Diatom analysis of Lake St. Croix sediments for recent and historical phosphorus reconstruction

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by

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Abstract

Two 2-m piston cores were recovered in 1999 from Lake St. Croix sub-basins near Lakeland, Minnesota and Prescott, Wisconsin. Dating chronologies based on ^{210}Pb inventories indicated both cores recovered a continuous chronosequence of sediments dating from pre- and post-European settlement (c. 1850) in the St. Croix River basin. Cores were subjected to magnetic susceptibility, loss-on-ignition, and diatom microfossil analysis to identify post-settlement signals of land use, trophic change, and sedimentation. Sedimentary increases in magnetic susceptibility were indicative of increased erosion and transport of ferromagnetic mineral grains due to initiation of settlement and logging activities in the basin. A three-fold increase in sediment accumulation began in the mid 1800s in the northern basin and by 1900 in the southern basin. Increases in sediment accumulation were primarily inorganic; however, organic and carbonate accumulation also began increasing between 1850 and 1900, depending on coring site. Diatom accumulation increased twenty to fifty-fold since settlement with a shift from benthic–dominated to planktonic-dominated assemblages. Simultaneous with the assemblage shift was the introduction and establishment of many planktonic diatoms considered ubiquitous indicators of eutrophy (e.g., Cyclostephanos invisitatus, C. tholiformis, Fragilaria crotonensis, F. capucina and var. mesolepta). The fossil diatom assemblages were further analyzed using weighted-averaging calibration and reconstruction of historical water column total phosphorus (TP) using several available species optima models. Reconstructed TP values showed that water column nutrient values have increased 2.5- to 3-fold since presettlement times. Presettlement values of c. 0.02 mg l^{-1} TP were found in both cores with increases beginning c. 1910. Modern reconstructed TP values (c. 0.055 mg l^{-1}) were similar to reported TP concentrations measured in Lake St. Croix by direct monitoring during the last two decades. Upstream core 6B showed earlier changes in most measured sedimentary environmental signals (sediment and diatom accumulation) compared to downstream core 1B. Core 6B also had more rapid increases in historic TP values (to an initial peak by c. 1935) compared to core 1B, although both cores had similar magnitudes of change between reconstructed presettlement and modern TP values.

Introduction

Changes in landscape due to natural processes and/or human modification impact receiving waters worldwide. Elevated sediment and nutrient loadings to surface waters from point and non-point sources typify many landscape changes, especially human modifications. The result has been wide-spread eutrophication in North America with ~50% of impaired lakes and ~60% of impaired rivers suffering from excess nutrient loading (Carpenter et al. 1998).

Establishing sound management policy for controlling or reducing nutrient inputs to surface waters requires knowledge of two specifics. The first prerequisite is a modern assessment of current loading trends. This information is typically determined through permitting of dischargers, monitoring efforts, and calculating nutrient budgets. The second, and much more difficult assessment that is necessary, is an understanding of historical or baseline nutrient dynamics within a system. Historical water quality records may provide this second factor, but in most cases the establishment of water quality monitoring came as a response to degraded conditions. Furthermore, laboratory methods have also changed, making historical data difficult to compare with modern values. However, by knowing baseline conditions, such as those existing before European settlement or WWII, within which a given aquatic system was operating, policymakers can create sensible management targets.

The St. Croix River is a major tributary system to the upper Mississippi River and is located in east-central Minnesota and northwest Wisconsin. The St. Croix River has been variously declared by the states of Wisconsin and Minnesota to have "outstanding" to "exceptional resource value," and hence, has been the focus of protection and remediation concerns. The river basin has undergone significant land-use changes since European settlers arrived in the 1840s. Andersen et al. (1996) used historical land surveys and demographic records to reconstruct the land-use history of the basin and noted three major phases. Settlement was initiated by logging interests around 1839 with the construction of the first sawmill in the Lower St. Croix Basin. Logging activity peaked in 1889 and was done in conjunction with land clearance and a shift to agriculture. From 1880 to 1940, the population was stable; agriculture dominated land-use within the watershed with peak farming levels c. 1935. The third phase has lasted from 1940 to present with declines in farming interests and increased urbanization and parcelling associated with an expanding St. Paul-Minneapolis metropolitan area in the lower St. Croix (Andersen et al. 1996).

Understanding the impacts of historical land-use changes on sedimentation and nutrient dynamics of the St. Croix River is the focus of this project. Water quality monitoring data are available in minimal form for some parameters since the 1930s; however, data on nutrient levels have sporadic availability only since the 1950s. Several groups have compiled the historical water quality record in an effort to decipher variability and recent trends in nutrient loading to the St. Croix River.

Troelstrup et al. (1993a) compiled data over two periods, 1950-1975 and 1976-1992, and noted a general decrease in total phosphorus from c. 0.080 mg l^{-1} TP to 0.050 mg l^{-1} TP between the time periods. Over the entire study (1950-1992) median TP concentrations were 0.054 mg l^{-1}, with higher seasonal values in spring-summer (0.060 mg l^{-1}) compared to fall-winter (0.040 mg l^{-1}). Troelstrup et al. (1993a) concluded that "general water quality within the St. Croix River is good relative to other river systems within the region."

Kroenig and Stark (1997) studied variability in nutrient values in the upper Mississippi basin, including the St. Croix River, between 1984 and 1993. The St. Croix River had the lowest TP values of three major upper Mississippi tributaries (Mississippi, Minnesota, St. Croix Rivers) with median TP values of c. 0.050 mg l^{-1} and no discernable trends over that time period.

Malischke et al. (1994) analyzed water quality data from throughout the St. Croix Basin from 1975 to 1989. They noted a general downstream increase in nutrient and chlorophyll values. At a monitoring station (St. Croix Falls, Wisconsin) slightly upstream of the headwaters of Lake St. Croix, mean values of TP from 1975 to 1983 were 0.050 mg l^{-1}. Closer to the headwaters of Lake St. Croix (at the mouth of the Apple River), TP concentrations in the late 1980s were 0.060 mg l^{-1}.

No clear trend in water quality in the St. Croix River was identified in any of these studies. However, the St. Croix Basin Water Resources Planning Team, an interagency cooperative of federal and state agency (Minnesota and Wisconsin) representatives, identified management of nutrient loadings as crucial to their goal of protecting and improving water quality in the St. Croix River. Their interim policy is "no net increase of nutrients in permitted discharges" (St. Croix Interagency Basin Team 1998). Critical to modification of this policy is developing a baseline understanding of pre-1950 and pre-European nutrient dynamics in the St. Croix River.

Paleolimnology offers a powerful alternative approach for assessing historical environmental change from lake-sediment records, especially trophic change. But paleolimnology is often limited in its utility when attempts are made to apply it to river systems. Erosion and sedimentation are too dynamic in rivers to permit stable and lengthy sediment sequences to accumulate. However, reservoirs or impoundments provide one sedimentary environment where paleolimnological techniques can be cautiously applied to river systems (Engstrom and Almendinger 1998, Balogh et al. 1999).

Two previous paleolimnological efforts have targeted the natural impoundment at the terminus of the St. Croix River, Lake St. Croix, to address historical environmental change in the basin. Eyster-Smith (1991) collected a 19-m long core-series in the mid-1970s. Sediment and pollen analysis corroborated an earlier proposed date of 9500 ^{14}C yBP for the lake's formation and also identified the Ambrosia pollen (ragweed) at c. 1860 associated with widescale land clearance following settlement. Troelstrup et al. (1993b) analyzed geochemistry and pigments in three ^{210}Pb dated cores from Lake St. Croix for post-settlement signals. Gradual changes were noted over the last 150 years in sedimentation rate, and organic, carbonate, and pigment concentrations. Sedimentation rates, although low compared to most constructed reservoir systems, began increasing between 85 and 120 years ago from presettlement values of 0.125-0.2 g cm^{-2} yr^{-1} to maximum levels recorded c. 1930 of 0.3-0.6 g cm^{-2} yr^{-1}. Increases in organic content accompanied initial logging activity on the river, and subsequently organic, carbonate, and chlorophyll concentrations increased between 1940 and 1990. These latter increases were considered indicators of cultural eutrophication in Lake St. Croix associated with urbanization in the lower basin.

This study builds on these earlier paleo efforts by analyzing diatom remains and geochemistry in two dated cores from Lake St. Croix for post-settlement signals of trophic change and sedimentation. For inferring historical total phosphorus (TP), diatom-based reconstructions have been adopted as the most powerful tool at hand (Fritz et al. 1991, 1993, Anderson and Rippey 1994, Reavie et al. 1995, Rippey and Anderson 1996). Whereas earlier diatom-based methods provid qualitative measures of historical water chemistry or productivity using categorical indicator values (ter Braak and van Dam 1989), 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 applies a transfer function developed from a training set of diatom assemblages and select environmental parameters in modern lakes to historical diatom assemblages in sediment cores to reconstruct specific environmental variables. 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. The weighted averaging method is statistically robust and based on ecologically sound organismal responses (ter Braak and Prentice 1988, Birks et al. 1990b); however, interpretation is strongest when multiple lines of paleoenvironmental evidence are considered (Fritz et al. 1993).

