A PALEOLIMNOLOGICAL STUDY OF BARTLETT LAKE, KOOCHICHING COUNTY, MINNESOTA

Joy M. Ramstack Hobbs, Mark B. Edlund, Adam J. Heathcote, and Daniel R. Engstrom

St. Croix Watershed Research Station, Science Museum of Minnesota, 16910 152nd Street North Marine on St. Croix, MN 55047; jramstack@smm.org; medlund@smm.org; 651-433-5953

Final Report Submitted to:

Denise Oakes
Minnesota Pollution Control Agency, Detroit Lakes Office, 714 Lake Avenue, Suite 220, Detroit Lakes, MN 56501; denise.oakes@state.mn.us

Recommended citation: Ramstack Hobbs, J.M., M.B. Edlund, A.J. Heathcote, and D.R. Engstrom. 2017. A paleolimnological study of Bartlett Lake, Koochiching County, Minnesota. Final report submitted to the Minnesota Pollution Control Agency. St. Croix Watershed Research Station, Science Museum of Minnesota, Marine on St. Croix, Minnesota, 55047.

wq-iw5-17n

TABLE OF CONTENTS

TABLES

FIGURES

SUMMARY

1. Paleolimnological techniques were used to reconstruct the trophic and sedimentation history of Bartlett Lake in Koochiching County, Minnesota.

2. Four piston cores were collected throughout the basin in August 2015. Lead-210 activity was analyzed on two of the cores to develop dating models and determine the sediment accumulation rate over the past 150-200 years. Sediments were analyzed for inorganic, organic, and carbonate components using loss-on-ignition (LOI) analysis; features in the LOI profiles were used to align all four cores. Geochemical analyses also included total sediment phosphorus (P), P fractions and biogenic silica. Subfossil diatoms in the sediments were analyzed to reconstruct changes in lake ecology and trophic state. In addition to diatoms, algal pigments were measured to determine historical changes in other algal groups.

3. The sedimentation rate in the lake began to increase in the late 1800s, and has continued to rise since that time. The sedimentation patterns were similar in both the east and west sides of the basin, and the sedimentation rate in recent years is approximately five times higher than it was pre-settlement.

4. Analysis of P fractions and inventory throughout the basin suggested that a high proportion of exchangeable and labile P fractions are present and available for internal loading in Bartlett Lake. The current P budget for Bartlett Lake suggests that as much as 75% of P may be from internal loading. Much of this internal load represents legacy phosphorus that is mobile in the sediments and still available for exchange with the water column. However, there is a substantial portion of the legacy P that is being removed from the lake through burial in the sediments, in spite of Bartlett's lack of a significant surface outlet.

5. The largest shift in the diatom community assemblage occurred in the 1970s/80s, coincident with the closing of a local creamery (1974), construction of a new sanitary sewer (1979), and development of a settling pond for street runoff; since that time the assemblage has been dominated by planktonic species that are indicative of nutrient enrichment, shallow polymictic lakes, and eutrophic conditions.

6. Diatom-inferred total phosphorus (TP) suggested that Bartlett Lake was in the mesotrophic range from the mid-1800s through the mid-1900s; the lake moved into the eutrophic range in the 1960s/70s and has remained eutrophic through 2015.

7. Pigments associated with cyanobacterial groups began to slowly rise in the early1900s, peaked in the early 1980s, and then decreased or leveled off in recent decades.

8. The most significant external load of P to Bartlett Lake was strongly curtailed when the creamery on the southwest side of the lake closed in 1974 and a new sanitary sewer system eliminated discharge directly to the lake. Monitoring records from the mid-1970s showed the lake to be hypereutrophic based on TP and chlorophyll levels. The water quality of the lake has rebounded slowly since that time. A decrease in concentration of cyanobacterial pigments coincided with the closing of the creamery and new sanitary sewer; however other indicators such as diatoms, monitoring, and P fractions in the core suggest continued impairment. Results suggest that Bartlett Lake continues to be impaired due to the legacy effects of prior nutrient loading.

INTRODUCTION

Lakes are a prominent feature and a valued resource within the landscape of the glaciated regions of the Upper Midwest. Land and resource use in the watersheds over the past several hundred years, including logging, agriculture, and urban development, have raised concerns over the current state of lakes in this region as well as the best management strategy for the future. Knowledge of the state of a particular lake prior to European settlement, as well as an understanding of the timing and magnitude of historical ecological changes, are critical components of an effective management plan.

A basic understanding of natural fluctuations within the system is important for any lake management plan. Reliable long-term data sets, on the order of 30 - 50 years, are generally not available for most regions of the country. Through the use of paleolimnological techniques and quantitative environmental reconstruction, we can estimate past conditions, natural variability, timing of changes, and determine rates of change and recovery. This information allows managers and researchers to put present environmental stresses into perspective with the natural variability of the ecosystem. It can also be used to identify response to, and recovery from, short-term disturbances. In this project, paleolimnological techniques were used to reconstruct the trophic and sedimentation history of Bartlett Lake in Koochiching County, Minnesota.

The primary aim of this project was to use paleolimnological and sediment techniques to reconstruct the nutrient and algal history, temporal and spatial trends in sedimentation, and the distribution and availability of phosphorus within the sediments of Bartlett Lake. Results provide a history of ecological changes that have occurred in the lake during the last 150 years, and form the foundation for developing a nutrient and lake management strategy.

Four cores were collected from the lake basin to fully characterize the sediment depositional environment and current distribution of sediment phosphorus in the lake. Two cores were fully dated using radioisotopes; all cores had loss-on-ignition analyses run to allow alignment among cores, followed by analysis of sediment phosphorus in all cores. A single core from the lake's central basin was further subjected to diatom, fossil pigment, and biogenic silica analysis to assess whole lake algal response histories.

Diatom remains were used to model changes in water column total phosphorus (TP). Diatoms quite often make up the main type of algae in a lake and therefore changes in diatom community structure are symptomatic of algal changes in response to water quality. Multivariate analyses, diatom-based transfer functions, and comparison of diatom assemblages with an 89 Minnesota lake data set were used to relate changes in trophic conditions and diatom communities to human impacts in the local watershed. Diatoms have been widely used to interpret environmental conditions in lakes (Dixit and Smol 1994). Many species are sensitive to specific water conditions and are useful as bioindicators. Over the past 25 years, statistical methods have been developed to estimate quantitative environmental parameters such as historical lake TP from diatom assemblages. These methods are statistically robust and ecologically sound (Birks 1998). They have been used successfully in reconstructing a wide variety of environmental parameters including pH, total phosphorus (TP), and salinity (e.g. Fritz et al. 1991, 1999; Hall and Smol 1992; Ramstack et al. 2003). In the state of Minnesota, diatom analysis has been used as one line of evidence for developing lake nutrient criteria (Heiskary and Wilson 2008), lake-specific nutrient standards (Edlund and Ramstack 2007), and prioritizing management actions (Edlund et al. 2008).

In addition, changes in algal productivity and nutrient availability were characterized using additional biogeochemical analyses of the cores. Biogenic silica concentration and flux were

measured in the central basin core to determine historical levels of diatom production; diatoms readily respond to historical nutrient additions (Edlund et al. 2009). While diatoms are an important component of the lake algae, other groups of algae can be ecologically important in eutrophic and hypertrophic lakes (e.g. blue-green algae). The primary pigments (chlorophylls, carotenoids, and their derivatives) of lake algae are often reliably preserved in lake sediments over time (Leavitt and Hodgson, 2001). The concentration of these pigments is directly proportional to the abundance of each algal group and were measured in the central basin core to document historical abundance and community shifts in Bartlett Lake algae. Whereas the relative percent change in diatom communities is an effective measure of water quality over time (using diatom-inferred TP), whole lake algal changes can inform us about the absolute changes in algal production and the historical presence of nuisance algae, such as blue-green algae.

The burial efficiency and behavior of phosphorus (P) in sediments are critical for understanding how a lake will respond to nutrient reductions. Lakes that experience excess loading of P can lose it in one of two ways. It can leave via outflow or get permanently buried in the sediments. For lakes with low linear sedimentation rates and/or long residence times, the ability to bury P is key to lake recovery from excess nutrient loading. We estimated pre-European and modern rates of P burial, inventoried the active pool of P (total and exchangeable/labile forms) that is involved in internal loading, and compared these data against current loading estimates to Bartlett Lake.

Study Area

Bartlett Lake is located just outside of the town of Northome, Minnesota. The lake surface area is over 300 acres (121 hectares) and reaches a maximum depth of about 16 feet (4.9 m). The lake has a long history of environmental stress that has resulted in frequent cyanobacterial blooms and winter fish kills. Although current loadings of phosphorus to the lake have been strongly curtailed (currently most unnatural sources are limited to some storm drainage and a few lake homes), the lake still suffers from extremely high P levels and poor water quality, with Secchi readings often less than 1 m and water column TP values approaching hypereutrophic levels. Historical loading of nutrients likely occurred from several lumber mills (Engelking, McCarthy, Plummer, and McLinn mills) along the E and N shore, a creamery that was located on Bartlett's SW shoreline and in operation from 1916 to 1974 (Albrecht and Thomas 1977), street sewers that flowed to the lake, and a sanitary sewer system that delivered primary treated sewage (Imhoff tank) directly to Bartlett Lake from 1915-1979 (Minnesota Department of Health 1952, MPCA 1982). Although the P loading from the creamery and sewer ended over 40 years ago when the creamery ceased operation and a new sanitary sewer constructed in 1979 directed wastewater to stabilization ponds that discharged to Caldwell Creek (MPCA 1982), legacy effects through internal loading may be continuing to impact this resource.

Current concern for the lake centers on its impaired status because it does not meet current State standards for shallow lakes in the Northern Lakes and Forests (NLF) ecoregion (30 ppb TP). There is some evidence that water quality has improved in Bartlett Lake. Water quality measurements from the 1976-1978 had mean TP values of 122 µg/L; by 2002 mean TP had dropped to 62 µg/L, and recent years (2014, 2015) have had mean TP of 31 µg/L and 38 µg/L, respectively, but still above current nutrient criteria (MPCA 2017). These impairments and a known history of excess nutrient loadings have led to questions of how the productivity of Bartlett Lake has changed over time, what the natural or historical condition of the lake was, what the current trajectory of the lake is given some improvement since the 1970s, and how to best set management goals for this valued regional resource.

METHODS - SEDIMENT CORING

Four piston cores were collected from Bartlett Lake on August 19, 2015 using a drive-rod piston corer equipped with a 6.5 cm diameter polycarbonate barrel (Wright 1991). The cores were collected from widely-spaced locations throughout the basin to determine the spatial distribution of P in this multi-basin lake (Table 1, Figure 1). Core 1 was collected in a flat and deep area in the center of the lake; this central location provided an integrated sample of diatom community structure for the lake as a whole, and was therefore designated as the primary core for focused analyses.

