Final Report on
Sediment Diatom Reconstructions for Four Itasca County Lakes

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Summary

Due to potential threats to water quality and fishery health, four lakes in Itasca County (Minnesota) were selected for retrospective analyses. Primary goals were to determine background conditions and track probable long-term degradation, timing of impacts and remediation. The lakes range from developed (Buck, Shallow and Round lakes) to currently undeveloped (Willeys Lake). Sediment cores were collected from each lake and sediment intervals were dated using isotopic analyses. Diatom assemblages were assessed from sediment intervals and inferred trophic conditions in the profiles were derived using a regional diatom-based model for Minnesota lakes. Fossil remains, in concord with other stratigraphic indicators (organic and inorganic materials, sedimentation rates, other biological entities), were used to reconstruct the ~200-year history of each lake system. Buck Lake experienced eutrophication and other anthropogenic impacts, but in recent decades the lake has at least partly remediated. Shallow Lake has apparently undergone numerous nearshore anthropogenic shifts, but development has not resulted in an overall increase in nutrient concentrations. Water quality response to early watershed modifications of Round Lake was limited but eutrophication became a problem in the latter portion of the 20th century due to historic and recent land use activities. Despite being selected as an "undeveloped" lake, Willeys Lake showed some subtle impacts due to likely deforestation in the lake's catchment.

Background and Introduction

Among the many human-induced landscape changes, agriculture, hydromanagement, water removal, drainage and tiling, point source loadings, recreation and industrial use have led to widespread impairment of U.S. surface waters. For many bodies of water in North America, eutrophication has been the outcome, with ~50% of impaired lakes and ~60% of impaired rivers suffering from excess nutrient loading (Carpenter et al. 1998, Correll 1998). Developing sound management plans to improve impaired waters requires that we have an understanding of the natural or background conditions of a lake. This information is made available from water quality sampling, modeling or paleoecology.

Diatom calibration and training sets have become powerful tools for paleoecological reconstruction and monitoring of surface water quality. Throughout the past 15 years, statistical methods have been developed to reconstruct specific environmental parameters from diatom assemblages. Whereas earlier diatom-based methods provide qualitative measures of historical water chemistry or productivity using categorical indicator values (e.g., ter Braak and van Dam 1989, Agbeti 1992), the development of weighted averaging regression and calibration introduced a method of quantitative reconstruction of historical environmental variables (Birks et al. 1990a,b). The method uses a transfer function developed from a training set of modern diatom assemblages and their relationships to environmental gradients. The transfer function can be applied to historical diatom assemblages in sediment cores to mathematically reconstruct specific environmental variables. The weighted averaging method is statistically robust and based on ecologically sound organismal responses (ter Braak and Prentice 1988, Birks et al. 1990b), and the approach has been used successfully in reconstructing a wide variety of environmental parameters including pH, total phosphorus (TP), dissolved organic carbon? (DOC) and salinity (e.g. Anderson 1989; Fritz et al. 1991, 1999; Dixit et al. 1992; Hall and Smol 1992).

For inferring historical TP, diatom-based reconstructions have been adopted as the most powerful tool at hand (Fritz et al. 1993, Anderson and Rippey 1994, Reavie et al. 1995, Rippey and Anderson 1996). In the Minnesota region, the most readily applied training set was developed by Ramstack (1999) from surface-sediment diatom assemblages from 55 Minnesota lakes of varying trophic status that were earlier cored for a regional mercury study (Engstrom et al. 1999). This original training set has been progressively amended to include 90 additional lakes from the Western Corn Belt Plains (WCBP), the Northern Glaciated Plains (NGP) and the Northern Lakes and Forests (NLF, containing Itasca County).

The primary goals of the work summarized in this document were to: 1) collect, identify and enumerate diatom assemblages in dated sediment cores collected from four Itasca County lakes; and 2) reconstruct the anthropogenic history of these lakes using physical and chemical characteristics, diatom assemblages and diatom-inferred total phosphorus derived with the regional model.

Study Sites

The four study lakes are located in the north-central part of Minnesota, in Itasca County. The lakes have a variety of current conditions (Table 1), ranging from highly developed (e.g., Buck Lake) to currently undeveloped (i.e., Willeys Lake). There is concern -- led by the Itasca Soil and Water Conservation District and various local organizations -- about maintaining water quality and fishery health. Although development activities such as deforestation occurred in the watershed of Willeys Lake, this lake was selected as a control against the other three lakes, all of which are more heavily influenced by shoreline domestic development or past agricultural or land clearing activities (Table 1).

Prior to 1800, the watersheds of these lakes were an area of virgin timber and wetlands. The indigenous people were in the area in low density, and no signs of major indigenous settlements occured in the watersheds. Beavers were the most important landscapers and water-level modifiers. During the half-century from 1800–1850 Europeans extensively harvested the area for beaver and other furs, but established no major settlements in the watersheds. The next half-century (1850–1900) saw the decline of the fur trade and the initiation of the timber harvest. After 1950, agriculture declined, roads improved and more use was made of the lakes as places for seasonal, summertime recreation. From 1990 to the present, development pressure and populations have noticeably increased.

Buck Lake

Historical information was not available for Buck Lake at the time of publication. It is likely that Buck Lake's watershed history reflects that for the region (described above). Future collection of historical data for this lake would be valuable to identify specific reasons for paleolimnological trends.

Shallow Lake

Anecdotal information suggests that white pine logging ensued in Shallow Lake's watershed in the late 1800s until approximately 1910. A large fire occurred around the lake in 1918, and in the 1920s some ditching took place for farming; these ditches may or may not have been connected to the lake. In the 1920s the paved road US HWY 2 was built along the north shore of the lake, but it is likely an unpaved road was present for some time before it was established as a highway. The now-paved Shallow Lake Road is along the south and west sides of the lake, and it is believed that this road was developed in the 1940s as cabins and homes were built in these areas. Based on aerial photographs, farming was prevalent in the watershed from the 1930s through approximately 1970, and anecdotal accounts suggested that livestock were permitted access to the lake. Many of these farms have since been converted into resorts. In 1950 a major crude oil pipeline was installed along the north side of Shallow Lake. The extent of disturbance to the shoreline is not known, but records indicated that lake water was used to flush the pipes following installation. The lake is now moderately developed with approximately 100 homes, cabins and resort structures.

Round Lake

Although pre-20th century historical information for Round Lake is sparse, the mid-1800s likely experienced forest clearance similar to that throughout the region. Recorded information from the 1930s and 1940s indicates that about half of the lake's watershed had been cleared for agricultural practices.

From the 1930s through the 1950s, three significant farm plots were developed, including cattle with direct access to the lake's shoreline. This land conversion as well as nutrient loads from animals most likely had a significant impact on the water and nutrient load to the lake. Anectodal evidence suggests algal blooms occurred as early as the 1930's during the month of August.

Round Lake's water level increased by several inches during the 20th century likely owing to an increased water yield as a result of watershed clearance. This is supported by a small island that was present on the lake until approximately 1940 and is now covered by almost 30 cm of water.

