A Paleolimnological Study of Big Blake Lake, Polk County, Wisconsin

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Executive Summary

1. Paired sediment cores were recovered from the northern basin of Big Blake Lake, Polk County, Wisconsin, in September 2013 and analyzed to reconstruct a historical record of sedimentation, ecological change, and water quality from the early 1800s to present. Management concerns for Big Blake Lake are centered on the prevalence of *Potamogeton crispus*, cyanobacterial blooms, elevated nutrient levels, 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 and sedimentation rates for the core site, 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, extraction and determination of sediment phosphorus fractions to determine past nutrient loading and threat of internal loading, and analysis of macrofossils including chironomid head capsules, zooplankton fossils, aquatic macrophyte remains to identify ecological shifts that have occurred in Big Blake Lake.
3. Sedimentation rates in the lake increased following Euroamerican settlement, and current sedimentation rates are approximately five times greater than pre-settlement levels.
4. Loss-on-ignition analysis showed that inorganics are the predominant fraction of Big Blake Lake sediments followed by organic components and then carbonates. Inorganic components show increased accumulation after 1900, likely reflecting changes in sediment loading following logging, land clearance, and development of the shoreline, while organic constituents decreased.
5. Biogenic silica concentrations in the cores, a marker of diatom algae abundance, are high compared to most lakes in the Midwest and represent 8-14% of the dry weight of Big Blake Lake sediment. Accumulation rates of biogenic silica show diatom growth has increased in the last two decades.
6. The concentration and accumulation rates of phosphorus (P) fractions in the Big Blake Lake sediment core show general increases toward the top of the core. Organic P is the most abundant in the top few cm of sediment. NaOH-extractable P and exchangeable P also increase in the top few centimeters of the core providing a readily available source of P during periods of internal loading. Internal loading appears to be more significant in recent decades when bottom water go anoxic during *Potamogeton crispus* senescence and periodic breakdowns of stratification throughout the summer months which can initiate cyanobacteria blooms.
7. The diatom communities preserved in Big Blake Lake's sediment are dominated by six species. A significant diatom community shift occurs in the 1920-30s, a time when cottage and resort communities were expanding and agricultural practices were likely shifting in the region. This time period shows a decrease in the planktonic mesotrophic indicator *Aulacoseira ambigua* and benthic diatoms *Staurosira construens* and *S. venter* coincident with an increase in the dominance of the eutrophic species *Aulacoseira granulata*.
8. Estimates of historical total phosphorus (TP) were generated using a diatom-TP model based on species environmental relationships in 89 Minnesota lakes. The model suggests that Big Blake Lake has shifted from a mesotrophic lake to a eutrophic system. Diatom-

inferred TP estimates increase following European settlement, increase further in the 1940s to peak levels in the 1960s through present day. Modeled TP estimates for the last ten years (49-52 µg/l) are similar to monitored values taken during the growing season (40-80 µg/l TP) when cyanobacterial blooms can occur. Diatom reconstructed TP values are almost identical to the mean annual TP levels based on a comprehensive monitoring program from 2013-2015 (49.9 µg/l), and predictions modeled using the Wisconsin Lakes Modeling Suite (43-50 µg/l).

9. Pigment analysis of different algae groups showed that algae, including cyanobacteria, have increased in recent decades. Evidence suggests that nitrogen-fixing, and possibly toxic, forms of cyanobacteria (via aphanizophyll), have increased dramatically over the last three decades.
10. Analysis of zooplankton remains shows a general decrease in cladocerans since the 1960s and 1970s. There is a sharp reduction in both *Eurycercus* sp. and *Alona* sp. since the 1960s. These species are often associated with aquatic plants in the littoral zones of ponds and lakes in North America and Europe and their decline corresponds to decline of the native aquatic plant community in Big Blake Lake since the 1960s.
11. Chironomid head capsules shows sharp decrease in littoral species after the 1950s similar to changes in zooplankton composition, again reflecting changes in ecosystem quality associated with the loss of the native aquatic plant community.
12. Aquatic macrophyte fossils show a loss in both species richness and total number of indigenous species since the 1960s. Fossils of the aquatic invasive species *Potamogeton crispus* appear in the 1980s.
13. Paleolimnology-based management recommendations and additional analysis are provided in the Big Blake Lake comprehensive Lake Management Plan.

Acknowledgments

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Introduction

Lakes are prominent features in the glaciated landscape of the Upper Midwest. They are valued resources for recreation, fisheries, wildlife, and leisure for lakeshore owners. Water management concerns have been raised about the state of lakes and how to best manage them due to current, historical, and future land and resource use that is certain to see further change. To develop effective management plans it is important to determine the natural state of a lake and have an understanding of the timing and magnitude of historical ecological changes that have occurred. We can estimate past conditions and natural variability through the use of paleolimnological techniques to identify the timing of ecological change, and determine the rates of change and recovery. Linking this information to historical land-use changes and known environmental impacts helps target management options.

Big Blake Lake (WBIC 2627000) is located in the Town of Georgetown in central Polk County, Wisconsin (T35N, R16W, S22, 26, and 27, Fig. 1). The lake has a surface area of 217 acres, a maximum depth of 4.3 meters (14 feet), and a mean depth of 2.7 meters (9 feet). The Big Blake Lake watershed is part of the Upper Apple River watershed in the St. Croix River Basin. The watershed (or drainage area) of Big Blake Lake is approximately 15,369 acres. The watershed to lake area ratio is approximately 70:1. The lake is classified as a drainage lake, meaning that it is fed primarily by inflowing streams or rivers. The Straight River flows in from the southeast via Big Round and Little Blake Lake, and an unnamed creek that drains from Lost Lake flows in on the north side of the lake. Fox Creek flows out of the lake at the northwest end. Big Blake Lake is also designated as an Area of Special Natural Resource Interest (ASNRI) and as a Public Rights Feature (PRF). Significant public access and use opportunities are available on Big Blake Lake. There is a resort located on Big Blake Lake on the northwest side (Sherrards Resort). Big Blake Lake has two public boat landings, one which provides parking for seven car-trailer units and a carry-in launch.

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 to 50 years are generally not available for most of the country and Big Blake Lake is no exception. Incomplete water quality data have been collected intermittently from Big Blake Lake since 2000. Most of the data sets do not include chlorophyll a or total phosphorus TSI averages and there are large stretches of time where no data have been collected. The most recent data suggest that Big Blake Lake is eutrophic; however, the large lag times between sampling events make these data inconclusive. The most recent water quality study on Big Blake Lake was completed in 2004 by Aquatic Engineering, Inc. to determine management recommendations to protect and improve water quality on Big Blake Lake. Northern Lake Service, Inc. also completed a study in 1979 and the DNR Office of Inland Lake Renewal completed a study in 1981. The Wisconsin state phosphorus standard of 30 µg/L was exceeded in both of these reports. The highest readings of total phosphorus in the reports were 69 µg/L and 95 µg/L. The highest reading for chlorophyll a concentrations was 55 µg/L (Williamson, unpublished data). The 1981 DNR Office of Inland Lake Renewal study further concluded that sediment was a major source of the total phosphorus load to Big Blake Lake.

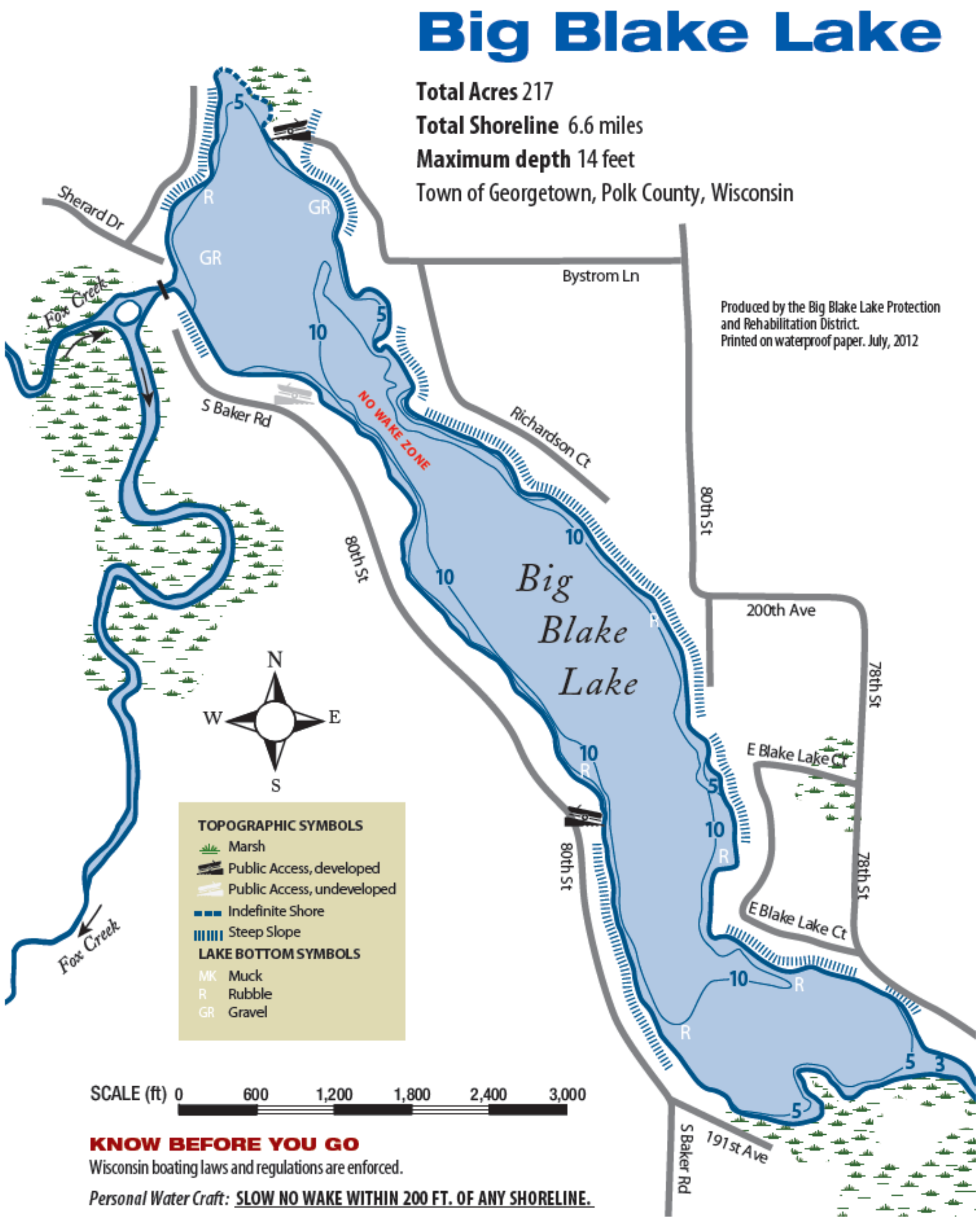


Figure 1. Map of Big Blake Lake.

