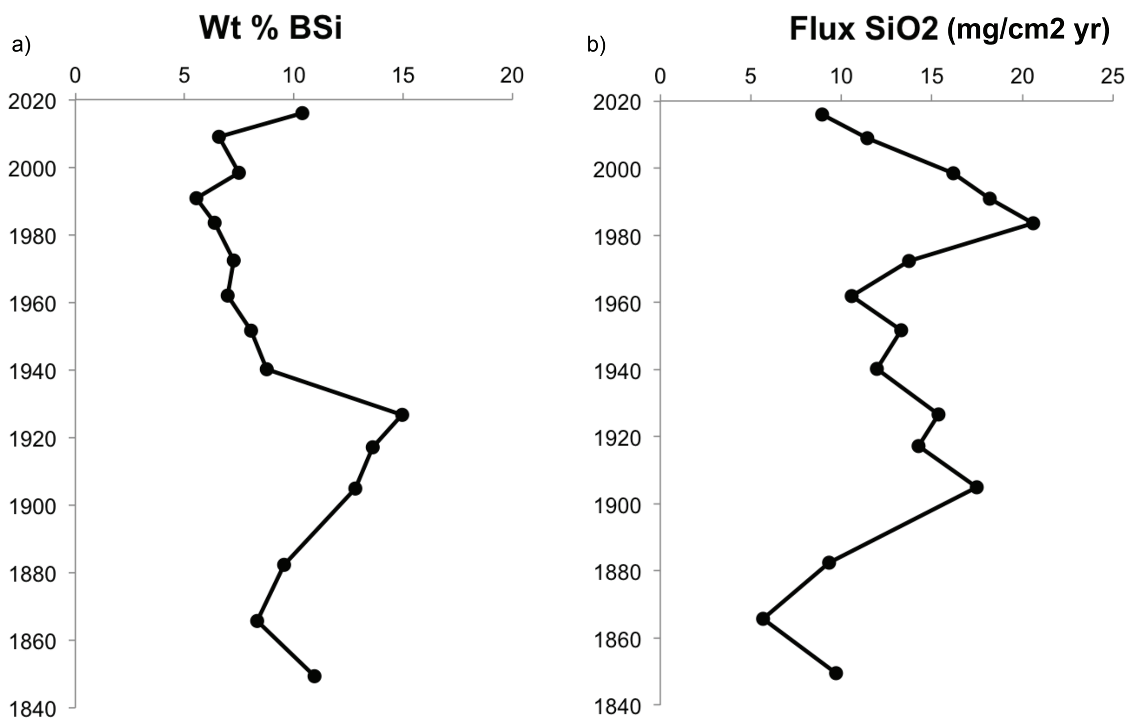


Figure 16. Concentration (a) and flux (b) of total phosphorus in the Moody Lake core, plotted against lead-210 depth.

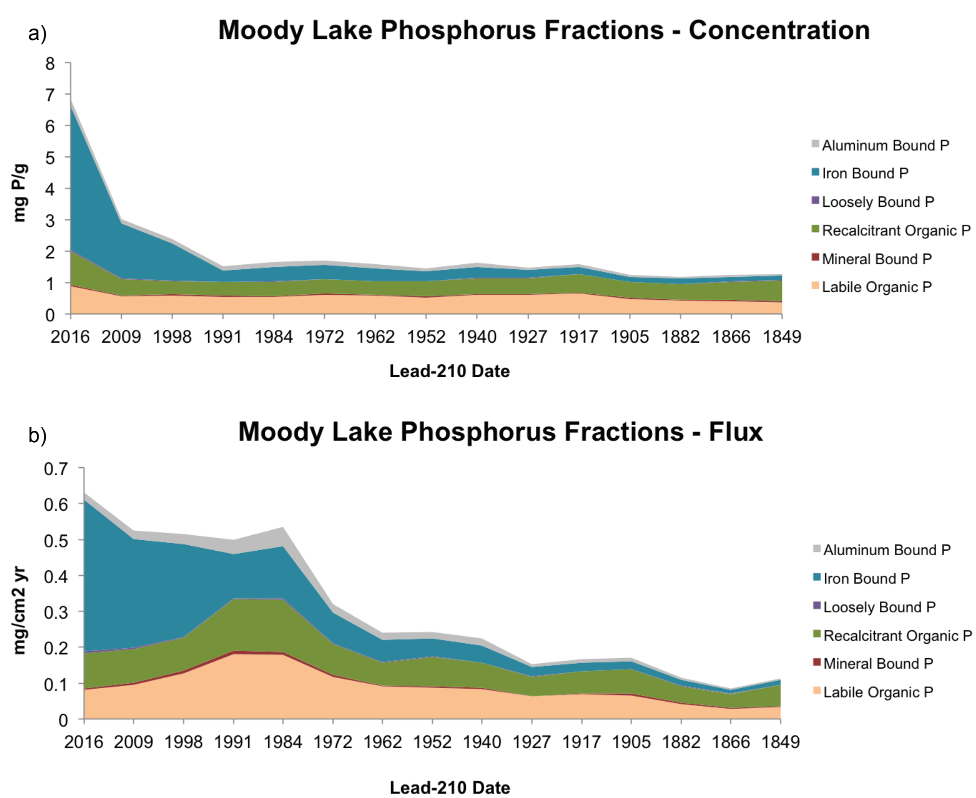


Figure 17. Weight percent of biogenic silica (BSi) (a) and flux (b) in the Comfort Lake core, plotted against lead-210 date.