By the 1960s, cattle were no longer present in the lake's catchment, but at that time improvements to C.S.A.H. 71 included ditching and paving that increased flux of water, sediments and nutrients to the lake. Algal blooms were occasionally noted in the 1960s. The 1970s and 1980s experienced development of five seasonal and seven permanent residences that resulted in more land clearing. Minor algal blooms were noted in the 1970's and 80's. In the 1990s residential development slowly increased, and roads on the east and west shores were improved. Road improvements to the unpaved township road on the east shore increased the sediment load to the lake during the summer months. One significant animal farm plot restarted in the late 1980's or early 1990's. In the last decade, significant problem growths of the macrophyte *Elodea* have been noted. There have been year-to-year fluctuations in the density of *Elodea* blooms, but significant blooms were observed in 1998, 2000, 2005 and 2007-2009. Although the sediment core was collected prior to 2007, *Elodea* and algal blooms are apparently an increasing problem.

Willeys Lake

Like many of the small-watershed lakes in the region, Willeys has low dissolved mineral content. The lake likely receives its water from groundwater sources. Recent logging activity is noted on the western and northern side of the lake. These areas are currently under aspen regeneration. An older red pine plantation exists on the south shore that was probably logged and planted to pine in the last half century. Despite deforestation, the watershed has never been developed for homestead, recreational or farming purposes. Otherwise, little historical data are available for the lake.

Methods

Sediment Sampling

Sediment cores were collected on 25-26 July 2006. Sediments were collected using a piston corer operated from the lake surface by rigid drive-rods. A surface corer equipped with a 7-cm diameter polycarbonate core barrel was used to collect a continuous, at least 100-cm, section of the upper sediments at all coring sites (Wright 1991). The core sections were held upright until the upper intervals of soft sediment (~20-40 cm) could be extruded vertically (at 1-cm increments) into polypropylene collection jars on shore. The remaining sections of stiff sediment were capped in the core tube and transported back to the lab in horizontal position. All core material was stored at 4 °C until further processing.

In the lab, cores were split lengthwise in their tubes using a band saw. Stratigraphic information (including sediment color, texture and anomalous entities) was recorded and the cores were photographed.

Inorganic and organic content

Magnetic susceptibility, a non-destructive measure of ferromagnetic particles, was performed on complete core profiles, with the exception of the surface intervals that were extruded in the field.

Increases in the magnetic signature in a core profile mark periods of increased erosion, and so are used to indicate periods of land clearance and other major watershed activities. Whole-core magnetic susceptibility was measured on all cores using a Geotek LTD multi-sensor core logger with a Bartington MS2 loop sensor in the Limnological Research Center (LRC) at the University of Minnesota. Cores were extruded from the core tube onto a split polycarbonate tube. Susceptibility measurements were taken at 1 cm intervals. On completion of analyses the cores were carefully sectioned into 1-cm intervals using a spatula, and sample intervals were stored in 100-ml polypropylene jars at 4 °C until further analyses.

Organic and inorganic loss-on-ignition (LOI) analyses followed Dean (1974). Sediment water content was determined from weight lost following oven drying of sediments at 100ºC for 24 hours. Weight loss after firing at 550ºC for two hours was used as an estimate of organic content. Weight loss after firing the remaining material for 2 hours at 1000ºC provided an estimate of carbonate content that is used to reflect inorganic carbonates (largely calcium carbonate) from terrestrial sources (Boyle 2001).

Alpha Spectrometry: Cores of lake sediments were analyzed for excess lead-210 (^{210}Pb) activity to determine age and sediment accumulation rates for the past 100-150 years. ^{210}Pb was measured at 15-20 depth intervals in each core through its grand-daughter product ^{210}Po, with ^{209}Po added as an internal yield tracer. The polonium isotopes were distilled from 0.5-3.0 g dry sediment at 550 °C following pretreatment with concentrated hydrochloric acid (HCl) and plated directly onto silver planchets from a 0.5 N HCl solution (modified from Eakins and Morrison 1978). Activity was measured for 1-6 x 10^5 s with ion-implanted surface barrier detectors and an Ortec alpha spectroscopy system. Unsupported ^{210}Pb was calculated by subtracting supported activity from the total activity measured at each level; supported ^{210}Pb was estimated from the asymptotic activity at depth (the mean of the lowermost samples in a core). Dates and sedimentation rates were determined according to the constant rate of supply (c.r.s.) model (Appleby and Oldfield 1978) with confidence intervals calculated by first-order error analysis of counting uncertainty (Binford 1990).

Gamma spectrometry: In the Shallow Lake core, the total ^{210}Pb activity did not indicate a clear supported/unsupported interface (circa 1850), suggesting that supported ^{210}Pb activities were affected by changes in sediment lithology in this lake. Gamma spectrometry was thus used to directly and independently measure supported (^{214}Pb) and total ^{210}Pb activities in selected samples from the estimated 1830 - 1890 period in this core. Freeze-dried sediment samples (1-4 g) were sealed in a 12 x 100 mm polypropylene sample tube with epoxy resin and ingrown for a minimum of 30 days to achieve secular equilibrium between the native ^{226}Ra and its decay products. Isotopic activities were measured for 7 - 20 x 10^4 s using an EG&G Ortec high-resolution germanium well detector and multichannel analyzer. Supported ^{210}Pb was measured as ^{214}Pb (295.2 and 351.99 kev), a short-lived intermediary on the radioactive decay sequence from ^{226}Ra to ^{210}Pb. Total ^{210}Pb was measured directly as ^{210}Pb (46.52 kev). An efficiency curve for the detector was generated using a sediment matrix spiked with known activities of ^{210}Pb, ^{137}Cs, ^{7}Be, ^{54}Mn and ^{109}Co, and was corrected for the small amount of native ^{210}Pb. Unsupported ^{210}Pb was calculated by subtracting supported activity from the total activity measured at each level. Dates and sedimentation rates were determined according to the c.r.s. model (Appleby and Oldfield 1978) with confidence intervals calculated by first-order error analysis of counting uncertainty (Binford 1990).

Diatom Preparation and Analysis

For siliceous microfossil analyses, a ~1 g subsample of sediment was digested for 1 hr in concentrated peroxide heated to 80 °C to remove organic materials and isolate the siliceous diatom valves. Samples were rinsed five times with distilled water to remove reagent residue and siliceous remains were plated on coverslips using the quantitative Battarbee (1986) method. The Battarbee method allows both the qualitative assessment of diatom assemblages, as well as quantitative assessment of algal accumulation rates and productivity. Coverslips were mounted on slides using Pleurax® medium, which has a high refractive index. For each slide, diatom valves were identified using an Olympus BX51 light microscope fitted with full oil immersion optics capable of 1000X magnification and numerical aperture greater than 1.30. For each prepared sample, siliceous specimens were identified along transects until at least 400 diatom valves were enumerated. Diatoms were identified to the species level or higher using standard floras and iconographs, including Hustedt (1927-1966), Patrick and Reimer (1966, 1975), Camburn et al. (1984-1986), Krammer and Lange-Bertalot (1986, 1988, 1991a, b), Cumming et al. (1995), Reavie and Smol (1998), Camburn and Charles (2000) and Fallu et al. (2000). Diatoms were counted when more than 50% of the valve was present or when a distinct valve fragment was present (e.g., central area of *Amphora libyca* or valve end in *Asterionella formosa*). The species dataset was reduced for statistical analyses; species that never achieved more than 1% relative abundance in any sample were considered rare and were not used in further evaluations.

Although diatoms were the primary indicators used, siliceous remains including chrysophyte stomatocysts, phytoliths and the plates of testate amoebae were also be enumerated to provide additional ecological information.