Table 1 details the coring location, water depth, and recovery for each of the cores. The sediment material in each of the cores was soft and required immediate sectioning in the field. Between 40 and 50 cm were sectioned off the top of each core in the field (cores 1 and 6 in 2-cm increments and cores 4 and 5 in 1-cm increments). The soft material and the necessity of field-sectioning meant that the cores were not suitable for magnetics logging. Core sections and remaining cores were returned to the laboratory for continued sectioning and were stored at 4°C.

METHODS - AERIAL PHOTOS

Aerial photos from the 1940s through the present were used to examine changes to Bartlett Lake and its watershed. Available aerial photos were downloaded from the University of Minnesota John R. Borchert Map Library's Historical Aerial Photographs Online collection (https://www.lib.umn.edu/apps/mhapo/; July 2017).

METHODS - LEAD-210 DATING

Lead-210 was measured in cores 1 and 6 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). In cores 1 and 6, 16 or 17 core sections were analyzed for lead-210 activity to determine age and sediment accumulation rate for the past 150 years.

METHODS - GEOCHEMISTRY

Loss on Ignition
Weighed subsamples were taken from regular intervals throughout each core (cores 1, 4, 5, and 6) for loss-on-ignition (LOI) analysis to determine bulk and dry density and dry weight percent of organic, carbonate, and inorganic matter. Sediment subsamples were heated at 105°C 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). Features in the loss-on-ignition profiles provided markers for aligning the four cores.

Biogenic Silica
Biogenic silica (BSi), a proxy for historical diatom and chrysophyte algal productivity, was measured using 15 weighed subsamples (30 mg) from core 1. The samples were digested for BSi analysis using 40 ml of 1% (w/v) Na_2CO_3 solution heated at 85°C in a reciprocating water bath for five hours (DeMaster 1979, Conley and Schelske 2001). A 0.5 g aliquot of supernatant was removed from each sample at 3, 4, and 5 hr. After cooling and neutralization with 4.5 g of 0.021N HCl solution, dissolved silica was measured colorimetrically on a Unity Scientific SmartChem 170 discrete analyzer as molybdate reactive silica (SmartChem 2012a).

Sediment Phosphorus
Sediment phosphorus fractions were analyzed for 19 increments from each of the four cores following the sequential extraction procedures in Engstrom (2005), Engstrom and Wright (1984), Psenner and Puckso (1988), and Kopácek et al. (2005). Extracts were analyzed colorimetrically on a Unity Scientific SmartChem 170 discrete analyzer using methods described by SmartChem (2012b). In addition to TP in cores, sediment P fractions were measured; this included the refractory forms *Mineral-bound P*, *Recalcitrant Organic-P*, *Al-bound P* and the labile or readily exchangeable forms of *Fe-bound*, *labile Organic-P*, and *loosely-bound P*.

To characterize the spatial distribution of P in the lake, TP sediment flux was calculated for the two lead-210 dated cores (1 and 6), taking into account the correction for focusing by lead-210. TP burial was calculated for cores 1 and 6 for the recent time interval of 1995-2005, which was determined to be below the portion of the core that is affected by diagenesis and upward diffusion, and a pre-settlement interval (1850-1910). Inventories of TP and labile P were calculated for the upper 10 cm of all four cores; labile P was defined as the sum of the readily exchangeable forms (Fe-bound, labile Organic-P, and loosely-bound P). These values represent the pool of surface-sediment P that contributes to internal loading; the labile-P pool is a lower estimate and the TP pool is an upper estimate. Whole-basin values for P-burial and surface-sediment inventories were also calculated using the lake surface area.

METHODS - DIATOM AND NUMERICAL ANALYSES

Fifteen samples from core 1 were analyzed for diatoms. Diatom and chrysophyte cysts were prepared 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 an 85°C water bath. After cooling, the samples were rinsed with distilled deionized water to remove oxidation biproducts. Aliquots of the remaining material, containing the diatoms, were dried onto 22x22 mm #1 coverglasses, which were then permanently attached to microscope slides using Zrax mounting medium. Diatoms were identified along random transects to the lowest taxonomic level under 1250X magnification with oil immersion optics. A minimum of 400 valves was counted in each sample. Abundances are reported as percent abundance relative to total diatom counts. Identification of diatoms used regional floras (e.g. Patrick and Reimer 1966, 1975; Camburn and Charles 2000) and primary literature to achieve consistent taxonomy.

A stratigraphy of predominant diatoms (species with greater than or equal to 5% relative abundance in one or more core depths) was plotted against core date. Relationships among diatom communities within the sediment core were explored using the unconstrained ordination method of Non-Metric Multidimensional Scaling (NMDS) in the software package R (R Core Development Team 2012). Core depths/dates were plotted in ordinate space and their relationships and variability used to identify periods of change, sample groups, and ecological variability among core samples. A general rule for interpreting an NMDS biplot is that samples that plot closer to one another have more similar diatom assemblages. Diatom community relationships were also explored using a constrained cluster analysis, using the CONISS method with Euclidean distance. Significant breaks in the constrained cluster analysis were evaluated using a broken stick model.

Downcore diatom communities were also used to reconstruct historical epilimnetic total phosphorus levels. A transfer function for reconstructing historical logTP was developed earlier based on the relationship between modern diatom communities and modern environmental variables in 89 Minnesota lakes (Ramstack et al. 2003, Edlund and Ramstack 2006) using

7

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 was 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. Data are presented as both logTP values and as backtransformed values, to TP in µg/l.

METHODS - ALGAL PIGMENT ANALYSIS

Algal pigment analyses were performed on 15 subsamples from core 1. Carotenoids, chlorophylls, and derivatives were extracted (acetone:methanol:water, 80:15:5 at 4°C, dark, N_2) from freeze-dried sediments according to Leavitt et al. (1989), measured on a Hewlett-Packard model 1050 high performance liquid chromatography system, and are reported relative to total organic carbon (TOC; Hall et al. 1999).

RESULTS AND DISCUSSION - AERIAL PHOTOS

Aerial photographs from 1940, 1972, 1980, and 1988 showed very little variation in Bartlett Lake shoreline, watershed characteristics, or lake features (Figure 2). There were no significant changes in the lake level in these historic photos, and alterations to the surrounding land were minimal. There does appear to be some loss of macrophyte beds after 1980.

RESULTS AND DISCUSSION - DATING AND SEDIMENTATION

Core 1 - The unsupported lead-210 activity, the resulting lead-210 dating model, and the sediment accumulation rate for core 1 are shown in Figure 3a-c. In core 1, the lead-210 activity declined throughout the core, and reached background levels at approximately 81 cm (Figure 3a). The sedimentation rate was lowest in the early to mid-1800s, with an average rate of 0.014 g/cm^2 yr (Figure 3c). The rate began a slow rise in the late 1800s, which continued to the core top. The average sedimentation rate from 1994-2015 was 0.047 g/cm^2 yr, over three times the average rate in the early 1800s.

Core 6 - The unsupported lead-210 activity, the resulting lead-210 dating model, and the sediment accumulation rate for core 6 are shown in Figure 4a-c. In core 6, the lead-210 activity declined throughout the core; background levels were reached at approximately 106 cm, slightly deeper than in core 1 (Figure 4a). The sedimentation rate in core 6 was comparable to that of core 1 in the early to mid-1800s (average of 0.013 g/cm^2 yr); and as in core 1, the rate began a steady increase in the late 1800s, which continued to the core top (Figure 4c). The average sedimentation rate from 2009 to 2015 was 0.067 g/cm^2 yr, over five times the average rate in the early 1800s. It is also notable that the sedimentation rate at the core 6 site, which was nearer the creamery and sewer outflows, had a greater increase in sedimentation than core 1 between 1920 and 1970.

RESULTS AND DISCUSSION - GEOCHEMISTRY

Loss on Ignition

Features in the loss-on-ignition profiles provided markers for aligning the four cores (Figure 5). Carbonate content was low (12% or less) in all four cores. The most significant features, which

were used for alignment, were the switches between the percent of organic and inorganic matter. In each of the four cores, the percentage of organic and inorganic matter fluctuated between 35% and 57% throughout the length of the cores. The uppermost feature used for alignment was when the percentage of organic and inorganic matter were equal at 24 cm in core 1, 28 cm in core 4, 27 cm in core 5, and 34 cm in core 6 (Figure 5); this date on this feature was 1998 in core 1 and 1995 in core 6. The second feature used for alignment was when organic and inorganic matter percentages were equal again at 69 cm in core 1, 75 cm in core 4, 74 cm in core 5, and 90 cm in core 6 (Figure 5); the date on this second feature was 1885 in core 1 and 1886 in core 6. The very close match in dates on these features in the dated cores allowed for confidence in aligning all four cores.

For the two cores that were lead-210 dated (1 and 6), the flux of sediment to the core was calculated by multiplying the fraction of each component of the sediment (organic, carbonate, inorganic) by the sedimentation rate at that interval (Figure 6). These dry mass accumulation rates (DMAR) showed that the rise in sedimentation rate that began in the late 1800s consisted of slightly higher amounts of inorganic matter than organic matter; this was true until the 1980s/90s. In both cores, that pattern has switched in recent years, with more organic matter being delivered to the core site in the last decade.

The fact that the profiles were so similar in both cores 1 and 6 demonstrates that sedimentation patterns have been very similar in the east and west side of the basin, even though the rate of accumulation has been slightly higher in the western core 6 site (Figure 4c).

Biogenic Silica

The weight percent of biogenic silica in core 1 fluctuated between about 3 and 5% from the mid-1800s to the early 2000s (Figure 7). In recent years (2006-2015), there has been a rise in the weight percent of BSi in the core, reaching over 8% at the core top. The silica flux to the core site showed an initial rise in the mid-1900s and then a large increase in recent years. This suggests that diatom/chrysophyte algal productivity was contributing to the increased organic matter flux over the last decade.

Sediment Phosphorus

The concentration of P in each of the cores showed a general increase in P over time, with peaks at the top of each core (Figure 8). There are slight increases in the labile or readily exchangeable forms of P (Fe-bound, labile Organic-P, and loosely-bound P) at the top of each of the cores.

For the cores that were lead-210 dated (1 and 6) the TP flux was calculated, and corrected for focusing by lead-210 (Figure 9a). The TP flux for these two cores was almost identical, suggesting that TP flux was uniform over these two areas of the basin.

TP concentration and iron-bound P concentration were plotted together for all four cores (Figure 9b and c). These plots for the four cores are again nearly identical, lending support to the conclusion that P has historically been distributed equally throughout the Bartlett Lake basin, and not preferentially deposited in the western basins near historic point sources. Both of these plots showed an exponential increase in P concentrations in all four cores over the most recent ten years (0-15 or 20 cm); this increase can likely be attributed in a large part to sediment diagenesis and mobility.

P burial and inventory calculations were made for the cores, as well as basin-wide extrapolations. Basin-wide extrapolations, simply calculated using the lake surface area, were valid because results showed that P was distributed evenly throughout the basin. The term burial was used

for calculations made below the diagenetic peak; this is where it was assumed that P has been permanently buried in the sediments, and is no longer available for resuspension and exchange with the water column. Inventory refers to calculations made in the upper 10 cm of the sediments; these values represent the pool of surface-sediment P that can contribute to internal loading.