Site Description

Lake St. Croix encompasses the terminal 37 km of the St. Croix River from Stillwater, Minnesota to Prescott, Wisconsin along the interstate boundary (Fig. 1). The St. Croix River (266 km long) drains a watershed of approximately 22,196 km^2 in conjunction with 16 major tributary systems. The river serves a basinwide population of over 300,000 (Andersen et al. 1996) including more than 50 permitted point-source dischargers (Meyer et al. 1999). The Lower St. Croix, including Lake St. Croix, was designated a National Scenic Riverway in 1972.

Lake St. Croix is a natural impoundment of the St. Croix River that was formed approximately 9500 years ago by downstream progradation of the delta produced by the Mississippi River at the headwaters of Lake Pepin (Eyster-Smith et al. 1991). The delta eventually formed the Point Douglas sand bar at Prescott, Wisconsin, damming the mouth of the St. Croix River. Secondary deposition of alluvial tributary fans within the lake from the Willow River, Valley Creek, and Kinnickinnic River, subdivided Lake St. Croix into four basins. Moving downstream, Basin 4 stretches from Stillwater to the

Willow River Bar at Hudson, WI, and has a maximum depth of c. 10 m. Basin 3 reaches from the Willow River bar to Catfish Bar (Valley Creek mouth) at Afton, MN, and is c. 20 m deep. Basin 2 continues from Afton, MN to the Kinnickinnic Bar and has a maximum depth of over 22 m. Basin 1 terminates the lake at the mouth of the St. Croix River at Prescott, WI, and is over 17 m deep (Fig. 1).

Materials and Methods

Coring. Two sediment cores were recovered from Lake St. Croix on 15 October 1999 using a drive-rod piston corer equipped with a 2.4 m long, 7 cm diameter polycarbonate barrel (Wright 1991). Core 1B was 1.89 m long and recovered upstream of Prescott, Wisconsin in the southernmost basin from 11.9 m of water at 44°45'27.584" N and 92°48'25.250" E (Fig. 1). Core 6B was 2.03 m long and recovered near Lakeland, Minnesota from 14.86 m of water at 44°56'51.178" N and 92°45'19.340" E (Fig. 1). The top 20 cm of each core were extruded in the field in 2-cm increments and the remaining core material sealed and transported to 4°C laboratory storage.

Magnetic susceptibility. Each core was brought to room temperature, horizontally extruded in the laboratory, and separated into 1-m sections for magnetic susceptibility logging. Magnetic susceptibility provides a non-destructive measure of ferromagnetic particles within the core and was done using a Bartington MS2 core logging sensor with an automated trackfeed capable of manipulating 1-m core sections. Susceptibility measures were taken at 1-cm intervals which integrated a signal over a 5-10-cm length of core. Data were subsequently spliced at core breaks for plotting. Following susceptibility logging, downcore smearing was removed from the core exterior, the cores sectioned in 2-cm intervals, and intervals returned to 4°C cold storage.

Loss-on-ignition. Subsamples were taken of each homogenized 2-cm sediment interval for loss-on-ignition analysis to determine dry density and weight percent organic, carbonate, and inorganic matter. 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. Data are expressed as percentage of dry sediment weight and converted to sedimentary accumulation rates using the ^{210}Pb dating model and accompanying sedimentation rates as noted below.

Dating and sedimentation rates. Twenty-five samples were selected from each core for ^{210}Pb analysis to determine chronology and sedimentation rates over the last 150 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 x 10^5 s using an Ortec alpha spectrometry system. Supported ^{210}Pb is quantified by the mean activity levels 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 sedimentaton 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. Downcore extrapolation suggests core 6B sampled approximately the last 600 years and that core 1B sampled the last 1000 years; however, all downcore data presentation is truncated at c. 1800 to emphasize changes and trends following European settlement in the region.

Microfossil analysis. Between 25 and 60 mg of freeze-dried material were used for microfossil analysis. To remove organic matter, weighed subsamples were first heated at 150°C in 20 ml 30% H_2O_2 for 30 min. Twenty-five ml of concentrated HNO_3 were carefully added and the solution heated for another hour at 175°C. Material was cooled and rinsed with distilled water six times with six hours of settling between rinses. Lastly, all cleaned material was dried onto coverslips using settling chambers (Battarbee 1973) and the coverslips mounted on microslides with Naphrax.

Twenty-one sections from core 1B and 23 sections from core 6B were analyzed for siliceous microfossil remains. Siliceous remains (diatom valves and chrysophyte cysts) along one or more random microslide transects were counted on an Olympus

BX50 microscope using full oil immersion optics capable of N.A. 1.4 and 1250X until a total of 500 diatom microfossils was reached. Raw data counts were converted to absolute abundance of cysts and whole diatom valves per g dry sediment by species and ecological groups and subsequently combined with sedimentation rates to generate historical microfossil accumulation rates. Percent abundance of ecological groups reflects abundance relative to all siliceous microfossils. Percent abundances of diatom species are relative to total diatom abundance. All microfossil data are graphed relative to downcore age to account for different linear sedimentation rates between cores.

Water column TP reconstruction. Weighted averaging calibration and reconstruction (Birks et al. 1990a) were used to infer historical water column total phoshorus (TP) in Lake St. Croix. We used Ramstack's (1999) training set of 55 Minnesota lakes that had water column total phosphorus values from 0.0075 to 0.1393 mg l^{-1}. Surface sediments from these 55 lakes were collected in conjunction with numerous environmental variables including water column TP, and the diatom assemblages from each lake quantified by identifying 400 specimens. Species data and environmental data were analyzed using weighted average regression software (CALIBRATE; Juggins 1998) to calculate TP optima for 108 diatom taxa in the training set for subsequent use in historical reconstruction of TP values from 0.009 to 0.105 mg l^{-1} (Ramstack 1999).

Within the Lake St. Croix cores, sixty-five diatom taxa (Table 1) were present in >1% relative abundance in two sediment samples or >5% relative abundance in one sample (selection criteria from Ramstack, 1999). However, only thirty-three taxa were common with the Ramstack (1999) TP training set, and additional calibration models were consulted. Due to its regional focus, the Ramstack TP model was preferentially chosen for TP optima. For taxa not present in the Ramstack model, TP optima for 12 additional taxa were taken from Reavie et al. (1995), a training set developed for British Columbia lakes with TP values ranging from 0.005 to 0.085 mg l^{-1}. Lastly, TP optima of two taxa were taken from Fritz et al. (1993), a training set from Michigan lakes with TP values ranging from 0.001 to 0.051 mg l^{-1}. Because three sources of TP optima were used and tolerances were not available from the Fritz et al. and Reavie et al. models, only weighted averaging calibration was applied (rather than tolerance-weighting). Initial TP estimates were corrected (Birks et al. 1990) using the inverse deshrinking regression from the Ramstack (1999) model. Error estimates from the Ramstack model are based on the initial log transformed data set and thus the log TP error is –0.2488.

Results

Magnetic susceptibility. Magnetic susceptibility profiles from Lake St. Croix record downcore changes in the concentration of fine-grained ferromagnetic minerals. Core 6B had relatively uniform susceptibility from 130 to 200 cm in the lower half of the core (Fig. 2). Unfortunately, the core was split for magnetic logging at 120 cm, exactly where an upcore increase in susceptibility began. Highest levels of susceptibility were at 100 cm and then decreased upcore with several local maxima. Core 1B had two peaks in susceptibility between 110 and 190 cm (Fig. 2). The lower peak corresponded to a sand lens deposited during the late 1100s and may represent upstream deposition of coarse-grained sediment during catastrophic flooding on the Mississippi River (J. Knox, Univ. of Wisconsin, pers. comm.). Susceptibility increased upcore between 70 and 40 cm, then decreased slightly. In core 1B, the susceptibility increase at 70 cm was identified as the settlement horizon; ^{210}Pb dating confirmed this level to be c. 1850 (Fig. 2). The upcore increase in susceptibility beginning at 120 cm in core 6B was targeted as the settlement horizon, although ^{210}Pb dating subsequently identified 112 cm to approximate 1850 (Fig. 2).

Dating. Both cores showed relatively monotonic downcore declines in total ^{210}Pb activity from upper-level sediments to core depths (68 cm in 1B and 114 cm in 6B) with constant supported ^{210}Pb levels (Fig. 3a). Unsupported ^{210}Pb activity in surface sediments was relatively low and variable between cores, from 5-8 pCi g^{-1}, suggesting some dilution of atmospheric inputs by sediment accumulation (Fig. 3a). Cumulative unsupported activity ranged from 47 to 68 pCi g^{-1}, representing a mean unsupported ^{210}Pb flux of between 1.5 pCi cm^{-2} yr^{-1} (core 1B) and 2.2 pCi cm^{-2} yr^{-1} (core 6B) in the lake. These values range from 3 to 5 times mean regional atmospheric deposition (0.45 pCi cm^{-2} yr^{-1}; Urban et al. 1990) indicating that a significant portion of the ^{210}Pb activity in the cores is derived from watershed deposition and downstream export to Lake St. Croix.

