

# A Paleolimnological Study of Bone Lake, Polk County, Wisconsin

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## **Executive Summary**

- 1) A single sediment core was recovered from the southern basin of Bone Lake, Polk County, Wisconsin, in October 2013 and analyzed to reconstruct a historical record of sedimentation and water quality from the early 1800s to present. Management concerns for Bone Lake are centered around cyanobacterial blooms, elevated nutrient levels, curly-leaf pondweed, response to and prevention of aquatic invasives, and sustaining high quality recreational and fishing opportunities in the lake.
- 2) Sediment cores were subjected to multiple analyses including radioisotopic dating with Pb-210 to establish a date-depth relationship for each core, loss-on-ignition to determine major sediment constituents, biogenic silica to estimate historical diatom productivity, diatom communities to identify ecological changes and estimate historical water column phosphorus, and extraction and determination of sediment phosphorus fractions.
- 3) Sedimentation rates in the lake increased following Euroamerican settlement, and current sedimentation rates are approximately 2-fold greater than pre-settlement levels.
- 4) Loss-on-ignition analysis showed that inorganics are the predominant fraction of Bone Lake sediments followed by organic components and then carbonates. Organic constituents show the most dramatic increase in dry weight percent in the 1960's, whereas inorganic components show increased accumulation after 1900, likely reflecting changes in sediment loading following logging, land clearance, and development of the shoreline.
- 5) Biogenic silica concentrations in the cores, a marker of diatom algae abundance, are extremely high compared to most midwestern lakes; much of the inorganic core material is diatom shells, which represent 24-44% of the dry weight of Bone Lake sediment. Accumulation rates of biogenic silica show two peaks in diatom growth in the 1920s-1950s and in the most recent decades.
- 6) The concentration and accumulation rates of phosphorus fractions in the Bone Lake sediment core show general increases toward the core top. Organic phosphorus fraction is the dominant form found in Bone Lake sediments. Labile or mobile forms of phosphorus including exchangeable and NaOH-extractable forms are most abundant in the upper few cm of sediment and provide an accessible and readily available source of P during periods of internal loading. This appears to occur on a regular basis in Bone Lake when bottom waters go anoxic during mid-summer followed by the breakdown of stratification in late summer or early fall, which may initiate noxious cyanobacterial blooms.

7) The diatom communities preserved in the Bone Lake core are dominated by six species that are common in the plankton of many meso- to eutrophic midwestern lakes. A single significant shift in diatom communities occurred during the 1930s-1940s at a time when agricultural practices were changing in the region and when cottage and resort development around the lake was likely occurring. The most significant changes in the diatom community are the decreased abundance upcore of the mesotrophic indicator species, *Aulacosiera ambigua*, the historical dominance of the eutrophic species *A. granulata* and *Stephanodiscus niagarae*, and the post-1940s increase in small *Stephanodiscus* species.

8) Historical TP estimates were generated using a diatom-TP model based on species-environment relationships in 89 Minnesota lakes and suggest that Bone Lake has long been a eutrophic system. Diatom-inferred TP estimates increased following Euroamerican settlement to peak levels between 1940 and 1990 before dropping slightly since the mid-1990s. Modeled TP estimates for the last 10 years (62-80 ppb) are similar to monitored values present in the late summer and fall in Bone Lake (46-93 ppb TP), a period of the year known for cyanobacterial blooms. However, diatom reconstructed TP values are higher than the mean or median TP levels based on monitoring between 2007 and 2014.

9) Management recommendations based on these paleolimnological results are provided and include continued and enhanced efforts to minimize sediment and nutrient loading, additional analysis of fossil pigments in cores to determine whether cyanobacterial blooms are a recent or long-term characteristic of Bone Lake, detailed analysis of annual patterns of algal growth and water quality, and the possible expansion of the Minnesota 89-lake diatom model to include some Wisconsin lakes.

## **Acknowledgements**

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## Introduction

Within the glaciated regions of the Upper Midwest, lakes feature prominently in the landscape and are a valued resource for lakeshore owners, recreation, fisheries, water management and wildlife. Current and historical land and resource uses around lakes in this region have raised concerns about the state of the lakes and how to best manage them in a future certain to bring change. To effectively develop management plans, knowledge of the natural state of a lake and an understanding of the timing and magnitude of historical ecological changes become critical components. But reliable long-term data sets are generally not available for most regions of the country. Through the use of paleolimnological techniques and quantitative environmental reconstructions, we can estimate past conditions and natural variability, identify timing of ecological changes, and determine rates of change and recovery.

Bone Lake in Polk County, Wisconsin is large multibasin lake oriented along a N-S axis. The north central basin reaches 13.1 m (43 ft) deep, whereas the shallower southern basin reaches approximately 9.1 m or 30 ft deep. The lake is a flow-through system, part of the Upper Apple River Watershed, and drains via Fox Creek. Much of the shoreline is developed with seasonal or year-round residences and there are four resorts located on Bone Lake: E-Z Livin' Resort, Wilkins Resort, Pine Grove Resort, and Rest Point Resort. Current issues facing lake managers include the presence of curly leaf pondweed, periodic late summer and fall cyanobacteria blooms, and nutrient levels exceeding standards set for similar lakes (e.g. total phosphorus standard of 30  $\mu\text{g/l}$ ). In the case of Bone Lake, total phosphorus (TP) levels are highly variable and routinely run between 19 and 93  $\mu\text{g/l}$  (ppb) based on sporadic monitoring records going back to the mid-2000s. These impairments have led to questions whether the productivity of the lakes has changed over time, what the natural or historical condition of the lake was, what the current ecological trajectory of the lake is, and how to best set management goals.

With any lake management plan it is important to have a basic understanding of natural fluctuations within the system. Long-term water quality data sets, on the order of 30 - 50 years, are typically unavailable for most of the country, and Bone Lake is no exception. The primary aim of this project was to use paleolimnological analysis of a dated sediment core to reconstruct changes in the lake condition over the last 150-200 years using multiple lines of evidence including biogeochemistry, sediment accumulation, and diatom remains as biological indicators. In an effort to further understand presettlement conditions, and historical lake response to land use and past management, the proposed paleolimnological study will use diatom remains to model changes in water column TP. Diatoms quite often make up the main types of algae in a lake and therefore changes in diatom community structure are symptomatic of algal changes in response to water quality. Diatoms have been widely used to interpret environmental conditions in lakes (Dixit et al., 1992). 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 from diatom assemblages. These methods are statistically robust and ecologically sound. In the states of Minnesota and Wisconsin, diatom analysis has been used as one line of evidence for developing nutrient criteria

(Heiskary and Wilson 2008), lake-specific nutrient standards (Edlund and Ramstack 2007), and prioritizing management actions (Edlund et al. 2008).

