Mark Edlund and Joy Ramstack

St. Croix Watershed Research Station
Science Museum of Minnesota
16910 152nd St N
Marine on St. Croix, MN 55047

Final Report Summary (Result 2 - Reconstruct historical water quality and habitat conditions in the seven coldwater sentinel lakes)

submitted to:

Peter Jacobson, Don Pereira, Jeff Reed, and Brian Herwig
Minnesota Department of Natural Resources
500 Lafayette Rd.
St. Paul, Minnesota 55155

July 2012

Result 2 rationale – To complement modern sampling and inform modeling of future lake responses, we have comprehensively evaluated post-European colonization changes in lake conditions and evaluated major environmental events that coincided with these changes using analysis of biogeochemical signals preserved in sediment cores from the seven sentinel lakes. The sediment record of a lake faithfully preserves chemical and biological clues or proxies that can be used to reconstruct the environmental history of a lake and its watershed. With any environmental assessment such as the SLICE program it is important to have a basic understanding of natural fluctuations within the system. Reliable long-term data sets, on the order of 30 - 50 years, are generally not available for most regions of the country, including most lakes in Minnesota. Through the use of paleolimnological techniques and quantitative environmental reconstruction, we can estimate past environmental conditions and natural lake variability, and determine timing and rates of change and recovery. In Minnesota, paleolimnological techniques, especially diatom-based analyses, have been used throughout the state to quantitatively reconstruct historical environmental conditions, including nutrient concentrations (Ramstack et al. 2003; Edlund and Kingston 2004, Edlund et al. 2009), inform TMDLs and nutrient reduction targets (Edlund et al. 2009), and to develop nutrient criteria specific to ecoregion and lake-type (Heiskary and Wilson 2008). These successes have been based on paleolimnological analysis of only about 200 of Minnesota's 13000 lakes. Although lake environmental histories vary across the wide range of ecoregions and land uses in Minnesota, major periods of change are generally associated with initial Euroamerican settlement, logging, and land clearance, post-WWII changes in agricultural practices, (sub)urbanization, and climate change, although other site-specific land uses (cottage development, waste water treatment plant [WWTP] operations, damming) have also been identified as drivers of change.

Coring, site selection, geochemistry, core dating, diatom analysis

Sediment cores were recovered between 2009 and 2011 from seven coldwater or deep sentinel lakes including: Elk (Clearwater County), Carlos (Douglas), Ten Mile (Cass), Cedar (Morrison), White Iron (St. Louis, Lake), Trout (Cook), and South Twin (Mahnomen). Coring was accomplished using a polycarbonate tube outfitted with a piston and operated using rigid drive rods from the ice or an anchored boat (Wright 1991). One lake, Ten Mile Lake, was also cored using an HTH gravity corer (Renberg and Hansson 2008) that recovers only 30-50 cm of upper sediment. Most lakes were cored in the deepest part of the basin; however, because of physical limitations of the coring apparatus and complexity of the lake basin, Elk and Ten Mile lakes were cored in secondary depositional basins. The dates and site of core collection, lake depth at the coring site, and the length of core recovered are reported in Table 2.1.

All cores were sectioned in the field or lab in 0.5 to 1-cm increments. Sediments were analyzed for lead-210 activity to determine core age and sediment accumulation rates for the past 150-200 years (Fig. 2.1). Lead-210 was measured at ~20 depth intervals by lead-210 distillation and alpha spectrometry methods, and dates and sedimentation rates were determined according to the c.r.s. (constant rate of supply) model (Appleby and Oldfield 1978). Dating and sedimentation errors were determined by first-order propagation of counting uncertainty (Binford 1990). Sedimentation rates often increase in Minnesota lakes in response to increased erosion following logging and land clearance, or due to increased lake productivity (Engstrom et al. 2007, Edlund et al. 2009).

Weighed subsamples were taken from regular intervals throughout the cores for loss-on-ignition (LOI) analysis to determine core geochemistry including dry density and weight percent organics, carbonates, and inorganic matter (Fig. 2.1). Sediment subsamples were heated at 105ºC for 24 hr to determine dry density, then sequentially heated at 550°C and 1000°C to determine organic and carbonate content from post-ignition weight loss, respectively (Dean 1974). Changes in sediment constituents are often related to watershed disturbance (e.g. increased delivery of inorganics to a lake following land clearance), changes in nutrient loading or lake productivity (e.g. increased organic matter when algal production increases after phosphorus levels rise).

Twelve core sections were prepared for diatom analysis by placing approximately 0.25 cm^3 of homogenized sediment in a 50 cm^3 polycarbonate centrifuge tube and adding 2-5 drops of 10% v/v HCl solution to dissolve carbonates. Organic material was subsequently oxidized by adding 10 ml of 30% hydrogen peroxide and heating for 3 hours in a 85°C water bath (Renberg 1990). After cooling the samples were rinsed with distilled deionized water to remove oxidation byproducts. Aliquots of the remaining material, which contains the diatoms, were dried onto 22x22 mm #1 coverglasses and permanently attached to microscope slides using Zrax mounting medium. Diatoms were identified along random transects to the lowest taxonomic level under 1250X magnification (full immersion optics of NA 1.4). A minimum of 400 siliceous microfossils were counted in each sample. Diatom abundances are reported as percentage abundance relative to total diatom counts, as a diatom:chrysophyte cyst ratio, and as the planktonic:benthic ratio of diatom species. Identification of diatoms used regional floras (e.g. Patrick and Reimer 1966, 1975, Krammer and Lange-Bertalot 1986-1991, Edlund 1994, Camburn and Charles 2000) and primary literature to achieve consistent taxonomy.

Species present at greater than 1% relative abundance in two or more samples or at greater than 5% relative abundance in one sample were included in further analyses; the same selection criteria were used by Ramstack et al. (2003). Stratigraphies of subdominant diatoms were plotted against downcore date. Relationships among diatom communities within the sediment core were explored using Principal Components Analysis (PCA) or Detrended Correspondence Analysis (DCA), which is available in the software package R (Ihaka & Gentleman 1996). Constrained cluster analysis, also available in the software package R, was used to identify biostratigraphic zones in sediment cores based on historical diatom assemblages. Downcore diatom communities were used to reconstruct historical epilimnetic phosphorus levels in each lake. A transfer function for reconstructing historical logTP was earlier developed based on the relationship between modern diatom communities and modern environmental variable in 89 Minnesota lakes (Edlund and Ramstack 2006) using weighted averaging

(WA) regression with inverse deshrinking and bootstrap error estimation (C2 software; Juggins 2003). The strength of the transfer function was evaluated by calculating the squared correlation coefficient (r^2=0.83) and the root mean square error (RMSE=0.181) between the observed logTP with the model estimates of logTP for all samples. Bootstrapping is used in model validation to provide a more realistic error estimate (RMSEP, the root mean square error of prediction=0.208) because the same data are used to both generate and test the WA model (Fritz et al. 1999). Reconstructed estimates of logTP (diatom-inferred TP, or DI-TP) for each downcore sample were determined by taking the logTP optimum of each species, weighting it by its abundance in that sample, and determining the average of the combined weighted species optima. Reconstructed logTP values are reported for downcore depths and also backtransformed to TP in ppb. Error bars represent the root mean squared error of prediction (RMSEP, bootstrapped), i.e. the error of the model. In interpreting change in a reconstruction, we assign significance to changes that are greater than the RMSEP (Ramstack et al. 2003 and others).

Changes in siliceous algal communities (diatoms and chrysophytes), sedimentation rates, and core geochemistry were compared to potential drivers of change in the sentinel lakes. In addition to the fossil diatom communities being used to infer historical phosphorus levels (Ramstack et al. 2003), some diatom species are indicators of trophic level, lake productivity, or habitat. For example, eutrophic diatom communities are often dominated by *Aulacoseira granulata*, small *Stephanodiscus* species, and *Fragilaria capucina* v. *mesolepta*, mesotrophic communities dominated by *Aulacoseira ambigua*, *A. subarctica*, *Fragilaria crotonensis*, and *Stephanodiscus niagarae*, and oligotrophic communities dominated by centric diatom species such as *Cyclotella ocellata*, *C. bodanica*, *C. lemanica*, and *Discostella stelligera*. Diatom species also differ among habitats; non-motile planktonic species grow in the open water as single cells (e.g., *Cyclotella* or *Stephanodiscus* species), filaments (*Aulacoseira* species), or various colonial arrangements (e.g. star-shaped *Asterionella* colonies or band-shaped colonies of the *Fragilaria* species). Other diatoms species have a benthic habit and live attached or are motile on substrates including sediments (*Staurosira* and *Staurosirella* species), plants or rocks (e.g., *Achnanthidium*, *Cymbella*, *Amphora* species). Diatom communities can also be used as indices such as the planktonic to benthic ratio or the diatom to chrysophyte cyst ratio; both ratios typically increase when lakes undergo eutrophication (Smol 1995).