In addition to inadequate water quality data, there is a lack of ecological data and biological monitoring for the lake, a problem that is not unique to Blake Lake. Monitoring of aquatic macrophytes has been carried out since 2006 by the Polk County Land & Water Resources Department (LWRD), and two of the three main goals in the Blake Lake Aquatic Invasive Species Management Plan address preserving and protecting native plant functions and reducing curly-leaf pondweed. Algae and zooplankton data are absent.

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, zooplankton fossils, chironomid head capsules, aquatic macrophyte remains, 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 paleolimnological study uses diatom remains to model changes in water column TP. Diatoms 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 biogeochemical 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). Fossilized algae pigments were analyzed in order to investigate changes in the composition of algae as well as total algae production. Zooplankton fossils, chironomid head capsules, and aquatic macrophyte remains were analyzed to characterized habitat changes and the faunal and food web response to such changes. We also characterized the total phosphorus and phosphorus fractions in the core 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

Coring

Figure 2. Sediment core recovered from Big Blake Lake in September 2013

A pair of sediment cores, each measuring approximately 1.6 m in length, was recovered from the north basin of Big Blake Lake (45°30'11.68"N, 92°20'10.24"W) on 12 September 2013 (Fig. 2). The cores were recovered from 3 meters 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 45 cm of the core were vertically extruded and sectioned in 1.0-cm increments. The remaining core material was stabilized, transported back to the laboratory and further sectioned in 2-cm increments to 154 cm core depth for core one and 155 cm core depth for core two. Paired cores were taken to ensure we had sufficient material for all planned analyses.

Isotopic Dating and Geochemistry

The sediment core was analyzed for ^{210}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}Po, which is considered to be in secular equilibrium with the parent isotope. Aliquots of freeze-dried sediment were spiked with a known quantity of ^{209}Po as an internal yield tracer and the isotopes distilled at 550°C after treatment with concentrated HCl. Polonium isotopes were then directly plated onto silver planchets from a 0.5 N HCl solution. Activity was measured for 1-3 x 10^5 s using an Ortec alpha spectrometry system. Supported ^{210}Pb was estimated by mean activity in the lowest core samples and subtracted from upcore activity to calculate unsupported ^{210}Pb. Core dates and sedimentation rates were calculated using the constant rate of supply model (Appleby and Oldfield 1978, 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°C for 24 hr to determine water content and dry bulk density, then heated at 550°C and 1000°C to calculate organic and carbonate content from post-ignition weight loss, respectively. These data were used in combination with ^{210}Pb dating to calculate sedimentation rates (mg cm^{-2} yr^{-1}) for each core and its sediment constituents.

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)."

Biogenic silica (BSi), a proxy for historical diatom and chrysophyte algal productivity, was measured using weighed subsamples (30 mg) from each primary core, which 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 Lachat QuikChem 8000 flow injection autoanalyzer as molybdate reactive silica (McKnight 1991).

Diatom Analysis

Diatoms were used in this study to provide a timeline of changes in the Big Blake Lake algal community and estimates of historical water column total phosphorus concentrations. The analytical steps are as follows: Diatoms and chrysophyte cysts were prepared by placing approximately 50 mg freeze dried core material 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% H_2O_2 and heating for 3 hr in an 85°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 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). 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 or ppb.

Analysis of Chitinous and Vegetative Remains

Chironomid head capsules and zooplankton remains were analyzed along with aquatic macrophyte remains to assess ecosystem level changes in Big Blake Lake such as habitat loss, changes in fisheries, and colonization by invasive species. Wet sediment samples (2 cm^3) were first disaggregated in hot water. Samples were then sieved through a 125 µm (no.120) standard soil test sieve and specimens picked out using a fine forceps under a stereo microscope at 25X magnification. Samples were either slide mounted or identified in a Borgorov counting chamber under magnification appropriate for each taxon. All specimens picked from the samples were identified to the lowest taxonomic using available taxonomic literature (e.g., Brooks et al. 2007, Crow and Hellquist 2000, Korosi and Smol 2012). Predominant species were stratigraphically plotted against core date. Autecology of individual taxa was investigated, and species groups with similar ecological niches were used to infer ecological change.

Algal Pigment Analysis

Carotenoids, chlorophylls, and derivatives were extracted (4°C, dark, N2) 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

Core Dating and Sedimentation Rates

The Big Blake Lake core showed a monotonic decrease in Pb-210 inventory to supported levels below 45 cm core depth. Using the date-depth relationship, 20 cm down the core represents approximately 1960 and sediments deposited deeper than 33 cm are dated before 1880. Sedimentation rates in Big Blake Lake began increasing immediately after European settlement and continue to increase upcore. Modern sedimentation rates are approximately four times greater than pre-1900 rates (Figure 3). Pre-settlement sedimentation rates in Big Blake Lake were approximately 0.007 g/cm^2 yr compared to 0.028 g/cm^2 yr since the 1990s. Increases in sedimentation rates are common in Midwestern lakes following logging, land clearance for agriculture, and changes in land use/cover.

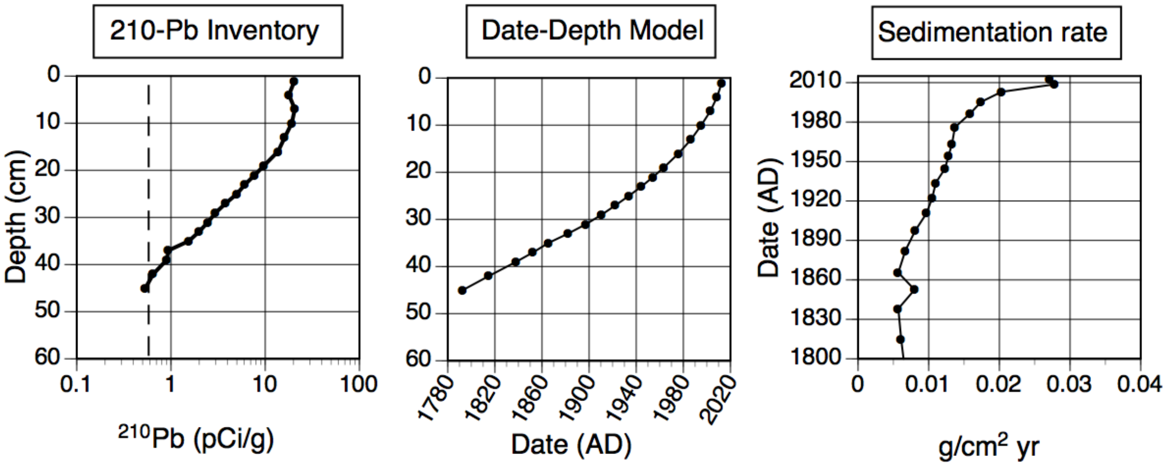


Fig. 3 Pb-210 inventory, date-depth model, and historical sedimentation rates for Big Blake Lake.

Loss-on-ignition

Sediments in Big Blake Lake have shifted from being dominated by the organic fraction (pre-settlement; 54.7% organic matter) to being dominated by the inorganic fraction (present day; 45.7% inorganic matter) (Figure 4). Carbonates rise from 6.4% of the sediment fraction in pre-settlement and increase to 16% in recent sediments; carbonates commonly increase in sediments as a consequence of greater plant and algae production in a lake (carbonates are precipitated as a result of photosynthesis). Inorganics notably increased in accumulation to a peak in the 1940s before dropping slightly until 1980 before increasing in most recent times. Increases in inorganics around 1900 are generally an erosional signal of logging and land clearance associated with settlement in the region.