In addition, we further characterize changes in algal productivity and nutrient availability using geochemical analyses of the cores. Biogenic silica (BSi) is a component of two major algal groups—the diatoms and chrysophytes. The amount of BSi preserved in sediments and its accumulation rate represent a straightforward measure of algal productivity through time that is particularly responsive to nutrient inputs (Edlund et al. 2009). We also characterized the total phosphorus and phosphorus fractions in each core level to understand the historical sources of P to the lake, the distribution of P and P fractions within the cores, and to assess the relative capability (or lack of capability, i.e. internal loading) of the lake to sequester phosphorus in its sediments.

## Methods

### Lake-Sediment Coring and Analyses

#### ***Coring***

A single sediment core measuring 1.95 m in length was recovered from the south basin (45°30.316' N, 92°22.743'W) of Bone Lake on 16 October 2013 (Fig. 1). The core was recovered from 9.1 m of water using a piston corer consisting of a 6.5 cm diameter polycarbonate tube outfitted with a piston and operated with rigid drive rods working from an anchored boat on the lake surface (Wright 1991). The core was transported to shore where the uppermost 46 cm of the core were vertically extruded and sectioned in 1.0-cm increments. The remaining core was stabilized, transported back to the laboratory and further sectioned in 2-cm increments to 100 cm core depth.

#### ***Isotopic Dating and Geochemistry***

The sediment core was analyzed for  $^{210}\text{Pb}$  activity to determine age and sediment accumulation rates for the past 150 to 200 years. Lead-210 activity was measured from its daughter product,  $^{210}\text{Po}$ , which is considered to be in secular equilibrium with the parent isotope. Aliquots of freeze-dried sediment were spiked with a known quantity of  $^{209}\text{Po}$  as an internal yield tracer and the isotopes distilled at 550°C after treatment with concentrated HCl. Polonium isotopes were then directly plated onto silver



*Figure 1. The 1.95-m sediment core recovered from Bone lake in October 2013. Photo courtesy Bob Boyd.*

planchets from a 0.5 N HCl solution. Activity was measured for  $1-3 \times 10^5$  s using an Ortec alpha spectrometry system. Supported  $^{210}\text{Pb}$  was estimated by mean activity in the lowest core samples and subtracted from upcore activity to calculate unsupported  $^{210}\text{Pb}$ . Core dates and sedimentation rates were calculated using the constant rate of supply model (Appleby and Oldfield 1978, Appleby 2001). Dating and sedimentation errors represented first-order propagation of counting uncertainty (Binford 1990).

Bulk-density (dry mass per volume of fresh sediment), water content, organic content, and carbonate content of sediments were determined by standard loss-on-ignition techniques (Dean 1974). Weighed sediment subsamples were dried at  $105^\circ\text{C}$  for 24 hr to determine water content and dry bulk density, then heated at  $550^\circ\text{C}$  and  $1000^\circ\text{C}$  to calculate organic and carbonate content from post-ignition weight loss, respectively. These data were used in combination with  $^{210}\text{Pb}$  dating to calculate sedimentation rates ( $\text{mg cm}^{-2} \text{ yr}^{-1}$ ) for each core and its sediment constituents.

Biogenic silica (BSi), a proxy for historical diatom and chrysophyte algal productivity, was measured using weighed subsamples (30 mg) from the core, which were digested for BSi analysis using 40 ml of 1% (w/v)  $\text{Na}_2\text{CO}_3$  solution heated at  $85^\circ\text{C}$  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 Lachat QuikChem 8000 flow injection autoanalyzer as molybdate reactive silica (McKnight 1991).

Sediment phosphorus fractions were analyzed following the sequential extraction procedures in Engstrom (2005) and Engstrom and Wright (1984). Extracts were analyzed colorimetrically on a Lachat QuikChem 8000 flow injection autoanalyzer. Measured sediment P concentrations were also converted to flux using bulk sedimentation rates in each core. In addition to total phosphorus in cores, sediment fractions include the refractory forms HCl-P and Organic-P and the labile or readily exchangeable forms of NaOH-P and "exchangeable P (Ex-P)."

### ***Diatom Analysis***

Diatoms were used in this study to provide a timeline of changes in the Bone Lake algal community and estimates of historical water column total phosphorus concentrations. In short the analytical steps are as follows. Diatoms and chrysophyte cysts were prepared by placing approximately 50 mg freeze dried core material in a  $50 \text{ cm}^3$  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%  $\text{H}_2\text{O}_2$  and heating for 3 hr in an  $85^\circ\text{C}$  water bath. After cooling the samples were centrifuged and rinsed 4-6 times with deionized water to remove oxidation byproducts. Material was then transferred to 22x22 mm square #1 coverglasses. Coverglasses were permanently attached to microscope slides using Zrax mounting medium (Ramstack et al. 2008). Diatoms were identified along measured random transects to the lowest taxonomic level under 1000-1250X magnification (full immersion optics of  $\text{NA} > 1.3$ ). A minimum of 400 valves was counted in each sample. Identification of diatoms relied on floras and

monographs such as Hustedt (1927-1966, 1930), Patrick and Reimer (1966, 1975), Krammer and Lange-Bertalot (1986-1991), Reavie and Smol (1998), Camburn and Charles (2000), and Fallu et al. (2000). All diatom counts were converted to percentage abundances by species or taxon; abundances are reported relative to total diatom counts in each sample.

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 constrained cluster analysis (CONISS) and the unconstrained ordination method of Detrended Correspondence Analysis (DCA), in the software package R (R Core Team 2014). 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 a DCA is that samples that plot closer to one another have more similar diatom assemblages.

Downcore diatom communities were also used to reconstruct historical epilimnetic 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 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=0.209 logTP units) 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  $\mu\text{g/l}$  or ppb.

## Results and Discussion

### ***Pb-210 inventory***

The Bone Lake showed a monotonic exponential decline in  $^{210}\text{Pb}$  inventories to supported depths (Fig. 2); the core reached supported levels of  $^{210}\text{Pb}$  at 55 cm depth. Using the c.r.s. model, a date-core depth relationship was established for the core. In the south bay of Bone Lake sediments dated to the 1850s were found at 48 cm, 1900 around 40 cm, 1950 at 25 cm, and 2000 at 7 cm depth.

### ***Sedimentation rates***

The Bone Lake core showed a general trend toward increasing sedimentation rates upcore with modern rates approximately two-fold greater than pre-1900 rates (Fig. 2).

Presettlement sedimentation rates in Bone Lake were approximately 0.012 g/cm<sup>2</sup> yr compared to sedimentation rates since the 1920s of 0.022 g/cm<sup>2</sup> yr. Historical increases in sedimentation are common in midwestern lakes following logging and land clearance for agriculture.