Potential drivers of change in Minnesota lakes that were examined included historical records of Euroamerican settlement, logging, predominant landuse, and records of shoreline development that were assembled for the Sentinel Lakes report series (e.g. Engel et al. 2010). Records of atmospheric nitrogen deposition from Minnesota monitoring stations (at Marcell, Fernberg Road [Ely], Hovland, and Camp Ripley) were downloaded from the NADP website (http://nadp.sws.uiuc.edu/sites/sitemap.asp?state=mn). Climate records for north central Minnesota were assembled from The Minnesota Climatology Working Group website (http://climate.umn.edu/doc/historical.htm).

Reconstruction of pre- to post-European to present sedimentation rates, sediment geochemistry, algal communities, and water chemistry

Carlos Lake (Douglas County) – Similar to an earlier core analyzed from Carlos Lake (Engstrom 1995), we confirmed that sediments deposited below 30 cm represent pre-1900 accumulation (Fig. 2.1). The large shift in core geochemistry above 35 cm (dated 1849.2 AD) marks the onset of Euroamerican settlement in the region (1860-1880 AD). Sedimentation rates increase after the 1890s in Carlos to a peak in the 1930s, before decreasing to near pre-settlement rates by the late 1960s (15 cm). But sedimentation rates increase after the 1960s and peak at about 1.6 times pre-settlement rates in recent sediments (Fig. 2.1). Pre-Euroamerican sediments deposited below 35 cm are primarily carbonate (60-65% dry weight) and secondarily made up of inorganics (20-25% dry weight) and organics (10-15% dry weight). Above 35 cm core depth sediment constituents change rapidly with decreasing carbonate content and increasing inorganic content (Fig. 2.1). These changes are consistent with lake response to Euroamerican settlement and land clearance in many lakes across Minnesota. Organic content remains at approximately 15% dry weight to 20 cm core depth (ca. 1950), before increasing to 25% dry weight at the core surface.

Biological and water quality changes were evaluated using siliceous microfossils including diatoms and chrysophyte cysts preserved in the Carlos core (Fig. 2.2). There were problems with diatom preservation in the deeper levels of the core likely due to the high carbonate content of the cores and overall high alkalinity of Carlos Lake,. In particular, strong evidence of diatom dissolution was present at 35 cm (c. 1850) and 21 cm (c. 1934) and caution must be used with interpretations of those and nearby core depths. Two sediment biological indices, the diatom:chrysophyte cyst ratio, and as the plankton:benthic ratio suggest potential increased productivity or eutrophication in Carlos Lake (Fig. 2.2). Both ratios increased after the 1960s. Biostratigraphy of the Carlos core identifies two periods in Carlos' history in the last 150 years: 1849-1961, and post 1960s (Fig. 2.2). The deepest sediments are dominated by chrysophyte cysts and a diverse benthic diatom assemblage including the subdominants *Staurosira construens* and *Martyana martyi*. Planktonic species during this period include Cyclotella *michiganiana*, *Cyclotella radiosa*, and the araphid *Pseudostaurosira brevistriata*. The first major shift in diatom assemblages occurred after settlement. The diatom communities between 1900 and 1960 were similar to pre-settlement floras with the exception of decreases in some of the more abundant benthic taxa (e.g. *Staurosira construens*, *Martyana martyi*) and increased in some planktonic araphids (*Fragilaria vaucheriae*, *Pseudostaurosira brevistriata*). The most dramatic changes in Carlos Lake began in the 1960s. Three new species came to dominate the diatom flora (i.e., *Cyclotella comensis*, *Fragilaria crotonensis*, and *Asterionella formosa*), indices suggest increased diatom productivity, and benthic species generally decrease in abundance. The ecology of the three new species has been well studied. *Cyclotella comensis* often increases in abundance as mixing depths change in the lake (Saros et al. in press). However, it also responds to nutrient additions, especially nitrogen (Saros et al. 2005, in press). In contrast the species *F. crotonensis* and *A. formosa* are more often indicators of P enrichment, but will respond to N additions under oligotrophic conditions (Saros et al. 2005). The simultaneous increase of these taxa is most likely a reflection of changes in the physical or mixing environment of Carlos Lake.

Diatom-inferred changes in water quality showed little change in total phosphorus from presettlement through the 1960s. Since the 1960s DI-TP shows a declining trend with values from 1999 to 2009 ranging from 13 to 20 ppb TP. Recent SLICE monitoring reported annual average TP of 16.7-17.5 ppb in Carlos Lake, similar to diatom-inferred values.

Potential historical drivers of change in Carlos Lake include resort/cottage/home development, a largely agricultural watershed, historical N-deposition, upgradient point sources, and climate changes. Engel et al. (2010) summarize current land use patterns in the watershed and identify the primary use as cultivated crops. Engel et al. (2010) also report that shoreline development has progressed from 11 resorts and 137 cabins in 1948, to 342 homes and 9 resorts with 73 cabins in 1980, to 420 homes and 5 resorts in 1992. Patterns of inorganic nitrogen deposition at Camp Ripley suggest overall increasing trends from 1983 to present, which may corroborate the changes noted above for the post 1960s diatom assemblages in concert with warming trends.

Cedar Lake (Morrison County) – Lead-210 dating of the Cedar Lake core showed that sediment below 32 cm was deposited before 1900 AD (Fig. 2.1). Sedimentation rates increased after European settlement (post-1880) peaking in the 1960s, before declining to consistent levels from the 1970s to present. Current sedimentation rates are approximately 2.1-fold greater than presettlement rates. The core is more variable in sediment composition than many of the cores being analyzed in this study. Carbonates dominate the sediment and account for 45-70% of core dry weight below 20 cm depth. Carbonates then decrease upcore to account for only 10% of the dry weight at the core top. Inorganics make up the next greatest portion of the sediment with sediments from 40 cm to 20 cm increasing from 20% to 40% inorganics by weight. Above 20 cm (mid-1960s) inorganics increase from 40% to 55% dry weight at the core top. The Cedar Lake core further stands out as it appears contain a varved record for much of its length, i.e., the sediments are banded suggesting that layers represent annual deposition of sediments.

The sediment core from Cedar Lake records significant biological change in the last 150 years that can be separated into three biostratigraphic zones: pre-settlement to 1919, 1940-1980, and 1989 to present (Fig. 2.3). Two peaks in the plankton:benthic diatom ratio (mid 1960s and post-1990) suggest recent shifts to greater dominance of plankton productivity, although planktonic diatoms dominate the entire length of the core. Sediments from pre-Euroamerican settlement through 1919 are dominated by *Fragilaria crotonensis*, *Stephanodiscus minutulus*, *S. parvus*, with pre-1850 peaks in *Aulacoseira ambigua*, *Asterionella formosa*, and *Discostella pseudostelligera*. Between 1940 and 1980 Cedar Lake sediments have a large peak in abundance of *F. crotonensis*, initial increases in *Synedra ulna* v. *chaseana*, C. *michiganiana*, and lesser abundance of *S. minutulus* and *S. parvus*. Post-1980 sediments are dominated by *C. comensis*, which is limited in extent to these core strata, a recent peak in *Asterionella formosa* and *D. pseudostelligera*, and lower but high levels of *F. crotonensis*. The upcore increase in *C. comensis* may reflect changes in mixing depth and/or changes in nitrogen loading to the lake. The latter seems less likely as the TN:TP ratio in Cedar Lake is 46 suggesting strong P limitation (Bergström 2010).

The diatom-inferred record of total phosphorus for Cedar Lake shows the most rapid changes in water quality occurred following initial settlement as DI-TP increased from 17 to 34 ppb between 1842 and 1919. After that initial peak, DI-TP has essentially decreased steadily upcore from around 20 ppb in the 1950s to 9-12 ppb since the 1980s. Modern monitoring of Cedar Lake reported an annual average TP of 13 ppb (data from the 2008 monitoring year; Anderson P et al. 2010).

Currently relatively clear with mesotrophic water quality that is outstanding among NCHF lakes, Cedar Lake's watershed is approximately 34% forested and 42% agriculture or pasture (Anderson P et al. 2010). The lakeshore is relatively little developed with only 12 homes/cottages, a bible camp, and a 50-site campground. As such, potential stressors to water quality are limited, but suggest that changes since the 1980s are related to physical changes in the lake, including changes in mixing depth. As the lake is strongly P-limited there is less possibility of a response to enhanced deposition of nitrogen that has been recorded at Camp Ripley (Fig. 2.3).

Elk Lake (Clearwater County) – The Pb-210 date model for Elk Lake shows that sediments deposited below 34 cm (1890 AD) represent pre-Euroamerican settlement (Fig. 2.1). Sedimentation rates increase after settlement until 1929, where they remain at levels that are about 1.4 times presettlement rates. Percent organics rise from 15% at the core bottom to 30% near the core top. Inorganics are found at 20% of dry weight from 50 cm to 36 cm depth and then rapidly increase upcore to 40-50% dry weight. Carbonates behave in contrast to inorganics and make up about 60% of dry weight from 50 cm to 36 cm, then drop to about 20% dry weight to the core top.