Diatom-Inferred Environmental Conditions. To derive a set of useful diatom indicators, a diatom transfer function is derived by relating diatom species assemblages in a training set of samples (e.g., from lakes, river reaches, coastal locales) to an environmental variable of interest (e.g., total phosphorus or nitrogen, pH, chloride, suspended solids) from a particular region (Charles 1990). The transfer function consists of species coefficients (e.g., environmental optima and tolerances) that can be used to infer quantitative information about the variable of interest, based on the relative abundance of each species in a sample assemblage. Past total phosphorus (TP) concentrations were inferred from the fossil diatom assemblages using the diatom-based reconstructive model that has been developed (Ramstack et al. 2003) and progressively updated (Heiskary and Swain 2002, Edlund and Kingston 2004, Reavie et al. 2005) for Minnesota Lakes. Paleoecological reconstructions were based on weighted-averaging regression and calibration using the statistical program C2 (Juggins 2003). C2 quantitatively reconstructs environmental variables using weighted averaging of the diatom species and their associated environmental optima and tolerances. Long-term inferred trends in the lakes were used alongside diatom profiles, other microfossil indicators, sediment accumulation rates and historical information to delineate the environmental history at each core site.

Results and Discussion

Total ^{210}Pb in recent (core-top) sediments was relatively high, ranging from 27 pCi/g in Shallow Lake to 56 pCi/g in Willeys Lake, and down-core declines were largely smooth and monotonic (Figure 1). With the exception of Shallow Lake the systems had typical decay curves, exhibiting exponential declines in 210Pb concentrations. The depth at which unsupported (excess) ^{210}Pb became undetectable – the ^{210}Pb dating horizon – ranged from 31 cm in Shallow to 85 cm in Buck. This horizon was fairly clear-cut in Buck and Round, but less certain in Willeys and Shallow, primarily because of greater variability in supported ^{210}Pb in the later two cores. Supported ^{210}Pb was well defined in Buck and Round by four widely spaced deeper intervals with near constant values (0.8 and 0.6 pCi/g, respectively). In Willeys and Shallow, supported values were higher (1.1 and 1.7 pCi/g, respectively) and more variable. In the Shallow Lake core, the transition to supported ^{210}Pb appeared initially to be rather abrupt. Subsequent analysis of ^{214}Pb revealed a local minimum in supported ^{210}Pb at this same level 31-32 cm, and unsupported ^{210}Pb values were adjusted accordingly (as opposed to assuming constant supported activity). Dates calculated according the c.r.s. model were reliable back to the mid-1800s in all four cores. While the chronologies extend beyond that, these older dates have very high uncertainty (± 40-60 years), and should be used with caution. Dating uncertainty for the last century is generally better than ± 5 years. Overall, these profiles would be expected in lakes with consistent sediment accumulation regimes, and we are confident that undisturbed sedimentary profiles were obtained.

Loss-on-ignition (LOI), magnetic susceptibility (MS) and sediment accumulation rate profiles are also presented for each lake to support microfossil interpretations (Figures 2, 4, 6, 8). Sediment accumulation rates were relatively low in all cores, despite the appearance of a high linear rate of accumulation owing to very high water content (typically in excess of 90%). Accumulation rates were near constant in Willeys Lake, whereas the other three records showed a systematic increase at the time of European settlement in the late 1800s. Additional discussion of accumulation rates is provided in the context of their microfossil profiles.

We encountered approximately 320 diatom taxa in the four lake cores. Figures 3, 5, 7 and 9 present the more common taxa observed in each core, as well as total accumulation rates of various fossil groups, diatom diversity and diatom-inferred total phosphorus concentrations (DITP). For clarity, the interpretation for each lake has been broken into an 1800s period (the period of initial development and deforestation in the catchments of many Minnesota lakes) and a 1900s period (the period of rapid population increase, continued development and in some cases in recent decades, rehabilitation measures). Large amounts of data are presented for each lake; not all profile data presented are addressed in this discussion, but instead we consider each lake's data in context and focus on key trends for interpretation.

Buck Lake (Figures 2, 3)

1800s: Buck Lake appeared to eutrophy following the initial development and deforestation phase of the mid-1800s. LOI and sediment accumulation rate data suggested an increase in organic material accumulation at that time, and the diatom communities indicated a shift from a predominantly benthic community to a more productive phytoplankton community. In particular, the shift from typically low-nutrient *Staurosira* and *Staurosirella* to the higher-nutrient *Aulacoseira ambigua* suggested pelagic nutrient enrichment, likely resulting from deforestation of the catchment and augmented nutrient flux to the lake.

1900s: Although the lake has remained plankton-dominated, the appearance of typically oligotrophic *Cyclotella* species indicated that pelagic nutrient levels began to decline in the mid-1900s; this was mirrored by the clear drop in DITP during that time. The occurrence of a mixture of low- and high-nutrient diatoms since the 1980s suggested that periods of low and high nutrient flux were seasonal. The recent increase in organic material and carbonates suggested that continuing human development in the catchment has an influence on water quality; however the microfossil trends indicated that eutrophication is not as severe as that observed following deforestation in the mid-1800s. Furthermore, during the last ~40 years the lake experienced a recovery of sediment accumulation rates to pre-development rates. Although the biological ecology of the lake may have reached a stable state unlike the pre-settlement state, current prevailing nutrient concentrations in the lake appeared similar to those from pre-settlement times.

Shallow Lake (Figures 4, 5)

1800s: Early human development in Shallow Lake's catchment had a notable impact on the lake's sedimentary regime, but apparently little overall impact on water quality. The lake is likely naturally meso- to slightly eutrophic, dominated by planktonic diatoms such as *Aulacoseira* and *Fragilaria*. Based on DITP, nutrient concentrations between 20 and 30 µg/L changed very little until the 1900s, however LOI and sediment accumulation rate data indicated an increase in the amount of material transported to the lake basin. It is likely this increase in accumulation resulted from watershed clearance and associated increase in sediment runoff. This was corroborated by a late-1800s peak in the accumulation of phytoliths that would have come from terrestrial sources.

1900s: Algal accumulation rates notably increased for an approximate 30-year period in the early 1900s. This period was also denoted by a short-lived peak in amoeba plate accumulation, suggesting an increased development of nearshore wetlands and macrophytes. This contribution of wetland species may also have been attributed to flushing activity during construction of the oil pipeline. Typically one would observe nutrient flux increasing during such a period of development; however neither the diatom assemblage nor DITP reflected such an increase. It is possible that the prevailing nutrient levels (i.e., the annual average) did not increase, but instead slugs of nutrient- and sediment-laden inputs caused short-lived algal blooms that were not detectable in the paleolimnological resolution.

Shallow Lake appeared to have undergone oligotrophication in the last ~30-40 years. This is especially indicated by the known low-nutrient indicators *Cyclotella michiganiana* and *C. comensis* (Reavie et al. 2005). Recent DITP indicated prevailing nutrient levels between ~10 and 15 µg/L TP, corresponding with DNR records. The continued slight increase in carbonates and total sediment accumulation rate during this period suggested that anthropogenic development continues to supply large amounts of watershed sediments to the lake via runoff, but no simultaneous increase in nutrient flux. Increased runoff may have increased prevailing turbidity in the lake, stifling littoral algal growth (and favoring a higher relative amount of phytoplankton, as observed in the upper sediments). Long-term records of surface water turbidity or suspended solids would be needed to confirm this trend.

