

Biomonitoring using diatoms and paleolimnology in the Western Great Lakes National Parks

(*Cooperative Agreement*, H6000C02000, Funding Authorization No: 2105-2000-NII)

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Annual Report (2005-2006) submitted to:

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May 2007

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ANNUAL SUMMARY

Our 2005-2006 monitoring year activities targeted Pictured Rocks National Lakeshore (PIRO) and Sleeping Bear Dunes National Lakeshore (SLBE). Water quality monitoring and collection focused on 15 randomly selected lakes: six lakes from PIRO and nine lakes from SLBE. In conjunction with water quality monitoring, a single surface sediment sample was collected from the depositional basin of the lakes in the fall of 2005. Three lakes were selected for long core collection. Grand Sable Lake in PIRO was cored in July 2005. Lake Manitou and Shell Lake in SLBE were cored in September 2005. A backup core was also retrieved from Bass Lake (Leelanau County) in SLBE but the core was not satisfactory for further analysis. The focus of this annual report is the integration of 2005 water quality data with 2005 surface sediment diatom communities for initial calibration (training) set development, collection and analysis (geochemical and biological) of three sediment cores, identification of historical patterns of environmental change in PIRO and SLBE lakes, and an initial demonstration of how modern water quality data, modern diatom communities, and historical diatom assemblages from sediment cores can be integrated to identify ecological stressors.

Water quality sample analysis was completed and ice-free mean data for field year 2005 are summarized. Characterization of PIRO and SLBE lakes was explored using Principal Components Analysis and showed that the PIRO and SLBE lakes covered rather short environmental gradients, and primarily differed based on chlorophyll, alkalinity, conductivity, dissolved organic carbon, pH, and sulfate ion.

Surface sediments from 14 lakes were analyzed for modern diatom communities (SLBE School Lake did not yield a suitable sample). Over 380 diatom species were identified in the fourteen 2005 surface sediment samples from PIRO and SLBE. Diatom assemblages in sediments from the SLBE and PIRO lakes were dominated by north temperate planktonic species such as *Asterionella formosa*, *Aulacoseira ambigua*, *A. subarctica*, *Cyclotella (Discostella) stelligera*, *C. michiganiana*, *C. comensis*, *Pseudostaurosira brevistriata* and *Fragilaria crotonensis*. Benthic and periphytic species were also common in some GLKN lakes including *Denticula kuetzingii* (Shell Lake, SLBE), *Navicula cryptotenella* (Shell Lake, SLBE), *Staurosira construens* (Round and Tucker, SLBE) and *S. construens* v. *venter* (Miners and Florence, PIRO). A canonical correspondence analysis (CCA) was run to explore the diatom species-environment relationship in SLBE and PIRO lakes and to begin construction of a calibration data set for GLKN parks. Based on vector length and orientation with CCA axes 1 and 2, the environmental factors that most strongly explain the distribution of diatoms in SLBE and PIRO include TN, pH, TP, DOC, chlorophyll a, and silicate. This training set will continue to be developed as additional GLKN lakes are added in subsequent field years.

All cores, except Grand Sable Lake (PIRO), showed increased sedimentation rates following Euro-American settlement. Historical diatom communities were analyzed from 15 levels (ca. 1750-2005) in each of three cores. Correspondence analyses (or a PCA) were used to identify core stratigraphies, periods of historical ecological change, and within-core ecological variability among samples. Cores generally showed three distinct historical periods corresponding to a pre-Euro-American settlement zone characterized by low ecological variability, a period lasting from

post-settlement to the 1970s-90s that was characterized by a shift in diatom communities and greater ecological variability among samples, and a more recent shift in diatom communities characterized by increased abundance of small centric species possibly in response to climate change or atmospheric deposition. In no lake have the diatom communities returned to communities that were present before Euro-American settlement. Changes in cores were further correlated with historical land use change in the two park units.

Historical diatom assemblages were passively plotted on to a CCA of species-environment relationships for PIRO and SLBE lakes. Changes in the cores were placed in context of the current environmental and ecological variability in the park units. In the context of park lakes, Grand Sable Lake (PIRO) and Shell Lake (SLBE) had minimal change. In contrast, Manitou Lake (SLBE) had a strong ecological trajectory aligned with increasing pH and/or decreasing phosphorus levels. A 20th century increase in carbonate deposition in Manitou Lake corroborates the former; however, decreased phosphorus loading is a predicted outcome of global warming.

Key words: biomonitoring, inventory and monitoring, water quality, diatoms, landuse, climate change, paleolimnology, geochemistry

Abbreviations: PIRO-Pictured Rocks National Lakeshore, SLBE-Sleeping Bear Dunes National Lakeshore, GPS-global positioning system, UTM-universal transverse meridian, CCA-canonical correspondence analysis, PCA-principal components analysis, CA-correspondence analysis, WQ-water quality.

INTRODUCTION

With any environmental monitoring program 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 and natural variability, identify 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. Paleolimnology can also be used to determine response to and recovery from short-term disturbances. It is particularly important in areas of low impact, such as wilderness areas, to have background information on natural variations. Such information makes it possible to identify early signs of unusual disturbance and allows for early action toward remediation or restoration.

In Great Lakes Network (GLKN) park units, climate change, environmental contaminants, exotics, and land and resource uses including shoreline and urban development, recreation, water level management, logging, and agriculture have raised concerns about the state of the parks' resources and how to best manage them in a future certain to bring change. In this report, we summarize the first year of a strategy to integrate the use of paleolimnological techniques and diatom analysis in an inventory and monitoring framework. Results of this and subsequent annual reports will provide a management foundation by determining the natural variability or reference condition of national park lakes and by reconstructing a detailed history of lake response to ecological changes that have occurred in and around the lakes during the last 150 years. Because lake-sediment records integrate across both spatial and temporal scales, research results can be further used as a biomonitoring strategy by revisiting lakes on regular intervals (3-5 years) to quantify modern environmental conditions relative to historical conditions, to detect early ecological change and recent trends, and to evaluate success of management actions.

METHODS

Water quality sampling: Sampling for physical and water chemistry parameters took place on four sampling dates during field year 2005 in SLBE and PIRO (Elias 2006). Fifteen lakes were randomly selected with six in PIRO and nine in SLBE. Lakes were selected after an initial screening using deletion or preference criteria of lake depth (shallow lakes removed), boat accessibility, inside or on boundary of park, knowledge of lake conditions (lakes known to lack diatom preservation removed), and park priority lakes. Methods, initial compilation of data, and QC have been summarized (Elias 2006). For subsequent analyses in conjunction with sediment sampling, all WQ data have been expressed as mean values of the ice-free season.

Surface sediment and long core collection: A line-operated gravity corer (design by Harold Wiegner, Harold.Wiegner@state.mn.us) was used to collect the upper 0-1 cm and 1-2 cm of sediment at the same site that water quality measures were taken. These sediments represent a

spatially and temporally integrated assessment of biological remains and lake conditions during the past 1-3 years. Collection sites were precisely located by GPS to allow resampling in the same location in subsequent years; sampling sites always target central depositional basins in each lake (Table 1).

A 1-2 m long sediment core was collected from four target lakes in the GLKN parks in 2005: Grand Sable Lake (PIRO), Lake Manitou (SLBE), Bass-Leelenau (SLBE), and Shell Lake (SLBE) (Table 2). Lakes and sampling sites were chosen in consultation with the parks and GLKN staff; coring locations targeted central depositional basins in each lake, usually the same location where water quality measures were taken. Cores were taken from an anchored boat using piston-coring methods that recover the very loose uncompacted sediment surface without disturbance (Wright 1991). All core locations were recorded using GPS. Two strategies were used for initial handling of cores. At Grand Sable, the upper 18 cm of the sediment core were extruded vertically from the coring tube in the field at 1-cm increments and placed in polypropylene jars; the remainder of the core was capped. Cores from SLBE were sectioned in their entirety in the field at 1-cm increments and placed in polypropylene jars. Cores and sectioned material were transported to 4° C laboratory storage for further processing.

Sediment subsampling and freeze-drying: Sediment samples will be homogenized and subsampled for loss-on-ignition and/or diatom analyses. The remaining sediments will be freeze-dried within the sample jars for ^{210}Pb analysis and archived at the St. Croix Watershed Research Station (Science Museum of Minnesota).

Loss-on-ignition: Dry-density (dry mass per volume of fresh sediment), water content, organic content, and carbonate content of sediments will be determined by standard loss-on-ignition techniques (Dean 1974). In short, weighed sediment subsamples were dried at 105°C for 24 hr to determine dry density, then heated at 550°C and 1000°C to determine organic and carbonate content from post-ignition weight loss, respectively.

Lead-210 dating of cores: Sediment cores were analyzed for ^{210}Pb activity to determine age and sediment accumulation rates for the past 150-200 years. Lead-210 activity was measured from its daughter product, ^{210}Po , which is considered to be in secular equilibrium with the parent isotope. Aliquots of freeze-dried sediment were spiked with a known quantity of ^{209}Po as an internal yield tracer and the isotopes distilled at 550°C after treatment with concentrated HCl. Polonium isotopes were then directly plated onto silver planchets from a 0.5 N HCl solution. Activity was measured for $1-3 \times 10^5$ s using an Ortec alpha spectrometry system. Supported ^{210}Pb was estimated by the mean activity in the lowest core samples and subtracted from upcore activity to calculate unsupported ^{210}Pb . Core dates and sedimentation rates were calculated using the constant rate of supply model (Appleby and Oldfield 1978). Dating and sedimentation errors represent first-order propagation of counting uncertainty (Binford 1990). Pre-1850 dates and sedimentation rates represent down-core extrapolations of mean dry-mass accumulation immediately pre-settlement.

Diatom analysis—surface sediments and long cores: Surface sediments and fifteen increments from each core were analyzed for diatom microfossils. Samples were taken at approximately decadal intervals over the past 200 years to provide a chronology of environmental change following regional European settlement and a measure of reference or pre-settlement conditions. Sampling can also be adapted for specific research questions. Diatoms and chrysophyte cysts

were prepared by placing approximately 0.25 cm³ of homogenized sediment in a 50 cm³ polycarbonate centrifuge tube, 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 a 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). Diatoms that could not be identified to a known species were given provisional names such as *Cyclotella* "mich-like" or "*Cyclotella comensis* PIROv1". A minimum of 400 valves was counted in each sample. Abundances are reported as percentage abundance relative to total diatom counts.

Biogenic silica—long cores: The same fifteen samples from each long core that were analyzed for diatoms were also analyzed for biogenic silica. Weighed subsamples (30 mg) from each primary core were digested for biogenic silica analysis using 40 mL of 1% (w/v) Na₂CO₃ solution heated at 85°C in a reciprocating water bath for five hours (DeMaster 1979, Conley and Schelske 2001). A 0.5 g aliquot of supernatant was removed from each sample at 3, 4, and 5 h. After cooling and neutralization with 4.5 g of 0.021N HCl solution, dissolved silica was measured colorimetrically on a Lachat QuikChem 8000 flow injection autoanalyzer as molybdate reactive silica (McKnight 1991).

Numerical analysis: A number of multivariate techniques were used to analyze environmental data, modern diatom communities, and historical diatom assemblages among GLKN lakes and sediment cores. Relationships among lakes and environmental variables were explored using Principal Components Analysis (PCA) performed on a correlation matrix of 12 water quality variables (Table 4) using the software package R (Ihaka and Gentleman 1996) following scaling of all variables to zero mean and unit variance.

Relationships among diatom communities within a sediment core were explored using Principal Components Analysis, Correspondence Analysis, or Detrended Correspondence Analysis (depending on gradient length as determined by DCA). Core depths were plotted in ordinate space and their relationships and variability used to identify periods of change, sample groups, and ecological variability among core samples.

Relationships among environmental variables and species distributions for the 2005 GLKN lakes were explored using canonical correspondence analysis (CCA), a multivariate ordination technique for direct gradient analysis (ter Braak and Prentice 1988) available in the software package R (Ihaka and Gentleman 1996). Species present at greater than 1% relative abundance in two or more samples or at greater than 5% relative abundance in one sample were included in ordination analyses; the same selection criteria were used by Ramstack et al. (2003).

Environmental variables were variously transformed (log, inverse, square root, inverse square root, or no transformation) to approximate a normal distribution. The distribution of species among samples was initially explored with detrended correspondence analysis (DCA) and correspondence analysis (CA), respectively, to determine gradient length and examine the variation in the species data. These preliminary analyses are the first step in developing a calibration or training set that will allow diatom communities in GLKN park lakes to be used to

infer modern and historical water quality data. This training set will continue to be developed as additional GLKN lakes are added in subsequent field years. Downcore community data were passively plotted in the environmental-diatom CCA to identify ecological trajectories for each sediment core and along what environmental gradients the community may be changing.

Land-use history: A record of major land-use changes from each park unit over the last 150 years has been assembled by the resource manager at each park or taken from the published literature. For PIRO, Ms. Lora Loope provided an Excel file of major changes (Table 5). For SLBE, a historical record of agriculture and settlement was published by Haswell and Alanen (1994) and summarized in Table 6. These land-use histories will be compared with trophic reconstructions from the sediment cores to determine whether major changes in trophic conditions are temporally correlated with specific disturbances in the watershed.

RESULTS

WATER CHEMISTRY

Sampling for physical and water chemistry parameters took place in SLBE and PIRO on four sampling dates during field year 2005. Fifteen lakes were randomly selected with six in PIRO and nine in SLBE. Lakes were selected after an initial screening using deletion or preference criteria of lake depth (shallow lakes removed), boat accessibility, inside or on boundary of park, knowledge of lake conditions (lakes known to lack diatom preservation removed), and park priority lakes. Initial compilation of data and QC have been summarized by Joan Elias in emails dated 11 Oct 2005 and 26 Oct 2005 and in an annual report (Elias 2006). Concerns have been raised on laboratory detection limits for many WQ parameters (Joan Elias email dated 11 Jan 2006). For purposes of integrating water quality analysis and diatom community analysis we calculated summer mean values for all measured WQ parameters. When multiple labs had contributed to the analyses, we preferentially used SCWRS results (Table 3 and see Elias 2006). Water quality measures are summarized and discussed in Elias (2006).

To begin exploration of the relationships between water quality measures and modern diatom assemblages, ice-free WQ averages from SLBE and PIRO lakes were ordinated using Principal Components Analysis. School Lake (SLBE) was removed from the analysis as acceptable surface sediment samples were not collected in 2005 (see below). For most multivariate analyses, data are transformed to approximate normality. Each WQ metric was tested with numerous transformations (log10, square root, inverse, inverse square root, and untransformed) and the transformation with results closest to achieving normality were used in subsequent analyses (Table 4).

Alkalinity, specific conductance, chlorophyll, chloride, sulfate, and silica were most strongly loaded on PCA axis 1, whereas DOC, pH, and TN were more strongly loaded on PCA axis 2 (Fig. 1). Minor variables and a subset of correlated environmental variables were removed from the final analysis (see Table 4). These variables can be included in future analyses when more lakes/parks are added to this GLKN data set. Lakes from PIRO plotted to the right on axis 1, a

tribute to their lower alkalinity and conductivity and slightly higher chlorophyll values in comparison to most SLBE lakes. Most SLBE lakes plotted negative on axis 2 as they had higher pH, total nitrogen and DOC compared to many of the PIRO lakes. Florence Lake (SLBE) was clearly separated from other SLBE lakes as it has low sulfate and low silica values in comparison to other SLBE lakes. Florence Lake may also be a seepage lake. Miners Lake (PIRO) and Trappers Lake (PIRO) plotted separate from other PIRO lakes; the former has significantly higher alkalinity and conductivity, whereas the latter is very shallow and has high TN and low DOC and sulfate.

SURFACE SEDIMENT

A line-operated gravity corer was used to collect the upper 0-1 cm of sediment for an integrated assessment of sedimentation during the past 1-3 years (Table 1). Fifteen lakes, six from PIRO and nine from SLBE were selected using a random process after pre-screening lakes with criteria that included lake depth (shallow lakes deleted), knowledge of lake conditions (lakes known to lack diatom preservation removed), and park priorities. Collection sites were precisely located by GPS to allow resampling in the same location in subsequent years. Sampling sites targeted central depositional basins in each lake. School Lake (SLBE) did not yield an acceptable sample and was dropped from further analyses.

SEDIMENT CORING

Single drive piston cores of 1-1.5 m in length were collected from four lakes in SLBE and PIRO. Coring locations were marked using GPS (Table 2) and all cores were sectioned in their entirety using extrusion in 1-cm increments in the field or lab.

LEAD-210 CORE DATING AND CORE BIOGEOCHEMISTRY

Lead-210 dating was completed on three cores. The core from Bass (Leelenau) Lake is problematic and will not be suitable for this project. We did not reach supported levels of ^{210}Pb at 100 cm core depth, thus the core is too short for our research questions. The core from Bass Lake will not be discussed further.

PIRO cores—The Grand Sable Lake core showed a monotonic decrease in ^{210}Pb activity (Fig. 2) and reached supported levels at approximately 23 cm core depth (ca. 1855). This indicated that the core was suitable for further diatom and geochemical analyses. Sediment accumulation rates have been relatively stable over the period of analysis at approximately $0.06 \text{ g cm}^{-2} \text{ yr}^{-1}$ (Fig. 3). Grand Sable Lake sediments are largely inorganic with some post settlement decrease in inorganic content concomitant with a post-settlement increase in organic and carbonate content (Fig. 4). As sedimentation rates are relatively constant, these changes likely reflect some post-settlement changes in lake productivity.

The biogenic silica (BSi) content and accumulation rate in a core provides one proxy for historical diatom productivity. In Grand Sable Lake, pre-European concentrations of BSi were approximately 2-3% dry weight (Fig. 5). BSi increased after 1830 in Grand Sable Lake to peak weight percent and flux values in the late 1940s (7% by weight, 11-12 mg cm⁻² yr⁻¹). BSi levels have remained high since 1950 with weight percent and flux rates approximately three-fold higher than pre-1830 levels.

SLBE cores—Lake Manitou shows a steady decline in ²¹⁰Pb activity reaching supported levels at approximately 75 cm core depth (Fig. 6; ca. 1830). Core recovery was sufficient to use this material for further diatom and biogenic silica analyses. Sedimentation rates in Lake Manitou have varied considerably over the last 150 years. Most notable is a large increase in sedimentation rate between 1900 and 1920 that corresponds to landuse changes on the island (Fig. 7). Modern sedimentation rates are approximately three-fold higher than pre-settlement rates. The pre-settlement sediment was largely organic; however, dramatic changes occurred at about 50-55 cm depth (1890s) to a carbonate-dominated sediment (Fig. 8). There has been no return to presettlement sediment composition or sedimentation rates since the large shift in the 1890s despite abandonment of all North Manitou Island farms by the 1950s. The large increase in carbonates is of interest and may be a result of both increased productivity (but we would expect a similar increase in organics) or we suggest that hydrology in the basin has changed to bring additional carbonates into the lake likely via groundwater sources.

Biogenic silica content and flux show temporal changes similar to organic and carbonates in Lake Manitou. Biogenic silica increases from <3% by weight before 1890 to modern values of 7-10 weight percent. Biogenic silica peaked in concentration and flux (15% by weight and 5 mg cm⁻² yr⁻¹, respectively) between the 1920s and 1940s in Manitou Lake before falling to modern concentration and flux levels that are three-fold higher than pre-settlement rates (Fig. 9).

