The Prevalence of Cyanobacteria: A historical perspective from lake sediment

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Abstract

Anderson Lake in Jefferson County, Washington experiences annual cyanobacteria blooms that produce high concentrations of the neurotoxin, anatoxin-A. As a result, the lake has been closed for recreation over the summer each year since cyanotoxin monitoring began in 2006. The goal of this project was to understand whether cyanobacteria have been a dominant part of the lake phytoplankton historically. The project entailed:

- Collecting a lake sediment core.
- Establishing sediment ages using radioisotopes.
- Analyzing the sediment intervals for fossil algal pigments.

The pigment analysis recorded a diverse cyanobacteria community in the sediments, extending back to at least the mid-1700s. We now know that the physical, and likely chemical (i.e., nutrients), setting of the lake naturally supported a diverse cyanobacteria community. Measured pigments in the sediment representing filamentous (canthaxanthin) and colonial cyanobacteria (myxoxanthin), in addition to general cyanobacteria pigments (zeaxanthin and echinenone), were compatible with observations of modern cyanobacteria blooms. The accumulation of organic matter (largely algal-derived) and cyanobacteria pigments increased dramatically from ~1900–1970, while farming and cattle grazing occured on the shore of the lake. In 1969, a state park was established around the lake, and within ~10 years, the cyanobacteria productivity had returned to historical levels. This decreasing trend in cyanobacteria productivity (rate of production/accumulation) could be in response to reduced nutrient inputs once agricultural activities ceased and/or hydrologic alteration of the lake outlet due to construction of a road just prior to when the park was established.

Background

Cyanobacteria (blue-green algae) are common in many inland waters worldwide. This diverse group of algae has a variety of life histories and habitat niches; however, the most widely recognized are the planktonic (open water) species. Some species are capable of producing toxins (collectively called cyanotoxins) that are harmful to humans and wildlife. This has often led to all cyanobacteria being referred to as "toxic algae."

Anderson Lake, located on the Olympic Peninsula in Washington State (Figure 1), has a long history of algal blooms dominated by cyanobacteria of the genus *Dolichispermum* (syn. *Anabaena*), *Aphanizomenon*, *Lyngbya*. *Microcystis*, and *Woronichinia*. Previous monitoring[1] of the blooms has documented harmful concentrations of the cyanotoxins, anatoxin-A and microcystin. Cyanotoxins have caused the closure of the lake every year during the summer since monitoring began in 2006. Measured anatoxin-A concentrations in Anderson Lake are among the highest found in Washington State (Figure 2).

