Paleolimnological Analysis of Sauk Lake and the Horseshoe Chain of Lakes

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REPORT CONTENTS

EXECUTIVE SUMMARY

1. In this project, we use paleolimnological techniques to reconstruct the trophic and sedimentation history of Sauk Lake (Stearns and Todd Co., MN), and the Horseshoe Chain of Lakes (Stearns Co., MN).

2. Sediment cores were collected from Sauk Lake North, Sauk Lake South, and Horseshoe Lake; these three primary cores were analyzed in detail. Sediment cores were also collected from Bolfing Lake and Cedar Island Lake, and were used for a core-top/core-bottom analysis (a core was also collected from Krons Bay, but was not selected for analysis).

3. All five of these lakes currently have marginal to poor water quality and are the subject of local and state concern to develop management plans that include an understanding of presettlement conditions and management targets, historical lake response to landuse and past management, and TMDL planning.

4. All three primary cores show increases in sedimentation rate beginning in the late 1800s/early 1900s. Horseshoe Lake has a high and erratic sedimentation rate, which pushes the limits of the lead-210 dating technique and results in large errors on downcore dates.

5. Since the late 1700s, the North Basin of Sauk Lake has been primarily dominated by diatoms that are representative of eutrophic conditions. The total phosphorus (TP) reconstruction of this lakes shows that the lake had elevated TP levels in pre-European settlement times. Sauk Lake South was a mestrophic system prior to European settlement, increases in TP levels in this basin occurred in the early to mid-1900s.

6. In Horseshoe Lake, the diatom stratigraphy and TP reconstruction show that this lake has undergone some changes since European settlement. The TP reconstruction shows that Horseshoe Lake has always been a productive system, but has increased in productivity since the early to mid-1900s, coinciding with the large-scale industrialization of agriculture. Bolfing Lake and Cedar Island Lake have undergone distinct changes since European settlement; both lakes were in the mesotropic range in pre-settlement times, and are both currently eutrophic to hypereutrophic systems.

INTRODUCTION

Within the glaciated regions of the Upper Midwest, lakes feature prominently in the landscape and are a valued resource for tourism, municipalities, home and cabin owners, recreational enthusiasts, and wildlife. Current and historical land and resource uses around the lakes in Stearns County, including shoreline development, sport fisheries, waste and stormwater discharge, water level management, and agriculture, have raised concerns about the state of the lakes and how to best manage them in a future certain to bring change. To effectively develop management plans, knowledge of the natural state of a lake and an understanding of the timing and magnitude of historical ecological changes become critical components. In this project, we use paleolimnological techniques to reconstruct the trophic and sedimentation history of Sauk Lake (Stearns and Todd Co., MN), and the Horseshoe Chain of Lakes (Stearns Co., MN). Results will provide a management foundation for TMDL development by determining the natural or reference condition of these lakes and reconstructing a history of ecological changes that have occurred in the lakes during the last 150 years.

With any lake management plan it is important to have a basic understanding of natural fluctuations within the system. Reliable long-term data sets, on the order of 30 - 50 years, are generally not available for most regions of the country. Through the use of paleolimnological techniques and quantitative environmental reconstruction, we can estimate past conditions, natural variability, timing of changes, and determine rates of change and recovery. This type of information allows managers and researchers to put present environmental stresses into perspective with the natural variability of the system. It can also be used to determine response to and recovery from short-term disturbances.

Sauk Lake is a multi-basin lake and wetland complex on the Sauk River drainage immediately upstream of Sauk Centre, Minnesota. The lake is primarily made up of two basins. The northern or upstream basin is approximately 4.5 miles long and 0.5 miles across and generally comprises a single basin reaching a maximum depth of just over 50 ft. The southern basin is approximately two miles long and is largely a shallow basin of less than 10 ft depth, except for a basin immediately downstream of the Hwy 71 crossing that reaches a maximum depth of 19 ft. Sauk Lake is a reservoir and currently dammed at the town of Sauk Centre; a dam has been in place at the current location since 1860. The Sauk River drains a primarily agricultural watershed, but has seen historically elevated nutrient loading from permitted point sources (Richmond, Melrose, Sauk Centre POTWs). Modern water quality is notably impaired in the southern basin of Sauk Lake. Two sediment cores were collected and analyzed from this system, one from the North basin and one from the South.

The Horseshoe Chain of lakes is a multi-basin lake and wetland complex on the Sauk River drainage, located downstream of Sauk Lake and made up of eight basins: Becker Lake, Horseshoe Lake, Krons Bay, East Lake, Cedar Island Lake, Great Northern Lake, Zumwalde Lake, and Krays Lake. Several additional lakes surround the Horseshoe Chain including: Roschien, Big, Meyers, Ganzer, Deep, Flint, Long, Browns, and Thein Lakes. The Horseshoe Chain has been dammed intermittently since 1857; it is in a primarily agricultural landuse area, has seen historically elevated nutrient loading from permitted point sources (Richmond, Melrose, Sauk Centre POTWs), and is surrounded by recreational and year-round residences. One primary core and three secondary cores were collected from the Horseshoe Chain of lakes.

The primary aim of this project is to quantitatively reconstruct historical environmental change in Sauk Lake, Stearns and Todd County, and the Horseshoe Lake Chain, Stearns County, Minnesota, utilizing paleolimnological analysis of dated sediment cores (Anderson and Rippey 1994, Dixit and Smol 1994). The lakes currently have marginal to poor water quality and are the subject of local and state concern to develop management plans that include an understanding of presettlement conditions and management targets, historical lake response to landuse and past management, and TMDL planning. These goals are well-suited to paleolimnological study of mulitiple sediment cores. Analytical tools include radioisotopic dating of cores, geochemical analyses to determine local sediment accumulation rates, and analysis of subfossil algal 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 human impacts in the local watershed. Diatoms have been widely used to interpret environmental conditions in lakes (Dixit *et al.*, 1992); many species are sensitive to specific water conditions and are useful as bioindicators. Over the past 15 years, multivariate statistical methods have been developed to estimate quantitative environmental parameters from diatom assemblages. These methods are statistically robust and environmentally sound. They have been used successfully in reconstructing a wide variety of environmental parameters including pH, total phosphorus (TP), salinity, and recently, dissolved organic carbon (DOC).

METHODS-SEDIMENT CORING

Six piston cores and four Livingston cores were collected in August and September of 2006. Piston cores were taken using a drive-rod piston corer equipped with a 7 cm diameter polycarbonate barrel (Wright 1991). A Livingston corer was used to collect a secondary core from sediment depths below that of the piston core in locations where it seemed likely that the sedimentation rate would be too high to capture sediments dating prior to European settlement within the length of the piston core. One piston core was collected from the north basin of Sauk Lake and one from the south basin of Sauk Lake. On the Horseshoe Chain, one piston core and one Livingston core was collected from each of the following lakes: Horseshoe Lake, Krons Bay, Bolfing Lake, and Cedar Island Lake.

Horseshoe Lake and Krons Bay were re-cored in March 2008 because preliminary dating analyses indicated that the original cores may not have been long enough to represent pre-European settlement times. Four overlapping Livingston cores were collected from each site, representing a sediment depth of 3.98 m in Horseshoe Lake and 4.07 m in Krons Bay.

Recovered piston cores were transported to the shore and extruded vertically in 2-cm increments to a depth with cohesive sediment texture. Core sections, material remaining in the core barrels, and Livingston cores (wrapped in aluminum foil), were returned to the laboratory and stored at 4°C. Lakes, coring locations, and core recovery are provided in Table 1.

METHODS-MAGNETIC SUSCEPTIBILITY LOGGING AND CORE IMAGING

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 productivity.

A Geotek Standard MSCL with an automated trackfeed was used for magnetic susceptibility logging. Susceptibility measures were taken at 1-cm intervals, which integrated a signal over a 5-10-cm length of core. Following susceptibility logging, cores were split lengthwise, physically described, and digital images taken of each core section using a Geoscan Corescan-V. Following scanning, cores were returned to storage at 4°C. Magnetic susceptibility logging and core imaging were performed at the Limnological Research Center's core lab facility at the University of Minnesota.

All cores (piston and Livingston) were logged for magnetic susceptibility; in addition, the piston cores were split, imaged, and described. Appendix 1(a-f) shows the core image, magnetic susceptibility curve, and the physical description of each of the piston cores. Note that these analyses were performed on the intact portion of each core; therefore these data do not exist for the portions of the core that were field-sectioned. For example, in Appendix 1a (Sauk Lake-North), 0 cm actually corresponds to 50 cm depth, because 50 cm were sectioned off the top of the core in the field (refer to Table 1 for the length of core that was field sectioned). The magnetic susceptibility profiles for the Livingston cores are shown in Figures 1 and 2 (the depths in these figures are actual depths; note that there is some overlap between the piston core and the Livingston core, as well as overlap between the multiple Livingston cores taken from Horseshoe Lake and Krons Bay).

METHODS-LEAD-210 DATING

Sediments in the three primary cores were analyzed for lead-210 activity to determine age and sediment accumulation rates for the past 150-200 years. In the Sauk Lake North, Sauk Lake South, and Horseshoe Lake cores, lead-210 was measured at numerous depth intervals 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 the secondary cores from the Horseshoe Chain (Krons Bay, Bolfing Lake, and Cedar Island Lake), select downcore samples were analyzed using gamma lead-210 dating to identify sediments that pre-date European settlement. Two to four downcore samples from each core were selected for measurement of unsupported ^{210}Pb using a high-resolution germanium well gamma detector and multichannel analyzer. The presence of any unsupported ^{210}Pb in a core subsample would be an indication that the sample is dated at less than seven half-lives of ^{210}Pb, approximately 150 years, or from a time period of very high sedimentation that would mask an unsupported ^{210}Pb signal. From this analysis we determined whether downcore sediment levels were deposited before European settlement. As a further check of core dates, 137Cs was also quantified in the core samples. Cesium-137 is an isotopic product of atmospheric nuclear bomb testing and its presence indicates sediments deposited after 1950.

METHODS-BIOGEOCHEMISTRY

Weighed subsamples were taken from regular intervals throughout the cores (both the piston and Livingston cores) for loss-on-ignition (LOI) analysis to determine dry density and weight percent organic, carbonate, and inorganic matter. Sediment subsamples were heated at 105ºC for 24 hr 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.

METHODS-DIATOM AND NUMERICAL ANALYSES

Eleven samples were analyzed for diatoms in each of the Sauk Lake cores, and sixteen samples were analyzed in the Horseshoe Lake core. Cedar Island Lake and Bolfing Lake were analyzed for diatoms using a “top-bottom” approach; two samples from the core top were analyzed to represent modern conditions, and two samples were analyzed that represented pre-European settlement. See Table 2 for a list of samples prepared for diatom analysis.

Diatoms 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, which contains the diatoms, were dried onto 22x22 mm #1 coverglasses, which were then permanently attached to microscope slides using Zrax mounting medium. Diatoms were identified along random transects to the lowest taxonomic level under 1250X magnification (full immersion optics of NA 1.4). A minimum of 400 valves was counted in each sample. Abundances are reported as percentage abundance relative to total diatom counts. Identification of diatoms used regional floras (e.g. Patrick and Reimer 1966, 1975, Edlund 1994, Camburn and Charles 2000) and primary literature to achieve consistent taxonomy.

Stratigraphies of predominant diatoms (species greater than or equal to 5% relative abundance) were plotted against core date. Relationships among diatom communities within a sediment core were explored using Correspondence Analysis (CA), which is available in the the software package R (Ihaka & Gentleman 1996). 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 interpretting a CA is that samples that plot closer to one another have more similar assemblages.

Downcore diatom communties were also used to reconstruct historical epilimnetic phosphorus levels in each lake. A transfer function for reconstructing historical logTP was earlier developed based on the relationship between modern diatom communities and modern environmental variable 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 is 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 backtransformed values, to TP in µg/l.