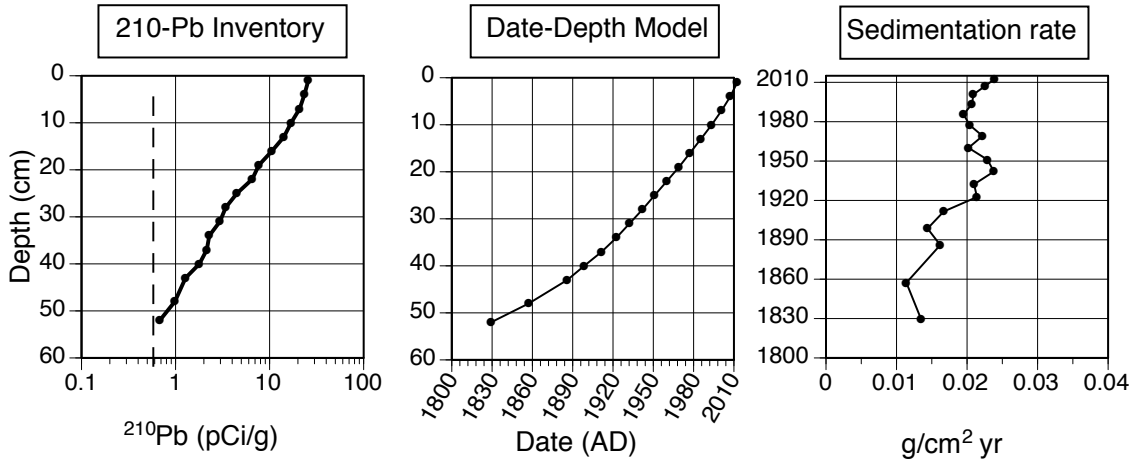


Figure 2. Inventory of <sup>210</sup>Pb by depth (cm), date-depth (cm) model, and bulk sedimentation rates (g/cm<sup>2</sup> yr) by date (AD) for Bone Lake core.

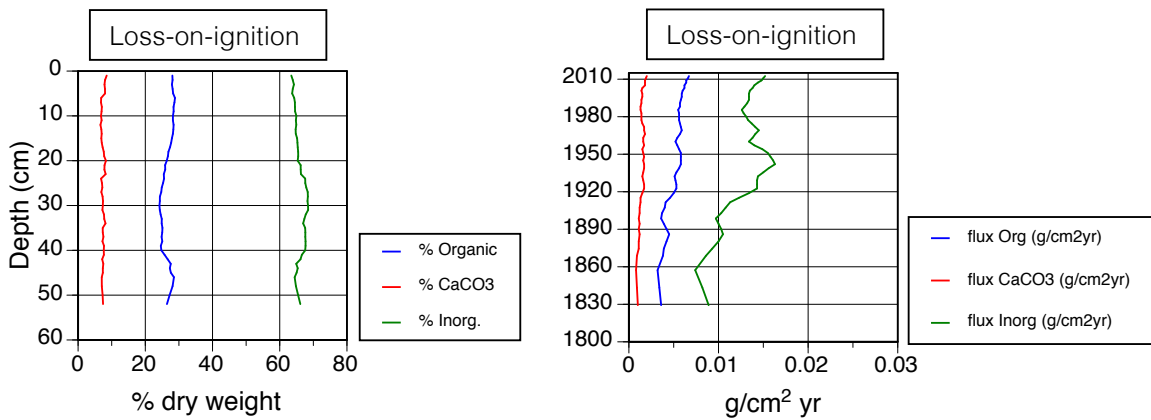


Figure 3. Sediment constituents in Bone Lake core based on loss-on-ignition analysis. Left panel shows fractions of inorganics, organics, and carbonates (CaCO<sub>3</sub>) by dry weight percent; right panel shows flux or accumulation rates of the same constituents.

### Loss-on-ignition

Sediment in Bone Lake is dominated by the inorganic fraction, which generally composed between 60 and 70% of the dry sediment weight (Fig. 3). Organics comprised the next predominant sediment constituent with the Bone Lake core having 24 to 29% organics by dry weight with the slightly higher measures above 20 cm depth (ca 1966). Carbonates made up between 6.7 and 8.5% dry weight of the Bone Lake core. Sediment constituents were also converted to accumulation or flux rates. All constituents showed

the most dramatic increase in accumulation rates after 1900. Inorganics notably increased in accumulation to a peak in the 1940s before dropping slightly until 1980 before increasing in most recent times. Increases in sedimentation rates around 1900 are generally a signal of logging and land clearance associated with settlement in the region.

**Biogenic silica (BSi)**

Biogenic silica composed 24.4-44.6% of the dry weight of Bone Lake sediment, with lowest values in the 1940s to 1960s and highest values in presettlement times (Fig. 4). Upcore increases in BSi concentration were noted in near surface sediments. This core represents some of the highest abundances of biogenic silica that the authors have ever seen in lake sediments. Most lakes have from 2-6% biogenic silica by weight. When

converted to accumulation rates, the flux of BSi increases toward the top of the Bone Lake core (post-1990) and during the 1920s-1950s. Modern accumulation of biogenic silica is approximately 30% greater than in pre-Euroamerican settlement times.

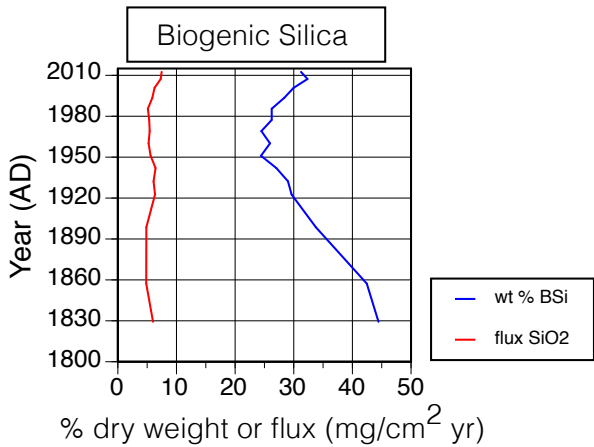


Figure 4. Biogenic silica content (percent dry weight) and accumulation rate (mg/cm<sup>2</sup> yr) for Bone Lake.

**Sediment phosphorus fractions**

Total phosphorus in Bone Lake sediment ranged from 0.8 to nearly 2.5 mg P/g with increasing amounts upcore to the highest values at the core top. (Fig. 5). The organic-P made up the largest proportion of P fractions followed by the NaOH-P fractions. This is significant because we must consider the potential mobility and possibility of