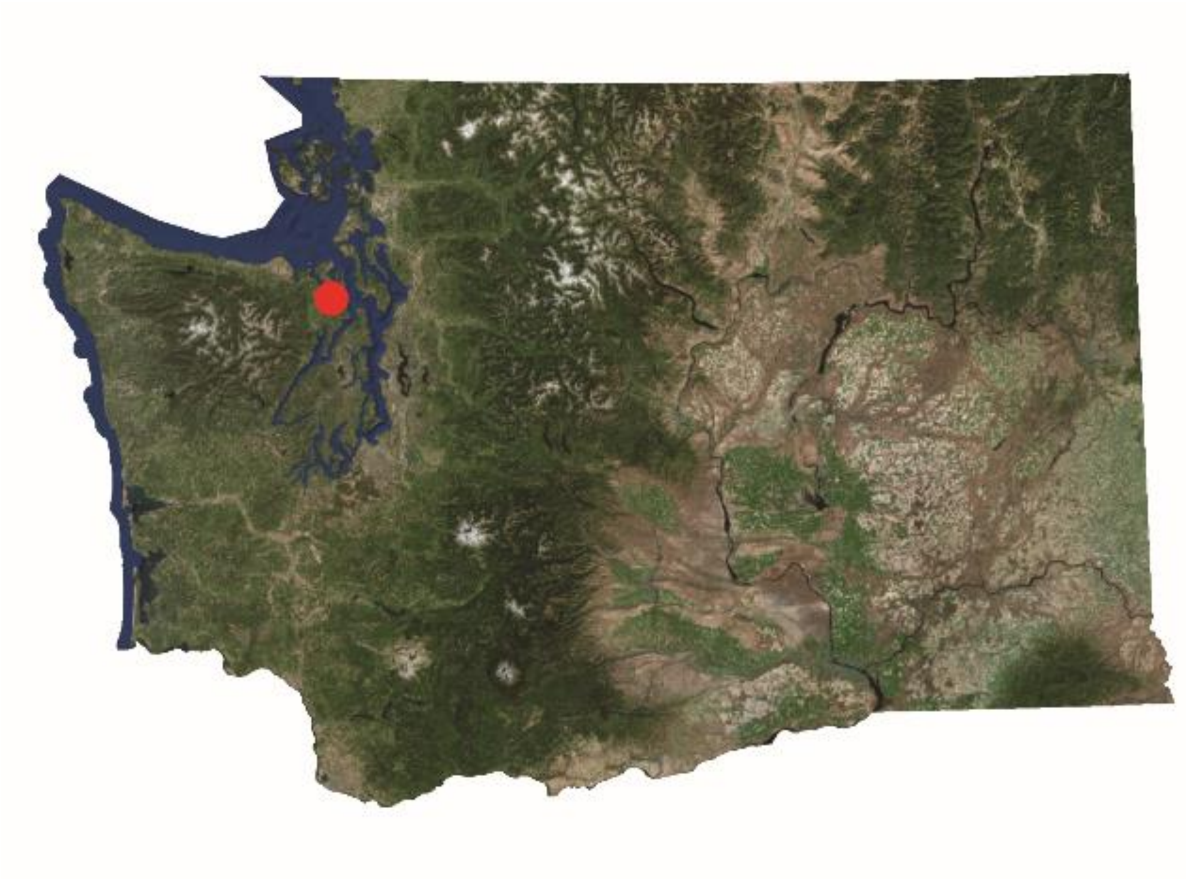

Figure 1. Washington State map with the location of Anderson Lake.

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[1] https://www.nwtoxicalgae.org/Data.aspx?SiteID=75