Biological and water quality changes recorded in Elk Lake sediments have been well studied (Bradbury et al. 2002). In the SLICE sediment core dramatic changes in the algal communities are found in three biostratigraphic zones: presettlement (1853-1890 AD), 1929-1974, and 1986-2010 (Fig. 2.4). Presettlement communities in Elk Lake are dominated by indicators of relatively productive waters including small *Stephanodiscus* species, *Fragilaria crotonensis* and *Asterionella formosa*. From 1929-1974, the diatom communities shift to become dominated by *Tabellaria flocculosa*, *Aulacoseira ambigua*, *Cyclotella bodanica*, while *F. crotonensis* and *Asterionella formosa* remain important components of the flora. The diatom communities from 1986 to present contain a mixed assemblage including *F. crotonensis*, *Discostella stelligera*, *Cyclotella michiganiana*, *C. bodanica*, and *F. vaucheriae*.

These findings corroborate Bradbury's (2002) reports of high nutrients in the late 1800s likely in response to logging. Diatom-inferred estimates of total phosphorus show a highly variable nutrient history since 1850 with presettlement values of 40 ppb, a secondary peak in nutrients around 1960 that has since declined to values of 20-25 ppb from 1986 to present. SLICE monitoring at Elk from 2008-2010 reported average TP values of 15-21 ppb, similar to the mesotrophic conditions reported from the sediment core reconstructions.

Elk Lake is perhaps the least anthropogenically impacted lake among the sentinel lakes. With its entire watershed within the bounds of Itasca State Park, there are few direct anthropogenic factors that drive the large changes noted in the sedimentation and biology of the lake. There is no shoreline development on Elk Lake and it is estimated that less than 1/3 of its watershed was ever logged. There has been minor control structures placed at its outlet since the 1930s but these have not dramatically changed the depth of the lake. Rather, Bradbury et al. (2002) has identified how Elk Lake responds especially strongly to climate drivers that impact its mixing regime and nutrient cycling. Notably the shift between 1986 and the present suggest less vigorous spring mixing, less nutrient availability, and warmer (and stormier?) summers. Atmospheric deposition of nitrogen, as recorded near Grand Rapids, shows little trend between 1978 and 2010 (Fig. 2.4). TN:TP ratios at Elk Lake are 29 to 33 suggesting that there is likely P-N co-limitation in the lake and that a response to N addition may be possible (Bergström 2010).

South Twin Lake (Mahnomen County) – Sediments from below 36 cm (1886 AD) in South Twin Lake were deposited before Euroamerican settlement (Fig. 2.1). There was a slight increase in sedimentation rates after settlement, and again at the very top of the cores. Modern sedimentation rates are approximately 1.5 times greater than presettlement rates. Loss on ignition analysis suggests that an inflection in core geochemistry occurs at Euroamerican settlement. Carbonates are the major constituent of the South Twin core ranging in abundance from 60-70% dry weight (30-50 cm) to 50% dry weight from 30 cm to surface. Organics generally increase in content upcore from 20% to 25%. Inorganics similarly increase in content upcore from about 18-20% dry weight from 36 to 50 cm to 20-27% above 30 cm core depth.

South Twin samples studied with the light and scanning electron microscope showed heavy dissolution of diatom microfossils in older sediments that hindered some diatom analysis efforts. In particular there was relatively poor preservation in pre-1930 sediments, although the 1890 sample had reasonable preservation. Additionally the sample dated 1861 was identified as a diatom community outlier during statistical analysis due to dissolution artifacts and interpretations based on that sample are not considered. Community analysis of the South Twin core identified three biostratigraphic zones: 1887-1943, 1958-1982, and 1988-2009 (Fig. 2.5). Overall, sediments from South Twin are dominated by benthic taxa, especially small araphids such as *Staurosira construens*, S. *construens* v. *venter*, and *Staurosirella pinnata*. These taxa are most common in shallower lakes such as South Twin (47% littoral) and are easily resuspended into the water column during mixing events. The earliest strata in the core are dominated by these three species and additionally the benthic *Martyana martyi* and few planktonic species such as *Cyclotella michiganiana*. From 1958 to 1982 the benthic species continue to dominate the sediment assemblage, but *Pseudostaurosira brevistriata* v. *inflata* begins to increase in abundance. It is the sediments deposited since 1988 that are most different from the remaining core. Here the plankter *C. comensis* appears and becomes a dominant component of the flora along with renewed inclusion of *Aulacoseira ambigua* in the flora. *Cyclotella comensis* is a species that responds to both N additions and stratified conditions by inhabiting the deep chlorophyll layer in stratified lakes.

Diatom-inferred changes in TP suggest little change in phosphorus dynamics between 1886 and 2004 with TP reconstructed at mesotrophic levels of 20 to 27 ppb. The most recent core sample (dated at 2009) analyzed reconstructed at 14 ppb TP, which is similar to monitored values between 2008 and 2010 of 16-17 ppb TP.

South Twin Lake is located in the NLF ecoregion and its watershed is 74% forested. The lake is currently mesotrophic and has normally been well-mixed in summer above 6 m depth at its regular monitoring station. However it was stratified in July 2008 at a deepest sampling point (MPCA 2009; wq-slice44-0014) and is classified as intermittently stratified. Development on the lake began as early as 1918 with resort construction. It has seen steady development focused on the south shore with 30 homes in the 1950s, 137 homes, two resorts and 84 campers by 2001, and 148 docks counted in 2010 (O'Hara et al. 2011a). The biological trends in South Twin present a conundrum with the most modern sediments having subdominance by three planktonic species: *Cyclotella comensis*, *Aulacoseira ambigua*, and *Pseudostaurosira brevistriata* v. *inflata*. The latter two taxa are abundant in well-mixed lakes, whereas *C. comensis* is more often associated with stratified conditions. However, *C. comensis* also responds to N additions in lakes (Saros et al. in press), and although atmospheric deposition trends are steady in the NLF (Fig. 2.5), exports to lakes in similar forested regions has been shown to be increasing with warmer winter temperatures and less snowpack (Stottlemyer et al. 1998, Toczydlowski and Stottlemyer 2009). The TN:TP ratio of South Twin is 31-35 (2008-2010 data) suggesting that the lake may show co-limitation for N and P (Bergström 2010).

Ten Mile Lake (Cass County) – A 1.32 m long core was recovered from 37.8 m (143 ft) of water in Ten Mile Lake on 06 August 2010. Coring and sectioning were hindered by the extreme depth of Ten Mile Lake and subsequent temperature and pressure changes after core recovery. The core had very high levels of methane and underwent degassing that disturbed the top 15 cm of the core during transport to shore and sectioning. An additional HTH gravity core (45 cm long) was taken in June 2011 from Ten Mile Lake to provide more consolidated surface sediments. A combined date-depth model based on analysis of both cores suggests that sediments deposited below 75 cm (1889 AD) predate Euroamerican settlement in the region (Fig. 2.1). Sedimentation rates increase quickly after settlement to peaks around 1950 and the early 1970s that are 5-fold pre-settlement rates. After the 1970s, sedimentation rates decline, but remain at levels that are currently four times pre-settlement rates. Ten Mile Lake sediments are predominantly inorganics, which make up 55-64% of the core weight with a trend toward higher inorganics upcore. Organics make up the next most abundant fraction of the core with levels increasing from 20-25% of core weight below 25 cm and increasing to about 30% dry weight of organics at the core top. Carbonates decrease upcore from 25% dry weight downcore to only 6% dry weight in the core top.

Diatom communities preserved in the Ten Mile core are dominated by two *Aulacoseira* species, *A. ambigua* and *A. subarctica*, over the last 150 years (Fig. 2.6). The communities can be divided into four biostratigraphic zones including presettlement (1833-1889), 1922-1985, and then two narrow zones near the core top (1997-2003 and 2008-2010). In addition to the two *Aulacoseira* species, presettlement communities include as subdominants the planktonics *Stephanodiscus minutulus* and *Pseudostaurosira brevistriata* v. *inflata*, and the araphid benthics *Staurosirella pinnata* and *Staurosira venter*. Following settlement, the primary species response was a dramatic increase in the abundance of *A. ambigua* including its peak abundance around 1950. After 1950 there were also increases in *S. minutulus* and *Tabellaria flocculosa*. From 1997 to recent samples the sedimented diatom assemblage is again marked by the appearance and increased abundance of *Cyclotella comensis*. This occurs in conjunction with the only marked declines of the *Aulacoseira* species and *S. minutulus*.