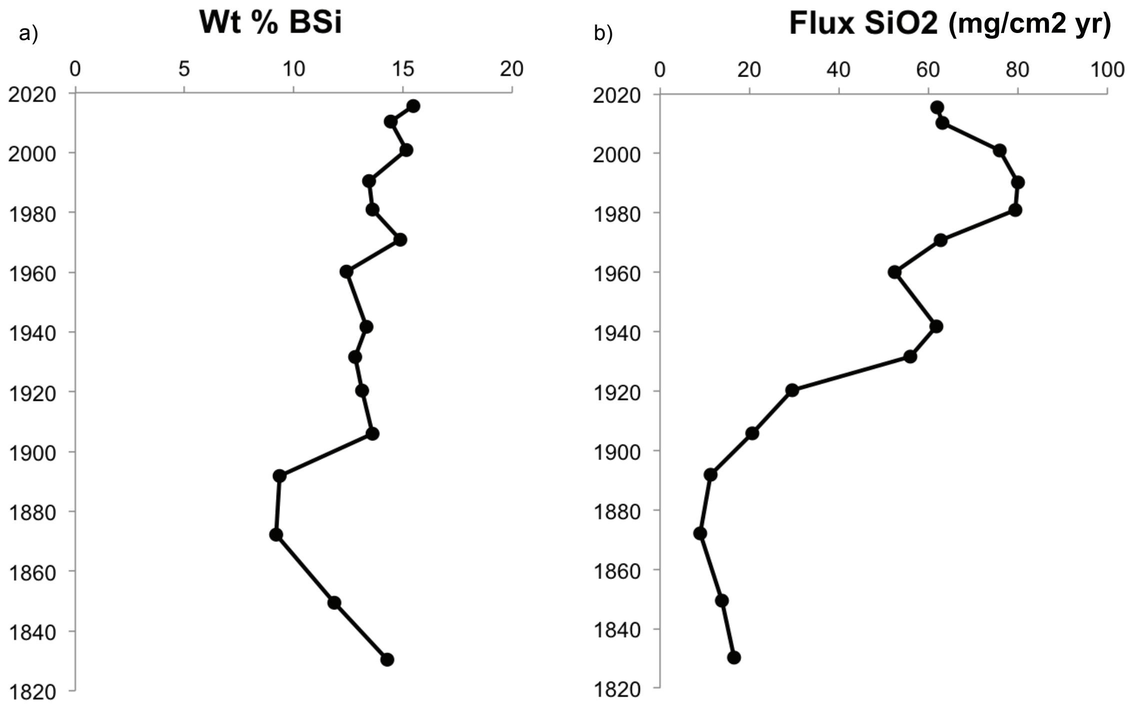


Figure 18. Concentration (a) and flux (b) of total phosphorus in the Comfort Lake core, plotted against lead-210 depth.

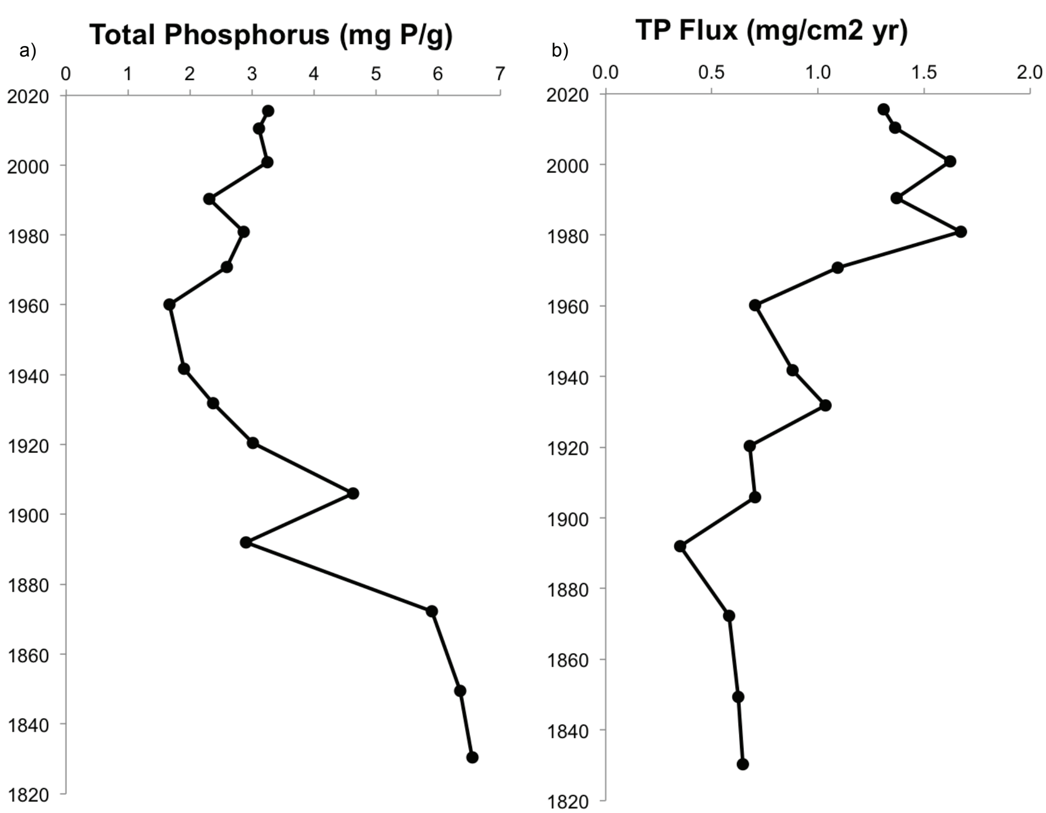


Figure 19. Non-Metric Multidimensional Scaling (NMDS) biplot of diatom communities from Shields Lake (1918-2016).