RESULTS & DISCUSSION-CORING, MAGNETIC SUSCEPTIBILITY AND CORE IMAGING

Sauk Lake North: A 184 cm long piston core was recovered from Sauk Lake North and 50 cm were extruded from the top of the core in the field (Table 1). There is a distinct color change in the core at 100 cm with darker sediments above and lighter sediments below. A decrease in magnetic susceptibility begins at about 70 cm (Appendix 1a). Decreases in magnetic susceptibility can result from increased autochthonous productivity, for example from lake eutrophication.

Sauk Lake South: A 195 cm long piston core was recovered from Sauk Lake South, with 46 cm extruded off the top of the core in the field (Table 1). As in Sauk Lake North there is a distinct color change in this core, with lighter sediments in the bottom of the core and darker sediments above; in the Sauk Lake South core this color change occurs at 77 cm (Appendix 1b). There is a small decrease in magnetic susceptibility at about 50 cm, which could be the result of increased autochthonous productivity; the decrease in magnetics in this core is less pronounced than in the Sauk Lake North core.

Horseshoe Lake: A 1.9 m long piston core and a 0.94 m overlapping Livingston core were collected from Horseshoe Lake in August of 2006 (Table 1). Initial lead-210 dating analyses indicated that these cores may not have been deep enough to recover sediment from pre-European settlement times. Therefore, in March of 2008, a series of four overlapping Livingston cores were recovered from the lake representing a maximum sediment depth of 3.98 m. There is a decrease in magnetic susceptibility at approximately 63 cm which may be the result of increased autochthonous productivity, for example from lake eutrophication (Appendix 1c). There are fluctuations in magnetic susceptibility farther downcore, including a rise at approximately 225 cm (Figure 2); however, given the complex nature of the magnetic signature of this core, there is no clear increase that can be confidently attributed to European settlement and initial land clearance.

Krons Bay: A 1.89 m long piston core and a 0.97 m overlapping Livingston core were collected from Krons Bay in August of 2006 (Table 1). Initial dating analyses indicated that these cores may not be deep enough to represent pre-European settlement times. Therefore, in March of 2008, a series of four overlapping Livingston cores were recovered from the lake representing a maximum sediment depth of 4.07 m. There is a rise in magnetics in the Livingston core, beginning at approximately 220 cm (Figure 1). Increases in magnetic susceptibility may be correlated with land use changes including land clearance, increases in terrestrial-derived sediments, and paleosols; therefore, this rise in magnetics may represent European settlement and initial land clearance.

Bolfing Lake: A 1.87 m long piston core and a 0.99 m overlapping Livingston core were collected from Bolfing Lake (Table 1). There is a spike in magnetic susceptibility in the piston core at approximately 97 cm (Appendix 1e). There is a gradual rise in magnetics in the Livingston core, beginning at approximately 215 cm which may represent European settlement (Figure 1).

Cedar Island Lake: A 1.88 m long piston core and a 1.00 m overlapping Livingston core were collected from Cedar Island Lake (Table 1). There is a rise in magnetic susceptibility at the bottom of the piston core (Appendix 1f) and the top of the Livingston core (Figure 1), which begins at approximately 190 cm. An increase in magnetic susceptibility is often seen at the time of European settlement, when initial land clearance increased the amount of terrestrial-derived sediments to the lake. There is a subtle and gradual color change in the piston core, beginning at about 80 cm, with lighter sediments above and darker sediments below (Appendix 1f). There is a gradual decrease in magnetic susceptibility, beginning at approximately 110 cm, which may be the result of increased autochthonous productivity, for example from lake eutrophication (Appendix 1f).

RESULTS & DISCUSSION-BIOGEOCHEMISTRY

Sauk Lake North: There is a sharp rise in the relative amount of inorganic material in the core at 100 cm (which corresponds with the distinct color change seen in the core), from approximately 20% inorganic material to 60%. The amount of inorganics begin to decrease at about 40 cm, but only falls to about 40% at the top of the core (Figure 4). Based on the lead-210 dating model, this sharp rise in inorganics occurred at approximately 1860, so this shift corresponds with initial settlement, land clearance, the onset of agriculture, and also with damming of the system.

Sauk Lake South: As with the Sauk Lake North core, there is a sharp rise in the amount of inorganic material in the core (in this core, changing from about 20% to about 45%), with a slight decrease at the core top (falling back to about 35%). In this core the sharp rise occurs at about 80 cm (again corresponding to the distinct color change seen in the core) and begins to decline at approximately 30 cm (Figure 4). Based on the lead-210 dating model, the sharp rise in inorganics in the Sauk Lake South core occurred at approximately 1850; as in the Sauk Lake North core, this shift corresponds with initial settlement, land clearance, the onset of agriculture, and also with damming of the system.

Horseshoe Lake: The loss-on-ignition results from the Horseshoe Lake core show that the sediments are primarily composed of inorganic material (Figure 4). From about 75 cm depth to the top of the core there is a steady decrease in the relative amount of inorganic material, with a corresponding increase in $CaCO_3$; however, even at the core top, the sediments have a large percentage of inorganic material (approximately 60%), as might be expected given the proximity of the coring site to the mouth of the Sauk River where it enters the Horseshoe chain of lakes.

RESULTS & DISCUSSION-DATING AND SEDIMENTATION

Sauk Lake North: The unsupported lead-210 activity, the resulting lead-210 dating model, and the sediment accumulation rate for Sauk Lake North are shown in Figure 3a. Lead-210 activity reached supported levels just below 100 cm core depth. The sedimentation rate in Sauk Lake North showed a large rise in the late 1800s/early 1900s (coincident with European settlement and damming) that continued until the 1960s/70s. In the 1980s the sedimentation rate decreased, and has remained fairly constant in recent decades; however the modern sedimentation rate is still higher than the pre-disturbance rate.

Sauk Lake South: The unsupported lead-210 activity, the resulting lead-210 dating model, and the sediment accumulation rate for Sauk Lake South are shown in Figure 3b. Lead-210 activity reached supported levels just above 80 cm core depth. The sedimentation rate in Sauk Lake South showed a large rise in the late 1800s/early 1900s (coincident with European settlement and damming). The sedimentation rate in this lake leveled off around the 1930s, and has only showed minor fluctuations since that time. In Sauk Lake, both the North and South basins had similar pre-settlement sedimentation rates (approximately $0.05 g/cm^2/yr$ or less), and have similar sedimentation rates in modern times (approximately $0.15 g/cm^2/yr$). However, from roughly the 1950s to the 1980s, the North basin had a peak in sedimentation rate (peaking over $0.3 g/cm^2/yr$) that was not seen in the South basin, suggesting that the North basin may be acting as a trap for sediment coming in from the Sauk River.

Horseshoe Lake: The unsupported lead-210 activity, the resulting lead-210 dating model, and the sediment accumulation rate for Horseshoe Lake are shown in Figure 3c. Lead-210 activity reached supported levels below 200 cm core depth. The sedimentation rate of Horseshoe Lake increases after the late 1800s, and is very erratic; riverine systems such as Horseshoe Lake with high and erratic sedimentation rates are very difficult to date, and push the limits of lead-210 dating. Therefore, errors on lead-210 dates are very large near the bottom of the core. The sedimentation rate at the bottom of the core was used to extrapolate dates for the bottom core sections used for diatom analysis (1801, 1692, and 1626). Given the large errors in dating at the bottom of this core these dates are only an approximation and should be interpreted as “pre-European settlement” instead of specific dates.

Krons Bay, Bolfing Lake and Cedar Island Lake: Intervals were chosen for gamma lead-210 analysis based on changes in magnetic susceptibility which may be representative of European settlement and initial land clearance. In the Krons Bay core, sediments at 151 cm and 230 cm did have excess amounts of lead-210, indicating that they were less than 150 years old. However, dating of sediments from Krons Bay proved to be difficult, with poor success using gamma lead-210 on this core. In the Bolfing Lake core, excess lead-210 was found at 145 cm, but not at 220 cm or 260 cm. In the Cedar Island core, no excess lead-210 was found in sediments at 151 cm or 205 cm. These results indicate that sediments at 220 cm and below in Bolfing Lake, and 151 cm and below in Cedar Island Lake, are older than 150 years.

Due to the difficulty in dating the core from Krons Bay, Bolfing Lake and Cedar Island Lake were chosen as the two cores to be used for the top/bottom diatom analysis. The intervals representing 2 cm and 12 cm were analyzed as the modern (core top) samples for each of these cores. In Bolfing Lake, 220 cm and 225 cm represented the pre-European settlement (core bottom) samples; 151 cm and 156 cm were used as the pre-European settlement samples in Cedar Island Lake (Table 2).

RESULTS & DISCUSSION-DIATOM STRATIGRAPHY AND ORDINATIONS

Sauk Lake North: This core has been primarily dominated by *Aulacoseira amigua* and *Aulacoseira granulata*, with *A. ambigua* becoming much less abundant after 1942 (Figure 5). *Stephanodiscus hantzschii* and *Stephanodiscus minutulus* have become more abundant in recent decades. *Cyclostephanos tholiformis* increased in abundance in the late 1800s and early 1900s. Other species that were present in large numbers throughout the sections analyzed were *Stephanodiscus medius, Stephanodiscus niagarae, Fragilaria capucina* v. *mesolepta,* and *Asterionella formosa*. Overall, the species that make up the diatom community throughout the Sauk Lake North core are indicative of eutrophic conditions although some can also be found in mesotrophic systems (e.g. *Aulacoseira ambigua, Stephanodiscus niagarae*).

A principal components analysis (PCA) of the Sauk Lake North core shows that samples from 1780-1942 cluster together (Figure 6), indicating that these samples are most similar to each other in their diatom species assemblage. The 1960 sample plots by itself; this sample is characterized by a marked increase in *A. granulata*. The three most recent samples (1979-2003) form another cluster; these samples are characterized by the decline in *A. ambigua* and the increase in *Stephanodiscus hantzschii* and *Stephanodiscus minutulus*.

Sauk Lake South: The diatom stratigraphy in the Sauk Lake South core can be divided into two zones. From 1781 to 1916 the core was dominated by small *Fragilaria* species; this benthic assemblage suggests that as this time Sauk Lake South was a shallow lake or wetland system. From 1935 to 2000 the core is dominated by small *Stephanodiscus* species, *Aulacoseira ambigua, Aulacoseira granulata, Synedra rumpens* v. *familiaris,* and *Asterionella formosa* (Figure 7), which are indicative of eutrophic conditions.

A correspondence analysis (CA) of the Sauk Lake South core confirms these two clusters, and shows that the 1935 sample is a transitional assemblage between these two groups (Figure 8). In addition, the CA illustrates that the 2000 sample is showing additional changes, suggesting that there may be new stressors affecting this system.

Horseshoe Lake: The diatom stratigraphy of the Horseshoe Lake core shows that the core is dominated by *Aulacoseira, Stephanodiscus, Cyclostephanos, Cyclotella,* and *Fragilaria* species, which are indicators of eutrophic conditions (Figure 9). The most notable change in this core is that the three lowest samples (1801 and earlier) show notable amounts of benthic species (*Amphora*, *Navicula,* and *Cocconeis* species), which then drop out of the diatom assemblage upcore; these benthic species are indicative of less turbid, or shallower, water conditions.

A CA of the Horseshoe Lake core shows that the samples from 1896 to 2002 cluster together based on their diatom species assemblage (Figure 10). The three lowest samples, which have notable amounts of benthic species, are removed from this cluster. In addition, the 2006 sample shows a change in the diatom community assemblage; this sample is dominated by the species *Cyclotella pseudostelligera*.

Bolfing Lake: The diatom stratigraphy of Bolfing Lake shows distinct differences in community assemblage between the core top and core bottom samples (Figure 11). The top sections of the core are primarily dominated by *Aulacoseira granulata*, as well as *Aulacoseira ambigua, Stephanodiscus hantzschii,* and *Stephanodiscus medius.* The bottom of the core is dominated by *Cyclotella pseudostelligera*, as well as *Cyclotella michiganiana, Cyclotella stelligera, Fragilaria crotonensis,* and *Asterionella formosa*; this assemblage is characteristic of a mesotropic system.