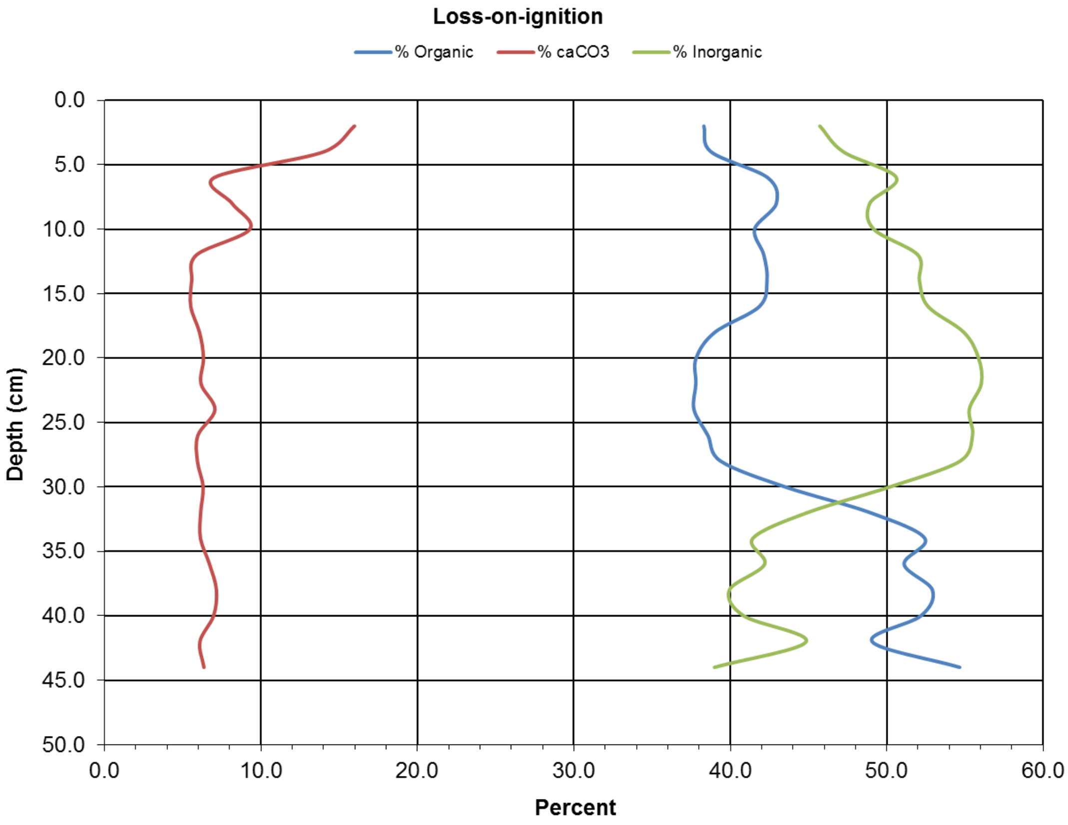


Fig. 4. Loss-on-ignition

Biogenic Silica (BSi)

Biogenic silica composed 8.3-13.7% of the dry weight of Big Blake Lake sediment, with the lowest values in the 1990s to present day (as BSi content is diluted by carbonates) and the highest values from pre-settlement to the 1880s (Figure 5). Upcore decreases in BSi were noted in the top 6 cm of sediment. Big Blake Lake has relatively high levels of BSi, most lakes have from 2-4% biogenic silica by weight. When BSi is presented as accumulation rates, the flux of BSi increases in the 1930s to the top of the Big Blake Lake core. Modern accumulation rates of biogenic silica are almost 70% greater than in pre-European settlement times likely reflecting greater diatom algae productivity in recent decades.

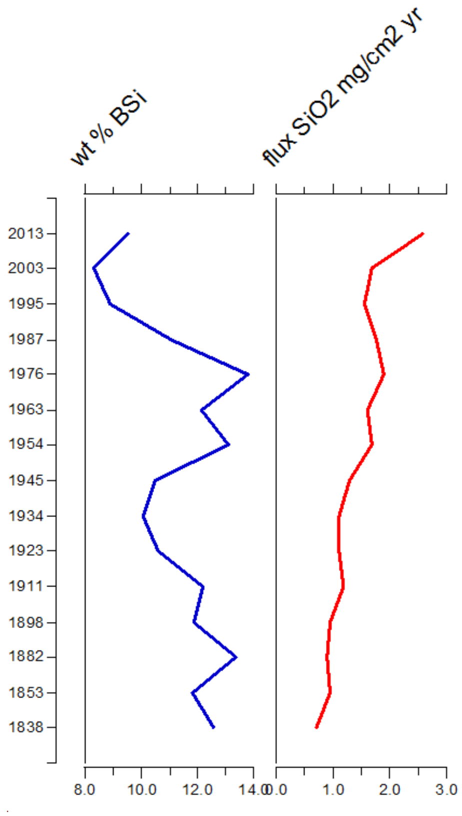
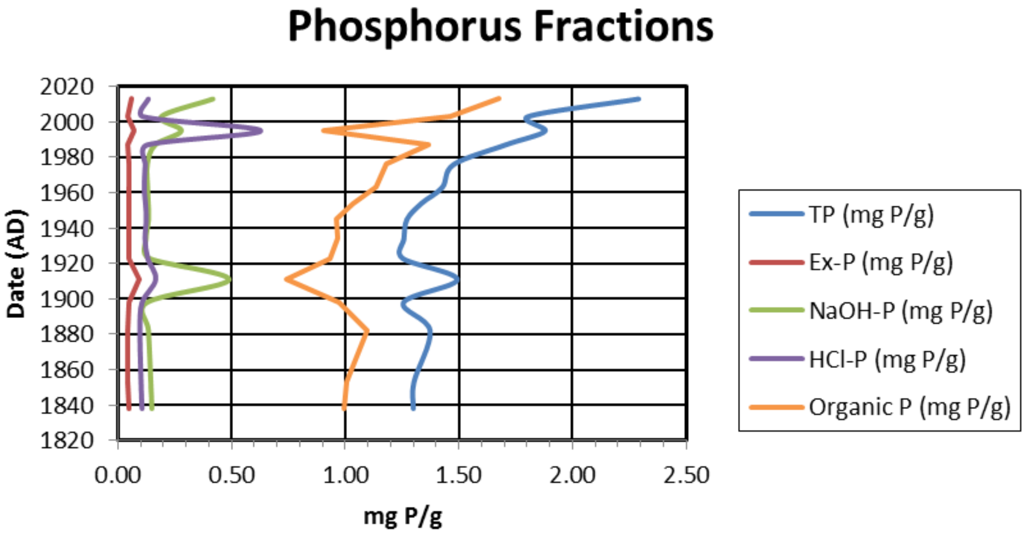


Fig. 5 Biogenic silica content (percent dry weight) and accumulation rate (mg/cm^2 yr-^{1})

Sediment Phosphorus Fractions

Total phosphorus in Big Blake Lake sediment ranged from 1.3 to 2.3 mg P/g with increasing amounts moving upcore and the highest values at the core top (Figure 6). The organic-P made up the largest proportion of the fractions followed by NaOH-P and HCl-P fractions. We must consider the potential mobility and possibility of exchange of P with the water column in the distribution and abundance of the refractory (HCl-P, Org-P) and labile/exchangeable P (Ex-P, NaOH-P). In Big Blake Lake, an active pool of labile P forms is strongly distributed in the top 4 cm of the core suggesting that while Big Blake 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 the outflow), there is a ready pool of P to fuel internal loading during certain times of the year.



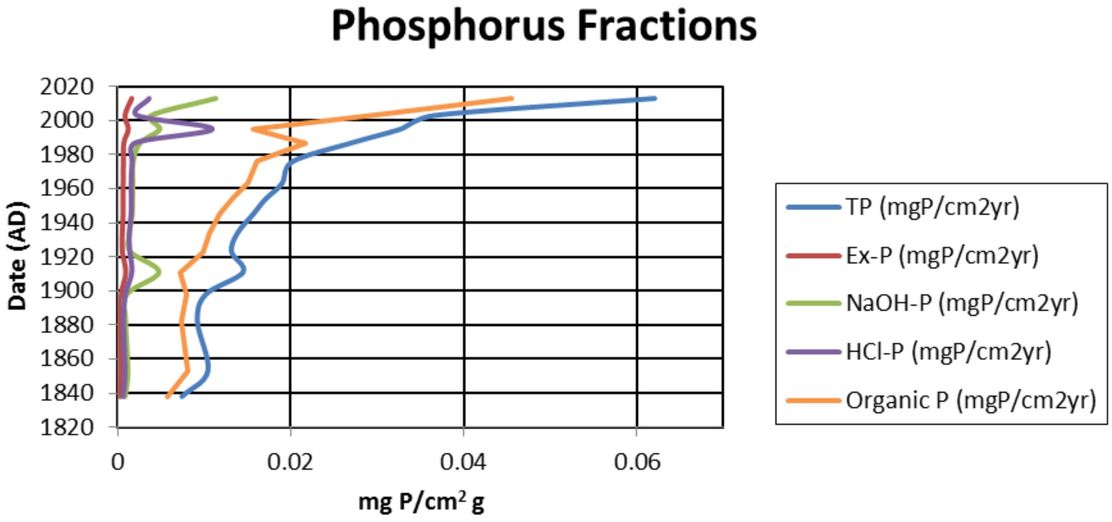


Fig. 6 Sediment phosphorus fractions in Big Blake Lake core including total phosphorus (TP), exchangeable P (Ex-P, NaOH extractable P (NaOH-P), HCl extractable P (HCl-P), and organic P (Org-P)

Accumulation rates of organic P and total P in the cores increase after 1900 to levels that are almost five-fold higher than pre-European settlement (Figure 6). There are less dramatic increases in the other fractions of P; however, NaOH-P and Ex-P may be a limited but active pool of P available to the water column. The greatest flux of labile P occurs in the top few centimeters of the core. This pool of P is important given the propensity for the lake to have anoxic bottom waters in mid-summer following senescence of *Potamogeton crispus* by early summer, which releases additional labile P from the sediments to fuel frequent cyanobacterial blooms.