High sediment loading normally limits reliable ^{210}Pb dating of riverine impoundments to less than a century, but because of the excess (watershed) flux of ^{210}Pb to Lake St. Croix, dating could be extended back to the mid-1800s in both cores. However, error terms for the c.r.s.-derived chronologies increase substantially for ages older than about 120 years, and dates corresponding to the onset of European settlement (c. 1850) have an uncertainty of 2-3 decades. Despite such limitations, the ^{210}Pb chronology for core 1B places the date of 1852 at 66 cm, precisely on the rise in magnetic susceptibility that signals the beginning of European agriculture (Fig 2). The fit between ^{210}Pb and this magnetic feature is not quite so good in core 6B where the 1850 datum is placed 6-8 cm above the magnetic settlement marker. Nonetheless, this correspondence is well within the precision of the ^{210}Pb, and suggests that more recent dates (those for the 20^{th} century) should be reasonably correct.

Sedimentation rate. Presettlement sediment accumulation rates of approximately 0.06 to 0.08 g cm^{-2} yr^{-1} were similar for cores 6B and 1B (Fig. 4). Core 6B showed an earlier post-settlement increase in sedimentation than core 1B. Sedimentation rates began to increase in core 6B as early as 1850 and continued with some variability to the highest rate of 0.34 g cm^{-2} yr^{-1} around 1970 (Fig. 4). Since 1970, sedimentation rates in core 6B have decreased slightly to approximately 0.25 g cm^{-2} yr^{-1}. Post-settlement increases in sedimentation were not pronounced in core 1B until c. 1910 (Fig. 4). Sedimentation rates in this core increased to a local maximum of 0.36 g cm^{-2} yr^{-1} by 1959, decreased to 0.23 g cm^{-2} yr^{-1} by 1982, increased slightly to present-day values of approximately 0.30 g cm^{-2} yr^{-1} (Fig. 4).

Loss-on-ignition. Loss-on-ignition analysis confirmed what was suggested by the monochrome gray-black appearance of Lake St. Croix sediments—very little change in general sediment composition over the last 200 years and predominance of inorganic matter (silt and clay-size clastics). Core 6B had little variability in organic, carbonate, and inorganic proportions. Percent inorganic dropped slightly upcore from presettlement values of 83% to modern values of 76%, while organic and carbonate percentages showed a corresponding increase from presettlement to modern; organic contribution to dry mass rose from 15 to 19% and carbonates increased from 3 to 6% (Fig. 5a). In core 1B organics have remained approximately 85% throughout, while organic and carbonate proportions varied inversely. Presettlment sediments had higher carbonate percentages, which subsequently declined upcore to about 6%. Organics increased upcore to modern levels of 11% (Fig. 5a).

When sediment proportions are calculated as accumulation rates, large changes in organic, inorganic and carbonate fluxes are revealed. In core 6B, inorganic accumulation increased starting 1850 and continued past several local maxima to a peak of nearly 0.3 g cm^{-2} yr^{-1} in the early 1970s. Levels of inorganic accumulation have since decreased to around 0.2 g cm^{-2} yr^{-1} over the last 25 years (Fig. 5b). Organic matter and carbonates also increased in accumulation shortly after settlement. Carbonate flux reached highest levels in modern times, whereas organic accumulation had local maxima between 1870 and 1885, the 1920s, and reached highest levels in the early 1970s (Fig. 5b). In core 1B inorganic accumulation increased from steady pre-1900 levels of 0.075 g cm^{-2} yr^{-1} to a 1960 maximum of > 0.3 g cm^{-2} yr^{-1} (Fig. 5b). Inorganic accumulation declined after the 1960s, although a slight increase to 0.25 g cm^{-2} yr^{-1} in recent times was noted. Accumulation of carbonates and organics also increased after 1900 in core 1B, but have remained relatively constant since 1920; 0.03 g cm^{-2} yr^{-1} for organics and 0.02 g cm^{-2} yr^{-1} carbonates (Fig. 5b).

Microfossil analysis. Chrysophyte cysts and 351 diatom taxa and were identified in sediment cores from Lake St. Croix. Absolute abundance of siliceous microfossils varied from 42.2 million to 467.8 million diatoms per g dry sediment in Core 6B and from 4.3 million to 126 million diatoms per g dry sediment in Core 1B (Fig. 6a). Core 6B had greater absolute abundance of diatoms throughout its length compared to core 1B, typically four to ten times greater (Fig. 6a). Total annual microfossil accumulation was likewise higher in core 6B, with 6 to 131 x 10^6 microfossils deposited per cm^2 compared to 0.5 to 36 x 10^6 microfossils deposited per cm^2 in core 1B (Fig. 6c). Core 6B had large increases in microfossil acumulation beginning about 1920, whereas core 1B had major increases starting about 1950 (Fig. 6c). Both cores record maximum abundance of microfossils in the near-surface sediments (Figs 6a,c). Core 1B had a secondary peak in abundance and accumulation in the mid-1980s, while core 6B showed maximum annual accumulation in the early 1960s and oscillated around 100 million microfossils per cm^2 since that time (Figs 6a,c).

The siliceous microfossil assemblage was further separated into three groups: chrysophyte cysts, benthic diatoms, and planktonic diatoms. Throughout the length of both cores, chrysophyte cysts remained a consistent, but minor component of the assemblage. Cysts showed slight increases in absolute abundance and accumulation in both cores after 1950 (Figs 6b,c). Absolute abundance and accumulation of diatoms was low and dominated by benthic species before c. 1920 in core 6B and before c. 1950 in core 1B (Figs 6b,c). After these dates, both groups of diatoms began to increase markedly in abundance and accumulation, especially planktonic species. By 1935 in core 6B and 1950 in core 1B, dominance in the Lake St. Croix diatom community had shifted completely to planktonic species (Fig. 6b). In upstream core 6B, both diatom groups reached initial peaks in accumulation and abundance c. 1963 (Figs 6b,c). Since that time, annual accumulation of benthic diatoms oscillated around 30 million valves per cm^2 and that of planktonic diatoms around 65 million valves per cm^2 (Fig. 6c). In downstream core 1B, benthic and planktonic diatom abundance and accumulation increased steadily upcore after 1950 with a small local accumulation and abundance peak in the mid-1980s (Fig. 6b,c).

Relative abundance calculations show the inexorable shift of dominance from benthic to planktonic forms within the diatom community of Lake St. Croix which followed European settlement (Figs 7,8). From presettlement to c. 1920, benthic diatoms composed over 60% of the diatom assemblage preserved in core 6B with planktonic species always less than 30% relative abundance (Fig. 7). The shift toward lower benthic and higher planktonic relative abundance started as early as c. 1870, and by 1935 planktonic forms were greater than 50% of the total. Planktonic abundance values have remained at approximately 60% for the last 40 years in core 6B (Fig. 7). A more dramatic shift has been recorded in core 1B. From presettlement until c. 1910 benthic diatoms composed over 60% of the fossil assemblage, whereas planktonic diatoms remained near 20% relative abundance (Fig. 8). Between 1910 and the early 1960s, planktonic diatoms increased to approximately 70% relative abundance, while benthic diatoms decreased to c. 20% (Fig. 8).

This shift from benthic to planktonic dominance is obviously driven by the changing abundance of individual diatom species. In sediments deposited before 1920 in both cores, the planktonic flora was dominated by Aulacoseira granulata, A. ambigua and Stephanodiscus niagarae (Figs 7,8). The pre-1920 benthic flora was composed of a diverse assemblage dominated by "small fragilarioid" taxa such as Staurosirella pinnata, S. leptostauron v. dubia, Staurosira construens and var. venter, Martyana martyi, Pseudostaurosira brevistriata and var. inflata, and the mono- and bi-raphid attached forms Cocconeis neodiminuta, C. placentula v. euglypta, Planothidium frequentissimum, Amphora pediculus, and Cavinula scutelloides (Figs 7,8). After 1920, the plankton dominants Aulacoseira granulata, A. ambigua, and Stephanodiscus niagarae increased in relative abundance in both cores (Figs 7,8). In core 6B, A. granulata and A. ambigua have further alternated in relative abundance since 1920 (Fig. 7). As conditions continued to change in Lake St. Croix, several new planktonic taxa appeared. In cores 6B and 1B, Stephanodiscus parvus and Fragilaria capucina var. mesolepta became established and increased in abundance shortly after 1910 A.D., and A. subarctica became temporarily established for the next 50 years (Figs 7,8). In core 6B, Fragilaria capucina and A. alpigena appeared during the 1930s and 1940s, and F. crotonensis, Cyclostephanos invisitatus, and C. tholiformis became abundant after 1950 (Fig. 7). These same trends were seen but with slightly lower abundances and slightly later appearances of each taxon in core 1B (Fig. 8). Although still present in Lake St. Croix sediments, most benthic taxa declined in relative abundance in both cores during the last 200 years to minimum values in the uppermost sediments (Figs 7,8). Fragilaria vaucheriae is the only common benthic taxon that did not follow this pattern; it increased in relative abundance upcore.