TP burial was calculated for cores 1 and 6 over two time periods (Figure 10a). Recent TP burial was calculated from 1995-2002; this time interval is just below the diagenetic increase shown in Figure 9b and c, and should therefore represent permanent burial. TP burial was also calculated from 1850-1910, representing a period prior to European settlement. During both time periods, the burial rates in cores 1 and 6 are nearly the same, indicating that burial is about the same in the east and west sides of the basin. The recent TP burial rate was about 0.38 g/m^2/yr, and was approximately five times higher than the pre-settlement rate (0.08 g/m^2/yr).

The TP inventory, as well as the labile P inventory (sum of Fe-bound, labile Organic-P, and loosely-bound P) was calculated for all four cores (Figure 10b). The values in each category were nearly the same for all four cores, again suggesting that P is evenly distributed throughout the basin. The TP inventory averages 5.5 g/m^2, and the labile P inventory averages 2.5 g/m^2. These values represent the pool of surface-sediment P that can contribute to internal loading; the labile pool is a lower estimate and the TP pool is an upper estimate.

Lakewide TP burial was calculated to have been 95 kg/yr during the pre-settlement period (1850-1910), and 450 kg/yr from 1995-2005, representing nearly five times the pre-settlement rate (Figure 10c). Lakewide TP and labile P inventory were calculated for the surface sediments (0-10cm) (Figure 10d); this showed that nearly 6,500 kg of TP, including 3,000 kg of labile P are currently in the lake and could potentially contribute to internal loading (again, the labile pool is a lower estimate and the TP pool is an upper estimate).

The modern phosphorus load allocation for Bartlett Lake is 465 kg P/yr; this is divided among external inputs of 115 kg P/yr (watershed inputs of 78 kg P/yr and atmospheric inputs of 37 kg P/yr), and unaccounted or what is assumed to be internal sources of 350 kg P/yr (Denise Oakes, MPCA, pers. comm.). If we use the lakewide active pool of P as bounded at the low end by 3,000 kg labile or exchangeable P and at the high end by 6,500 kg total P combined with a burial rate of 450 kg/yr, we can project the future of the active pool of P in Bartlett Lake sediments by estimating the depletion in the active pool given an annual loss of 450 kg/yr to burial and the added external inputs to the lake of 115 kg p/yr. At the low end, the lake will reach a new steady state having depleted its legacy load of labile P by 2025, and at the high end of the active pool (total P) it will take until 2035 to finally deplete that legacy pool of total P. The burial rate of P in Bartlett Lake is very high compared to current load allocations and is an effective means of depleting P from the lake. However, it should be noted that it has already taken 40+ years to bury the 60+ years of high P loading that occurred from milling, creamery, and sewer along the shores of Bartlett Lake.

RESULTS AND DISCUSSION - DIATOM STRATIGRAPHY AND ORDINATION

The ordination biplot from the NMDS showed how the core samples clustered based on similarity of diatom assemblage (Figure 11). The samples from 1848 to 1930 clustered tightly together; this indicated that there was little change in the diatom community during that time. Samples from 1942 to 1974 showed some change along axes 1 and 2. The biggest change in the diatom community assemblage came between 1974 and 1983; samples from 1983 to 2015 clustered near each other.

The stratigraphic diagram showed the predominant diatoms that were driving the shifts in the community assemblages, as well as the results of the constrained cluster analysis, and the percentage of plankton throughout the core (Figure 12). From the mid-1800s until the 1970s, Bartlett Lake was dominated by tychoplanktonic species, primarily *Staurosira construens* and *Staurosira construens* var. *venter*. These species are primarily benthic, but are often swept-up and suspended into the water column; many of these species are adapted to live on fine-grained sediments, such as those found in shallow lakes. These species are also considered generalists and are found in a variety of water quality conditions. Beginning in the 1940s/50s there was a slow rise in *Stephanodiscus minutulus*, which reached a peak in the 1970s; this small planktonic species is indicative of nutrient enrichment. The largest shift in the diatom community occurs in the late 1970s/early 1980s. The shift was characterized by a decline in the relative abundance of the tychoplanktonic *Staurosira* species and a sharp rise in the planktonic *Aulacoseira* species. *Aulacoseira ambigua* and *A. granulata* are characteristic of nutrient-rich, turbid, wind-swept conditions.

The constrained cluster analysis showed that the largest shift in the diatom community assemblage was between 1974 and 1983; this shift was significant when evaluated against a broken stick model (Figure 12). This change coincided with the shift from primarily tychoplanktonic to planktonic species. The average percent plankton was 13% before the shift and 50% after.

The significant shift in the diatom community assemblage coincides with the closing of the creamery in 1974 and the construction of the new sewage ponds in 1979. Although the diatoms indicative of nutrient enrichment generally increased after the external point source P inputs were ended, it could be that the diatoms responded to a shift in P load. When the creamery closed and sewage was redirected, the dominant P load in the lake would have shifted from a continuous external load of P to primarily a seasonal internal load from sediment diffusion and resuspension. This would have changed the seasonality of the P inputs to the water column (with internal loading of P being most severe in the summer months), and the diatoms shifted from primarily generalist species living in a year-round cyanobacterial soup, to species adapted to living in eutrophic, polymictic shallow lakes.

RESULTS AND DISCUSSION - PHOSPHORUS RECONSTRUCTION

In order for a diatom-inferred total phosphorus (TP) reconstruction to be meaningful, changes in the diatom community assemblage over time must be primarily driven by changes in TP concentrations, as opposed to other factors that could drive community change such as pH, light penetration, and habitat availability. One way to evaluate TP as a driver of change is to project the core sections on the MN calibration set (the model used to reconstruct TP) to determine if changes in the diatom assemblage in the core correlate with the TP gradient in the model (Juggins et al. 2013).

Another way to evaluate the reconstruction is to determine the amount of variance in the diatom data that can be accounted for by the TP reconstruction. This can be calculated by the variance explained by the first axis of an ordination of the sediment assemblages constrained to diatom-inferred TP, divided by the variation explained by an unconstrained ordination of the sediment assemblages (λ_r / λ_p). A maximum λ_r / λ_p value of 1.0 would mean that TP was the best explanatory variable of diatom community change (Juggins et al. 2013).

When passively plotted on the MN calibration set, the Bartlett Lake core showed movement along the TP gradient (associated with axis 1); however, there was also change along axis 2 (Figure 13). This suggests that while nutrients may have been driving some of the change in Bartlett Lake,

there are other drivers that are equally important in influencing diatom community turnover. Alternative drivers include: habitat alterations, changes in turbidity due to sediment load, or other stressors that were not measured in the calibration set. It is possible that the drivers of ecological shifts change over time, meaning that TP may have been a more important variable during certain periods and less important during others.

The fraction of the maximum explainable variation in the diatom data that can be explained by TP (λ_r / λ_p) was 0.97. This suggests that TP was an important driver of change in the diatom community in Bartlett Lake, and therefore it is valid to infer TP from the diatom assemblage.

The diatom-inferred TP reconstruction suggested that Bartlett Lake was in the mesotrophic range from the mid-1800s through the mid-1900s (Figure 14; Table 2), with pre-European TP levels estimated at 20 µg/l. TP levels began to slowly rise, and the lake became eutrophic in the 1950s/60s. Diatom-inferred TP reached its peak in the early 1980s at 50 µg/l before dropping slightly (39-48 µg/l) in the last few decades. Diatom-inferred TP in 2015 was 48 µg/l. This matches closely with the measured TP in the lake, which averaged 38 µg/l over the growing season in 2015 (MPCA 2017).

The extremely high monitored levels of TP from the 1970s (1976-1978 mean 122 µg TP/L) were not matched in our diatom reconstruction. While our model does perform well in certain lake types up to 90 µg/l, it will not reconstruct extremely hypereutrophic lake conditions (>100 µg TP/L), because at these high levels of TP, diatom community turnover is no longer responding to P but to other nutrients, habitat, or lake conditions. In Bartlett Lake, the diatom model clearly shows a rapid increase in lake trophic status following settlement and the start of nutrient inputs to the lake, a peak in lake productivity in the 1970s/80s, and a slight decline in the last few decades with modern diatom-inferred TP closely matching recent monitoring records.

RESULTS AND DISCUSSION - HISTORICAL ALGAL COMMUNITIES

Total algal production, as measured by beta-carotene and chlorophyll *a*, showed that overall production began to slowly rise in the early 1900s and reached a peak in the early 1980s; then, with the exception of the uppermost sample, total algal production has declined in recent decades (Figure 15). The cyanobacteria (blue-green algae) showed this same pattern. The peak concentration of cyanobacterial pigments coincided with the closing of the creamery and shift in sanitary sewage to the new stabilization ponds in 1979, and then declined in recent decades. However, the pigments associated with diatoms did not show the same decline in recent decades, and the diatoms generally showed continued high concentrations after the early 1980s.

Cyanobacteria have been present in Bartlett Lake since the early 1800s, although the pigments were much lower in concentration. Pigments associated with nitrogen-fixing forms (canthaxanthin and aphanizophyll) and potentially toxic forms (myxoxanthophyll) were present throughout the core, and all increased in concentration in the early to mid-1900s.

In general, the cyanobacteria tracked the timing of the operation of the creamery and primary sanitary sewage discharge to the lake. It is likely that this algal group was responding to the continuous P load from the creamery and sewage with constant year-round growth, and then decreased in abundance after the creamery closed and sewage was redirected in the 1970s. The diatoms were able to shift their community and grow in abundance after the point source P loads from the creamery and sewer ceased, and the lake began to function more typical of a heavily eutrophic, polymictic shallow lake. It's likely that the cyanobacteria were suppressing the planktonic diatoms prior to the 1970s, and that the diatoms were able to take advantage of a change in P source in Bartlett Lake, from an external load to primarily a seasonal internal load.

Pigments of purple-sulfur bacteria (okenone) first showed up in the 1920s, peaked in the 1970s/80s, and have declined in recent decades. Purple sulfur bacteria are indicative of anoxic bottom water conditions, and are often present when the lake has thick macrophyte beds. The decline in recent decades could indicate a loss of macrophyte beds in the lake, which appears to have occurred in localize areas of the lake after the 1980s based on aerial photos. Alternatively, under point source loading the lake may have had long periods of deepwater anoxia that permitted the growth of photosynthetic purple-sulfur bacteria.

CONCLUSIONS

Although external P loading to Bartlett Lake has been strongly curtailed, most notably with the closing of the creamery in 1974 and redirection of sewage away from the lake to stabilization ponds in 1979, the condition of the lake has not fully rebounded, and instead the lake has been on a trajectory of slowly improving water quality. Since the 1970s, cyanobacterial groups have decreased or leveled off. However numerous other indicators, including measured TP in the water column, measured P fractions in the core, diatom-inferred TP, and a diatom species assemblage indicative of eutrophication, all suggest continued impairment of the lake.