Cedar Island Lake: The diatom stratigraphy of Cedar Island Lake also shows distinct changes between the core top and bottom sample (Figure 12). As in Bolfing Lake, the core top is primarily dominated by *Aulacoseira granulata*, as well as *Stephanodiscus hantzschii, Stephanodiscus medius,* and *Cyclostephanos invisitatus.* The bottom of the core is dominated by *Aulacoseira ambigua, Cyclotella bodanica* var. *lemanica, Cyclotella michiganiana, Fragilaria crotonensis,* and *Asterionella formosa*; this assemblage is characteristic of a mesotrophic system.

All Cores: Plotting the diatom communities from all of the sediment cores together in a CA illustrates how this entire river system has changed over time (Figure 13). With the exception of the top sample (2006) from Horseshoe Lake, all of the modern samples from all cores cluster together on the CA, indicating that in modern times the diatom species assemblage in all 5 of these lakes is very similar. However, three of these lakes (Cedar Island, Bolfing, and the South basin of Sauk Lake) all had distinctly different diatom communities in the past. Both Cedar Island and Bolfing had distinct diatom species assemblages prior to European settlement, but now support diatom communities very similar to the rest of the lakes in the chain, suggesting that damming of the system had a large impact on these lakes. Sauk Lake South was also a unique basin, in terms of its diatom community, until approximately 1935, when it began to move in the direction of Sauk Lake North and Horseshoe Lake. This suggests that prior to 1935, the South basin of Sauk Lake may have had less communication with the river than it does today. The fact that the most recent sample from Horseshoe Lake (2006) is plotting away from the cluster suggests that there may be some changes currently going on in that lake, or that the year or two preceding coring were notably different in temperature or precipitation.

RESULTS & DISCUSSION-PHOSPHORUS RECONSTRUCTION

Sauk Lake North and South: Total phosphorus (TP) reconstructions of the North and South basins of Sauk Lake indicate that these two basins have differed historically (Figure 14). The TP reconstruction of Sauk Lake North shows that this basin has been enriched with TP throughout the time period analyzed, fluctuating between 76 and 105 µg/l TP since the late 1700s. The South basin of Sauk Lake has a different history; TP levels in this lake indicate that the system was mesotrophic prior to European settlement (approximately 20 µg/l TP), with a large increase in TP levels beginning in the early 1900s.

Horseshoe Lake: The TP reconstruction of Horseshoe Lake shows that this lake has been very productive in the modern era, with TP levels fluctuating between 62 and 93 µg/l (Figure 15). The top sample from this core may indicate that conditions in the lake are changing; this sample was dominated by the diatom *Cyclotella pseudostelligera*, and had reconstructed TP value of 45 µg/l. The bottom of the core shows that the lake did have lower TP concentrations in the past but was still a fairly productive system (TP levels near 50 µg/l).

Bolfing Lake and Cedar Island Lake: Both Bolfing Lake and Cedar Island Lake show dramatic changes in TP levels since the time of European settlement (Figure 16). TP reconstructions on both lakes show that these systems were mesotrophic prior to European settlement (TP between 18 and 30 µg/l), and are in the eutrophic to hypereutrophic range in the modern core sections (greater than 65 µg/l in Cedar Island and near 100 µg/l in Bolfing).

CONCLUSIONS

Sauk Lake North and Sauk Lake South have high modern sedimentation rates; both basins showed an increase in the relative amount of inorganic material and a rise in sedimentation rate corresponding with the time of European settlement, initial land clearance, and damming. However, the diatom community and the corresponding TP reconstruction, indicates that the North basin has been a highly productive system since the late 1700s. This basin has not shown major changes in diatom community composition or TP levels during the period of time analyzed. In contrast, the South basin was affected in the mid-1900s; before this time it had been a mesotrophic system, but is now in the eutrophic range with a diatom community similar to that of the North basin. The analysis of diatom communities from all of the cores suggests that prior to 1935, the South basin of Sauk Lake may not have been in close communication with the river, but may have existed as an isolated basin; the diatom community assemblage from this time indicates that the South basin was a shallow or wetland system. From 1781-1916 the South basin was a mesotrophic system that supported a unique diatom community assemblage, but in modern times it has become eutrophic with a diatom community assemblage that is very similar to the North basin of Sauk Lake and Horseshoe Lake.

Horseshoe Lake was found to have a very high and erratic sedimentation rate, which pushes the limits of lead-210 dating and results in large errors in downcore dates. The diatom stratigraphy and TP reconstruction show that this lake has shown some changes since European settlement and damming. The abundance of benthic diatoms at the bottom of the core indicates that the lake was less turbid prior to European settlement; however, the system was still fairly productive at this time, with TP levels near 50µg/l. The TP reconstruction shows that Horseshoe Lake has been highly productive since the early to mid-1900s, coinciding with the large-scale industrialization of agriculture.

Both Bolfing Lake and Cedar Island Lake have been heavily impacted since European settlement. Both lakes showed clear shifts in their diatom community assemblage, and TP reconstructions indicated that both lakes have changed from mesotrophic to eutrophic or hypereutrophic systems. Analysis of the diatom communities from all of the cores together suggests that damming of the Horseshoe chain may have had large impacts on Bolfing and Cedar Island. Both of these systems had low TP levels and unique diatom communities prior to European settlement, but in modern times they are highly productive systems that support diatom communities that are very similar to the lakes that have always been in close communication with the Sauk River.

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Table 1. Lakes cored, length of core recovered, and results of field sectioning.

Lake/Bay Name	Coring Date	Coring Location	Type of Core	County	Water Depth (m)	Core length (m)	Field and lab sectioned (cm)
Sauk Lake - North	9/18/2006	45°48' 5.8" N 94°56' 19.8" W	Piston	Stearns and Todd, MN	14.32	1.84	0-50
Sauk Lake - South	9/18/2006	45°45' 30" N 94°56' 42.2" W	Piston	Stearns and Todd, MN	5.76	1.95	0-46
Horseshoe Lake	8/15/2006	45°25'52.5" N 94°31'46.3" W	Piston	Stearns, MN	14.05	1.87	0-44
Horseshoe Lake	8/15/2006	45°25'52.5" N 94°31'46.3" W	Livingston	Stearns, MN	14.05	0.94	--
Krons Bay	8/15/2006	45°25'10.3" N 94°31'22.9" W	Piston	Stearns, MN	10.48	1.89	0-50
Krons Bay	8/15/2006	45°25'10.3" N 94°31'22.9" W	Livingston	Stearns, MN	10.48	0.97	--
Bolfing Lake	8/15/2006	45°25'45.4" N 94°27'45.9" W	Piston	Stearns, MN	10.27	1.87	0-52*
Bolfing Lake	8/15/2006	45°25'45.4" N 94°27'45.9" W	Livingston	Stearns, MN	10.27	0.99	--
Cedar Island Lake	8/15/2006	45°25'21.5" N 94°30'2.6" W	Piston	Stearns, MN	9.48	1.88	0-56*
Cedar Island Lake	8/15/2006	45°25'21.5" N 94°30'2.6" W	Livingston	Stearns, MN	9.48	1.00	--
Horseshoe Lake	3/6/2008	45°25'53.0" N 94°31'46.4" W	Livingston	Stearns, MN	15.09	0.93	--
Horseshoe Lake	3/6/2008	45°25'53.0" N 94°31'46.4" W	Livingston	Stearns, MN	15.09	1.02	--
Horseshoe Lake	3/6/2008	45°25'53.0" N 94°31'46.4" W	Livingston	Stearns, MN	15.09	0.99	--
Horseshoe Lake	3/6/2008	45°25'53.0" N 94°31'46.4" W	Livingston	Stearns, MN	15.09	0.97	--
Krons Bay	3/6/2008	45°25'10.5" N 94°31'22.3" W	Livingston	Stearns, MN	10.38	1.03	--
Krons Bay	3/6/2008	45°25'10.5" N 94°31'22.3" W	Livingston	Stearns, MN	10.38	1.04	--
Krons Bay	3/6/2008	45°25'10.5" N 94°31'22.3" W	Livingston	Stearns, MN	10.38	1.05	--
Krons Bay	3/6/2008	45°25'10.5" N 94°31'22.3" W	Livingston	Stearns, MN	10.38	1.05	--

*Sectioned in 2-cm increments down to 4 cm, then sectioned in 4-cm increments.

Table 2. Samples prepped for diatom analysis.

Core	Sample Depth (cm)	Lead-210 Date
Sauk Lake N	4-6	2003
Sauk Lake N	22-24	1988
Sauk Lake N	44-46	1979
Sauk Lake N	58-60	1960
Sauk Lake N	76-78	1942
Sauk Lake N	82-84	1931
Sauk Lake N	88-90	1916
Sauk Lake N	96-98	1890
Sauk Lake N	100-102	1865
Sauk Lake N	106-108	1839
Sauk Lake N	116-118	1780
Sauk Lake S	8-10	2000
Sauk Lake S	14-16	1993
Sauk Lake S	22-24	1982
Sauk Lake S	30-32	1971
Sauk Lake S	44-46	1950
Sauk Lake S	52-54	1935
Sauk Lake S	60-62	1916
Sauk Lake S	68-70	1885
Sauk Lake S	72-74	1860
Sauk Lake S	80-82	1818
Sauk Lake S	86-88	1781
Horseshoe Lake	0-2	2006
Horseshoe Lake	18-20	2002
Horseshoe Lake	34-36	1996
Horseshoe Lake	64-66	1985
Horseshoe Lake	78-80	1980
Horseshoe Lake	94-96	1974
Horseshoe Lake	108-110	1967
Horseshoe Lake	120-122	1961
Horseshoe Lake	140-142	1953
Horseshoe Lake	160-162	1944
Horseshoe Lake	176-178	1935
Horseshoe Lake	180-182	1931
Horseshoe Lake	199-201	1896
Horseshoe Lake	219-221	1801
Horseshoe Lake	239-241	1692
Horseshoe Lake	251-253	1626
Cedar Island Lake	0-2	Modern
Cedar Island Lake	10-12	Modern
Cedar Island Lake	149-151	Pre-European Settlement
Cedar Island Lake	154-156	Pre-European Settlement
Bolfing Lake	0-2	Modern
Bolfing Lake	10-12	Modern
Bolfing Lake	218-220	Pre-European Settlement
Bolfing Lake	223-225	Pre-European Settlement

Figure 1. Magnetic susceptibility profiles from the four Livingston cores collected in August 2006.