Diatom-inferred changes in water quality show slight increases in TP following settlement and logging in the 1880-1900s to peaks in the 1950s of 46 ppb TP (Fig. 2.6). Following this peak, diatom-inferred TP levels decrease upcore to modern levels of 16 ppb (2008-2010), although DI-TP values were as high as 25 ppb in the late 1990s. Recent monitoring has recorded average TP values of 10-12 ppb (MPCA 2009; wq-slice11-0413.and O'Hara et al. 2010)

Ten Mile lake has had a lengthy history of landuse changes, lakeshore development and possible impacts on water quality. Logging in the region was completed by 1900 and by 1920 seven resorts were present on Ten Mile Lake. By 1948 there were 165 cabins on the lake and 16 resorts in operation, and by 2003, there were 506 cabins/homes and one resort operating at Ten Mile. During this period of development, there were clear indications of impairment, notably the presence of cyanobacterial blooms in the 1960s (O'Hara et al. 2010). This period of time coincides with the highest sedimentation rates in Ten Mile history as well as the highest DI-TP values. Lake association efforts to control animal, outhouse, and septic waste to the lake appear to have worked to improve water quality. The changes recorded in Ten Mile sediments after 1997 seem to be unique in the lake's recent history and involve appearance and increased abundance of *Cyclotella comensis*. The lack of any other typical diatoms that respond to nutrient additions suggests that physical changes, particularly changes in mixing depth and regime, may be driving the recent trajectory of Ten Mile Lake. Alternatively, TN:TP ratios of 27-29 in Ten Mile Lake suggest at least seasonal N-P co-limitation and a possibility that some of the biological changes may be in response to N additions (Bergström 2010).

Trout Lake (Cook County) – The dating and sediment accumulation model for Trout Lake shows that below 19 cm core depth (<1870 AD), sediments were deposited pre-Euroamerican settlement (Fig. 2.1). Sedimentation rates are the lowest among the sentinel lakes studied, but rates increase slightly from presettlement to ca. 1952 (9 cm), then decline to the core surface back to and even slightly less than presettlement rates. The composition of sediments in Trout Lake has remained very consistent through time as 70% inorganics, 10% carbonates, and about 20% organics.

Diatom communities in the Trout Lake sediment core show minor changes between 1871 and present (Fig. 2.7). During that time the diatom community is dominated by *Discostella stelligera* and *Aulacoseira subarctica*. Cluster analysis on the core identifies two major biostratigraphic zones in the sediments: 1871-1952 and 1964-2006. In addition to *D. stelligera* and *A. subarctica*, the earlier zone is characterized by slightly higher abundance of *Pseudostaurosira brevistriata*. The more recent sediments continue to be dominated by *D. stelligera* and *A. subarctica*, but show increased abundance of *Asterionella formosa*, *Cyclotella ocellata*, *C. lemanica*, and *D. pseudostelligera*.

Among the SLICE lakes that had sediment cores analyzed, Trout Lake showed the most minor diatom community changes and essentially no change in diatom-inferred TP reconstructions (Fig. 2.7). Between 1871 and 2006, DI-TP varied between 9.5 and 12.3 ppb TP. Modern measurements of TP in Trout Lake have varied between 6.2 and 8.0 ppb (2008-2010), closely matching our DI-TP reconstructions and similarly showing no discernible trend.

Trout Lake is currently an oligotrophic lake supporting a coldwater fishery. Land use in the watershed is over 75% forested and lake shore development is minimal with only ten cabins/homes on the shoreline (Anderson et al. 2011). Logging in the region took place in 1890-1920. Although N deposition has potential to drive lake changes, the limited record of deposition shows a slight declining trend between 1997 and 2010 (Hovland, MN: Fig. 2.7). It should be noted that the TN:TP ratio in Trout Lake has ranged from 39 to 64 (2008-2010) suggesting that the lake is strongly P-limited (Bergström 2010) and would likely not have a strong response to N additions. Other factors that could be affecting Trout Lake include climate patterns of increased wind (Austin and Colman 2007) and warmer temperatures near Lake Superior.

White Iron Lake (St. Louis and Lake counties) – The date-depth model resulting from Pb-210 analysis shows that sediments below about 35 cm (1895 AD) represent pre-Euroamerican sediment deposition (Fig. 2.1). Sedimentation rates increase from pre-Euroamerican rates, plateauing from 1930 to present at rates that are approximately 1.7 times pre-settlement. White Iron sediment composition has remained constant over time. Sediments are primarily inorganics, which make up over 65% of the core's dry weight. Organics constitute 22-24% dry weight, and carbonates make up 10-11% of core weight.

Biological changes in the White Iron core can be divided into three zones: 1866-1895 (presettlement), 1918-1977, and 1987-2010 (Fig. 2.8). Similar to Ten Mile Lake, the diatom communities have been dominated by *Aulacoseira subarctica* and *A. ambigua* over the last 150 years. The presettlement sediments are secondarily dominated by *Asterionella formosa*, *Aulacoseira tenella*, and *Tabellaria flocculosa*. The 1918-1977 group of samples sees continued dominance of the presettlement flora, but *Aulacoseira granulata*, *A. laevissima*, and *Fragilaria crotonensis* enter the diatom community. The most recent group of samples (1987-2010) sees greater abundance of mesotrophic *Aulacoseira ambigua*, lower abundance of *A. subarctica*, and decline of the unknown species called *Aulacoseira* sp. #4. In sum, there is little floristic change in the sedimented diatom flora from the north basin of White Iron Lake.

Diatom-inferred changes in water quality also suggest little change or trend in TP in the last 150 years (Fig. 2.8). Diatom-inferred values are mesotrophic and range from 29.8 to 37.5 ppb TP over the last 150 years, with the most recent reconstructions somewhat higher than monitored values. Recent monitored annual TP averages are 18.7-23.7 ppb (2008, 2009), suggesting that the core reconstructions may be slightly overestimating historical TP values.

The watershed of White Iron Lake is over 80% forested and contains a large portion of bogs and wetlands that supply humic-stained waters to White Iron that are mesotrophic, low conductivity, and slightly acidic. Logging was prevalent between 1900 and 1917 in the White Iron watershed and was followed by damming and shoreline development. By 1958 there were 96 cottages and 6 resorts on the lake and by 1982 the number of homes had increased to 135. In 2001, surveys showed 197 homes and 4 resorts on White Iron. The lake is considered intermittently stratified; the north basin where the core was collected is significantly deeper than the southwest basin. White Iron Lake was dammed in 1923 and continues to be managed as a reservoir along the Kawishiwi drainage. Its short residence times (45 days, MPCA 2009; wq-slice69-004) and little development in the watershed likely support the overall lack of trend in long-term water quality shown in monitoring data (Anderson et al. 2010), biostratigraphy, core geochemistry, sedimentation rates, or diatom-inferred nutrient values.

Result 2 Conclusions

Among the sediment records recovered from the seven deep or coldwater SLICE lakes, many but not all lakes showed significant changes in core geochemistry, sedimentation rates, diatom communities, and reconstructed water quality parameters over the last 150 years. In some lakes, the changes are correlated to known landuse associated with Euroamerican settlement, land clearance, logging, and impacts associated with shoreline development. Other drivers of environmental change must also be considered when interpreting ecological changes preserved in the SLICE sediment cores.

Lakes are distributed across numerous ecoregions in Minnesota from the Northern Lakes and Forests in the northeast to the Western Corn Belt Plains in the southwest. Along this geographical and ecoregional gradient, paleolimnological analysis of lakes has shown how the lakes differ in background and modern nutrient condition (Ramstack et al. 2003, Heiskary and Wilson 2008) as well as presettlement and modern sedimentation rates (Engstrom et al. 2007). Further, the importance of lakes in the global carbon cycle and the potential of lakes for long-term burial have also been considered (Heathcote and Downing 2011). In the seven SLICE lakes studied with paleolimnological analysis, sedimentation rates increased following Euroamerican settlement (Fig. 2.9) and either remained elevated or decreased to modern levels at (e.g. Trout Lake) or near (e.g. Elk Lake) presettlement levels. We analyzed sedimentation rates during four time periods (presettlement 1800-1860, 1890-1910, 1940-1960, 1990-2005) for all seven lakes and show that the median of focus-corrected modern sedimentation rates are 1.7 times greater than presettlement rates (Fig. 2.9). Similarly we analyzed carbon burial rates in the same time periods and show that modern carbon burial rates are 1.9 times greater than presettlement rates. The increases in sedimentation and carbon burial rates for the seven coldwater SLICE lakes are slightly less than all NLF and NCHF lakes whose sediment records have been studied to date (Robert Dietz, Univ of Minnesota, unpublished data).