Diatom-inferred TP showed that phosphorus concentrations in the lake began to rise in the early to mid-1900s, and reached a peak in the early 1980s. Given what we know about land use history in the watershed, this was likely due to an external TP load from the creamery (1916-1974) and primary treated sanitary sewage (1915-1979). Diatom-inferred TP dropped slightly but has remained in the eutrophic range after the creamery ceased operation in 1974 and sewage was redirected in 1979, and recent diatom-inferred values closely matched recent measured water column TP (38 μg/l in 2015). Since we know that the significant external P load has decreased, the continued impairment to the lake has likely been due to internal loading of legacy TP.

The measured P fractions in the core, as well as burial and inventory calculations, support the conclusion that internal loading of P continues to affect the lake. All cores showed an increase in labile, or readily exchangeable, forms of P in the upper centimeters; these forms of P are readily available to organisms through diffusion from the lake bottom or as the sediment is resuspended. Since surface discharge from Bartlett Lake is very minimal, P will not be lost from the system until it is permanently buried in the sediments. Whole-lake inventories of total P and labile P in the active layer, as well as recent P burial rates, were estimated. Current P loads were 465 kg P/yr with over 75% of that load from internal loading, and recent P burial rates were estimated at 450 kg P/yr. Thus, burial is an effective long-term mechanism for removing P from Bartlett lake; after 40+ years since point sources were removed, Bartlett Lake is likely within 10-20 years of depleting the active legacy load.

Although the diatom record showed one small *Stephanodiscus* species that tracked the gradual nutrient enrichment of the lake through the mid-1900s, the large shift in the community, from primarily a benthic assemblage to an assemblage dominated by planktonic, eutrophic indicator diatoms did not occur until just after the creamery ceased operation (1974) and the new sanitary sewer was built (1979), and at the time that cyanobacteria decreased. This was likely due to the change in seasonality of nutrient inputs in this stressed system, which arose from the switch from external year-round point sources to primarily an internal load of P. Internal loading of P is generally more severe in the summertime, and it is likely that this shift in seasonality has favored planktonic diatoms over cyanobacteria.

It has been shown in shallow lakes, that the modern water quality of the lake can be defined by the legacy of large perturbations in the past (Ramstack Hobbs et al. 2016). The results suggest that Bartlett Lake has shifted from a mesotrophic lake with primarily benthic diatoms, to a

hypereutrophic lake dominated by cyanobacteria, to a eutrophic lake dominated by a planktonic diatom assemblage with a possible decline in macrophyte beds. Recently, the lake has been on a slow trajectory of improving water quality after the primary source of P was removed, but the current condition of the lake has been defined by the legacy effects of prior nutrient loading.

ACKNOWLEDGEMENTS

REFERENCES

Albrecht, L. and D. Thomas. 1977. Northome Gemmell Mizpah 1903-1976. Northome
    Bicentennial Book Committee. 204 pp.

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.

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

Birks, H.J.B. 1998. D.G. Frey & E.S. Deevey Review #1, Numerical tools in palaeolimnology –
    Progress, potentialities, and problems. Journal of Paleolimnology 20:307-332.

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.

Conley, D.J. and C.L. Schelske. 2001. Biogenic silica. In Smol, J.P., H.J.B. Birks, and W.M. Last,
    (eds.), Tracking Environmental Change Using Lake Sediments. Volume 3: Terrestrial, Algal,
    Siliceous Indicators. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp 281-293.

Dean, W.E. 1974. Determination of carbonate and organic matter in calcareous sediments
    and sedimentary rocks by loss on ignition: comparison with other methods. Journal of
    Sedimentary Research 44: 242-248.

DeMaster D.J. 1979. The marine budgets of silica and ^{32}Si. Ph.D. Dissertation, Yale University.

Dixit, S. S. and J.P. Smol. 1994. Diatoms as indicators in the Environmental Monitoring
    and Assessment Program-Surface Waters (EMAP-SW). Environmental Monitoring and
    Assessment 31:275-306.

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

Edlund, M.B., and J.M. Ramstack. 2007. Historical water quality and biological change in Peltier
    Lake, Anoka Co., MN. Final report submitted to Emmons and Olivier Resources, Inc. and the
    Rice Creek Watershed District, 19 pp.

Edlund, M.B., A.L.C. Shinneman, and J.R. Ramstack. 2008. Diatom-Inferred TP in MCWD
    Lakes. Phase II. Final Report to Minnehaha Creek Watershed District, Work Order #107-06.

Edlund, M.B., D.R. Engstrom, L. Triplett, B.M. Lafrancois, and P.R. Leavitt. 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

Engstrom, D.R. 2005. Long-term changes in iron and phosphorus sedimentation in Vadnais Lake, Minnesota, resulting from ferric chloride addition and hypolimnetic aeration. Lake and Reservoir Management 21:95-105.

Engstrom, D.R. and H.E. Wright, Jr. 1984. Chemical stratigraphy of lake sediments as a record of environmental change. In E.Y. Haworth (Ed.), Lake sediments and environmental history. Leicester University Press: 11-67.

Fritz, S.C., S. Juggins, R.W. Battarbee, and D.R. Engstrom. 1991. Reconstruction of past changes in salinity and climate using a diatom-based transfer function. Nature 352:706-708.

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

Hall, R.I and J.P. Smol. 1992. A weighted-averaging regression and calibration model for inferring total phosphorus concentration from diatoms in British Columbia (Canada) lakes. Freshwater Biology 27: 417-434.

Hall, R.I., P.R. Leavitt, R. Quinlan, A.S. Dixit, and J.P. Smol. 1999. Effects of agriculture, urbanization, climate on water quality in the northern Great Plains. Limnology and Oceanography 44:739-756.

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

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.

Juggins, S., N.J. Anderson, J.M. Ramstack Hobbs, and A. Heathcote. 2013. Reconstructing epilimnetic total phosphorus using diatoms: statistical and ecological constraints. Journal of Paleolimnology. DOI 10.1007/s10933-013-9678-x.

Kopácek, J., J. Borovec, J. Hejzlar, K.U. Ulrich, S.A. Norton, and A. Amirbahman. 2005. Aluminum control of phosphorus sorption by lake sediments. Environmental Science & Technology 39:8784-8789.

Leavitt, P.R., S.R. Carpenter, and J.F. Kitchell. 1989. Whole-lake experiments: The annual record of fossil pigments and zooplankton. Limnology and Oceanography 34:400-717.

Leavitt, P.R. and D.A. Hodgson. 2001. Sedimentary pigments. In: Smol JP, Birks HJB, Last WM (eds) Tracking environmental change using lake sediments. Terrestrial, algal, and siliceous indicators, vol 3. Kluwer, Dortrecht, pp 155–202.

Minnesota Department of Health. 1952. Census, Water Pollution Control. St. Paul, MN.

MPCA (Minnesota Pollution Control Agency). 1982. Wastewater Disposal Facilities Inventory, State of Minnesota. Minnesota Pollution Control Agency, St. Paul, MN, 81 pp.

MPCA (Minnesota Pollution Control Agency). 2017. https://cf.pca.state.mn.us/water/ watershedweb/wdip/waterunit.cfm?wid=36-0018-00

Patrick, R. and C.W. Reimer. 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 C.W. Reimer. 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.

Psenner, R. and R. Puckso. 1988. Phosphorus fractionation: Advantages and limits of the method for the study of sediment P origins and interactions. Archiv für Hydrobiologie 30:43-59.

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

Ramstack Hobbs, J.M., W.O. Hobbs, M.B. Edlund, K.D. Zimmer, K.M. Theissen, N. Hoidal, L.M. Domine, M.A. Hanson, B.R. Herwig, and J.B. Cotner. 2016. The legacy of large regime shifts in shallow lakes. Ecological Applications 26:2662-2676.

SmartChem. 2012a. SmartChem 170 Method SIL-001-A (Rev: May 2012). Silica in Water, Waste Water and Soil Extracts and Other Aqueous Samples, 0.1-20 mg SiO_2/L. Unity Scientific, 1117 Old State Road, Brookfield, CT 06804.

SmartChem. 2012b. SmartChem 170 & SmartChem 200 Method PHO-001-A (Rev: May 2012). Phosphorus, All Forms, Orthophosphate, Hydrolyzable, and Total in Water, Waste Water and Soil Extracts and Other Aqueous Samples. Unity Scientific, 1117 Old State Road, Brookfield, CT 06804.

Wright, H.E., Jr. 1991. Coring tips. Journal of Paleolimnology 6:37-49.

Table 1. Location of each core collected, water depth at core site, sediment recovered, and description of how each core was used.

Core	Lat (N)	Long (W)	Water Depth (m)	Recovery (m)	Description
Bartlett 1	47.87807	94.2634	3.9	1.52	Primary core Lead-210 dated
Bartlett 4	47.87708	94.26917	3.3	1.52	Used for analysis, not dated
Bartlett 5	47.87838	94.27359	2.7	1.32	Used for analysis, not dated
Bartlett 6	47.87600	94.27464	2.9	1.45	Lead-210 dated

Table 2. Diatom-inferred total phosphorus values for each core section.

Lead-210 Date	Diatom-Inferred TP µg/l
2015	48
2006	40
2000	45
1994	39
1983	50
1974	43
1962	33
1952	29
1942	26
1930	23
1916	20
1901	19
1885	19
1866	20
1848	20

Figure 1. Bathymetric map of Bartlett Lake (water depth in feet); coring locations are in red.

Figure 2. Historical aerial photographs of Bartlett Lake.