Water column TP reconstruction. Forty-seven diatom taxa representing between 75.2 and 93.4 percent of the identified diatom assemblage in cores 1B and 6B were used in the reconstruction of historical water column TP (Table 1). Reconstructed pre-settlement values were between 0.017 and 0.027 mg l^{-1} TP with downstream core 1B showing slightly higher presettlement values (Fig. 9). In both cores, historical water column TP values remained at or near pre-settlement levels until c. 1910. At this time, reconstructed TP values began to increase in both basins (Fig. 9). In core 6B, TP values rose more rapidly to 0.040 mg l^{-1} by the mid-1930s and then continued in a general upcore increase with some variability to modern reconstructed values of 0.050 to 0.055 mg l^{-1} TP (Fig. 9). Core 1B showed a similar increase beginning c. 1910; however, the rise has been more or less continuous to modern reconstructed levels of 0.052 to 0.060 mg l^{-1} (Fig. 9).

Discussion

By most lake standards (TP, chlorophyll-a, Secchi, various indices), modern Lake St. Croix would be considered eutrophic (MPCA, 2001). Determining whether this teminal lake of the St. Croix River basin has always been a eutrophic system is critical for establishing effective management policy on future nutrient and sediment loadings (St. Croix Interagency Basin Team 1998). Analysis of historical water quality data has failed to identify significant recent trends (improvement or degradation) in water quality since the 1950s in Lake St. Croix (Troelstrup et al. 1993a, Malischke et al. 1994, Kroenig and Stark 1997). Previous paleolimnology efforts did, however, indicate that sedimentation and trophic conditions in Lake St. Croix began to change well before 1950. Troelstrup et al. (1993b) analyzed three cores in the lake and found that sediment accumulation rates had increased (c. 1870) shortly after logging and settlement began in the basin to 2-3 times presettlement levels by the 1930s. Elevated percent abundance of sedimented organics, carbonates, and chlorophyll derivatives was a clear signal of increased productivity in the lake from 1940 to 1990.

Our study builds on Troelstrup et al. (1993b) to provide a more detailed picture of the changes in sedimentation and trophic conditions that have occurred in Lake St. Croix since European settlement. Key to this approach was determination of sedimentary flux from two dated cores in conjunction with a diatom-based reconstruction of water column total phosphorus levels (Hall and Smol 1992, Ramstack 1999) to quantify changes in trophy and sedimentation.

A consistent increase in the magnetic susceptibility provided a clear settlement marker in both cores. Sedimentation rates in Lake St. Croix's northern basin (core 6B) began to increase immediately following logging and settlement in the basin (Anderson et al. 1996). In downstream core 1B similar increases in dry-mass sedimentation rate were lagged to about 1900. In both cores sedimentation increased three-fold from presettlement to peak values of about 0.3 to 0.4 g cm^{-2} yr^{-1} in the 1960s. Presettlement sedimentation rates were similar to those found in Lake Pepin, a natural impoundment on the Mississippi River (Engstrom and Almendinger 1998); however, post-settlement increases in Lake St. Croix were much lower than the order of magnitude increases found post-settlement in Lake Pepin. Loss-on-ignition analysis of the sediment showed that inorganic clastics were by far the most abundant component in weight percent and post-settlement flux. High inorganic content is characteristic of sedimentation in riverine impoundments; sediments in natural lakes in the Upper Midwest are more evenly divided between organics, carbonates, and inorganic matter (e.g., Fritz et al. 1993, Engstrom et al. 1999). The post-settlement increase in inorganic sedimentation was likely due to increased erosion and transport from land clearance and increasing agriculture practices in the St. Croix Basin (Anderson et al. 1996). The increased upcore flux of carbonates is more likely a signal of greater within-system productivity associated with increased nutrient loading to the system (Engstrom and Swain 1986, Hodell et al. 1998). Organics may signal increased inputs of allochthonous material accompanying erosion and/or increased within-system productivity.

Patterns in sedimentation can be correlated to changes in basin land-use as reported by Anderson et al. (1996). Logging and land clearance for agriculture was initiated in the 1840s and logging peaked c. 1890. In upper Lake St. Croix, these land-use changes are reflected in immediate increases in sedimentation rates. From c. 1870 to 1940, agriculture was the primary land-use in the lower St. Croix. Continued increases in sedimentation over this time period clearly reflect the increasingly agricultural character of the landscape. Anderson et al. (1996) reported that 50% of the lower St. Croix basin was in agriculture by 1880 and by 1928 over 75% of SW Wisconsin farms, including in the lower St. Croix, had serious erosion problems. Sedimentation rates continued to increase in Lake St. Croix into the 1960s as land-use began to shift from peak agriculture in 1935 to increased urbanization. Post-1960 decreases in sedimentation rates may be an indication of less intensive agriculture in the region, improved soil conservation and management practices, or reestablishment of ground and forest cover as agricultural lands have been converted to low- to medium-density urban land-use. However, in core 1B recent sedimentation rates showed an increase since the 1980s, possibly due to accelerated urbanization in the Lower St. Croix (Anderson et al. 1996).

Diatom-based reconstructions of historical water column TP concentration in Lake St. Croix show that phosphorus levels did not begin to appreciably increase above presettlement values of about 0.02 mg l^{-1} until c. 1910. In core 6B, reconstructed TP levels quickly increased to a local maximum in 1935, before dropping and oscillating upcore to maximum TP values in the 1990s of 0.055 mg l^{-1}. In core 1B, TP increased similarly from presettlement values beginning about 1910 to modern levels of between 0.052 and 0.059 mg l^{-1}. As such, water column TP concentrations in Lake St. Croix are between two- and three-fold greater than reconstructed levels pre-1910. The strength of our reconstruction is evident, as diatom-inferred TP in the uppermost levels of both cores closely approximates measured TP values in Lake St. Croix, especially during the last two decades. Kroenig and Stark (1997) reported no discernable trends in TP measurements between 1984 and 1993 in the lower St. Croix River, with median TP values of c. 0.050 mg l^{-1}, precisely where our core-top reconstructions fell. Similarly, Malischke et al. (1994) reported mean values of TP slightly upstream of the headwaters of Lake St. Croix of 0.050 mg l^{-1} from 1975 to 1983 and slightly higher values of 0.060 mg l^{-1} in the late 1980s. The slightly higher historical TP levels reported by Troelstrup et al. (1993a) between 1950 and 1972 (median 0.080 mg l^{-1}) were not clearly shown in our reconstructions; TP reconstructions from core 6B have oscillated around 0.050 mg l^{-1} since the 1960s.

Trends in siliceous microfossil accumulation tracked reconstructed TP levels. Core 6B showed a slight increase in diatom accumuluation immediate post-settlement, and then a major increase beginning in the 1910s that peaked in the 1960s and oscillated thereafter to the present. Core 1B had an increase in microfossil accumulation beginning in the 1910s that peaked in the 1980s and 1990s. The largest increases in siliceous microfossil accumulation occurred during the 1950s and early 1960s in upstream core 6B and the 1960s and early 1970s in downstream core 1B.

Both cores had post-settlement increases in the relative abundance of planktonic diatoms coupled with decreases in benthic diatoms. Shifts from benthic to planktonic productivity have typified the trophic response of many systems to increased nutrient loading. For example, Schelske et al. (1999), found a phosphorus-mediated shift from benthic- to planktonic-dominated productivity in the shallow Florida Lake Apopka. Critical to understanding the response of Lake St. Croix to increased phosphorus load is that while benthic diatoms decreased in relative abundance, they actually increased in absolute abundance or annual accumulation. Thus both ecological components of the diatom community responded positively to nutrient addition. Whereas presettlement productivity was defined by low abundance and accumulation of benthic diatoms, more recent conditions (since 1960 in core 1B and the 1940s in core 6B) are characterized by high accumulation of both ecological groups, but especially the plankton. The increase in planktonic relative abundance occurred in concert with increasing TP levels c. 1910.

Corresponding to the productivity shifts were changes in the relative abundance of dominant diatom taxa. Benthic taxa generally declined in abundance upcore, a response typical for nutrient enrichment (Fritz et al. 1993). A few benthics such as Staurosirella pinnata and Pseudostaurosira brevistriata var. inflata responded positively to initial perturbation in the region; both taxa showed increases in relative abundance between 1850 to 1920, especially in core 1B. Fragilaria vaucheriae actually increased in absolute abundance upcore; this may be testament to its tychoplanktonic adaptability for growth either attached or suspended within the water column (Stoermer and Yang 1969). The shift to plankton-dominated production saw the increase of the plankton dominants (Aulacoseira granulata, A. ambigua and Stephanodiscus niagarae) and introduction and establishment of many planktonic diatoms considered ubiquitous indicators of eutrophy (e.g., Cyclostephanos invisitatus, C. tholiformis, Fragilaria crotonensis, F. capucina and var. mesolepta). Whereas the character of the planktonic community is still defined by Aulacoseira spp. dominance, an increased contribution of the chain-forming Fragilaria spp. and small centrics with higher TP optima, clearly differentiates the modern planktonic community from the pre-settlement plankton. Furthermore, the presence of bloom-forming blue-green algae during the summer months in the plankton of Lake St.

Croix, a common signal of increased trophic level, has been noted since the 1960s (Brook, in Troelstrup 1993a).

