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The altered ecology of Lake Christina: A record of regime shifts, land-use change, and management from a temperate shallow lake

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ABSTRACT

We collected two sediment cores and modern submerged aquatic plants and phytoplankton from two sub-basins of Lake Christina, a large shallow lake in west-central Minnesota, and used stable isotopic and elemental proxies from sedimentary organic matter to explore questions about the pre- and post-settlement ecology of the lake. The two morphologically distinct sub-basins vary in their sensitivities to internal and external perturbations offering different paleoecological information. The record from the shallower and much larger western sub-basin reflects its strong response to internal processes, while the smaller and deeper eastern sub-basin record primarily reflects external processes including important post-settlement land-use changes in the area. A significant increase in organic carbon accumulation (3–4 times pre-settlement rates) and long-term trends in $\delta^{13}C$, organic carbon to nitrogen ratios (C/N), and biogenic silica concentrations shows that primary production has increased and the lake has become increasingly phytoplankton-dominated in the post-settlement period. Significant shifts in $\delta^{15}N$ values reflect land-clearing and agricultural practices in the region and support the idea that nutrient inputs have played an important role in triggering changes in the trophic status of the lake. Our examination of hydroclimatic data for the region over the last century suggests that natural forcings on lake ecology have diminished in their importance as human management of the lake increased in the mid-1900s. In the last 50 years, three chemical biomanipulations have temporarily shifted the lake from the turbid, algal-dominated condition into a desired clear water regime. Two of our proxies ($\delta^{13}C$ and BSi) measured from the higher resolution eastern basin record responded significantly to these known regime shifts.

1. Introduction

Due to their significance to the global carbon cycle and the growing exploration of alternative stable regime theory, there is interest in developing historical reconstructions from shallow lake sediments (e.g. (Downing et al., 2008; Scheffer et al., 1993)). Efforts have been made to apply multiple biological and geochemical proxies from these records to address questions about the influence of human settlement and the longer-term controls on the ecology of shallow lakes. In two recent papers, Sayer et al. (2010a) and Sayer et al. (2010b) examined both modern and sedimentary remains of macrophyte and phytoplankton communities from shallow English lakes to examine modern dynamics and historical records and their implications for future ecological changes in the lakes. Schelske et al. (1999) successfully used diatom benthic/planktonic ratios and carbon to nitrogen ratios (C/N) in sedimentary organic matter from a core taken from Lake Apopka, a large, shallow lake (mean depth 1.7 m) in Florida to identify a known stable regime transition that occurred in 1947. Lake Apopka and three other shallow lakes were later studied by Kenney et al. (2010), who found that statistical analysis of C/N, biogenic silica (BSi), and total phosphorus results from sediment cores was a more effective means of identifying past sources of organic matter and interpreting whether the lakes were in a clear or turbid regime over the past two centuries. Others have used C and N stable isotopes (Das et al., 2008; Jinglu et al., 2007), chironomid assemblages (Brodersen et al., 2001), and diatoms and pollen (Vermaire and Gregory-Eaves, 2008) to track changes in the abundance of macrophytes and in the trophic status of shallow lakes. The overwhelming majority of lakes investigated in these studies have shown a clear post-settlement (or more recent) shift to algal dominance and/or loss of macrophyte diversity that is largely the result of human influence.

An improved understanding of the paleoecology of shallow lake systems is desirable as we consider how to best manage them. Recent

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work on shallow lake dynamics has revealed that shallow lakes can fluctuate between various alternative regimes, including two end members: a clear-water regime dominated by aquatic macrophytes with little phytoplankton abundance, or a turbid-water regime dominated by phytoplankton (Scheffer et al., 1993; Scheffer and van Nes, 2007). Shallow lakes are often the critical habitat for waterfowl and there is empirical evidence that shallow lakes and wetlands with rich macrophyte communities normally support diverse communities of waterfowl (Hanson and Butler, 1994a; Wallsten and Forsgren, 1989). The recent work also highlights the significance of shallow lakes and wetlands as natural carbon sinks (e.g. Cole et al., 2007; Euliss et al., 2006) and the ecosystem state of the lake may be important to its carbon burial potential. Here we use ^{210}Pb age-dated lake sediment core records from two morphologically-distinct basins in Lake Christina, a relatively large shallow lake in west-central Minnesota. Lake Christina has been both heavily managed and extensively monitored over the past 40–50 years. Analyzing sediment cores from both the large shallow basin and the smaller deep basin of the lake in conjunction with historical information allowed us to address the following questions: 1) How does the post-settlement ecology of the lake compare with pre-settlement conditions?, 2) What impacts have human activity such as land-clearing and regional agriculture had on Lake Christina's condition and how do these influences compare with the influence of historical climate trends?, 3) Do our proxies respond to known stable regime shifts that were forced as part of management efforts for the lake? To address these questions we measured BSi in sediment cores and C and N elemental and stable isotopic values in cores and modern plants collected from two sub-basins in the lake and calculated carbon accumulation rates for approximately the past two centuries. Our findings reveal marked ecological changes in Lake Christina following settlement of the region. Interestingly, these changes were manifested differently in the sedimentary records of the two sub-basins. We first discuss modern Lake Christina and its known history before explaining the multi-proxy methods we used and the high-resolution results we obtained for the past two centuries and lower resolution results that extend to nearly the past millennium.

2. Methods

2.1. Site description

Lake Christina (46.09° N, 95.74° W), is a shallow (mean depth 1.5 m; 80% of lake has depth of 1.2 m), eutrophic lake in west-central Minnesota that sits in calcareous glacial till (Fig. 1). The lake is relatively large (16.1 km^2) and can be separated into two distinct sub-basins; a large western sub-basin with fairly uniform morphology and depth (nearly all ~1.2 m) which is connected by a narrow stretch of water to a much smaller and deeper eastern sub-basin (max. depth 4.3 m is located here). While both of these basins might be lumped together as "shallow", there are important differences in the physical, chemical, and biological processes in each. Monitoring of Lake Christina over the past three decades has shown that the east basin has notably higher levels of surface water primary production in most years and a somewhat distinct pattern of change when compared to the west basin (Fig. 2A). This is likely due to the differences in depth and morphology between the two basins. Ongoing monitoring of several small shallow lakes near Lake Christina reveals that even minor differences in depth can have important implications on lake mixing. For example, temperature and dissolved oxygen data we collected during late summer 2010 from a small shallow lake basin of 1.5 m depth (a slightly greater depth than the west basin of Christina) shows a continually well-mixed water column. In contrast, a similar basin that is just 1.2 m deeper (2.7 m depth) is stratified for the majority of the same period (Fig. 2 B–E).

