PALEOECOLOGICAL STUDY OF BUTTERNUT LAKE, PRICE/ASHLAND COUNTIES

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Introduction

Questions often arise concerning how a lake's water quality has changed through time as a result of watershed disturbances. In most cases there is little or no reliable long-term data. Questions often asked are if the condition of the lake has changed, when did this occur, what were the causes, and what were the historical condition of the lake? Paleoecology offers a way to address these issues. The paleoecological approach depends upon the fact that lakes act as partial sediment traps for particles that are created within the lake or delivered from the watershed. The sediments of the lake entomb a selection of fossil remains that are more or less resistant to bacterial decay or chemical dissolution.2 These remains include diatom frustules, cell walls of certain algal species, and subfossils from aquatic plants. The chemical composition of the sediments may indicate the composition of particles entering the lake as well as the past chemical environment of the lake itself. Using the fossil remains found in the sediment, one can reconstruct changes in the lake ecosystem over any period of time since the establishment of the lake.

Butternut Lake is a 1006 acre lake located in northern Price and southern Ashland counties, near the city of Park Falls. The maximum depth is 32 feet with a mean depth of 14 feet. A sediment core was collected from the lake on 7 February 2005. The core was collected with a piston core with a plastic tube having an inside diameter of 8.8 cm. The core was collected from the deep area of the lake. The location of the coring site was 45º 58.397' north, 90º 31.086' west in a water depth of 22 feet (6.75 m). The core was sectioned into 1 cm intervals for the entire core (72 cm). The core was dated by the ^{210}Pb method and the CRS model used to estimate dates and sedimentation rate. The diatom community was analyzed to assess changes in nutrient levels and changes in the macrophyte community and geochemical elements were examined to determine the causes of changes in the water quality and changes in oxygen conditions in the bottom waters.

Results and Discussion

Dating

In order to determine when the various sediment layers were deposited, the samples were analyzed for lead-210 (^{210}Pb). Lead-210 is a naturally occurring radionuclide. It is the result of natural decay of uranium-238 to radium-226 to radon-222. Since radon-222 is a gas (that is why is sometimes is found in high levels in basements) it moves into the atmosphere where it decays to lead-210. The ^{210}Pb is deposited on the lake during precipitation and with dust particles. After it enters the lake and it is in the lake sediments, it slowly decays. The half-life of ^{210}Pb is 22.26 years (time it takes to lose one half of the concentration of ^{210}Pb) which means that it can be detected for about 130-150 years. This makes ^{210}Pb a good choice to determine the age of the sediment since European settle-

Figure 1. Map of Butternut Lake showing the coring site. The water depth at the site was 22 feet.

ment began in the mid-1800s. Sediment age for the various depths of sediment were determined by constant rate of supply (CRS) model (Appleby and Oldfield, 1978). Bulk sediment accumulation rates (g cm^{-2} yr^{-1}) were calculated from output of the CRS model (Appleby and Oldfield, 1978). Accumulation rates of geochemical variables were computed for each sediment depth by multiplying the bulk sediment accumulation rate (g cm^{-2} yr^{-1}) by the corresponding concentration (mg g^{-1}) of each constituent in the bulk sediment.

There can be problems with this dating technique. For example, when sediment has moved after it was deposited, large changes in sediment deposition over the last 150 years, and errors associated with lab analysis with sediments that are over 100 years old. For these reasons the accuracy of the ^{210}Pb dates is verified by other methods. These methods usually involve measuring parameters that are known to have been deposited at a certain time and comparing stratigraphic changes in the core in Round Lake with other lakes in the region.

Cesium-137 (Cs^{137}) can be used to identify the period of maximum atmospheric nuclear testing (Krishnaswami and Lal, 1978). The peak testing occurred by the USSR in 1963 and thus the ^{137}Cs peak in the sediment core should represent a date of 1963. The depth of these peaks is very close to the date of 1963 calculated by the ^{210}Pb model indicating that the model results are very good.

Sedimentation Rate

The mean mass sedimentation rate for the last 180 years was 0.026 cm^{-2} yr^{-1}. This is below the median sedimentation rate of 0.032 cm^{-2} yr^{-1} of 41 lakes that have been measured in Wisconsin (Figure 2). The average linear rate for the same time period is 0.24 cm yr^{-1} which equates to about 0.1 inch of sediment per year.