Shell Lake sediments have a steady decline in ²¹⁰Pb activities and reach a mean level of unsupported activity of 0.1875 pCi/g by 58 cm (Fig. 10). Pre-European settlement sediments are present below 41 cm (ca. 1847). Sedimentation rates increased dramatically in Shell Lake after 1880 from pre-1880 rates of <0.01 g cm⁻² yr⁻¹ to a peak in sedimentation of > 0.035 g cm⁻² yr⁻¹ from the 1920s-1960s (Fig. 11). Recent sedimentation rates are approximately 0.03 g cm⁻² yr⁻¹ or about three times pre-European levels. The geochemistry of Shell Lake sediments has changed dramatically from pre-European sediments that were alternately dominated by organics or rarely by carbonates (Fig. 12). The shift in geochemistry began in the 1880s with a shift from about 50% organic content to less than 25% organic content from 1920-1970. Simultaneously the carbonate content increased from about 20% dry weight to over 50% content. However, after the 1970s, carbonate content falls and organic content increases; both components have modern values of approximately 40-50% dry weight.

Pre-European biogenic silica levels were about 6% dry weight in Shell Lake but dropped to 1-3% dry weight by the 1890s (Fig. 13). Modern BSi values are from 2-3%. Flux of biogenic silica has varied little in Shell Lake in contrast to weight percent BSi due to the increased sedimentation rates in the 20th century.

MODERN DIATOM COMMUNITIES—SURFACE SEDIMENTS

A primary goal of this project over the course of the next three years (field years 2005-2007) is the development of a calibration set of diatom species-environment relationships that will allow us to 1) estimate WQ variables for both historical (sediment core) collections and modern samples, and 2) to detect directional change (environmental trajectories) in lakes by comparing recent samples with previous samples and/or sediment core assemblages.

To develop the calibration set, diatom counts from surface sediment samples from 2005-2007 will be pooled and combined with existing regional training sets (Ramstack et al. 2003). Counts from the first field season are completed and we have completed preliminary data analysis, taxonomic harmonization, and exploration of species-environment relationships. Over 380 diatom species were identified in the fourteen 2005 surface sediment samples from PIRO and SLBE. Many taxa were rare in the samples; however, 44 species fit our selection criteria of >5% relative abundance in any sample or >1% relative abundance in two or more samples and were included in a preliminary analysis of species-environment relationships (Table 5). Because we are currently measuring more environmental variables than lakes, we pared down the environmental variables for our initial analysis by removing highly correlated and redundant variables as required for canonical correspondence analysis (Table 4). Environmental variables that we used in this 2005 analysis included: chlorophyll a, total phosphorus, total nitrogen, ammonium, DOC, alkalinity, chloride, sulfate, silica, Secchi depth, pH, and electrical conductivity. Variables were transformed as noted in Table 4. We will consider all environmental variables in the development of the final training set once sampling of GLKN lakes is complete.

Diatom assemblages in sediments from the SLBE and PIRO lakes were dominated by north temperate planktonic species such as *Asterionella formosa*, *Aulacoseira ambigua*, *A. subarctica*, *Cyclotella (Discostella) stelligera*, *C. michiganiana*, *C. comensis*, *Pseudostaurosira brevistriata* and *Fragilaria crotonensis* (Table 5). A small, apparently undescribed *Cyclotella* species ("mich-like") was common to dominant in Lake Manitou (SLBE), Bass Lake (SLBE), Beaver (PIRO), Trappers (PIRO). Benthic and periphytic species were also common in some GLKN lakes including *Denticula kuetzingii* (Shell Lake, SLBE), *Navicula cryptotenella* (Shell Lake, SLBE), *Staurosira construens* (Round and Tucker, SLBE) and *S. construens* v. *venter* (Miners and Florence, PIRO).

A canonical correspondence analysis was run to initially explore the diatom species-environment relationship in SLBE and PIRO lakes (Figs 14). Because we have more environmental variables than lakes, we treated only a subset of environmental data (Table 4). Furthermore, the environmental gradients in these two parks are not extremely broad; this will change as lakes from additional GLKN parks are added in subsequent sampling years. Based on vector length and orientation with CCA axes 1 and 2, the environmental factors that most strongly explain the distribution of diatoms in SLBE and PIRO include TN, pH, TP, DOC, chlorophyll a, and silicate. This is in contrast to ordination results using only the environmental data where alkalinity and

conductivity produced strong environmental gradients (see Fig. 1). The PIRO lakes, Grand Sable, Chapel, Miners, and Little Beaver are clustered with SLBE Tucker (Fig. 14) in the lower left of ordinate space, whereas the SLBE lakes Manitou and Bass are grouped near PIRO lakes Beaver and Trappers along the positive CCA axis 2. Loon, North Bar, Round, and Florence Lakes (SLBE) are grouped near the origin of the CCA, . Shell Lake (SLBE) remains an outlier on the CCA because of its unique benthic-dominated diatom assemblage.

LAND USE HISTORIES—PIRO AND SLBE

Land use histories that may be driving or have driven modern and/or historical environmental change in the GLKN parks have been compiled by park resource managers using literature and historical sources (Tables 6-7). In temperate North America, initial European settlement, logging and land clearance, damming, development of agriculture, agriculture intensification and abandonment, forest regeneration, introduction of exotic species, fisheries collapse, cottage development, waste water treatment, and urbanization have been major drivers of change in aquatic ecosystems. More recently, climate change is increasingly being identified as a driver of environmental change in aquatic ecosystems.

Land use changes that have likely impacted PIRO include initial settlement in Grand Marais in the early 1860s, the opening of the first sawmill in Grand Marais in 1879, and extensive logging in the late 1800s and early 1900s (Table 6). The logging boom was followed by major wildfires and some drought during the 1910s-1930s. Cottages soon followed as Grand Sable Lake had many seasonal cabins built in the 1930s-1950s.

Because of its tempered Great Lakes climate, the land use history of SLBE is much more dominated by agricultural activity (Table 7). Several Native American villages were present before the 1840s and included some subsistence agriculture. Euro-American settlers arrived in the 1840s with an economy centered on supplying cordwood for Great Lakes steamships. Settlers also engaged in subsistence agriculture raising potatoes and corn. Increasing numbers of foreign settlers arrived in the 1860s with communities focused on cordwood production, but with increasing agricultural interests. By the 1870s the cordwood industry was declining; however, the arrival of rail and improved roads opened up markets for agricultural products, especially fruit production. Rail also opened up additional forests for logging and by the 1890s, forest products dominated the local economy. The 1890s began the decline of logging, but with an increase in orchard production and the beginnings of the tourist industry in the area. Following the turn of the century farming began a slow decline that persists today. The number of farms decreased, but remaining farms increased in size. Following World War II, farming steeply declined with loss of 40% of the farms between 1945 and 1950. This trend continued into the 1970s and was concomitant with land also being removed from production. For example, in 1910 approximately 50% of Benzie County was in agricultural production, but by 1969 only 19% of the land was in agriculture. North Manitou Island saw an even earlier decline in farming beginning in the 1890s with the last independent farmer leaving the island in 1940. With the decline in agriculture, tourism, retirement, and hobby homes have increased in the area. In October 1970, Sleeping Bear Dunes National Lakeshore became established.

CORE STRATIGRAPHIES

Grand Sable-PIRO—Diatom communities were analyzed in 15 levels from Grand Sable Lake covering a period from 1782-2005. A total of 289 diatom species was encountered in the core with 39 taxa found at >5% relative abundance in one sample or >1% abundance in two or more samples. Downcore abundances of these taxa are plotted in Fig. 15. Sediments are dominated by *Aulacoseira ambigua* and *A. subarctica*, *Cyclotella (Discostella) pseudostelligera*, *Fragilaria crotonensis*, and *Asterionella formosa*. A principal components analysis (used because of short gradient lengths) of downcore diatom assemblages identifies three historical assemblage zones (Zones 1-3 in Figs 15-16) separated by periods of large community change in the recent history of Grand Sable Lake.

Zone 1 (1782-1887) is characterized by abundant *Aulacoseira ambigua*, *A. subarctica*, and *A. distans*, peak abundances of *Cyclotella (Discostella) pseudostelligera* and *C. michiganiana*, and high abundance of *Staurosirella pinnata*.

Zone 2 (1903-1960) is characterized by peaks in abundance of *Aulacoseira ambigua* and *A. subarctica*, decreased abundance of *Cyclotella (Discostella) pseudostelligera*, continued abundance of *Staurosirella pinnata*, increased abundance of *Stephanodiscus niagarae*, and low abundance of *Asterionella formosa*.

Zone 3 (1973-2001) is characterized by slightly lower abundances of *Aulacoseira ambigua* and *A. subarctica*, a peak in abundance of *Fragilaria crotonensis* and *Asterionella formosa*, decreased abundance of *Staurosirella pinnata*, and establishment of *Cyclotella comensis* PIROv1, an apparently undescribed species with affinities to *C. comensis*.

Manitou Lake-SLBE—Diatom communities were analyzed in 15 core sections covering 1757-2005. The diatom flora of Manitou Lake is dominated by the planktonic diatom *Aulacoseira ambigua*. Modern sediments are secondarily dominated by small *Cyclotella* species and *Asterionella formosa*; whereas historical assemblages had higher abundance of benthic species such as *Staurosira construens* and its var. *venter*, *Staurosirella pinnata*, and *Pseudostaurosira brevistriata* (Fig. 17). A total of 28 taxa met our inclusion criteria for plotting of downcore abundance and community analyses. A correspondence analysis (CA) of Manitou Lake shows two periods of dramatic ecological change separating three historical assemblage zones (Fig. 18). The first zone captures the period from 1757 until 1886; this zone's tight cluster in the CA shows minimal ecological variability during this period of pre-European settlement. The Zone 1 diatom assemblage is characterized by high abundance of benthic araphid taxa including *Staurosira construens* and its var. *venter*, *Staurosirella pinnata*, and *Pseudostaurosira brevistriata* and the raphid and monoraphid taxa *Sellaphora vitabunda* and *Achnathes zeigleri*, respectively.

Zone 2 captures the period from 1904-1972 and we begin to see greater variability among diatom assemblages during this period. Zone 2 sediments are dominated by a rapid increase in abundance of *Aulacoseira ambigua*, establishment of the planktonic centric diatoms *Cyclotella michiganiana*, *Discostella stelligera*, *Stephanodiscus minutulus* and *S. niagarae*, establishment

of the araphid planktonic taxa *Fragilaria crotonensis* and *Asterionella formosa*, and a decrease representation by the araphid taxa that dominated Zone 1 sediments.

Zone 3 sediments were dated from 1982 to 2002 and represent a new trajectory for diatom assemblages in Manitou Lake. In Zone 3 sediments we see the shift in dominance from *Aulacoseira ambigua* to sudden dominance by small centric planktonic species (*Cyclotella comensis* and *Cyclotella* sp "mich-like"). *Stephanodiscus niagarae*, *Fragilaria crotonensis*, and *Asterionella formosa* remain important parts of the Zone 3 assemblage; however, other small centrals that were common in Zone 2 become less important in Zone 3. Similarly, the benthic taxa that were common in Zone 1 remain poorly represented in Zone 3 sediments.

Shell Lake-SLBE—Fifteen depths from the Shell Lake core were analyzed and covered a period from 1727 to 2005. Shell Lake is very different than all SLBE and PIRO lakes as its diatom community is currently and has been historically dominated by benthic diatoms, especially *Denticula kuetzingii* (Syn: *Nitzschia denticula*). Other benthic species that are common in Shell lake sediments include *Navicula vulpina*, *N. cryptotenella*, *N. rhynchocephala*, *N. oblonga*, *Amphora libyca*, *Sellaphora laevisissima* and *S. cf. blackfordensis*. The only common planktonic form in Shell Lake is *Cyclotella michiganiana*, which is rarely present at greater than 2% relative abundance (Fig. 19). A total of 42 taxa met our inclusion criteria for plotting and multivariate analyses (Fig. 19). A correspondence analysis of downcore assemblages identified three historical diatom zones (Fig. 20)

Zone 1 sediments encompassed the period from 1727 to 1889 and as a group have less variable diatom communities than other more recent periods in the history of Shell Lake. In addition to *Denticula kuetzingii*, Zone 1 sediments were dominated by *Navicula vulpina*, *N. rhynchocephala*, *N. oblonga*, *Aneumastus tusculum*, among others.

Zone 2 (1912-1991) sediments were characterized by continued abundance of *Denticula kuetzingii* except in samples dated 1941 and 1953, when *Psammothidium abundans* var. *rosenstockii* dominated Shell Lake sediments. Zone 2 sediments also show a peak in abundance of *Sellaphora laevisissima*, *Placoneis explanata*, *Navicula oblonga*, *Amphora libyca*, *Achnanthisidium minutissimum*, and *Rossithidium linearis*.

Zone 3 (1997-2003) is represented by only two samples but it appears that the diatom communities have shifted toward a new ecological trajectory in contrast to Zone 2 assemblages. Driving this shift in Zone 3 sediments is continued abundance of *Denticula kuetzingii*, the establishment of *Navicula cryptotenella* and *N. cryptocephala*, and loss or lower abundance of many Zone 2 diatoms including the monoraphids, and the raphid taxa *Sellaphora laevisissima*, *Sellaphora cf. blackfordensis*, *Amphora libyca*, and *Placoneis explanata*.

ENVIRONMENTAL CHANGE IN GLKN LAKES

Pictured Rocks National Lakeshore - Grand Sable Lake—The biogeochemical record from Grand Sable Lake surprisingly does not record dramatic changes in either sedimentation rate or

organic, carbonate, and inorganic content over the last 250 years. Rather subtle changes take place in the 1890s as inorganic content decreases, and organic and carbonate content increase slightly. These changes continue up to modern times in Grand Sable Lake. An increase in biogenic silica content and flux began early in the 19th century, well before Euro-American settlement. The biogenic silica increase continued until 1950 and has remained slightly higher than presettlement rates through modern times.

In contrast to geochemical signals, the diatom community in the Grand Sable Lake core has gone through three distinct periods between 1782 and 2005. The first period (Zone 1) lasted from 1782-1887, the second period (Zone 2) from 1903-1960, and the third period (Zone 3) from 1973-2005. Shifts in abundance of planktonic taxa define these assemblage zones, especially the loss of *Aulacoseira distans*, *Cyclotella michiganiana*, and *Stephanodiscus parvus* and increased abundance of *A. subarctica* and *A. ambigua* during the transition from Zone 1 to 2, and the increase in abundance of *C. comensis* PIROv1, *Fragilaria crotonensis*, and *Asterionella formosa* during the transition from Zone 2 to 3.

The transition from Zone 1 to Zone 2 and the slight shift in core geochemistry correspond closely with dating of the "settlement horizon" identified in other paleoecological projects in the PIRO area (see Table 6); however, the shift in Grand Sable Lake is much more subtle than many other sediment records of settlement impacts in the Upper Midwest. The shift likely reflects the impact of logging and some initial increases in diatom productivity as noted by increased flux of biogenic silica to the core. Of more immediate interest is the ecological shift noted in diatom assemblages between 1960 and the mid-1970s (Fig. 16). During this time, there are minimal changes in land use recorded in the park, yet a clear shift occurred in the diatom community of Grand Sable Lake. As noted in other GLKN sediment cores (this study, unpublished results from VOYA, Kling 2005), this time frame of ecological change is increasingly being identified in sediment records from "unimpacted" areas of the northcentral United States and Canada. Common to many of these records is an increase in abundance of small centric diatoms (Fritz et al. 1993, Smol et al. 2005, as noted in Grand Sable Lake by the increased abundance of *C. comensis* PIROv1. One of the strongest correlates of this 1970s shift in diatom communities are climate records that identify a mid-1970s inflection associated with records of global warming. Alternative explanations should be sought in records of atmospheric deposition across the region.

Sleeping Bear Dunes - Manitou Lake and Shell Lake—In contrast to the Grand Sable Lake (PIRO) sediment record, lakes in SLBE record much more dramatic change in their biogeochemical and diatom records. Both Manitou and Shell Lakes have large increases in sedimentation rates between 1880 and 1900. In both lakes this change is coincident with shifts in geochemistry from organic to carbonate-dominated sediments; however, the increase in sedimentation rate further accentuates an increase in carbonate flux and inorganic flux in the SLBE lakes. The Manitou Lake biogenic silica record shows an increase in 20th century diatom productivity, whereas the Shell Lake record has only slight 20th century increases in biogenic silica flux and decreased biogenic silica content due to dilution by carbonates.

Although the lakes support significantly different diatom floras (the much shallower and more productive Shell Lake has a community dominated by benthic species), similarities exist in the

timing of ecological change in the diatom records from SLBE. Correspondence analyses identified three diatom assemblage zones in each lake with coincident ecological shifts from Zone 1 to 2 occurring in the late 1800s. Zone 2 communities in both lakes are more variable than their Zone 1 counterparts, although less variable in Shell Lake. Between 1972 and 1982, the diatom community in Manitou Lake underwent a shift driven by the establishment of *Cyclotella comensis* and *Cyclotella* sp. (*mich*-like). Shell Lake diatom communities began a new ecological trajectory somewhat later than Manitou Lake; the shift occurred in the early 1990s and was driven by changes in abundance of several benthic species.

Euro-American settlement records from the SLBE area date back to the 1840s; however, significant landuse changes probably post-date the 1860s as immigration, logging, cordwood, and clearing for agricultural land began in earnest. The peak in logging occurred in the 1890s which also was a time of changes in agricultural production. It is during the 1890s that we see the "settlement horizon" in sediment cores from the SLBE lakes. This is fairly late in the settlement process; however, it does coincide with the peak of logging activity and conversion to agricultural lands in northern Lower Michigan, which is the likely cause of increased sedimentation rates in SLBE lakes. The increase in carbonate content and flux in sediments from SLBE lakes is perhaps the most notable characteristic of the sediment records. Whereas increase in carbonate deposition is a typical consequence of increased lake productivity (increased algal and macrophyte productivity such as that caused by nutrient loading), the changes in the SLBE lakes stand out as an indicator of potential regional hydrologic change. The increase in carbonate content and flux is not concomitant with increases in organic content and flux as might be expected with increased productivity. Rather we conjecture that logging and land clearance has irrevocably changed groundwater hydrology in this region such that greater recharge is delivering increased carbonates to SLBE lakes. Removing land from production, second growth forest regeneration, and the establishment of the national lakeshore have not returned these lakes to presettlement conditions. Of further concern is that changes in diatom communities in the 1970s in Manitou Lake are again correlated with signals of climate change (see PIRO lake discussion above) and are characterized by increases in small *Cyclotella* species. For sites as remote as Manitou Lake that are not experiencing any substantial landuse change or recreational use, biological changes may be a signal of regional-scale forcing of environmental change.

A DEMONSTRATION OF DIATOMS AS BIOLOGICAL INDICATORS

Although it will take at least three field seasons to fully sample the GLKN I&M lakes and develop a diatom calibration set that will be used for quantitative reconstruction and assessing environmental trajectories, we thought it appropriate to provide a demonstration of how these water quality and biological data may be used as indicators of environmental change. One technique is to passively plot repeat samples or sediment assemblages in environment-species ordinate space based on canonical correspondence analysis of modern diatom assemblages and water quality. The ecological trajectories within sediment cores or among repeat samples are plotted in relation to the range of modern conditions and communities in the GLKN parks. Direction and magnitude of community change can thus identify stressors driving ecological change in the GLKN parks.