Lake Christina is primarily a groundwater fed lake with inflow rates ranging from 0.6 to 1 m^3 s^{-1} and an average of 0.7 m^3 s^{-1} over a 17 year monitoring period (1982–99). Surface water flow is estimated at half the groundwater flow into the lake (Minnesota Department of Natural Resources). Lake pH ranges from 7.6 to 9.5 and a $CaCO_3$ alkalinity of 190–290 mg L^{-1} as measured during 1987–88 (Hanson et al., 1990). Lake sediments have high concentrations of calcium carbonate due to this water chemistry and can be especially high during the warm season when primary productivity causes whiting events. Lake Christina lies within the Prairie Pothole Region, a large (nearly 900,000 km^2) area that includes millions of shallow lakes and wetlands. The lake is nationally recognized as a prime area for waterfowl production and is one of the only 40 lakes in Minnesota that has been designated a Wildlife Management Lake. As part of the management effort, Lake Christina has been periodically restored from a less desirable, phytoplankton-dominated condition that greatly reduced the waterfowl activity to a preferred clear water condition through three biomanipulations in the past 45 years. These treatments resulted in significant water quality improvements, re-establishment of macrophytes, and the return of waterfowl and associated invertebrates to the lake (Hanson and Butler, 1994a,b; Hobbs et al., in press). In the first half of the 1900s, Lake Christina was likely in a clear regime based on the observation of very high numbers of waterfowl which peaked in the late 1930s and early 1940s (Ordal, 1966). In 1937, a dam was constructed on the western basin outlet, increasing lake water depth by 0.25–0.75 m over the next decade (Hobbs et al., in press). By 1959 conditions had deteriorated, leaving the lake with a <25 cm transparency, very few macrophytes, and a dramatic reduction in waterfowl. In 1965 the lake was treated with the chemical toxaphene and macrophyte abundance increased sharply (Hobbs et al., in press). However, by the late 1970s clarity had decreased and by the early 1980s it was again turbid leading to another biomanipulation with the chemical rotenone in 1987 (Hanson and Butler, 1994a,b). This pattern of macrophyte recovery and eventual return to turbid phytoplankton-dominated conditions was repeated again over the next decade leading to another biomanipulation using rotenone in 2003 (Hobbs et al., in press). This known history of the trophic status of the lake provided an opportunity to examine the response of geochemical proxies (δ^{13}C, C/N, δ^{15}N, and BSi) to regime shifts in the lake. Because these biomanipulations have only been effective over periods of several years, but not in the long-term, a pump station was recently installed (Nov. 2010) with the goal of maintaining a low water level that is beneficial to the growth of macrophytes.

2.2. Modern plant sample collection and analyses

During July 2006, phytoplankton samples were collected from Lake Christina's western basin by filtering water through an 80 μm mesh to remove zooplankton, and then filtered onto pre-combusted Whatman GF/F filters with a 0.7 μm nominal pore size. Filters were dried and stored desiccated until time of analysis. Submerged aquatic macrophytes have been collected from the lake since 1947, with annual sampling since 1980. Plant abundance estimates were compiled from weighted rake tows that included at least 35 stations on the lake (Hansel-Welch et al., 2003). Macrophytes were also collected for elemental and stable isotopic analysis. Samples were collected by hand, frozen, and immediately transferred to the laboratory for analysis. In the laboratory, macrophytes were separated by species (*Myriophyllum sibiricum* and *Stuckenia pectinata*), rinsed, washed with dilute acid to remove any precipitated inorganic C, dried and ground. Each macrophyte sample was weighed and wrapped in a tin capsule, then stored in a dessicator for analysis. C and N concentrations and stable isotopic values of phytoplankton and macrophytes were measured using an isotope ratio mass spectrometer at the Colorado Plateau Analytical Laboratory. Accuracy of δ^{13}C was +0.21‰.

2.3. Core collection and geochemical analyses

A 1.4 m core was collected from the eastern sub-basin of the lake in January, 2006 (EB-06) and both a 1.2 m core and a 0.79 m core

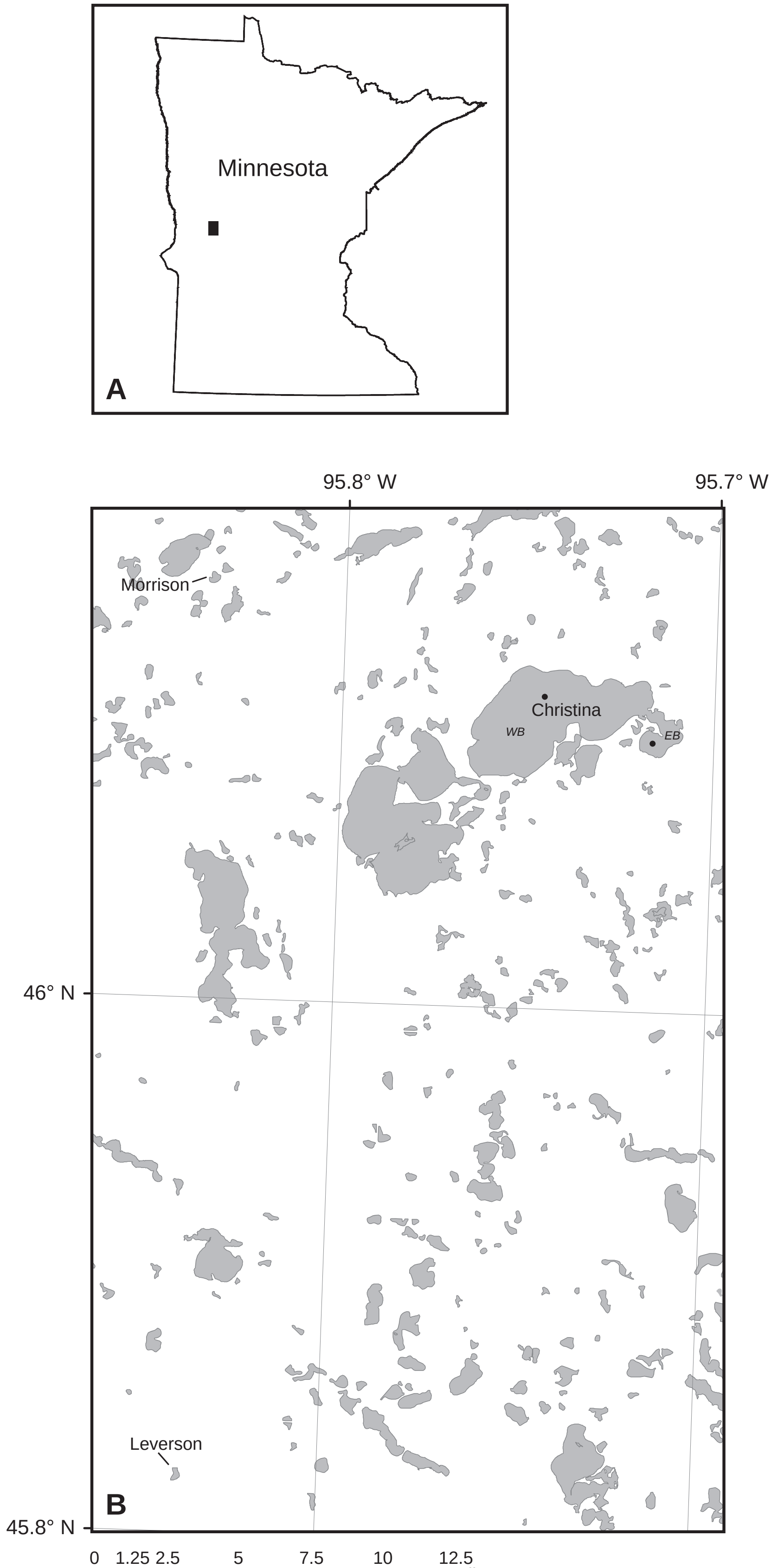

Fig. 1. Site map of Lake Christina. (A) State map of Minnesota showing the approximate location of the study area with a black square. (B) Regional map of Lake Christina and the two small shallow lakes (Leverson and Morrison) discussed in the text. The two closed circles indicate coring sites on Lake Christina, and the two lake sub-basins (East basin and West basin) are indicated with the text “EB” and “WB” respectively.