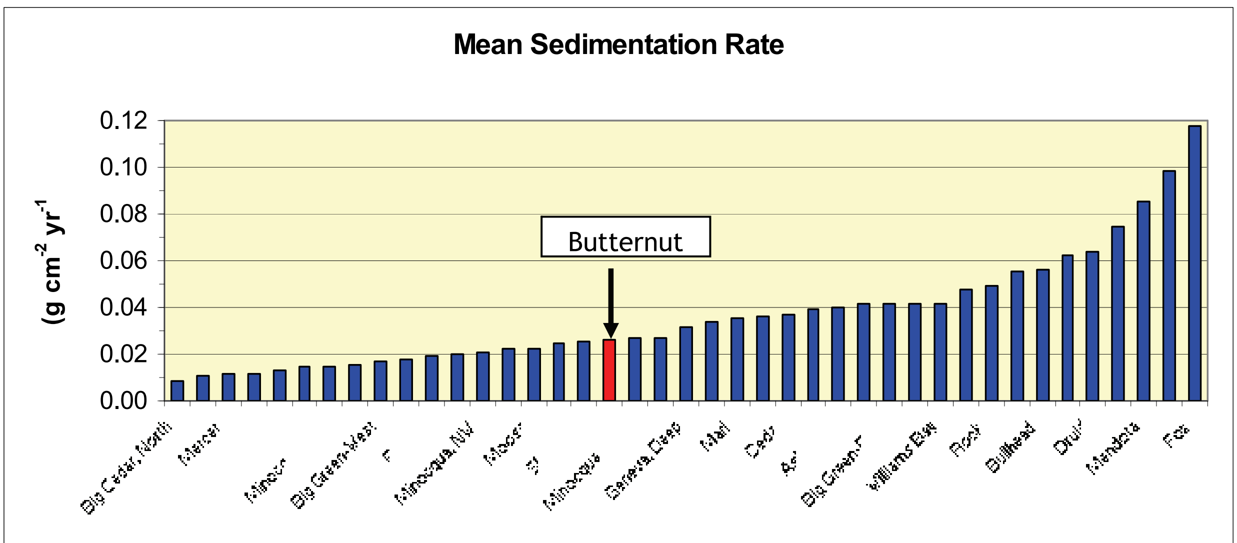

Figure 2. Mean sedimentation rate for the last 180 years for 41 Wisconsin lakes. The arrow indicates Butternut Lake.

To account for sediment compaction and to interpret past patterns of sediment accumulation, dry sediment accumulation rates were calculated. The presettlement sedimentation rate was 0.007 g cm^{-2} yr^{-1}. By 1870 the rate had increased to 0.021 g cm^{-2} yr^{-1} and it continued to increase to a peak of 0.078 g cm^{-2} yr^{-1} by 1935 (Figure 3). This peak was the highest rate measured in the core but a secondary peak occurred around 1970. Besides these peaks the sediment accumulation rate was about 0.030 g cm^{-2} yr^{-1} for the period 1930-80. Since 1990 the rate has steadily increased and at the top of the core it was 0.046 g cm^{-2} yr^{-1}. The peak rates at 1935 and 1970 most likely resulted from episodic erosional events but the steady increase in the sedimentation rate during the last decade probably indicates a change in landuse in the lake's watershed which is impacting the lake.