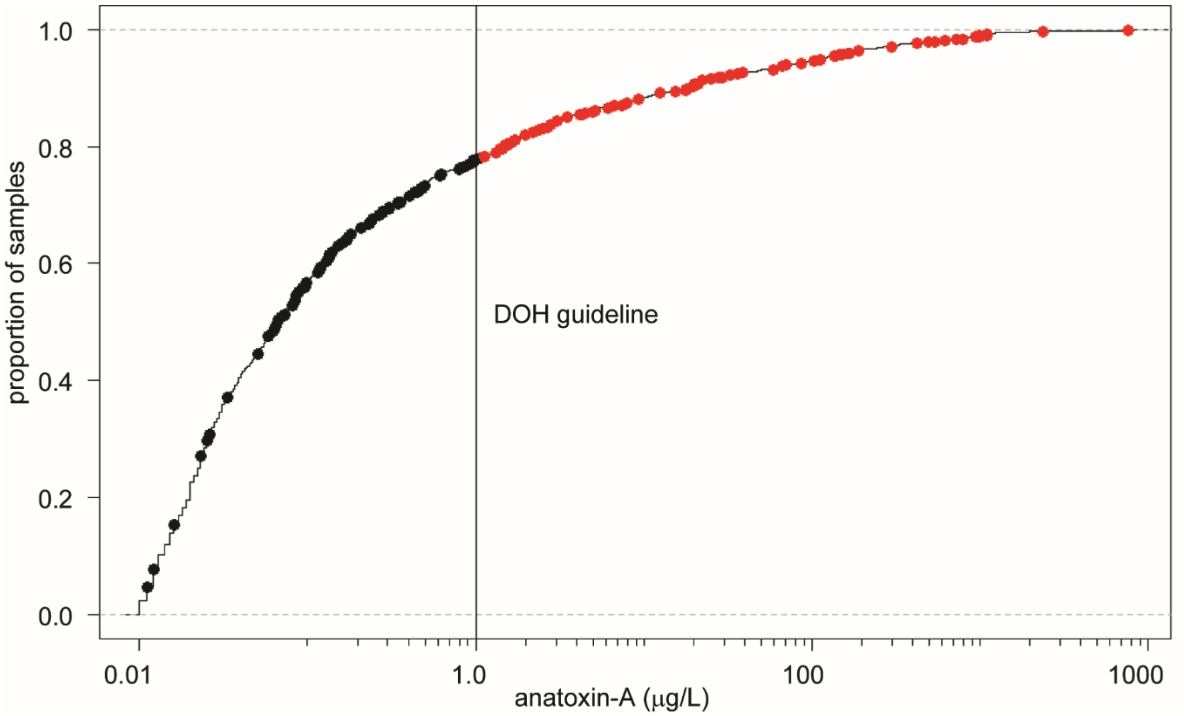

Figure 2. Cumulative distribution of measured anatoxin-A in Washington Lakes.

Underlying line is all measured anatoxin-A concentrations in Washington (2007–2018) (n=1133).

Black dots are concentrations in Anderson Lake below the Washington State Department of Health (DOH) guideline (Hardy, 2008).

Red dots are concentrations in Anderson Lake above the guideline.

Lake sediment cores are an effective way of describing long-term ecological changes and the historical context of lakes over the last ~150 years or more. Microcystin has been successfully measured in lake sediment cores (Efting et al., 2011; Zastepa et al., 2017), however, anatoxin-A biodegrades rapidly and is not preserved in lake sediment (Rapala et al., 1994). An additional proxy of the prevalence of cyanobacteria is the pigments in the algal cells that are deposited on the lake bottom over time (Pal et al., 2015). This is an effective way to show how algal communities have changed over time and if there are coincident external drivers of algal change (Taranu et al., 2015). Such a historical perspective from a sediment core is not available for any of Washington's lakes that experience routine toxic algal blooms. Therefore, the goal of this study was to analyze a sediment core from Anderson Lake and ask the question: Have cyanobacteria been prevalent in the lake over the last ~150 years?

Methods

Study Site

Anderson Lake is located in Jefferson County on the Olympic Peninsula in Washington State. It is situated in a state park and surrounded by cedar, fir, and alder (Figure 3). The park was established in 1969 through land acquisition. Prior to the land acquisition, an area of land on the southwest shoreline was farmed and cattle were grazed beginning in the early 1900s. In the early 1960s, a road was constructed over the outlet stream, filling in a marsh area and a culvert was installed. Beaver activity near the culvert has reportedly affected outlet flow in the past (*personal comm*., Michael Dawson, 2019).

The lake is 25 ha (60 acres) in area and has maximum and mean depth of 7.6 m (25 ft) and 3.7 m (12 ft), respectively (Figure 3). There is a large marsh at the south end of the lake. The lake's submerged plant community was assessed in 1996 and 2017 by the Washington State Department of Ecology. Common waterweed and pond-lilies dominated the communities in 1996. In 2017, plants were dominated by bulrush, bur-reed, pondweeds, and the noxious weed, reed canary grass.

Anderson Lake is stocked with rainbow trout by the Washington State Department of Fish and Wildlife; however, since 2006 algal blooms have closed the lake to all recreational activity for part of each year (usually from May through September), the blooms are dominated by the cyanobacteria genus *Dolichospermum*. In Anderson Lake, a species of *Dolichospermum* is responsible for very high concentrations of anatoxin-A, owing to a genetic structure that allows it to produce much higher concentrations than more common *Dolichospermum* species (e.g., *Dolichospermum flos-aquae*) (Brown et al., 2016). Unfortunately, the strain of *Dolichospermum* is not identifiable using algal pigment remains in the sediments.