1940
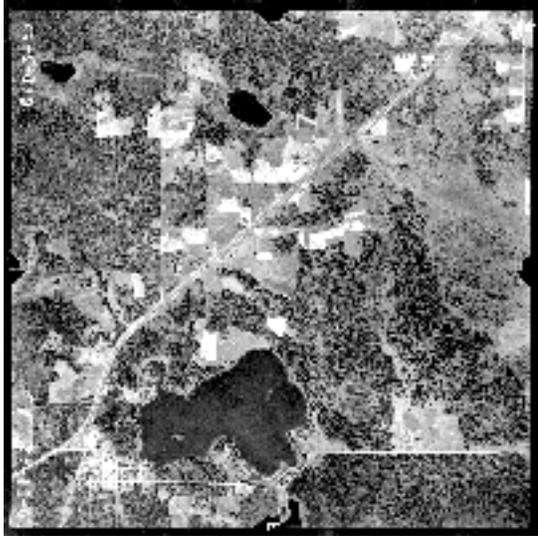
1972
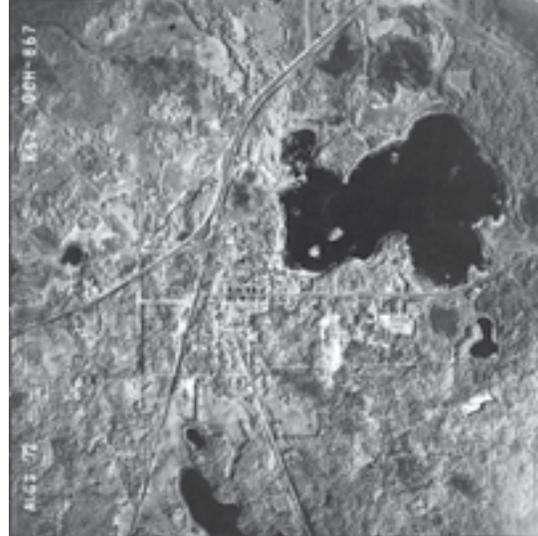
1980
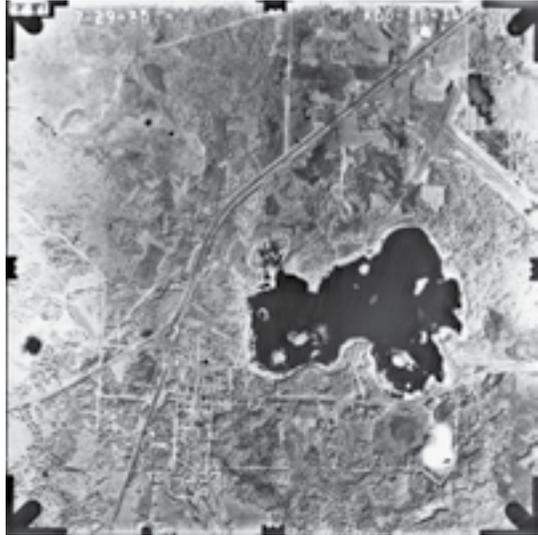
1988
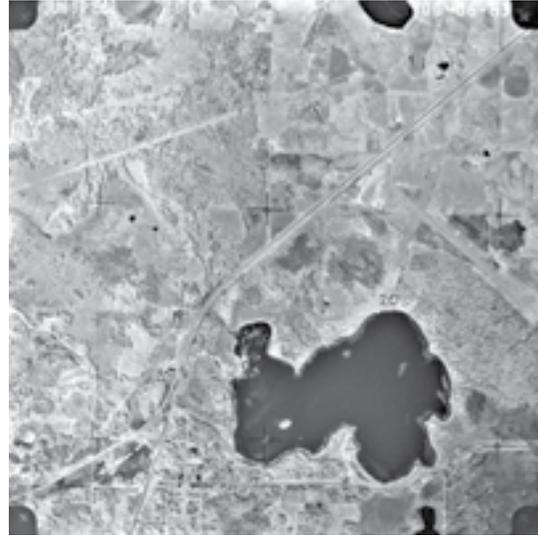
Figure 3. Unsupported lead-210 activity (a), lead-210 dating model (b), and sediment accumulation rate (c) for Bartlett Lake Core 1.

a)

b)

c)
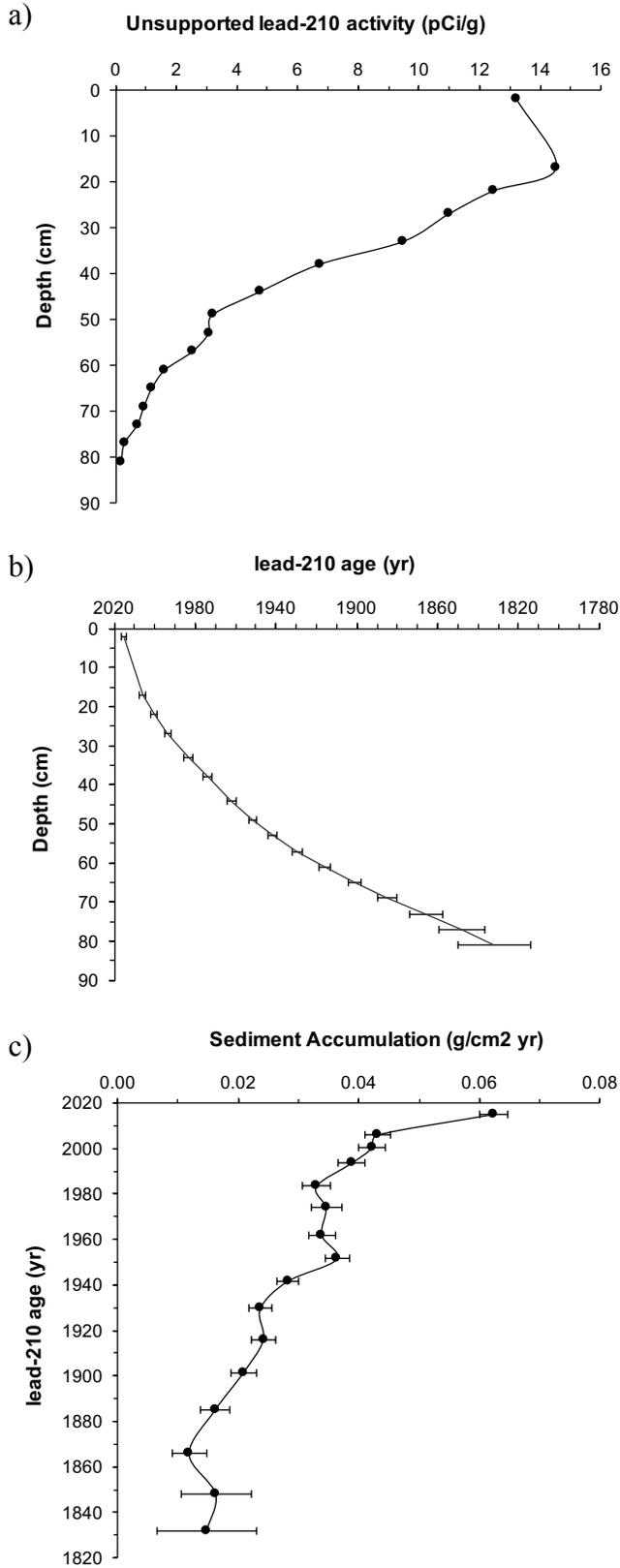
Figure 4. Unsupported lead-210 activity (a), lead-210 dating model (b), and sediment accumulation rate (c) for Bartlett Lake Core 6.

a)

Unsupported lead-210 activity (pCi/g)

b)

lead-210 age (yr)

c)

Sediment Accumulation (g/cm2 yr)
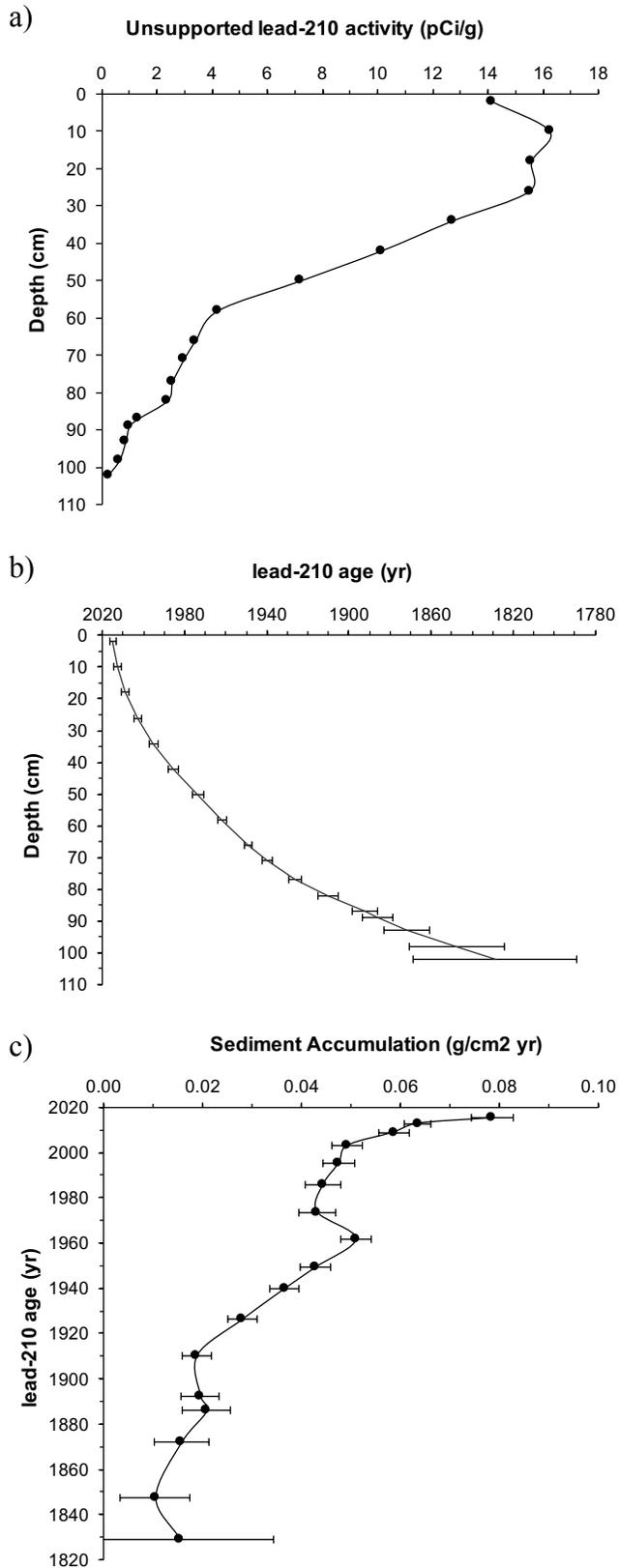
Figure 5. Percent dry weight of organic matter, inorganic matter, and carbonate (CaCO3) in each of the four cores plotted against depth in the sediment. Lines denote features that were used to align the cores.

