A Paleolimnological Study of Bone Lake, Polk County, Wisconsin: Fossil Algal Pigments

Mark B. Edlund

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

and

Jeremy Williamson
Polk County Land & Water Resources Department
100 Polk County Plaza, Suite 120
Balsam Lake, WI 54810

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Bone Lake Management District
2051 100th St
Luck, WI 54853-2304

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Project Rationale

Management concerns for Bone Lake have been focused around prevalence of 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.
In a previous study of a sediment core from Bone Lake (Edlund et al. 2015), a variety of evidence was presented to develop a history of ecological changes that have occurred in the lake since Euroamerican settlement. It was shown that sedimentation rates have increased by about two times since settlement and that the increased sedimentation represented increased deposition of inorganic and organic matter. These changes generally reflect increased erosion in the basin and increased productivity in the lake. Accumulation rates of biogenic silica show two peaks in diatom (algae) growth in the 1920s-1950s and in the most recent decades with modern levels about 30% greater than pre-settlement. The diatom community showed a significant shift in 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 change in the diatom community was the decreased abundance upcore of a mesotrophic indicator species (e.g., *Aulacoseira ambigua*), and the post-1940s increase in small *Stephanodiscus* species (an indication of increased eutrophication). It was also notable that the diatom community has always been historically dominated by other meso- to eutrophic indicator species including *A. granulata* and *Stephanodiscus niagarae*. The diatoms were also used to estimate historical TP levels in Bone Lake and showed that diatom-inferrred 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.

What may be contributing to those cyanobacterial blooms is evidenced in the concentration and accumulation rates of phosphorus fractions in Bone Lake sediments. Sediment phosphorus and its fractions showed 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. This provides an accessible and readily available source of P (phosphorus) during periods of internal loading driven by anoxic bottom waters during stratification in summer. The breakdown of stratification in late summer or early fall makes that phosphorus available to the entire water column, which may initiate noxious cyanobacterial blooms.

The purpose of this study was to determine whether the occurrence of cyanobacterial blooms has been a long term characteristic of Bone Lake, or whether those blooms are a more recent phenomenon. A recommendation of the previous sediment core study was to analyze a sediment core from Bone Lake for fossil algal pigments. All algal groups contain pigments that are preserved in sediment cores in approximate ratios and quantities that reflect their historical abundance in a lake. As such, an analysis of fossil algal pigments was used to determine if cyanobacterial blooms are a recent or long-term characteristic of Bone Lake's seasonal cycle.

Methods

A new 1.54 m long sediment core was collected from Bone Lake on 07 August 2015 at the same location as the earlier core collected in 2013 (Edlund et al. 2015). Sediment is deposited in lakes in conformable patterns so that a core collected close to a previous core site and within a few years can have the earlier dating model applied to it.

Fossil pigments including carotenoids, chlorophylls, and their derivatives were extracted according to Leavitt et al. (1989) (4°C, dark, under N_2 gas) from freeze-dried sediments, 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); TOC was measured earlier on the 2013 Bone lake core. Pigment data are grouped by algal types including diatoms, cryptophytes, green algae, blue-green algae, general algae indicators, purple sulfur bacteria, and indicators of pigment degradation; all data are reported by downcore date.

Results

Fifteen pigment or pigment breakdown products were identified from the samples analyzed in the Bone Lake core (Fig. 1). The pigments and breakdown products represent various algal groups or indicators as shown in Table 1 and are expressed as nmol (nanomoles) of pigment per gram of organic carbon (C). Within the core, there are three major break points in pigment profiles in the last 150-200 years. We will discuss each of these time periods, how algal communities responded in each one, and synthesize the data with management recommendations based on this study.