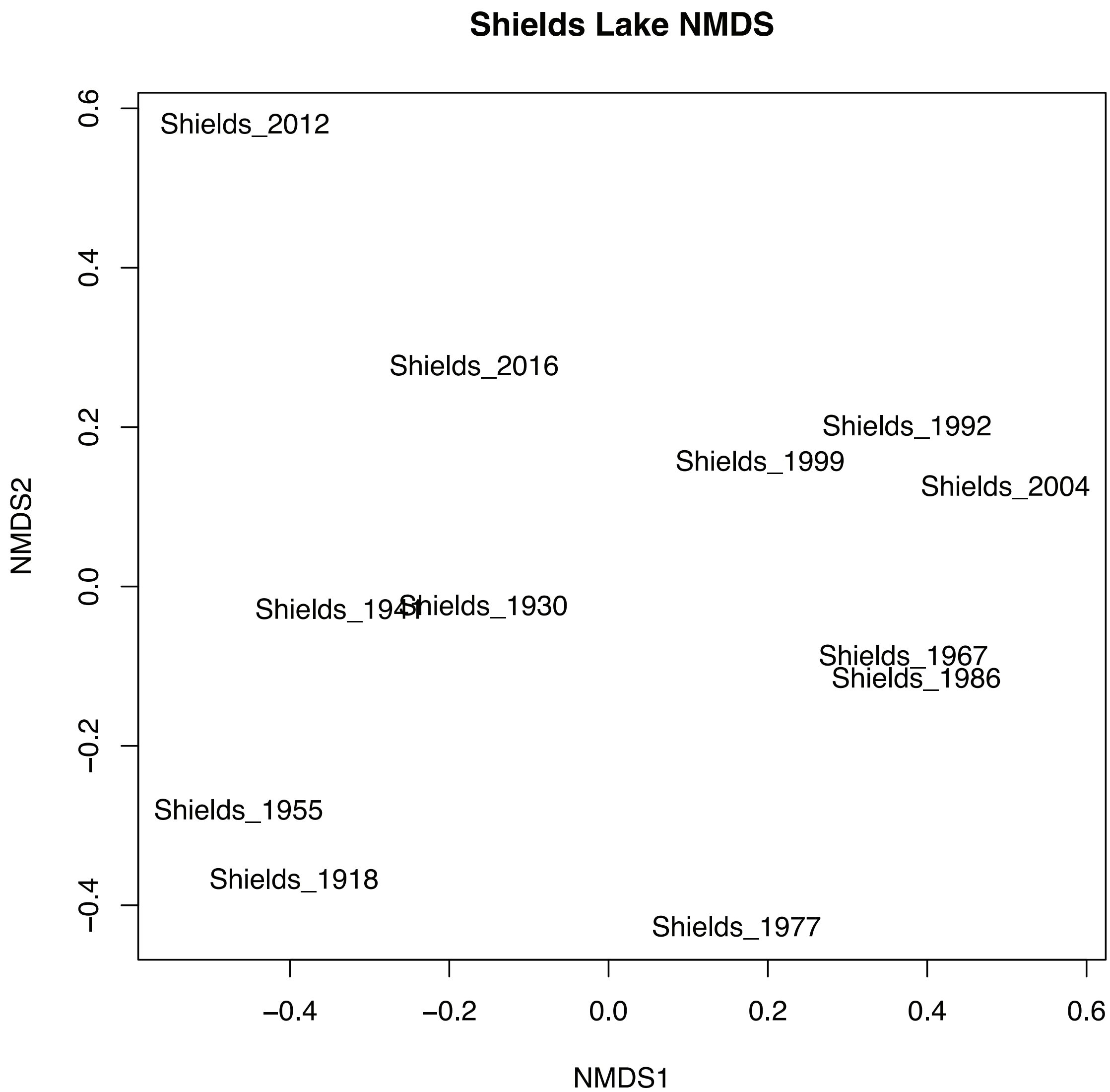


Figure 20. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance), results of a constrained cluster analysis, and percent plankton in Shields Lake (1918-2016).

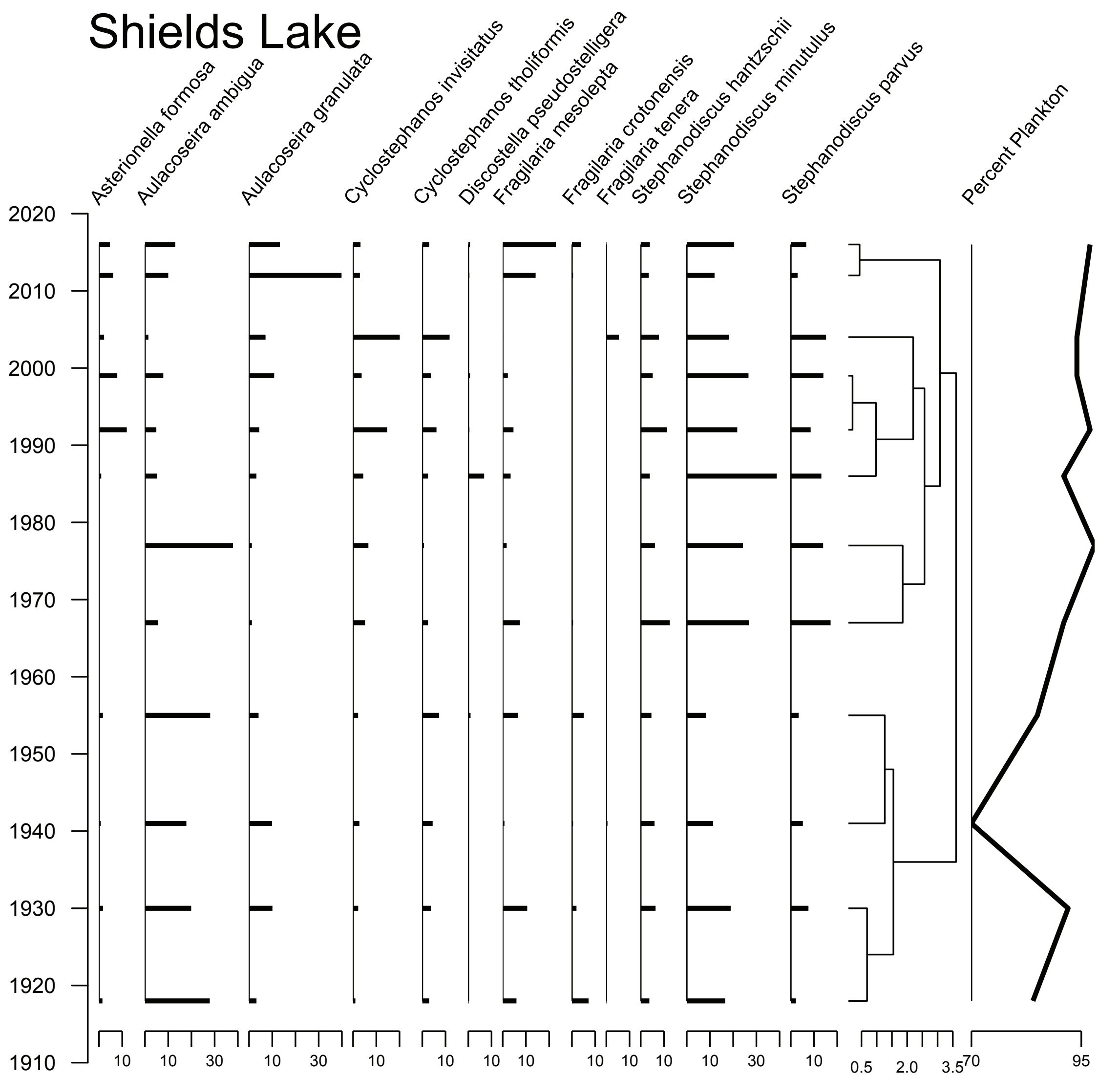


Figure 21. Non-Metric Multidimensional Scaling (NMDS) biplot of diatom communities from Moody Lake (1849-2016).