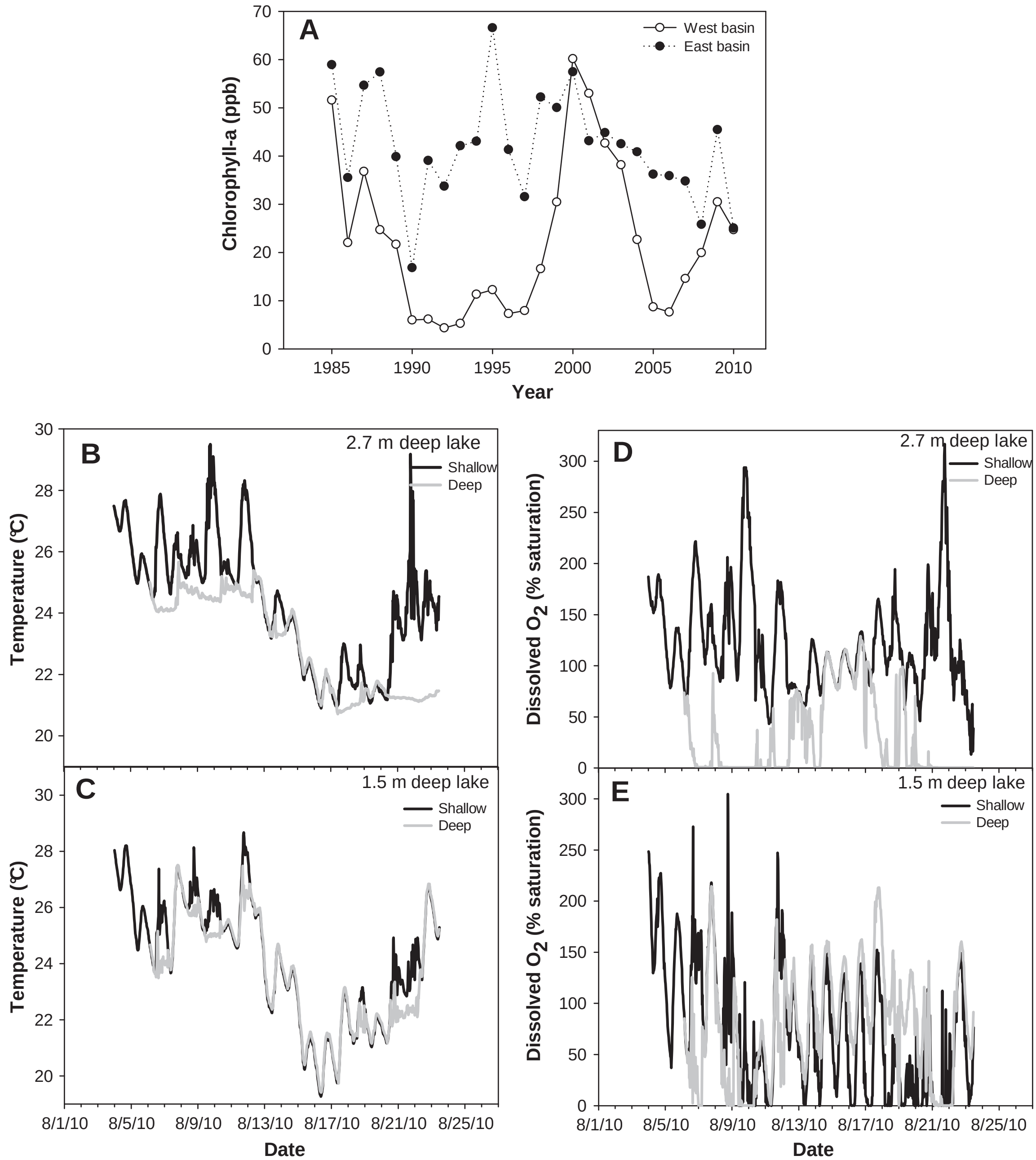

Fig. 2. (A) Chlorophyll-a data collected from the west (open circles) and east (closed circles) basins of Lake Christina from 1985 to 2010. (B–E) Temperature and dissolved O_2 data collected during August 2010, using multi-probe sondes in Lakes Morrison and Leverson, shallow west-central MN lakes. Temperature and dissolved O_2 data from Lake Morrison (2.7 m deep) (B, D) compared to Lake Leverson (1.5 m deep) (C, E). In each panel, the black line represents a near-surface measurement and the gray line represents a measurement near the deepest part of the water column.

were collected from the eastern and western sub-basins during October, 2008 (EB-08 and WB-08). All cores were collected using a piston coring device, and care was taken to preserve the sediment–water interface. Cores were kept in cold storage (~4 °C) until they were sub-sampled. Cores were dominated by homogeneous tan to light brown carbonate-rich silt. There was no indication of fine-scale bedding or other sedimentary structures in the cores. However, well-preserved fossil ostracods were abundant throughout the cores.

EB-06 and WB-08 were sub-sampled for bulk sedimentary organic matter (SOM) at 1 and 0.25 cm intervals, respectively, in the Geology Laboratory at the University of St. Thomas (UST). Samples were dried at 60 °C, ground, weighed, and treated with 6% sulfurous acid to remove all carbonate phases (Verardo et al., 1990). Samples were analyzed for total organic carbon (TOC), total nitrogen (TN), $\delta^{13}C$, and $\delta^{15}N$ using a Carlo Erba NA1500 elemental analyzer/Conflo II device coupled with a Finnigan Delta Plus mass spectrometer in the Stable Isotope Laboratory at Stanford University. The C/N, $\delta^{13}C$, and $\delta^{15}N$ values of SOM and the accumulation rates of organic carbon (OC MAR) are widely known for their utility in identifying sources of organic matter and detecting changes in paleoproductivity (e.g. (Meyers, 1997)). Published values for phytoplankton sources of organic matter in lakes have both low C/N and $\delta^{13}C$ (avgs. 7, −27‰). Macrophytes and terrestrial plants can have $\delta^{13}C$ values that span a large range but they tend to have higher C/N values, thus a combination of the two proxies can be used to identify the general sources of organic matter (Meyers, 1997). Organic C/N (atomic) values were calculated based on TOC and TN results. All $\delta^{13}C$ values are expressed relative to the Pee Dee Belemnite (PDB) standard and all $\delta^{15}N$ values are expressed relative to atmospheric N_2.

Approximately 5% of unknowns were replicated yielding average standard deviations of 0.480% for TOC, 0.113% for TN, 0.119‰ for $\delta^{13}C$, and 0.314‰ for $\delta^{15}N$. Assuming the organic carbon can be linked to autochthonous processes, the organic carbon mass accumulation rate (OC MAR) is a reliable indicator of primary production in a lake. We calculated the OC MAR using [TOC] (mg g^{-1}) multiplied by the sediment accumulation rate (g m^{-2} yr^{-1}) for each sediment interval.

Subsamples from Cores EB-08 and WB-08 were measured for biogenic silica at the St. Croix Watershed Research Station. The analysis of BSi in sediments provides a quantification of the total accumulation of siliceous algal fossils (diatoms and chrysophyte cysts). We used a modified wet alkali digestion method from DeMaster (1991) on approximately 30 mg of freeze-dried sediment (Conley and Schelske, 2001). Sediments were digested in a 1% Na_2CO_3 solution, while in a shaking water bath at 85 °C, and aliquots were removed at 3, 4, and 5 h for analysis of dissolved Si. This method allows for the sequential digestion and separation of BSi and the aluminosilicate fraction. The concentration of dissolved silica (as H_4SiO_4) in the extract was then analyzed using the heteropoly blue method (Clescerl et al., 1999) with a flow-injection analysis auto-analyzer (Lachat Quikchem 8000). The percent relative standard deviation amongst method triplicate samples, which were run on 10% of the sediment intervals, was <5%.