Table 1. Pigment and pigment breakdown products and their sources or indicator value (from Leavitt and Hodgson 2001)

Alloxanthin	cryptophytes
Aphanizophyll	cyanobacteria, N_2 fixers, Nostocales, *Aphanizomenon*
Beta carotene	all algae (total)
Canthaxanthin	Nostocales (colonial cyanobacteria)
Chlorophyll a	all algae (total), easily degraded
Chlorophyll b	green algae, some picoplankton
Diadinoxanthin	dinoflagellates, diatoms, chrysos, cryptophytes
Diatoxanthin	diatoms, chrysophytes, some dinoflagellates
Echinone	cyanobacteria
Fucoxanthin	siliceous algae, and some dinoflagellates, easily degraded
Lutein-zeaxanthin	green algae (lutein), some reds (lutein), cyanobacteria (zeaxanthin)
Myxoxanthophyll	colonial cyanobacteria, including potential toxic forms
Okenone	purple-sulfur bacteria
Pheophytin b	derivative of Chl b
Chl a:Phaeo A	preservation indicator

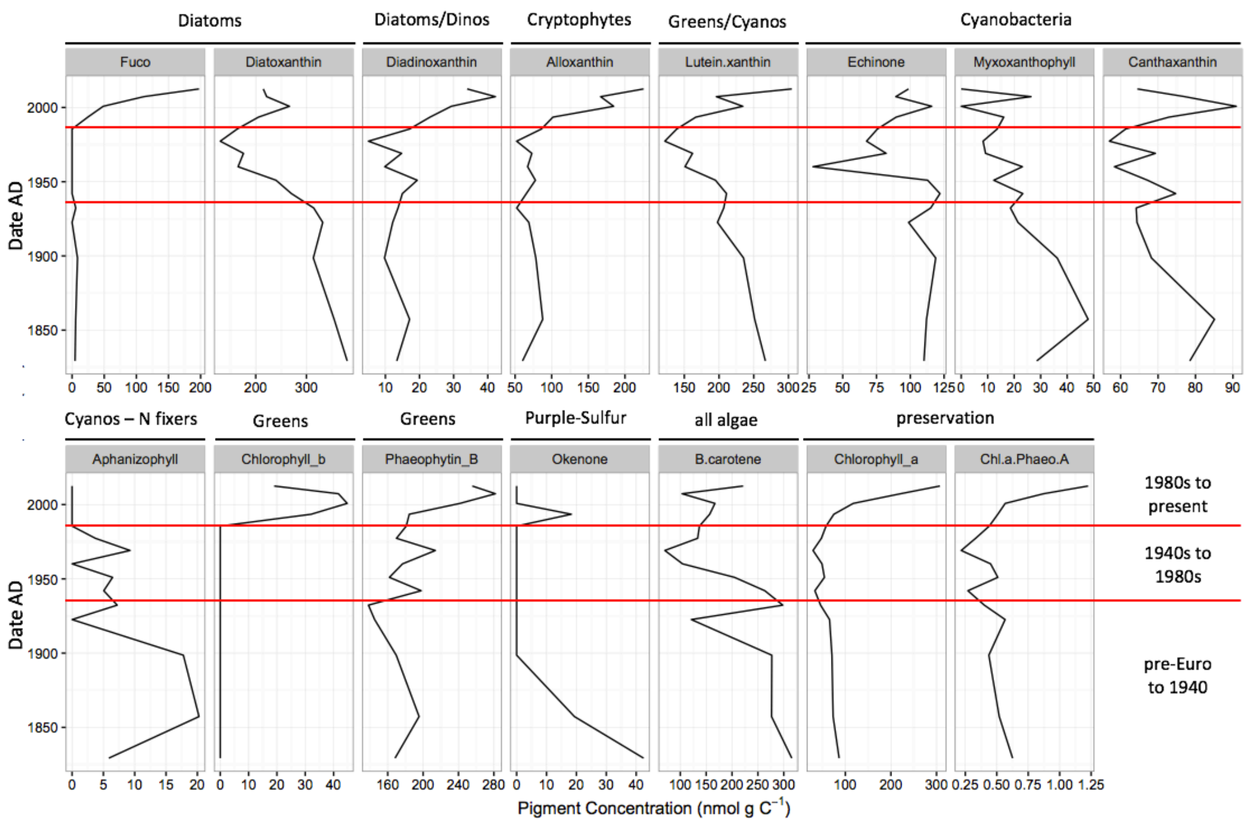

Fig. 1. Downcore profiles by date (AD) of fifteen photosynthetic pigments or indicators (nmol gC^{-1}) in Bone Lake. Pigment source or indicator value noted above each graph. Red lines denote major periods of historical change in algal communities.