The timing of many changes recorded in the sediments is later in downstream core 1B compared to core 6B. Whereas both cores showed strong magnetic signatures at settlement, the higher erosional forces at the headwaters of Lake St. Croix coupled with higher sediment retention within the northern basin may have caused the lag in the increased sedimentation rate signal in the southern basin until 1900. A more detailed land-use history may also find that initial land clearance and logging activities were focused above Lake St. Croix, rather than in the side-valley tributary watersheds of its more southern basins. The post-settlement increase in reconstructed water column TP occurred simultaneously in core 6B and 1B, c. 1910. Reconstructed TP values for core 6B, however, increased more quickly than in core 1B. Even the record of establishment for planktonic diatom taxa is lagged downstream. Differences in upstream land use, hence loadings, and/or sufficient residence time in the northern basin to assimilate TP loads through production and sedimentation could explain these lags. Ongoing analysis of sediment retention of phosphorus among Lake St. Croix four basins may also clarify this difference.

Increased diatom accumulation, a shift toward plankton-dominated production, the establishment of eutrophic indicators, increased sedimentation rates, and increased accumulation of carbonates and organic mattter provide clear multiple signals of post-settlement changes in Lake St. Croix water quality. Clearly, sedimentation rates and water quality were substantially impaired from presettlement levels when water quality monitoring of Lake St. Croix began in the 1950s. Our quantitative reconstruction of the timing and magnitude of change in total phosphorus levels in Lake St. Croix should allow managers to shift their policy emphasis from protection to remediation of water quality in the lower St. Croix if they so choose. With these paleoenvironmental data in conjunction with modeling/monitoring programs, managers can develop sensible policy targets for controlling nutrient loading to the St. Croix River in conjunction with monitoring programs.

Acknowledgments

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Figure Legends

Figure 1. Map of Lake St. Croix showing multiple basins, major towns and cities, and location of coring sites 6B and 1B (X).

Figure 2. Magnetic susceptibility vs. sediment depth (cm) in core 6B (left panel) and core 1B (right panel). The core depth dated to 1850 by ^{210}Pb is marked by dashed lines.

Figure 3. Lead-210 profiles and chronology for core 6B (left panels) and core 1B (right panels). (3a.) Total-^{210}Pb activity plots; supported ^{210}Pb indicated by dashed line; error bars represent ± 1 s.d. (3b.) Calculated age (years before 1999) vs. sediment depth (cm) based on the constant rate of supply (c. r. s.) model.

Figure 4. Dry-mass sedimentation accumulation (g cm^{-2} yr^{-1}) vs. ^{210}Pb date for core 6B (left panel) and core 1B (right panel)

Figure 5. Sediment composition and accumulation as determined by loss-on-ignition vs. ^{210}Pb date. (5a.) Percent dry mass. (5b.) Accumulation rates (g cm^{-2} yr^{-1}).

Figure 6. Microfossil concentration and accumulation vs. ^{210}Pb date for core 6B (left panels) and core 1B (right panels). Left panels are core 6B, are core 1B. Microfossils are separated into three ecological groups: chrysophyte cysts, planktonic diatoms, and benthic/periphytic diatoms. (6a.) absolute microfossil abundance; (6b.) absolute microfossil abundance by group; (6c.) microfossil accumulation by group.

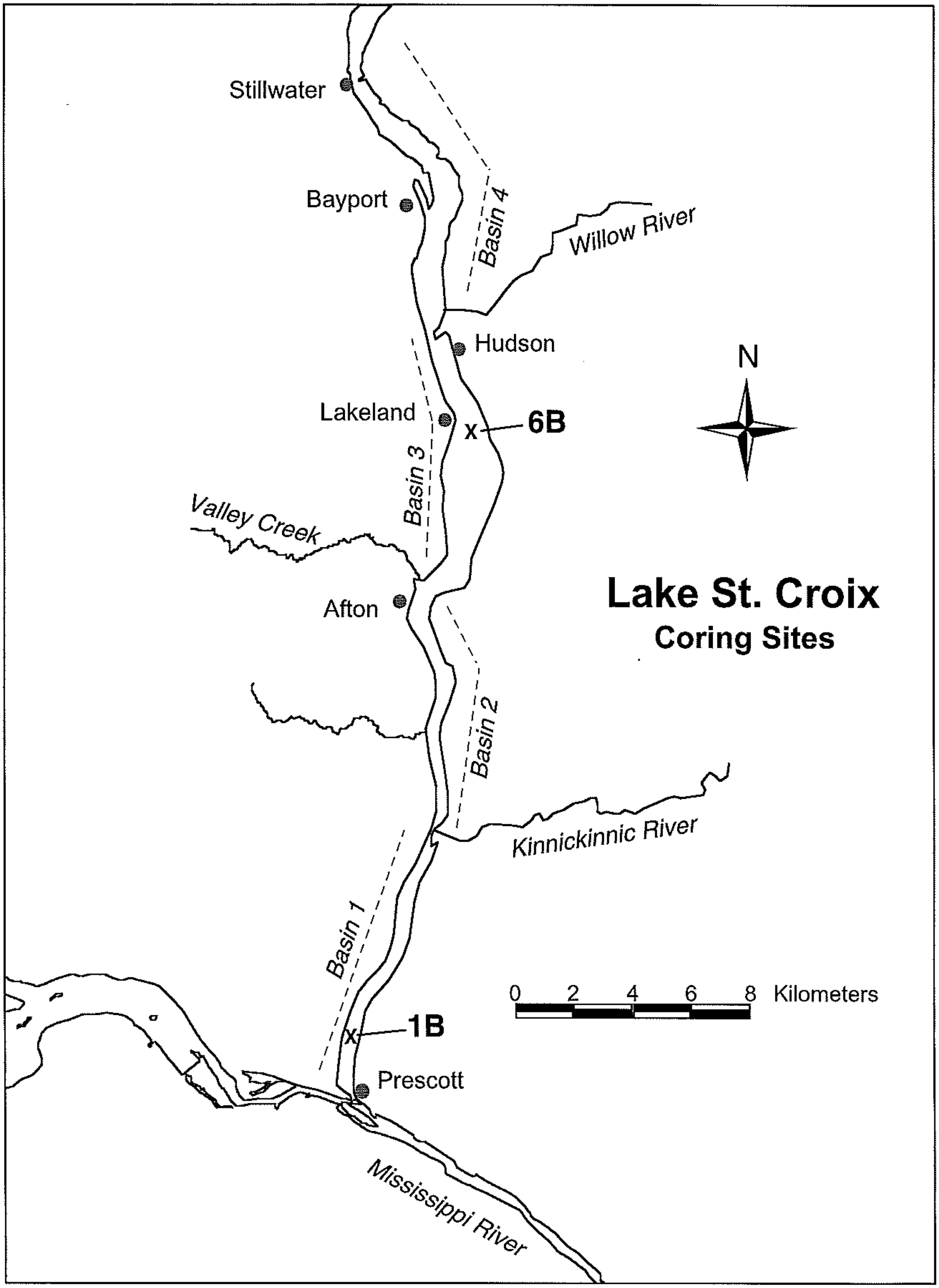
Figure 7. Relative abundance of planktonic and benthic diatom taxa present at >3% total diatom counts in core 6B sediments. Upper panel is planktonic taxa and lower panel is benthic/periphytic taxa.

Figure 8. Relative abundance of planktonic and benthic diatom taxa present at >3% total diatom counts in core 1B sediments. Upper panel is planktonic taxa and lower panel is benthic/periphytic taxa.

Figure 9. Diatom reconstructed water column total phosphorus (mg l^{-1}) vs. ^{210}Pb date. Left panel is core 6B, right panel is core 1B.

Tables

Table 1. Diatom taxa used in water-column TP reconstruction, with their TP optima and the published source. These taxa were present in Lake St. Croix sediments at >1% in two samples or >5% in one sample


Stillwater
Bayport
Basin 4
Willow River
Hudson
N
Lakeland
6B
Basin 3
Valley Creek
Afton
Lake St. Croix
Coring Sites
Basin 2
Kinnickinnic River
Basin 1
0 2 4 6 8 Kilometers
1B
Prescott
Mississippi River