Dry Weight Percent
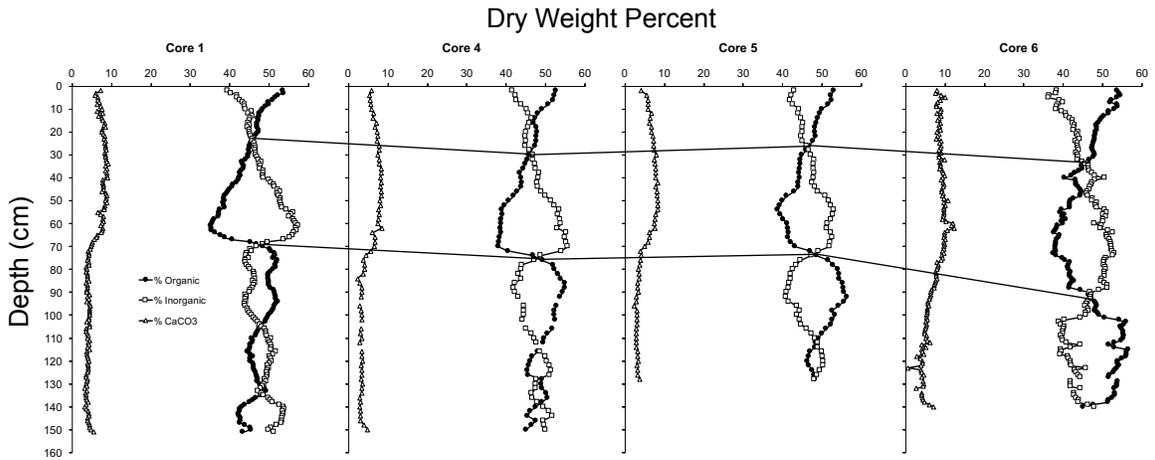
Figure 6. Dry mass accumulation rates (DMAR) of organic matter, inorganic matter, and carbonate (CaCO3) to cores 1 and 6. DMAR was only calculated for the length of the core within the lead-210 record (0-81 cm in core 1; 0-102 cm in core 6).
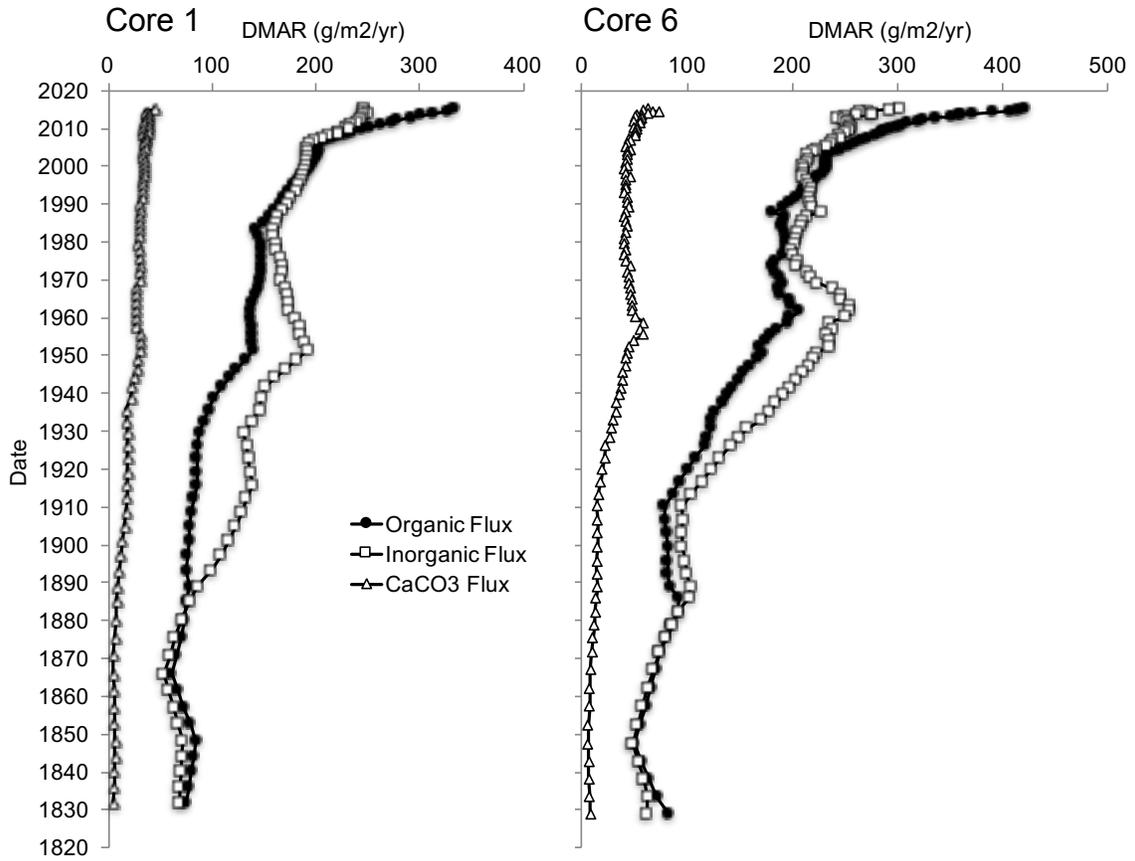
Figure 7. Weight percent of biogenic silica (BSi) (a) and SiO2 flux (b) in core 1, plotted against lead-210 date.