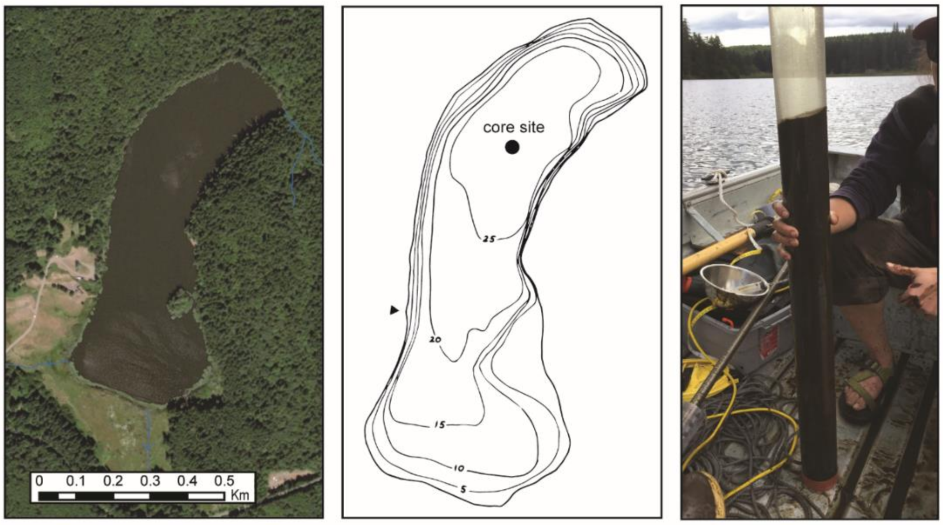

Figure 3. Anderson Lake State Park, lake bathymetry and lake sediment core location.

Bathymetry contours are in feet.

A 73-cm sediment core was retrieved.

Field Methods

A 73-cm long sediment core was recovered from the deepest point in the lake using a percussion-type corer (Reasoner, 1986; Glew et al., 2001). The core was capped with overlying water intact, wrapped in foil, and transported upright on ice back to a laboratory for sectioning. The core was sectioned at 1-cm intervals, and samples were frozen within 48 hours and freeze-dried. All samples were stored in the freezer to avoid photodegradation of the algal pigments (Leavitt and Hodgson, 2001).

Laboratory Methods

All laboratory quality objectives and procedures were outlined in the Quality Assurance Project Plan (Hobbs, 2018). All measurement quality objectives defined in the Quality Assurance Project Plan were met.

Sediment composition was determined using loss-on-ignition (LOI), which describes the relative percent of organic matter, carbonate, and mineral content (Heiri et al., 2001). The content of carbon (C) and nitrogen (N) was measured at IsoLab (University of Washington) using a Costech Elemental Analyzer. Sediments were dated using the activity and modelled decay of radioisotopes (^{210}Po-^{210}Pb) (Appleby, 2001). Samples were analyzed by TestAmerica using alpha spectroscopy (Eakins and Morrison, 1978). The constant rate of supply model was then used to establish an age-depth model (Appleby and Oldfield, 1978).

Sediments were analyzed for algal pigment concentrations by Dr. Rolf Vinebrooke, University of Alberta, using reverse-phase high-pressure liquid chromatography (Mantoura and Llewellyn, 1983). Pigment concentrations were quantified via calibration equations and an electronic spectral library constructed using standards purchased from DHI Water and Environment (Agern Alle 5, DK-2970 Hørsholm, Denmark). HPLC chromatograms were also compared to Jeffrey et al. (2005). Because some primary pigments can be affected by diagenesis (e.g., Hobbs et al, 2010), we created the following summary fractions: total chlorophylls (all primary chlorophylls and derived pheopigments) and total diatom carotenoids (fucoxanthin and diatoxanthin).

Results and Discussion

Sediment Dating

A reliable age-depth model was established for the sediment core based on conformable, exponential decay of unsupported or excess ^{210}Pb activity (Figure 4). The model is dependent on measuring the supported (background) ^{210}Pb activity, which was reached at a depth of 40 cm. In order to estimate the age of the sediment below the supported activity, we extrapolated the mass accumulation rate of the sediment and calculated ages based on the measured dry bulk density of the sediment (Binford, 1990).