The sediment record from Manitou Lake provides a good example of this technique. Sediment diatom assemblages from the 2005 core were passively plotted on to the CCA of the fourteen lakes sampled from PIRO and SLBE in 2005 (compare Fig. 21 to Fig. 14). The diatom assemblage Zones 1-3 are easily identified in the passive plot with Zone 1 samples from 1757-1886 tightly clustered below CCA axis 1, Zone 2 samples (1904-1972) plotted above Zone 1 but still negative on CCA axes 1 and 2, and Zone 3 samples (1982-2002) are plotted in quadrant 2 (Fig. 21). The 2005 surface sediment sample is plotted even further positive along CCA axis 2. The ecological trajectory of the Manitou Lake core is generally along CCA axis 2. Because pH and TP (as 1/sqrt TP) were strongly loaded on CCA axis 2, these two environmental variables warrant additional investigation as to how they may be driving ecological change in Manitou Lake. For example, the 1890s shift in carbonate deposition would likely drive an increase in pH, and decreased allochthonous phosphorus loading is one predicted outcome of climate warming.

Similar exercises with the Shell Lake core and the Grand Sable Lake core do not reveal as dramatic of a change as seen in the Manitou Lake core. In relation to the community and environmental variability of PIRO and SLBE lakes, Shell Lake (Fig. 22) has always been an outlier in both community composition and water chemistry. All core samples from Shell Lake, except for 1941 and 1953, are tightly clustered near the 2005 surface sediment sample from Shell Lake, suggesting little directional change in historic or modern Shell Lake communities or chemistry.

Historical diatom assemblages from Grand Sable Lake are similarly tightly grouped in the lower left quadrant of Fig. 23. In spite of the PCA identifying several diatom assemblage zones in the history of Grand Sable Lake, the magnitude of change is not so great as to produce an obvious ecological trajectory when placed in context of the range of environmental and community variation of SLBE and PIRO lakes.

REFERENCES

- Appleby, P.G., and Oldfield, F. 1978. The calculation of lead-210 dates assuming a constant rate of supply of the unsupported lead-210 to the sediment. *Catena* 5: 1-8.
- Barrett, L.R. 1995. A stump prairie landscape in northern Michigan: soils, forest vegetation, logging, and fire. Ph.D. Dissertation. Michigan State University. East Lansing, MI. 206 pp.
- Binford, M.W. 1990. Calculation and uncertainty analysis of 210-Pb dates for PIRLA project lake sediment cores. *J. Paleolimn.* 3: 253-267.
- Booth, R.K., Jackson, S.T. and Gray, C.E.D. 2003. Paleoecology and high-resolution paleohydrology of a kettle peatland in upper Michigan. *Quaternary Research* 61: 1-13.
- CCI (Cleveland-Cliffs Iron Co.) 1920. The Cleveland -Cliffs Iron company, 1850-1920. Cleveland, OH. 52 pp.
- Conley, D.J., and Schelske, C.L. 2001. 14. Biogenic Silica, p. 281-293. *In* J. P. Smol, H. J. B. Birks, and W. M. Last [eds.], *Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestrial, Algal, and Siliceous Indicators*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

- Dean, W.E. 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: Comparison with other methods. *J. Sediment. Petrol.* 44: 242-248.
- DeMaster, D.J. 1979. The marine budgets of silica and ^{32}Si . Ph.D. Dissertation, Yale University.
- Elias, J. May 2006. Report on 2005 Water Quality Sampling at Pictured Rocks and Sleeping Bear Dunes National Lakeshores. Great lakes Inventory and Monitoring Network, National Park Service, Ashland, Wisconsin, 51806. 9 pp + appendices.
- Frederick, D.J., Rakestraw, L., Eder, C.R. and Van Dyke, R.A.. 1977. Original forest vegetation of the Pictured Rocks National Lakeshore and a comparison with present conditions. Report to the agency. Michigan Technological University. Houghton, Michigan. 16 pp.
- Fritz, S.C., Kingston, J.C. and Engstrom, D.R. 1993. Quantitative trophic reconstruction from sedimentary diatom assemblages: a cautionary tale. *Freshwater Biology* 30: 1-23.
- Futyma, R.P. 1990. Fossil pollen stratigraphy of Twelvemile Bog, Pictured Rocks National Lakeshore, Michigan. Report to the agency. New York State Museum, The State Education Department. Albany, NY. 7 pp + appendices
- Haswell, S.O. and Alanen, A.R. 1994. A garden apart: An agricultural and settlement history of Michigan's Sleeping Bear Dunes National Lakeshore region. National Park Service, Midwest Regional Office, Omaha, Nebraska. 181 pp.
- Ihaka, R. and Gentleman, R. 1996. R: a language for data analysis and graphics. *J. Comput. Graph. Stat.* 5: 299-314.
- Kling, H. 2005. Paleolimnological investigation of Kabetogama Lake cyanobacteria blooms and other indications of increased trophic status. National Park Service Great Lakes Inventory and Monitoring Network Report GLKN/2005/18.
- Lytle, D.E. 2005. Palaeoecological evidence of state shifts between forest and barrens on a Michigan sand plain, USA. *The Holocene* 15: 821-836.
- McKnight, R. 1991. QuikChem method 10-114-27-1-A, Determination of Silica in Waters by Flow Injection Analysis, 0.2 to 20.0 mg SiO_2/L . Lachat Instruments, 6645 West Mill Road, Milwaukee, Wisconsin 53218-1239.
- Ramstack, J.M., Fritz, S.C., Engstrom, D.R. and Heiskary, S.A. 2003. The application of a diatom-based transfer function to evaluate regional water-quality trends in Minnesota since 1970. *J. Paleolimnol.* 29: 79-94.
- Smol, J.P., Wolfe, A.P., Birks, H.J.B., Douglas, M.S.V., Jones, V.J., Korhola, A., Pienitz, R., Rühland, K., Sorvari, S., Antoniades, D., Brooks, S.J., Fallu, M-A., Hughes, M., Keatley, B.E., Laing, T.E., Michelutti, N., Nazarova, L., Nyman, M., Paterson, A.M., Perren, B., Quinlan, R., Rautio, M., Saulnier-Talbot, É, Siitonen, S., Solovieva, N., and Weckström, J. 2005. Climate-driven regime shifts in the biological communities of arctic lakes. *Proceedings of the National Academy of Sciences* 102: 4397-4402
- Symon, C.A (ed.). 1986. Alger County, a centennial history 1885 - 1985. Bayshore Press. Munising, MI. 272 pp.
- ter Braak, C. J. F. and Prentice, I.C. 1988. A theory of gradient analysis. *Adv. Ecol. Res.* 18: 271-317.
- Vogel, J. 1999. Historical study of fish and fisheries in Pictured Rocks National Lakeshore. Heritage Research, Ltd. Menominee Falls, WI.
- Wright, H.E., Jr. 1991. Coring tips. *J. Paleolimnol.* 6: 37-49.

TABLES

Table 1. Surface sediment samples collected from PIRO and SLBE in Jul-Sept 2005 for diatom analysis.

Lake	Code	Date	Zone	Lat N	Long W	UTM northing	UTM easting	Park	Core depth (cm)
Bass L	SLBASS	9/28/2005	16T	44.55341	85.52993	4934393	616761	SLBE	0-1
Florence	SLFLOR	9/27/2005	16T	41.62116	87.09347	4607720	492213	SLBE	0-1
Loon	SLLOON	9/26/2005	16T	44.70735	86.12939	4950810	568966	SLBE	0-1
Manitou	SLMANT	9/27/2005	16T	45.12514	86.02289	4997316	576843	SLBE	0-1
Round	SLROND	9/26/2005	16T	44.6928	86.18459	4949149	564609	SLBE	0-1
Shell	SLSHLL	9/28/2005	16T	44.94909	85.90136	4977882	586666	SLBE	0-1
Tucker	SLTUCK	9/28/2005	16T	44.70394	85.95313	4950596	582933	SLBE	0-1
North Bar	SLNBAR	9/30/2005	16T	44.84353	86.06587	4965993	573824	SLBE	0-1
School	N/A	9/28/2005	16T	N/A	N/A	N/A	N/A	SLBE	0-10
Beaver	PIBEAV	10/13/2005	16T	46.57194	86.33476	5157812	550978	PIRO	0-1
Chapel	PICHAP	10/29/2005	16T	46.53018	86.44797	5153105	542335	PIRO	0-1
GrandSable	PIGRSA	10/14/2005	16T	46.64904	86.03316	5166618	573984	PIRO	0-1
Little Beaver	PILTBV	10/13/2005	16T	46.55851	86.36091	5156303	548986	PIRO	0-1
Miners	PIMINE	10/29/2005	16T	46.4808	86.53833	5147574	535437	PIRO	0-1
Trappers	PITRAP	9/14/2005	16T	46.58627	86.31558	5159417	552434	PIRO	0-1

Table 2. Lakes cored in 2005 and length of core recovered.

Lake	Coring Location Date	Park	Z (m)	Core length (cm)	Field and lab sectioned (cm)
Grand Sable	46°38.872'N 86°02.014W 29 Jul 2005	PIRO	19.19	141	0-18 (field), 18-140(lab)
Lake Manitou	45°07.616'N 86°01.422W 27 Sept 2005	SLBE	13.07	110	0-104 (field)
Bass (Leelenau)	44°55.341'N 85°52.993'W 28 Sept 2005	SLBE	7.90	107	0-104 (field)
Shell	44°56.845'N 85°53.963'W 28 Sept 2005	SLBE	4.03	110	0-107 (field)

Table 3a. Mean ice-free 2005 water quality variables from PIRO and SLBE lakes. Blue values are SCWRS lab data (see Elias 2006 for interlab variability).

PARK/lake	Chl-a	TP	TKN	TN	NO ₃ /NO ₂	NH ₄ -N	DOC	Alkalinity	Cl
	(µg/L)	(µg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
PIRO									
Grand Sable	3.33	8.11	0.36	0.21	0.008	0.06	5.6	46	0.3
Trappers	3.29	10	0.75	0.74	0.01	0.11	9.7	70	0.28
Chapel	2.9	8.58	0.36	0.23	0.016	0.09	7.3	86	0.28
Beaver	5.1	12.22	0.2	0.18	0.006	0.07	3.6	76	0.37
Little Beaver	9.4	21.2	0.42	0.31	0.005	0.07	5.5	66	0.29
Miners	1.99	16.34	0.43	0.42	0.097	0.13	5.6	142	1.24
SLBE									
Manitou	3.88	8.66	0.435	0.41	0.006	0.13	6.7	134	0.52
Florence	6.86	14.1	0.68	0.65	0.011	0.03	8.9	43.75	0.75
Shell	2.15	12.61	0.785	0.96	0.011	0.07	10	108.5	1.16
Bass (L)	3.24	9.26	0.82	0.59	0.008	0.13	9.4	100.25	4.51
School	4.5	21.9	0.815	1.08	0.006	0.04	13.4	89.25	9.45
Tucker	3.12	17.5	0.8	0.76	0.007	0.025	12	123	1.26
North Bar	4.33	10.9	0.4	0.51	0.122	0.06	3.5	145.5	4.07
Loon	3.39	10.68	0.37	0.22	0.012	0.02	3.3	132.25	7.87
Round	3.88	10.87	0.695	0.56	0.007	0.05	7.2	129.5	18.25

Table 3b. Mean ice-free 2005 water quality variables from PIRO and SLBE lakes. Blue values are SCWRS lab data (see Elias 2006 for interlab variability).

PARK/lake	SO ₄	Ca	Na	K	Mg	SiO ₂	Secchi depth	pH	EC25
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(m)	(units)	µS/cm
PIRO									
Grand Sable	4.47	14.09	0.93	0.75	5.09	4.75	3.9	8	110
Trappers	4.45	23.26	1.06	0.59	5.52	5.88	NA	8.5	148
Chapel	8.31	21.91	0.8	0.68	10.49	4.41	3.6	8.1	187
Beaver	6.65	26	1.09	0.62	5.46	9.29	3.9	8.2	164
Little Beaver	7.52	20.69	1.03	0.63	5.74	6.52	2.8	8.2	165
Miners	8.41	32.77	1.3	0.63	16.83	6.6	2.5	7.8	278
SLBE									
Manitou	6.39	33.51	1.38	0.55	15.52	1.17	2.6	8.6	270
Florence	3.15	12.97	0.63	0.63	5.74	0.39	2.5	8.4	111
Shell	20.02	32.94	1.57	0.41	14.32	13.66	3	8.5	262
Bass (L)	3.14	31.49	2.98	0.92	10.08	3.65	3.2	8.6	229
School	5.81	24.56	3.51	0.7	10.78	16.36	NA	8.8	212
Tucker	4.83	35.08	1.05	0.32	12.67	7.72	NA	8.3	262
North Bar	9.41	44.29	1.59	0.57	15.38	5.48	2.2	8.3	329
Loon	10.05	41.99	5.78	0.66	12.42	7.14	3.2	8.4	310
Round	9.67	29.62	12.04	0.59	15.91	6.72	4.6	8.7	319

Table 4. Transformations of environmental variables

Variable	Transformation	Units
Chla	log10	µg/L
TP	1/TP	µg/L
TN	none	mg/L
NH4	sqrt	mg/L
DOC	1/sqrt	mg/L
Alk	sqrt	mg/L
Cl	log10(Cl+1)	mg/L
SO4	1/sqrt	mg/L
SiO2	sqrt	mg/L
Secchi	1/sqrt	m
pH	none	std units
EC25	log10	µS/cm
Removed Variables		
TKN	sqrt	mg/L
NO3NO2	none	mg/L
Ca	sqrt	mg/L
Na	1/Na	mg/L
K	none	mg/L
Mg	sqrt	mg/L

Table 5a. Diatom taxa present at >5% relative abundance in one sample or >1% abundance in two or more samples from surface sediments collected in 2005 from PIRO and SLBE lakes.

Code	Taxon	Max Abund	Grand Sable	Trappers	Chapel	Bear	Little Beaver
			PIGRSA	PITRAP	PICHAP	PIBEAV	PILTBV
CYCSPMCH	<i>Cyclotella sp. mich-like</i>	0.5638	0.004	0.141	0.000	0.245	0.000
DENKEUTZ	<i>Denticula kuetzingii</i>	0.3885	0.000	0.004	0.000	0.004	0.000
CYCCOMEN	<i>Cyclotella comensis</i>	0.3846	0.067	0.018	0.004	0.052	0.000
AULAMBIG	<i>Aulacoseira ambigua</i>	0.3534	0.118	0.000	0.000	0.000	0.033
AULSUBAR	<i>Aulacoseira subarctica</i>	0.3243	0.094	0.000	0.000	0.000	0.324
NAVCRYPT	<i>Navicula cryptotenella</i>	0.3185	0.002	0.114	0.000	0.002	0.007
SRACONVE	<i>Staurosira construens var. venter</i>	0.2813	0.023	0.000	0.047	0.026	0.031
SRACONST	<i>Staurosira construens</i>	0.2589	0.012	0.000	0.015	0.002	0.031
PRABREVI	<i>Pseudostaurosira brevistriata</i>	0.1733	0.000	0.002	0.045	0.002	0.038
ASTFORMO	<i>Asterionella formosa</i>	0.1258	0.081	0.000	0.043	0.126	0.042
CYCSTELL	<i>Discostella stelligera</i>	0.1137	0.042	0.000	0.114	0.009	0.007
CYCMICHI	<i>Cyclotella michiganiana</i>	0.1094	0.002	0.051	0.058	0.017	0.000
FRACROTO	<i>Fragilaria crotonensis</i>	0.0906	0.091	0.000	0.073	0.020	0.049
ENPMICRO	<i>Encyonopsis microcephala</i>	0.0781	0.004	0.051	0.002	0.000	0.000
ACHMINUT	<i>Achnanthis minutissimum</i>	0.0773	0.064	0.022	0.077	0.037	0.020
ENCCFHEB	<i>Encyonema cf hebridicum</i>	0.0754	0.000	0.075	0.000	0.000	0.000
SLLPINNA	<i>Staurosirella pinnata</i>	0.0731	0.013	0.000	0.024	0.011	0.009
ROSLINEA	<i>Rosithidium linearis</i>	0.0705	0.008	0.000	0.019	0.000	0.004
ENPCESTI	<i>Encyonopsis cesatii</i>	0.0692	0.000	0.069	0.000	0.002	0.000
COCPLALI	<i>Cocconeis placentula var. lineata</i>	0.0684	0.000	0.000	0.017	0.000	0.007
TABFLOCC	<i>Tabellaria flocculosa</i>	0.0665	0.027	0.000	0.067	0.000	0.026
CYCOCELL	<i>Cyclotella ocellata</i>	0.0664	0.010	0.000	0.000	0.000	0.000
BRAVITRE	<i>Brachysira vitrea</i>	0.0631	0.002	0.063	0.000	0.002	0.000
SLLLAPPO	<i>Staurosirella lapponica</i>	0.0626	0.002	0.000	0.000	0.000	0.000
CYCDISTI	<i>Cyclotella distinguenda</i>	0.0553	0.000	0.000	0.000	0.004	0.000
NUPCFSCH	<i>Nupela cf schoemana</i>	0.0531	0.000	0.000	0.000	0.000	0.000
CYMCFTEN	<i>Cymbella sp. cf tenuissima</i>	0.0530	0.000	0.053	0.000	0.000	0.000
CYCSPNOR	<i>Cyclotella sp. coarse striae, plain center</i>	0.0509	0.000	0.051	0.000	0.035	0.000
COCNEOTH	<i>Cocconeis neothumensis</i>	0.0491	0.004	0.000	0.017	0.009	0.013
AMPPERPU	<i>Amphora perpusilla</i>	0.0456	0.021	0.000	0.000	0.017	0.000
NAVGLBO	<i>Navicula globosa</i>	0.0418	0.000	0.000	0.000	0.000	0.000
NAVMINIM	<i>Navicula minima</i>	0.0313	0.031	0.000	0.000	0.000	0.000
SYNFILIF	<i>Synedra filiformis</i>	0.0268	0.004	0.000	0.013	0.017	0.004
NAVVERCD	<i>Navicula verecunda</i>	0.0237	0.004	0.000	0.000	0.002	0.000
MAR1GLEI	<i>Martyana sp. #1 GLEI</i>	0.0193	0.019	0.000	0.006	0.004	0.011
ACHBIASO	<i>Achnanthes biasoletiana [KLB]</i>	0.0192	0.000	0.014	0.000	0.000	0.000
KARCLEVE	<i>Karayevia clevei</i>	0.0192	0.000	0.000	0.006	0.009	0.011
NITSUBLI	<i>Nitzschia sublinearis</i>	0.0179	0.004	0.006	0.011	0.007	0.000
SYNRADIA	<i>Synedra radians</i>	0.0176	0.004	0.002	0.006	0.007	0.000
AMPSUBCO	<i>Amphora subcostulata</i>	0.0172	0.004	0.000	0.004	0.009	0.002
CYCBODLE	<i>Cyclotella bodanica var. lemanica</i>	0.0156	0.006	0.002	0.011	0.004	0.002
NAVUTERM	<i>Navicula utermoehlii</i>	0.0146	0.000	0.000	0.002	0.000	0.000
GOMANGUS	<i>Gomphonema angustatum</i>	0.0146	0.002	0.000	0.000	0.004	0.000
MARMARTY	<i>Martyana martyi</i>	0.0110	0.000	0.000	0.006	0.007	0.011

Table 5b. Diatom taxa present at >5% relative abundance in one sample or >1% abundance in two or more samples from surface sediments collected in 2005 from PIRO and SLBE lakes.