2.4. ^{210}Pb and other age dating methods

In order to construct an accurate age chronology for the cores, ^{210}Pb activity was measured through its granddaughter product ^{210}Po at 18, 23, and 15 intervals downcore in the EB-06, EB-08, and WB-08 cores respectively. Po isotopes were distilled from 0.5 to 3.0 g dry sediment at 550 °C after they were pre-treated with concentrated HCl and plated directly onto silver planchets from a 0.5 N HCl solution (modified from Eakins and Morrison, 1978). Activity was measured for $1–6\times10^5$ s with ion-implanted surface barrier detectors and an Ortec alpha spectroscopy system. Unsupported ^{210}Pb was then 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 model with confidence intervals calculated by first-order error analysis of counting uncertainty (Appleby, 2001). Lake Christina EB-06 core dates have an uncertainty of less than $\pm$6 yrs back to the time of settlement of the region and the dating remains fairly precise back to the early 1800s ($\pm$13 years at 1826). WB-08 core dates have an uncertainty of less than $\pm$8.5 yrs for the last century but are somewhat less precise for the mid-late 1800s ($\pm$15 years at 1881). ^{210}Pb age models are shown in Fig. 3. The age models were made by linear interpolation between the individual ^{210}Pb age dates for each core.

In order to determine the age of core material older than ^{210}Pb age-dating allows, we obtained one ^{14}C age date from the EB-06 core. Bulk sediment samples from lakes can be especially prone to problems with old sources of carbon that can result in erroneous age dates. With this in mind, seeds of *Carex* spp. (sedge) which grow along the lake margins were carefully separated from a bulk sediment sample at 104–105 cm depth in the core and sent to Beta-Analytic Laboratories where they were further treated and analyzed by Accelerator Mass Spectrometry. The resulting radiocarbon date was calibrated using the INTCAL04 database (Reimer et al., 2004) giving a calibrated age of 980 $\pm$ 40 yr B.P. or approximately 1030 A.D. (Accession # Beta 244773).

2.5. Data transformations and statistics

In order to best compare select sedimentary data (BSi concentrations, $\delta^{13}C$ values) with independent historical datasets (Palmer Drought Severity Index, Lake Christina Plant abundance), smoothing and linear detrending techniques were applied to account for differences in sampling resolution between datasets and to reduce the influence of non-relevant trends. Data transformations (detrending and smoothing) and statistics (correlations) were done using Sigmaplot (Systat software).

3. Results

3.1. Geochemical results from eastern and western basin core samples for the last 200 years

Fig. 4 illustrates the correlation of C/N and $\delta^{13}C$ values in SOM samples representing the past 200 years from both the east ($n=135$, $r=0.604$, $P=<0.0001$) and west ($n=83$, $r=0.982$, $P=<0.0001$) basins of Lake Christina. C/N is a well-established indicator of various plant sources of OM and the good correlation suggests that both indicators are largely driven by changes in the sources of OM. The somewhat weaker correlation between these indicators in eastern basin SOM suggests the possibility of a more complex response, perhaps owing to both changes in the source material and in primary production. Downcore records spanning the last 150–200 years from the eastern and western basins of Lake Christina are presented in Fig. 5. Eastern basin TOC ranged from 8 to 12% with a long-term trend of declining values towards present. However, in the last 40 years this trend reversed and TOC increased from ~8.5% to nearly 12%. TN ranged from 1 to 2% and followed a pattern similar to TOC. Western basin TOC ranged from 3 to 14% with a long-term trend of increasing values towards the present. This trend was interrupted briefly in the early 1940s. TN ranged from 0.3 to 1.8% and again followed a pattern similar to TOC. Eastern basin C/N values were fairly stable for the majority of the last 200 years, rising slightly (~8.8–9.3) from 1800 to the early 1960s. However, values then declined sharply from 9.3 to 7.9 in the last 40 years of the record. Western basin C/N values spanned a wider range varying from 8.5 to 14.2. C/N values were generally higher, varying between ~11 and 14 in the earlier part of the record. The latter half of the record showed a steady long-term decrease in values since the early 1920s. The lowest C/N values (~8.5–9) occurred in the most recent part of the record.

In the eastern basin, organic carbon mass accumulation rates (OC MAR) ranged between 2.5 and 13.3 mg cm^{-2} yr^{-1}. These rates rose slightly from 2.5 to 3 mg cm^{-2} yr^{-1} from the early to late 1800s and then began to rise sharply in the early 1900s up to the highest rates (9.1–13.3 mg cm^{-2} yr^{-1}; roughly 4–5 times the pre-settlement rates) in the late 1950s and early sixties (Fig. 5A). MARs dropped somewhat in the late 60s and early 70s and varied between 4.5 and 7.7 mg cm^{-2} yr^{-1}. Western basin OC MARs were generally much slower than in the eastern basin and ranged from approximately 0.5 to 3.5 mg cm^{-2} yr^{-1} (Fig. 5B). Values rose slightly from ~1 mg cm^{-2} yr^{-1}around the time of settlement to ~1.5 mg cm^{-2} yr^{-1} by 1931. Rates then decreased below 1 mg cm^{-2} yr^{-1} and stayed relatively low over much of the next forty years. OC MAR then rose sharply after 1968, going from 0.5 mg cm^{-2} yr^{-1} to the highest rate of 3.58 mg cm^{-2} yr^{-1} in 2007.

In the period since settlement, eastern basin $\delta^{13}C$ values showed several rapid changes of approximately 1‰ and a rapid shift of greater than 2.5‰ to the lowest $\delta^{13}C$ values in the record from the late 1960s to the early 1990s. Since ~1993 values have remained stable at about −23.5‰. Western basin $\delta^{13}C$ values were both isotopically heavier and spanned a wider range. The trends in the record of $\delta^{13}C$ were very similar to those for C/N; with generally higher values (varying between 10 and 15‰) in the earlier part of the record, followed by a long-term decrease in values since the early 1920s. The lowest $\delta^{13}C$ values (−17 to −19‰) occurred in the most recent part of the record. From the time of settlement, eastern basin $\delta^{15}N$ values first showed a large increase of ~4‰, followed by a decrease of 2‰ to the present starting in the late 1960s. West basin $\delta^{15}N$ values