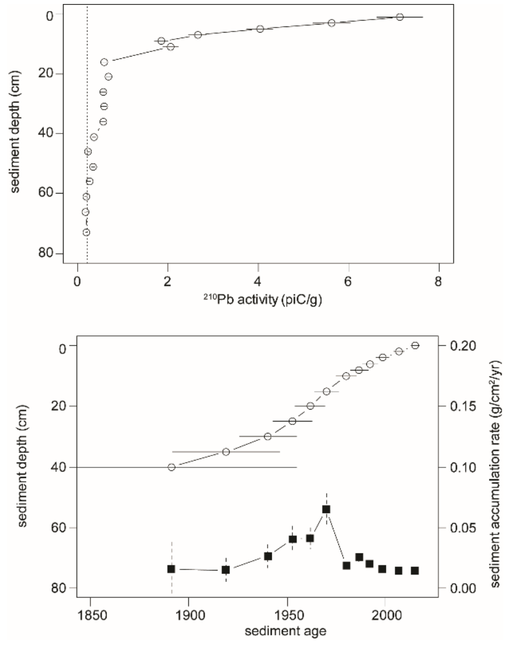

Figure 4. Sediment radioisotopes, estimated ages, and sediment accumulation rates.

Top: ^{210}Pb activity with sediment depth; dashed vertical line represents the supported ^{210}Pb.

Bottom: estimated sediment ages (o) and error with sediment depth; calculated sediment accumulation rates (■) and errors over time.

Sediment Accumulation and Composition

The rate at which sediment has accumulated at the core location has changed over time (Figure 4). Beginning in the early 1900s, sediment accumulation increases and peaks at around 1970, subsequently decreasing to historical sediment accumulation rates within ~10 years. The steady increase in sediment accumulation from 1900–1970 coincides with the period of farming adjacent to the lake, while the decrease after 1970 is during the time when the area around the lake became a state park.

The sediment at the bottom of Anderson Lake is composed primarily of organic matter (~60%) (Figure 5). Furthermore, this organic matter is primarily derived from in-lake production based on a fairly stable carbon:nitrogen (C:N) ratio that is compatible with in-lake production (14 ± 0.5) (Kaushal and Binford, 1999). There are also no continuous inlet streams to Anderson Lake, suggesting that delivery of organics from the watershed is likely minimal.

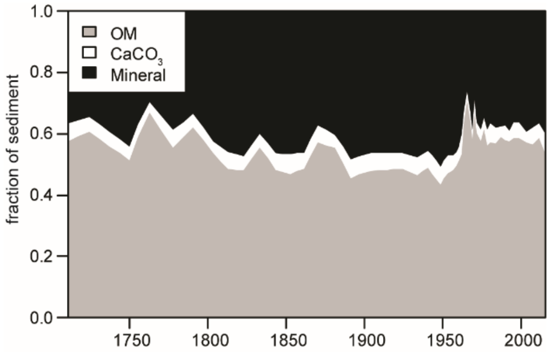

Figure 5. Sediment composition over time.

Combining the rate of sediment accumulation and organic matter concentrations gives a flux of organic matter (gOM/cm^2/yr) to the core site (Figure 6). Given the fairly consistent concentration of OM in the core, the sediment accumulation rate is the main driver of OM flux. The trend describes the steady increase in OM production in the lake during the period when there was farming and then the decrease following acquisition as a state park. The specific drivers of the trend in lake production could be related to nutrient inputs from farming, which would promote algal growth. However, the decrease in OM flux may not be due to a reduction in nutrient inputs following the establishment of the park. Around the time when the park was established, Jefferson County built a road near the southern shoreline, filling in a marsh area and installing a culvert. It is possible that the culvert and road construction altered the hydrology and lengthened the residence time of the lake water.

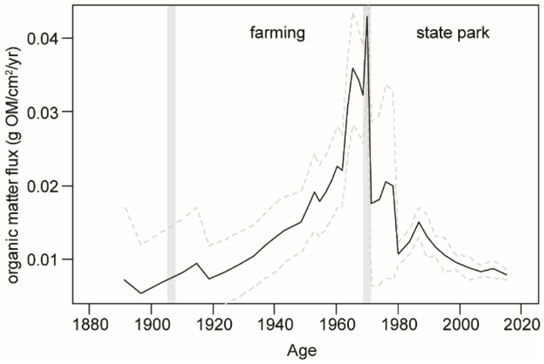

Figure 6. Organic matter flux over time.

Vertical grey bars represent known changes in the lake watershed land use; dashed grey lines are the confidence limits for the trend based on the error in sediment accumulation rates.