Community level changes in diatoms are also prevalent among the SLICE lakes, although some lakes show rather small shifts over the last 150 years (e.g. Trout and White Iron lakes). Most lakes show two major periods of ecological change in their diatom communities. The first shift occurs near the time period of settlement that is associated with logging in the NLF lakes, land clearance in the NCHF lakes (Carlos and Cedar), and initial shoreline development. The zone of biological change in response to settlement is centered in the 1910s among the SLICE lakes (Fig. 2.9). The second major period of ecological change recorded in the sediment cores occurs in the early 1980s (Fig. 2.9). In some SLICE lakes this is still a period of rapid shoreline development (e.g. Ten Mile Lake); however, for many lakes there is relatively little land use or development that would be considered as possible triggers of this change. Furthermore, the community changes are not consistent with typical phosphorus-driven changes in the lakes but rather reflect regional patterns of change in the SLICE lakes. For example, five of the seven lakes show post 1980s increases in the abundance of *Cyclotella comensis* or other species associated with physical changes in the lakes, notably the mixing depth (Saros et al. in press). Other regional drivers include atmospheric deposition of N, a global trend of the last approximately 100 years that has been increasingly identified as impacting lakes and landscapes in even remote regions (Holtgrieve et al. 2011). N-deposition patterns vary across north central Minnesota with increasing deposition (Camp Ripley), decreasing deposition (Hovland) and no apparent patterns (Marcell and Fernberg Road). We unfortunately have no direct measurements of N-deposition before the current NADP networks were established. Many of the SLICE lakes show N-P co-limitation and thus could be responsive to direct deposition or enhanced export of N noted in boreal landscapes (Stottlemyer et al. 1998, Toczydlowski and Stottlemyer 2009). The other factors that may be driving recent physical and biological changes in SLICE lakes are responses to climate change. For example, shifts in earlier ice-out and later ice-on dates have been well-documented for northern lakes (Jensen et al. 2007). Other meteorological trends that would directly affect physical conditions and mixing in lakes include increasing minimum temperature trends in summer and winter, decreased snowpack, and wind conditions (Minnesota Climatology Working Group, http://climate.umn.edu/doc/historical.htm). Individual lake modeling is likely necessary to fully test the effects of climate drivers on lakes (Fang and Stefan 1997), but paleolimnological records offer an independent record of climate impacts, especially in lakes that are little impacted by landuse activities in their watersheds.

References

Anderson, J., Thompson, D., Valley, R. and Butcher, J. 2010. Sentinel Lake Assessment Report White Iron Lake (69-0004) Saint Louis County, Minnesota. Minnesota Pollution Control Agency, St. Paul, Minnesota.

Anderson, J., Valley, R. Persons, S. and Butcher, J. 2011. Sentinel Lake Assessment Report Trout Lake (16-0049) Cook County, Minnesota. Minnesota Pollution Control Agency, St. Paul, Minnesota.

Anderson, P., Valley, R., Bublitz, C. and Becker, B. 2010. Sentinel Lake Assessment Report Cedar Lake (49-0140) Morrison County, Minnesota. Minnesota Pollution Control Agency, St. Paul, Minnesota.

Appleby, P.G., and F. Oldfield. 1978. The calculation of lead-210 dates assuming a constant rate of supply of the unsupported lead-210 to the sediment. Catena 5:1-8.

Bergström, A.-K. 2010. The use of TN:TP and DIN:TP ratios as indicators for phytoplankton nutrient limitation in oligotrophic lakes affected by N deposition. Aquat. Sci. 72:277-281.

Binford, M.W. 1990. Calculation and uncertainty analysis of 210-Pb dates for PIRLA project lake sediment cores. J. Paleolimnol. 3:253-267.

Bradbury, J.P., Cumming, B. and Laird, K. 2002. A 1500-year record of climatic and environmental change in Elk Lake, Minnesota III: measures of past primary productivity. Journal of Paleolimnology 27: 321-340.

Camburn, K.E., and D.F. Charles. 2000. Diatoms of low-Alkalinity Lakes in the Northeastern United States. Academy of Natural Sciences of Philadelphia Special Publication 18:152 pp.

Edlund, M.B. and Kingston, J.C. 2004. Expanding sediment diatom reconstruction model to eutrophic southern Minnesota lakes. Final report to Minnesota Pollution Control Agency, CFMS Contract No. A45276. 32 pp + appendix.

Edlund, M. B., Engstrom, D. R., Triplett, L., Lafrancois, B. M. and Leavitt, P. R. 2009. Twentieth-century eutrophication of the St. Croix River (Minnesota-Wisconsin, USA) reconstructed from the sediments of its natural impoundment. Journal of Paleolimnology 41: 641-657. DOI:10.1007/s10933-008-9296-1

Edlund, M.B. 1994. Additions and confirmations to the algal flora of Itasca State Park. II. Diatoms of Chambers Creek. J. Minn. Acad. Sci. 59:10-21.

Edlund, M.B. and Ramstack, J. 2006. Diatom-Inferred TP in MCWD Lakes. Final Report to Minnehaha Creek Watershed District, Work Order #116-04, 33 pp.

Engel, L., Valley, R., Beck, D. and Anderson, J. 2010. Sentinel Lake Assessment Report Lake Carlos (21-0057) Douglas County, Minnesota. Minnesota Pollution Control Agency, St. Paul, Minnesota.

Engstrom, D.R. 1995. Mercury Investigations of the Alexandria Chain of Lakes, Douglas County, Minnesota. Final Report prepared for the Douglas County, Office of Land and Resource Management and WesMin Resource Conservation and Development Council, Carlos and Le Homme Dieu Lake Associations, Minnesota Pollution Control Agency. Limnological Research Center, University of Minnesota.

Engstrom, D.R., Balogh, S.J. and Swain, E.B. 2007. History of mercury inputs to Minnesota lakes: Influences of watershed disturbance and localized atmospheric deposition. Limnol. Oceanogr. 52: 2467-2483.

Fang X. and Stefan, H.G. 1997. Simulated climate change effects on dissolved oxygen characteristics in ice-covered lakes. Ecol. Model. 103: 209-229.

Fritz, S. C., Cumming, B. F., Gasse, F. and Laird, K. 1999. Diatoms as indicators of hydrologic and climatic change in saline lakes. In Stoermer, E.F. and Smol, J. P. (eds.), The Diatoms: Applications for the Environmental and Earth Sciences. Cambridge University Press, Cambridge & New York, pp 41-72.

Heathcote, A.J. and Downing, J.A. 2011. Impacts of eutrophication on carbon burial in freshwater lakes in an intensively agricultural landscape. Ecosystems DOI:10.1007/s10021-011-9488-9

Heiskary, S. A. and Wilson, C. B. 2008. Minnesota's approach to lake nutrient criteria development. Lake and Reservoir Management 24:282-297.

Holtgrieve, G.W. and 18 others. 2011. A coherent signature of anthropogenic nitrogen deposition to remote watersheds of the Northern Hemisphere. Science 334: 1545-1548.

Ihaka, R. and Gentleman, R. 1996. R: a language for data analysis and graphics. J. Comput. Graph. Stat. 5: 299-314.

Jensen, O.P., Benson, B.J., Magnuson, J.J., Card, V.M., Futter, M.N., Soranno, P.A. and Stewart, K.M. 2007. Spatial analysis of ice phenology trends across the Laurentian Great Lakes region during a recent warming period. Limnol. Oceanogr. 52:2013-2026.

Juggins, S. 2003. C2 version 1.3, Software for ecological and palaeoecological data analysis and visualization. University of Newcastle, Newcastle upon Tyne, NE17RU, United Kingdom.

Krammer, K. and Lange-Bertalot, H. 1986-1991. Bacillariophyceae. in Ettl, H., Gerloff, J., Heynig, H. and Mollenhauer, D. (eds) Süsswasser flora von Mitteleuropa, Band 2/1-4. Gustav Fischer Verlag: Stuttgart, New York.

Lockhart, W.L., Wilkinson, P., Billeck, B.N., Danell, R.A., Hunt, R.V., Brunskill, J., Delaronde, J. and St. Louis, V. 1998. Fluxes of Mercury to Lake Sediments in Central and Northern Canada Inferred from Dated Sediment Cores. Biogeochemistry 40(2/3): 163-173 http://www.jstor.org/stable/1469319

O'Hara, K., Heiskary, S., Valley, R. and Erickson, M. 2011a. Sentinel Lake Assessment Report South Twin Lake (44-0014) Mahnomen County, Minnesota. Minnesota Pollution Control Agency, St. Paul, Minnesota.

O'Hara, K., Heiskary, S., Valley, R. and Habrat, M. 2011b. Sentinel Lake Assessment Report Elk Lake (15-0010) Clearwater County, Minnesota. Minnesota Pollution Control Agency, St. Paul, Minnesota.

O'Hara, K., Heiskary, S., Valley, R. and Shavlik, C. 2010. Sentinel Lake Assessment Report Ten Mile Lake (11-0413) Cass County, Minnesota. Minnesota Pollution Control Agency, St. Paul, Minnesota.

Patrick, R. and Reimer, C.W. 1966. The diatoms of the United States, exclusive of Alaska and Hawaii, Volume 1-Fragilariaceae, Eunotiaceae, Achnanthaceae, Naviculaceae. Academy of Natural Sciences of Philadelphia Monograph No. 13, 699 pp.