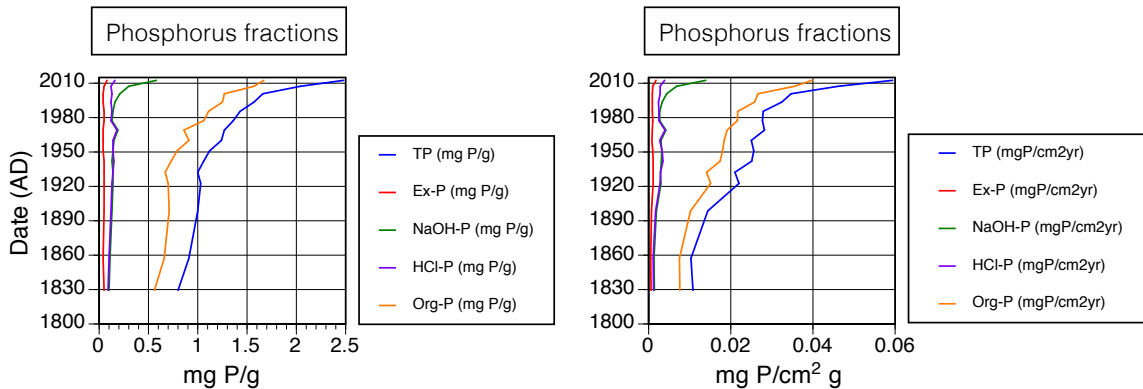


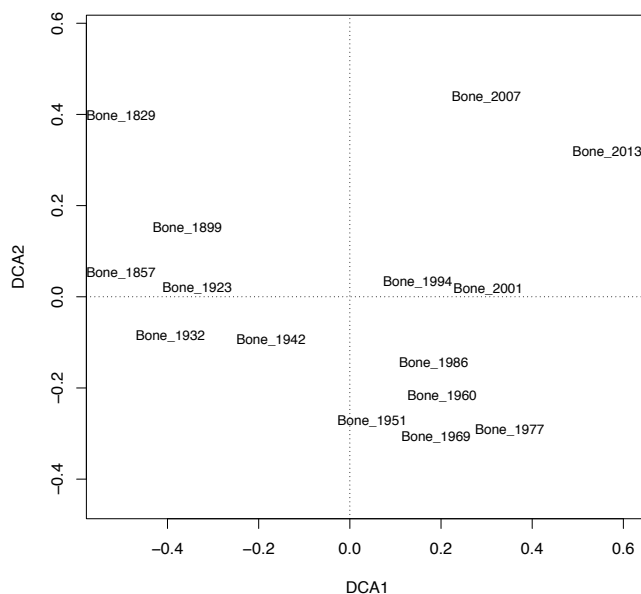
Figure 5. Sediment phosphorus fractions in Bone Lake core including total phosphorus (TP), exchangeable P (Ex-P), NaOH extractable P, HCl extractable P, and organic P (Org-P). Left panel shows concentration (mg P/g sediment) by core date; right panel shows accumulation rate (mgP/cm<sup>2</sup> yr) of each P fraction by core date.

exchange with the water column in the distribution and abundance of the refractory (HCl-P, Org-P) and labile/exchangeable fractions (Ex-P, NaOH-P). In Bone Lake, the active pool of labile forms is strongly distributed in the top 4 cm of the core suggesting that while Bone Lake can efficiently bury P in its sediments (one of only two ways for a lake to rid itself of excess P burdens—the other being through its outflow), there is a ready pool of P to fuel internal loading.

Accumulation rates of organic-P and total P in the cores increase upcore after 1900 to levels that are about 5-fold greater than pre-Euroamerican settlement (Fig. 5). There is less dramatic increases in the Ex-P, HCl-P, and NaOH-P fractions with greatest flux in the top few centimeters, again most likely representing a limited but active pool of P available for exchange with the water column. This pool of P is important given the propensity for the lake to have anoxic bottom waters in mid-summer to release labile P and loss of the thermocline by late summer to fuel late summer and fall cyanobacterial blooms (<http://dnr.wi.gov/lakes/waterquality/Station.aspx?id=493114>).

### ***Diatom communities and TP reconstructions***

Over 110 diatom species were present in the samples analyzed from the Bone Lake core. The most common species were planktonic forms that are typical and common in eutrophic midwestern lakes: *Aulacoseira ambigua*, *A. granulata*, *Stephanodiscus parvus*, *S. niagarae*, *S. minutulus*, and *Fragilaria crotonensis*. All levels of the core had greater than 85% of the diatoms representing planktonic forms.



*Figure 6. Detrended Correspondence Analysis (DCA) of diatom communities (by dated core level) from Bone Lake sediment core. In general, core levels that plot closer to each other are more similar.*

To determine how the diatom communities in each level of the core were related to one another, several analyses were run to develop stratigraphic groupings within the core. We first show an ordination biplot from detrended correspondence analysis (DCA) that shows how the core samples cluster based on similarity of diatom assemblage (Fig. 6). We also ran a second constrained cluster analysis (Fig. 7) that confirmed the DCA results

and suggests the major and only significant break among diatom assemblages occurs between 1932 and 1942 samples. The diatom community shows most of its change from the 1820s to the late 1980s along Axis 1 of the DCA plot; change over the last two decades is along Axis 2, suggesting that the lake may be experiencing multiple stressors over the past few decades.