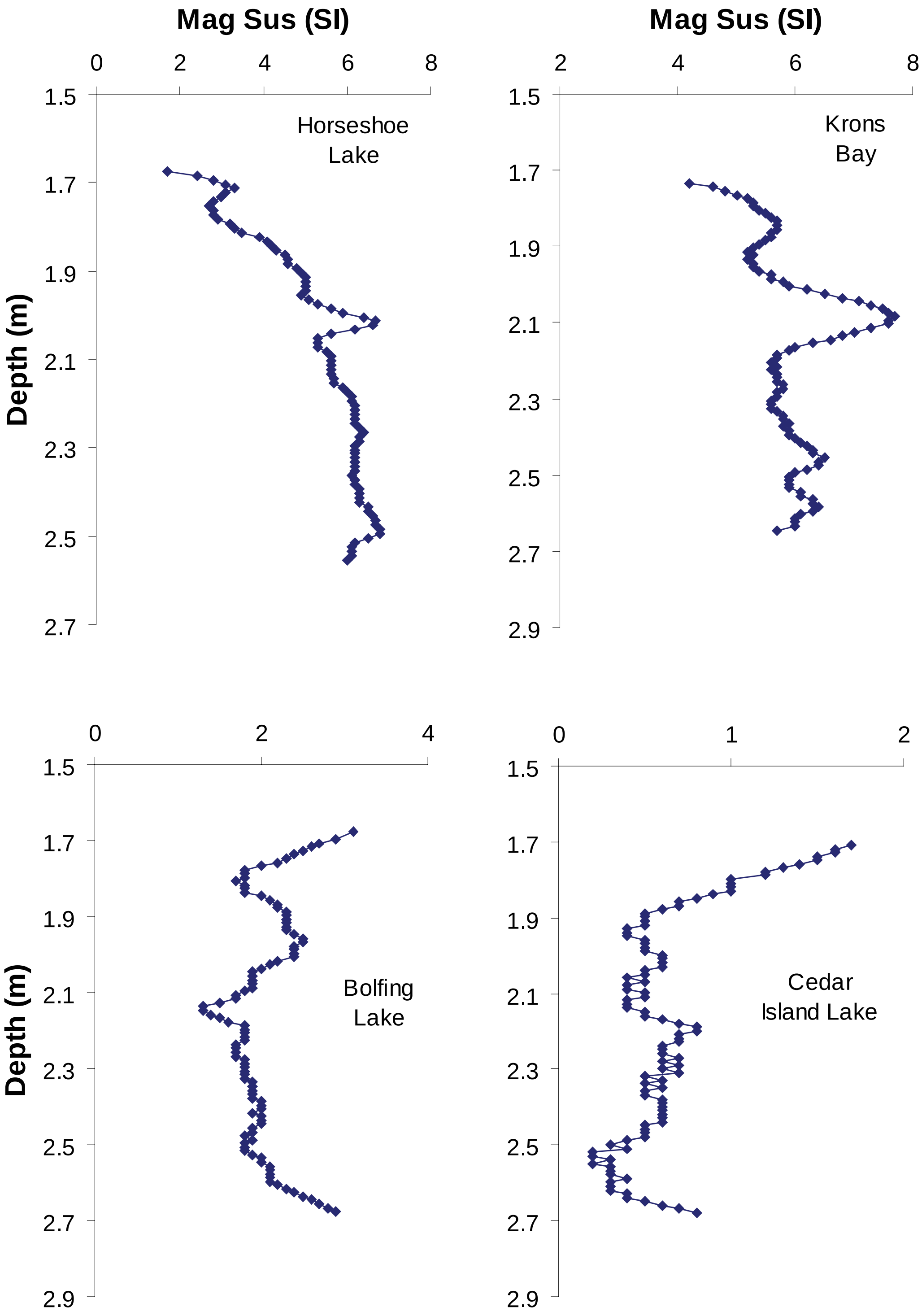

Figure 2. Magnetic susceptibility profiles of the overlapping Livingston cores taken from Horseshoe Lake and Krons Bay in March 2008.

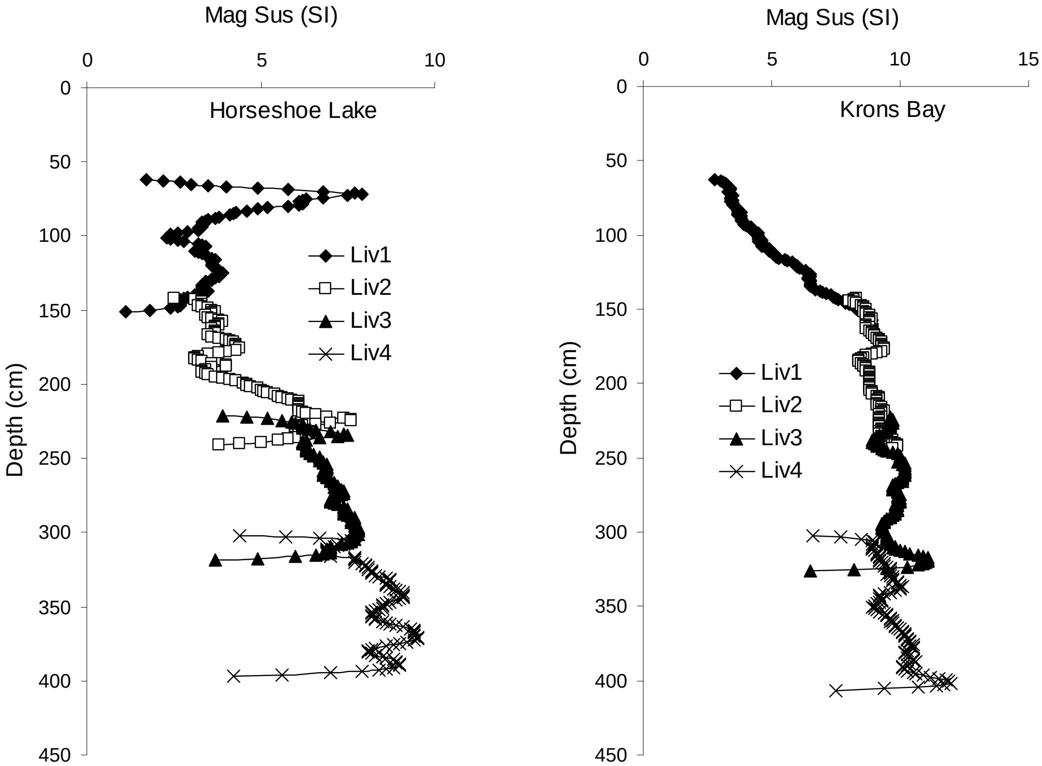

Figure 3a. Lead-210 dating model and sediment accumulation rate for the Sauk Lake North core.

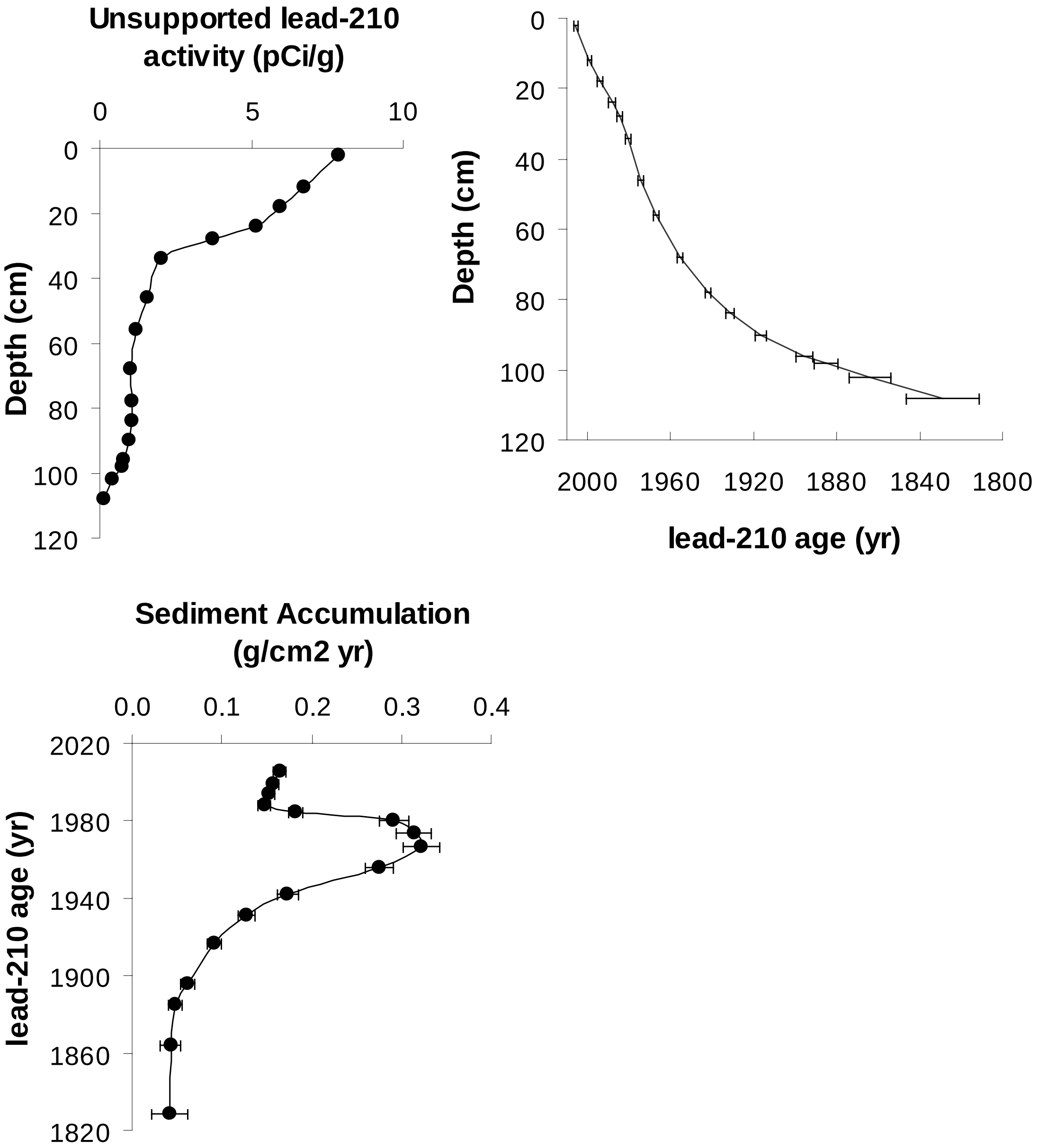

Figure 3b. Lead-210 dating model and sediment accumulation rate for the Sauk Lake South core.

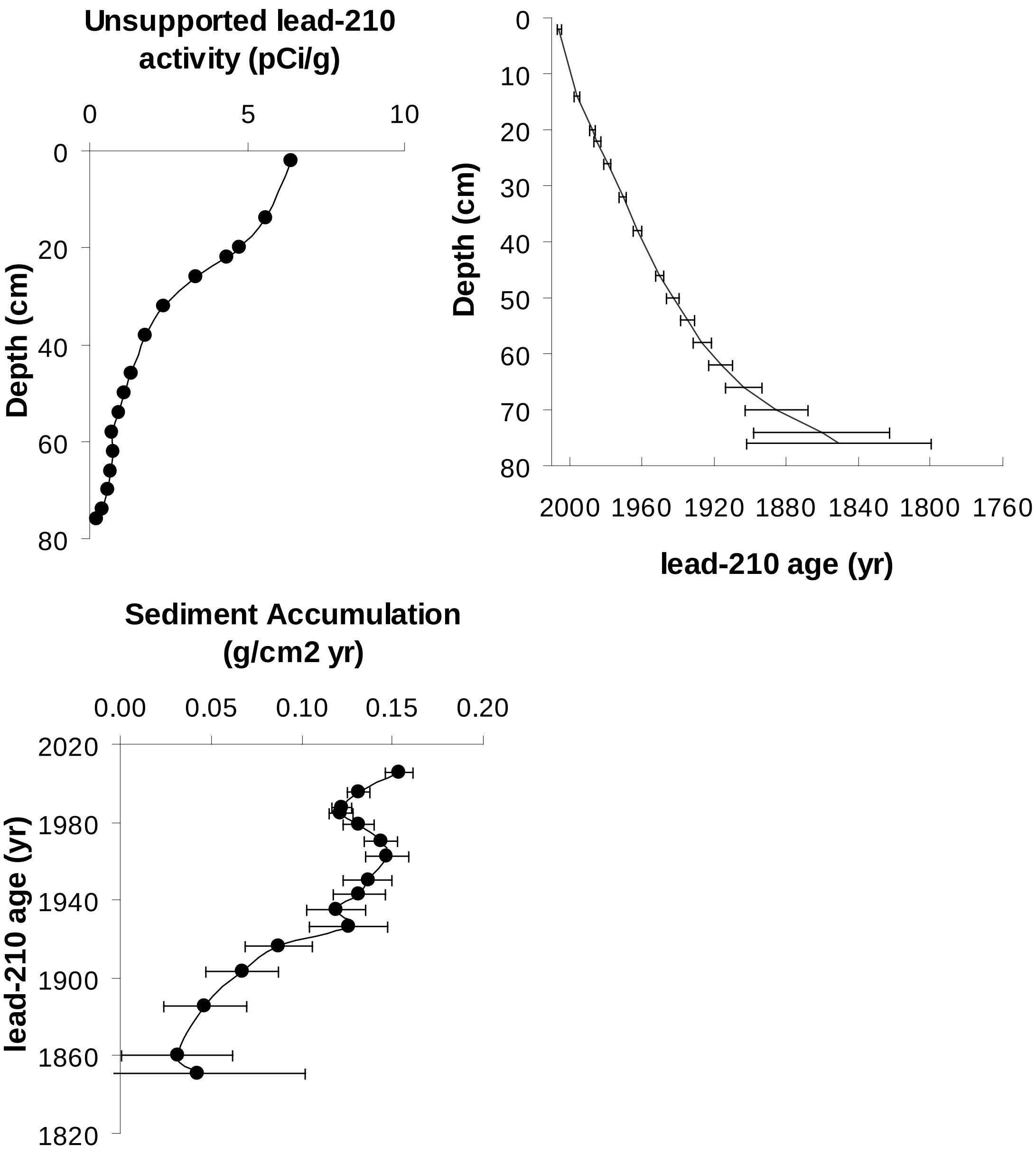

Figure 3c. Lead-210 dating model and sediment accumulation rate for the Horseshoe Lake core.