Round Lake (Figures 6, 7)

1800s: Based on profile analyses, Round Lake is a naturally mesotrophic system that was little affected by human development activities in the 1800s. Overall algal accumulation rates were relatively low in the 1800s, and the diatom community was dominated by mid- to low-nutrient species. The lake was apparently little affected by pre-20th century development.

1900s: Two distinct peaks were detected in sediment accumulation in Round Lake's history: one between 1900 and 1920, and another between 1940 and 1950. Based on corroborating MS, carbonate and diatom accumulation data, these peaks represented peak times of development in the lake's watershed, likely land clearance and the development of farms. The earlier peak appeared to represent forest clearance, as the profiles suggested an increased flux of inorganic material from exposed soils, but little or no increase in nutrient flux.

The later peak in sediment accumulation probably marked the beginning of significant nearshore development; the late 1900s exhibited a eutrophication trend since approximately 1950. This eutrophication was largely revealed as an increase in high-nutrient epiphytic species (e.g., *Achnanthidium minutissimum*) and a notable increase in the accumulation rates of the remains of all microscopic organisms we analyzed. The microfossil trends in the last 50 years suggested significant littoral development, particularly macrophyte growth. *A. minutissimum* is a known epiphytic diatom that is common on macrophytes in productive lakes, and the increase in amoeba plates suggested inputs of taxa common to plant-dominated wetlands and macrophyte beds. The temporary peak in phytolith accumulation between approximately 1950 and 1980 reflected a period of notable human development and increased soil erosion. Phytoliths typically come from grasses and during periods of land clearance in a lake's watershed, these remains are rapidly washed into the lake. Very low relative organic material in the sediment from this recent period further indicated the erosion of large amounts of inorganic material to the lake following nearshore land clearance. DITP data suggested that the lake shifted from a low to high mesotrophic condition over the last ~50 years. Overall, paleolimnological interpretations from the last 50 years suggested eutrophication and increases in sediment inputs from nearshore development (homesteads and road improvements). In particular, a clear signal of heavy macrophyte development in recent years was corroborated by anecdotal information regarding *Elodea* blooms. Furthermore, past nutrient loading from agricultural and pasturing activities probably contributed to the stored sedimentary nutrients, resulting in greater internal loading during the intermittent mictic periods.

Willeys Lake (Figures 8, 9)

1800s: Prior to human settlement of the region, Willeys Lake was an oligotrophic system containing an approximate 50:50 mixture of benthic and planktonic diatom species. The diatoms were dominated by mostly low-nutrient species. Land clearance in the mid to late 1800s had a subtle effect on the lake's water quality; diatom accumulation began to increase and there was a gradual increase in carbonates that would have been washed in from terrestrial sources. Although diatom accumulation rates increased, a concurrent increase in DITP did not occur, suggesting that water quality shifts resulted in ecological changes unrelated to nutrient enrichment.

1900s: According to DITP, nutrient concentrations remained low (~7-8 µg/L) until the ~1920s when more dramatic development occurred in the region. Although the shoreline of Willeys Lake has never been developed for homestead or recreational purposes, there was evidence that human activity elsewhere in the lake's watershed had an impact on water quality during the last century. In particular, the increase in phytolith accumulation starting in the early 1900s suggested land clearance and increased soil erosion. Further, the notable drop in organic material during this period reflected the concurrent increase in inorganic material from the watershed. Also note that total sediment accumulation rates changed very little throughout the 1900s, reflecting the shift from organic to more inorganic sediment accumulation. Timber harvest likely caused these changes due to an increased water yield carrying terrestrial materials including a slightly augmented nutrient load. Rapid changes were apparent during the last decade: Eutrophic diatom species (e.g., *Nitzschia palea*), chrysophyte remains and amoeba plates increased rapidly, all suggesting a massive littoral growth of macrophytes that tend to harbor these organisms. This inferred eutrophication trend was mirrored in the DITP increase from oligo-mesotrophic to eutrophic conditions in the uppermost two sediment intervals. Without additional work it is difficult to determine reasons for this sudden trend.

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Table 1. General characteristics of the study lakes

Lake	Buck	Shallow	Round	Willeys
DNR number	31-0069	31-0084	31-0209	31-0412
Latitude	47.54	47.13	47.21	47.53
Longitude	-93.19	-93.3	-93.36	-93.17
Surface area (acres)	492.23	541	99.45	48.2
Littoral area	180	268	98	
Maximum depth (ft)	30	85	16	28
Mean measured total phosphorus (ppb) (# measurements)	not available	15 (6)	34 (4)	not available
DNR trophic status	mesotrophic	mesotrophic	eutrophic	not available
Approximate proportion of shoreline developed (%)	95	75	50	0
General paleoecological interpretation	Naturally productive, some early eutrophication, recent recovery	Eutrophication during settlement, gradual recovery	Recent increase in nutrients and macrophytes	Early 20th century and recent increase in nutrients

FIGURES

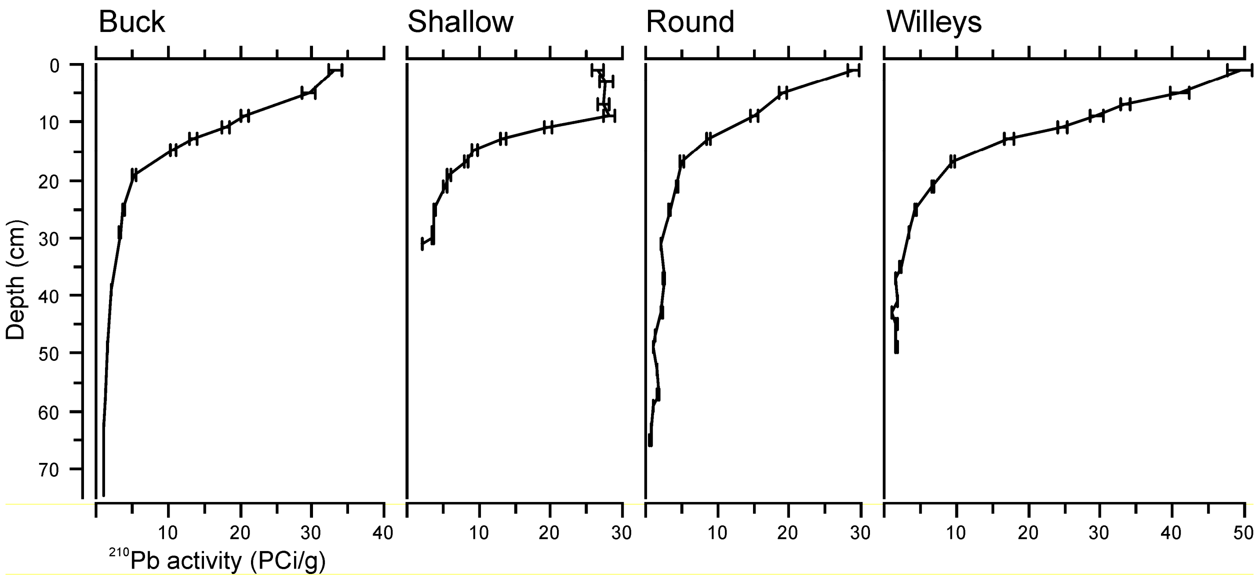


Figure 1. Lead-210 activities in sediment cores collected from the four study lakes.