*Impact of European settlement—*There appears to be minimal change in algal communities associated with initial European settlement in the Bone Lake watershed. In many areas of the Upper Midwest, especially in northern lakes, European settlement represents the greatest historical change in lakes as evidenced through increased sedimentation rates and changes in sediment makeup (both of these changes typically related to initial land clearance/logging and conversion to agriculture) as well as the first indication of nutrient increases. In Bone Lake, the same characteristic increase in sedimentation rate was present following European settlement with sedimentation rates increasing between settlement and the 1920s. Pigments deposited during this time provide evidence of the historical or reference condition of algae communities in Bone Lake. The presettlement algal community contained a diverse group comprising diatoms and dinoflagellates (diadinoxanthin), green algae (lutein/zeoxanthin, B-carotene) and a cyanobacteria strongly favored by nitrogren fixers (lutein/zeoxanthin, echinone, myxoxanthophyll, canthaxanthin, aphanizophyll). The strong cyanobacterial signatures suggest that the lake was productive and may have been seasonally N-limited and dominated by cyanobacteria. Notable changes suggest initial loss of macrophytes and water clarity as the pigment okenone disappear. Okenone is a pigment from photosynthetic purple-sulfur bacteria and is indicative of lakes with heavy macrophyte beds and clear water where light can penetrate to anoxic waters beneath the plant beds. Increased sedimentation and removal of tree protection around the lake from initial land clearance may have exacerbated plant loss due to increased sedimentation, greater mixing, and increased nutrient loading as noted in the earlier paleolimnology study.

*1940s reorganization of algal community–*The 1940s represented a period of change in both the history of Bone Lake and in its algal community. This period was the most significant change point for the diatom community in Bone Lake as a shift toward more eutrophic indicators such as *Aulacoseira granulata* and small *Stephanodiscus* species took place as noted in the earlier paleolimnological study. This time also began a period of higher nutrient levels in the lake based on diatom-TP reconstuctions. The 1940s are a pivotal time in many lake's histories because of two major land use changes that took place. First, agricultural practices shifted as intensification and mechanization of production ramped up. This was coupled with the shift toward chemical fertilizers as that industry was born out of industrial repurposing after WWII. Second, this was also the start of cottage development around lakes in this region. Lakes in the Upper Midwest often show dramatic changes in the 1940s including reorganization of their algal communities and increased productivity (Edlund et al. 2009). For Bone Lake, it appears that overall algal productivity increased in this period (increase in B-carotene, increased flux of organics to the sediments). In addition to the diatom community shift toward eutrophic indicators, green algae likely increased (Phaeophytin-b). It is the cyanobacteria that show the most dramatic shift in the 1940s with decreased proportions of aphanizophyll, myxoxanthophyll, and canthaxanthin. We believe this is indicative not of a loss of cyanobacteria in the system, but rather a shift in community structure away from N-fixers that were more strongly represented in the pre-European to 1920s Bone Lake. We suspect this would have been a loss of cyanobacteria such as *Gloeotrichia*, which is more common in northern mesotrophic lakes in the summer. The loss of this pre-Euroamerican community may have been in response to increased N loading to Bone Lake from watershed and atmospheric sources.