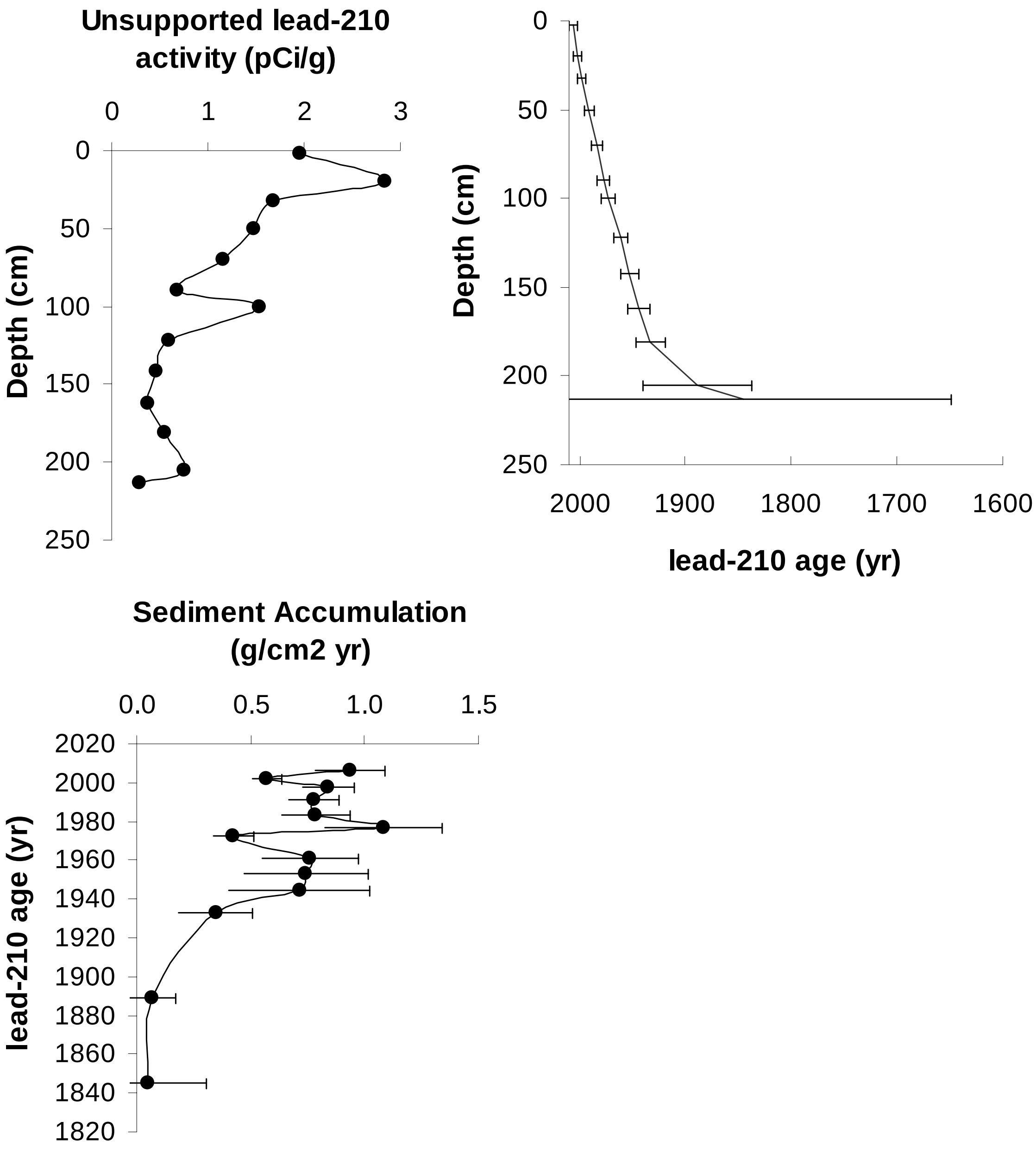

Figure 4. Percent concentration of organic, $CaCO_3$, and inorganic matter in the Sauk Lake North, Sauk Lake South, and Horseshoe Lake cores.

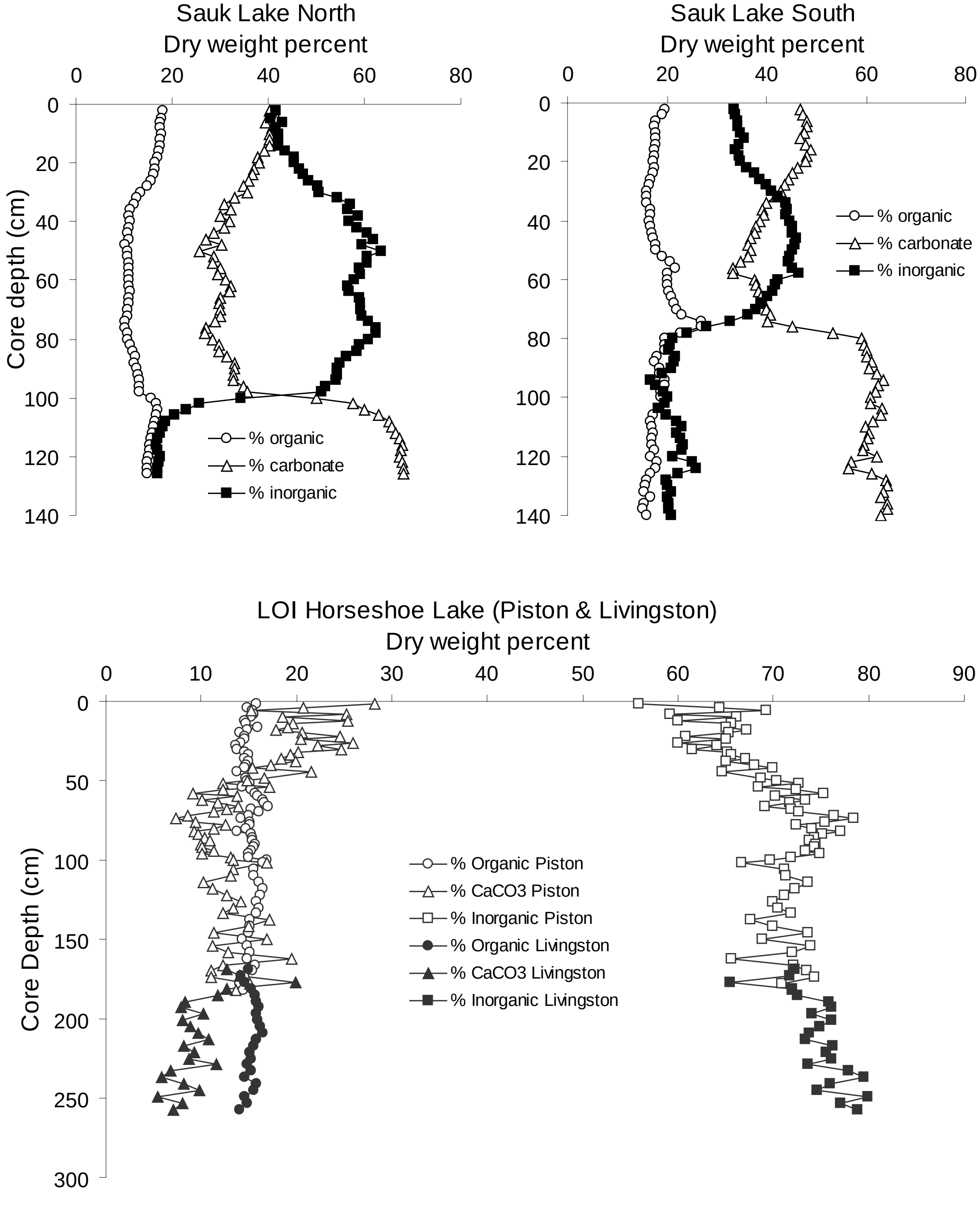

Figure 5. Downcore stratigraphies for predominant (greater than or equal to 5% relative abundance) diatom taxa in Sauk Lake North 1780-2003.

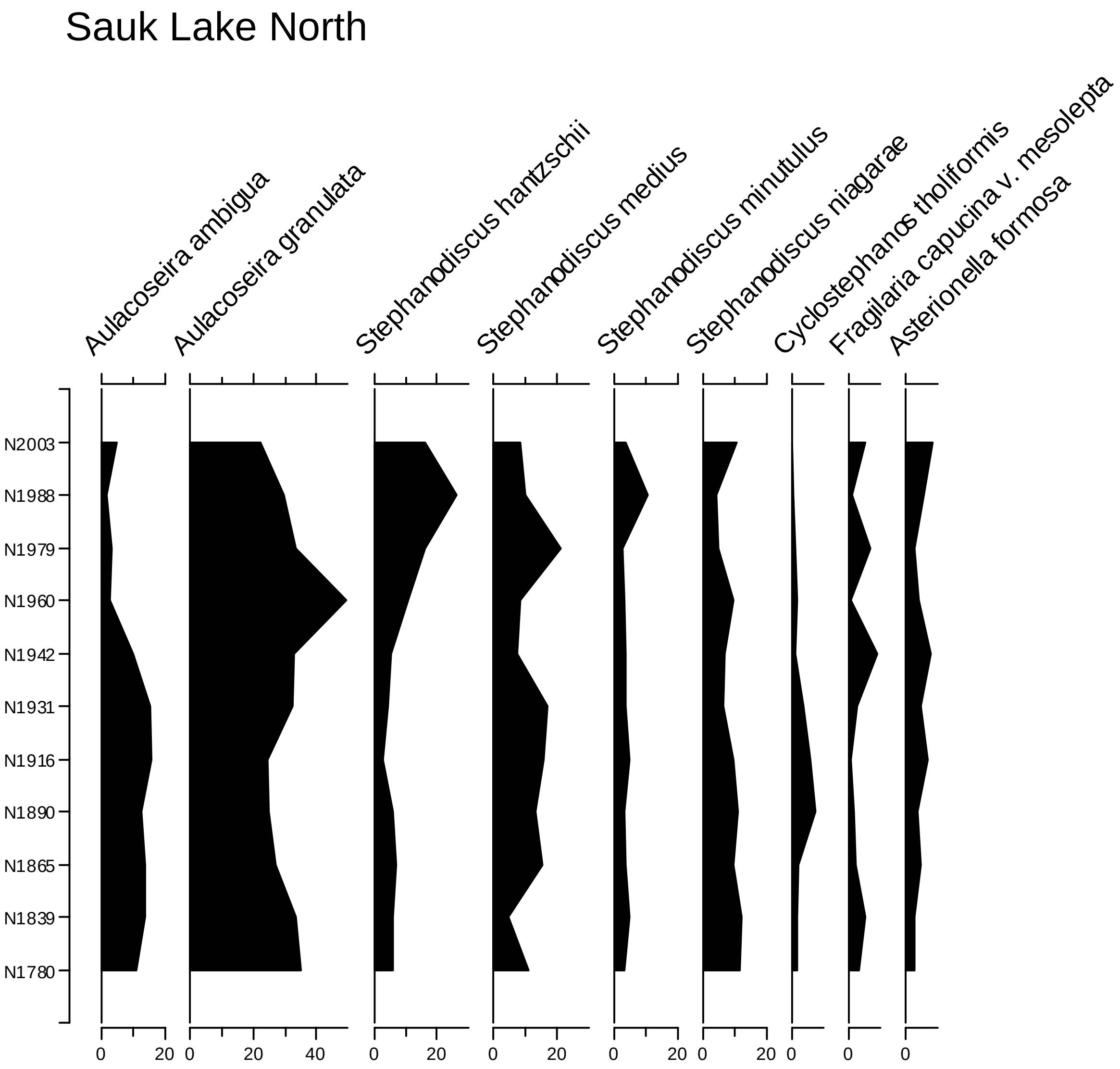

Figure 6. Principal components analysis (PCA) of the Sauk Lake North core. Arrow represents the trajectory through time.