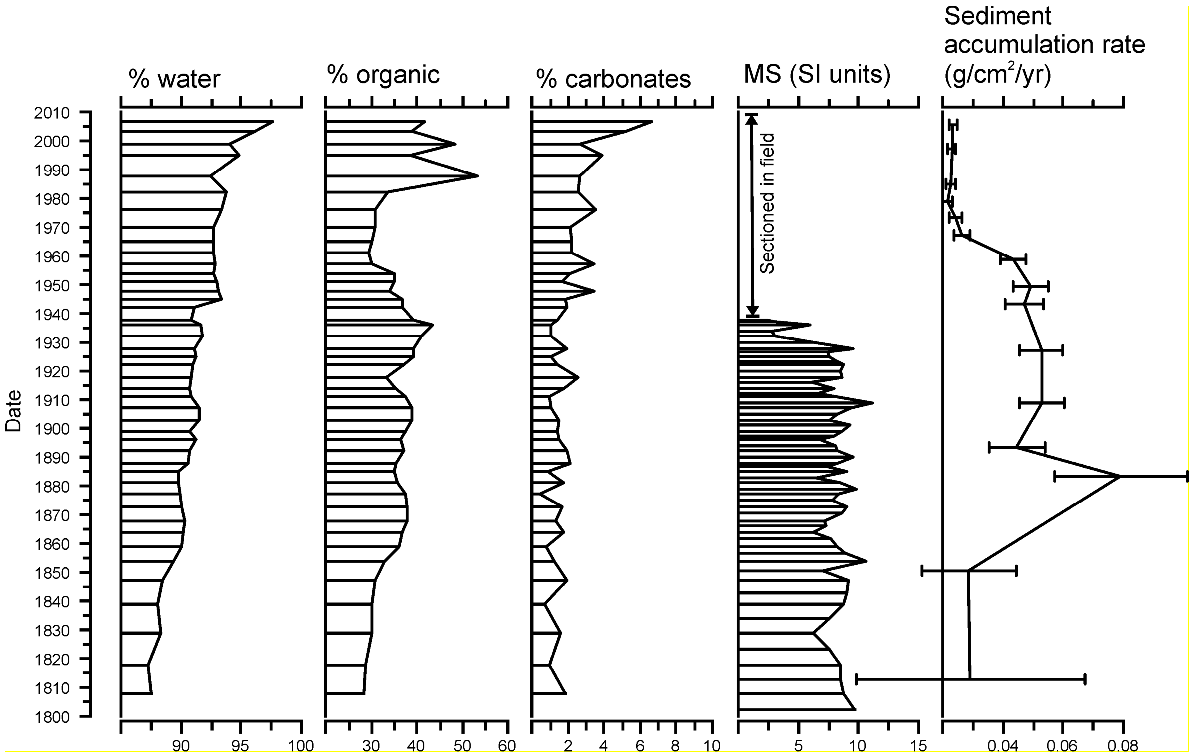
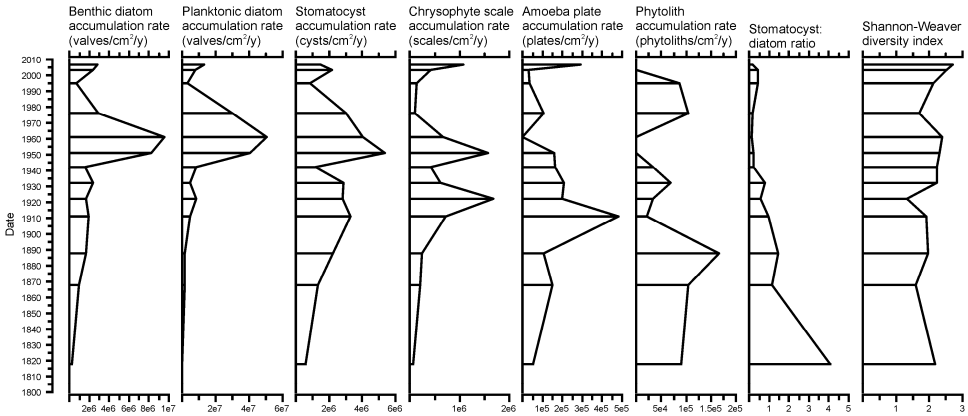


Figure 2. Downcore loss-on-ignition (LOI), magnetic susceptibility (MS) and sediment accumulation profiles from the Buck Lake sediment core. The MS profile is truncated because the upper intervals were sectioned in the field, and so could not be analyzed for MS as part of the remaining intact core.



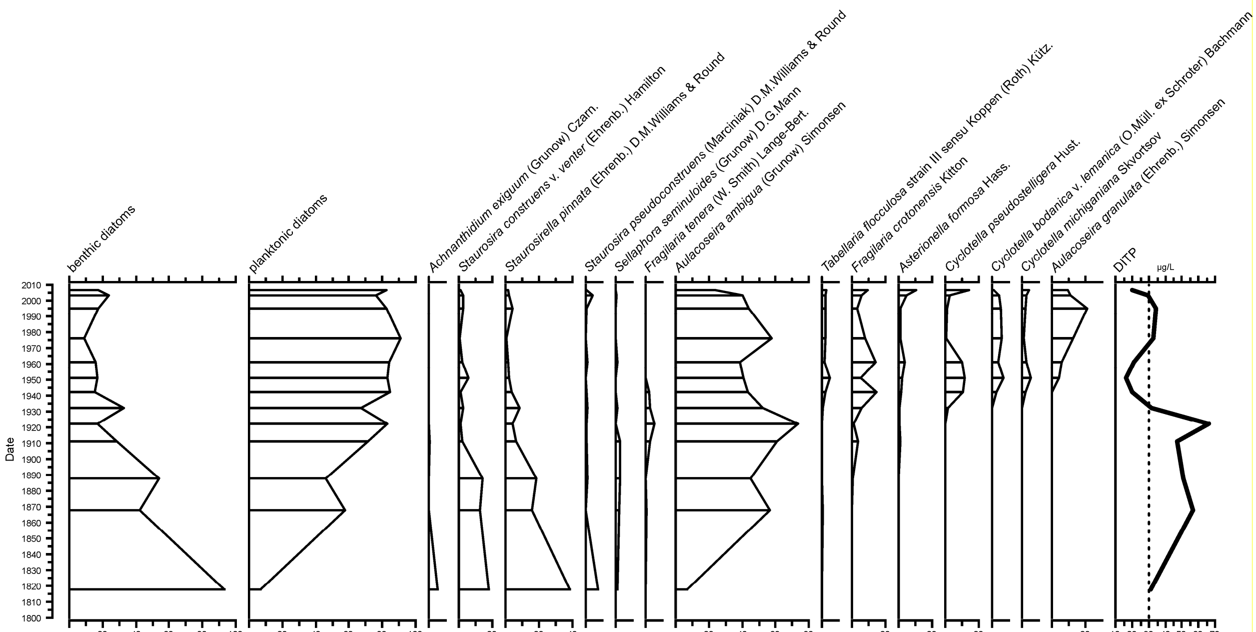


Figure 3. Downcore accumulation rates of various sediment-fossil remains, chrysophyte stomatocyst:diatom ratio, and Shannon-Weaver diatom diversity index (top) and relative abundances and diatom-inferred total phosphorus concentrations (DITP) (bottom) for Buck Lake. The dashed line on the DITP profile marks 30 µg/L, which may be used as a guideline for eutrophic conditions.