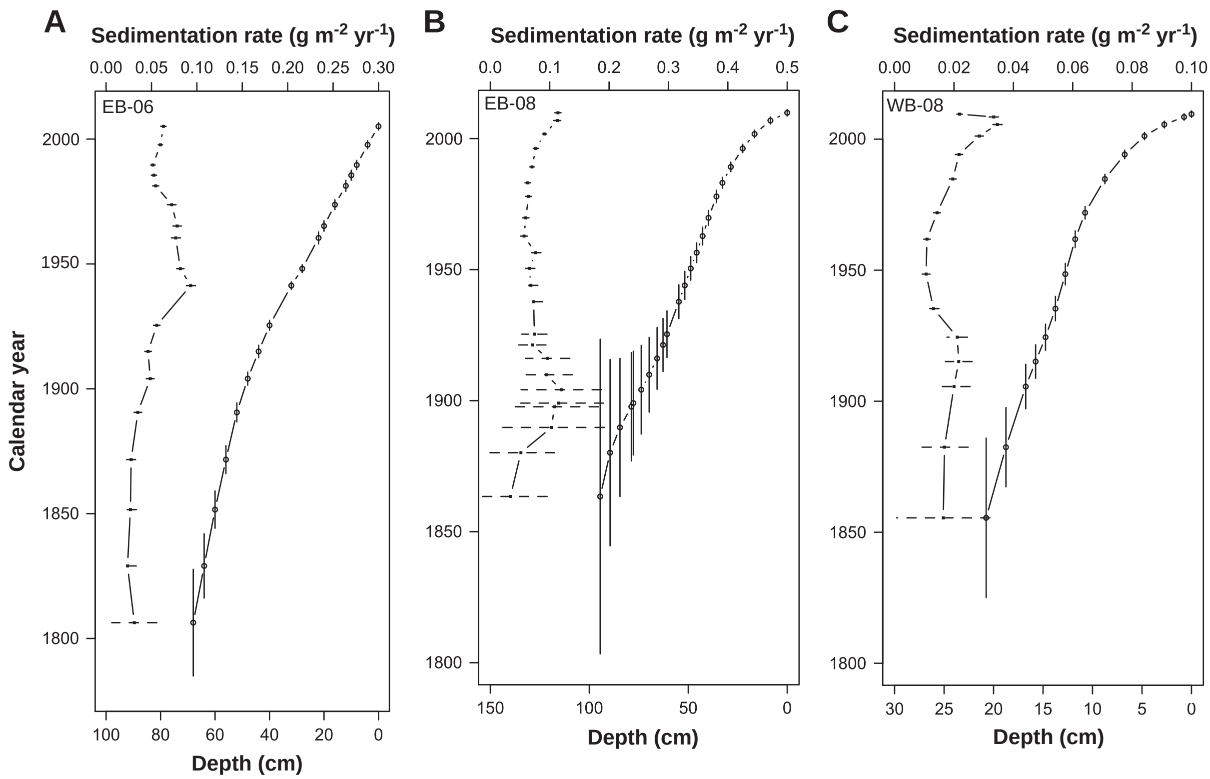

Fig. 3. ^{210}Pb age-dating results for the three sediment cores used in this study. (A) Line plot with open circles shows each of the determined ^{210}Pb ages versus depth in the EB-06 core. Dating errors are indicated with vertical error bars. Line plot with small dots shows the calculated sedimentation rate and dashed horizontal lines show associated error. (B) Same for core EB-08; (C) Same for core WB-08.

showed a subtle increase from the earliest part of the record to the early 1920s. From the 1920s to the present values decreased by ~2‰ (from ~0.5 to −1.5‰) to the present.

Our records of BSi concentrations extend from the early 1800s and the early 1940s in the eastern and western basins, respectively. In the eastern basin, concentrations rose from 3 to 5% from 1850 to the early 1870 s before rising sharply to ~8% near the time of settlement. BSi concentrations were fairly stable over the next 30 years and then jumped to nearly 13% between 1913 and 1919. BSi then fell to ~6% over the next two decades. Since the late 1930s, BSi has varied between 6 and 9% and the timing of these changes has closely followed three known lake management efforts (Fig. 5A). In the western basin

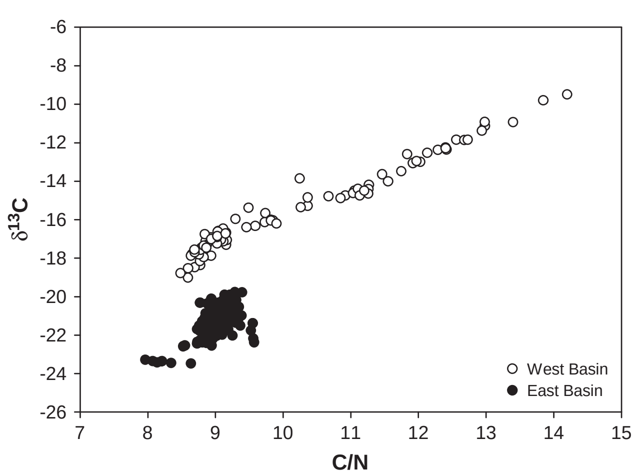

Fig. 4. Crossplot showing the correlation of $\delta^{13}C$ and C/N of sedimentary organic matter measured at the same depths in the western ($n=83$, $r=0.982$, $P=<0.0001$) and eastern ($n=135$, $r=0.604$, $P=<0.0001$) sub-basins of Lake Christina.

BSi gradually increased from 6.5 to 8.5% from the early 1950s to 1994. This was followed by a sharp drop of ~1.5% over the next 12 years. In the upper most few years of the record, BSi rose sharply reaching the highest recorded value of 9.8% at the most recent sampled interval.

3.2. Elemental and stable isotopic results from western basin modern plant samples and comparison with downcore SOM results

Modern phytoplankton from the western basin of Lake Christina has $\delta^{13}C$ values ranging from −14 to −15.5‰ and C/N values ranging from 9.5 to 11. In contrast submerged aquatic macrophytes have both higher $\delta^{13}C$ values (ranging from −9 to −12‰) and C/N values (from 20 to 29). Phytoplankton and macrophytes plot into distinctly different regions on a crossplot of their C/N and $\delta^{13}C$ values (Fig. 6). On the crossplot western basin C/N and $\delta^{13}C$ values for SOM samples spanning nearly the past two centuries form a clear, long-term linear trend with significantly higher values in the earlier part of that record (prior to and near the time of settlement) that are closer to the composition of modern macrophytes in the lake. However, by the mid-twentieth century (see year 1943 in Fig. 6) western basin SOM values had become nearly identical to modern phytoplankton values. The trend towards lower values continues up to the present with values that are lower than those recorded in modern lake phytoplankton, but consistent with those generally reported in the published literature for phytoplankton in other lake systems (Meyers, 1997). C/N and $\delta^{13}C$ values from all of the eastern basin SOM samples are lower than both western basin SOM and phytoplankton sources as measured in samples from the modern lake.

3.3. Geochemical results from eastern basin over the last 1000 years

Core EB-06 provides a longer view of pre-settlement trends for the eastern basin (Fig. 7). This approximately 1000-year record shows