Code	Miners	Manitou	Florence	Shell	Bass Lake	Tucker	North Bar	Loon	Round
	PIMINE	SLMANT	SLFLOR	SLSHLL	SLBASS	SLTUCK	SLNBAR	SLLOON	SLROND
CYCSPMCH	0.000	0.564	0.000	0.002	0.213	0.000	0.034	0.075	0.030
DENKEUTZ	0.000	0.000	0.000	0.389	0.013	0.023	0.009	0.004	0.051
CYCCOMEN	0.000	0.213	0.022	0.000	0.385	0.000	0.192	0.295	0.132
AULAMBIG	0.000	0.020	0.000	0.000	0.002	0.000	0.353	0.052	0.002
AULSUBAR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
NAVCRYPT	0.009	0.000	0.065	0.318	0.015	0.025	0.006	0.002	0.018
SRACONVE	0.126	0.002	0.281	0.000	0.018	0.046	0.024	0.025	0.073
SRACONST	0.017	0.028	0.000	0.002	0.002	0.169	0.000	0.006	0.259
PRABREVI	0.043	0.011	0.000	0.000	0.000	0.173	0.075	0.066	0.136
ASTFORMO	0.000	0.009	0.000	0.000	0.022	0.000	0.002	0.019	0.000
CYCSTELL	0.000	0.000	0.013	0.000	0.000	0.002	0.000	0.000	0.004
CYCMICHI	0.000	0.020	0.109	0.013	0.051	0.019	0.011	0.008	0.018
FRACROTO	0.000	0.009	0.000	0.004	0.007	0.008	0.047	0.060	0.010
ENPMICRO	0.000	0.005	0.078	0.015	0.026	0.000	0.000	0.004	0.006
ACHMINUT	0.073	0.007	0.067	0.004	0.011	0.015	0.011	0.044	0.010
ENCCFHEB	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SLLPINNA	0.015	0.020	0.000	0.002	0.009	0.073	0.004	0.012	0.028
ROSLINEA	0.071	0.000	0.025	0.004	0.015	0.050	0.004	0.012	0.004
ENPCESTI	0.000	0.000	0.000	0.011	0.011	0.000	0.000	0.000	0.004
COCPLALI	0.068	0.000	0.000	0.000	0.000	0.006	0.000	0.008	0.004
TABFLOCC	0.000	0.000	0.002	0.000	0.002	0.000	0.000	0.000	0.000
CYCOCELL	0.000	0.000	0.000	0.000	0.000	0.017	0.000	0.066	0.000
BRAVITRE	0.000	0.000	0.033	0.021	0.009	0.002	0.002	0.000	0.012
SLLLAPPO	0.000	0.000	0.000	0.000	0.000	0.063	0.017	0.000	0.006
CYCDISTI	0.000	0.000	0.000	0.000	0.000	0.000	0.015	0.002	0.055
NUPCFSCH	0.000	0.000	0.000	0.053	0.000	0.000	0.000	0.000	0.000
CYMCFTEN	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
CYCSPNOR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
COCNEOTH	0.049	0.000	0.000	0.000	0.000	0.000	0.000	0.004	0.000
AMPPERPU	0.024	0.000	0.000	0.000	0.000	0.000	0.000	0.046	0.000
NAVGLOBO	0.000	0.000	0.000	0.000	0.000	0.042	0.000	0.017	0.004
NAVMINIM	0.000	0.000	0.013	0.000	0.002	0.031	0.000	0.000	0.012
SYNFILIF	0.000	0.000	0.027	0.000	0.011	0.000	0.000	0.004	0.000
NAVVERCD	0.000	0.000	0.000	0.000	0.020	0.017	0.000	0.002	0.024
MARIGLEI	0.019	0.000	0.000	0.000	0.000	0.006	0.004	0.000	0.000
ACHBIASO	0.019	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
KARCLEVE	0.019	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.000
NITSUBLI	0.011	0.000	0.018	0.008	0.000	0.000	0.000	0.000	0.000
SYNRADIA	0.000	0.002	0.011	0.000	0.018	0.000	0.000	0.004	0.004
AMPSUBCO	0.013	0.000	0.000	0.000	0.000	0.000	0.017	0.012	0.008
CYCBODLE	0.000	0.000	0.016	0.006	0.015	0.000	0.006	0.000	0.004
NAVUTERM	0.002	0.000	0.013	0.000	0.000	0.015	0.000	0.000	0.010
GOMANGUS	0.002	0.000	0.000	0.013	0.000	0.015	0.002	0.000	0.000
MARMARTY	0.011	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table 6a. History and landuse change in and near Pictured Rocks National Lakeshore (1800-2005). Prepared by Lora Loope, resource manager, PIRO.

Calendar Years	Activity / Occurrence	Citation
16th century	Mega-drought (inferred)	Booth <i>et al.</i> 2003
1659	Radisson and Groseilliers leave written record of their travels along Lake Superior's south shore	Symon 1986
1688	Grand Sable Dunes appear on French maps	Symon 1986
1840s	Alger County was surveyed by US Gov't	Symon 1986
1845	Iron ore discovered in Marquette Co. (adjacent county to the west)	CCI 1920
1861	First trading post at Grand Marais	Symon 1986
1871	Commercial fishing begins from Grand Marais	Symon 1986
1874	Au Sable Lighthouse built at Au Sable Point	park historic documents
1879	First sawmill in Grand Marais	Symon 1986
~1880	Anthropogenic disturbance horizon (logging and fire 21cm & 38cm downcore from ponds 37km WSE of GSL), ²¹⁰ Pb dating	Lytle 2005
	European settlement (20-21 cm downcore of bog 26km from GSL): increased pollen of <i>Ambrosia</i> , <i>Compositae</i> , <i>Chenopodiaceae</i> / <i>Amaranthaceae</i> , <i>Plantago</i> , <i>Morus</i>	Futyma 1987
1882 - 1885	Logging camp operated at Sullivan's Landing on Lake Superior (22km W of GSL)	Frederick <i>et al.</i> 1977
1890 - 1895	Most logging activity and slash burning on Kingston Plains occurred (inferred from tax evaluations)	Barrett 1995
	White pine and hemlock logging (16 cm downcore of bog 26km W of GSL): charcoal peak, pine/fern pollen changes	Futyma 1987, Booth <i>et al.</i> 2004
~1910	Major fire in Kingston Plains area, 37km SW of GSL	Frederick <i>et al.</i> 1977
~1915 - 1930s	Drought and wildland fires (1939 aerial photos; testate amoeba-inferred paleohydrology from bog 16km S of GSL)	Booth <i>et al.</i> 2003, Barrett 1995
	fires: charcoal peak (7cm downcore of bog 26km from GSL)	Futyma 1987
1936	Fire on eastern Kingston Plains, ~37km SW of GSL	Barrett 1995

Table 6b. History and landuse change in and near Pictured Rocks National Lakeshore (1800-2005). Prepared by Lora Loope, resource manage, PIRO.

1930s -1950s	Seasonal rental cabins present in 1930s; most cabins were built in 1940s; but a few were built in the 1950s. There was only 1 year- around home on property adjacent to the lake.	per. comm. Brody Block of Grand Marais (2/23/2007)
~1946	H-58 from Grand Marais to Kingston Corners was upgraded from a two-track road to a graded road about 1946. This is the road on the north edge of GSL.	per. comm. Brody Block of Grand Marais (2/23/2007)
1908-1950	Smallmouth bass stocked by MiDNR	MiDNR, Vogel 1999
1934-1939	Bluegill stocked by MiDNR	MiDNR, Vogel 1999
1937-1942	Walleye (not native to the lake) stocked by MiDNR, but not observed since.	MiDNR, Vogel 1999
1940-2005	Lake trout (not native to the lake) stocked by MiDNR.	MiDNR, Vogel 1999
1950-1953	Rainbow smelt (non-native) stocked by MiDNR	MiDNR, Vogel 1999
1951-1962	Rainbow trout/steelhead (exotic) stocked by MiDNR	MiDNR, Vogel 1999
1965-1982	Splake (non-native hybrid) stocked by MiDNR	MiDNR, Vogel 1999
1969-1972	~30 cabins/seasonal homes removed from the E shore of GSL	park historic documents

Table 7. History and landuse change in and near Sleeping Bear National Lakeshore (1800-2005).

Calendar Years	Activity / Occurrence	Citation
1810	two native villages near Leland and Northport	Haswell and Alanen 1994
1830s	seven native villages in area	
pre-1840s	Ojibwa Indians subsistence regimen, hunting, fishing, gathering, raising corn, beans, squash	Haswell and Alanen 1994
late 1840s	Euro-American settlers arrive, logging (cordwood) for steamships.	Haswell and Alanen 1994
1840s-1860s	pioneering agriculture, mostly subsistence, potatoes, corn, maple syrup	Haswell and Alanen 1994
1860s	increased numbers of settlers arrive, German, Canadian, British, Norwegian, Bohemian, communities set up around cordwood trade to fuel Great Lakes steamships	Haswell and Alanen 1994
1870s	increased agriculture as railroad and roads allow access to markets, decrease of cordwood industry, but increased access to forests for logging with logging railroads	Haswell and Alanen 1994
1870s	local orchards set up, peach, apple, pear, plum, cherries (1890s)	Haswell and Alanen 1994
1880s	farming begins decline on N Manitou Island	Haswell and Alanen 1994
1890s	forest products dominate local economy, population 39% foreign-born	Haswell and Alanen 1994
1900s	forest products industry waning, agriculture, especially cherry production, increases, tourism industry becomes more important	Haswell and Alanen 1994
1910s-1930s	livestock and cropping (corn, hay, potatoes), S. Manitou Island targeted for new rye variety and hybrid beans, some decline in number of farms portends future	Haswell and Alanen 1994
1920s	N Manitou Island with fruit, limited corn, potatoes, hay, and cattle operation near Crescent City. Deer introduced to island.	
1930s	Depression, increased soil conservation techniques, electrification of farms	Haswell and Alanen 1994
1940s	number of farms decreasing, acreage withdrawn from production, farm size increases though	Haswell and Alanen 1994
1920s-1950s	limited agriculture on N. Manitou Island continues	Haswell and Alanen 1994
1940	last independent farmer leaves N. Manitou Island	Haswell and Alanen 1994
1945-1950	40% decrease in farm acres, loss of 20% of farms	Haswell and Alanen 1994
1950-1959	32% decrease in farm acres, loss of another 25% of farms	Haswell and Alanen 1994
1959-1969	25% decrease in farm acres. Compare 1969 when 19% of Benzie Co was in agriculture vs 50% in 1910. Leelanau Co 35% in agriculture in 1969 vs 75% in 1920.	Haswell and Alanen 1994
Oct 1970	Sleeping Bear Dunes established	Haswell and Alanen 1994

FIGURES

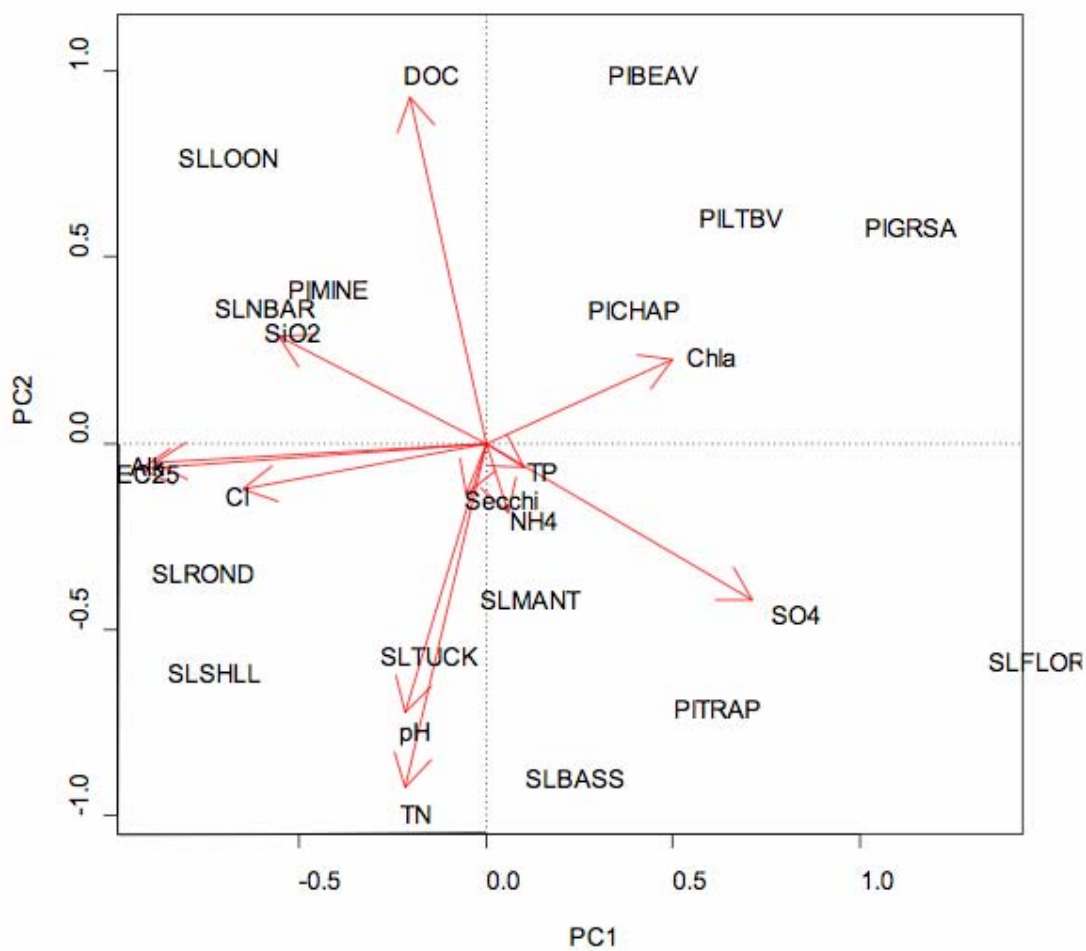


Figure 1. Principal components analysis (PCA) of twelve 2005 WQ variables (see Table 4 for variables and transformations) from SLBE and PIRO lakes, PCA axis 1 vs PCA axis 2, environmental vectors scaled at 0.7.

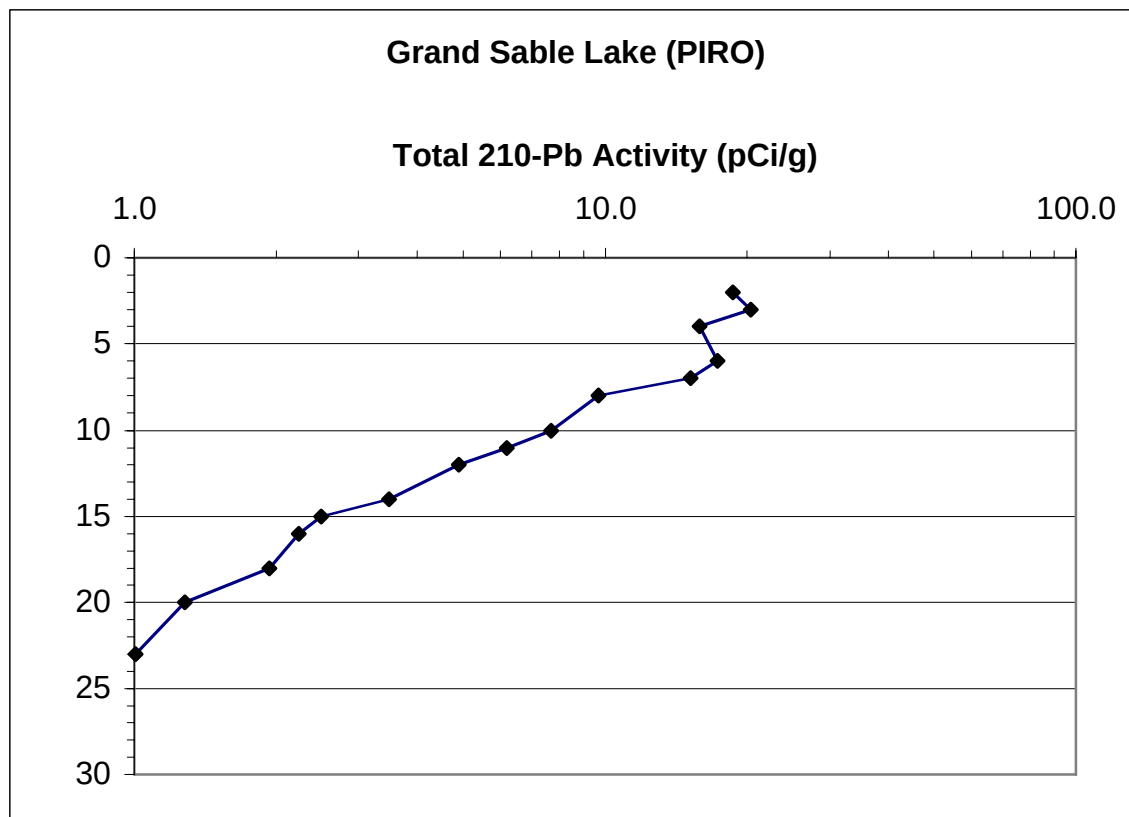


Figure 2. Total ^{210}Pb activity against core depth (cm), Grand Sable Lake (PIRO).

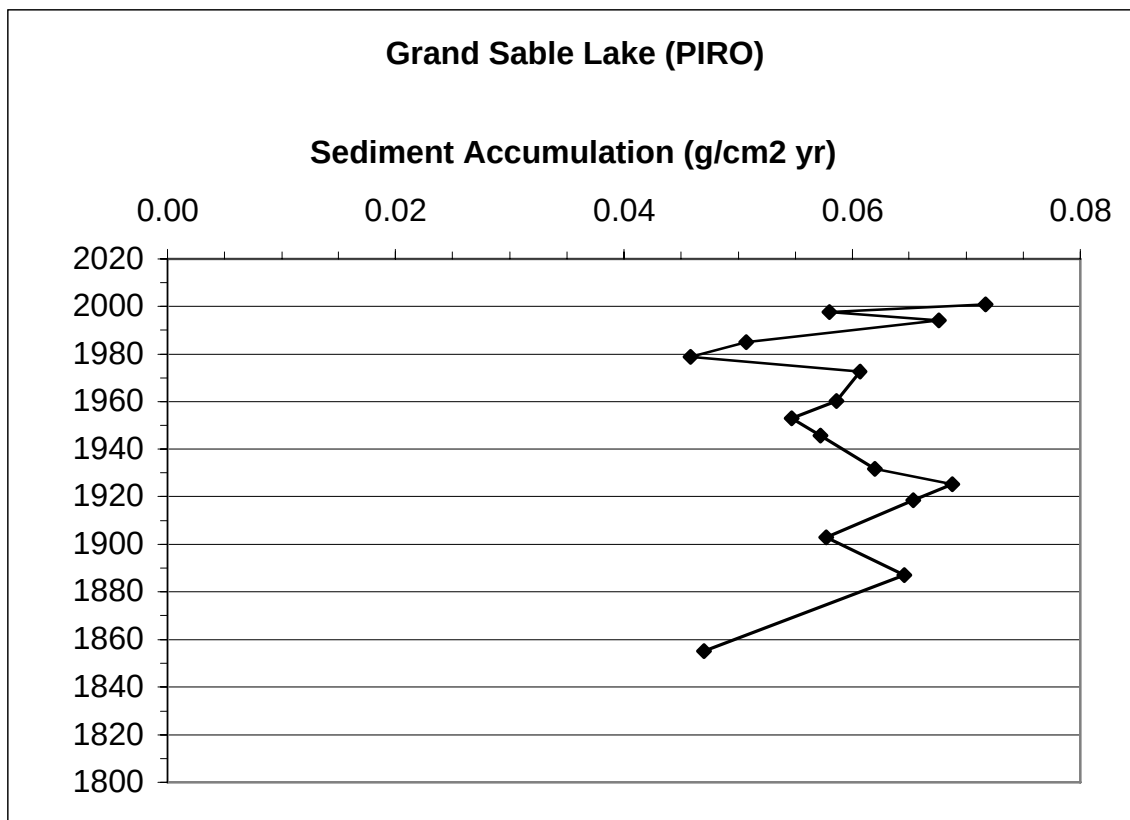


Figure 3. Sediment accumulation rate, Grand Sable Lake (PIRO), g cm⁻² yr⁻¹.