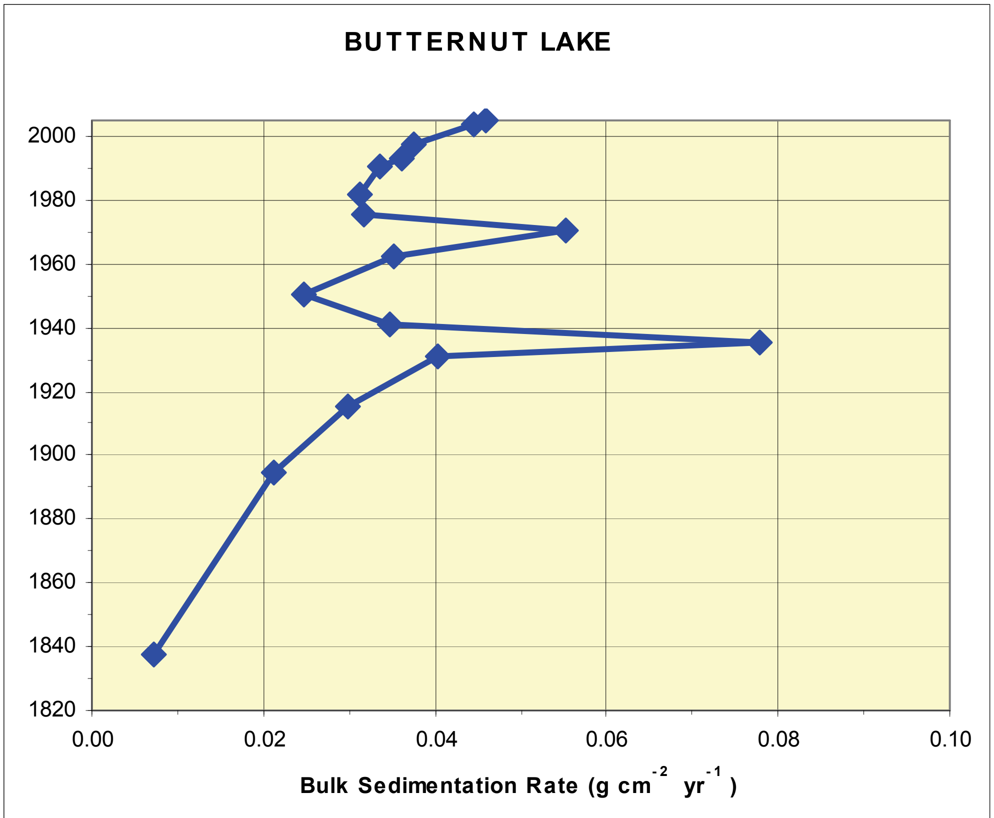

Figure 3. Sediment accumulation rate for Butternut Lake since 1840. The peaks at 1935 and 1970 reflect episodic cultural erosional events but the steady increase since 1990 indicates a change in landuse in the lake's watershed.

Sediment Lithology

The increase in the percent water content towards the top of the core was consistent with the general trend that is normally occurs in sediment cores (Figure 4). This increase is largely the result of minimal sediment compaction at the top of the core. Organic matter was constant at 27 percent until the beginning of the twentieth century when is began to decline. The percent organic matter was depressed until the last two decades. The decline in organic matter was associated with compensatory increases in inorganic matter (Figure 4) and reflects increased erosion as a result of cultural activities in the watershed. The decline of inorganic matter during the last two decades indicates that soil erosion rates declined. Since the sedimentation rate increased since 1990, this increase is not the result of soil erosion but must be the result of increased input of organic matter and other geochemical elements. Part of this increase is the result of increased carbonate. Although the percent of carbonate was low in the core it did increase slightly at the top of the core. This increase may be the result of the use of lime as a soil amendment for lawns of shoreline homes. This trend was observed in Round Lake near Hayward as a result of shoreland development (Garrison 2005).