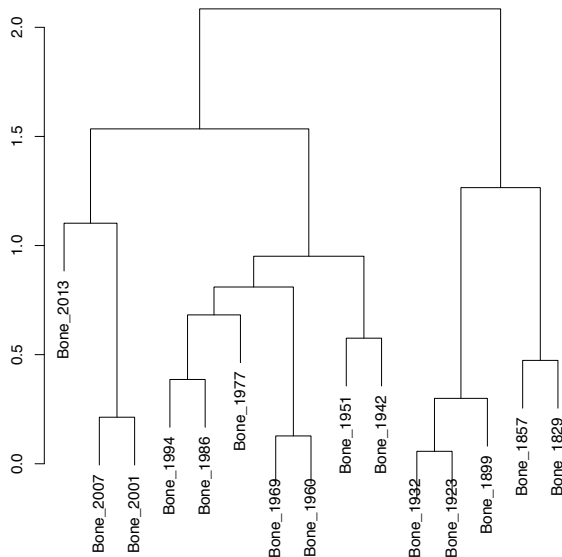


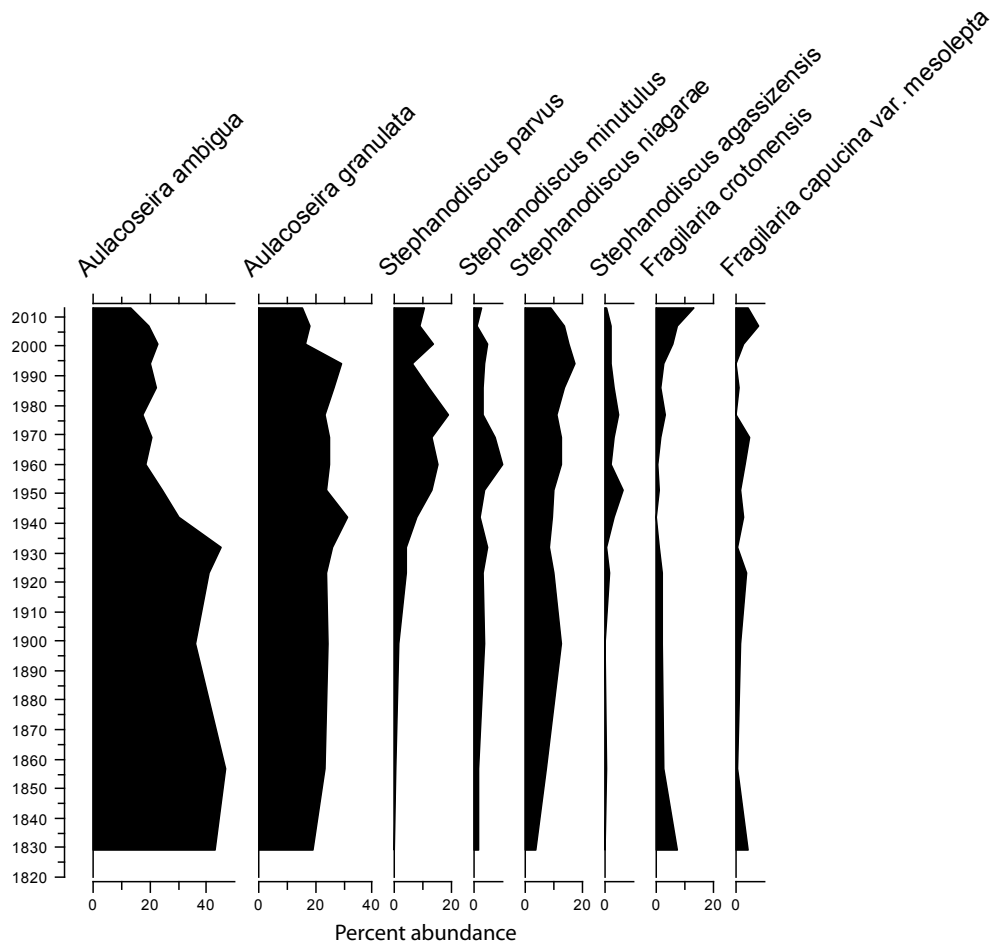
Figure 7. Constrained Cluster Analysis of diatom communities (by dated core level) from Bone Lake sediment core based on Euclidean distance. Only the two primary core groups are significant.

A stratigraphic diagram shows the changes in abundance of predominant diatoms (greater than 5% relative abundance) throughout the core (Fig. 8). The shift in the community between 1932 and 1942 is clearly evident in decreased abundance of *Aulacoseira ambigua* and increased upcore abundance of *Stephanodiscus parvus*, *S. minutulus*, *S. agassizensis*, and *Fragilaria crotonensis* (Fig. 8). The diatoms *A. granulata* and *S. niagarae* form significant proportions of the diatom community throughout the core. Recent increases in *Fragilaria crotonensis* and *F. capucina v. mesolepta* set the upper three samples (2001-2012) slightly apart from the rest of the core. It is also worthwhile to note that recent changes in the diatom assemblages are not returning the lake to a pre-Euroamerican settlement diatom community.

All of the common diatoms in the Bone Lake core are characteristic of meso- to eutrophic midwestern lakes. The two *Aulacoseira* species are indicative of strong spring mixing of the lake with *A. ambigua* more common in mesotrophic lakes and *A. granulata* more characteristic of eutrophic and shallow lakes during mixing events. *Stephanodiscus niagarae* is also a spring form that has a broad tolerance for higher nutrient levels in meso-, eu-, and hypertrophic lakes. The smaller *Stephanodiscus* species, *S. minutulus* and *S. parvus*, often respond to nutrient increases in lakes and become a more common planktonic components following nutrient enrichment.

The diatom communities were also used to reconstruct historical TP levels for Bone Lake. Many factors can contribute to changes in diatom communities (pH, light penetration, and habitat availability), and in order for a diatom-inferred total phosphorus

(TP) reconstruction to be meaningful, changes in the diatom community assemblage over time should be primarily driven by changes in TP concentrations. One way to evaluate TP as a driver of change in Bone Lake is to project the core sections on the MN calibration set that we 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). This analysis results in a cloud of data points for the Bone Lake core, with no strong directional change (Fig. 9). The lack of correlation with Axis 1 or log TP suggests that nutrients are not the primary driver of the changes seen in the diatom community for the majority of the record. Alternative drivers include: habitat alterations, changes in turbidity due to sediment load, nitrogen, climate drivers, or other stressors that were not directly measured in the calibration set. It is possible that the drivers of ecological shifts change over time, meaning that TP is an important variable during certain time periods.



*Figure 8. Downcore distribution of predominant diatom in the Bone Lake sediment core. Species shown were present in one or more core levels at greater than 5% abundance.*

Another way to evaluate the strength of a TP 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 (known as the lambda r/lambda p score; Juggins et al. 2013). In Bone Lake, this analysis shows that the fraction of the maximum explainable variation in the diatom data that can be explained by TP is very low (= 0.1998). The low score from this analysis, coupled with the lack of correlation with the logTP axis in the passive plot, suggests that TP has not always been the significant driver of diatom community change in this lake and therefore the TP reconstruction should be interpreted with caution.