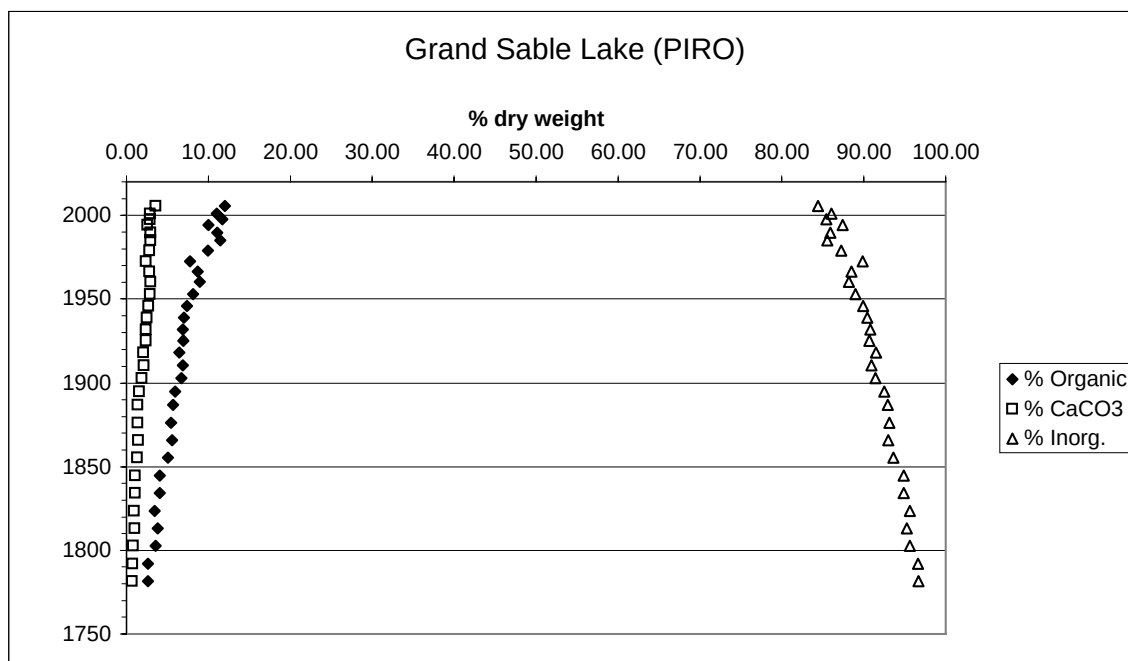


Figure 4. Percent concentration of CaCO₃, organic carbon and inorganic matter in Grand Sable Lake (PIRO) core.

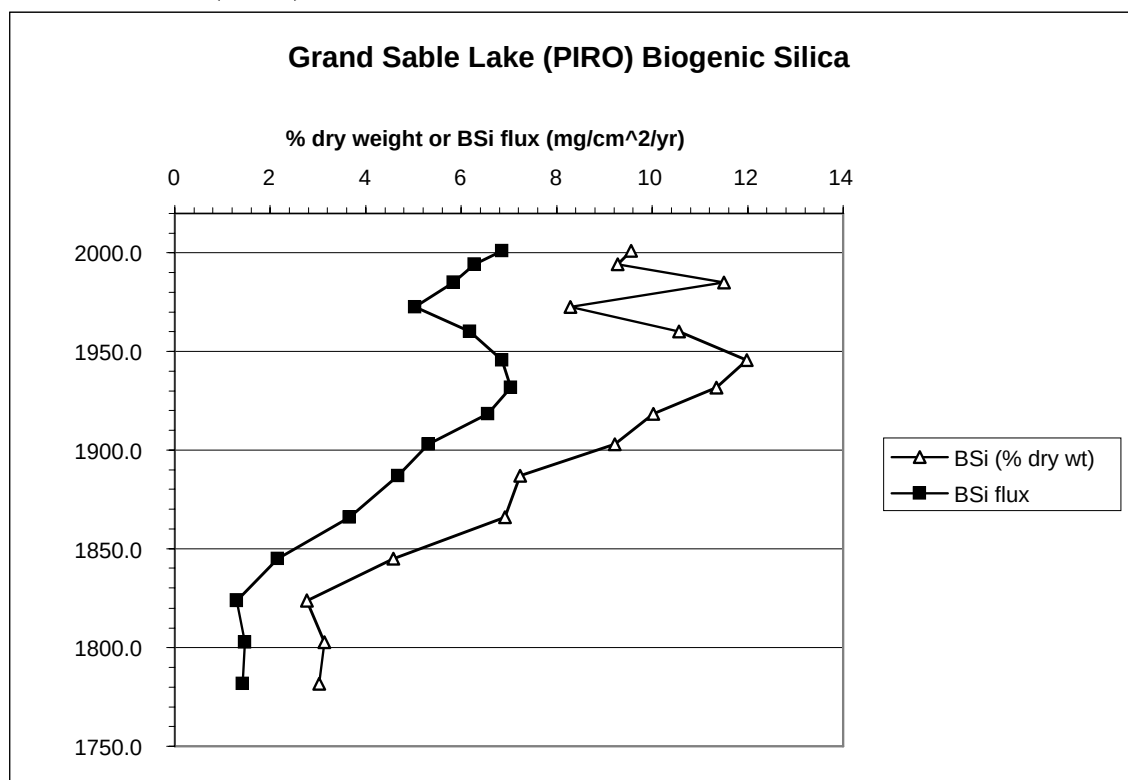


Figure 5. Biogenic silica dry weight percent and flux ($\text{mg cm}^{-2} \text{yr}^{-1}$), Grand Sable Lake (PIRO).

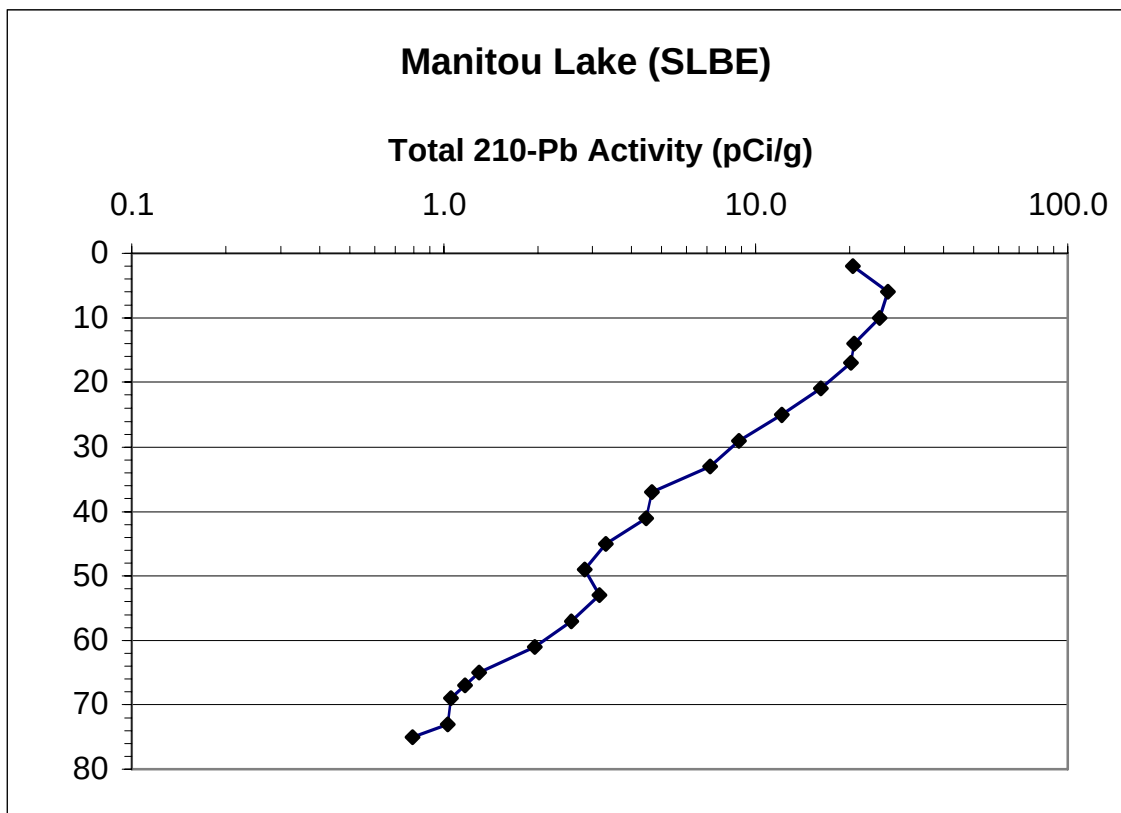


Figure 6. Total ^{210}Pb activity against core depth (cm), Manitou Lake (SLBE).

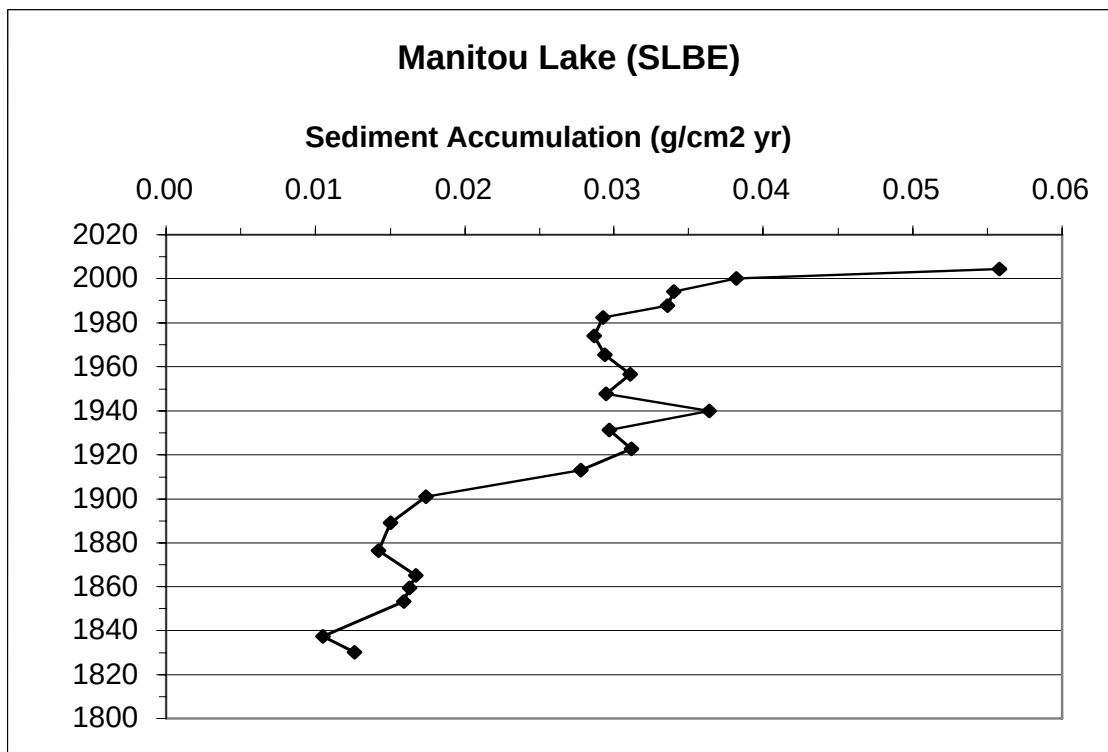


Figure 7. Sediment accumulation rate, Manitou Lake (SLBE), g cm⁻² yr⁻¹.

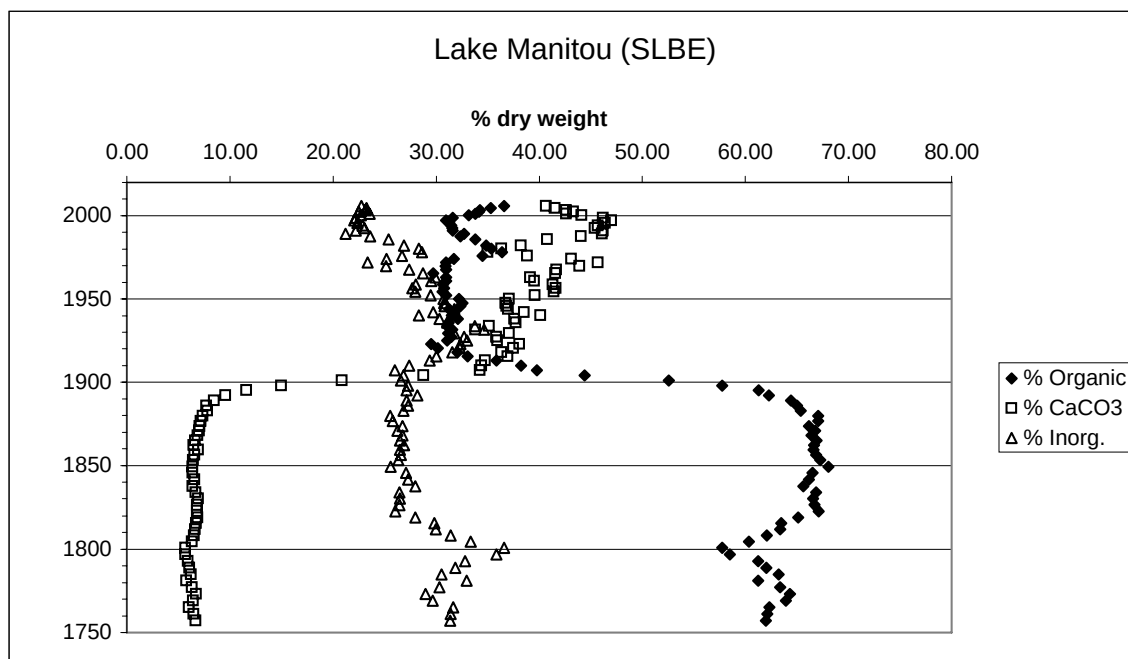


Figure 8. Percent concentration of CaCO₃, organic carbon and inorganic matter in Lake Manitou (SLBE) core.

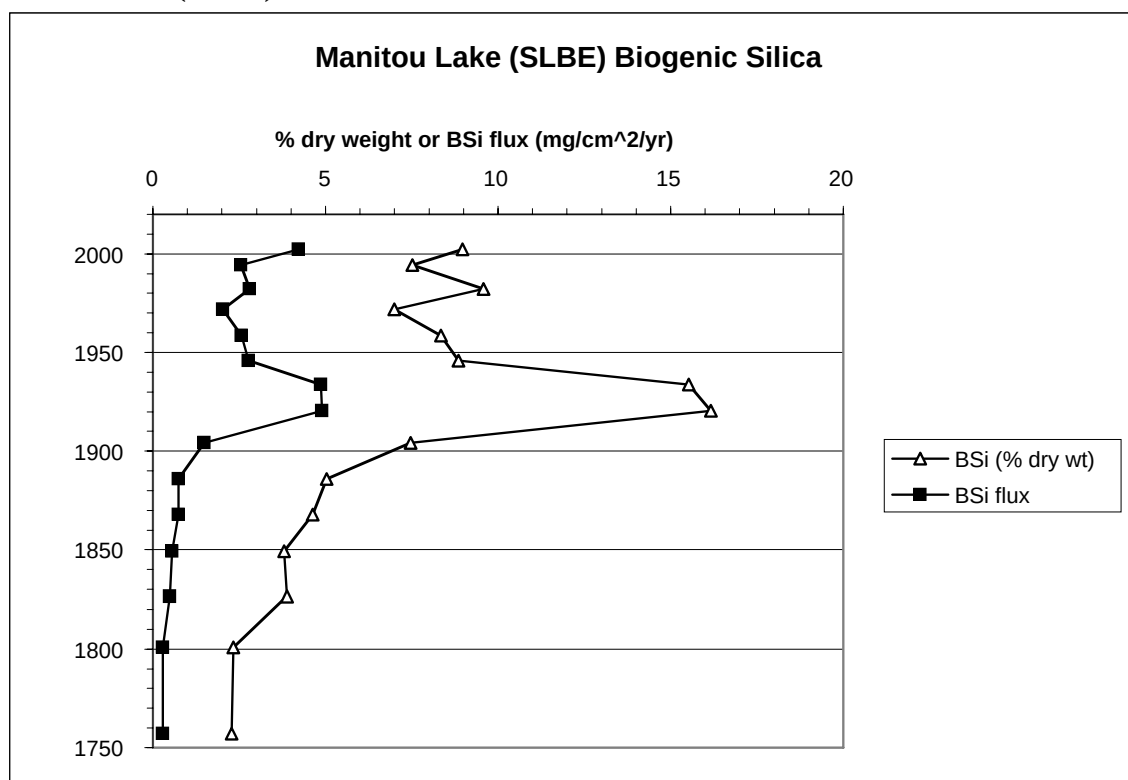


Figure 9. Biogenic silica dry weight percent and flux ($\text{mg cm}^{-2} \text{yr}^{-1}$), Manitou Lake (SLBE).