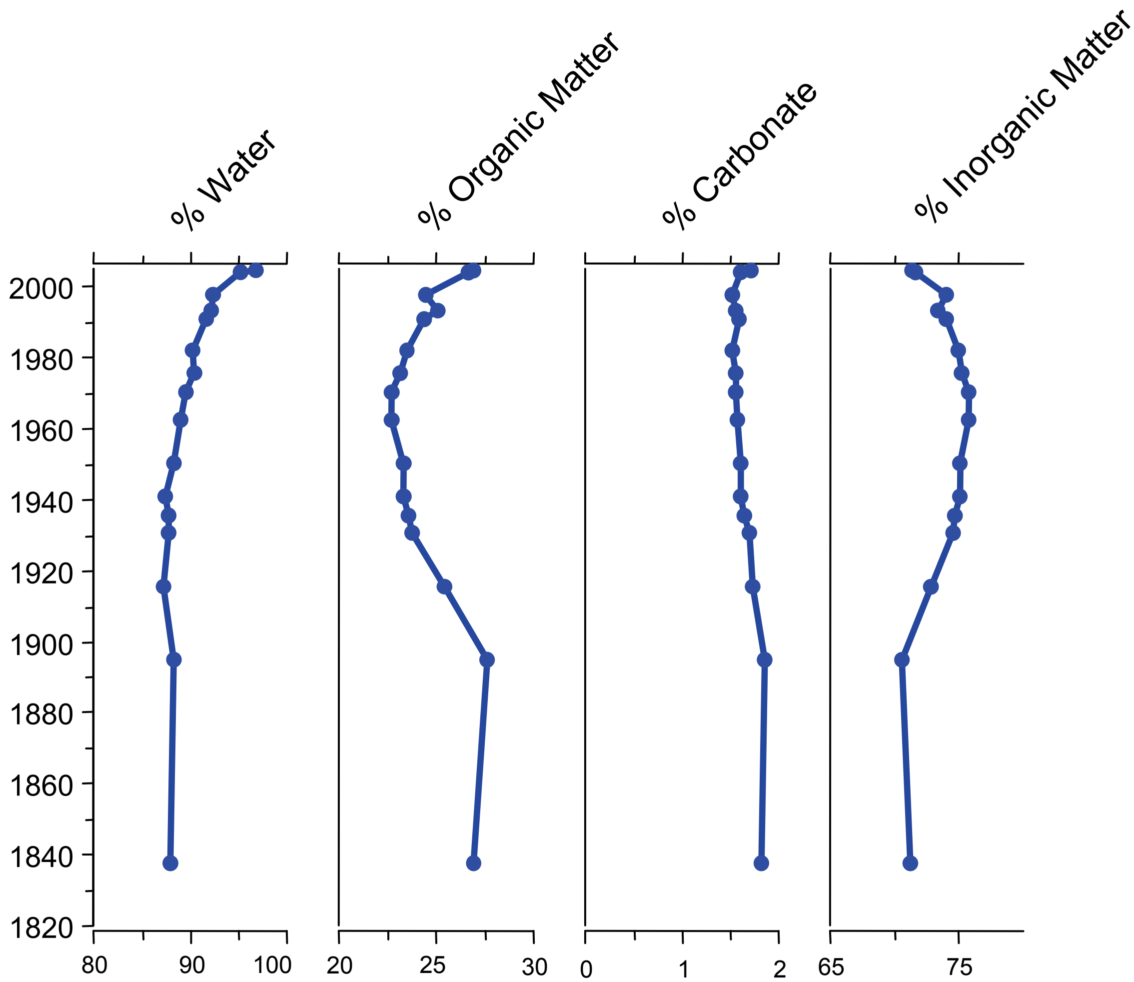

Figure 4. Percent water, organic matter, carbonate, and inorganic matter from the sediment core. Inorganic matter largely reflects changes in delivery of soil erosion from the watershed.

Sediment Geochemistry

Geochemical variables are analyzed to estimate which watershed activities are having the greatest impact on the lake (Table 1). The chemical titanium (Ti) is found in soil particles, especially clays. Changes in Ti are an indication of changes in soil erosional rates throughout the lake's history. Zinc (Zn) is associated with urban runoff because it is a component of tires and galvanized roofs and down-spouts. Nutrients like phosphorus and nitrogen are important for plant growth, especially algae and aquatic plants. Calcium is an indication of the use of soil amendments for lawns. Manganese is an indication of changes in oxygen levels in the bottom waters.

Table 1. Selected chemical indicators of watershed or in lake processes.

Process	Chemical Variable
Soil amendment	calcium
Soil erosion	aluminum, titanium
Urban	zinc, copper
Anoxia	manganese
Nutrients	phosphorus, nitrogen

The accumulation rate of the geochemical variables was largely unchanged during the 1800s. Starting around 1920 there was an increase in titanium which is a surrogate for soil erosion (Figure 4). This is