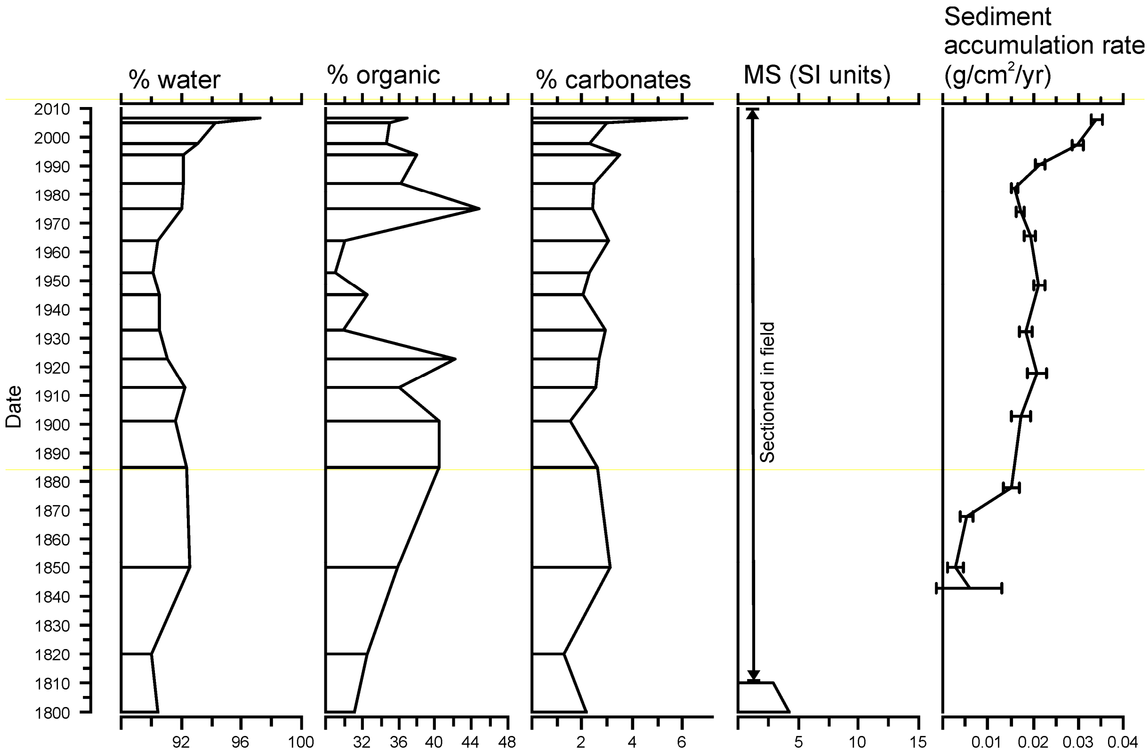


Figure 4. Downcore loss-on-ignition (LOI), magnetic susceptibility (MS) and sediment accumulation profiles from the Shallow Lake sediment core. The MS profile is truncated because the upper intervals were sectioned in the field, and so could not be analyzed for MS as part of the remaining intact core.

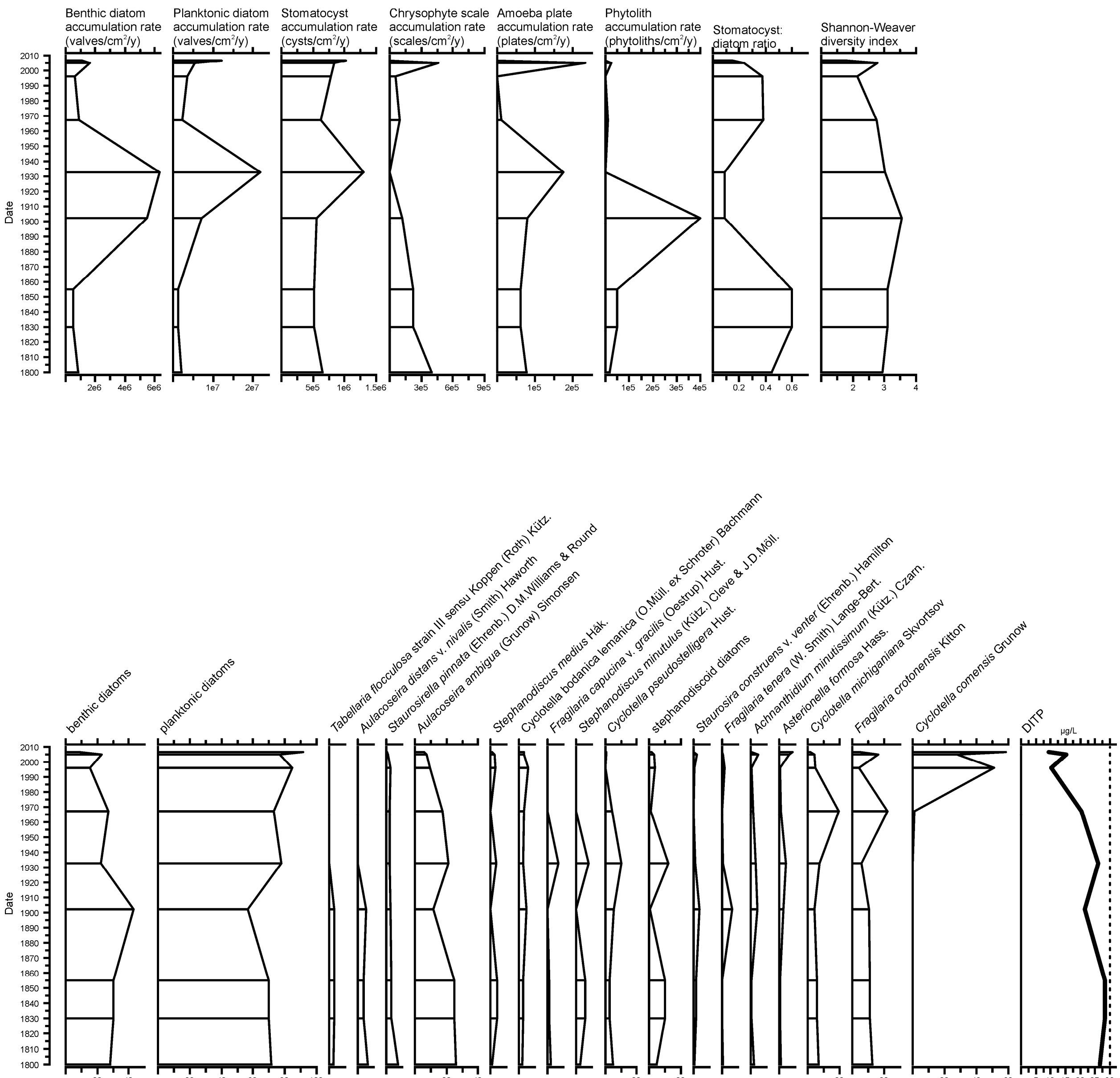


Figure 5. Downcore accumulation rates of various sediment-fossil remains, chrysophyte stomatocyst:diatom ratio, and Shannon-Weaver diatom diversity index (top) and relative abundances and diatom-inferred total phosphorus concentrations (DITP) (bottom) for Shallow Lake. The dashed line on the DITP profile marks 30 µg/L, which may be used as a guideline for eutrophic conditions.