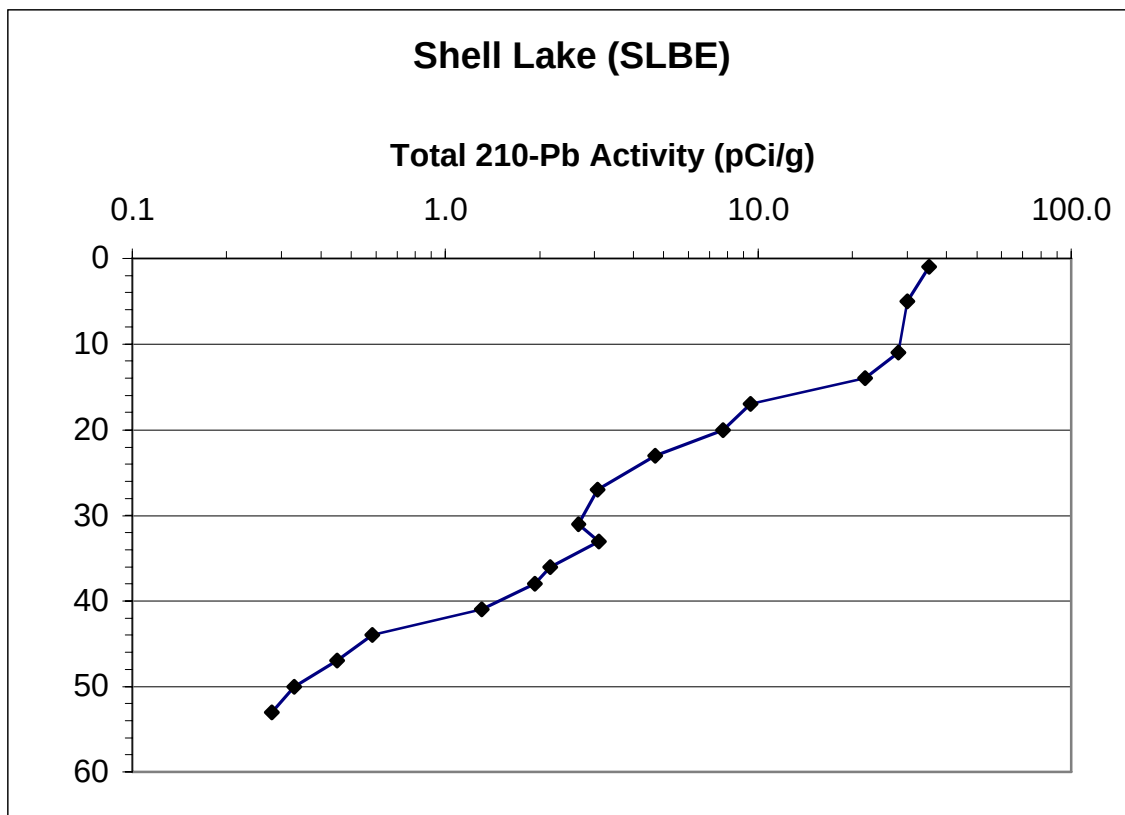


Figure 10. Total ^{210}Pb activity against core depth (cm), Shell Lake (SLBE).

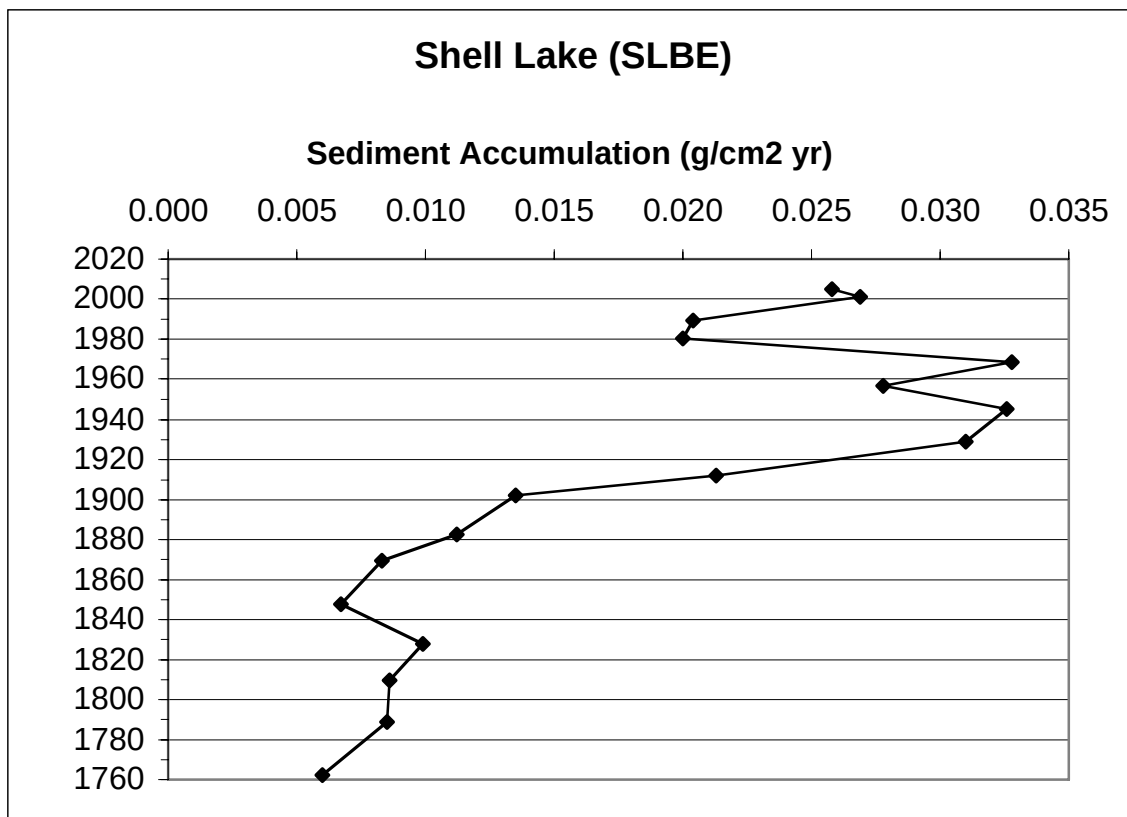


Figure 11. Sediment accumulation rate, Shell Lake (SLBE), g cm⁻² yr⁻¹.

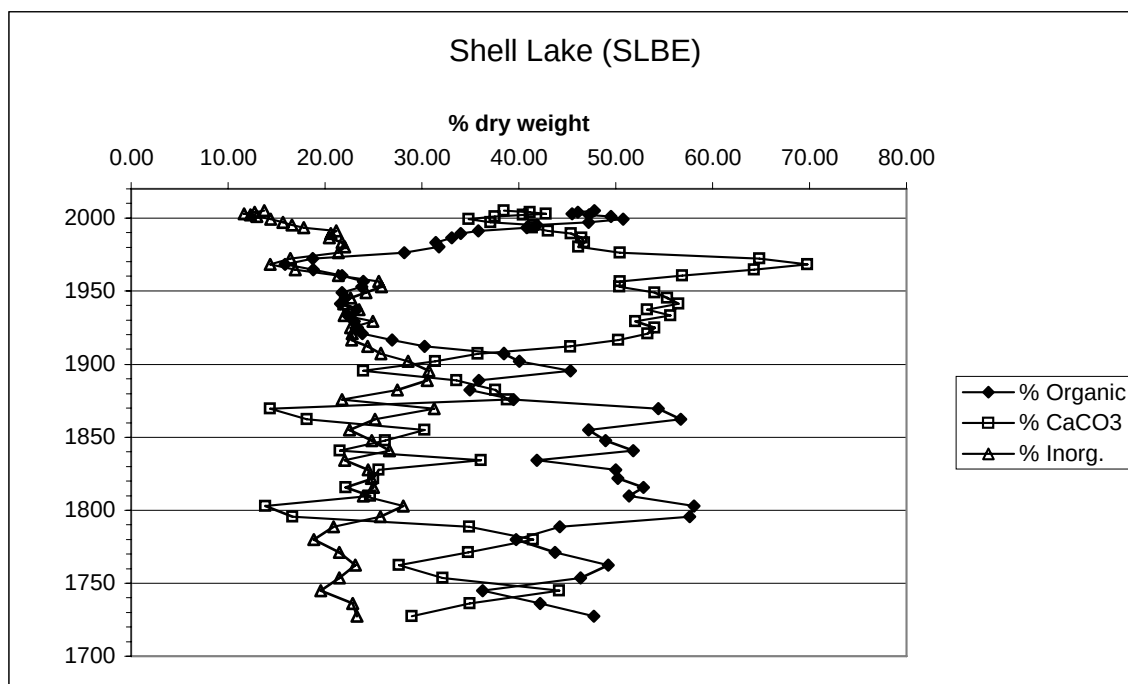


Figure 12. Percent concentration of CaCO₃, organic carbon and inorganic matter in Shell Lake (SLBE) core.

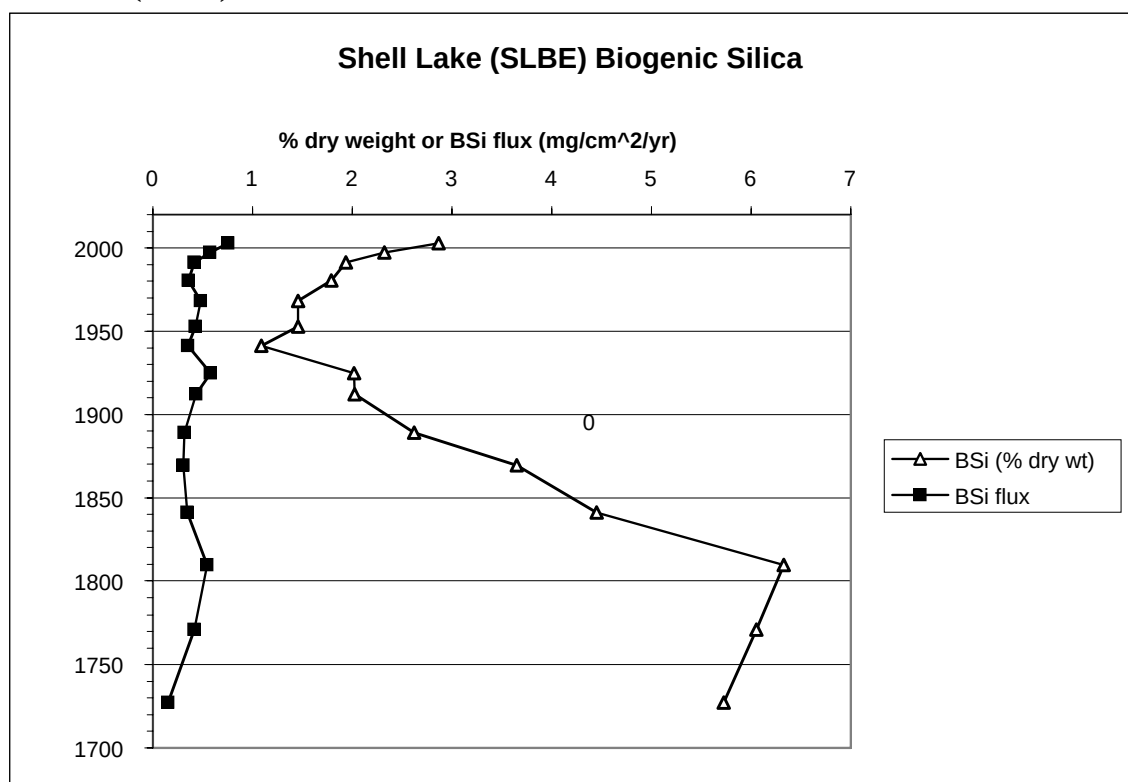


Figure 13. Biogenic silica dry weight percent and flux ($\text{mg cm}^{-2} \text{yr}^{-1}$), Shell Lake (SLBE).

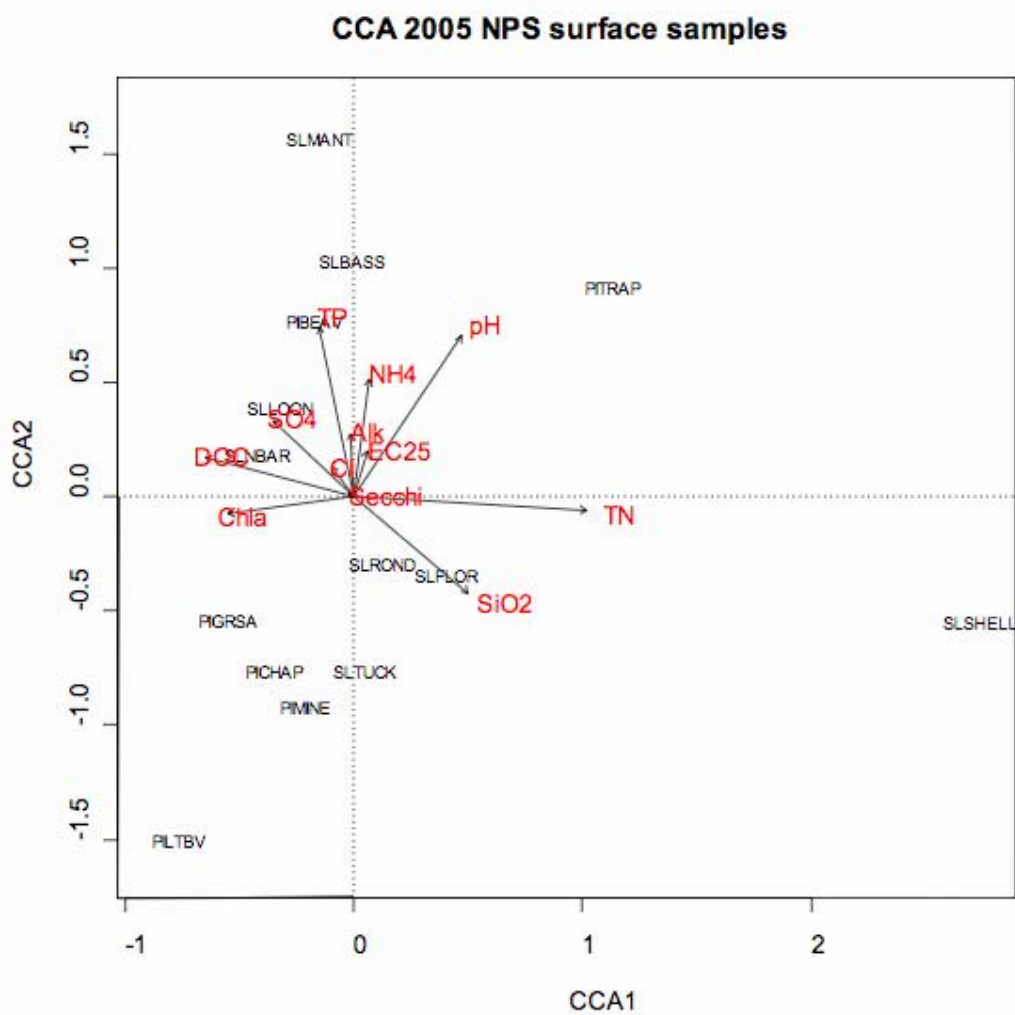


Figure 14. Canonical correspondence analysis (CCA) of diatom species-environment relationships in SLBE and PIRO lakes, site scores plotted on CCA axes 1 and 2.

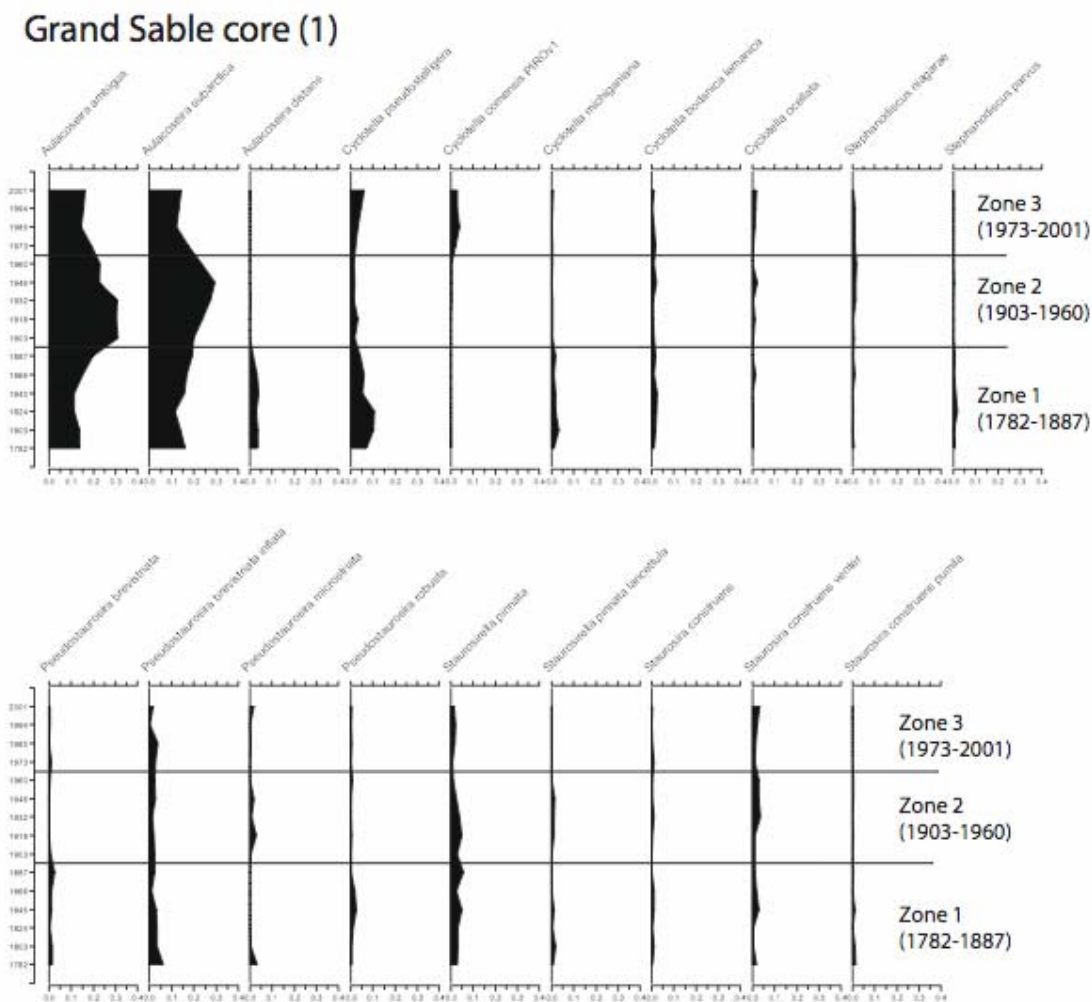


Figure 15a. Downcore abundances of taxa found at >5% relative abundance in one sample or >1% abundance in two or more samples in Grand Sable Lake (PIRO).