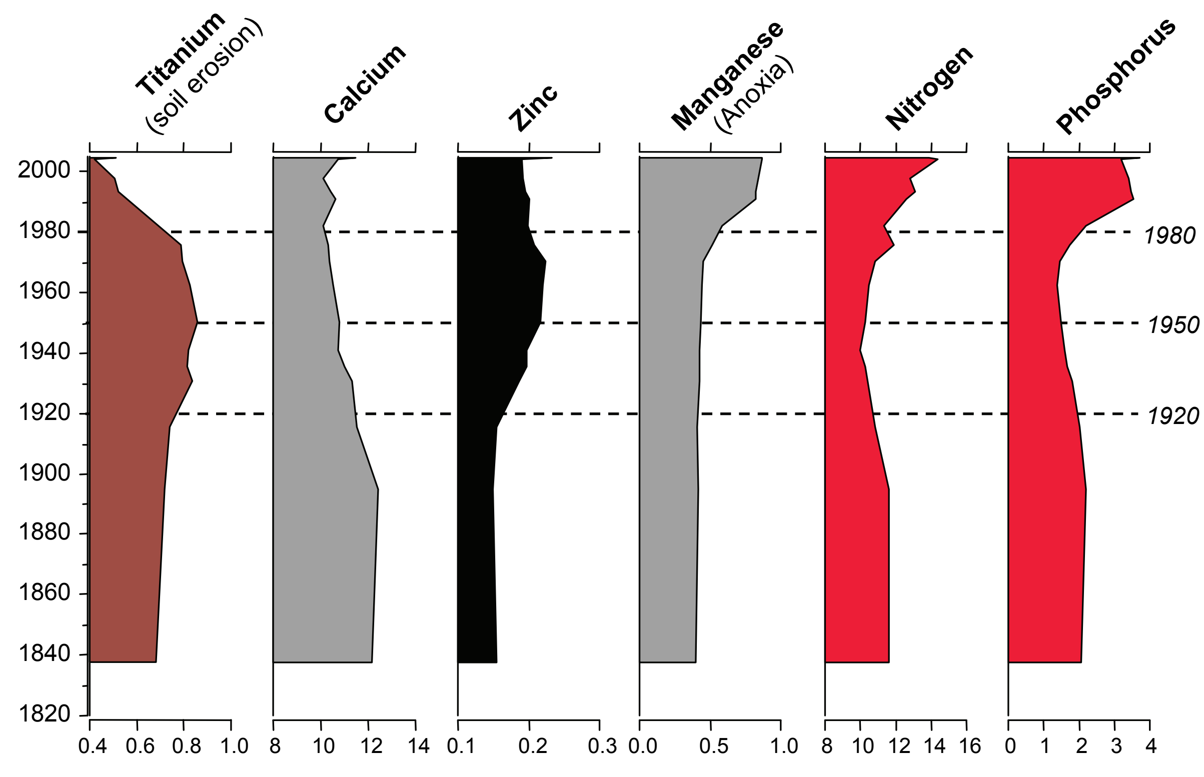

Figure 4. Profiles of the accumulation rate of selected geochemical elements. Titanium profiles are indicative of soil erosional rates in the watershed. Zinc profiles portray the history of lead-zinc smelting in the Upper Midwest while manganese profiles reflect trends of dissolved oxygen levels in the deep waters. Nitrogen and phosphorus profiles reflect changes in nutrient deposition rates.

the time period when the sedimentation rate was increasing (Figure 3) and the percent of inorganic matter was also increasing (Figure 4). Soil erosional rates remained elevated until the late 1970s when it began to decline. This rate continued to decline and at the present time it is less than presettlement values.

Calcium levels began to decline around 1900 much like the carbonate values. This is not surprising since calcium is a large component of the carbonates. Calcium accumulation rates increase at the top of the core, most likely as a result of the application of lime as a soil amendment on shoreline lawns.

Zinc often enters a lake as a result of urban runoff. Zinc can also enter a lake as a result of emissions from the smelting of lead-zinc ores (Dean 2002). Since urbanization is limited around Butternut Lake, the zinc profile likely reflects the history of lead-zinc mining and smelting in the Upper Midwest. Although shoreline development has increased in recent years around the lake, the peak in zinc deposition was around 1970 when smelting of lead-zinc ores was common in the Upper Midwest.

As the bottom waters become increasing devoid of oxygen, manganese (Mn) is mobilized from the sediments (Engstrom et al. 1985). This manganese then moves into the deepest waters resulting in the enrichment of manganese in the sediments of the deeper waters. Although Butternut Lake does not appear to stratify for long periods, the increase in Mn in the upper sediments indicates that anoxia occurs for a sufficient amount of time to mobilize Mn from the sediments and allow its migration to the deeper waters. The anoxia appears to have started around 1980 and has accelerated in the last 20 years as Mn deposition rates have increased during this time period (Figure 4).

Both phosphorus and nitrogen profiles begin to decline around 1900 (Figure 4). This depression of their deposition rates is likely the result of increased delivery of inorganic sediment from the watershed. Apparently there was little nitrogen and phosphorus associated with this material. Thus the increased deposition of these materials diluted both nitrogen and phosphorus. This trend changed during the 1970s both in response to a decline in soil erosion in the watershed but also as a result of increased anoxia in the deep waters of the lake. When the bottom waters become anoxic, phosphorus, in the form of inorganic P, and nitrogen, in the form of ammonium, are released from the sediments. This process is known as internal loading, and can accelerate the eutrophication process leading to increased algal blooms and a decline in water clarity.

Although phosphorus and nitrogen profiles have been used to reconstruct changes in historical loading of these elements, this can be misleading. As Engstrom and Wright (1984) summarize, there are many problems with using phosphorus profiles to reconstruct changes in loading. For example, P retention in sediments is strongly controlled by sorption onto iron oxides, and so variations in iron content and redox conditions may change phosphorus accumulation in sediments independent of changes in phosphorus loading. Anderson et al. (1993) showed that P concentration profiles did not accurately portray known changes in P loading in two small lakes in northern Ireland and Fitzpatrick et al. (2003), clearly show this is especially true in a bay from Lac Courte Oreilles, Sawyer County, Wisconsin. Although the P profiles may not accurately portray changes in loading rates, the increased deposition during the last 2 decades does indicate that there is a potential for increased P in the lake as a result of internal loading.

Diatom Community

Aquatic organisms are good indicators of water chemistry because they are in direct contact with the water and are strongly affected by the chemical composition of their surroundings. Most indicator groups grow rapidly and are short lived so the community composition responds rapidly to changing environmental conditions. One of the most useful organisms for paleolimnological analysis is diatoms. They are a type of alga which possess siliceous cell walls and are usually abundant, diverse, and well preserved in sediments. They are especially useful as they are ecologically diverse and their ecological optima and tolerances can be quantified. Certain taxa are usually found under nutrient poor conditions while others are more common under elevated nutrient levels. They also live under a variety of habitats, which enables us to reconstruct changes in nutrient levels in the open water as well as changes in benthic environments such as aquatic plant communities. Figure 5 shows photographs of two diatom species that were common in the sediment cores.