### CCA, 89 MN Lakes, Bone Lake fossil data

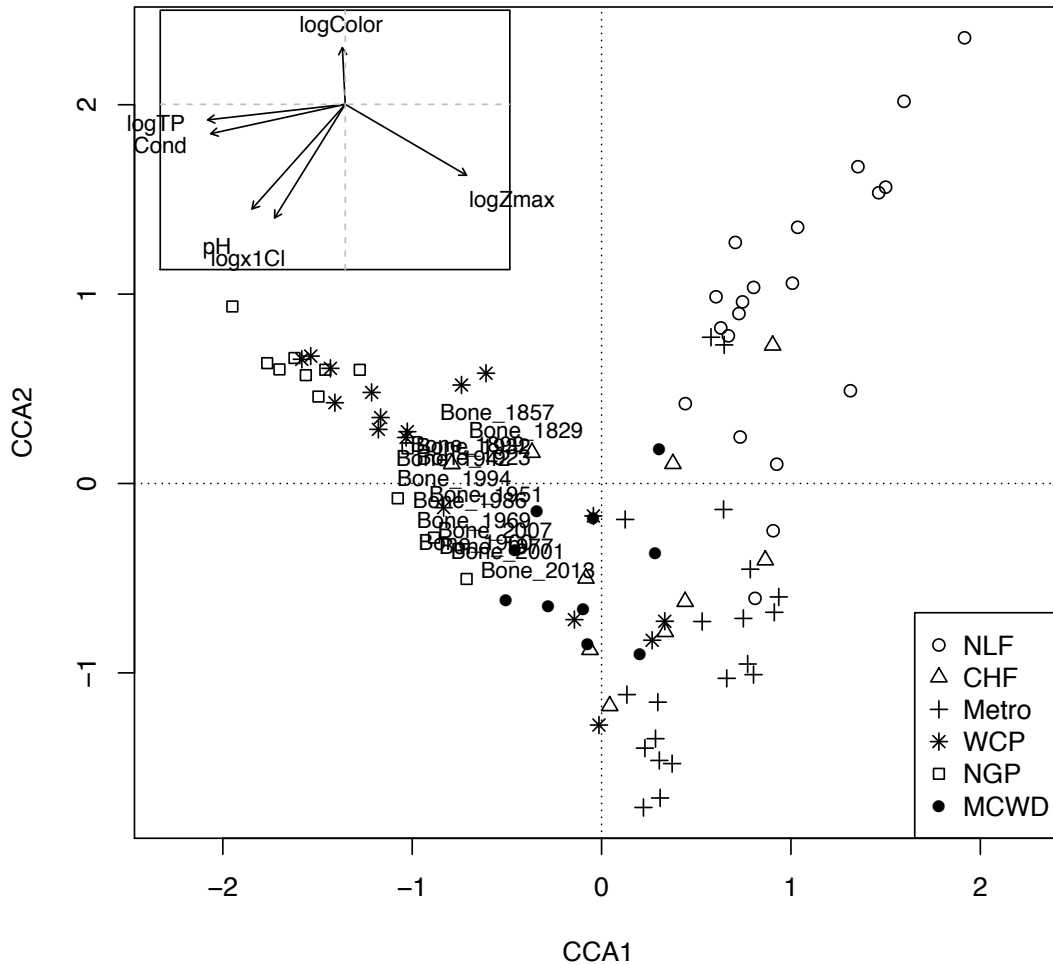
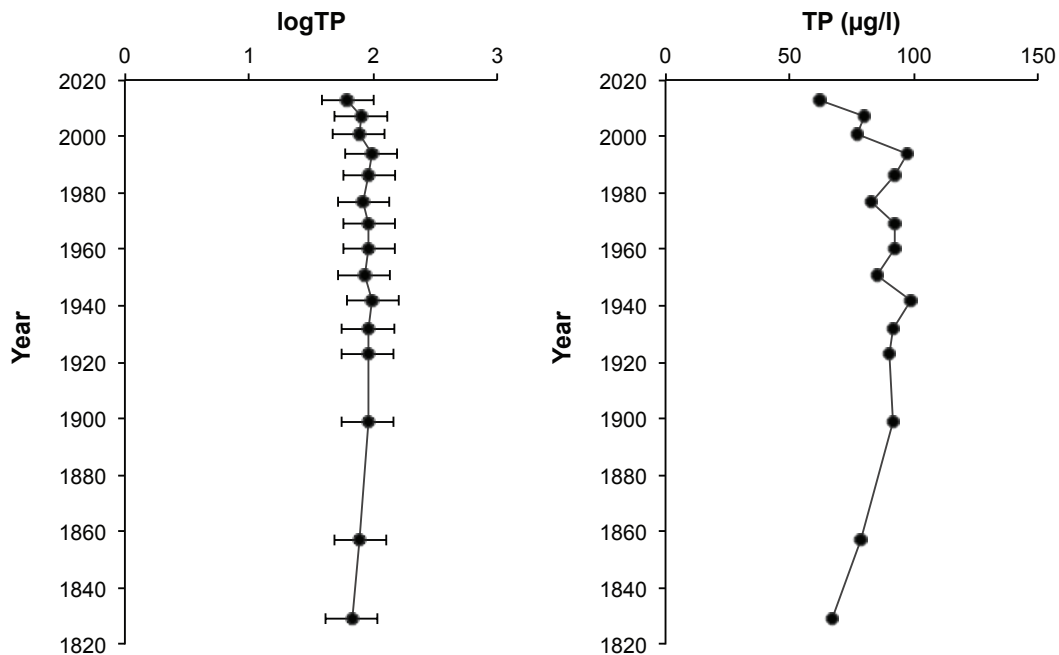


Figure 9. Diatom communities in dated Bone Lake core sections passively plotted onto the calibration set of 89 Minnesota lakes. The inset shows the strength and direction of environmental gradients that significantly explain diatom abundance in the calibration set lakes. If the historical diatom communities in Bone Lake were responding solely to changes in TP, we would expect them to be chronologically aligned with the logTP axis (see text).

Given those caveats, the TP reconstruction suggests that Bone Lake has always had fairly high nutrient levels, in the eutrophic category, with levels increasing immediately after Euroamerican settlement (Fig. 10). Diatom-inferred TP also suggests a return to lower nutrient levels in recent decades, since the mid-1990s. The changes in TP are not outside the error of the reconstruction model, i.e. the model results suggest there has not been significant change in TP levels in Bone Lake. Another way to evaluate the strength of the TP reconstructions is to compare TP results with measured TP levels generated through regular lake monitoring programs. Monitored TP between 2007 and 2014 ranged from 19 to 93 ppb TP with notably higher levels in late summer and fall that were associated with cyanobacterial blooms (<http://dnr.wi.gov/lakes/waterquality/Station.aspx?id=493114>). The diatom-inferred TP levels since the mid-1990s range from 62 to 80 ppb TP, which are very similar to late summer and fall TP concentrations based on monitoring. These values are markedly higher than annual average or median TP values based on monitoring, but they do show that the diatoms are reflecting measured values associated with late summer and fall mixing period in Bone Lake. The seasonality of diatom production has not been determined for Bone Lake (see Recommendations below) and there may be significant productivity in the late summer and fall following the breakdown of the thermocline and several months of complete water column mixing.



*Figure 10. Historical diatom-inferred TP levels for Bone Lake. Model reconstructions (left panel) are in log TP units and error bars represent the root mean square error of prediction or the model error estimates of 0.209 logTP units (RMSEP). The back transformed diatom-inferred TP levels are given in the right panel in the more commonly reported units of µg/l or ppb.*

## Summary and Recommendations

The dated section of the Bone Lake sediment core provided a nearly 200-year record of sedimentation, geochemistry, and diatom algae communities in the lake. Sedimentation rates in the lake increased following Euroamerican settlement and current sedimentation rates are approximately 2-fold greater than pre-settlement levels. Inorganic constituents show the most dramatic increase in accumulation likely reflecting changes in sediment loading following logging, land clearance, and development of the shoreline. Biogenic silica concentrations in the cores, a marker of diatom algae abundance, are extremely high compared to most midwestern lakes. The accumulation of biogenic silica levels in the core shows two peaks in the diatom growth in the 1920s-1950s and in the most recent decades. The concentration and accumulation rate of phosphorus fractions in the Bone Lake sediment core show general increases toward the core top. Labile or mobile forms of phosphorus including exchangeable and NaOH-extractable forms are most abundant in the upper few cm of sediment and provide an accessible and readily available source of P during periods of internal loading.

The diatom communities preserved in the Bone Lake core are dominated by six species that are common in the plankton of many meso- to eutrophic midwestern lakes. A single significant shift in diatom communities occurred during the 1930s-1940s at a time when agricultural practices were changing in the region and when cottage and resort development around the lake was occurring. The most significant changes in the diatom community are the decreased abundance upcore of the mesotrophic indicator species, *Aulacosiera ambigua*, the historical dominance of the eutrophic species *A. granulata* and *Stephanodiscus niagarae*, and the post-1940s increase in small *Stephanodiscus* species.