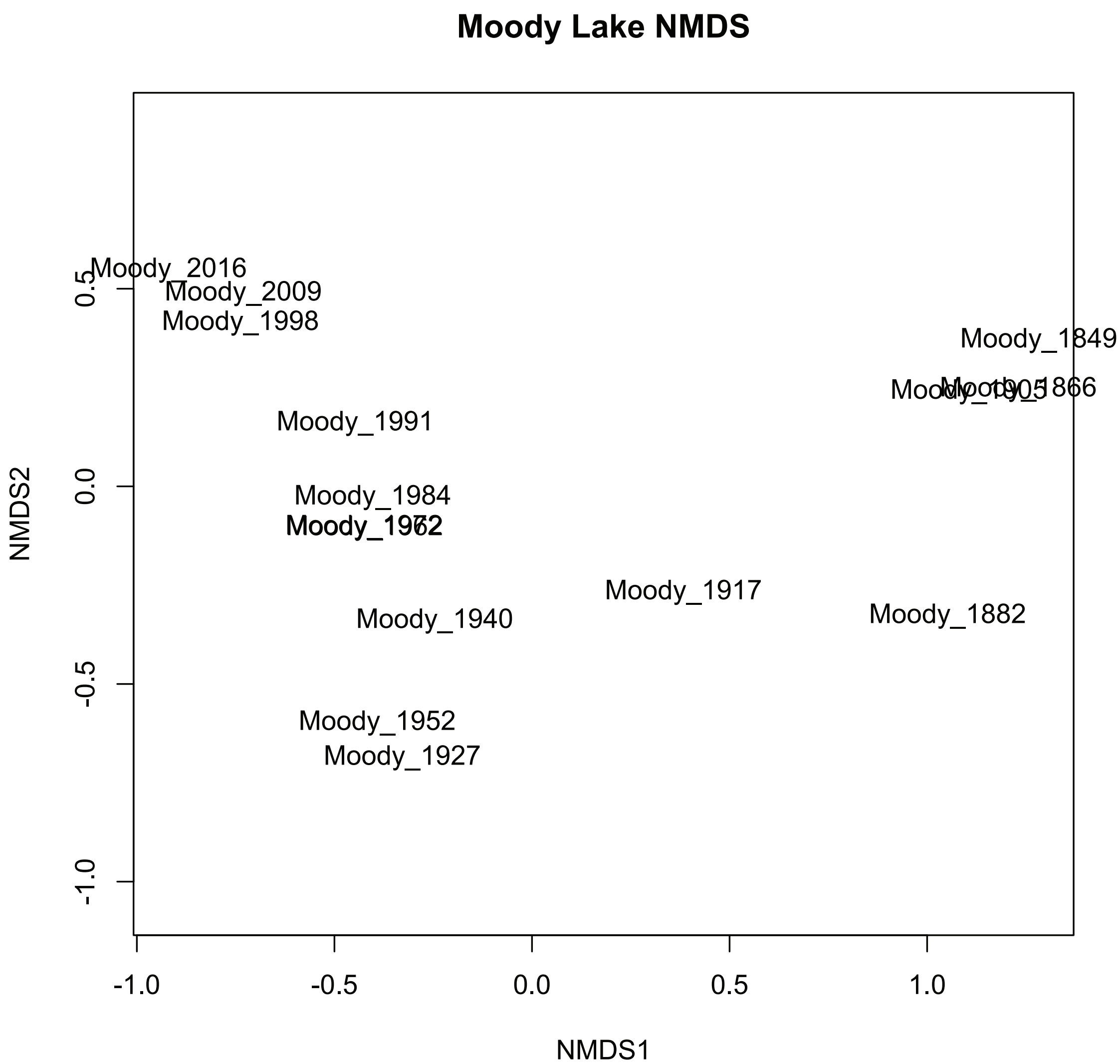


Figure 22. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance), results of a constrained cluster analysis, and percent plankton in Moody Lake (1849-2016). The red horizontal line denotes a significant break in the constrained cluster analysis.

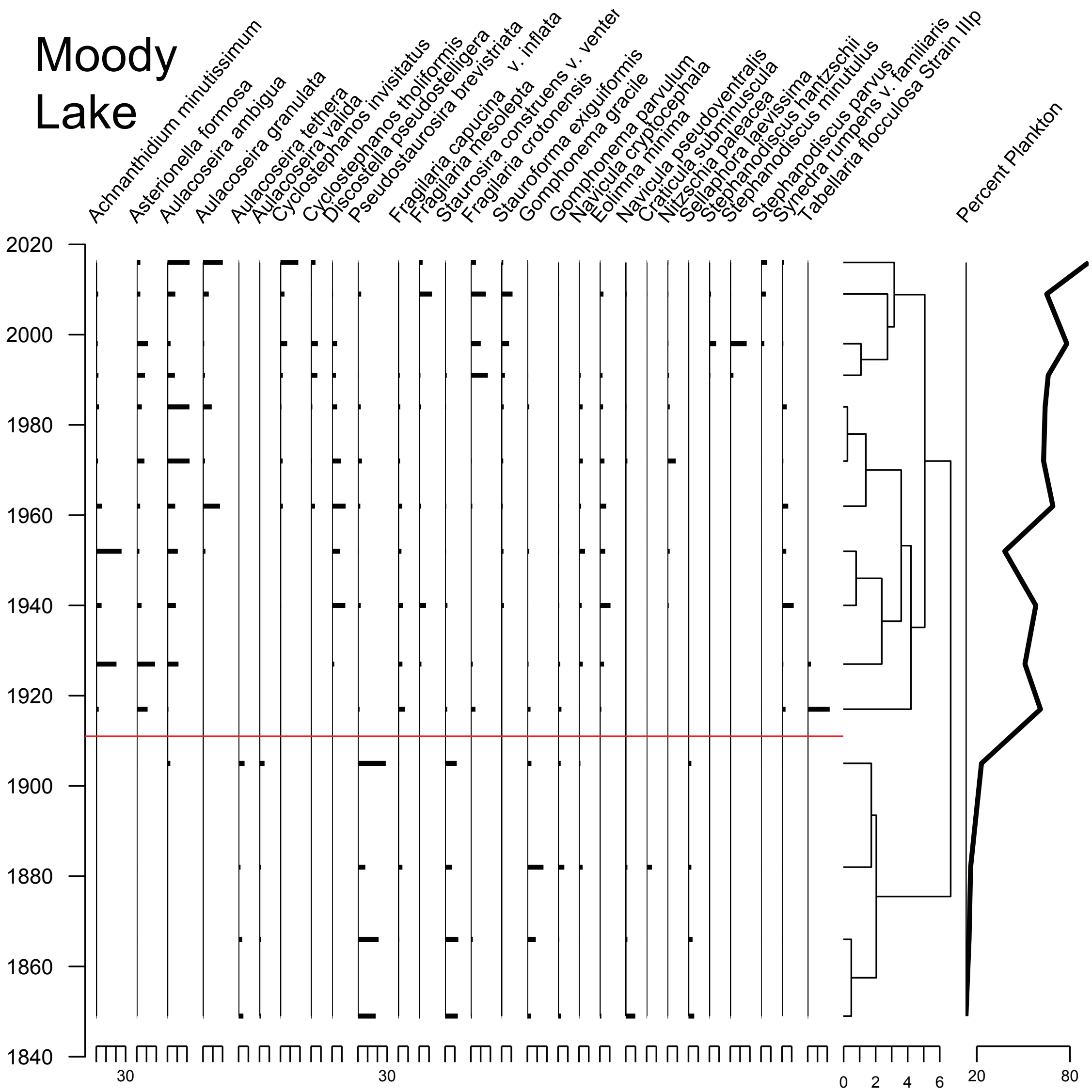


Figure 23. Non-Metric Multidimensional Scaling (NMDS) biplot of diatom communities from Comfort Lake (1830-2016).