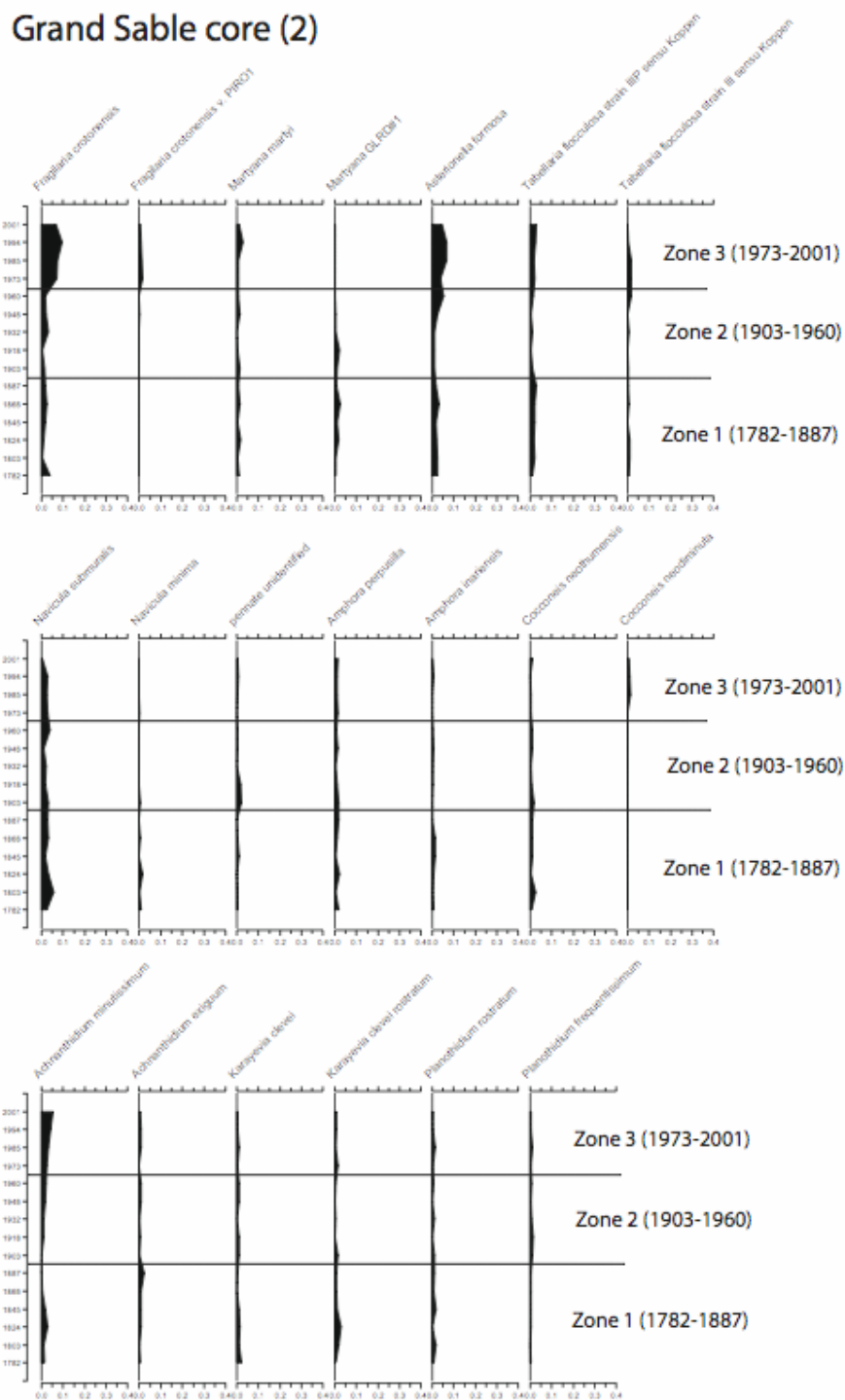


Figure 15b. Downcore abundances of taxa found at >5% relative abundance in one sample or >1% abundance in two or more samples in Grand Sable Lake (PIRO).

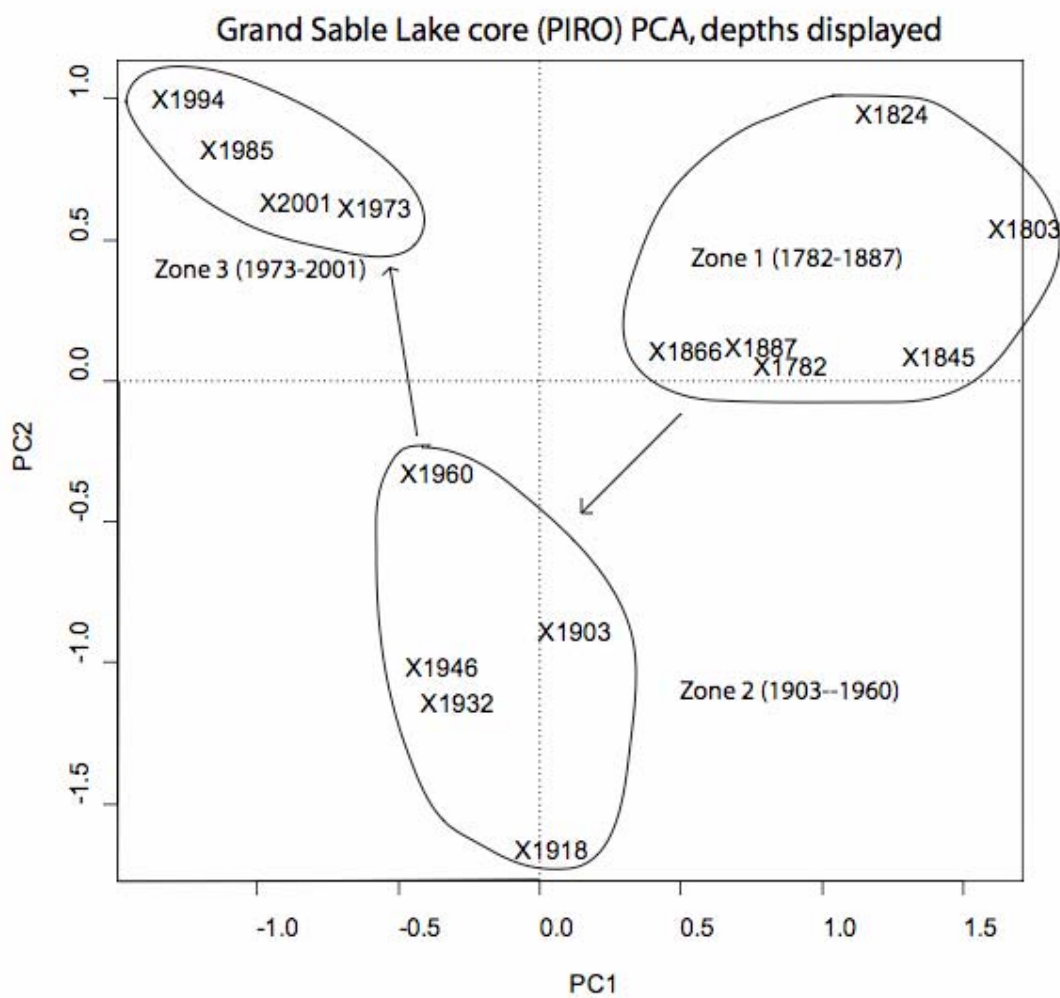


Figure 16. Principal components analysis (PCA) of downcore diatom assemblages from Grand Sable Lake (PIRO, 1782-2001), axes 1 and 2 loadings plotted for core depths.

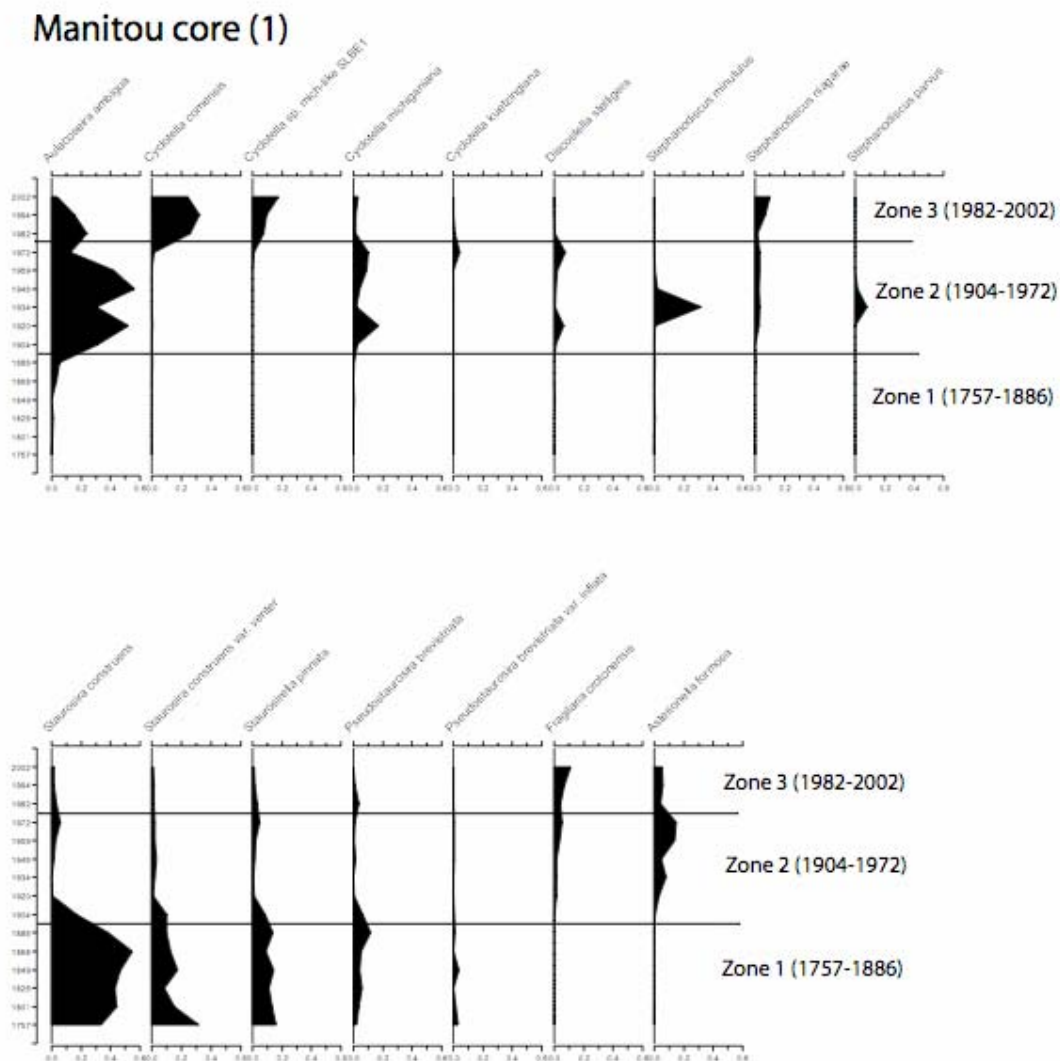


Figure 17a. Downcore abundances of taxa found at >5% relative abundance in one sample or >1% abundance in two or more samples in Manitou Lake (SLBE).

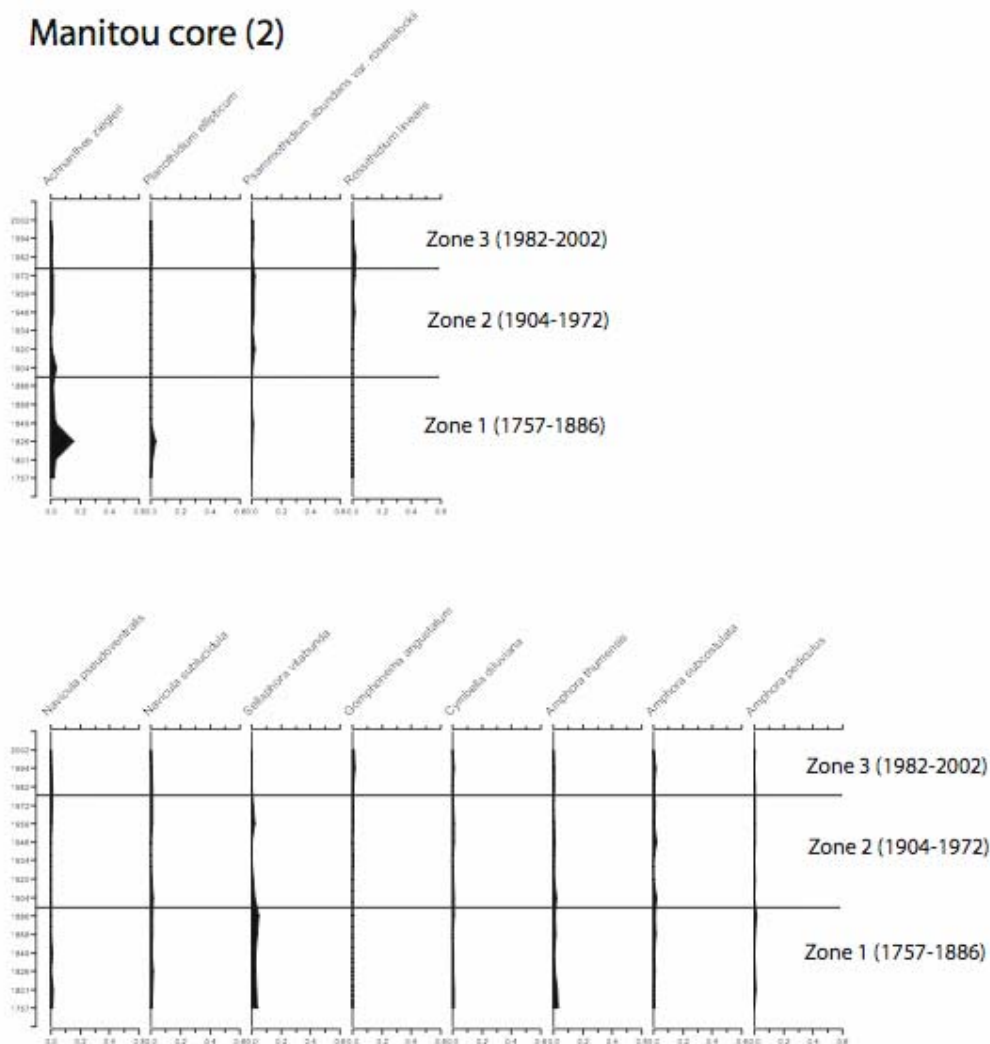


Figure 17b. Downcore abundances of taxa found at >5% relative abundance in one sample or >1% abundance in two or more samples in Manitou Lake (SLBE).

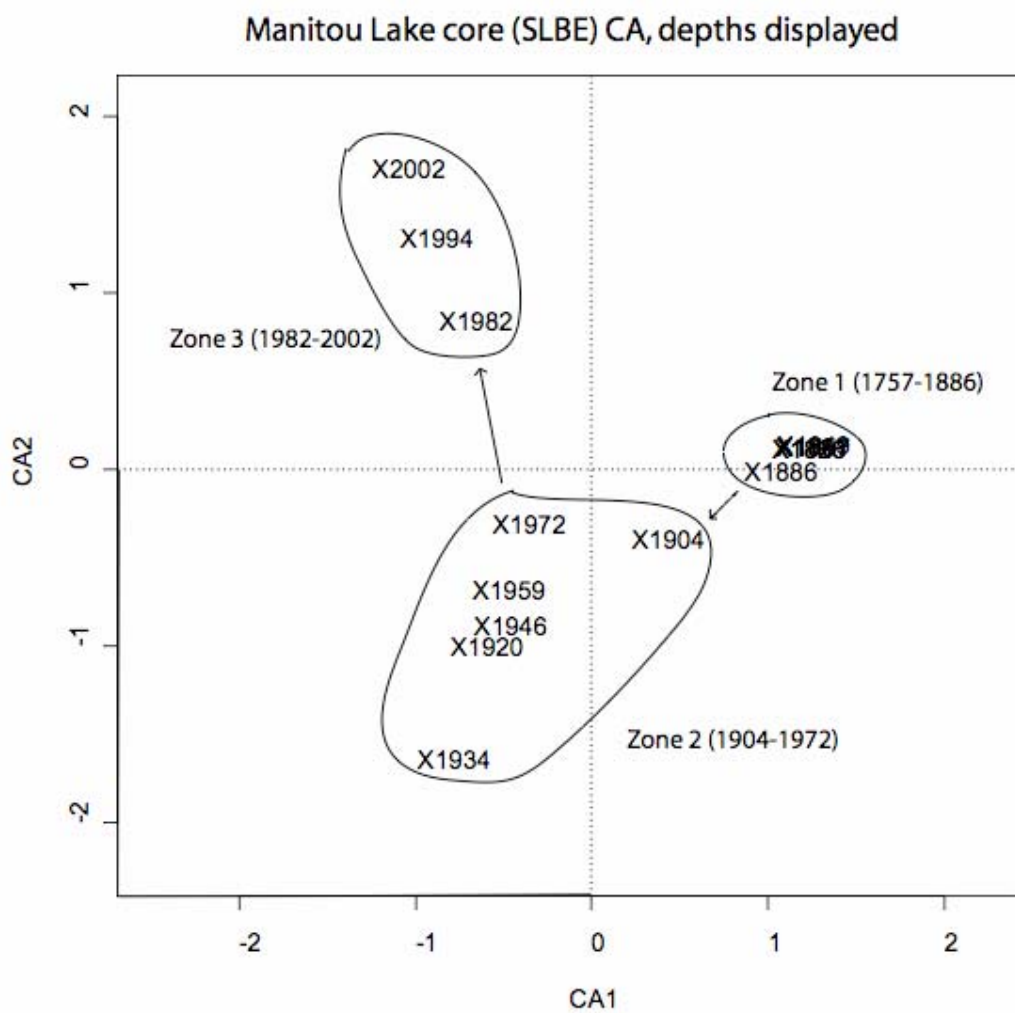


Figure 18. Correspondence analysis (CA) of downcore diatom assemblages from Lake Manitou (SLBE, 1757-2002), axes 1 and 2 loadings plotted for core depths.

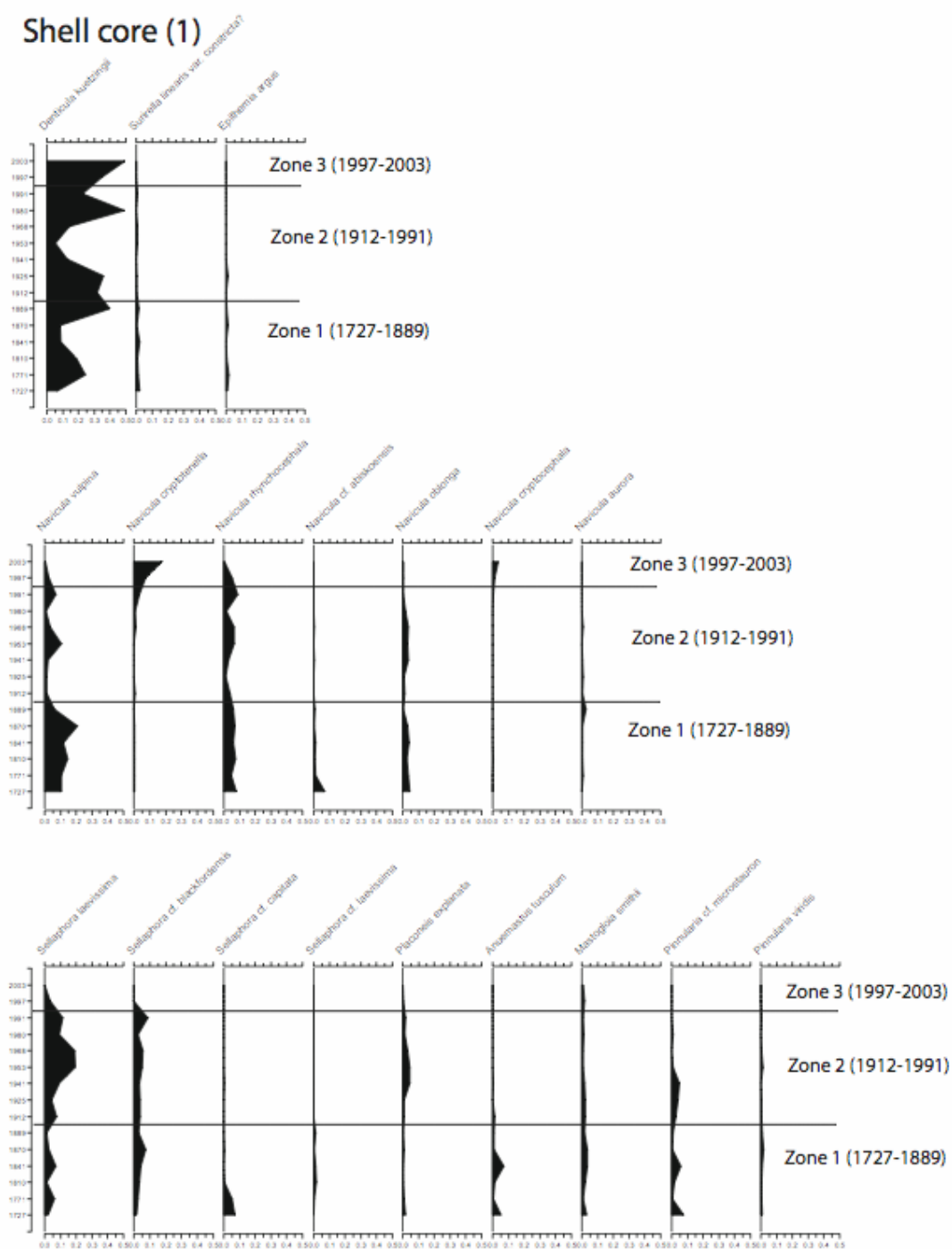


Figure 19a. Downcore abundances of taxa found at >5% relative abundance in one sample or >1% abundance in two or more samples in Shell Lake (SLBE).