Fossil Algal Pigments

The sediments of Anderson Lake had an abundance of well-preserved algal pigments (Figure 7). Chlorophylls and carotenoids from different algal groups were identifiable. Most importantly, there were a number of pigments associated with cyanobacteria. We were able to resolve pigments associated with filamentous cyanobacteria: canthaxanthin (Jeffrey and Vest, 1997) and possibly zeaxanthin (Bianchi et al., 2000), which would represent species of *Aphanizomenon* and *Dolichospermum* seen in Anderson Lake today. Pigment associated with colonial cyanobacteria (myxoxanthophyll), which would represent *Microcytis spp.*, was also resolved in the sediment record. In general, the sediment samples in the upper section of the core (post-2000) describe an algal community similar to what has been observed in Anderson Lake during regular water sampling over the summer since 2007: a phytoplankton community dominated by cyanobacteria, along with diatoms and other algae (e.g., cryptophytes and green algae).

The sediment record also contained bacteriochlorophyll, which is a pigment produced by phototrophic sulfur bacteria. The presence of this type of bacteria suggests that there is a strongly anoxic environment near the sediment surface that allows sulfur reduction to take place; it also suggests that light can penetrate near the sediment surface, allowing photosynthetic organisms to be present.

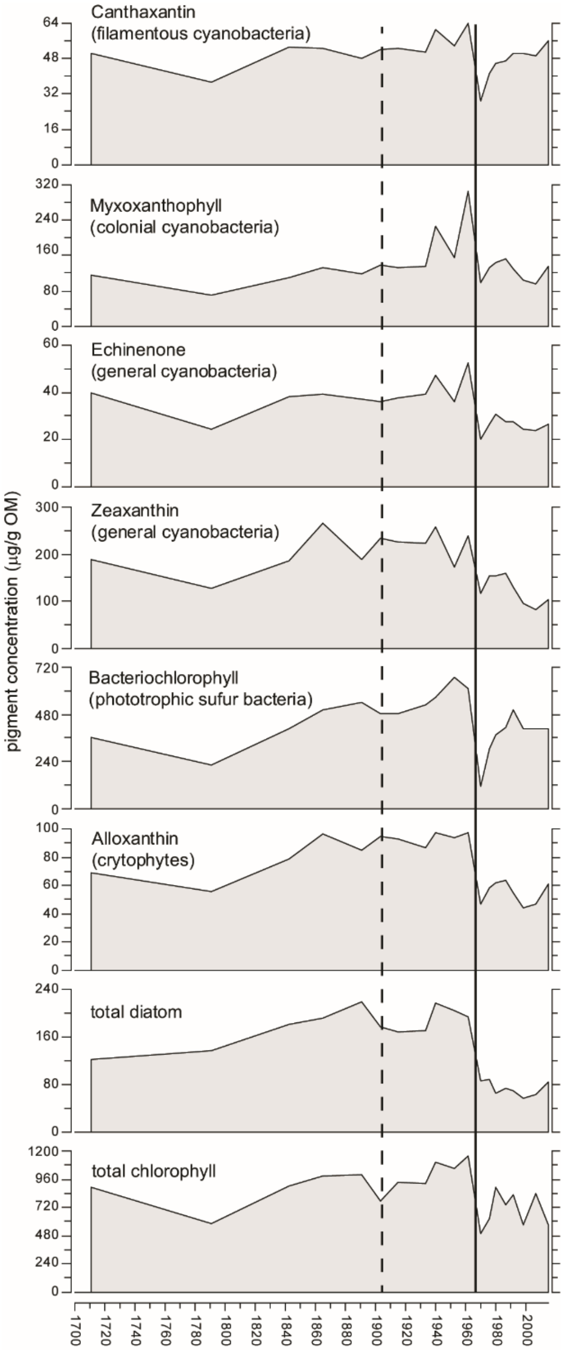

Figure 7. Algal pigment concentrations over time in Anderson Lake.

Vertical dashed line represents the start of farming; solid vertical line represents the conversion to a state park.