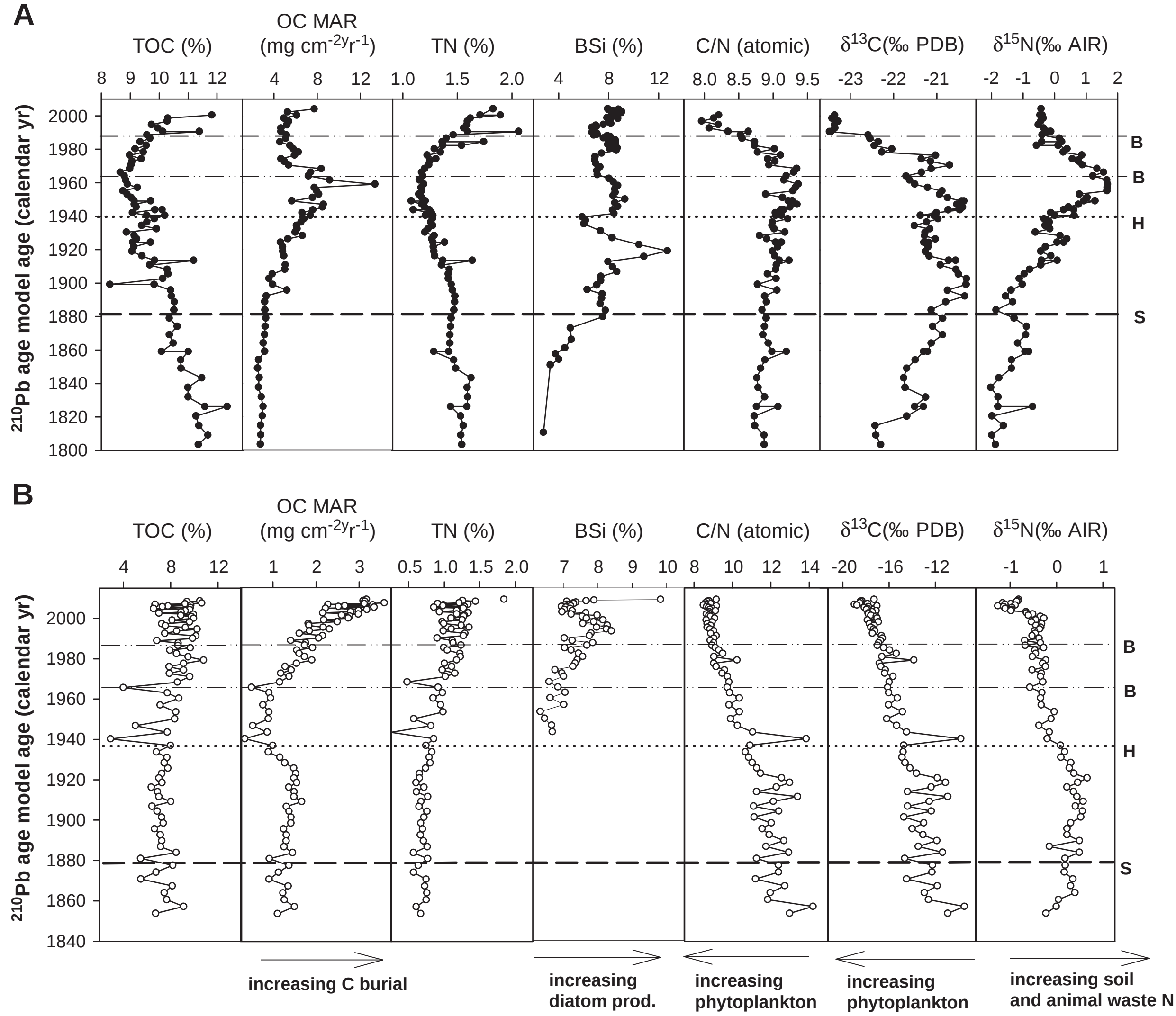

Fig. 5. Historical downcore records of elemental and stable isotopic information for (A) the eastern basin (core EB-06) and (B) the western basin (core WB-08). Total organic carbon (TOC), total nitrogen (TN), and biogenic silica (BSi) are all presented as concentrations (weight%). Organic carbon accumulation (OC MAR), C/N, and carbon and nitrogen isotopic data ($\delta^{13}C$, $\delta^{15}N$) are given as well. The dashed line with an "S" represents the time of European settlement (~1880), while the dotted line with "H" and the two dot-dash lines labeled with "B" represent the time of a known hydrological change (dam construction) and two chemical biomanipulations of the lake respectively.

how anomalous the post-settlement period has been relative to earlier times. TOC values were highest in the oldest part of the record (~14%) and then gradually trended towards lower values over the rest of the record, reaching values of <9% in the early 1900s before a sharp reversal towards higher TOC values in the last 40 years. TN values (ranging from ~1 to 2%) followed the same trends, but changed even more than TOC, nearly doubling in the last 40 years. C/N values ranged from 7.9 to 9.5. Values were stable through most of the record and varied notably in just three short intervals: one centered on about 800 yr BP, the second centered on ~650 yr BP, and the last in the most recent 40 years. $\delta^{13}C$ values varied from ~−20‰ to −23.5‰, rising and falling by 1–2‰ over a few multi-century periods before a large and rapid decline to the lowest values occurred in the last 40 years of the record. Eastern basin $\delta^{15}N$ values gradually decreased by approximately 2‰ (from ~0 to −2‰) from the earliest part of the record until about 200 yrs BP. They then rose gradually by about 1‰ prior to the sharp changes of the post-settlement period.

4. Discussion

Based on the downcore elemental and isotopic results and the burial rates we obtained, Lake Christina has generally been trending towards more phytoplankton production and organic C burial since the time of human settlement. Yet the records from the eastern and western sub-basins of the lake differ significantly in terms of the magnitude and timing of geochemical changes, reflecting site-specific responses. We suspect that many of the observed differences in the records from the two sub-basins are explained by their differing morphological characteristics. To briefly restate these differences, the western basin is comparatively quite large, of uniform depth throughout, and well-mixed. In contrast, the eastern basin is much smaller, has a deeper and more variable profile, and is stratified during at least part of the year. Although similar land-use changes occurred around both sub-basins after settlement, sediment focusing in the eastern basin resulted in a more enhanced response to these changes than in the western basin. On the other hand, the western basin responded more significantly to internal changes (such as changes to plant communities) than the eastern basin.

The large linear decline in both C/N and $\delta^{13}C$ values of SOM suggests that the plant communities in the shallower western basin have changed most dramatically, going from a macrophyte-dominated system in the mid-1800s, to one with an ever-increasing phytoplankton presence towards the present (Fig. 6). In contrast, the deeper eastern basin has continuously had a more significant phytoplankton presence

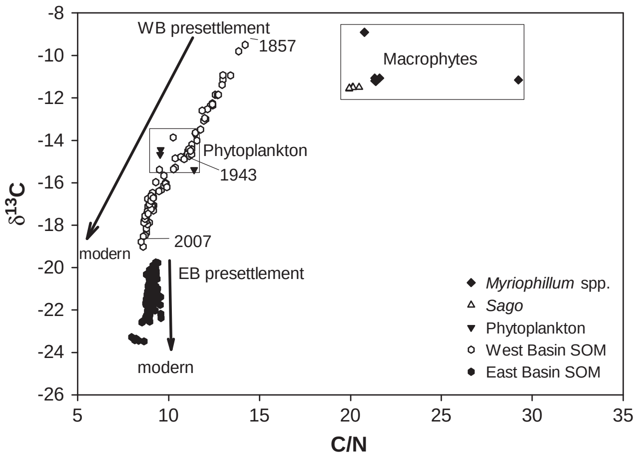

Fig. 6. Crossplot showing the geochemical relationship of SOM from each of the Lake Christina sub-basins to modern plants in the lake. The arrows show the trends in the geochemistry ($\delta^{13}C$ and C/N) of SOM from both of the sub-basins that occurred from pre-settlement to modern time. $\delta^{13}C$ and C/N values from west basin SOM samples dated to 1857, 1943, and 2007 are indicated to show the steady linear progression from C/N and $\delta^{13}C$ values in the earliest part of the dataset that are more closely associated with modern macrophytes (1857) to values that are typical of modern phytoplankton (reached by 1943), and finally to very recent values (2007) that are lower than those of the modern plants we made measurements on.

over this time span. The generally elevated C/N and $\delta^{13}C$ in the western basin relative to the eastern basin are likely the result of the shallow water conditions in the western basin which would tend to favor macrophyte production there (e.g. Scheffer et al., 1992). Interannual to decadal-scale variability is clearly more discernable in the eastern basin record. This is especially noticeable in the $\delta^{13}C$ and BSi records from the eastern basin where several rapid changes occurred during post-settlement time (Fig. 5A). The difference in the resolution of the two records is most likely due to the slower sedimentation rate in the western basin.

Both basins showed a significant increase in carbon burial rates (OC MAR) since the time of settlement, increasing by a factor of 3–4. The increased burial was likely the result of both increased terrestrial input to the lakes as a result of land-clearing for agriculture as well as increased primary production as nutrient supply to the lake increased (Hobbs et al., in press). The generally higher C burial rates in the eastern basin are most likely the result of sediment focusing into the small, deeper area of the eastern basin from which the core was collected. The rise in eastern basin burial rates that began shortly after settlement and ran until the early 1960s is most likely due to land-clearing, development and increased terrestrial input. This inference is supported by a more subtle rise in C/N values that spans the same period (Fig. 5A). The western basin was clearly less affected by these external changes and burial rates remained stable. The small but notable drop in western basin burial rates during the early to middle part of the twentieth century suggests a corresponding decrease in primary production beginning approximately at the onset of the “dust bowl” years of drought (~1933–1940) that affected this area (Fig. 5B). Historical aerial photographs of the lake and the character of the sediment indicate that the lake never dried out so it is unlikely that this was simply the result of desiccation and erosion under drought conditions. However, a number of the elemental proxies (BSi, TOC, and TN) were also at their lowest concentrations during this period, supporting our inference that primary production was reduced in the western basin. In contrast, the sharp rise in western basin burial rates from the 1960s to present was accompanied by increases in each of these proxies, signaling a sharp increase in production (Fig. 5B).