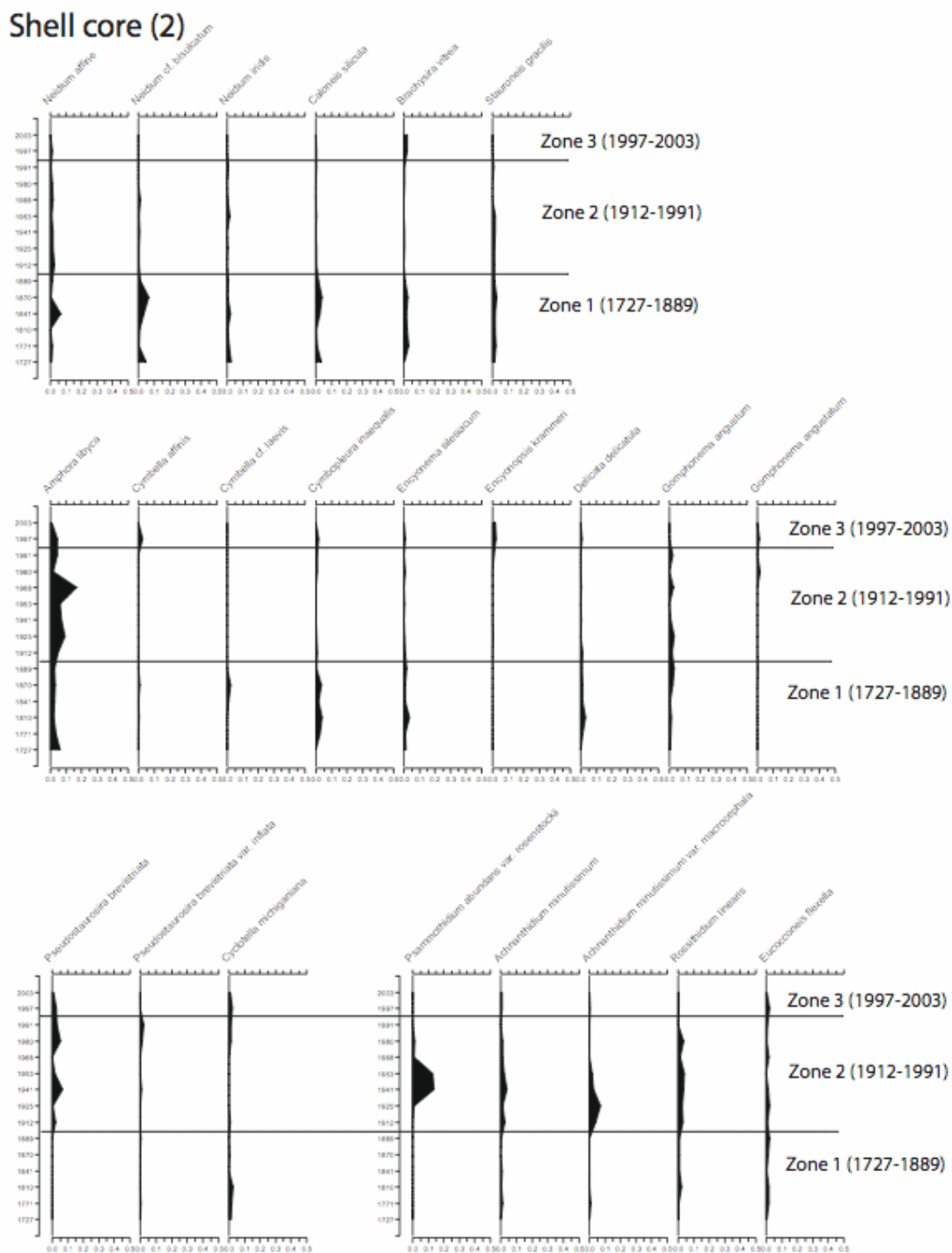


Figure 19b. Downcore abundances of taxa found at >5% relative abundance in one sample or >1% abundance in two or more samples in Shell Lake (SLBE).

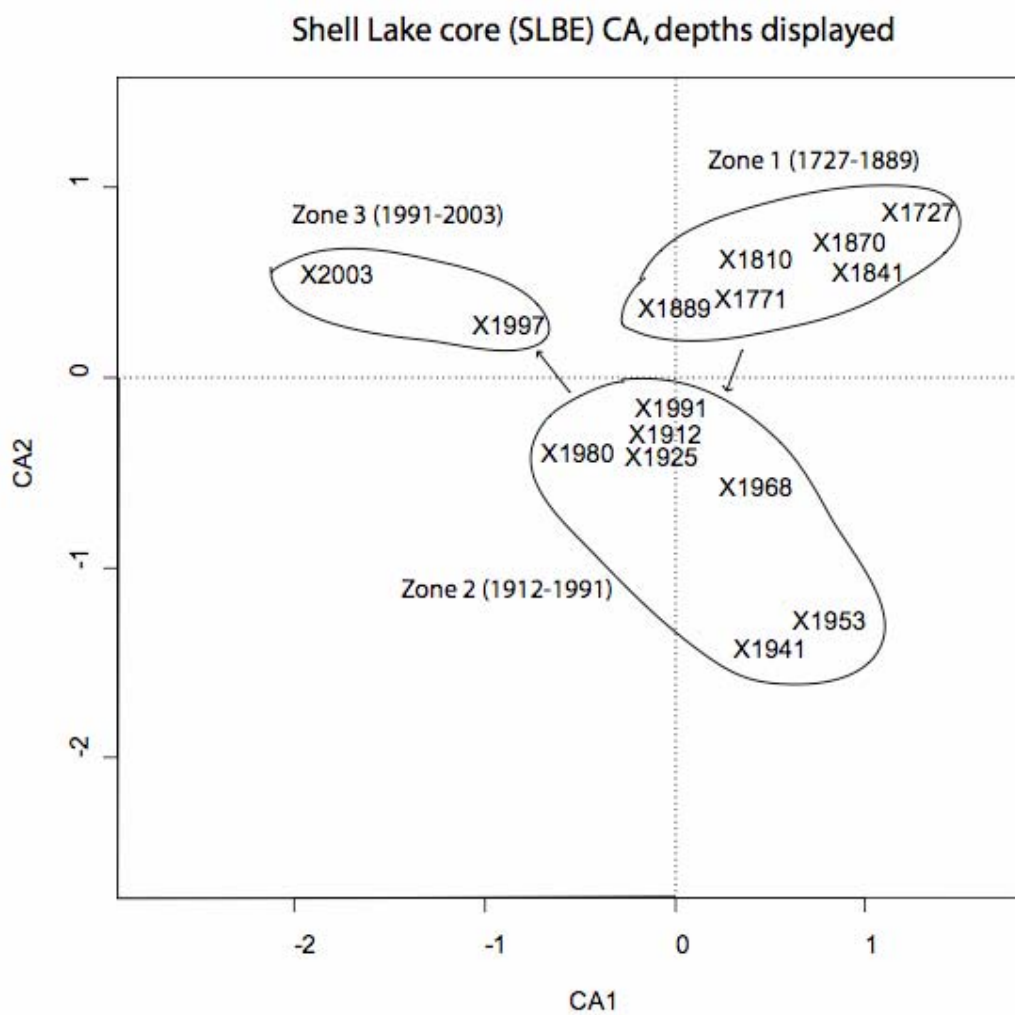


Figure 20. Correspondence analysis (CA) of downcore diatom assemblages from Shell Lake (SLBE, 1727-2003), axes 1 and 2 loadings plotted for core depths.

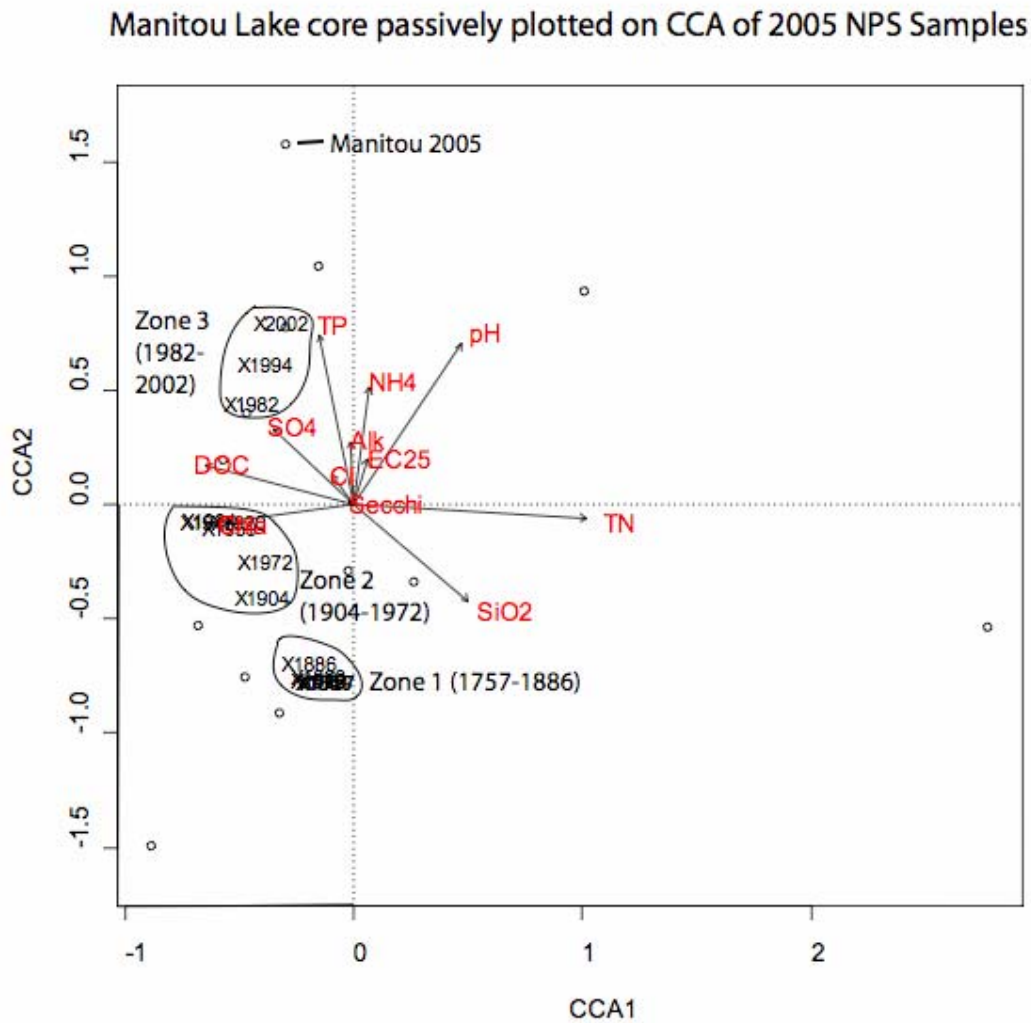


Figure 21. Diatom assemblages from 2005 Lake Manitou core plotted passively on CCA of diatom species-environment relationships in SLBE and PIRO lakes.

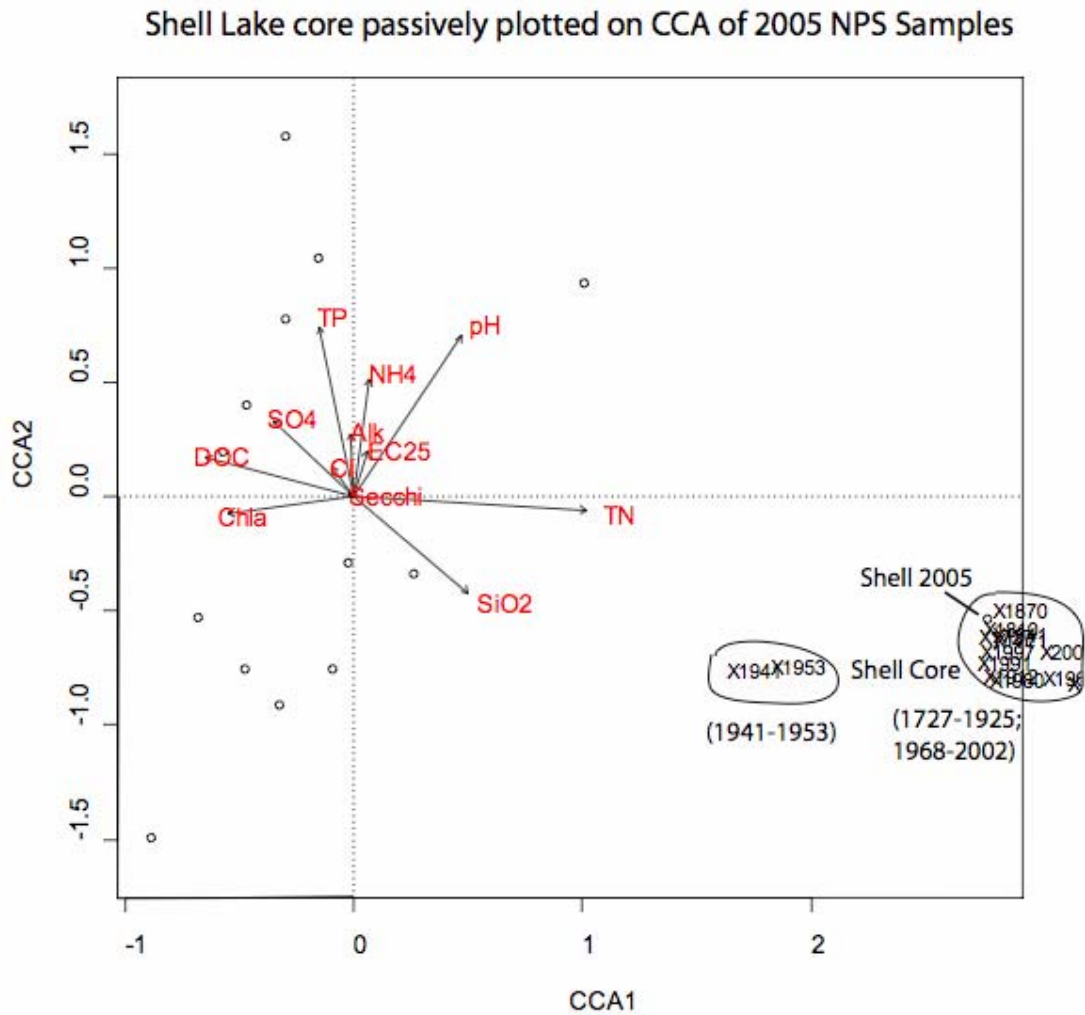


Figure 22. Diatom assemblages from 2005 Shell Lake core plotted passively on CCA of diatom species-environment relationships in SLBE and PIRO lakes.

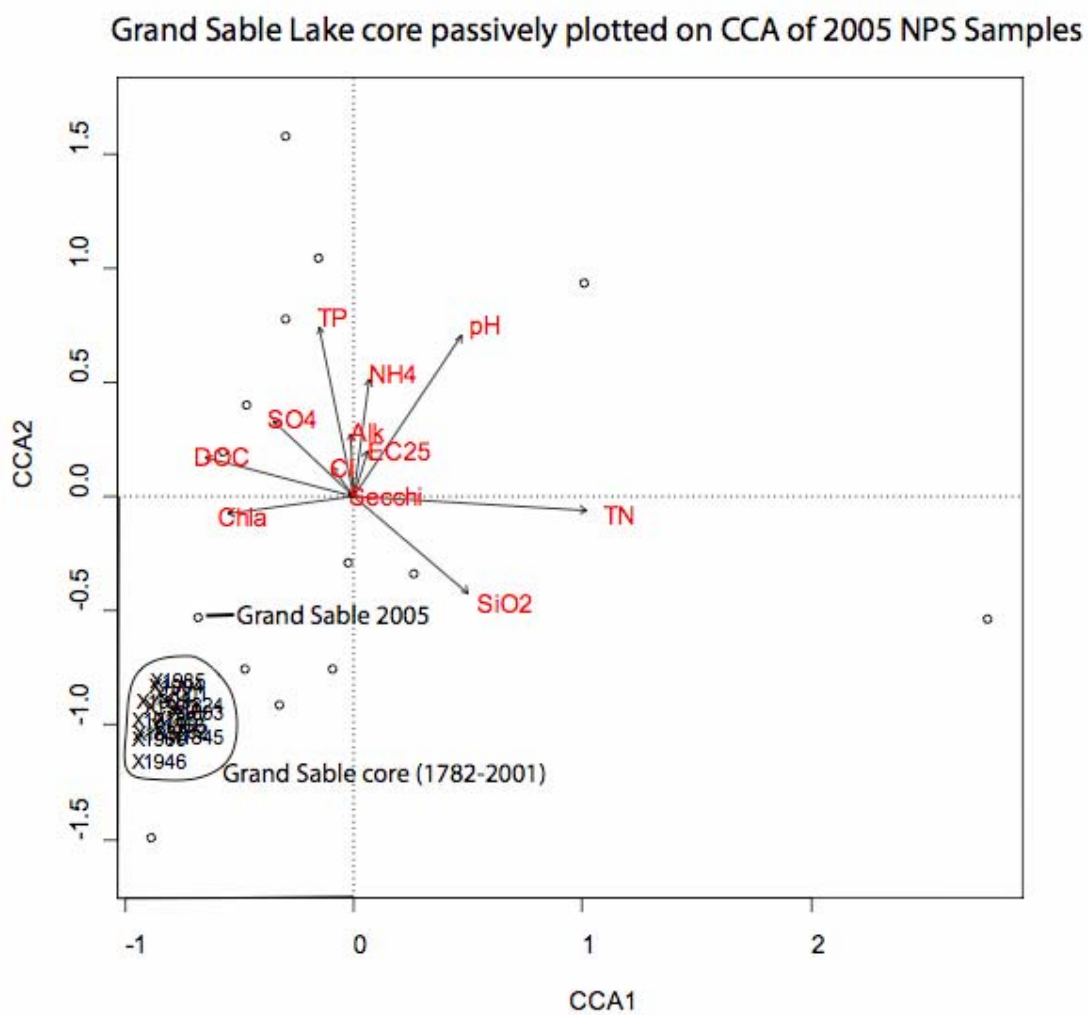


Figure 23. Diatom assemblages from 2005 Grand Sable Lake core plotted passively on CCA of diatom species-environment relationships in SLBE and PIRO lakes.