What is apparent from the sediment record is that cyanobacteria have been present in Anderson Lake at concentrations comparable to today since at least the early to mid-1700s. The most dramatic change in the concentrations of algal pigments occurred across all of them around 1970 when the state park was established. At this time, algal production decreased rapidly to below historic levels. This finding compliments the dramatic drop in OM flux in the sediment (Figure 6) and further supports the observation that the OM in Anderson Lake sediments is primarily algal-derived.

While the period of farming (~1900–1965) on Anderson Lake seems to have had some impact on overall algal production (OM flux), it did not appear to impact the cyanobacteria community present in the lake (Figure 7). However, if we use the rate of sediment accumulation to calculate a rate of algal deposition or algal productivity, there is a clear increase in the flux of cyanobacteria pigments to the bottom of Anderson Lake during the farming period (Figure 8). This is followed by a commensurate decrease when the lake becomes part of a state park, where cyanobacteria flux returns to historical levels by the late 1970s to early 1980s.

Figure 8. Cyanobacteria pigment flux (productivity) over time.

Vertical shaded bars represent the onset of farming (with age error) and the establishment of the park (with age error).

Management Implications

The sediment record from Anderson Lake provides historical context to the prevalence and composition of cyanobacterial communities in the lake over the last ~250 years. We now know that the physical, and likely chemical, setting of the lake naturally supports a diverse cyanobacteria community. The question is, how does this information assist with current management and recreational goals of the lake?

We propose that by understanding some of the long-term ecological changes in the lake, the expectation of any management strategy is better understood. For instance, in order for Anderson Lake to support cyanobacteria historically, nutrient concentrations in the water were likely similar to today. Any strategy to control current cyanobacteria growth in the lake should acknowledge that nutrient-rich waters are likely to persist in Anderson Lake.

Our ability to establish the long-term history of cyanobacteria in a lake also has implications for lakes where cyanobacteria were not present historically. In the case where cyanobacteria are now dominant because nutrient inputs have changed over time, a realistic historical benchmark for management goals is beneficial. Furthermore, we would hope that this information would help to predict how responsive a lake would be to rehabilitation efforts (*sensu* Hobbs et al., 2016).

Conclusions

In the summer of 2018, we investigated the historical prevalence of cyanobacteria in Anderson Lake (Jefferson County) using a dated lake sediment core. The following conclusions can be made:

- The sediment of Anderson Lake is composed largely of organic matter from in-lake algal production and has been since at least the mid-1700s.
- The rate at which sediment accumulates in Anderson Lake increased during the period of ~1900–1970, with a commensurate decrease to historical rates by the late-1970s.
- Concentrations of pigments in lake sediment were dominated by a diverse community of cyanobacteria with diatoms, cryptophytes, phototrophic sulfur bacteria, and other algae (e.g., green algae).
- The presence of phototrophic sulfur bacteria throughout the last ~250 years suggests that the environment near the sediment surface is anoxic (oxygen-deprived) and enough light reaches it for photosynthesis to occur.
- Cyanobacteria pigments in the sediment record suggest that Anderson Lake has had a similar community of cyanobacteria since at least the mid-1700s, meaning that cyanotoxins were likely present historically.
- It is likely that the productivity of cyanobacteria increased from ~1900–1970 while farming was taking place, but following the establishment of the park, productivity decreased to historical levels within 10 years.
- The establishment of the state park around Anderson Lake reduced cyanobacteria productivity (rate of production/accumulation) back to historical levels by either (1) reduction of nutrient inputs to the lake or (2) hydrologic alteration when a culvert at the outlet to the lake was constructed.

Recommendations

This work on Anderson Lake successfully described the historical prevalence of cyanobacteria in the lake over the last ~250 years. The following recommendations can be made:

- Any management plan for the control or mitigation of cyanobacteria blooms in Anderson Lake should acknowledge the historical prevalence of cyanobacteria in the lake and historically nutrient-rich waters.
- Lake Management Plans that aim to address harmful algal blooms should consider investigating the historical prevalence of cyanobacteria. This information provides a historical context that may be useful in establishing management goals.
- The sedimentary records of algal pigments are not able to describe whether the *Dolichospermum* strain in Anderson Lake was there historically, but the analysis of the sediment record for DNA evidence of this strain could.

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