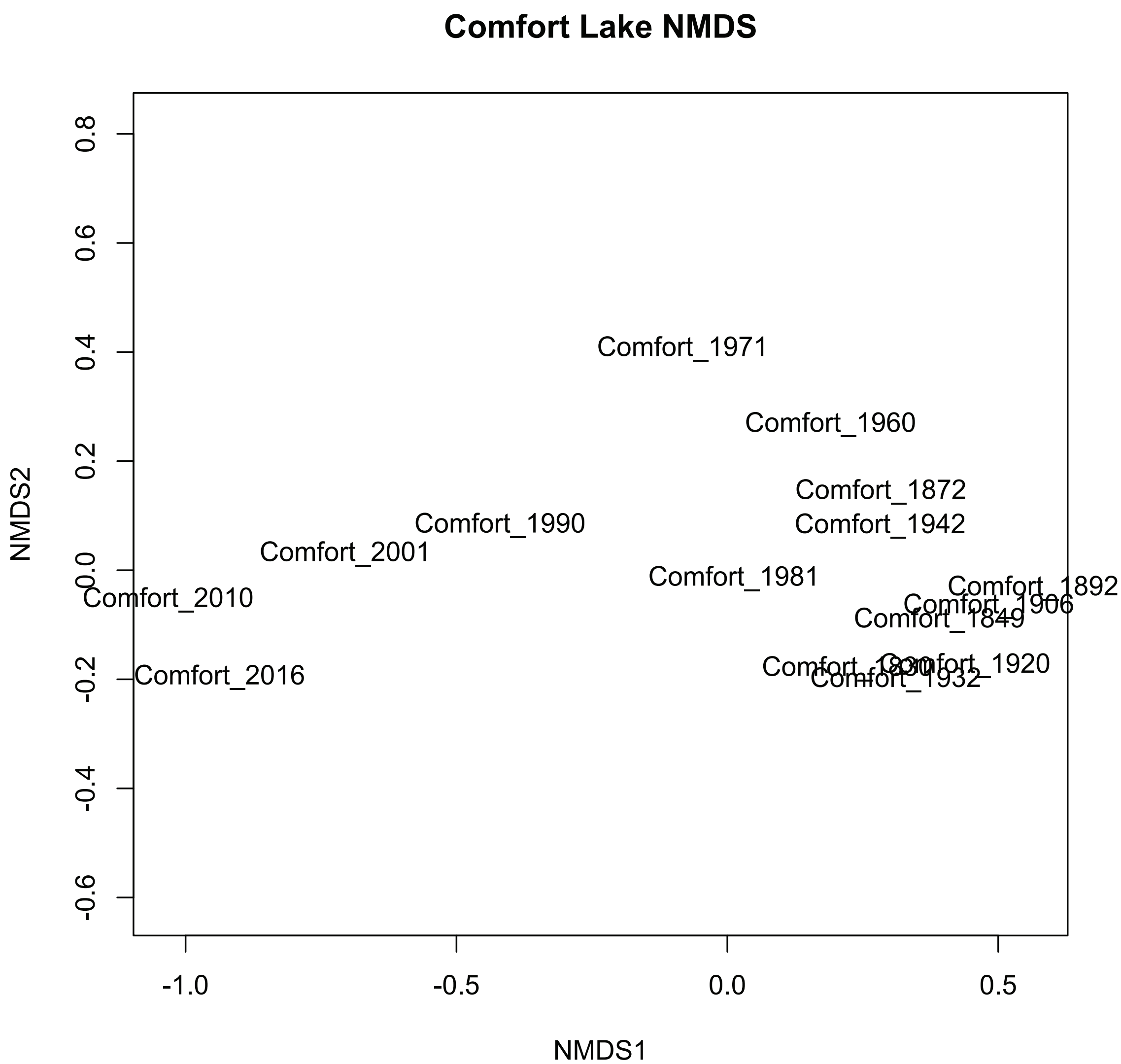


Figure 24. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance), results of a constrained cluster analysis, and percent plankton in Comfort Lake (1830-2016). The red horizontal line denotes a significant break in the constrained cluster analysis.

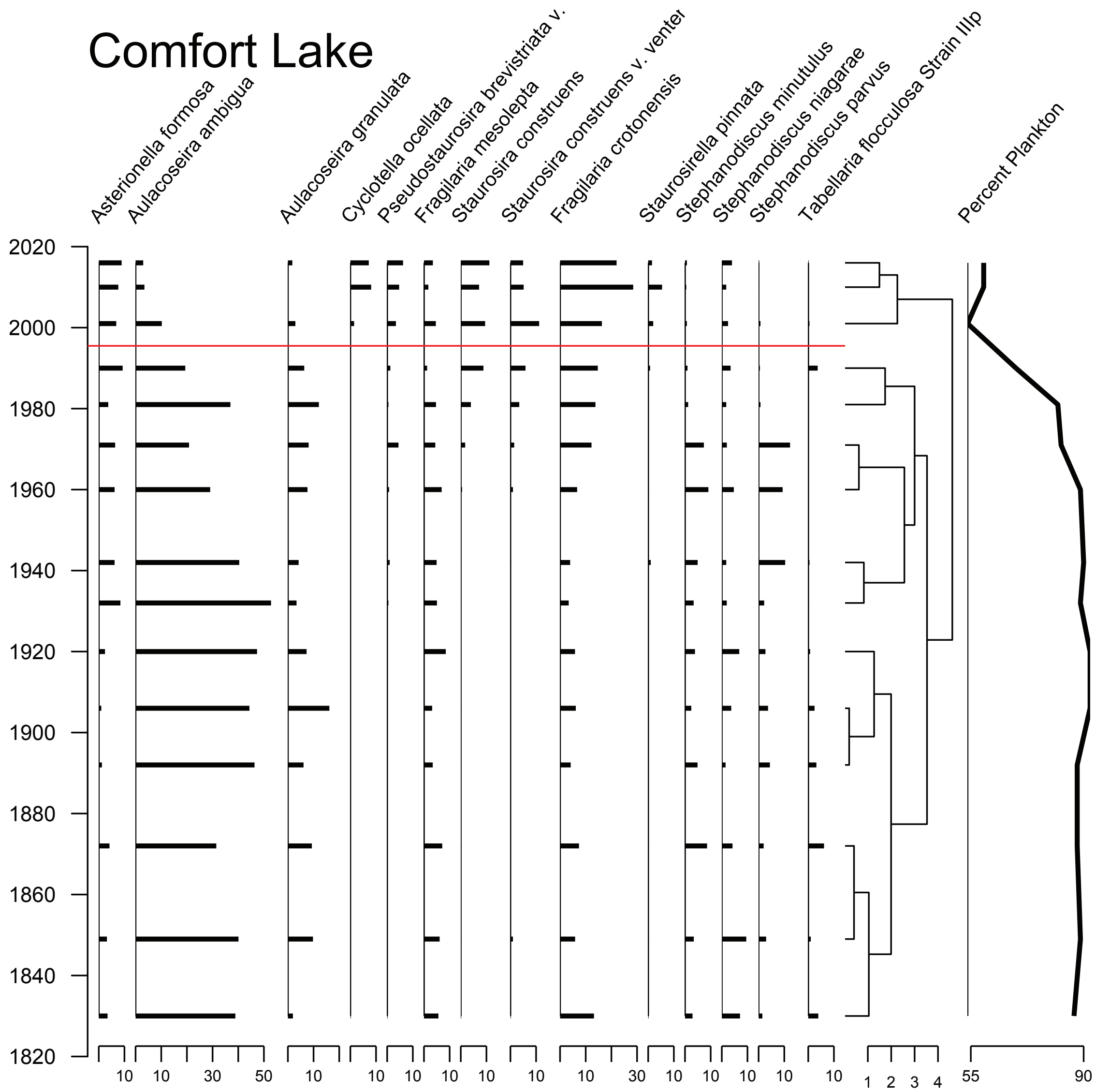


Figure 25. The core sections from Shields Lake projected onto the MN calibration set (denoted as "X core date"). Symbols represent the 89 MN lakes in the calibration set, coded by region; NLF=Northern Lakes and Forests, CHF=Central Hardwood Forests, Metro=Twin Cities Metropolitan Area, WCP=Western Corn 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.