Diatom Communities and TP reconstructions

In the Big Blake Lake core there were over 110 diatom species noted. In pre-European settlement samples, benthic or epiphytic (living on the bottom or on plants) species such as *Staurosira construens* and *S. venter* were dominant. After the 1940s planktonic species that live in the water column such as *Aulacoseira granulata* and *Fragilaria crotonensis* dominate the samples.

Several analyses were run to determine how the diatom communities in each level were related to each other and develop stratigraphic groupings. The first shows an ordination biplot from detrended correspondence analysis (DCA) that shows how the core samples cluster based on similarity of diatom assemblage (Figure 7). Note that the presettlement samples are grouped on the left of axis 1, undergo a rapid shift to the right on axis 1 between 1923 and 1954, and then remain to the right on axis 1, but vary more on axis 2 from 1954 to present.

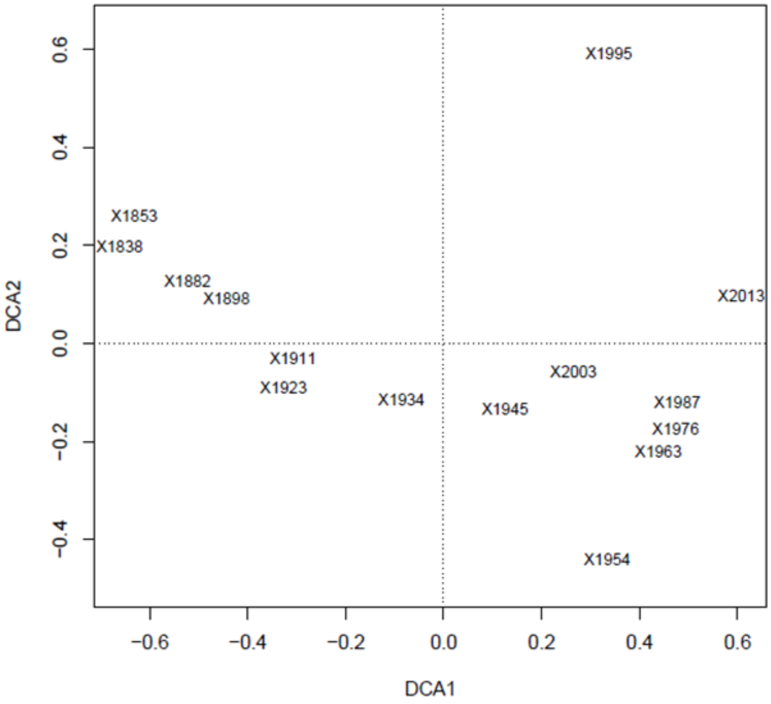


Fig. 7 Detrended Correspondence Analysis (DCA) of the diatom community from the Big Blake Lake sediment core by dated core level. Core levels that plot closer together are generally more similar.

A constrained cluster analysis was also run and confirms the DCA results (Figure 8). These results suggest that the major significant breaks among diatom assemblages occur between 1924 and 1934, 1945 to 1954, and 1987 to present day. Similarly, the diatom community show major changes from the 1890s to the 1960s along Axis 1 of the DCA plot; and change over the last sixty years along Axis 2. This may suggest that the lake has been experiencing multiple stressors over many decades.

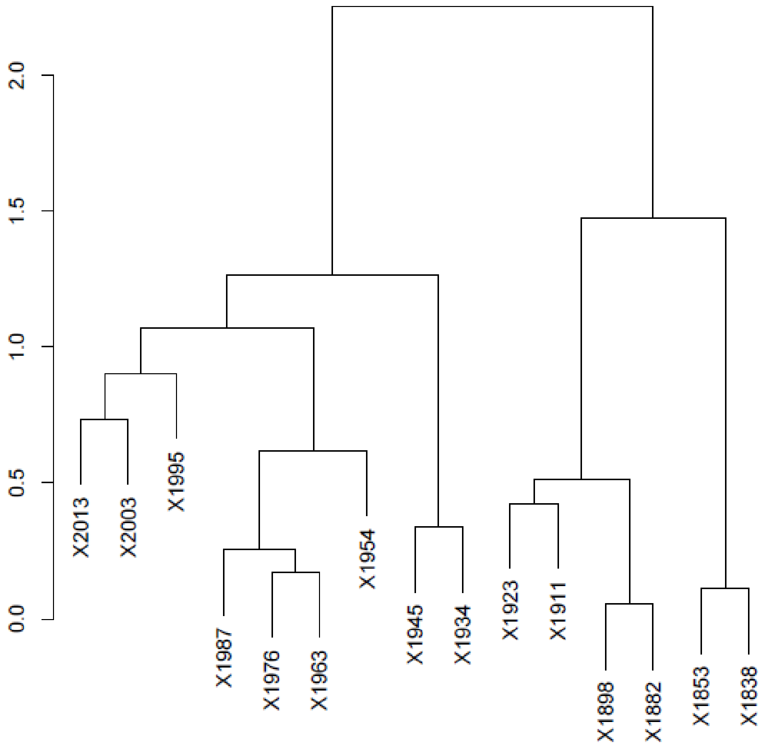


Fig. 8 Constrained Cluster Analysis of diatom communities by dated core level from the Big Blake Lake sediment core based on Euclidean distance.

Changes in the abundance of predominant diatoms can be seen in a stratigraphic diagram of the core (Figure 9). The shifts in diatoms communities can clearly be seen in the increases in *Aulacoseira granulata, Fragilaria crotonensis,* and the benthic *Staurosirella pinnata* and decreases in *Staurosira construens*, *S. venter*, and the mesotrophic species *Aulacoseira ambigua*. The sharp increase in *Fragilaria crotonensis* sets the very top of the core apart from the rest of the core, but there has clearly been changes thoughout the modern history of Big Blake Lake.

The common diatoms near the bottom of the Big Blake Lake core are indicative of a mesotrophic midwestern lake, while diatom communities at the top imply a eutrophic condition (Figure 10). The two *Staurosira* species, abundant in the bottom of the core, are both non-motile species that are likely benthic or epiphytic species that often form small colonies. The two *Aulacoseira* species are indicative of strong mixing of the lake. *Aulacoseira ambigua*, which decreases towards the top of the core, is more indicative of a mesotrophic lake; while *A. granulata*, which increases towards the top of the core, is more indicative of a shallow eutrophic lake. The sharp increase in *Fragilaria crotonensis* near the top of the core is an indication that the lake has continued to eutrophy over time.

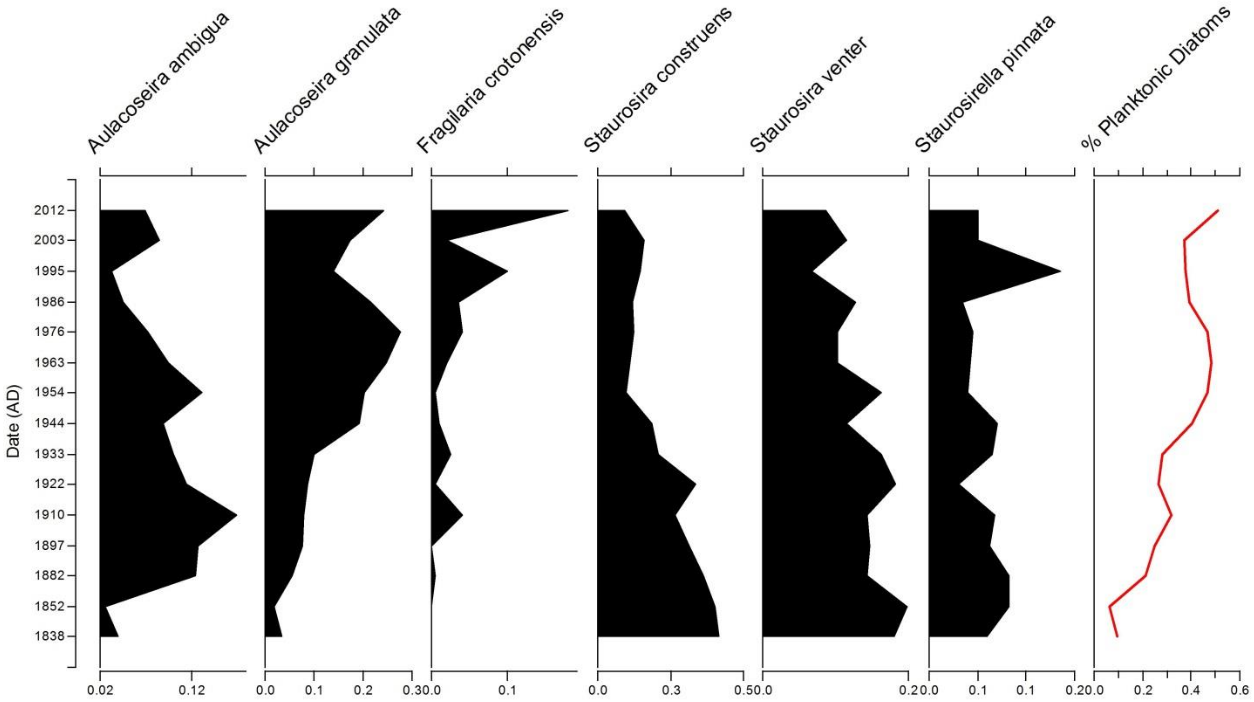
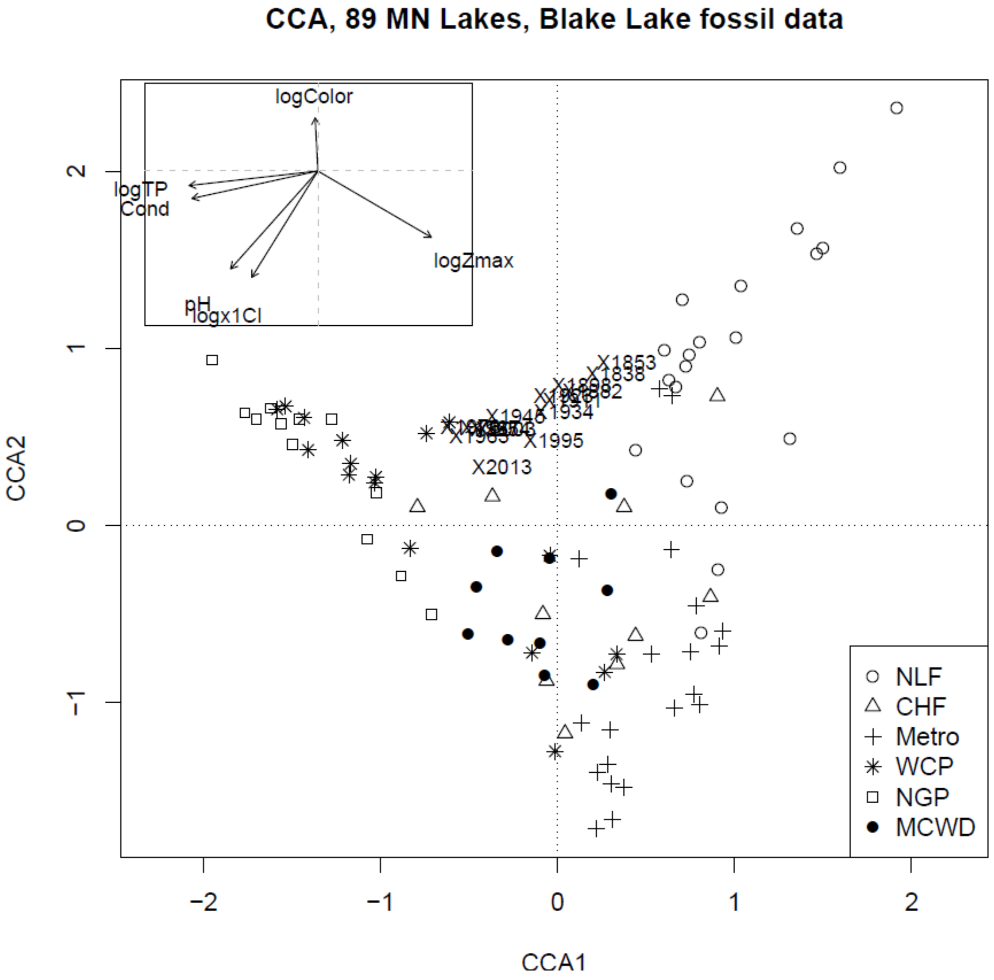