Patrick, R. and Reimer, C.W. 1975. The diatoms of the United States, exclusive of Alaska and Hawaii, Volume 2, Part 1-Entomoneidaceae, Cymbellaceae, Gomphonemaceae, Epithemaceae. Academy of Natural Sciences of Philadelphia Monograph No. 13, 213 pp.

Ramstack, J. M., Fritz, S. C., Engstrom, D. R. and Heiskary, S. A. 2003. The application of a diatom-based transfer function to evaluate regional water-quality trends in Minnesota since 1970. J. Paleolimnol. 29: 79-94.

Renberg, I., 1990. A procedure for preparing large sets of diatom slides from sediment cores. Journal of Paleolimnology 4: 87-90.

Renberg, I. and Hansson, H. 2008. The HTH sediment corer. Journal of Paleolimnology 40: 655-659.

Saros, J.E., Michel, T.J., Interlandi, S.J. and Wolfe, A.P. 2005. Resource requirements of *Asterionella formosa* and *Fragilaria crotonensis* in oligotrophic alpine lakes: implications for recent phytoplankton community reorganizations. Can. J. Fish. Aquat. Sci. **62**: 1681–1689 (2005)

Saros, J.E., Stone, J.R., Pederson, G.T., Slemmons, K.E.H., Spanbauer, T., Schliep, A., Cahl, D., Williamson, C.E. and Engstrom, D.R. *In press.* Climate-Induced Changes in Lake Ecosystem Structure Inferred from Coupled Neo- and Paleo-ecological Approaches. Ecology. http://dx.doi.org/10.1890/11-2218.1

Smol, J. P., 1995. Application of Chrysophytes to problems in pale- oecology. In Sandgren, C., J. P. Smol & J. Kristiansen (eds), Chrysophyte algae: Ecology, Phylogeny and Development. Cam- bridge University Press, Cambridge: 303–329.

Stottlemyer, R., D. Toczydlowski & R. Herrmann. 1998. Biogeochemistry of a mature borealecosystem: Isle Royale National Park, Michigan. Scientific Monograph NPS/NRUSGS/NRSM-98/01, National Park Service, 116 pp.

Toczydlowski, D. G. & R. Stottlemyer. 2009. 2008 Annual Report for Wallace Lake Watershed, Isle Royale National Park, Michigan.

Wright, H.E., Jr. 1991. Coring tips. J. Paleolimnol. 6:37-49.

Tables

Table 2.1. Site, date (YYYYMMDD), depth (Z, m), and length (m) of core recovered from seven deepwater SLICE lakes.

Lake/Core Name	Date	Lat (N)	Long (W)	County	Type	Z (m)	Recovery (m)
Carlos Lake	20091022	45°56.476'	95°22.029'	Douglas	piston	26.63	0.81
Elk Lake	20100121	47°11.467'	95°13.182'	Clearwater	piston	19.82	1.74
Trout Lake	20100608	47°52.230'	90°10.075'	Cook	piston	20.40	1.54
South Twin	20100610	47°13.893'	95°39.181'	Mahnomen	piston	7.75	1.78
Cedar_Morrison	20100806	45°48.769'	94°38.069'	Morrison	piston	26.11	1.66
Ten Mile	20100806	46°59.292'	94°33.499'	Cass	piston	37.80	1.32
White Iron	20100807	47°53.256'	91°46.798'	Lake	piston	10.21	1.17
Ten Mile-2	20110623	46°59.299'	94°33.489'	Cass	HTH	37.80	0.44

Figures

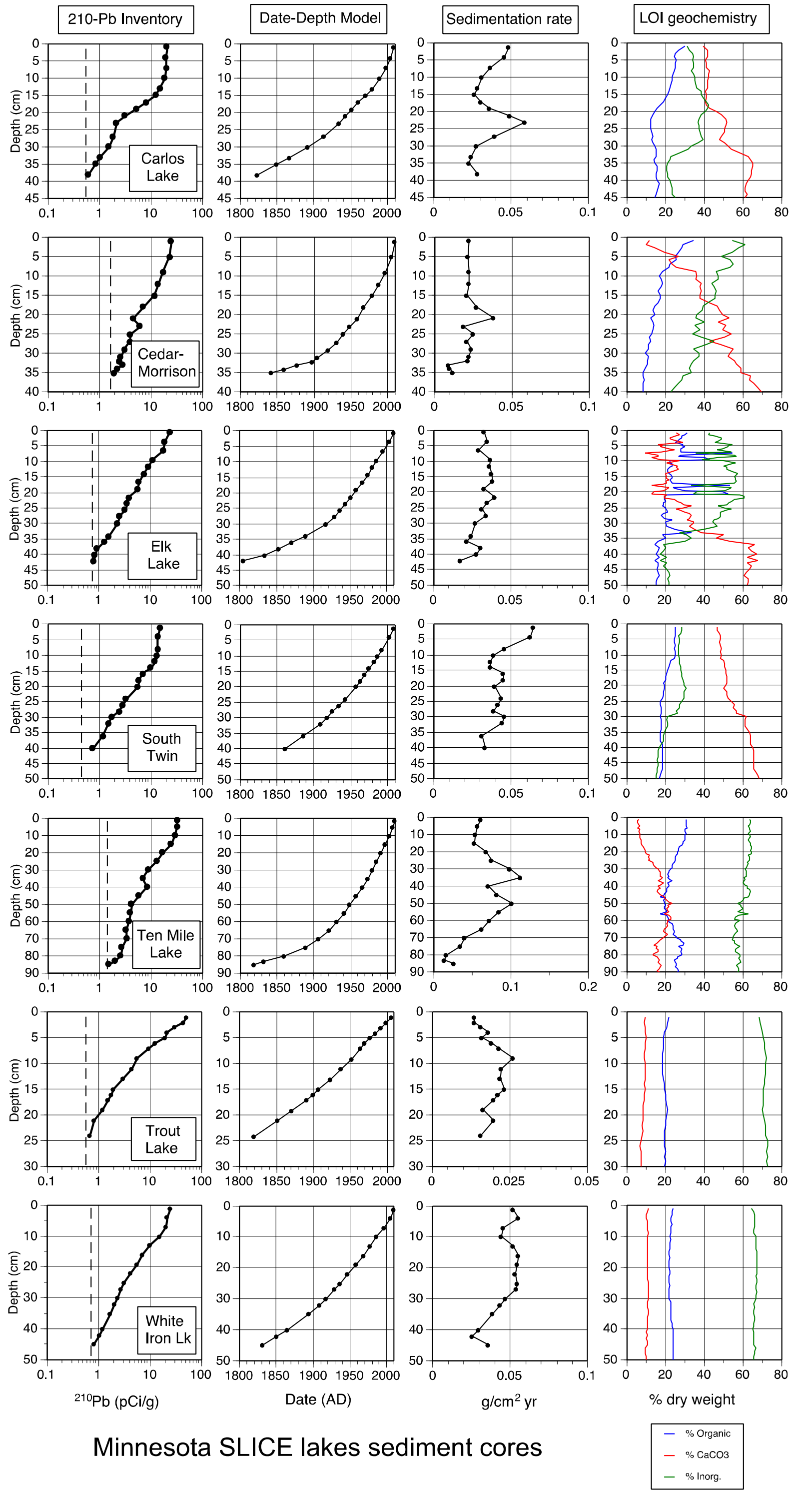

Fig. 2.1. Pb-210 inventory (pCi/g), date-depth model, sedimentation rate (g/cm^{2}yr), and percent composition of organics, carbonates, and inorganics for seven deepwater SLICE lakes.

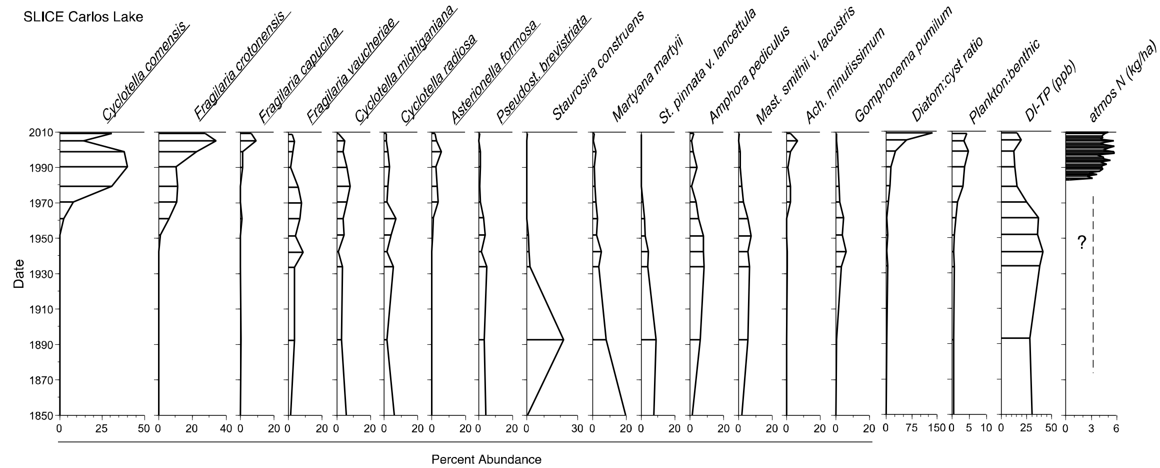

Fig. 2.2. Carlos Lake sediment core. Diatom biostratigraphy (species found at >5% relative abundance in one sample, planktonic species underlined), diatom:chrysophyte cyst ratio, plankton:benthic diatom ratio, diatom-inferred total phosphorus (TP) reconstruction (DI-TP in ppb), and atmospheric deposition rates of inorganic N at Camp Ripley NADP site.