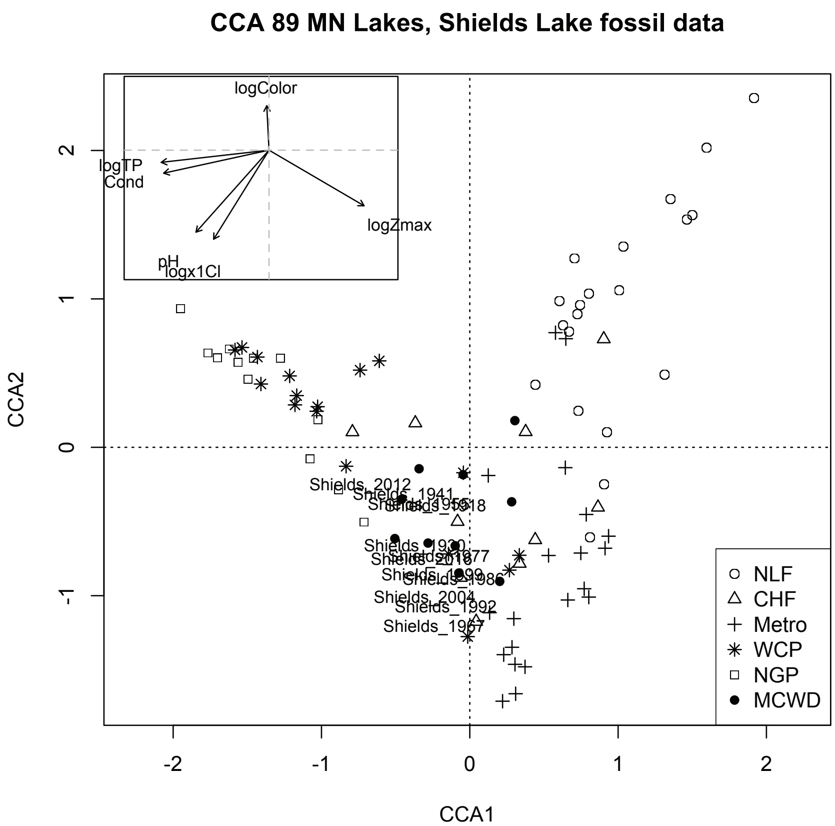


Figure 26. Diatom-inferred total phosphorus (TP) reconstruction for Shields Lake. Reconstruction is shown as log TP (left panel) and as backtransformed values in micrograms per liter (right panel). Error estimates on log TP are plus and minus the root mean square error of prediction from the TP transfer function.

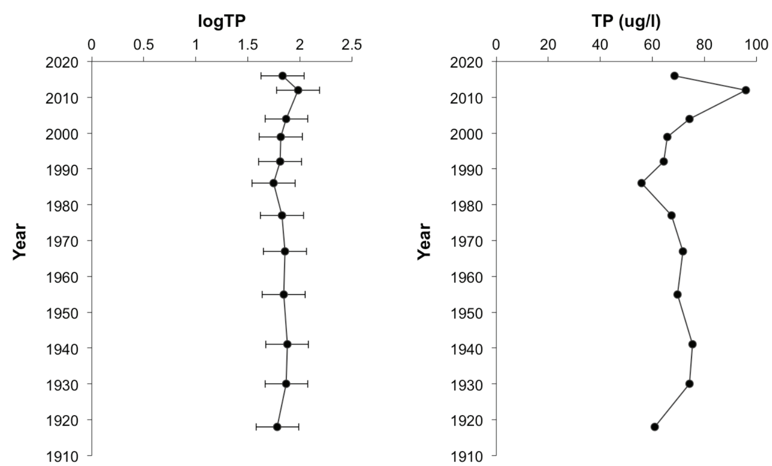


Figure 27. The core sections from Moody Lake projected onto the MN calibration set (denoted as "X core date"). Symbols represent the 89 MN lakes in the calibration set, coded by region; NLF=Northern Lakes and Forests, CHF=Central Hardwood Forests, Metro=Twin Cities Metropolitan Area, WCP=Western Corn 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.

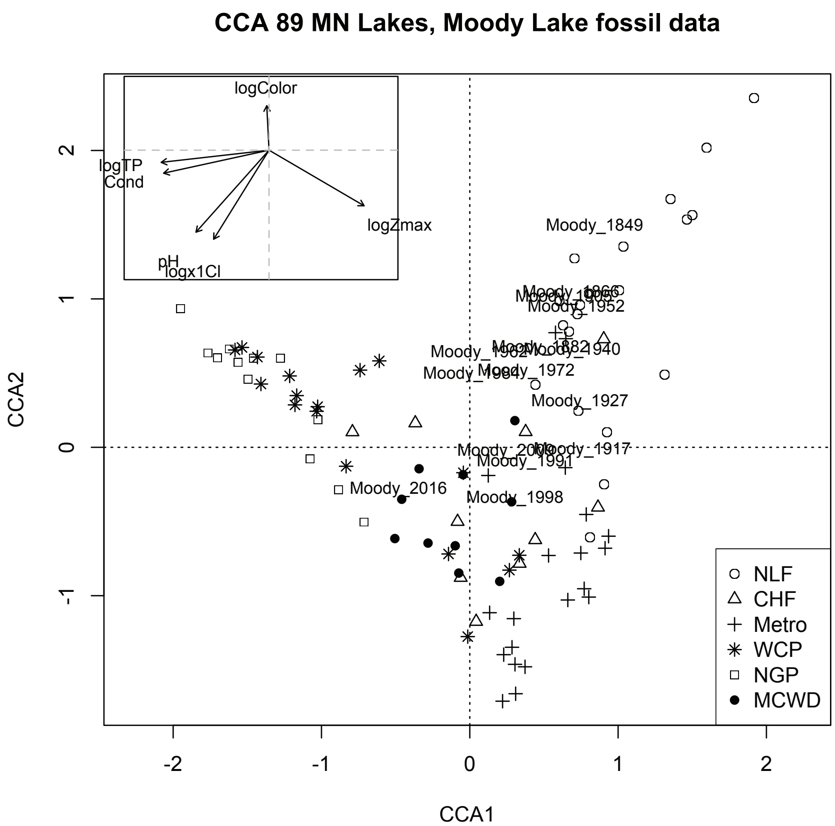


Figure 28. Diatom-inferred total phosphorus (TP) reconstruction for Moody Lake. Reconstruction is shown as log TP (left panel) and as backtransformed values in micrograms per liter (right panel). Error estimates on log TP are plus and minus the root mean square error of prediction from the TP transfer function.