Wt % BSi

Flux SiO2
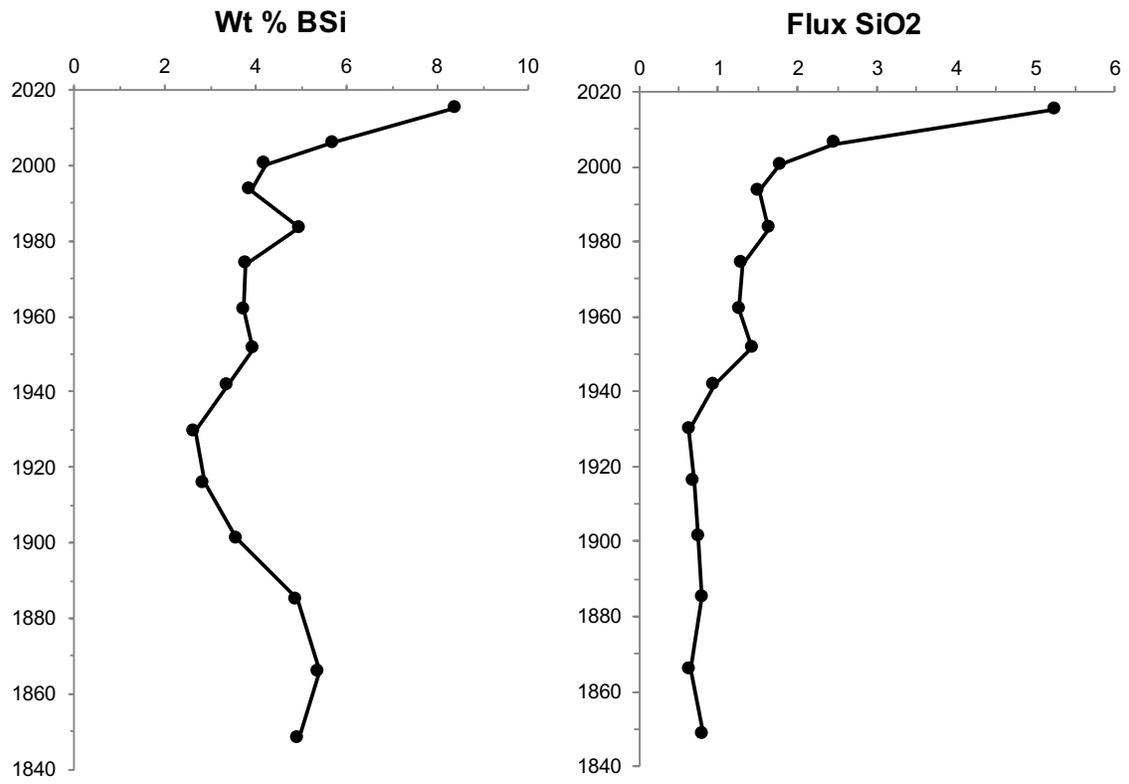
Figure 8. Concentration of phosphorus fractions in each of the four cores.
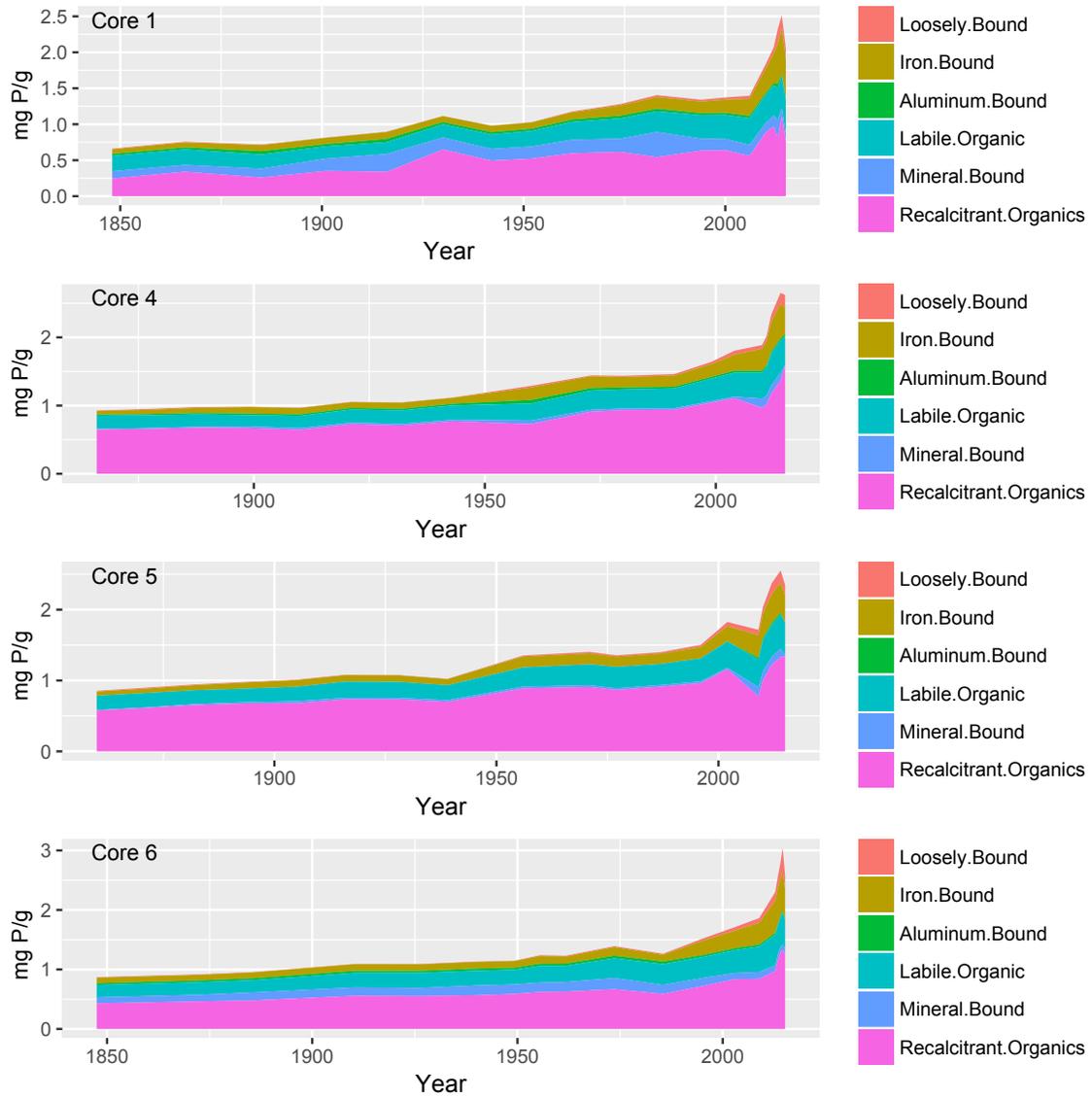
Figure 9. a) Total P flux, corrected for lead-210 focusing, to cores 1 and 6; b) TP concentration in each of the four cores; c) Iron-bound P concentration in each of the four cores. Yellow shading indicates the most recent ten years (from the core top to 15 or 20 cm depth), which is likely the pool that contributes to internal loading.
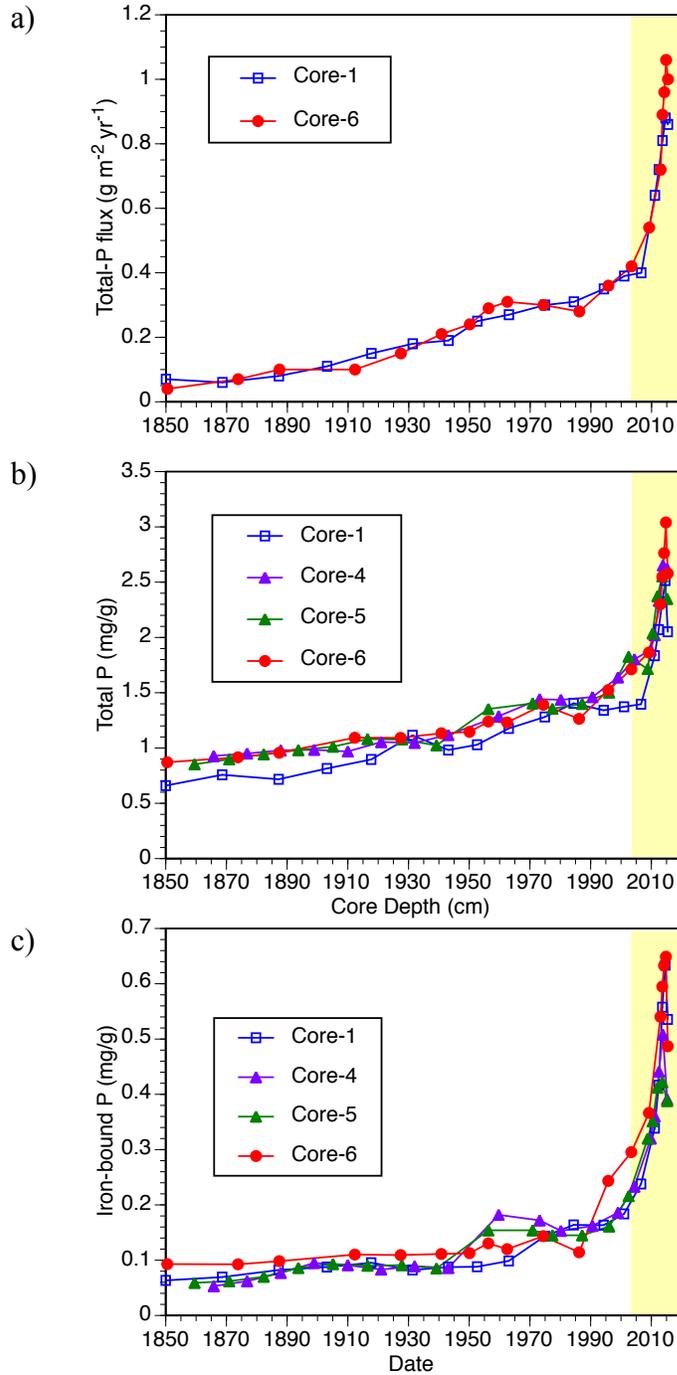
Figure 10. Estimates of P burial and inventory. a) Presettlement and modern rates of TP burial for cores 1 and 6; b) TP and labile TP inventory for the top 10 cm of all four cores; c) Lakewide presettlement and modern rates of TP burial; d) Lakewide TP and labile TP inventory (0-10 cm).
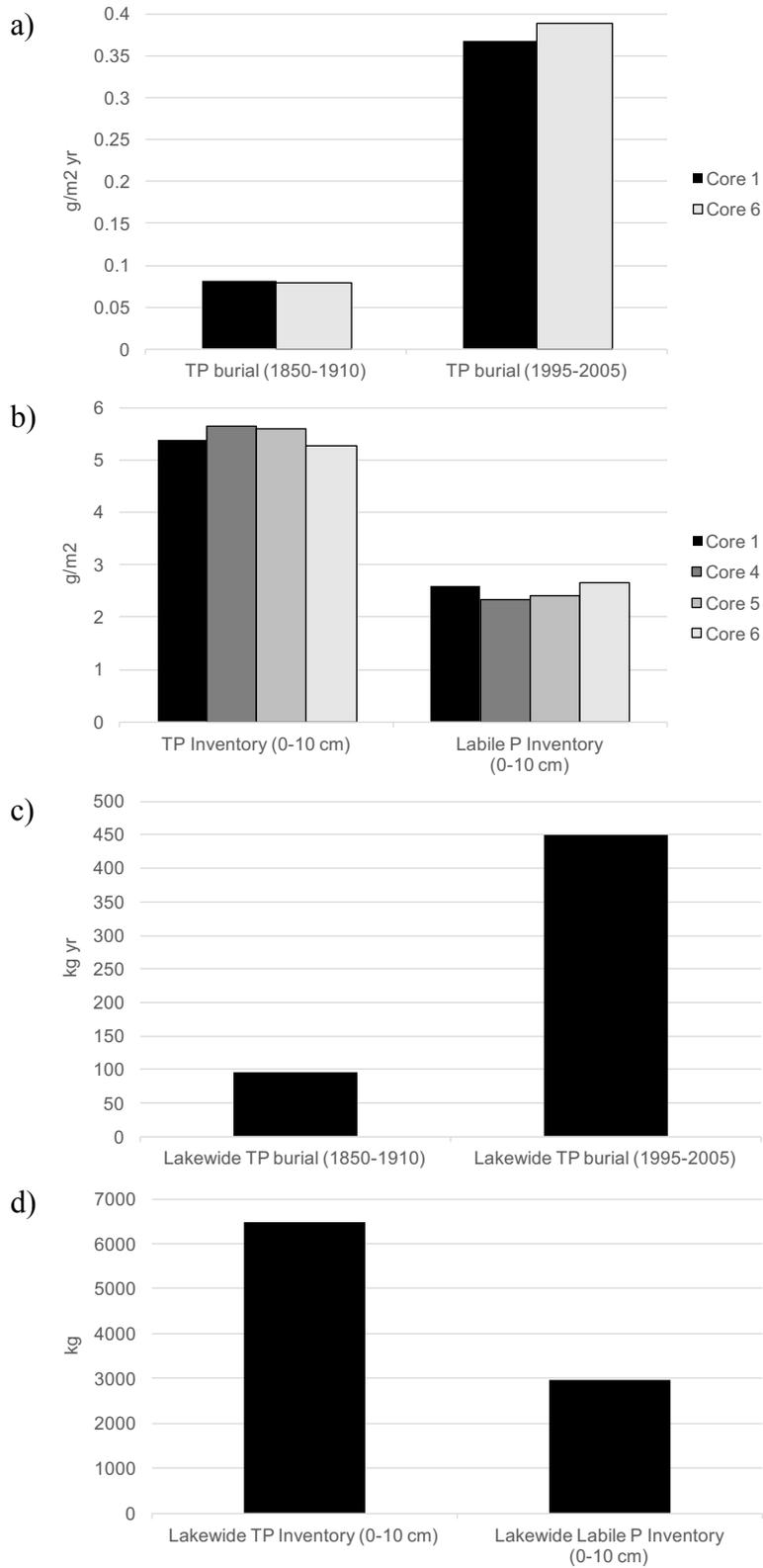
Figure 11. Non-Metric Multidimensional Scaling (NMDS) biplot of diatom communities from Bartlett Lake (1848-2015).
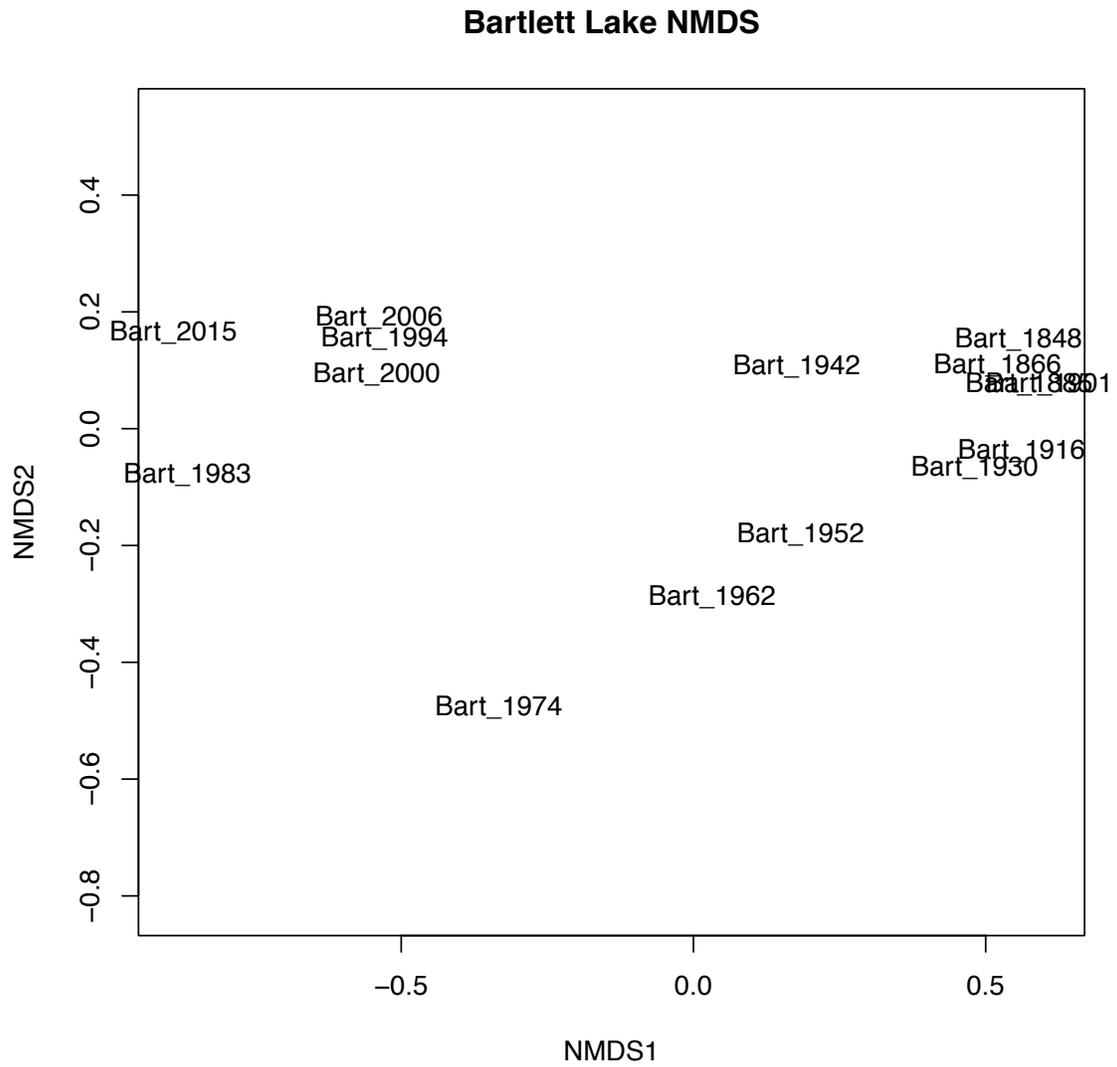
Bartlett Lake NMDS