Historical TP estimates generated using a diatom-TP model based on 89 Minnesota lakes suggest that Bone Lake has long been a eutrophic system. Diatom-inferred TP estimates increased following Euroamerican settlement to peak levels between 1940 and 1990 before dropping slightly since the mid-1990s. Modeled TP values for the last 10 years (62-80 ppb) are similar to monitored values present in the late summer and fall in Bone Lake, a period of the year known for cyanobacterial blooms. Diatom reconstructed TP values were higher than the mean or median TP levels based on monitoring between 2007 and 2014.

Management recommendations based on this paleolimnological analysis include:

1. There are additional analyses that can be run on sediment cores. Perhaps the most important question remaining is whether the occurrence of cyanobacterial blooms has been a long term characteristic of Bone Lake. All algal groups contain pigments that are preserved in sediment cores in approximate ratios and quantities that reflect their historical abundance in a lake. It would be informative to do an analysis of a sediment core for fossil algal pigments to determine if cyanobacterial blooms are a recent or long-term characteristic of Bone Lake's seasonal cycle. A similar approach proved very helpful in understanding the increased prevalence of blue-green blooms in Lake St. Croix on the Wisconsin-Minnesota border.

2. A study of the annual cycle of phytoplankton (algae) and associated water quality parameters in Bone Lake would provide a more clear sense of how and when late summer algal blooms form in the lake. The study should include regular sampling of lake profiles (depth, temperature, dissolved oxygen) as well as surface and bottom water nutrient levels. Integrated sampling of algal communities would then clarify the seasonality of plankton groups and what leads to the setup of blooms. Sediment traps could also be deployed to clarify algal seasonality in Bone Lake.

3. The model used to reconstruct TP from fossil diatoms was based the relationship between diatom communities and environmental measures from nearly 90 Minnesota lakes. Although there is little reason to believe that this model is not applicable to Wisconsin lakes, there is a smaller model based on Wisconsin lakes that might be combined with the Minnesota model and generate stronger TP reconstructions. Keep in mind that the diatom community changes over the last 200 years in Bone Lake are relatively subtle and are not definitively being driven by changes in TP during that entire time period; other drivers of change may also be affecting the lake (e.g., nitrogen, climate change breaking down the thermocline in late summer).

4. Sediment core records indicate that management efforts directed at controlling sediment and nutrient loading to Bone Lake are having a beneficial effect. The diatom-inferred TP trend shows slight decreases in water column TP levels since the mid-1990s. Moreover, if we discount for the diatom portion of the sediments, current sediment accumulation rates are similar to pre-Euroamerican settlement rates of accumulation (see Appendix Fig. 1). Watershed and shoreline efforts to control sediment and nutrient loading should continue to be prioritized in Bone Lake management plans.

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## Appendices

Appendix Table 1. Inventory of  $^{210}\text{Pb}$ , modeled calendar date, and sediment accumulation rate ( $\text{g}/\text{cm}^2 \text{ yr}$ ) of each core section (cm).

Base of Interval (cm)	$^{210}\text{Pb}$ Act (pCi/g)	Date A.D.	Sediment Accum. ( $\text{g}/\text{cm}^2 \text{ yr}$ )
1	25.8092	2012.5	0.0239
4	23.4598	2007.3	0.0226
7	20.8953	2000.8	0.0209
10	16.9330	1993.5	0.0207
13	14.1856	1985.5	0.0195
16	10.5912	1977.3	0.0204
19	7.6909	1969.1	0.0222
22	6.5322	1960.1	0.0202
25	4.4984	1951.0	0.0229
28	3.4181	1942.0	0.0238
31	2.9608	1932.3	0.0210
34	2.2850	1922.6	0.0214
37	2.1482	1911.6	0.0167
40	1.7927	1898.6	0.0144
43	1.2761	1886.0	0.0162
48	0.9837	1857.3	0.0114
52	0.6808	1829.3	0.0135

Appendix Table 2. Percent dry weight and accumulation rates ( $\text{g}/\text{cm}^2 \text{ yr}$ ) of organics, carbonates ( $\text{CaCO}_3$ ), and inorganics in Bone Lake core.

Depth (cm)	% Organic	% $\text{CaCO}_3$	% Inorg.	Organics ( $\text{g}/\text{cm}^2 \text{ yr}$ )	$\text{CaCO}_3$ ( $\text{g}/\text{cm}^2 \text{ yr}$ )	Inorganics ( $\text{g}/\text{cm}^2 \text{ yr}$ )
1.0	28.05	8.51	63.44	0.0067	0.0020	0.0152
2.0	28.11	8.02	63.88	0.0066	0.0019	0.0150
3.0	27.92	7.86	64.22	0.0064	0.0018	0.0148
4.0	28.13	8.00	63.87	0.0064	0.0018	0.0144
5.0	28.28	8.02	63.70	0.0062	0.0018	0.0140
6.0	28.83	6.87	64.31	0.0062	0.0015	0.0138
7.0	28.67	6.81	64.51	0.0060	0.0014	0.0135
8.0	28.40	7.07	64.53	0.0059	0.0015	0.0134
9.0	28.43	6.99	64.57	0.0059	0.0015	0.0134
10.0	28.22	6.82	64.95	0.0058	0.0014	0.0134
11.0	28.21	7.00	64.80	0.0057	0.0014	0.0132
12.0	28.42	6.65	64.93	0.0057	0.0013	0.0129
13.0	28.35	6.92	64.73	0.0055	0.0013	0.0126
14.0	28.21	7.02	64.77	0.0056	0.0014	0.0128
15.0	27.92	6.91	65.17	0.0056	0.0014	0.0131
16.0	27.69	7.04	65.27	0.0056	0.0014	0.0133
17.0	27.35	7.30	65.35	0.0057	0.0015	0.0137
18.0	26.88	7.64	65.48	0.0058	0.0017	0.0141
19.0	26.73	7.76	65.50	0.0059	0.0017	0.0145
20.0	26.38	8.28	65.34	0.0057	0.0018	0.0141
21.0	25.89	7.87	66.23	0.0054	0.0016	0.0138
22.0	25.93	7.83	66.24	0.0052	0.0016	0.0134
23.0	25.50	8.20	66.31	0.0054	0.0017	0.0140
24.0	25.58	6.84	67.58	0.0056	0.0015	0.0149
25.0	25.28	7.11	67.60	0.0058	0.0016	0.0155
26.0	24.89	7.22	67.90	0.0058	0.0017	0.0158
27.0	24.75	6.92	68.33	0.0058	0.0016	0.0161
28.0	24.34	7.29	68.37	0.0058	0.0017	0.0163
29.0	24.33	7.41	68.26	0.0056	0.0017	0.0156
30.0	24.21	7.36	68.42	0.0053	0.0016	0.0150
31.0	24.31	7.24	68.45	0.0051	0.0015	0.0144
32.0	24.56	7.70	67.74	0.0052	0.0016	0.0143
33.0	24.90	7.78	67.32	0.0053	0.0017	0.0143
34.0	24.87	8.16	66.97	0.0053	0.0017	0.0143
35.0	25.10	7.33	67.57	0.0050	0.0015	0.0134
36.0	25.04	7.34	67.62	0.0046	0.0013	0.0123
37.0	24.85	7.54	67.61	0.0041	0.0013	0.0113

Appendix Table 2, continued. Percent dry weight and accumulation rates ( $\text{g}/\text{cm}^2 \text{ yr}$ ) of organics, carbonates ( $\text{CaCO}_3$ ), and inorganics in Bone Lake core.