1980s shift in Bone Lake–Sediments deposited after 1980 record the most recent period of algal change in Bone Lake. We see further evidence of an overall community change in the Bone Lake algae that include community reorganization and increased productivity of some groups, notably diatoms (diadinoxanthin), dinoflagellates (diadinoxanthin), cryptophytes (alloxanthin), and cyanobacteria (echinone, myxoxanthophyll, canthaxanthin). Diatom microfossils recorded the continued dominance of eutrophic indicators plus an increase in *Fragilaria crotonensis* and *F. mesolepta* (Edlund et al. 2015). Phytoplankton monitoring (Jeremy Williamson, 2015, unpublished Polk Co. data) confirms these data with the modern diatom community dominated by *Stephanodiscus*, *Aulacoseira*, *Asterionella*, and *Fragilaria crotonensis* that predominate in the lake in the spring-early summer and fall. The other community that has changed most dramatically are the cyanobacteria. Overall increases in all cyanobacteria are evident from the echinone profile. Specific groups that have become more abundant are the colonial cyanobacteria including some of the toxic forms (e.g. *Microcystis*) and N-fixers in the Nostocales (*Anabaena*/*Dolichospermum*, *Aphanizomenon*). All of these forms are well-known from the late summer/fall plankton of Bone Lake and are known bloom-formers (Jeremy Williamson, 2015, unpublished Polk Co. data). Finally, several pigments that show sharp increases at the core top (e.g., chlorophyll b, chlorophyll a, fucoxanthin) are labile; the characteristic upcore profile only represents their breakdown following deposition and burial, not recent increases in algal productivity.

Conclusions and management implications

1) To supplement an earlier paleolimnological study on Bone Lake in Polk County, Wisconsin, a single sediment core was recovered from Bone Lake's southern basin in August 2015 and analyzed for fossil algal pigments to reconstruct a historical record of algae populations.

2) The pigment record from Bone Lake shows that cyanobacteria have long-been a substantial part of the lake's algae community and are a natural and native part of the lake's algae. However, two major periods of change in the 1940s and 1980s capture reorganization of the lake's algae that appear to have made bloom-formers and potentially toxic forms a common phenomenon in recent decades. The earlier change coincides with increases in P levels based on diatom-inferred reconstructions and may also reflect increased N deposition from watershed and atmospheric sources. The latter change shows enhanced numbers of cyanobacteria and increased numbers of diatoms that are eutrophic indicators.

3) The entirety of paleolimnological data (this study, Edlund et al. 2015) shows that since the 1990s some of the management markers for Bone Lake have been improving, particularly nutrient level. This shows that some of the management efforts put in place around Bone Lake and in the watershed have been successful. The lake district and county should continue its efforts and keep pushing nutrient management, responsible lakeshore stewardship, and promotion of shoreline and nearshore habitat enhancement. Protection is much easier that rehabilitating a lake.

4) Bone Lake is a lake that is very sensitive to change from both nutrient inputs and meteorological/climate forcing. Bone Lake is 11 m deep, the lake is naturally productive, and cyanobacteria are historically common and a native/natural part of the lake's algae community.

The lake is dimictic, meaning it forms a strong summer thermocline and mixes fully in the spring and fall. However, it also becomes anoxic in its deeper waters (hypolimnion) while stratified in the summer. When this occurs, nutrients, especially P, diffuse from the sediments into the bottom waters (we showed this in the first paleolimnology study that there is a large portion of exchangeable P sitting at the top of Bone Lake's sediments, Edlund et al. 2015). If stratification breaks earlier in the year (August-September) while there are long days and warm temperatures, a cyanobacterial bloom will be triggered. This phenomenon will be exacerbated in years with early ice-off and early stratification, trends that are occurring in Wisconsin; in other words, climate warming is not helping improve Bone Lake.

5) To better understand this behavior in Bone Lake, high frequency monitoring may be appropriate. This would include installation of a buoy outfitted with temperature loggers (to track thermal stratification) and dissolved oxygen loggers (to track anoxia in bottom waters). These buoys can be constructed and installed with very reasonable funding or even outfitted to upload data via cell coverage.

6) We further recognize there are things that may exacerbate problems in Bone including: additional loss of macrophytes, increased nutrient loading and erosion, and allowing carp and other invasive species to invade the lake.

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