The presettlement diatom community was composed of a diverse taxa with about half of the diatoms being species that live in the open water of the lake while the rest were diatoms that grow attached to substrates, e.g. submerged aquatic plants. The dominant planktonic diatoms where those belonging to the genera *Aulacoseira*. Diatoms of this genera are found in wide range of nutrient levels. The taxa that prefer low nutrients, *A. distans* and *A. tenella*, largely disappeared about 1950 (Figure 6), indicating an increase in phosphorus levels in the lake. During the time period when these *Aulacoseira* disappeared, *Stephanodiscus* numbers increased. *Stephanodiscus* generally prefer higher nutrient levels. Starting around 1940 there was an increase in the diatoms of the group benthic *Fragilaria*. These taxa grow attached to substrates, e.g. aquatic plants. Their increase indicates that there was an increase in the coverage and/or density of plants at this time. This likely is in response to increased nutrients entering the lake. Other studies have found that one of the first changes that occurs with increased nutrient delivery to the lake is the increased growth of submerged aquatic plants (Garrison and Wakeman 2000, Fitzpatrick et al. 2003, Garrison 2004, Garrison 2005). The abundance of benthic *Fragilaria* declined after 1990. This likely is the result of decreased water clarity as a result of increased algal blooms.

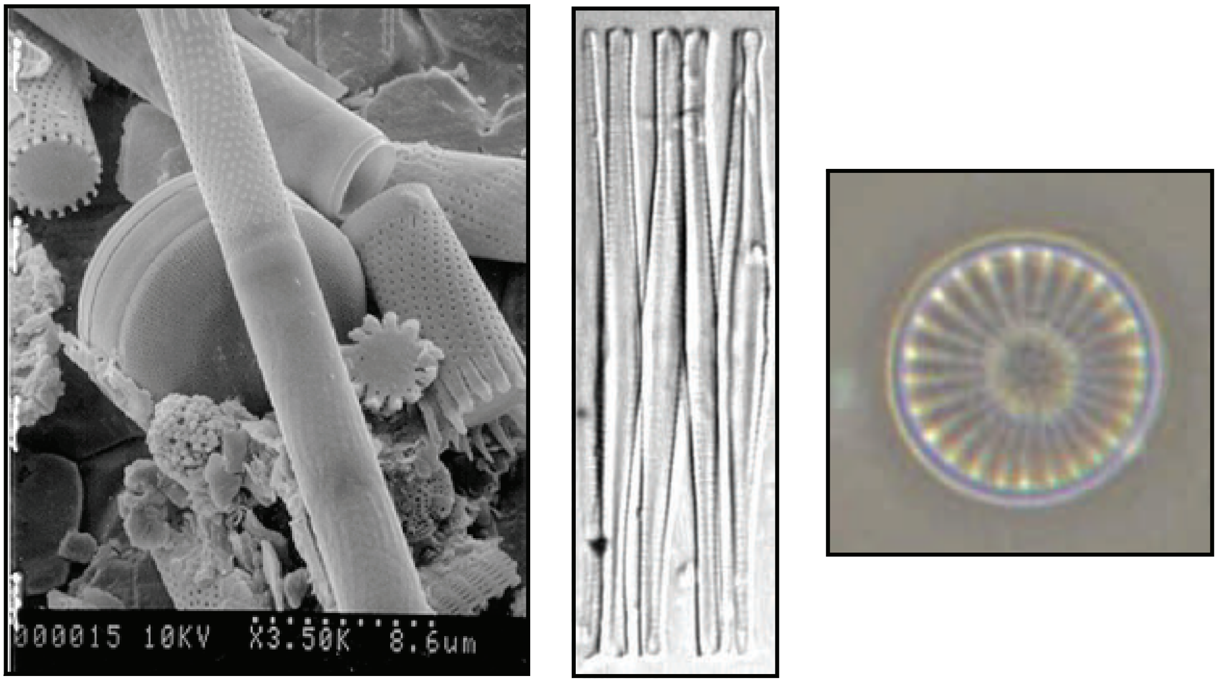

Figure 5. Micrographs of the diatoms *Aulacoseira* (left), *Fragilaria crotonensis* (middle), and *Stephanodiscus minutulus*. All of these diatoms are typically found floating in the open water. The *Aulacoseira* pictured is commonly found in low nutrient waters, *F. crotonensis* is usually found in waters with moderate levels of nutrients, while *S. minutulus* is more common in higher nutrient waters.

Diatom assemblages historically have been used as indicators of trophic changes in a qualitative way (Bradbury, 1975; Anderson et al., 1990; Carney, 1982). In recent years, ecologically relevant statistical methods have been developed to infer environmental conditions from diatom assemblages. These methods are based on multivariate ordination and weighted averaging regression and calibration (Birks et al., 1990). Ecological preferences of diatom species are determined by relating modern limnological variables to surface sediment diatom assemblages. The species-environment relationships are then used to infer environmental conditions from fossil diatom assemblages found in the sediment core.