Fig. 9 Downcore distribution by core date of predominant diatoms in the Big Blake Lake sediment core. Diatom abundances are given relative to total diatom count.

Fig. 10 Diatom communities for the Big Blake Lake sediment core circa 1852 (left) and 2012 (right).

The diatom communities were also used to reconstruct historical TP levels in Big Blake 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 Big Blake 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 (Figure 11; Juggins et al. 2013).

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 Big Blake Lake, this analysis shows that the fraction of the maximum explainable variation in the diatom data that can be explained by TP is very high (= 0.9291). The high score from this analysis, coupled with the strong correlation with the logTP axis in the passive plot (Figure 11), suggests that TP has been a significant driver of diatom community change in this lake and therefore therefore we can be confident in the TP reconstruction.



The TP

Fig. 11. Diatom communities in dated Big Blake 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. The historical diatom communities in Big Blake Lake were responding strongly to changes in TP, and are aligned with the logTP axis.

The reconstruction on Big Blake Lake suggests that the lake has gone from a mesotrophic state to a eutrophic state, with levels starting to increase immediately after Euroamerican settlement (Figure 12). Diatom-inferred TP also suggests a sharp increase in TP after 1940. A final 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 from 2012 to 2015 ranged from 23 to 135 ppb TP with notably higher levels in late summer and fall that were associated with cyanobacterial blooms.

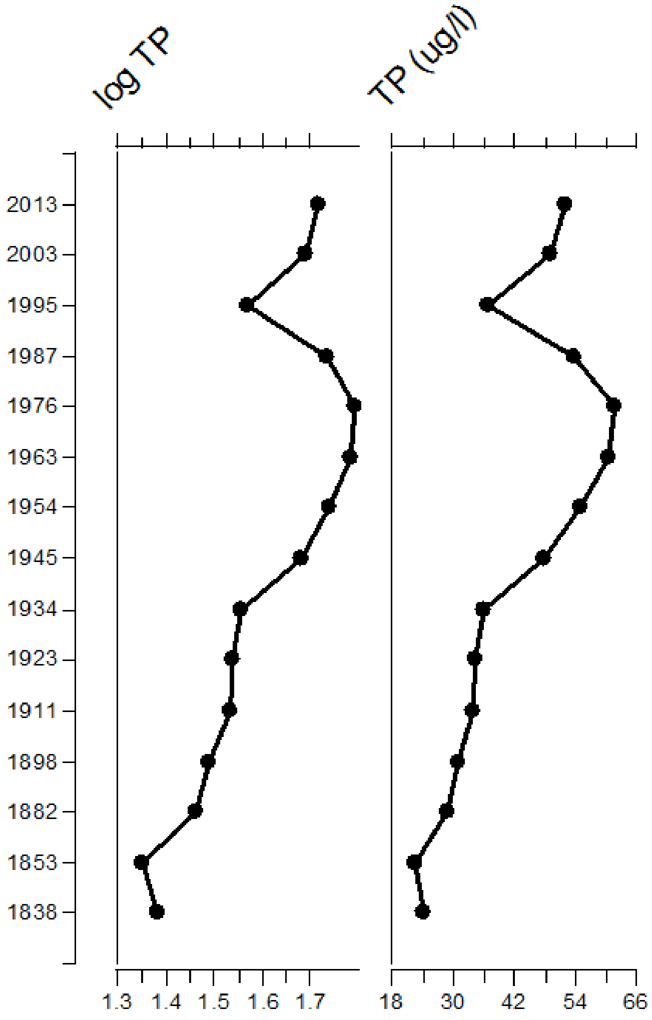


Fig. 12. Historical diatom-inferred TP levels for Big Blake Lake. Model reconstructions (left panel) are in log TP units (model error estimate is 0.2069 logTP units; RMSEP). The back transformed diatom-inferred TP levels are given in the right panel in the more commonly reported units of µg/l or ppb.

Historical Algal Communities

The algae consist of many biological groups of organisms that do not represent a single lineage on the evolutionary tree of life, but are linked by function—the algae generally are small, photosynthetic, and do not have organized tissues similar to higher plants (flowers and trees). From an ecological perspective the algae are critical to the functioning of the earth (algae account for about 50% of the photosynthesis—hence the oxygen we breathe) and form the base of the food web in most lake and river systems. The different algal groups are separated based on their cell structure (bacterial type or prokaryotes—the Cyanobacteria; or true cells or eukaryotes—the rest of the algal groups), storage products (starch, lipids, proteins), pigments, cell wall or membrane structure, cellular organization, and life history types. The types of algae present in a lake are influenced by environmental and biogeographical factors like climate, phosphorus, nitrogen, and silica concentrations and ratios, pH, grazing, substrate, and other factors in the lake basin. Lakes that have been heavily impacted with nutrients most often are dominated by blue-green algae for the greater part of the open water season with spring and winter the only periods where other algal groups might dominate.

Algal pigments were quantified in fifteen core sections to determine the historical concentration or production of different algal groups (Figure 13). Total algal production, as measured by betacarotene and chlorophyll *a*, showed that overall production was relatively low until the 1940s with sharp increases after the 1960s. The diatoms and most of the cyanobacterial groups followed this same pattern, with the exception of aphanizophyll which was not present until the 1980s.

Cyanobacterial groups were present throughout the length of the core, dating back to the 1800s. Cyanobacteria or blue-green algae are a natural and normal part of the algal flora in all lakes, but they tend to flourish in nutrient-rich waters, and may cause nuisance or harmful algal blooms. Pigments from the cyanobacteria are differentiated into various types that are associated with specific subgroups of blue-green algae (e.g., canthaxanthin, lutein-zeaxanthin, etc.), and there is evidence that pigments associated with potentially toxic, nitrogen-fixing forms (aphanizophyll) have become much more abundant in the lake in recent times. The recent dramatic increase in abundance of aphanizophyll in Big Blake Lake suggests that conditions were not conducive to support nuisance blooms of cyanobacteria until late in the 20th century. Evidence would also support that recent nutrient increases due to watershed development and the introduction of *Potamogeton crispus* have exacerbated cyanobacteria growth so that blooms are more prevalent than in the past.