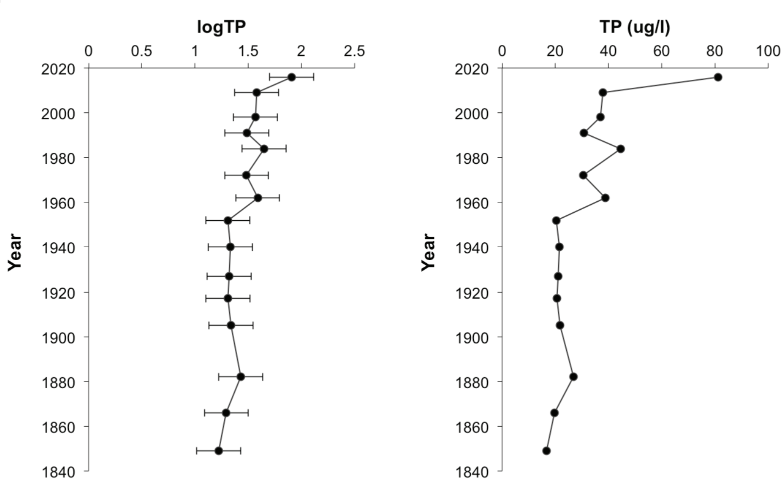


Figure 29. The core sections from Comfort Lake projected onto the MN calibration set (denoted as "X core date"). Symbols represent the 89 MN lakes in the calibration set, coded by region; NLF=Northern Lakes and Forests, CHF=Central Hardwood Forests, Metro=Twin Cities Metropolitan Area, WCP=Western Corn 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.

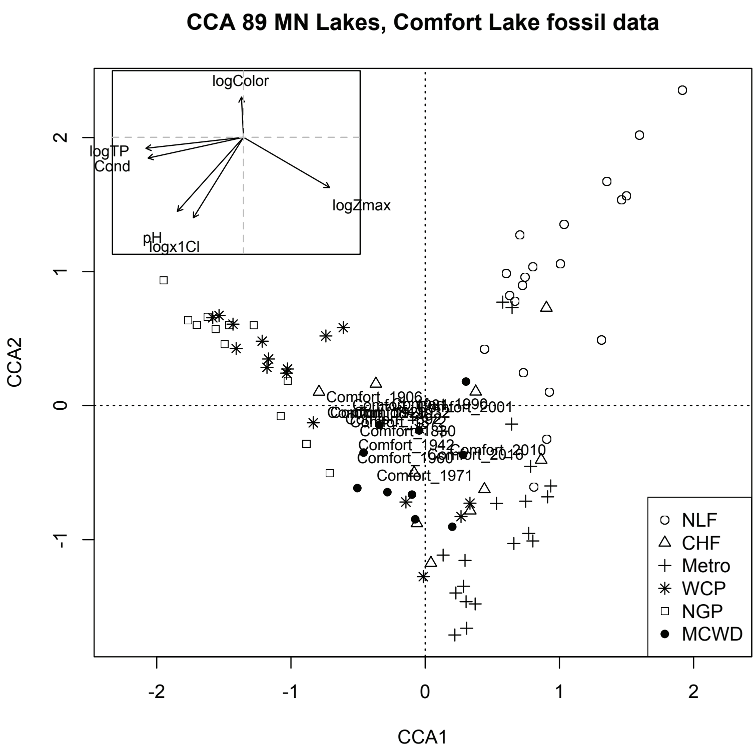


Figure 30. Diatom-inferred total phosphorus (TP) reconstruction for Comfort Lake. Reconstruction is shown as log TP (left panel) and as backtransformed values in micrograms per liter (right panel). Error estimates on log TP are plus and minus the root mean square error of prediction from the TP transfer function.

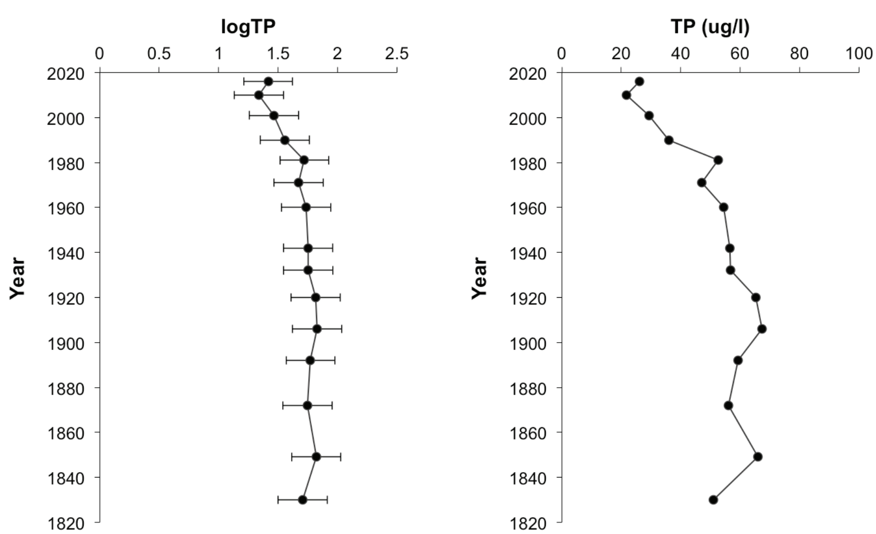


Figure 31. Sediment algal pigments quantified in ten core sections from Shields Lake. The group of algae associated with each pigment is shown along the x-axis.