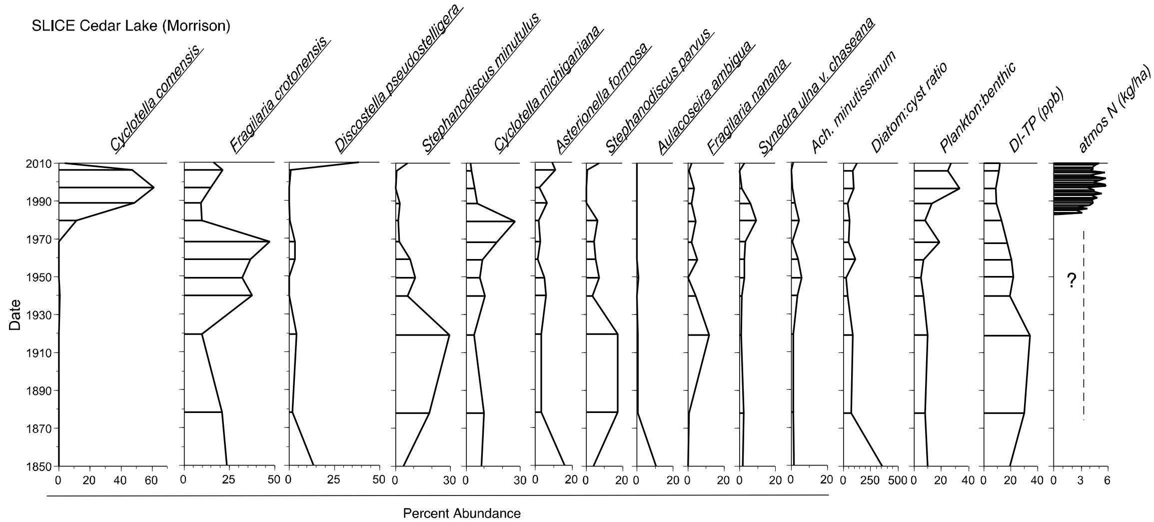

Fig. 2.3. Cedar Lake sediment core. Diatom biostratigraphy (species found at >5% relative abundance in one sample, planktonic species underlined), diatom:chrysophyte cyst ratio, plankton:benthic diatom ratio, diatom-inferred total phosphorus (TP) reconstruction (DI-TP in ppb), and atmospheric deposition rates of inorganic N at Camp Ripley NADP site.

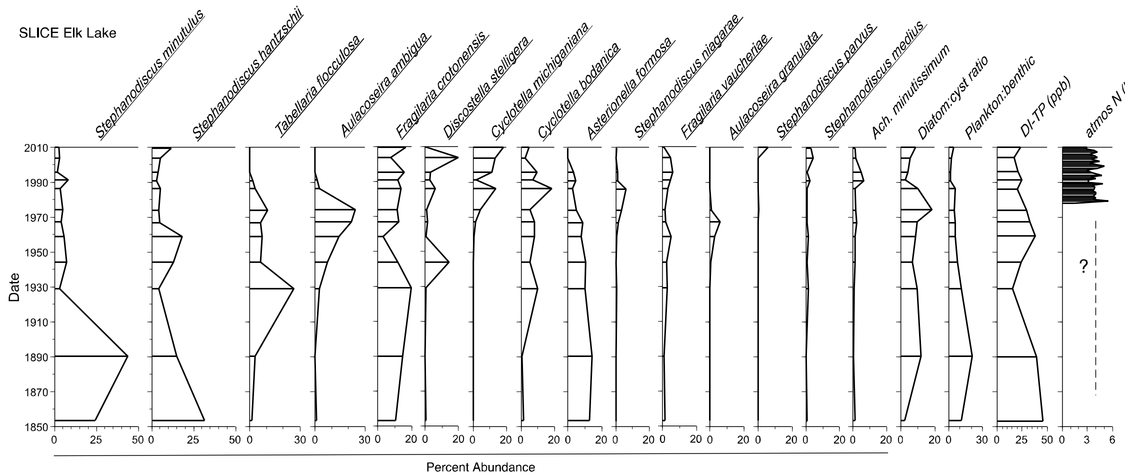

Fig. 2.4. Elk Lake sediment core. Diatom biostratigraphy (species found at >5% relative abundance in one sample, planktonic species underlined), diatom:chrysophyte cyst ratio, plankton:benthic diatom ratio, diatom-inferred total phosphorus (TP) reconstruction (DI-TP in ppb), and atmospheric deposition rates of inorganic N at Marcell NADP site.

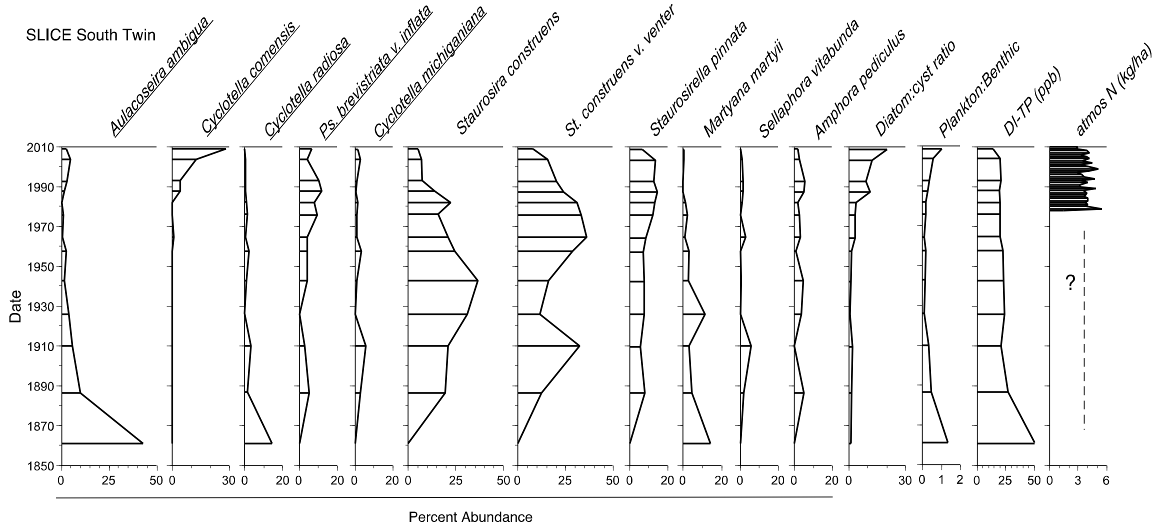

Fig. 2.5. South Twin Lake sediment core. Diatom biostratigraphy (species found at >5% relative abundance in one sample, planktonic species underlined), diatom:chrysophyte cyst ratio, plankton:benthic diatom ratio, diatom-inferred total phosphorus (TP) reconstruction (DI-TP in ppb), and atmospheric deposition rates of inorganic N at Marcell NADP site.