Depth (cm)	% Organic	% $\text{CaCO}_3$	% Inorg.	Organics ( $\text{g}/\text{cm}^2 \text{ yr}$ )	$\text{CaCO}_3$ ( $\text{g}/\text{cm}^2 \text{ yr}$ )	Inorganics ( $\text{g}/\text{cm}^2 \text{ yr}$ )
38.0	25.06	7.25	67.68	0.0040	0.0012	0.0108
39.0	24.61	7.71	67.68	0.0037	0.0012	0.0103
40.0	24.78	7.64	67.58	0.0036	0.0011	0.0097
41.0	25.74	7.68	66.58	0.0039	0.0012	0.0100
42.0	26.66	7.17	66.18	0.0042	0.0011	0.0103
43.0	27.57	7.51	64.91	0.0045	0.0012	0.0105
44.0	27.30	7.36	65.35	0.0042	0.0011	0.0100
45.0	27.61	7.37	65.02	0.0039	0.0011	0.0093
46.0	28.52	7.04	64.44	0.0038	0.0009	0.0086
48.0	28.12	7.06	64.82	0.0032	0.0008	0.0074
50.0	27.23	7.30	65.47	0.0034	0.0009	0.0082
52.0	26.44	7.43	66.13	0.0036	0.0010	0.0089

Appendix Table 3. Biogenic silica content (dry weight percent) and accumulation rate ( $\text{mg}/\text{cm}^2 \text{ yr}$ ) in Bone Lake sediments.

Date A.D.	wt % BSi	flux $\text{SiO}_2$ $\text{mg}/\text{cm}^2 \text{ yr}$
2012.5	31.24	7.47
2007.3	32.34	7.31
2000.8	29.97	6.26
1993.5	28.38	5.88
1985.5	26.24	5.12
1977.3	26.24	5.35
1969.1	24.48	5.43
1960.1	25.95	5.24
1951.0	24.41	5.59
1942.0	27.03	6.43
1932.3	29.01	6.09
1922.6	29.63	6.34
1898.6	33.77	4.86
1857.3	42.45	4.84
1829.3	44.45	6.00

Appendix Table 4. Total phosphorus and phosphorus fractions concentration (top table; dry weight percent) and accumulation rate (bottom table;  $\text{mg}/\text{cm}^2 \text{ yr}$ ) in Bone Lake sediments. Phosphorus fractions include exchangeable-P (Ex-P), NaOH-extractable P, HCl-extractable P, and Organic-P (Org-P).

Date A.D.	TP (mg P/g)	Ex-P (mg P/g)	NaOH-P (mg P/g)	HCl-P (mg P/g)	Org-P (mg P/g)
2012.5	2.48	0.08	0.58	0.16	1.67
2007.3	2.04	0.05	0.30	0.12	1.57
2000.8	1.66	0.04	0.21	0.13	1.27
1993.5	1.57	0.04	0.16	0.12	1.25
1985.5	1.43	0.05	0.14	0.13	1.11
1977.3	1.36	0.05	0.13	0.12	1.06
1969.1	1.27	0.04	0.19	0.18	0.86
1960.1	1.24	0.04	0.15	0.14	0.91
1951.0	1.12	0.04	0.14	0.14	0.79
1942.0	1.06	0.05	0.13	0.15	0.73
1932.3	1.00	0.05	0.14	0.14	0.67
1922.6	1.03	0.05	0.14	0.13	0.70
1898.6	1.00	0.05	0.13	0.12	0.71
1857.3	0.91	0.04	0.11	0.10	0.66
1829.3	0.80	0.05	0.10	0.09	0.56

Date A.D.	TP $\text{mgP}/\text{cm}^2 \text{ yr}$	Ex-P $\text{mgP}/\text{cm}^2 \text{ yr}$	NaOH-P $\text{mgP}/\text{cm}^2 \text{ yr}$	HCl-P $\text{mgP}/\text{cm}^2 \text{ yr}$	Org-P $\text{mgP}/\text{cm}^2 \text{ yr}$
2012.5	0.0594	0.0018	0.0139	0.0039	0.0398
2007.3	0.0461	0.0010	0.0068	0.0028	0.0355
2000.8	0.0347	0.0009	0.0044	0.0028	0.0266
1993.5	0.0324	0.0009	0.0033	0.0024	0.0258
1985.5	0.0279	0.0009	0.0027	0.0025	0.0217
1977.3	0.0277	0.0010	0.0027	0.0025	0.0216
1969.1	0.0282	0.0009	0.0042	0.0040	0.0191
1960.1	0.0250	0.0008	0.0030	0.0027	0.0184
1951.0	0.0256	0.0010	0.0032	0.0033	0.0180
1942.0	0.0251	0.0011	0.0031	0.0035	0.0174
1932.3	0.0210	0.0011	0.0029	0.0029	0.0141
1922.6	0.0220	0.0011	0.0030	0.0028	0.0151
1898.6	0.0144	0.0007	0.0019	0.0017	0.0102
1857.3	0.0103	0.0005	0.0013	0.0011	0.0075
1829.3	0.0108	0.0006	0.0014	0.0012	0.0076

Appendix Table 5. Diatom-inferred total phosphorus (TP) reconstructions for Bone Lake. Model reconstructions are in logTP units and have been back transformed to  $\mu\text{g/l}$

Date (AD)	log TP	TP ( $\mu\text{g/l}$ )
2013	1.79	62
2007	1.90	80
2001	1.89	77
1994	1.99	97
1986	1.97	93
1977	1.92	83
1969	1.97	92
1960	1.96	92
1951	1.93	85
1942	2.00	99
1932	1.96	91
1923	1.96	90
1899	1.96	91
1857	1.90	79
1829	1.83	67

Appendix Figure 1. In Bone Lake the high quantity of diatoms preserved in the sediments masks the other inorganic sediment components. If we remove the diatom fraction of inorganic sediments the record more realistically reflects sediment loading to the lake. Inorganic sediments reach peak abundance in 1950 following large increases that began with settlement. Inorganic sediment accumulation (flux) shows an initial peak in 1900 and again in the 1960s-1980s. Since the 1980s the flux of inorganics has dropped in Bone Lake, likely in response to management efforts to control sediment loading.