One of the important findings of this research is the anomalous post-settlement changes in the N-cycle of the lake and surrounding watershed that are indicated by significant $\delta^{15}N$ shifts, particularly in the eastern basin (Fig. 7). West-central MN is and has been an active agricultural region since the time of settlement and the vast majority of the land surrounding lake Christina is rural cultivated farmland. With this in mind, we believe that the explanation for the rise in $\delta^{15}N$ seen in the eastern basin record is the onset of significant inputs of eroded soil OM, human wastewater, and livestock waste inputs during the decades following settlement. All are isotopically heavy nitrate $\delta^{15}N$ sources (soil OM: 4–9‰, wastes: 10–22‰; (Heaton, 1986)) that are regularly detected in Minnesota lakes (Komor and Anderson, 1993) and there are animal feedlots within the lake watershed. The western basin record, showed little change in $\delta^{15}N$ in the decades immediately following settlement because it primarily responded to internal processes rather than external landscape changes. An alternative explanation for the post-settlement increase in $\delta^{15}N$ is that denitrification increased after settlement as a result of the observed increase in OC burial and the onset of lower dissolved O_2 levels in the deeper eastern basin. During denitrification, an isotopic fractionation occurs with ^{14}N preferentially taken up in the N_2 gas phase, resulting in residual nitrate that is enriched in ^{15}N and increased $\delta^{15}N$ values (Mariotti et al., 1982). In contrast, the well-mixed western basin never consistently

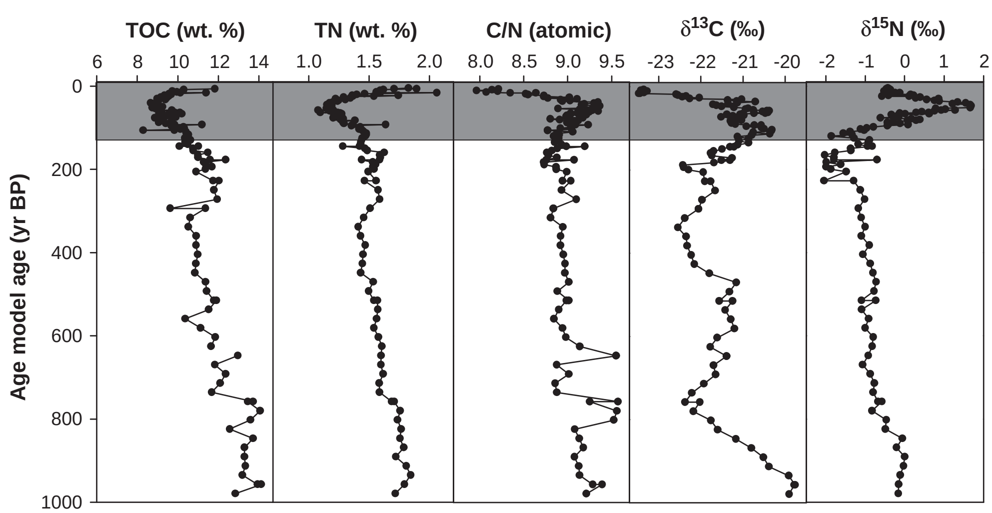

Fig. 7. Downcore records of TOC, TN, C/N, $\delta^{13}C$, and $\delta^{15}N$ for approximately the last 1000 years from the East basin of Lake Christina (core EB-06). Total organic carbon (TOC) and total nitrogen (TN) are presented as concentrations (weight%). C/N, and carbon and nitrogen isotopic data ($\delta^{13}C$, $\delta^{15}N$) are given as well. The shaded area is the post-settlement period.

developed the conditions required for denitrification and accordingly $\delta^{15}N$ values in SOM changed little after settlement (Fig. 5B). Both the post-1960 $\delta^{15}N$ decrease seen in the eastern basin record and the post-1920 decrease in the western basin record likely reflect the growing influence of fertilizer N with lower values than other sources (ranging from −4 to +4‰; Heaton, 1986). Assuming that the eastern basin $\delta^{15}N$ values are primarily driven by changing N sources (and not denitrification), the post-1960 decrease seen in the eastern basin record reflects a relatively greater input of fertilizer N over the inputs of isotopically heavier soil OM, human, and animal wastes into the lake over time. Indeed, records for Douglas County, where the majority of the lake lies show that total land within the county used for farming peaked in 1935 at ~93% before steadily declining and reaching a low of 63% by 1992 (Douglas County Land and Resource Mgmt. Dept., 1998). Moreover, the majority of the lost farmland was in dairy farming and other livestock operations. Douglas County land-use data collected between 1978 and 1992 show this steady decrease with the number of dairy farms decreasing by 47%, cattle farms by 36%, hog farms by 64%, and the number of poultry farms by 66% (Douglas County Land and Resource Management Department, 1998).

Climate is another important factor for us to consider as a possible driver for changing lake ecology and regime shifts in shallow lakes. We compared eastern basin $\delta^{13}C$ values and Palmer Drought Severity Index (PDSI) data for West Central Minnesota (Cook et al., 1999) over the past century. As discussed above, the $\delta^{13}C$ values are in large part an indicator of the source of organic material. Eastern basin values are more appropriate to consider since the higher sedimentation rate at the core site allows for greater resolution of interannual to decadal trends. The PDSI is an established hydroclimatic metric that integrates parameters that reflect the availability of water moving through the subsurface to the water table (Palmer, 1965). PDSI values reflect the magnitude and duration of departures from regional mean conditions (Alley, 1984). Eastern basin $\delta^{13}C$ values were negatively correlated with the PDSI during the earlier half of the record (Fig. 8, years 1896–1937; $n=15$, $r=-0.539$, $p=0.0379$). That is, during periods of more arid conditions in west central MN, $\delta^{13}C$ was higher than normal, and when conditions were wetter $\delta^{13}C$ was somewhat lower than normal. However, by the mid-1960s the records show a weaker relationship with no statistically significant correlation (Fig. 8, years 1939–2001; $n=32$, $r=0.234$, $p=0.179$). We hypothesize that the change was stimulated by a greater human influence on the lake system starting in the late 1930s with the construction of the dam on the lake. Prior to the 1937 installation of the dam, when the climate became wetter and lake level became higher (as indicated by positive PDSI values) this was more favorable to algae (as indicated by negative $\delta^{13}C$ values) and when the climate became drier and lake became level lower (as indicated by negative PDSI values) this was somewhat more favorable to macrophytes (as indicated by positive $\delta^{13}C$ values). One way that climate might influence shallow lakes is through its influence on lake water depth (Scheffer and van Nes, 2007). Shallower lakes have greater light at the bottom and allow macrophytes to grow through to the surface and avoid the effects of shading by phytoplankton (Scheffer et al., 1992). In contrast, high water levels can lead to a sharp reduction in macrophytes and a shift to the turbid regime (Engel and Nichols, 1994; Wallsten and Forsgren, 1989). In 1937 the dam was constructed and it is reasonable to assume that climatic influence on lake water depth was at least somewhat diminished. Our reconstruction shows that between the late 1930s and the early 1960s the $\delta^{13}C$ record was still out of phase with the PDSI record, but not to the same extent suggesting a slightly weakening link. By the mid-1960s when the first biomanipulation was done, any relationship between the PDSI and $\delta^{13}C$ became less clear suggesting an even weaker link between regional hydroclimatic influences and lake vegetation. A recent investigation of the Lake Christina plant community response to various environmental factors during the period 1985–1998 showed that water depth was the weakest of these factors, although changes in water depth were minimal during the study period (Hansel-Welch et al., 2003).