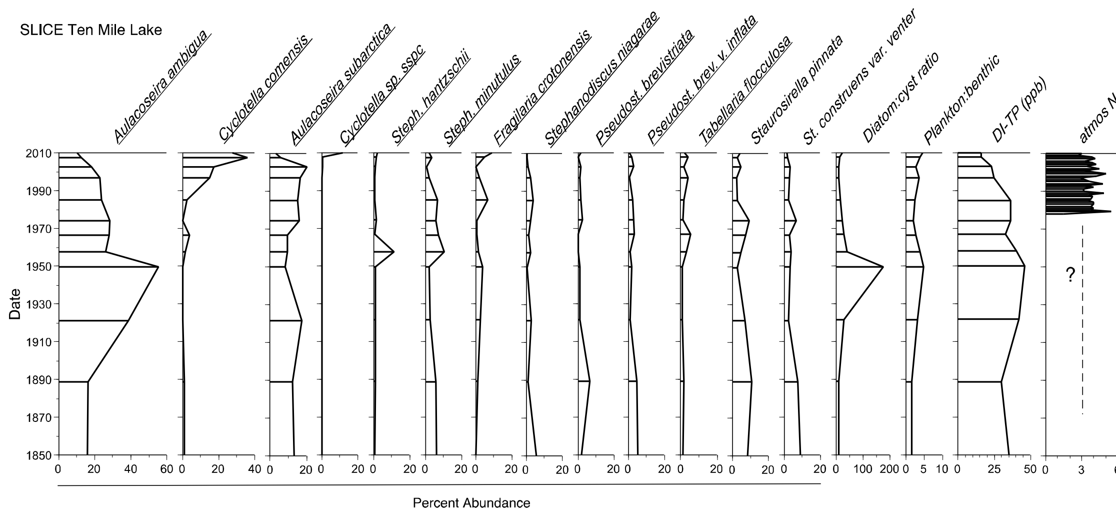

Fig. 2.6. Ten Mile Lake sediment core. Diatom biostratigraphy (species found at >5% relative abundance in one sample, planktonic species underlined), diatom:chrysophyte cyst ratio, plankton:benthic diatom ratio, diatom-inferred total phosphorus (TP) reconstruction (DI-TP in ppb), and atmospheric deposition rates of inorganic N at Marcell NADP site.

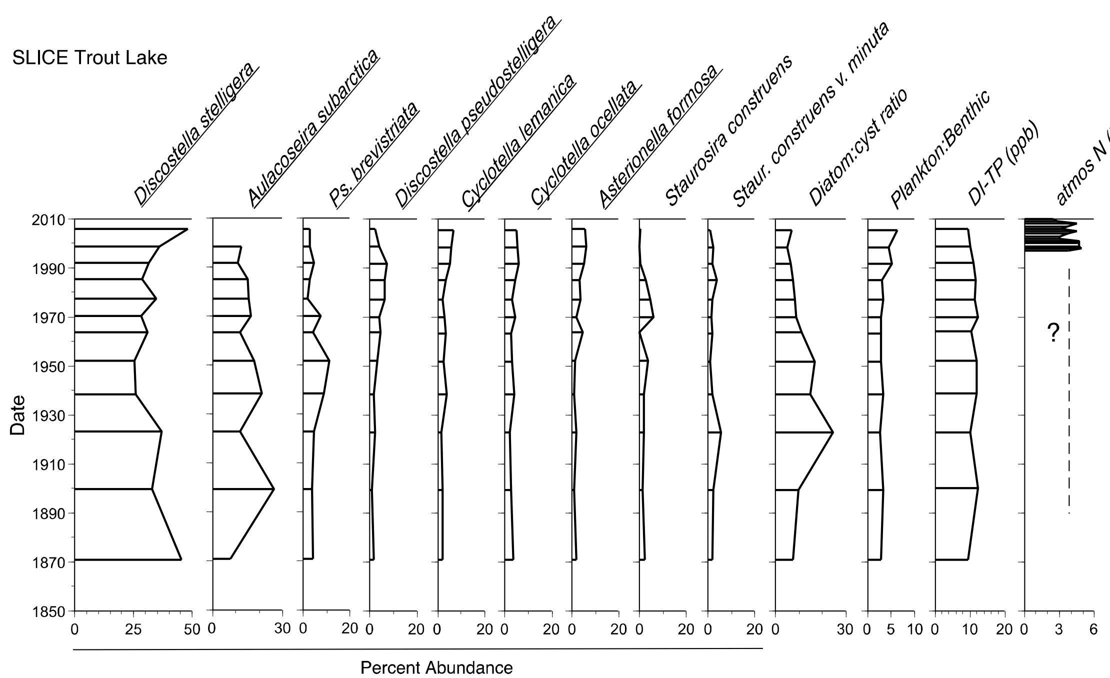

Fig. 2.7. Trout Lake sediment core. Diatom biostratigraphy (species found at >5% relative abundance in one sample, planktonic species underlined), diatom:chrysophyte cyst ratio, plankton:benthic diatom ratio, diatom-inferred total phosphorus (TP) reconstruction (DI-TP in ppb), and atmospheric deposition rates of inorganic N at Hovland NADP site.

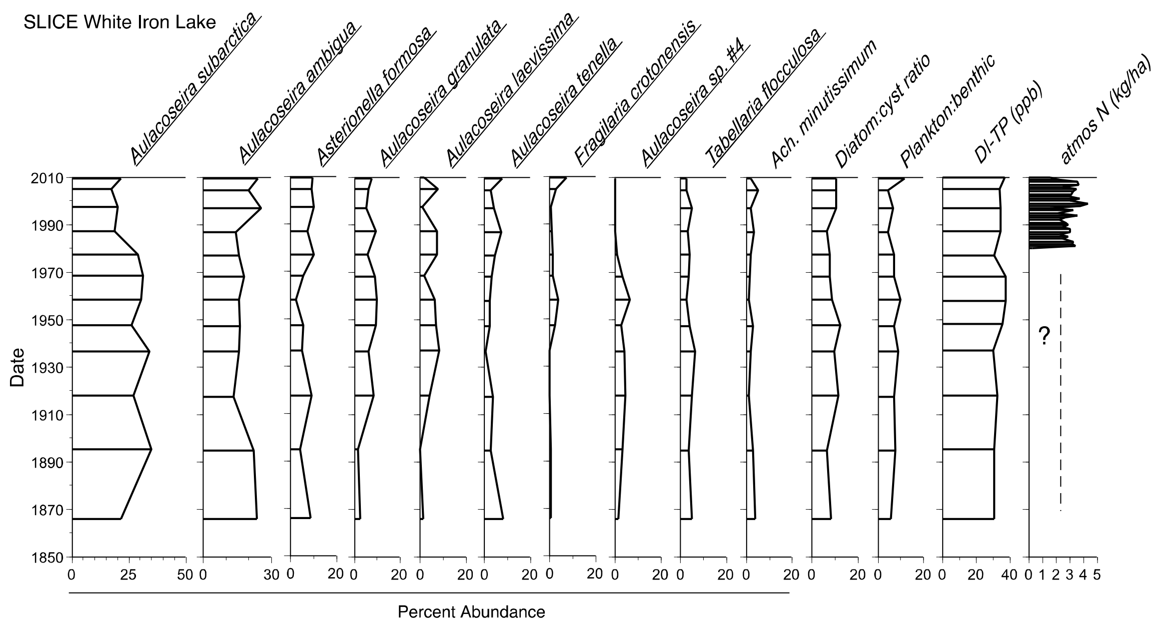

Fig. 2.8. White Iron Lake sediment core. Diatom biostratigraphy (species found at >5% relative abundance in one sample, planktonic species underlined), diatom:chrysophyte cyst ratio, plankton:benthic diatom ratio, diatom-inferred total phosphorus (TP) reconstruction (DI-TP in ppb), and atmospheric deposition rates of inorganic N at Fernberg Road NADP site.

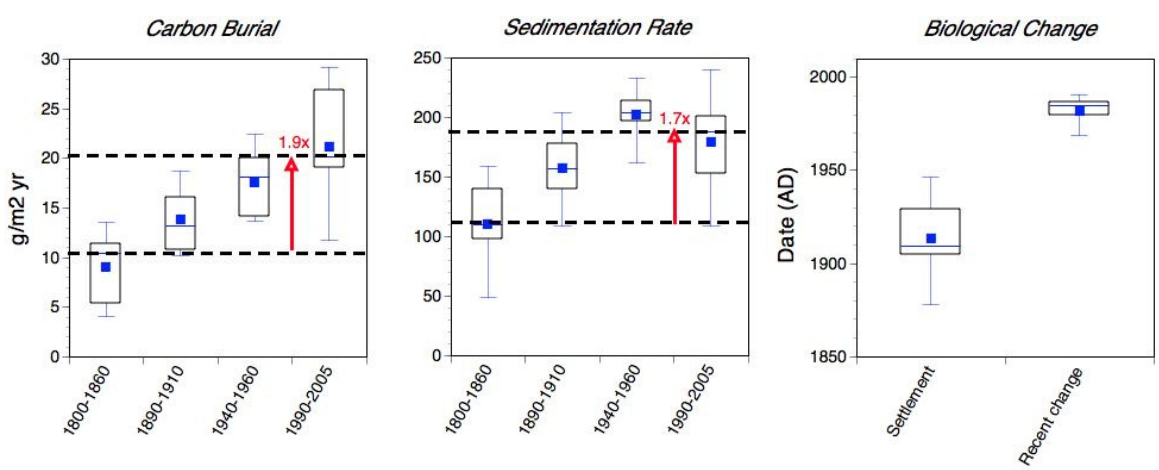

Fig. 2.9. Box plots of carbon burial and sedimentation rates during four time periods (presettlement 1800-1860, 1890-1910, 1940-1960, 1990-2005) (left panel) and timing of biological changes associated with Euroamerican settlement and the period of recent change in seven SLICE lakes.