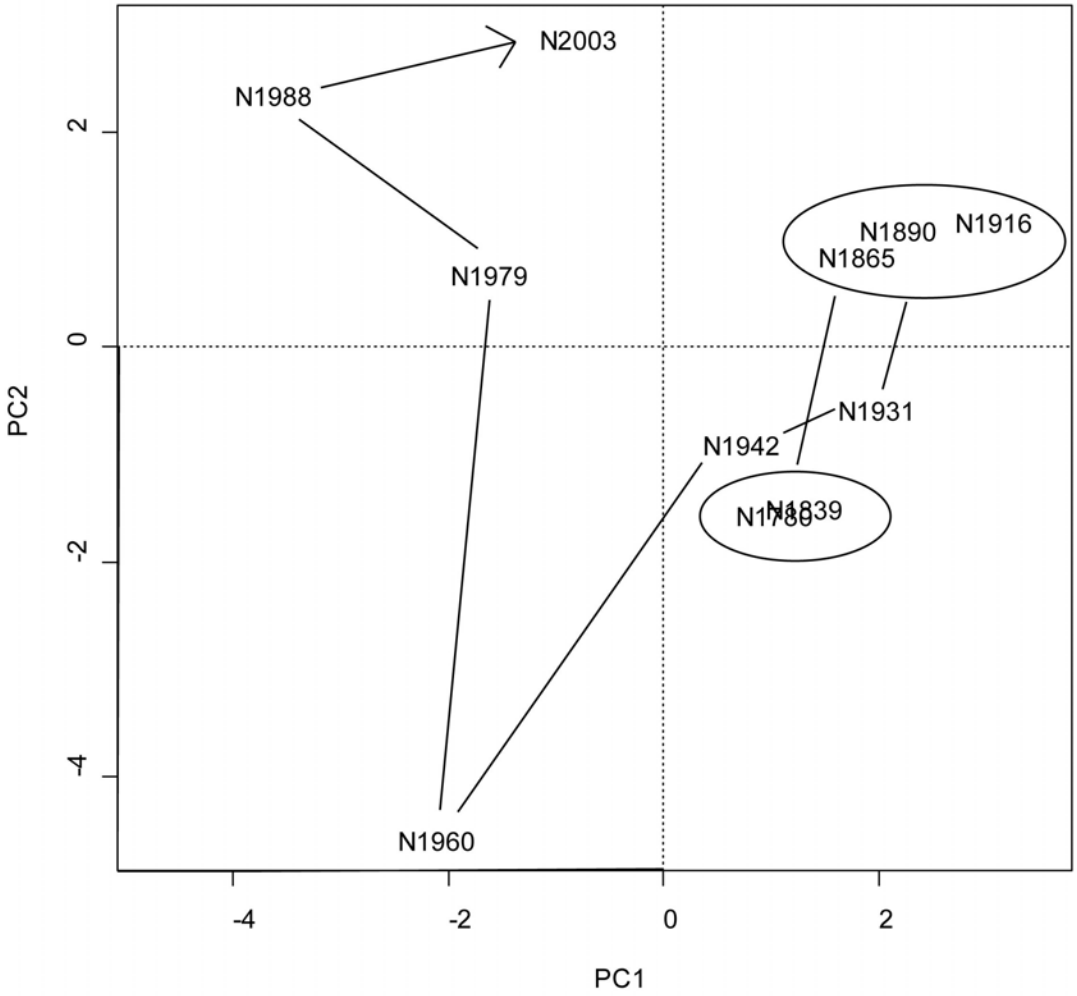

Figure 7. Downcore stratigraphies for predominant (greater than or equal to 5% relative abundance) diatom taxa in Sauk Lake South 1781-2000.

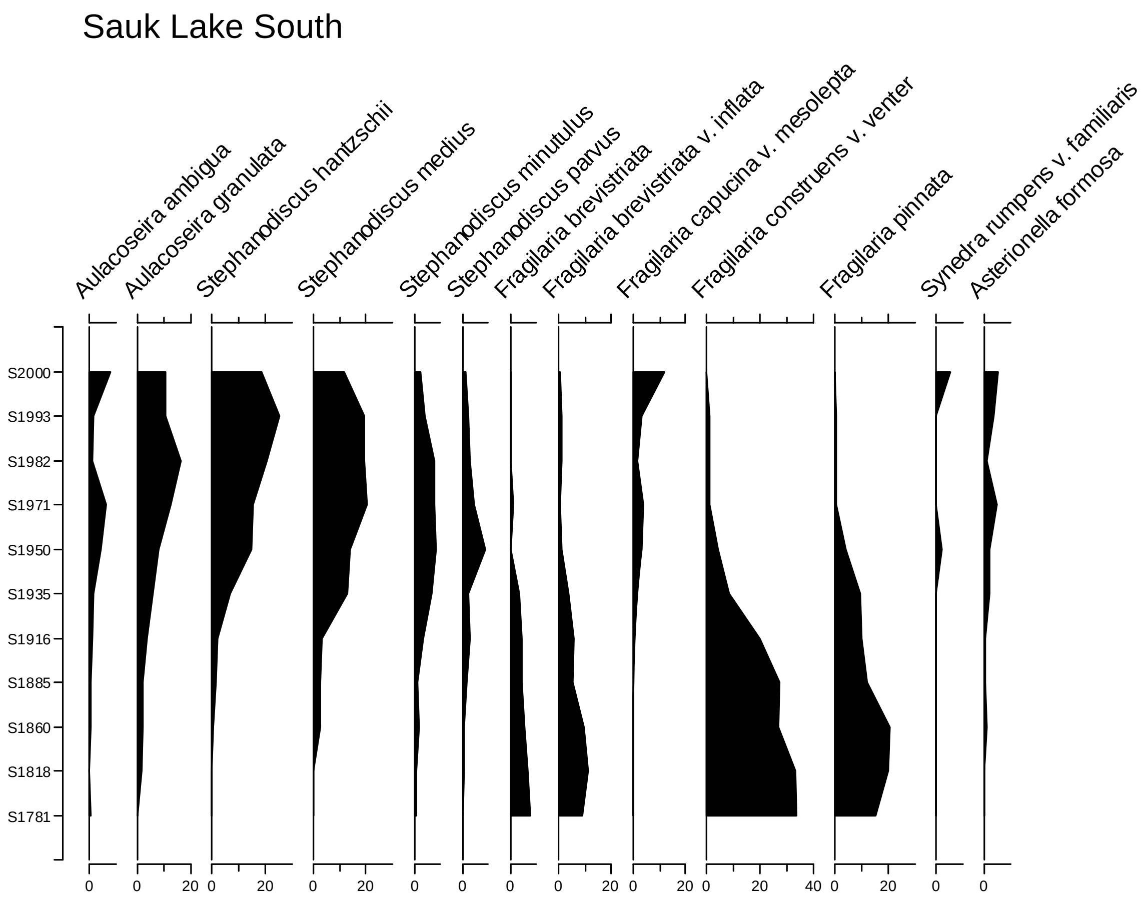

Figure 8. Correspondence analysis (CA) of the Sauk Lake South core. Arrow represents the trajectory through time.

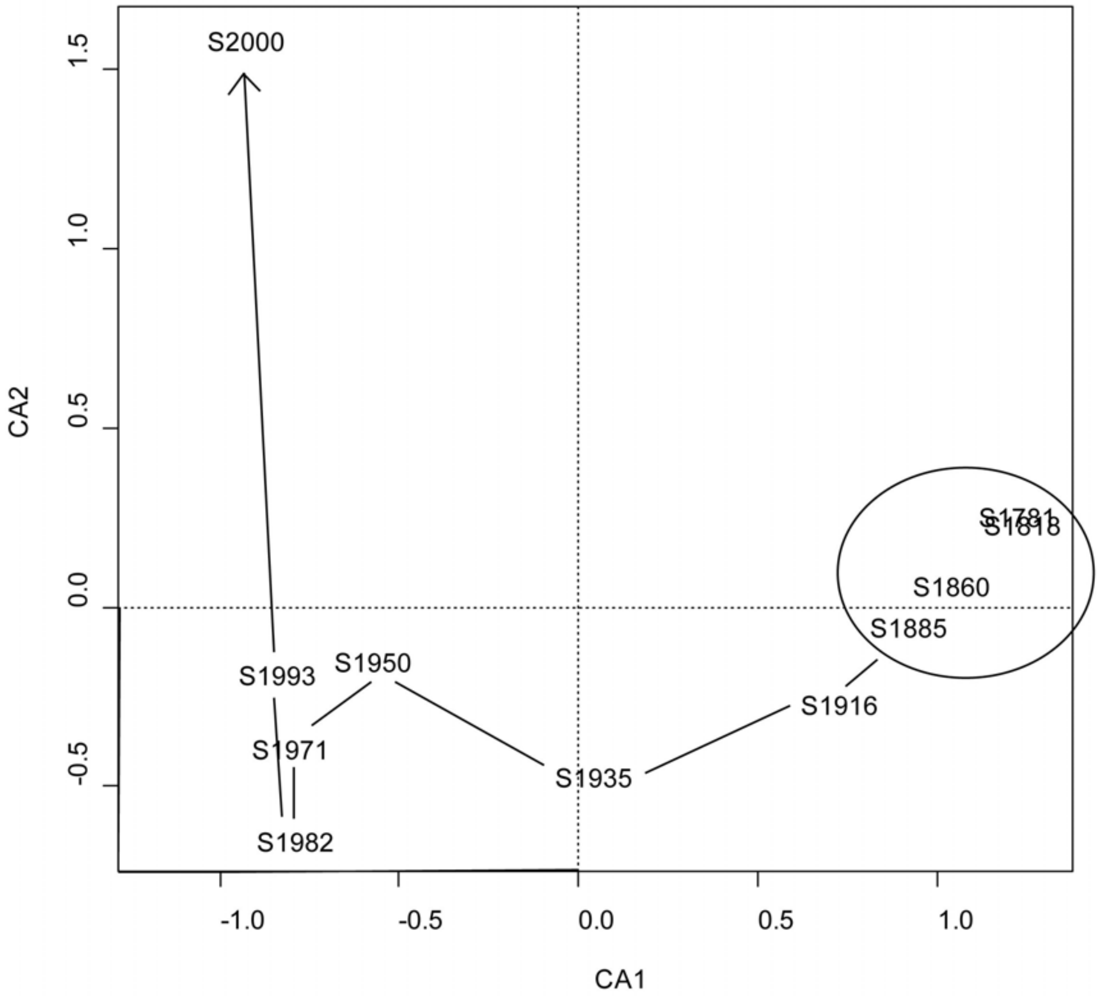

Figure 9. Downcore stratigraphies for predominant (greater than or equal to 5% relative abundance) diatom taxa in Horseshoe Lake 1626-2006.