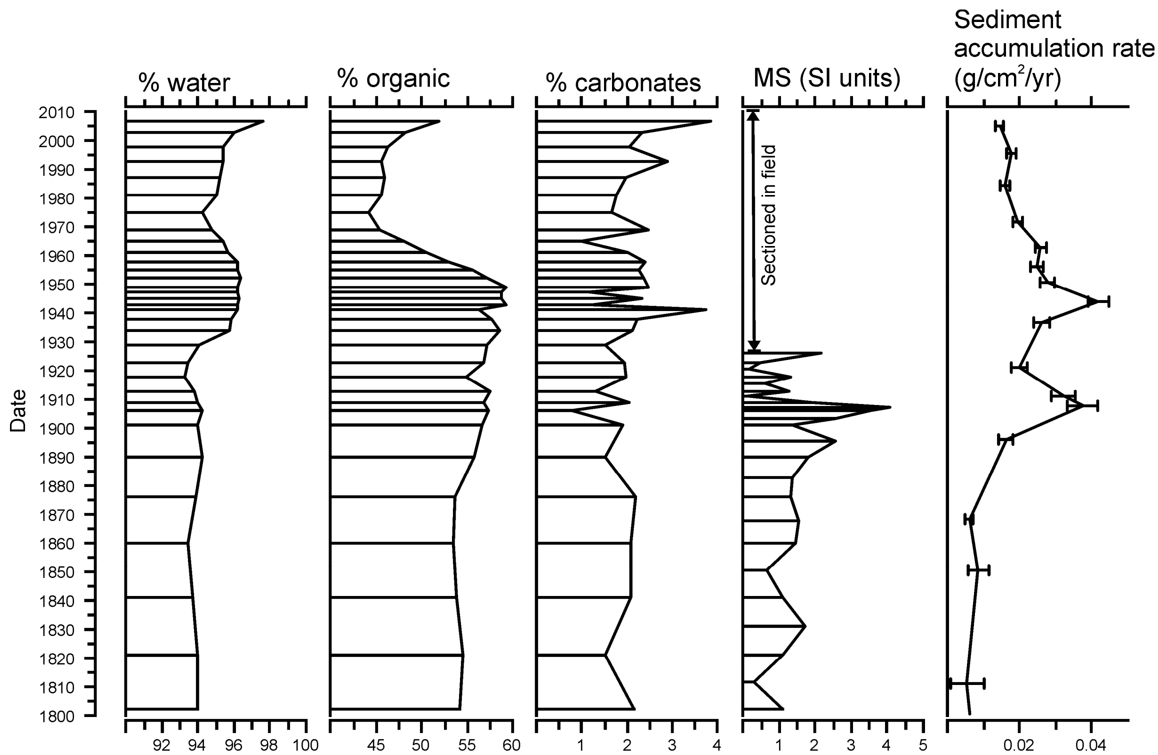


Figure 6. Downcore loss-on-ignition (LOI), magnetic susceptibility (MS) and sediment accumulation profiles from the Round Lake sediment core. The MS profile is truncated because the upper intervals were sectioned in the field, and so could not be analyzed for MS as part of the remaining intact core.

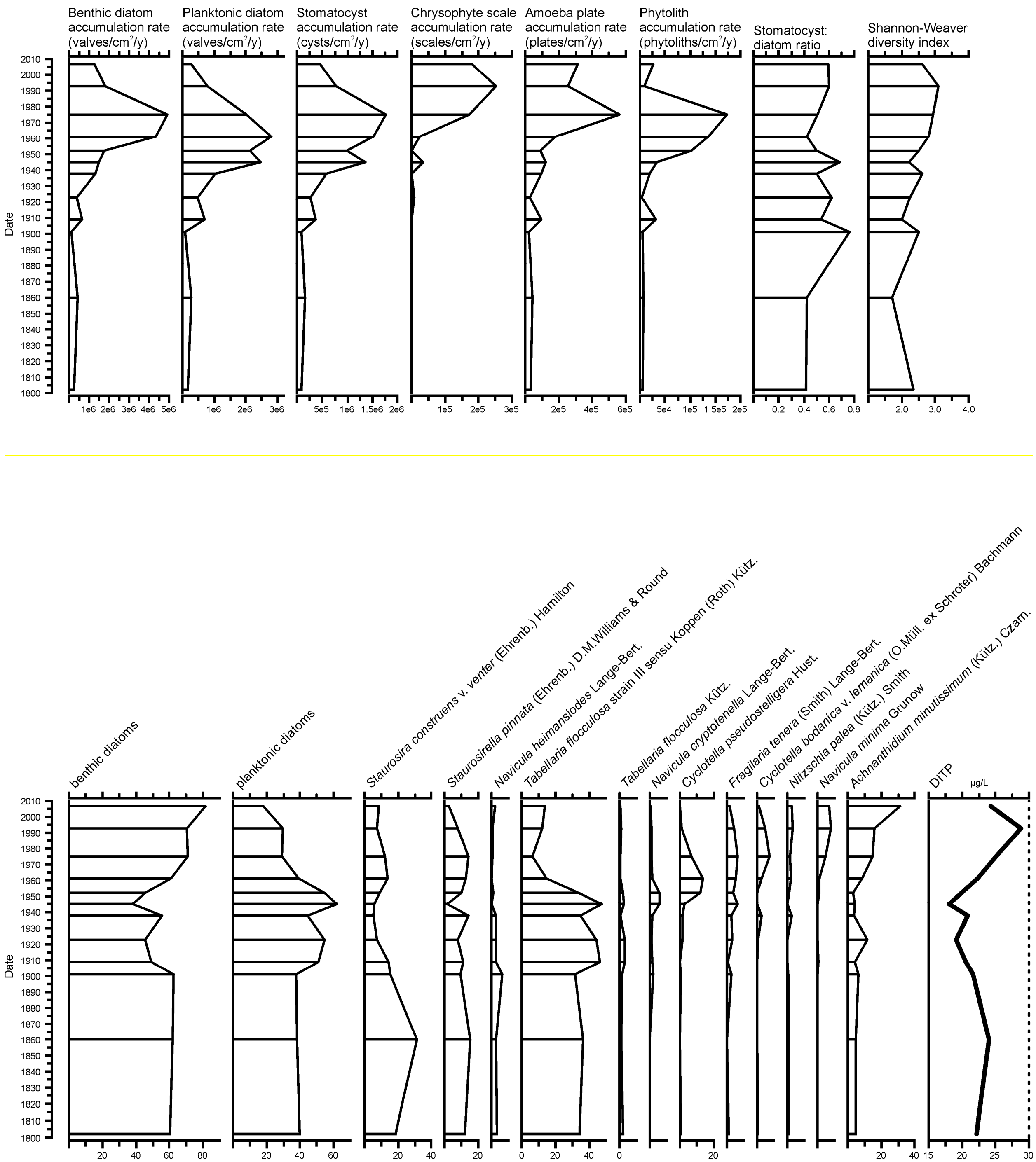


Figure 7. Downcore accumulation rates of various sediment-fossil remains, chrysophyte stomatocyst:diatom ratio, and Shannon-Weaver diatom diversity index (top) and relative abundances and diatom-inferred total phosphorus concentrations (DITP) (bottom) for Round Lake. The dashed line on the DITP profile marks 30 µg/L, which may be used as a guideline for eutrophic conditions.