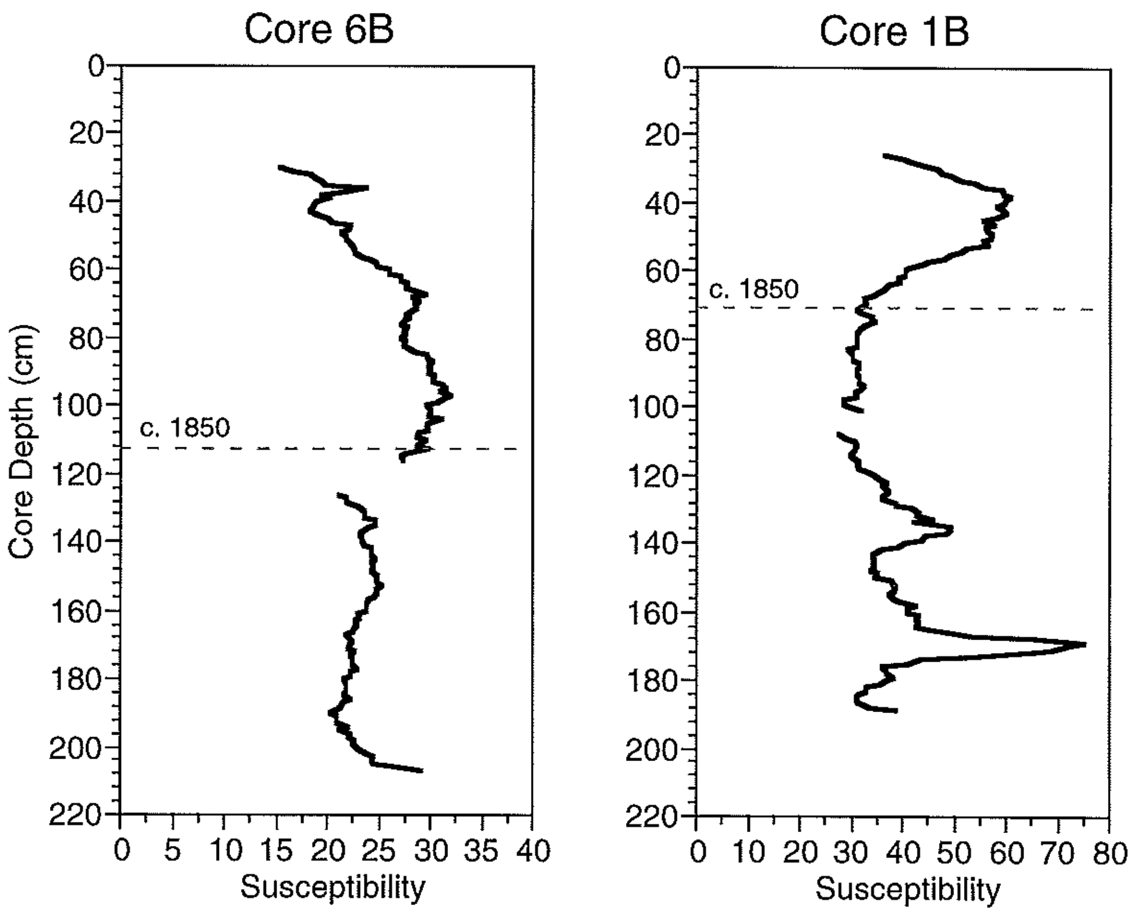


Figure 2. Magnetic susceptibility profiles.

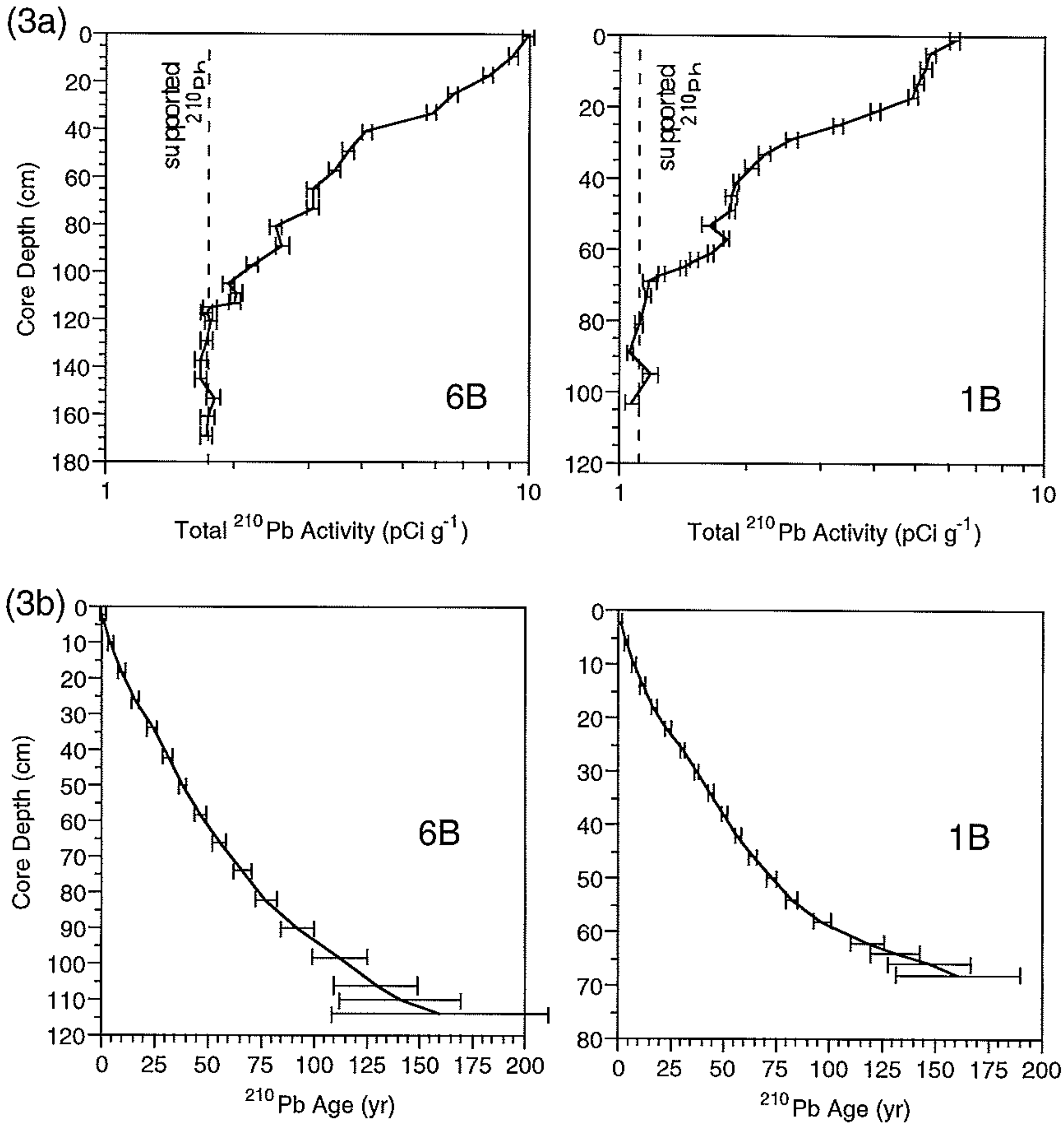


Figure 3. 210-Lead profiles and chronology.