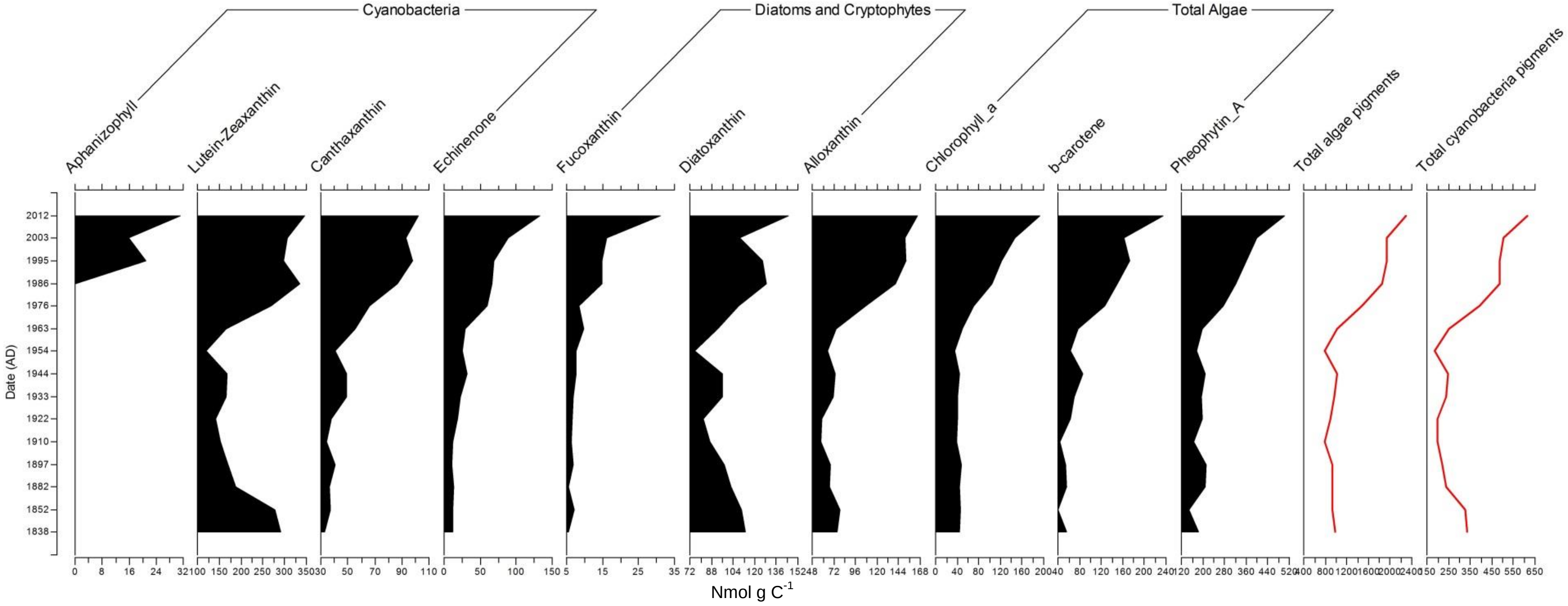


Fig. 13. The sediment algal pigments quantified in fifteen core sections from Big Blake Lake. The group of algae associated with each pigment is also shown along the x-axis.

Historical Zooplankton Communities

Cladoceran subfossils were quantified in fifteen core sections to determine the historical concentration or production of different zooplankton species (Figure 14). Total zooplankton, as measured by subfossil count, showed that overall abundance was high until the 1960s when sharp decreases in littoral species began. Other species followed this same pattern, with a small increase of production in the most recent two decades.

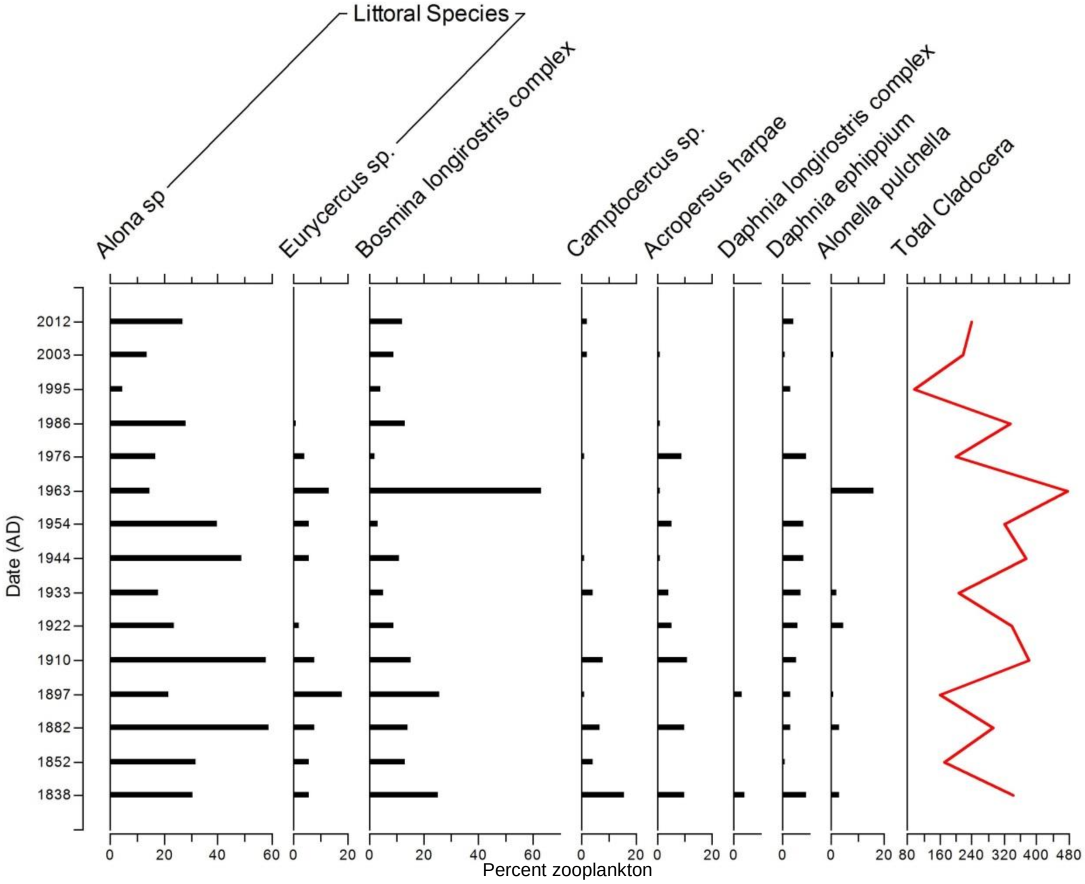


Fig. 14. The sediment cladoceran subfossils quantified in fifteen core sections from Big Blake Lake.

Zooplankton is often overlooked in paleolimnological studies, but their role in a lake is influential in structuring the algal and fish communities. Lake systems are valued primarily for water clarity, fishing, or other recreation, all of which are strongly linked to water quality and ecosystem health. Zooplankton is the primary link between the "bottom up" processes (through grazing) and "top down" processes (as a food source for fish) of the lake ecosystem.

Changes in the aquatic plant community and shoreland habitat can impact zooplankton populations. This occurs especially in shallow lakes where zooplankton are more likely to have the ability to migrate horizontally in and out of macrophyte (aquatic plant) beds to avoid predation from fish and other invertebrates, as is likely the case in Big Blake Lake. The loss of littoral taxa such as *Alona sp.* and *Eurycercus sp.* indicates changes in littoral habitat have occurred in Big Blake Lake, either from increased sedimentation, loss of the native aquatic plant diversity, or the introduction of invasive species such as *Potamogeton crispus*. The general decline in cladocerans is likely due to multiple stressors such as sedimentation, aquatic invasive species, and the increasing prevalence of cyanobacteria in the system.

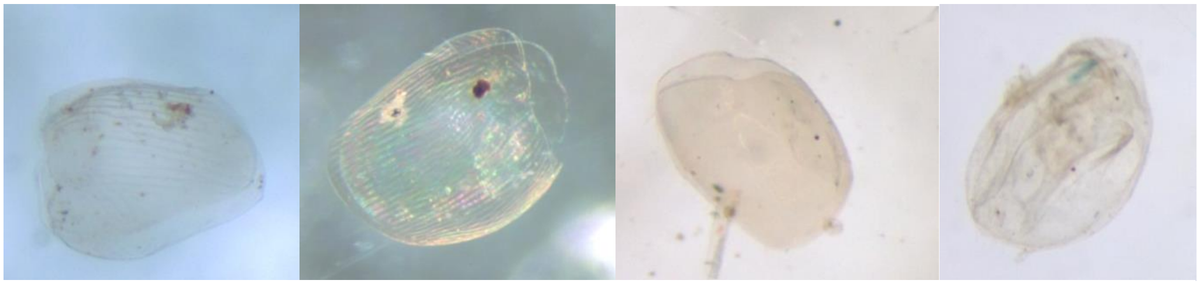


Fig. 15. Examples of subfossil cladocerans from Big Blake Lake recovered from various core depths.

Historical Chironomidae communities

Head capsules of larval chironomids, or the non-biting midges, have several attributes that make them useful as environmental indicators. They are stenotopic or able to tolerate only a restricted range of habitats or ecological conditions, but as a group are ubiquitous and abundant. In addition they are readily identifiable, species-rich, sensitive to change, and inferences drawn from chironomid assemblages can complement other paleoecological proxies (Brooks et al. 2007).

All head capsules from each sediment sample were identified to the lowest taxonomic level. Eleven taxa from five major groups were identified in the sediment samples (Figures 16 & 17). Some diagnostic characteristics that are used to separate taxonomic groups within the Chironomidae include: 1. the head capsule of the Tanypodinae looks very different than other chironomids as they do not have a distinctive row of teeth on the mentum, but have a hand-shaped ligula, 2. the Chironomini often have a large head capsule with fan-shaped striated ventromental plates and the mentum can have a variable number of teeth 3. Tanytarsini head capsules have sausage-shaped ventromental plates that are striated, and the mentum has one median tooth and five lateral teeth, and 4. the Orthocladiinae head capsule has a mentum that is very strongly arched (usually with 4-6 pairs of lateral teeth), with narrow, inconspicuous, unstriated ventromental plates, and sometimes has a beard. Another dipteran group that can be found in sediment is the phantom midges or Chaoboridae; for this group it is the mandibles rather than the head capsule that are preserved in lake sediment.