The presettlement summer phosphorus levels were about 15 µg L^{-1} (Figure 7). Phosphorus levels first began to increase in the 1890s during the logging era. Starting about 1920, phosphorus levels steadily increased until concentrations peaked around 35-40 µg L^{-1} during the last decade. For the period 2001-05 the mean summer P concentration measured in the lake was 41 µg L^{-1}. The close agreement between the diatom inferred P concentrations and measured values substantiates the validity of the modeling.

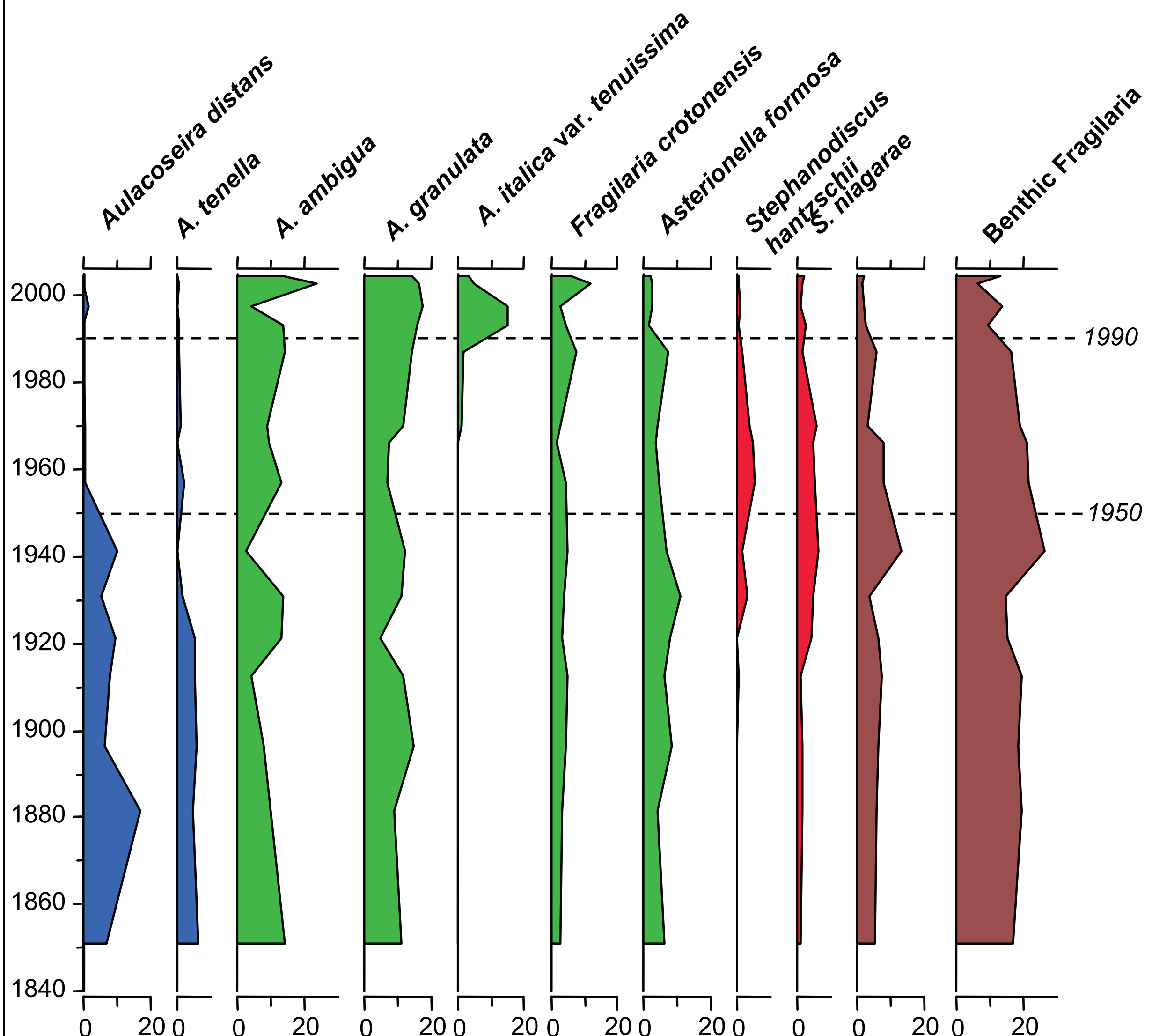

Figure 6. Profiles of selected diatom taxa. The taxa in blue are indicative of low nutrient levels while taxa in green are indicative of moderate nutrient levels. Those taxa colored in red generally indicate higher nutrient levels. The taxa in brown grow on substrates such as aquatic plants.