Using our data as an indicator of source material, we can evaluate the potential of our proxies to identify known regime changes in the lake through the earlier two of the regime shifts. In particular, the eastern basin BSi and $\delta^{13}C$ records show a response to the known state transitions in Lake Christina from the mid-1950s towards the present (Fig. 9). Since these datasets were each sampled at different time intervals, we compared ~2 year average values. We found a statistically significant negative correlation between plant abundance and BSi concentrations ($n=19$, $r=-0.51$, $p=0.013$) over a 44 year time period (1957–2001) and a slightly weaker positive correlation between plant abundance and $\delta^{13}C$ values over a 30 year period (1957–1987; $n=13$, $r=0.44$, $p=0.066$). Prior to the 1965 treatment when plant abundance was clearly declining, $\delta^{13}C$ shifted towards

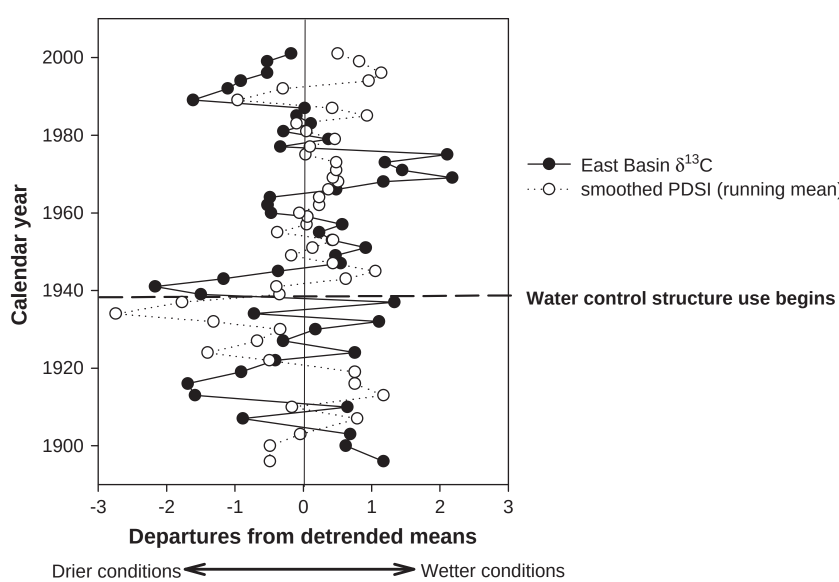

Fig. 8. Comparison of East basin $\delta^{13}C$ values and the Palmer Drought Severity Index (PDSI) for West-Central MN. PDSI data were smoothed at a time span comparable to sediment sampling intervals (~2 years). The East basin $\delta^{13}C$ was detrended in two parts to remove significant linear decreases in values both prior to 1937 and after 1960. Both records are expressed as departures from mean values. For the PDSI, positive values correspond to wetter than average conditions and negative values correspond to drier than average conditions. For $\delta^{13}C$, positive values are more consistent with macrophyte sources of OM, while negative values are more consistent with phytoplankton.

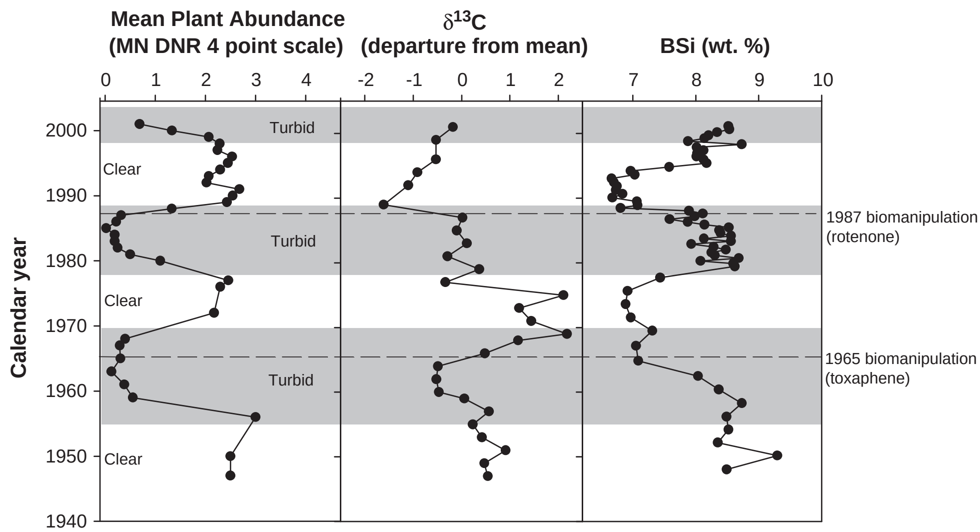

Fig. 9. Comparison of mean plant abundance as measured by the Minnesota DNR (Carlson et al., unpubl.), eastern basin $\delta^{13}C$ departures from the 1943–2001 mean values, and eastern basin BSi concentrations. In the 4-point scale used by the Minnesota DNR, 0–1 = 'Rare', 1–2 = Sparse, 2–3 = Abundant and 3–4 = 'Lush'. Shaded areas represent known periods of turbid water regime, white areas represent clear water regime.

more negative values, signaling a stronger influence of phytoplankton source material. After the biomanipulation when plant abundance sharply increased, $\delta^{13}C$ values increased and BSi concentration decreased, suggesting a somewhat stronger input of macrophyte material and reduced phytoplankton input. Again during the mid-1970s and early 1980s when plant abundance dropped sharply and turbid conditions set in, $\delta^{13}C$ followed suit with a decrease while the BSi concentration increased. After the 1987 biomanipulation of the lake plants again recovered, and BSi concentration decreased. A shift in $\delta^{13}C$ also occurred, but it was towards more negative values that are more consistent with phytoplankton rather than macrophytes. A possible explanation for the negative $\delta^{13}C$ shift may be found in lake management efforts that followed the 1987 biomanipulation. In the winter of 1987, the use of a large aeration system was initiated in the deepest part of the eastern basin in order to keep predatory fish alive. Use of this system continued for three years (T. Carlson, pers. comm.). Mixing of the water column during the aeration process would have re-circulated a ^{13}C-depleted pool of DIC (from degrading plant materials in deeper waters, e.g. McKenzie, 1985) into the surface waters, resulting in the observed sharp decrease in the $\delta^{13}C$ of SOM. We find the response of $\delta^{13}C$ and BSi to the biomanipulations to be compelling and we suspect that with further work these proxies might be useful indicators of past regime shifts in high-resolution sedimentary records from shallow lakes.

Our results show that Lake Christina has clearly become a more eutrophic lake in the time since settlement and especially since the mid-1900s when active management of the lake began. The biomanipulations have been effective in returning the lake to a desired clear water condition in the short run, but as eutrophication has progressed, management of the lake has become more difficult. This was made evident by the results of the most recent biomanipulation in 2003, the effects of which appear to have been especially short-lived as the lake has once again shifted to the turbid regime. Our proxy records show a lake that appears to be firmly locked into this condition with only brief shifts into the clear regime forced by lake management efforts.

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