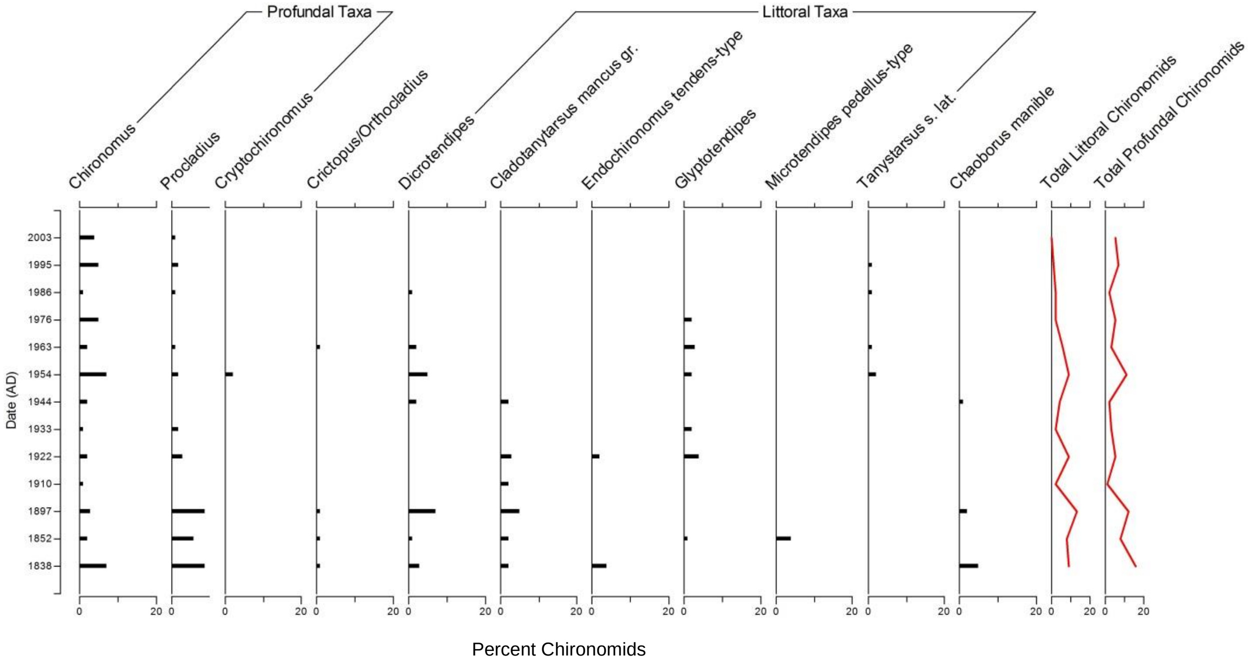


Fig. 16. The sediment chironomid head capsules and *Chaoborus* mandibles quantified in fifteen core sections from Big Blake Lake.

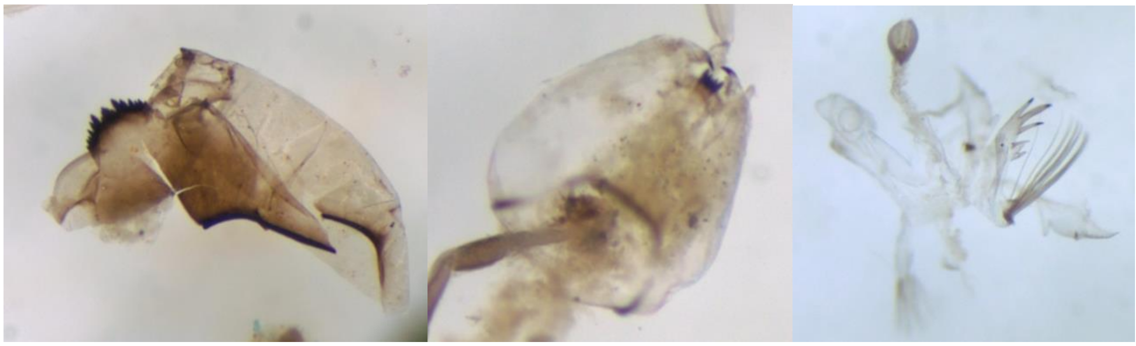


Fig. 17. Chironomid head capsules and a *Chaoborus* mandible from Big Blake Lake recovered from various core depths

Even with a low abundance of head capsules, differences in the chironomid community can be seen through time (Figure 16). There is a decline in *Procladius* starting in the early 1900s, while there is an increase in *Chironomus* in the 1950s. There is also a decline in *Chaoborus* in the early 1900s, and *Chaoborus* mandibles did not occur in the core after the 1940s. *Procladius* is carnivorous, and lives in fine sediments and may be eliminated during periods of anoxia; however, it can survive a long time in an anoxic environment. *Procladius* is most abundant in mesotrophic and eutrophic lakes. *Chironomus* is abundant in warm eutrophic lakes usually in the profundal zone. Due to the hemoglobin in their bodies, *Chironomus* is tolerant of low oxygen conditions and even anoxia for a few weeks. *Chironomus* is opportunistic and is often an early colonizer after environmental change. They are detritivores and filter feeders. *Chaoborus* are often referred to as phantom midges. A high abundance of remains can be indicative of anoxic conditions (Brooks et al., 2007). However, *Chaoborus* abundance is strongly influenced by fish predation, and remains can aid reconstructions of past fish population (Tolonen et al. 2012). There is also an increase of species of indicative of eutrophic conditions such as *Glyptotendipes*, *Dicrotendipes*, and *Chironomus* (Francis 2001) beginning around the 1920s. *Glyptotendipes* and *Dicrotendipes* are large tube-building larvae that depend on a rain of plankton and detritus as food.

Chironomid head capsules have been used to model many facets of environmental change ranging from mean July air temperature and hypolimnetic oxygen to chlorophyll *a*. In this study chironomids where used to augment plant macrofossils and cladoceran subfossils to assess habitat alteration due to increased sedimentation and the introduction of *Potamogeton crispus* into Big Blake Lake. There is a sharp decrease in littoral species in the 1950s and there were none found in the most recently deposited sediment whereas profundal taxa generally did not decrease over time (Figure 16). This would suggest that habitat alteration due to increased sedimentation, aquatic plant management, and the introduction of *Potamogeton crispus* has had a profound effect on chironomid taxa in Big Blake Lake.

Historical Aquatic Macrophyte Communities

Rich aquatic plant communities in midwestern lakes are an invaluable part of the lake's ecosystem, particularly to invertebrates and fish. In lakes, plant growth is limited to certain depths based on availability of light. With greater water clarity, light can penetrate to greater depths and be used by plants for growth. In Big Blake Lake the maximum depth of plants is generally around 2.7 meters. In the spring and early summer, within vegetated areas, *Potamogeton crispus* (curly-leaf pondweed) is the most frequently encountered plant while *Ceratophyllum demersum* (coontail) is the most frequent plant in the late summer and early fall (Figure 18).

Fig. 18 ***Ceratophyllum demersum* (coontail) macrofossil. Big Blake Lake core, 31 cm.**

Potamogeton crispus can have a particularly negative impact on aquatic macrophyte communities because of its life cycle; it germinates in the fall, lies dormant throughout the ice covered season, then actively grows in early spring before indigenous macrophytes have a chance to become established. Because of early germination, *Potamogeton crispus* also senescences early with the potential to release large pools of phosphorus from plant tissues and the sediment, and further reducing littoral coverage of indigenous species.

Because aquatic macrophytes play such an important role in lake ecosystems (especially shallow lakes) macrofossils were identified from 15 different core sections. All plant remains with diagnostic features where picked and identified to the lowest taxonomic resolution possible (Figure 19).