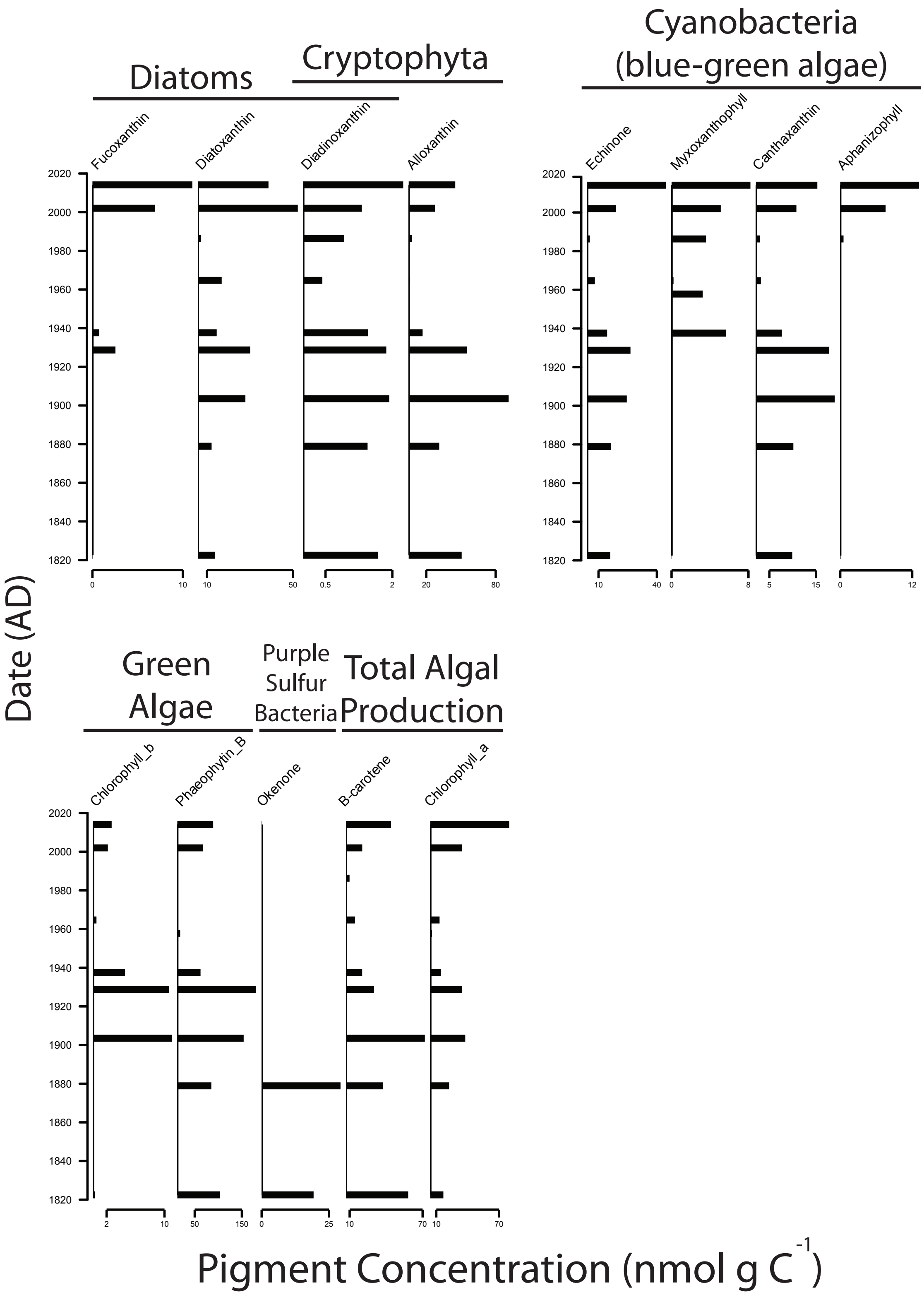


Figure 32. Sediment algal pigments quantified in ten core sections from Moody Lake. The group of algae associated with each pigment is shown along the x-axis.

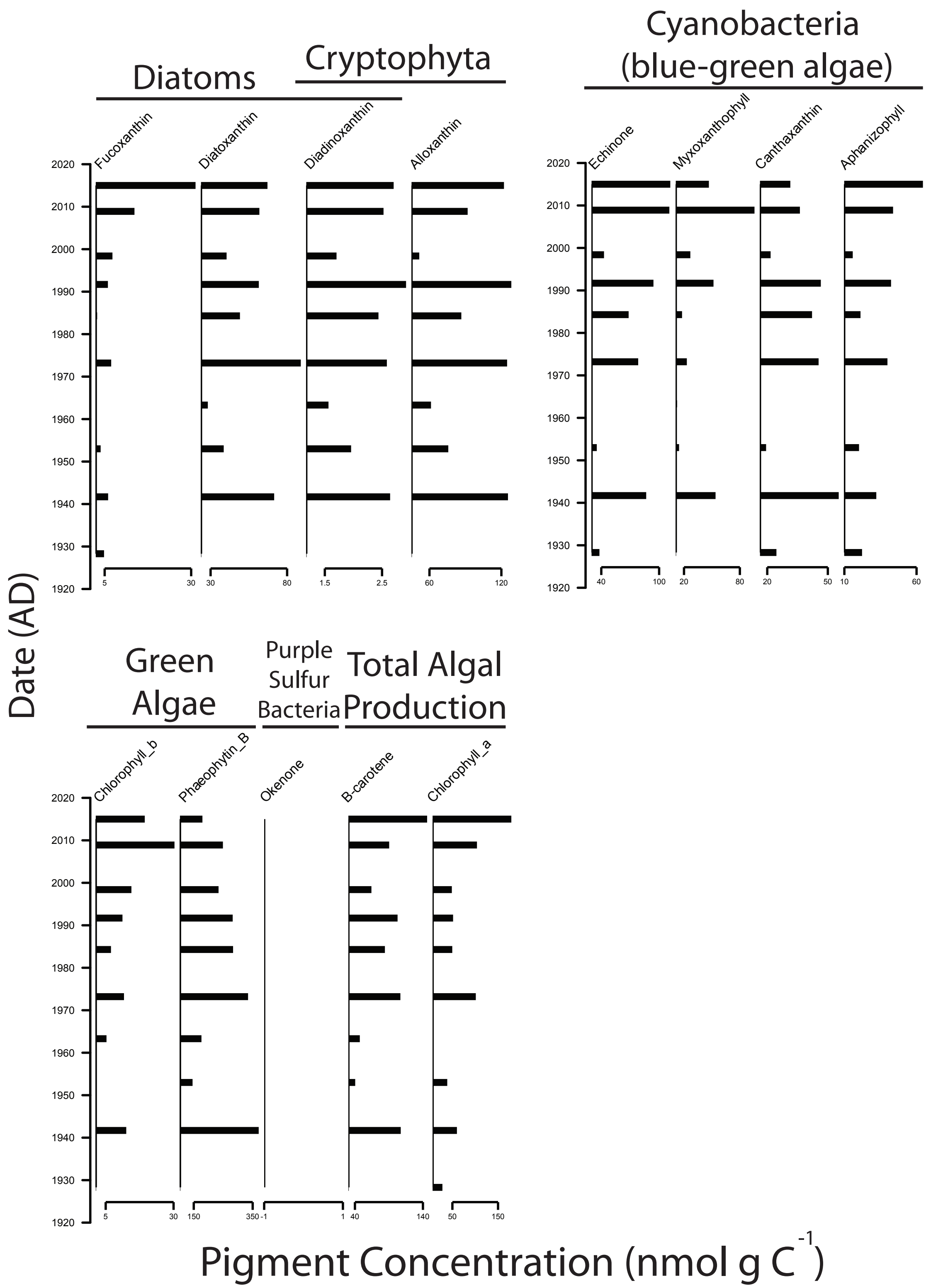


Figure 33. Sediment algal pigments quantified in ten core sections from Comfort Lake. The group of algae associated with each pigment is shown along the x-axis.