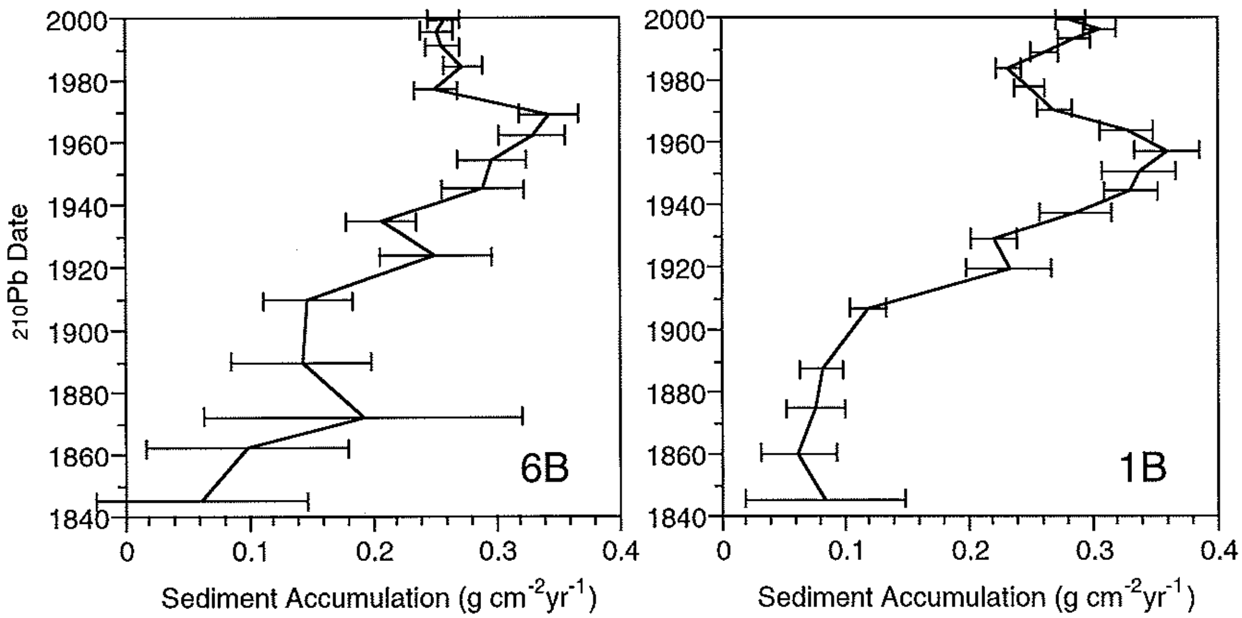


Figure 4. Dry-mass sediment accumulation

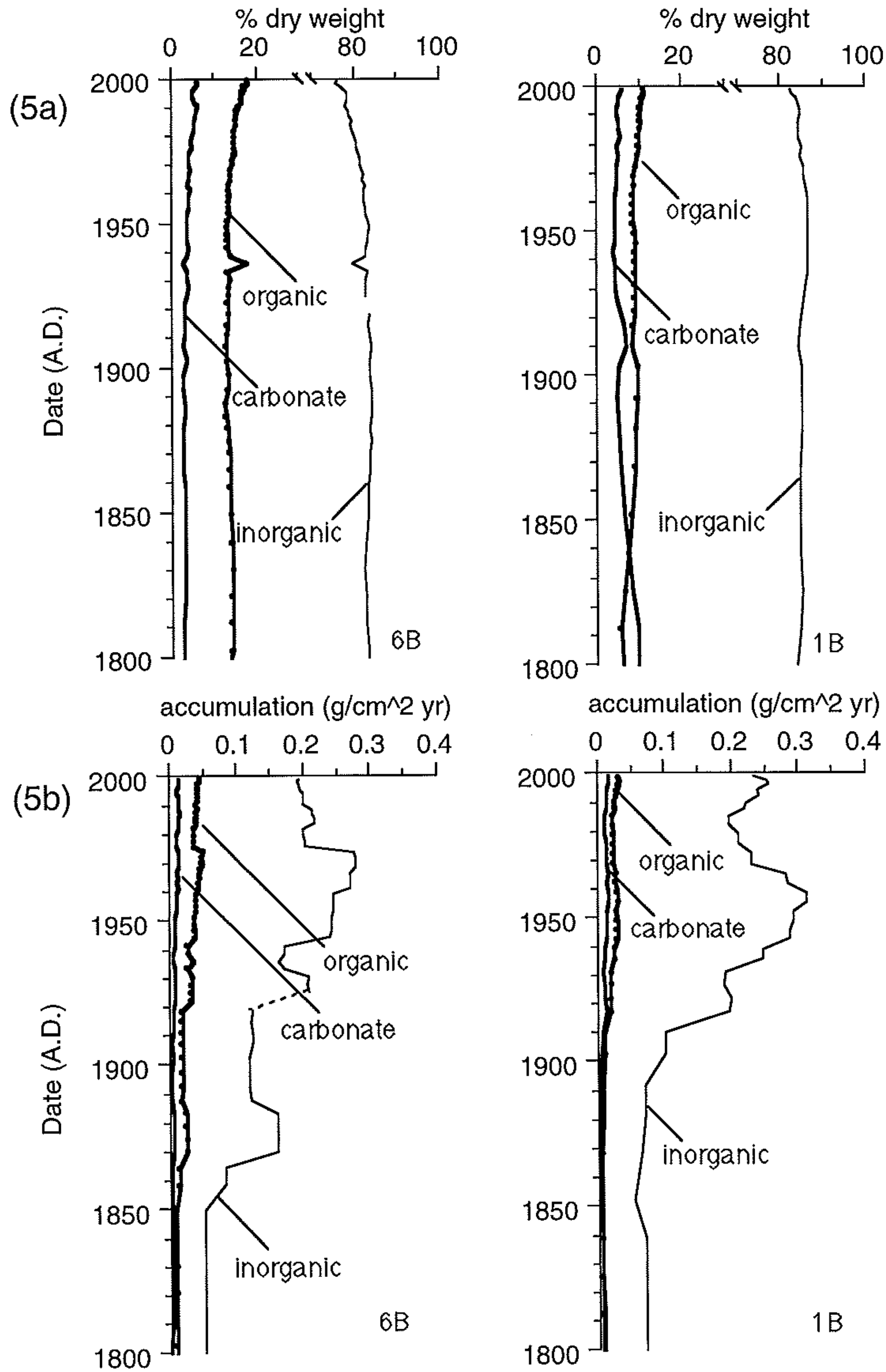


Figure 5. Sediment composition and accumulation.

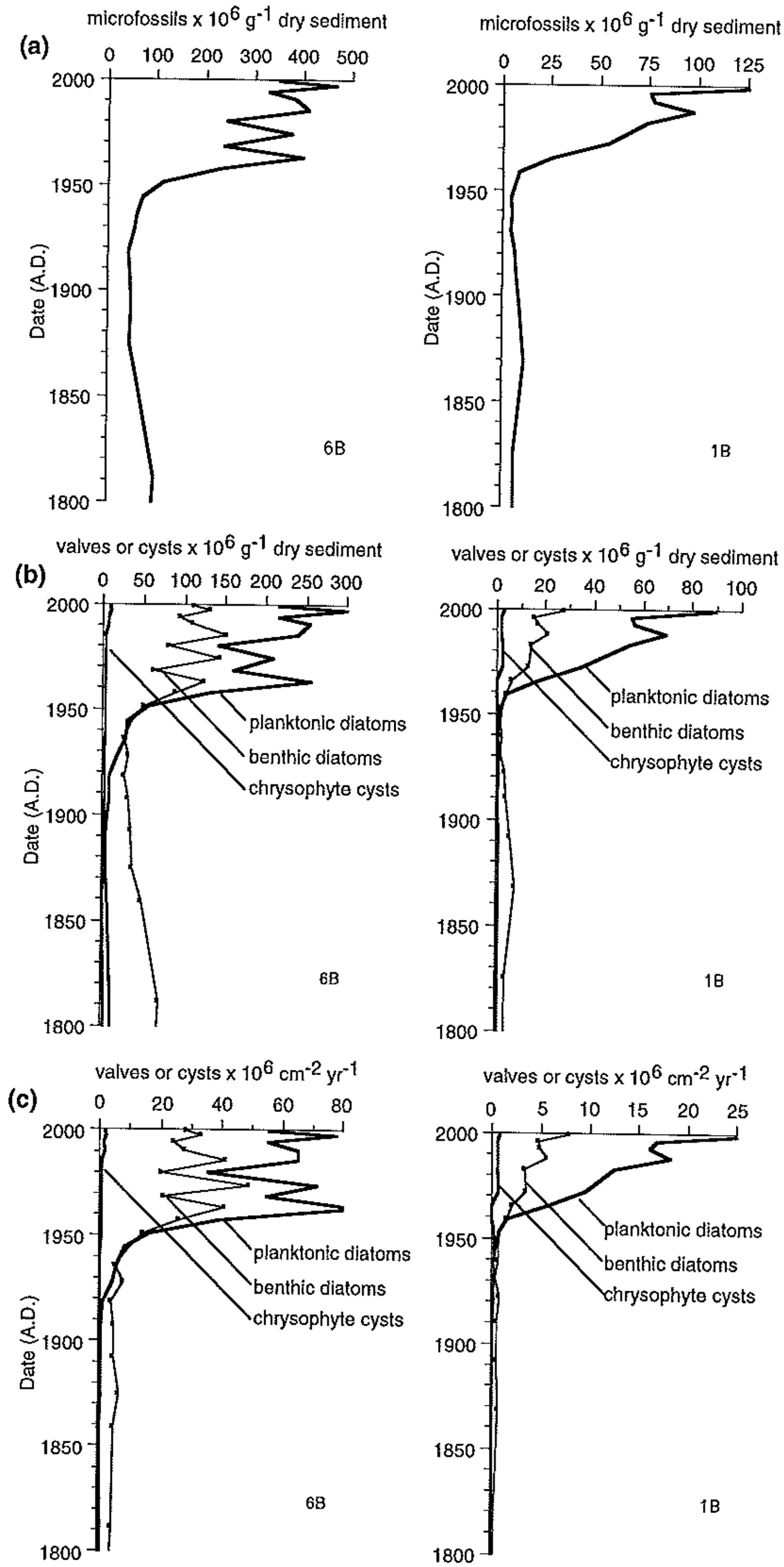


Figure 6. Microfossil concentration and accumulation

Figure 8. Relative abundance of planktonic and benthic diatoms in core 6B.