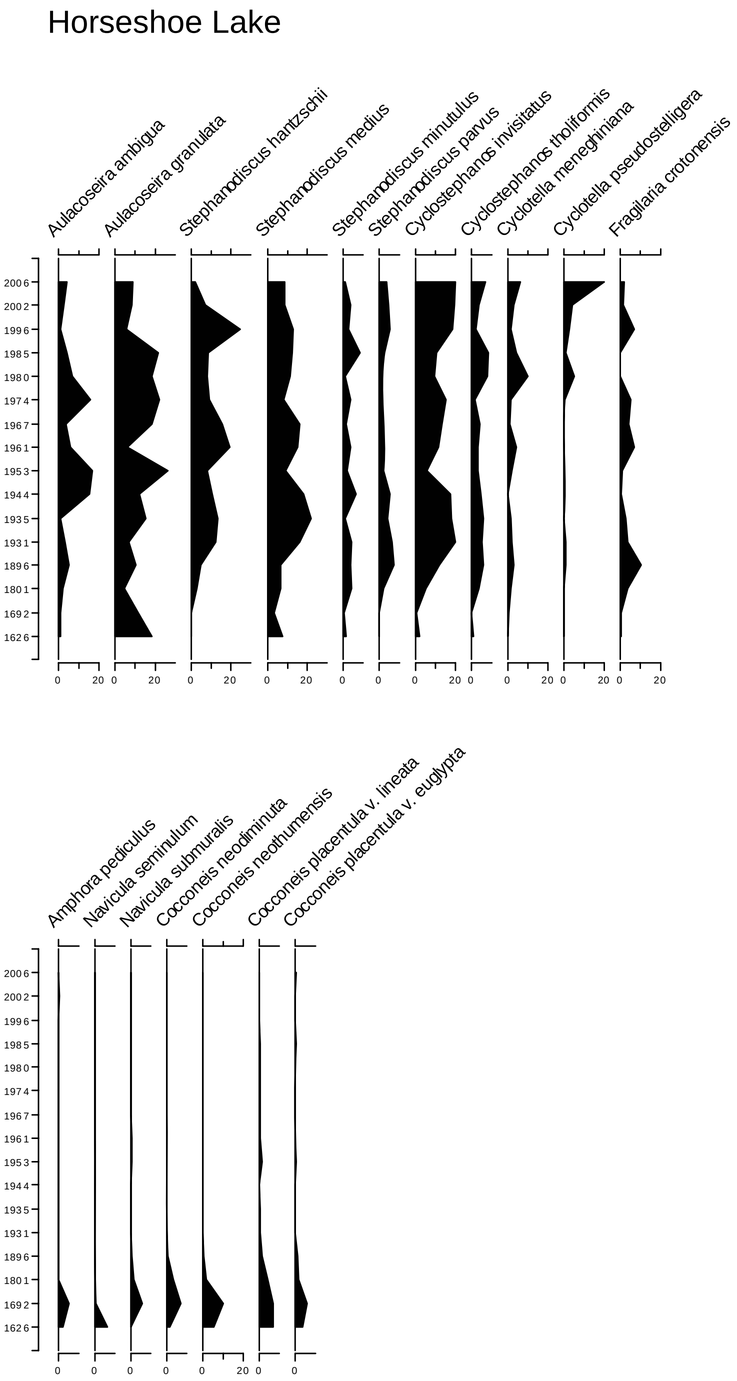

Figure 10. Correspondence analysis (CA) of the Horseshoe Lake core. Arrow represents the trajectory through time.

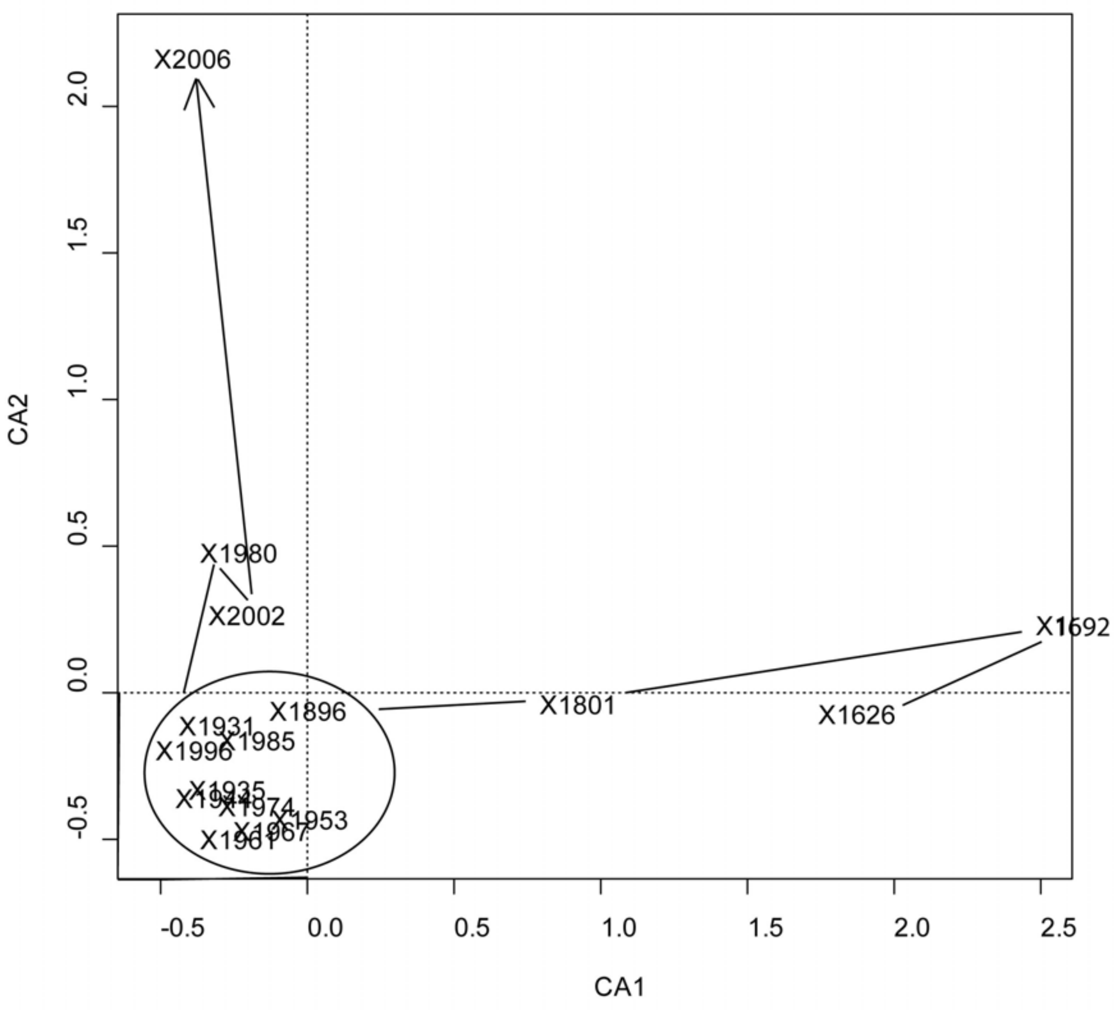

Figure 11. Downcore stratigraphies for predominant (greater than or equal to 5% relative abundance) diatom taxa in Bolfing Lake. The lower two samples represent pre-European settlement.

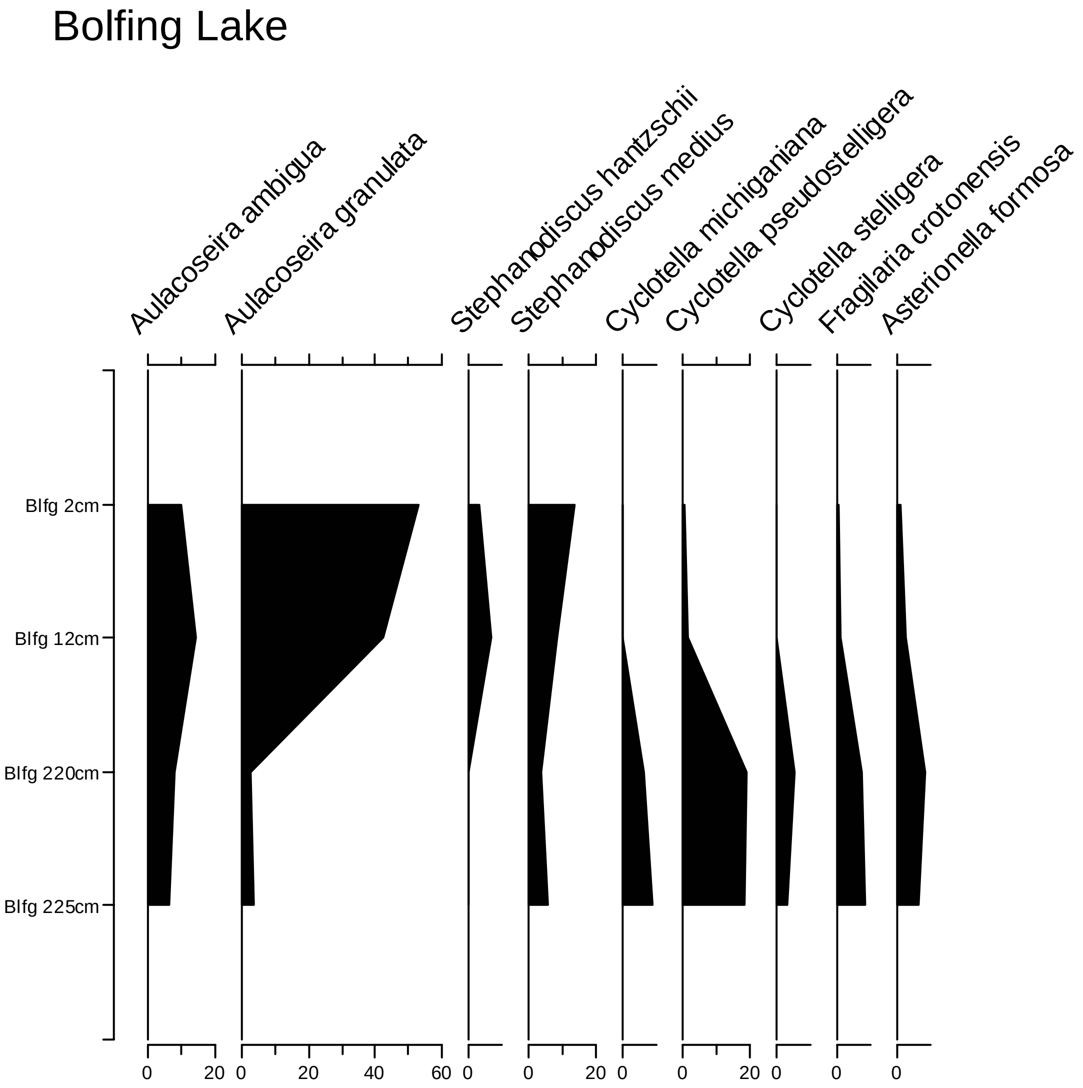

Figure 12. Downcore stratigraphies for predominant (greater than or equal to 5% relative abundance) diatom taxa in Cedar Island Lake. The lower two samples represent pre-European settlement.