The increase in the diatom inferred phosphorus levels that began around 1920 coincides with the increased delivery of soil erosion to the lake as indicated by the increase in inorganic matter (Figure 4) and titanium (Figure 5). Even though delivery of sediment from the watershed declined after 1980, phosphorus levels in the lake continued to increase. The manganese profile indicates that internal loading of phosphorus began during this time period thus providing phosphorus for algal blooms in the lake. Even though soil erosion in the watershed has declined, inlake processes continue to provide sufficient phosphorus so that phosphorus levels during the last decade are the highest they have been in the last 200 years.

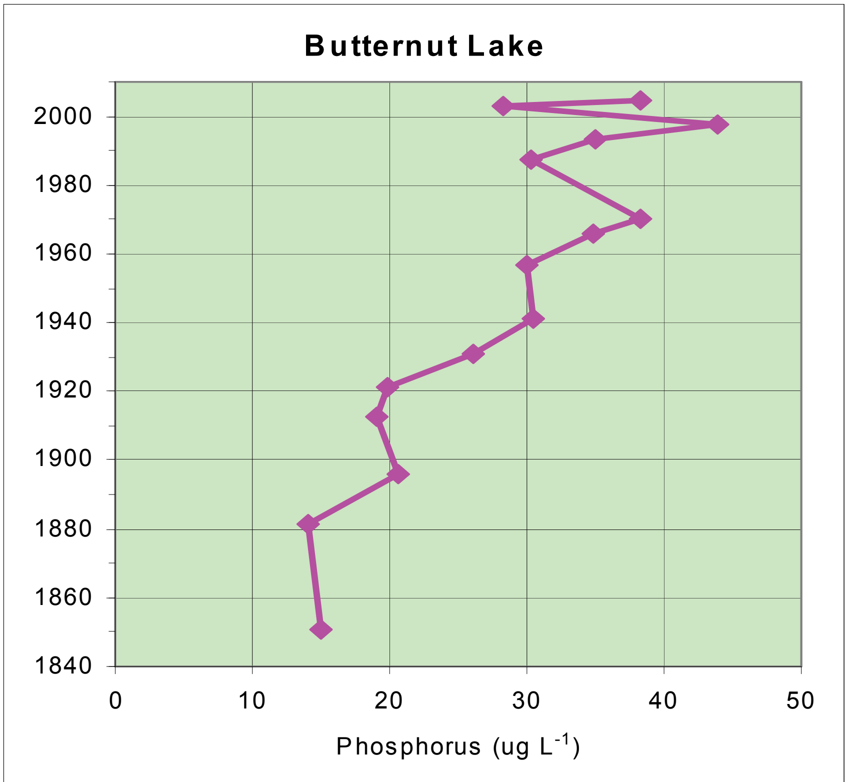

Figure 7. Mean summer phosphorus estimated from the diatom community using weighted averaging modeling.

SUMMARY

The water quality of Butternut Lake was stable during the 1800s. With increased cultural development in the lake's watershed starting around 1900, the sediment accumulation rate began to increase. Initially, much of the increase was the result of soil erosion in the watershed. This increased deposition of inorganic material reduced the deposition rate of other parameters. The sedimentation rate continued to increase and two peaks occurred in the core. The first, and largest, occurred during the 1930s and the second peak was around 1970. These were the result of episodic events. A more constant increase has occurred since 1990.

The recent increase is not the result of increased delivery of soil from the watershed. In fact, since 1980 soil erosion rates have declined. Part of the increase is the result of increased deposition of organic matter. Much of this organic matter likely is produced within the lake and is a sign of increasing eutrophication. The oxygen content in the bottom waters of the lake has declined in the last 2 decades and this has resulted in increased internal loading of phosphorus.

Presettlement phosphorus levels in the lake were about 15 µg L^{-1}. Concentrations initially increased to 20 µg L^{-1} around 1900. More significant increases began around 1920 associated with the increased soil erosion in the watershed. As increasing amounts of nutrients entered the lake from the watershed, the lake's phosphorus levels also increased to around 35-40 µg L^{-1} by 1970. Even though soil erosion rates declined after 1980, the phosphorus level in the lake remained high. The phosphorus levels within the lake since 1980 have largely been maintained by internal loading from the deeper water sediments. The present diatom inferred summer mean phosphorus concentration is about 40 µg L^{-1} which is the concentration that has been measured in the lake the last 5 years.

Butternut Lake has undergone considerable change during the last 100 years. The sedimentation rate at the present time is six times higher than it was in presettlement time. Although the input of sediment from the watershed is much less at the present time compared with 50 years ago, internal loading of phosphorus from sediments is significant and at the present time phosphorus levels are two and one half times higher at 40 µg L^{-1} than they were in the 1800s.

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