Lake St. Croix Core 6B

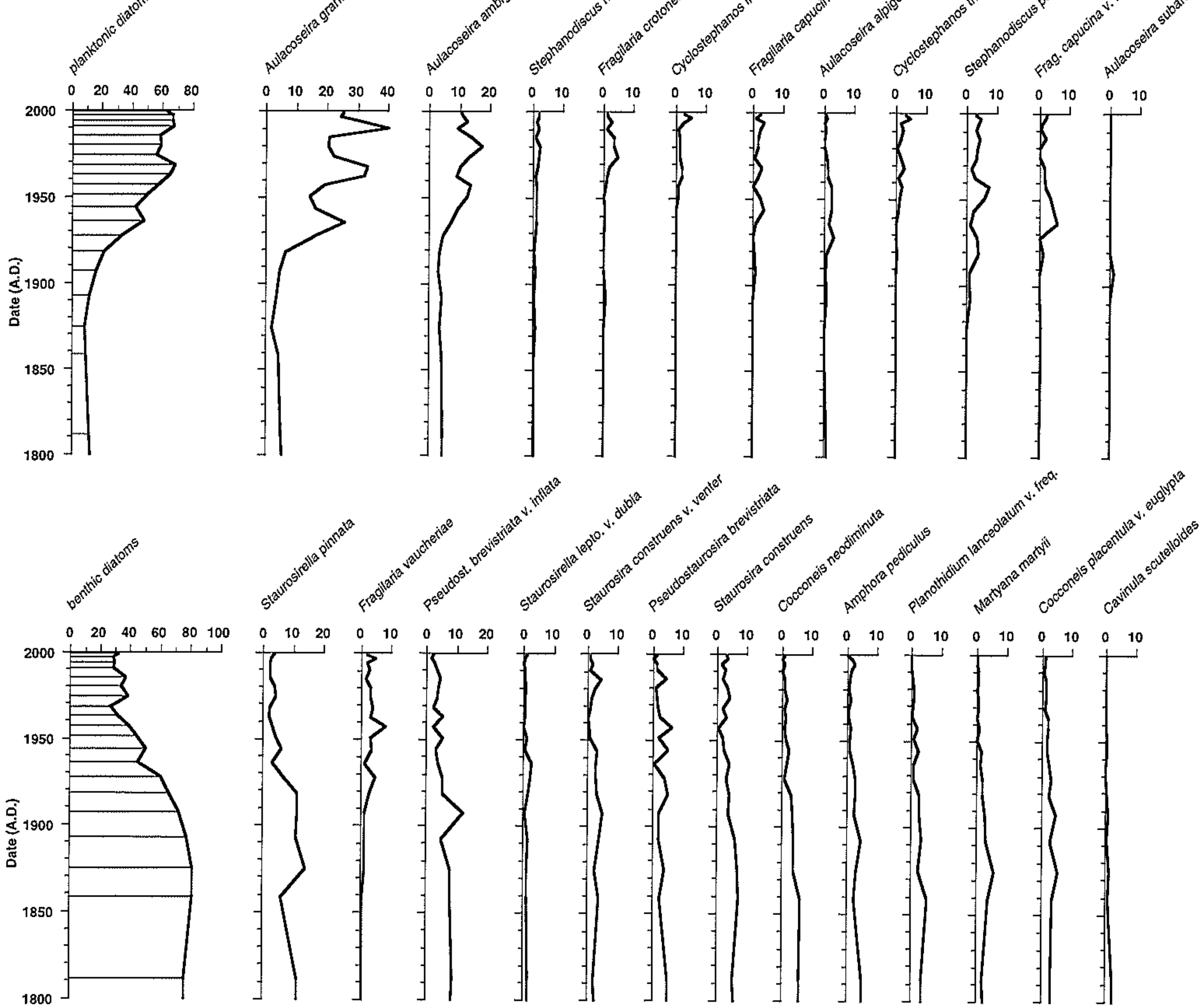
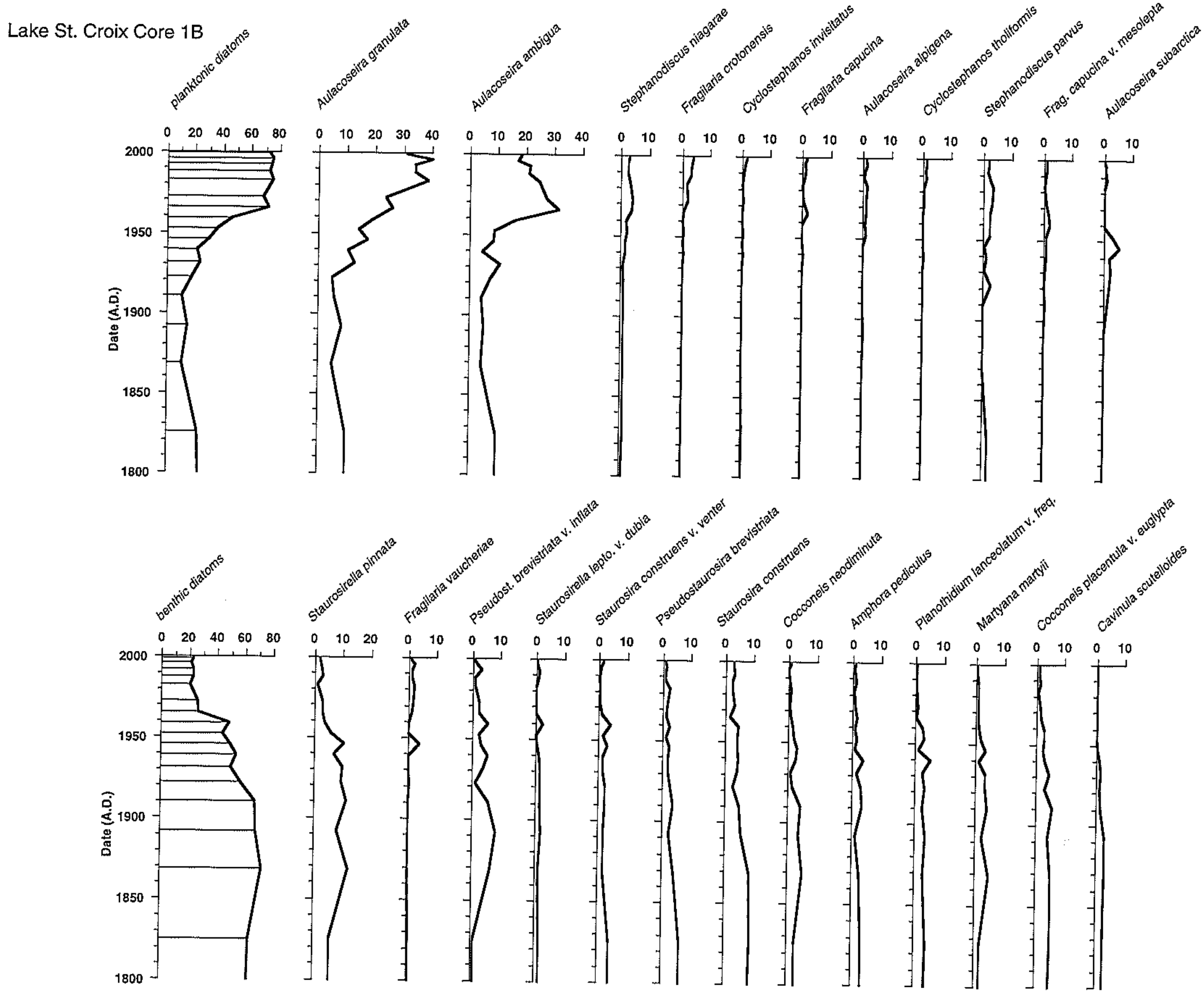


Figure 8. Relative abundance of planktonic and benthic diatoms in core 1B.



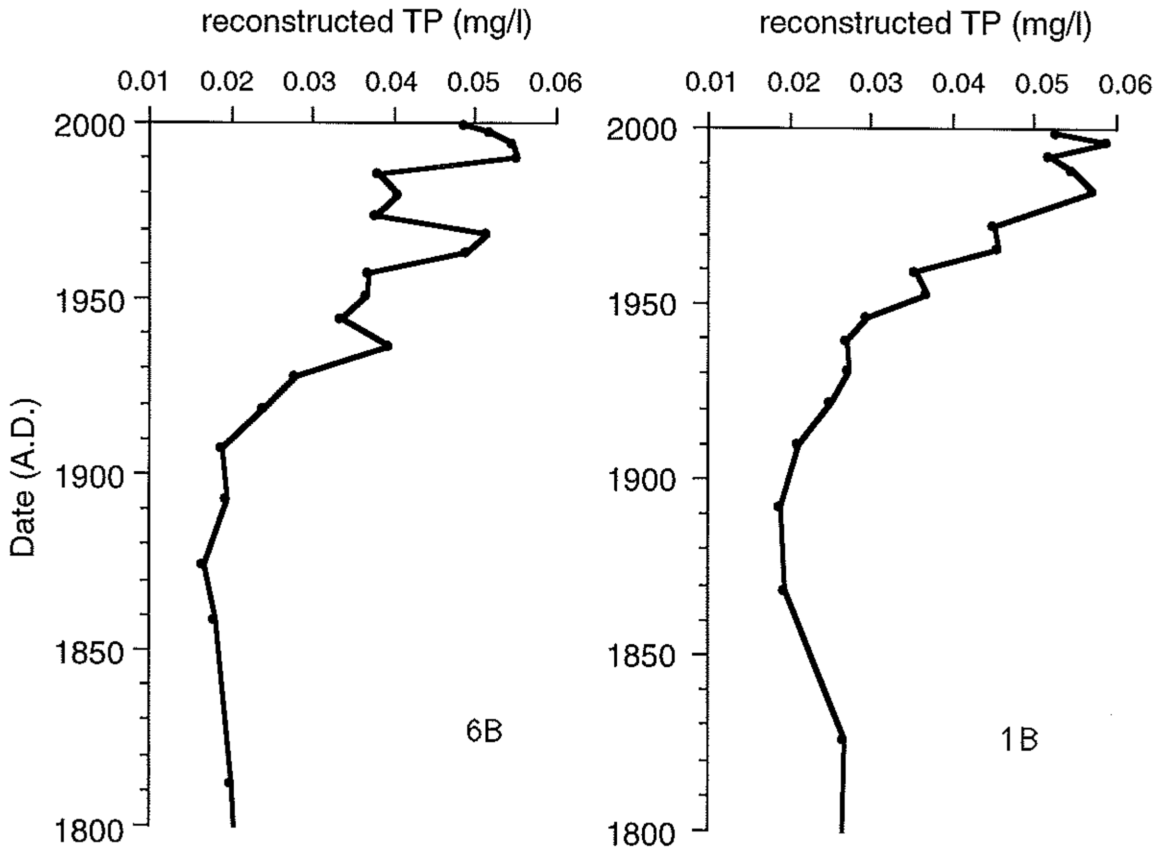


Figure 9. Diatom reconstructed water column total phosphorus