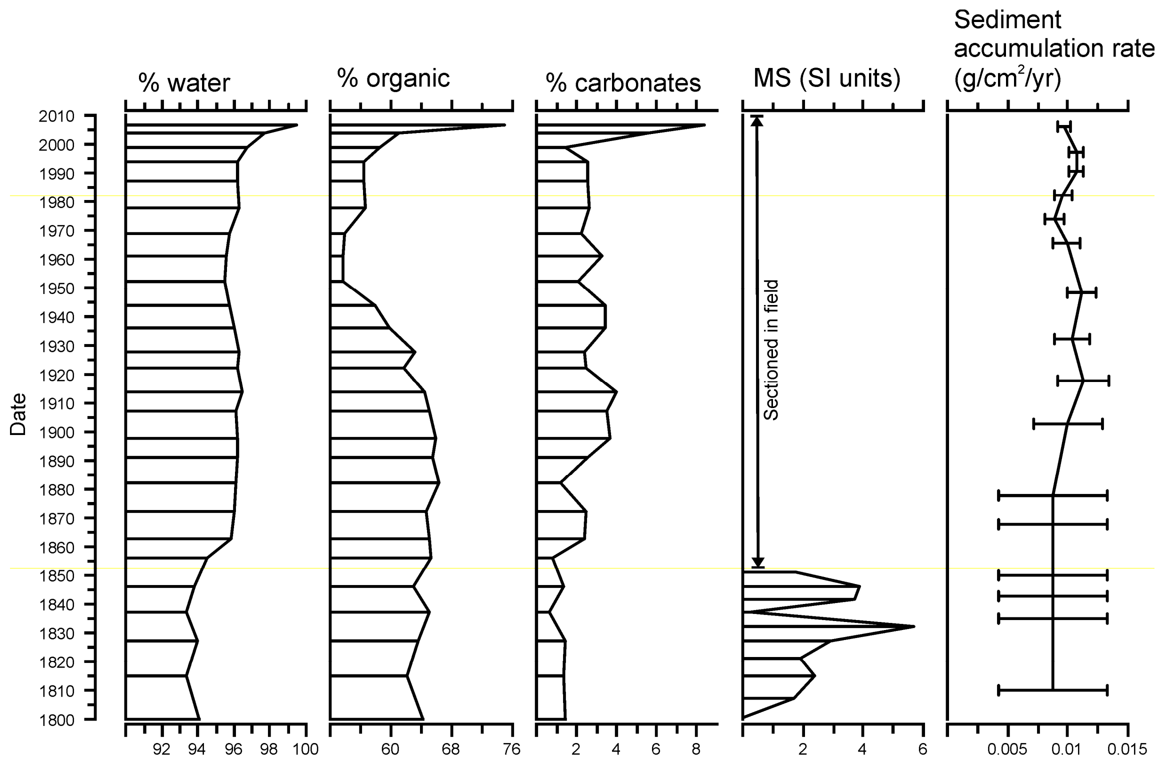


Figure 8. Downcore loss-on-ignition (LOI), magnetic susceptibility (MS) and sediment accumulation profiles from the Willeys Lake sediment core. The MS profile is truncated because the upper intervals were sectioned in the field, and so could not be analyzed for MS as part of the remaining intact core.

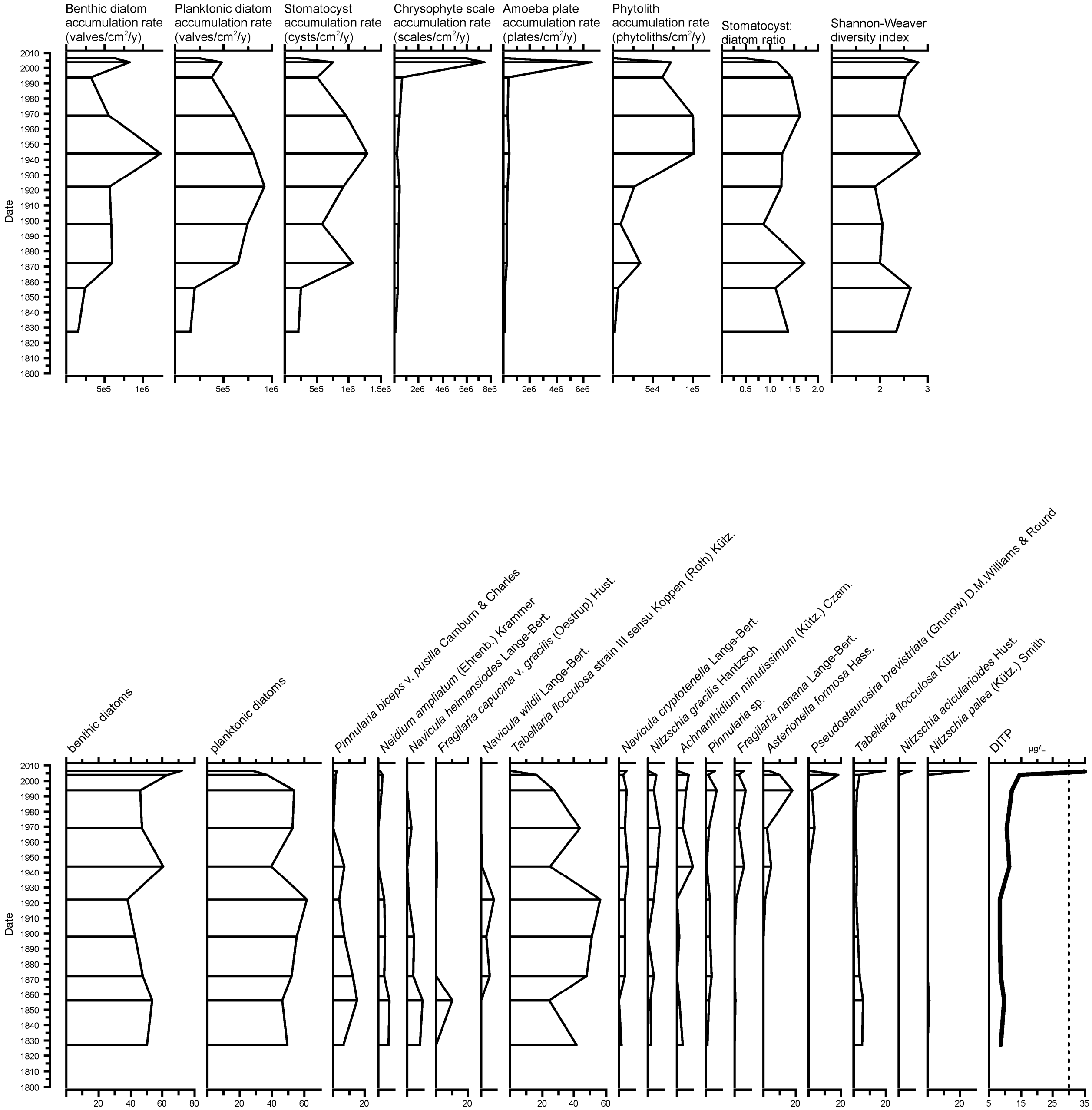


Figure 9. Downcore accumulation rates of various sediment-fossil remains, chrysophyte stomatocyst:diatom ratio, and Shannon-Weaver diatom diversity index (top) and relative abundances and diatom-inferred total phosphorus concentrations (DITP) (bottom) for Willeys Lake. The dashed line on the DITP profile marks 30 µg/L, which may be used as a guideline for eutrophic conditions.