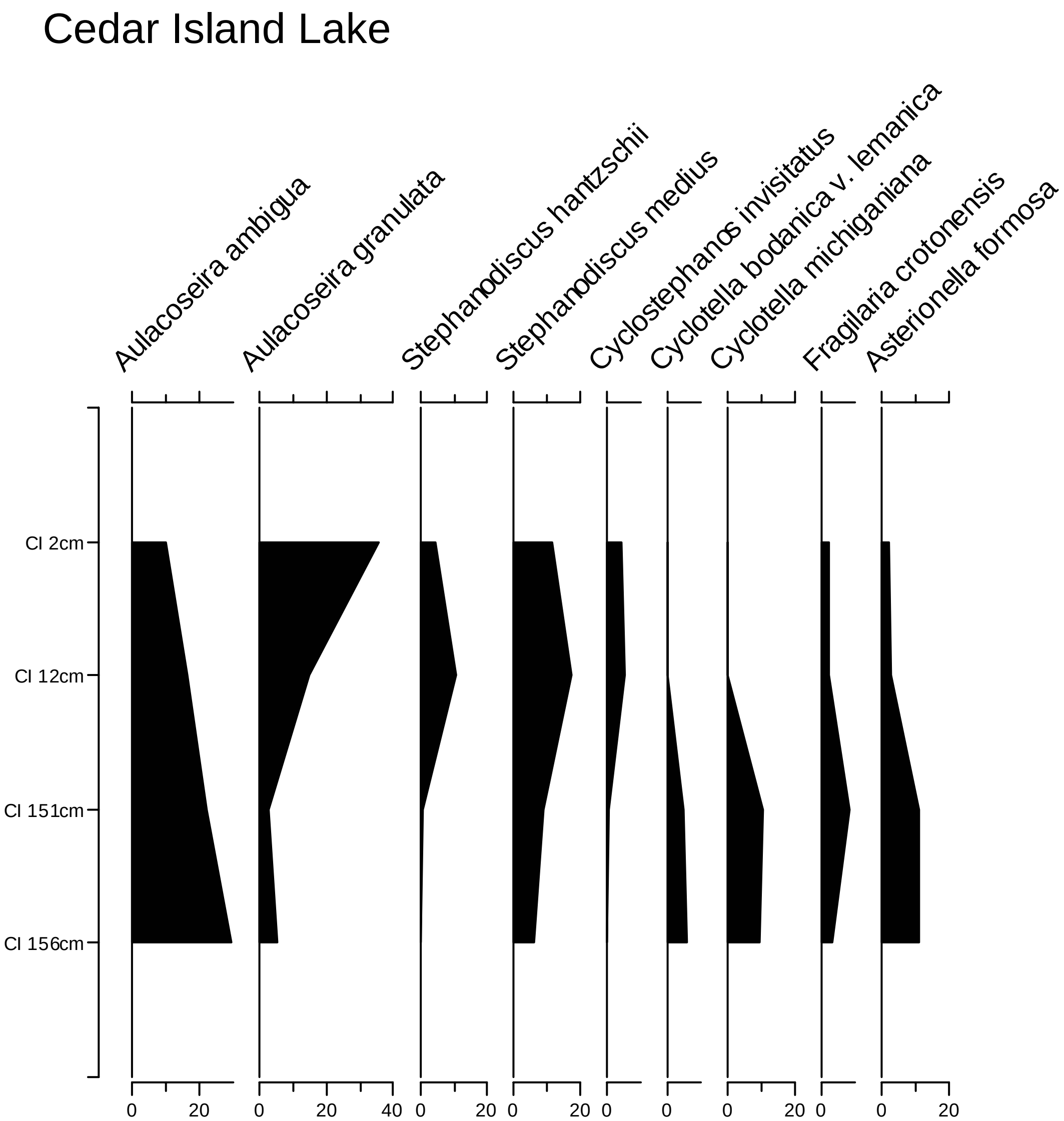

Figure 13. Correspondence Analysis (CA) of diatom communities from all cores. Arrows represent trajectories through time.

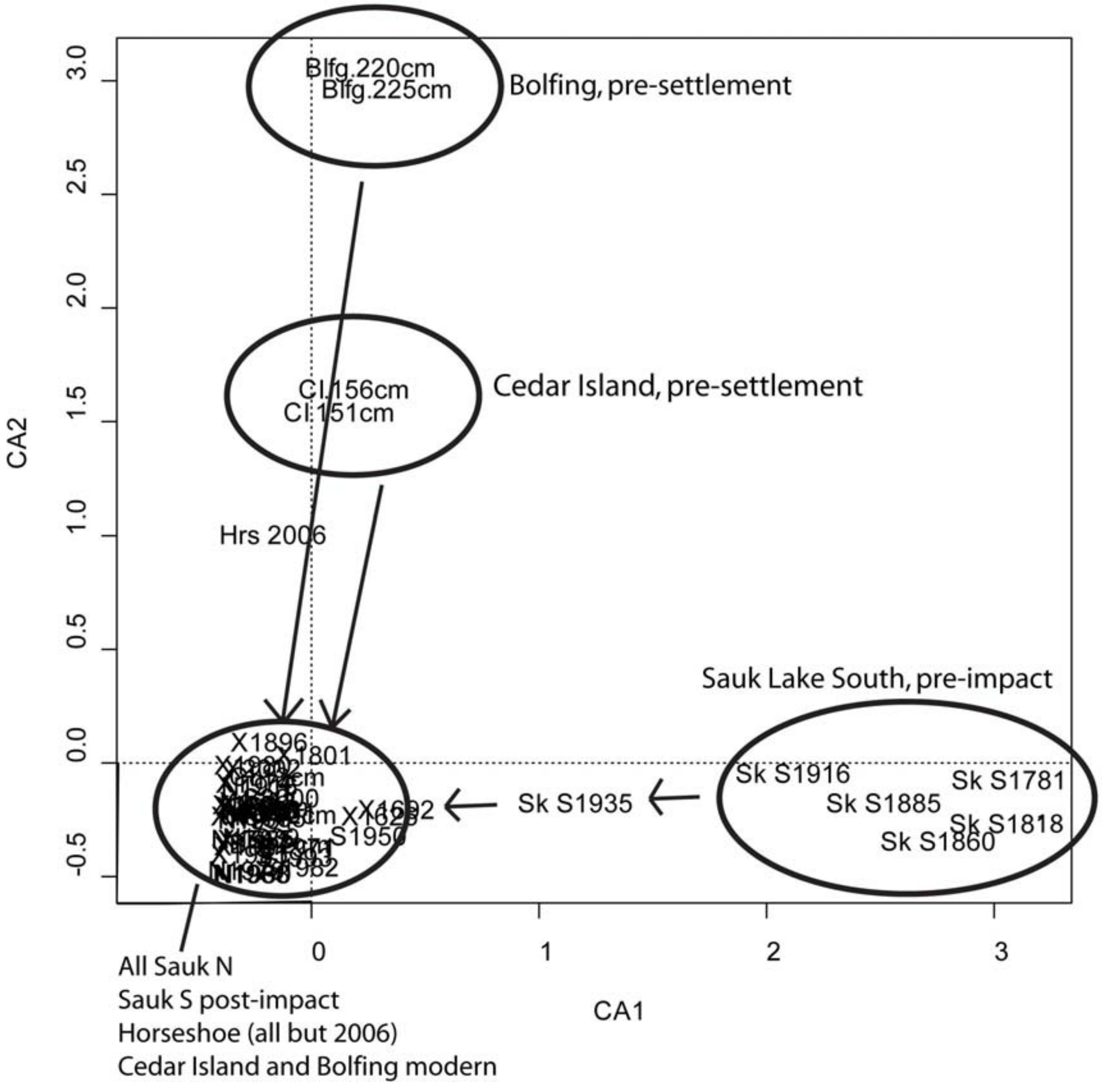

Figure 14. Total phosphorus (TP) reconstructions for Sauk Lake North and Sauk Lake South.

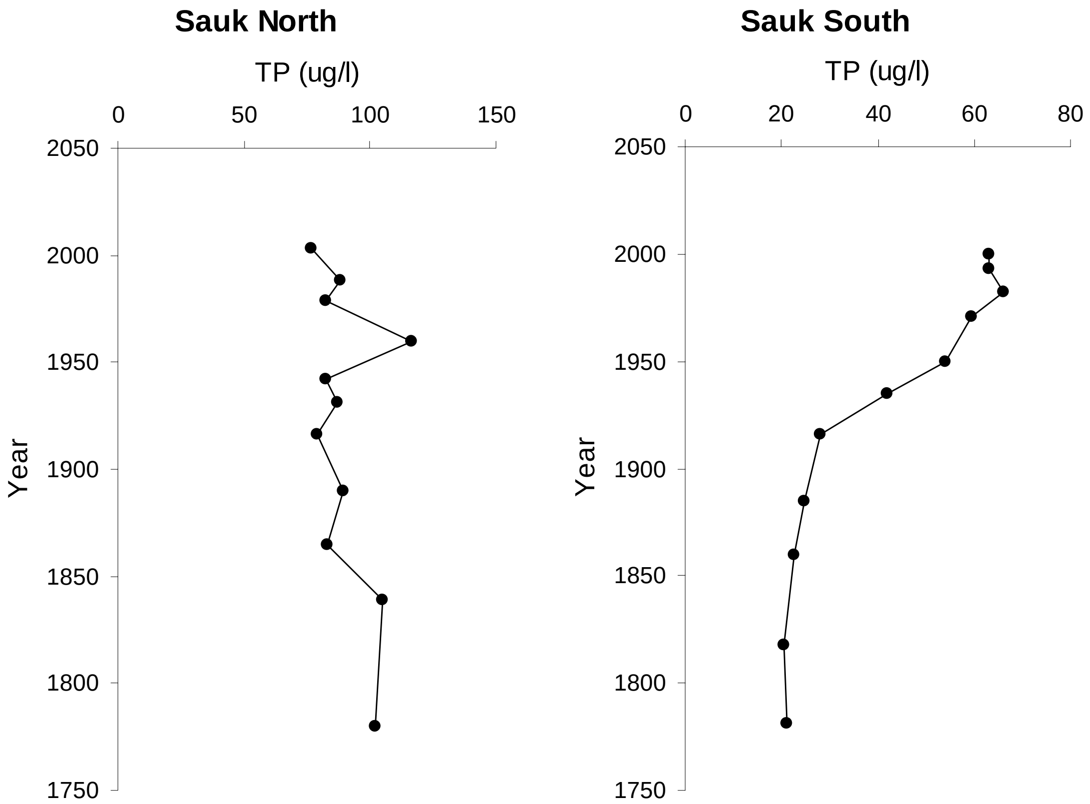

Figure 15. Total phosphorus (TP) reconstruction for Horseshoe Lake.

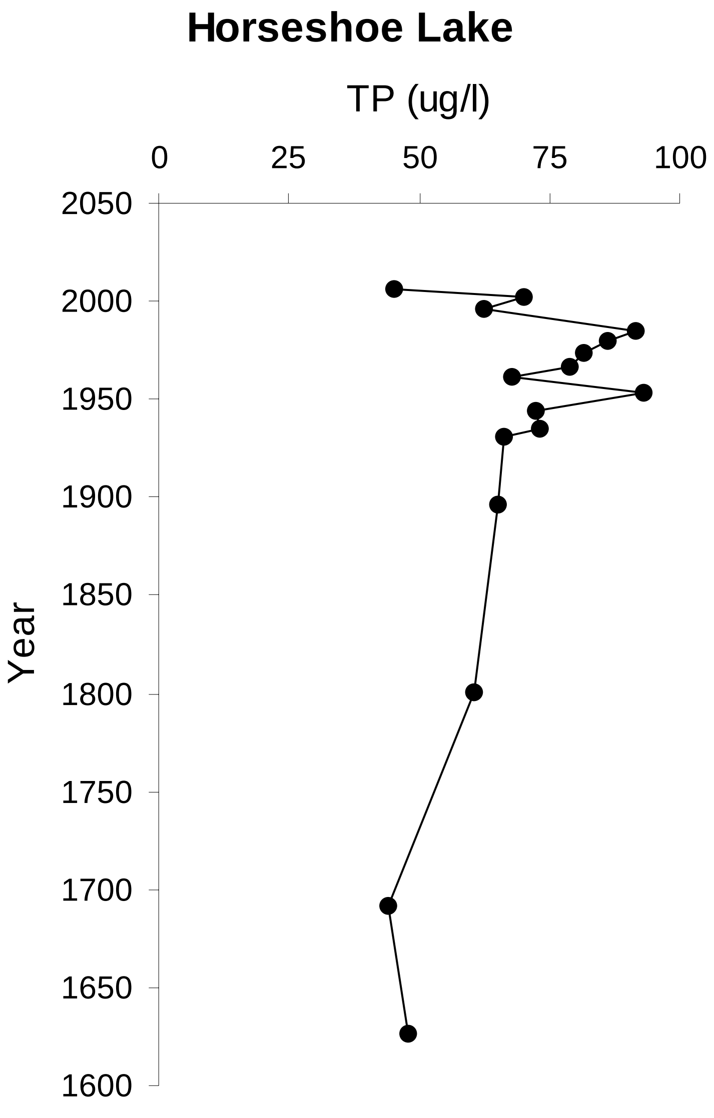

Figure 16. Total phosphorus (TP) reconstructions for Cedar Island Lake and Bolfing Lake. The lower two samples represent pre-European settlement.