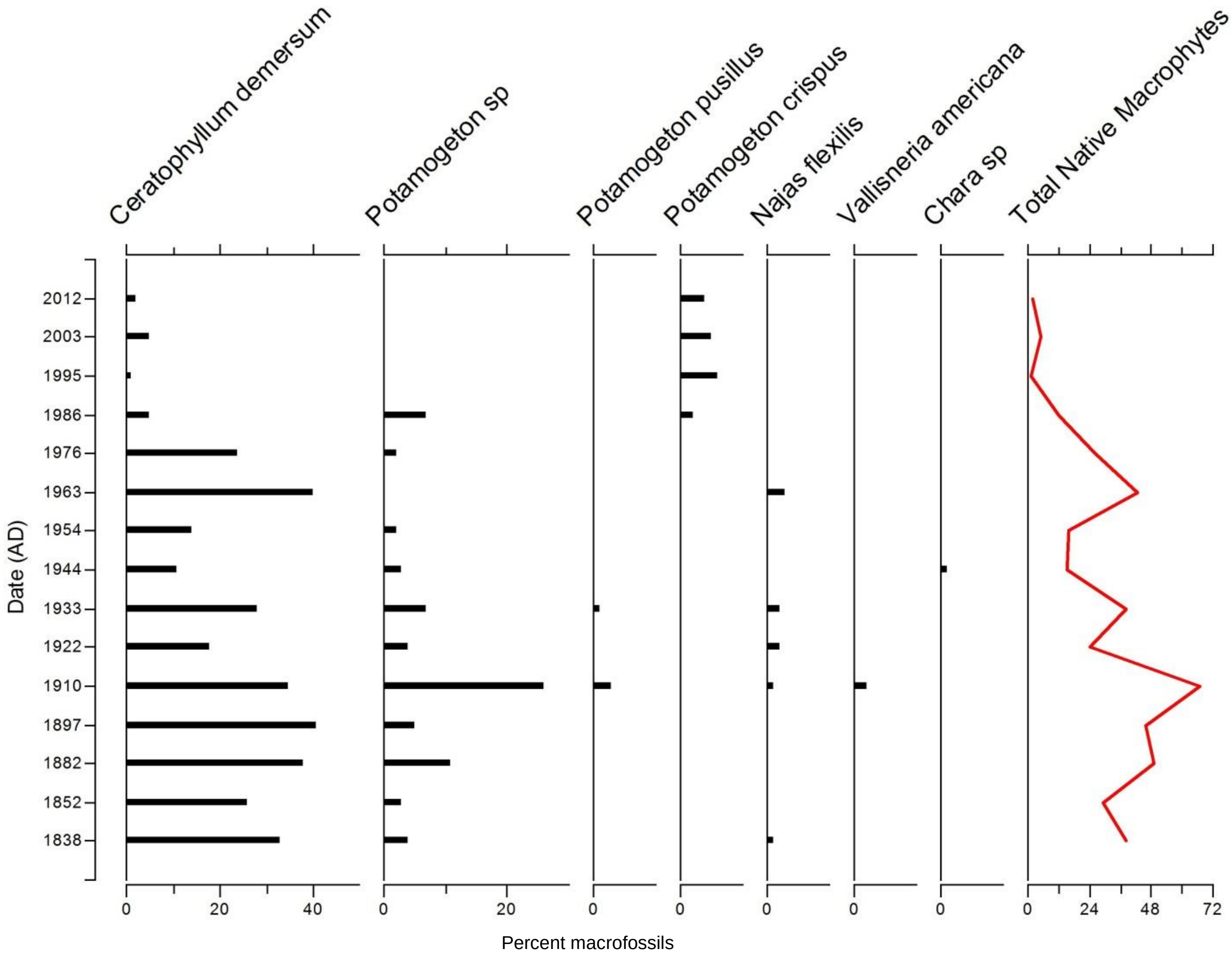


Fig. 19. The sediment aquatic plant remains quantified in fifteen core sections from Big Blake Lake.

Macrofossils of indigenous aquatic plants begin to decrease around 1910. This is likely to do land clearance on conversion in the watershed. There is a sharp decline in native macrophytes after the 1960s. This is likely due to additional watershed disturbances, the increase in nutrients, and the expansion of lake shore development, and eventually the introduction of *Potamogeton crispus* in the 1980s. The most recent decades have very few indigenous plant fossils but there is a higher occurrence of *Potamogeton cripus* beginning in the 1980s. Multiple stressors have severely altered littoral habitat in Big Blake Lake.

Conclusions

There have been dramatic changes in Big Blake Lake since pre-Euroamerican settlement. Sedimentation had a peak in 1910 and continued increasing after the 1940s to present day levels almost four times as high as historical sedimentation rates. The composition of the sediment has shifted from mostly organic to inorganic components. Sediment phosphorus and biogenic silica also see significant increases over the period that this study examined.

Overall, the sediment record shows multiple lines of correlated biological evidence of a shift in Big Blake Lake to its current eutrophic condition (Figure 20). For example, there were major changes in the diatom community of Big Blake Lake. The diatom flora was dominated by benthic and mesotrophic taxa from pre-settlement until the 1930s. By the 1940s the lake became dominated by eutrophic, planktonic taxa likely due to phosphorus enrichment. Indeed, diatom inferred TP concentrations show an increase to phosphorus levels considered eutrophic by the 1940s. A sharp increase in *Fragilaria crotonensis* accompanied a period when small seasonal cottages were being replaced with year-round lake homes. The algal pigment analysis showed that cyanobacteria have significantly increased since the 1960s with nitrogen fixing, possibly toxic forms appearing by the 1980s.

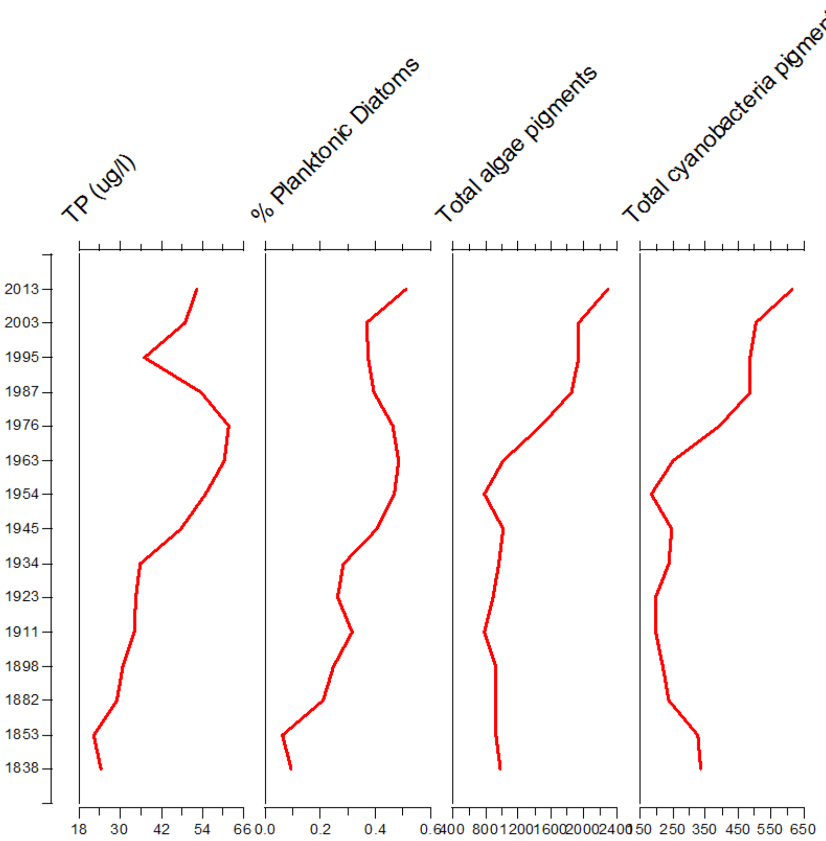
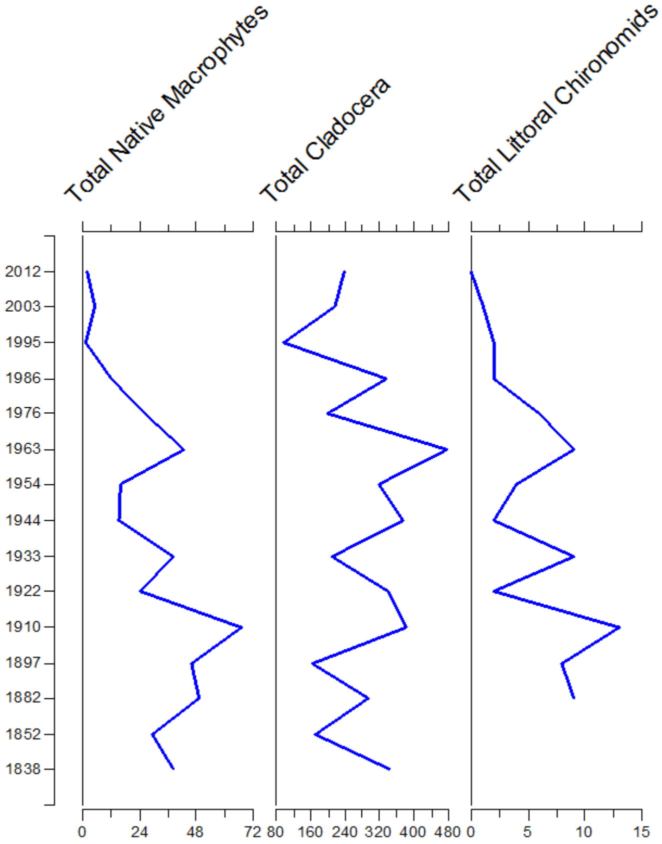


Fig. 20. Indicators for Big Blake Lake core showing a shift to a eutrophic state

Other biological indicators show how in-lake habitats have changed in Big Blake Lake (Figure 21). Cladoceran and littoral Chironomidae are greatly reduced after the 1960s indicating that there have been major habitat alterations in Big Blake Lake. This is like due to multiple factors such as sedimentation and changes in sediment composition, nutrient enrichment, loss of native plants, and the introduction of *Potamogeton crispus*. Aquatic plant remains of indigenous species decline sharply during this same time period as well. The absence of *Chaoborus* mandibles would indicate that habitat alterations also led to a change in the lake's fisheries.

Fig. 21. Indicators of littoral and mesotrophic state showing decline from the Big Blake Lake core



Big Blake Lake has seen significant changes over the period of this study. The lake has shifted from a mesotrophic lake with a healthy aquatic plant community and associated fauna to a nutrient-rich eutrophic lake dominated by *Potamogeton crispus* in the spring and early summer (Figures 20 & 21). The Big Blake Lake Protection and Rehabilitation District should continue control efforts by harvesting and removing *Potamogeton crispus* biomass. Wider control efforts in the watershed should emphasize working collaboratively with other districts in the Straight River watershed. Efforts should be made on Big Blake Lake to install best management practices for nutrient control around the lake, including nearshore and littoral habitat protection along with other management strategies. The district should maintain monitoring efforts that are in place to detect further changes in lake condition.

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