Figure 12. Downcore stratigraphy for predominant diatom taxa (greater than or equal to 5% relative abundance), results of a constrained cluster analysis, and percent plankton in Bartlett Lake (1848-2015). The red horizontal line denotes a significant break in the constrained cluster analysis.
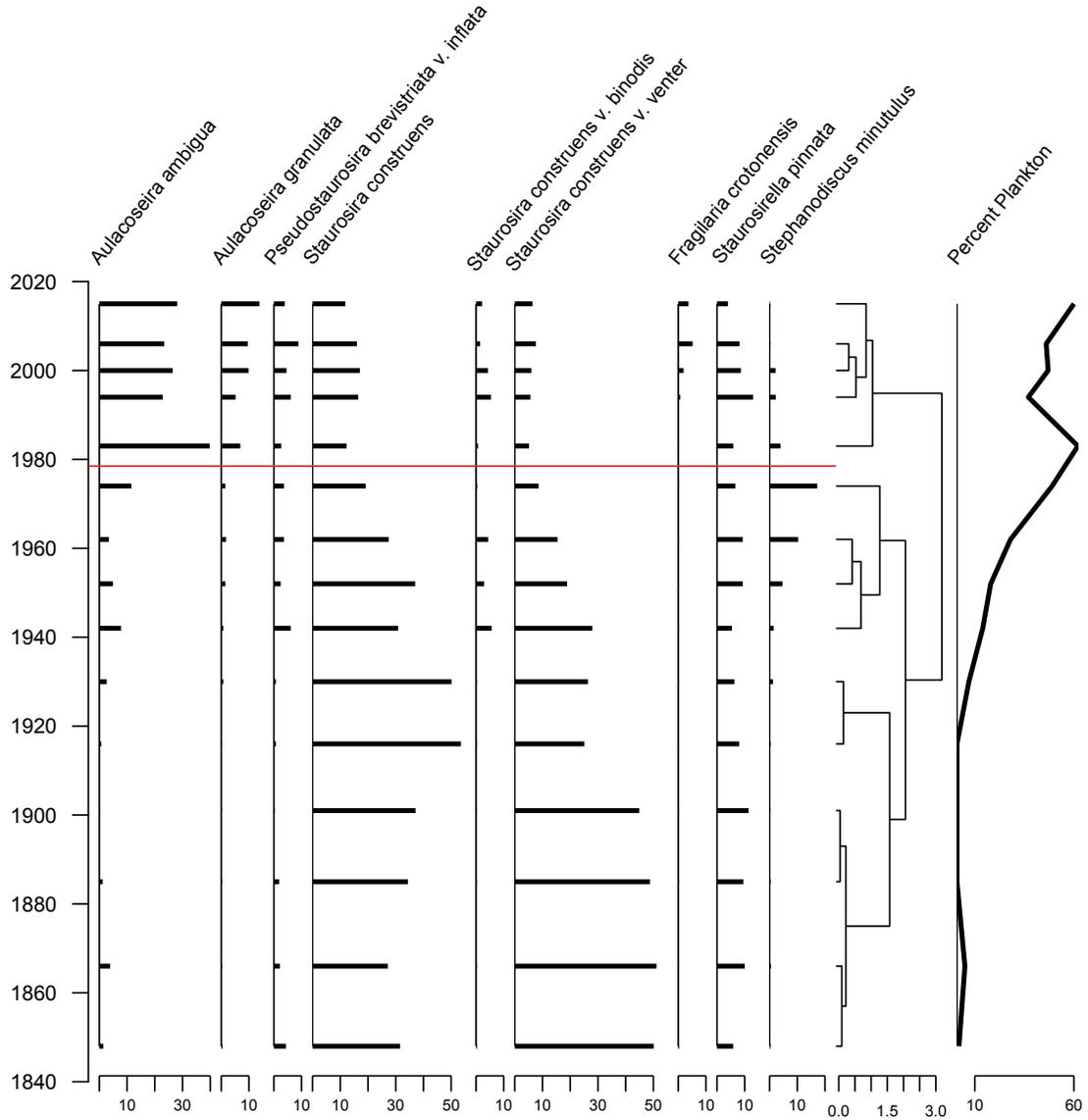
Figure 13. The core sections from Bartlett Lake projected onto the MN calibration set (denoted as "Bart_core date"). Symbols represent the 89 MN lakes in the calibration set, coded by region; NLF=Northern Lakes and Forests, CHF=Central Hardwood Forests, Metro=Twin Cities Metropolitan Area, WCP=Western Corn Belt Plains, NGP=Northern Great Plains, and MCWD=Minnehaha Creek Watershed Distric. Environmental vectors are shown on the inset plot. Note that logTP is strongly correlated with Axis 1.

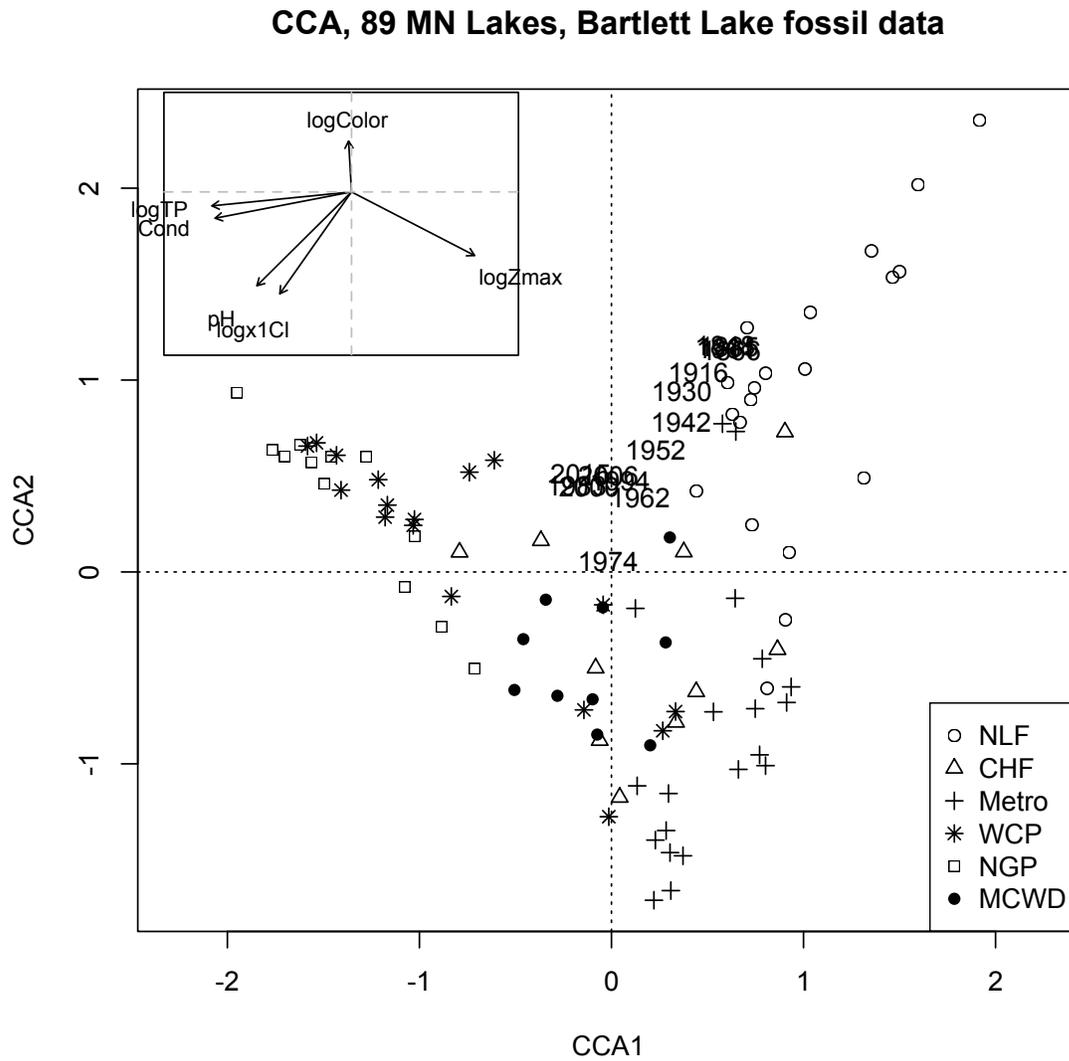
CCA, 89 MN Lakes, Bartlett Lake fossil data

Figure 14. Diatom-inferred total phosphorus (TP) reconstruction for Bartlett Lake.
Reconstruction is shown as log TP (left panel) and as backtransformed values in micrograms per
liter (right panel). Error estimates on log TP are plus and minus the root mean square error of
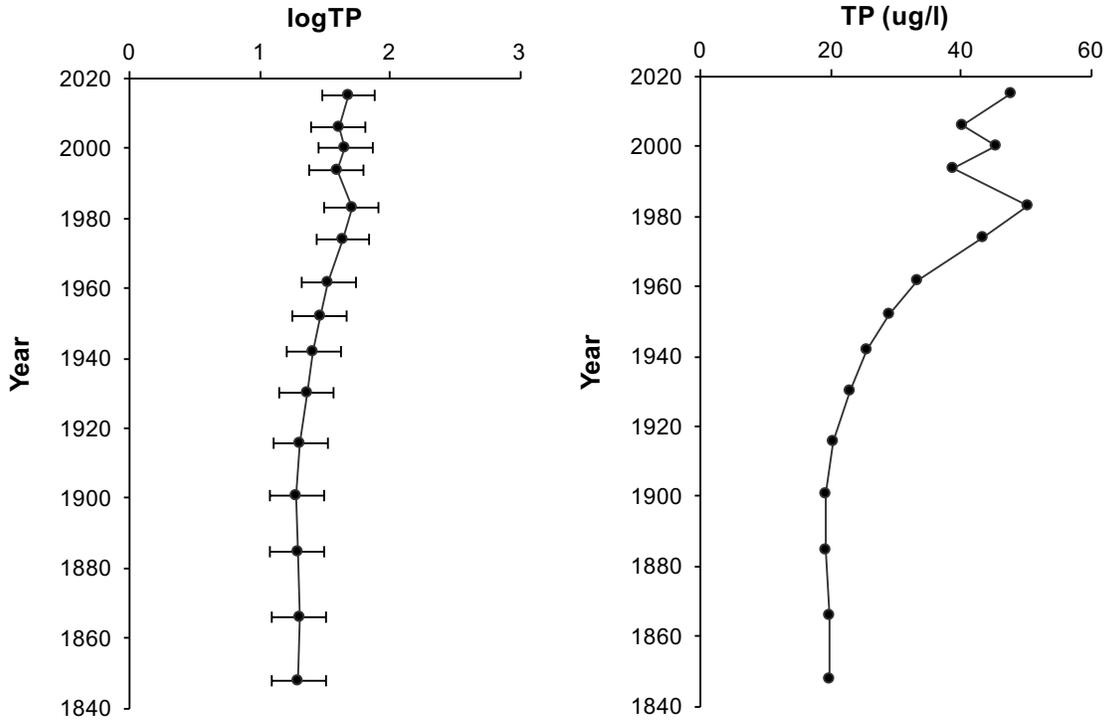prediction from the TP transfer function.

Figure 15. Sediment algal pigments quantified in fifteen core sections from Bartlett Lake. The group of algae associated with each pigment is shown along the x-axis.

Pigment Concentration (nmol g C⁻¹)