A PALEOECOLOGICAL STUDY OF WAUSHARA COUNTY LAKES

Paul J Garrison

Wisconsin Department of Natural Resources,

Bureau of Science Services

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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. 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.

A relatively inexpensive means of comparing present day conditions with pre-settlement conditions is top/bottom sediment cores. While a full core, which is assumed to cover a time period of European settlement, is collected, only the top and bottom sections are analyzed. It is assumed that the top section was deposited during the last 2-3 years. The bottom section is assumed to have been deposited prior to the arrival of Europeans during the latter part of the nineteenth century.

This report will examine eight lakes of Waushara County (Table 1, Figure 1) that have potentially been impacted by anthropogenic activities. The most common potential change in the lakes is eutrophication through the introduction of excess nutrients to the lakes. Originally seven lakes were selected but during 2012, Deer Lake was sampled as part of the U.S. EPA National Lake Assessment (http://water.epa.gov/type/lakes/lakessurvey_index.cfm).

A single sediment core was collected from the deep area of the lake (Table 1) generally using a piston corer during November 2012. This corer has an inside diameter of 8.8 cm. The total length of the cores was between 90 and 100 cm. Long and Pine lakes were cored with a gravity corer with a plastic tube with an inside diameter of 6.8 cm. This resulted in a shorter core length but long enough to reach sediments deposited at least 150 years ago. The cores were sectioned into 1 cm intervals for the top 40 cm and then at 2 cm to the bottom of the core. For this study usually the top section and a section very near the bottom of the core were examined for the diatom community composition. It is expected that the bottom sample was deposited at least 150 years ago and represent pre-settlement conditions in the lake. For Pleasant and Long lakes an intermediate section was examined. Deer Lake was sampled as part of another study. A gravity corer was used and the core was sectioned into 1 cm intervals throughout the core. The core collected was not as long (44 cm) as the other cores but it should have been deep enough to reach pre-settlement conditions.

Diatoms are a type of algae which possess siliceous cell walls and are usually abundant, diverse, and well preserved in sediments. They are especially useful for reconstructing past lake conditions as they are ecologically diverse and their ecological optima and tolerances can be quantified. Samples for diatom analysis were cleaned with hydrogen peroxide and potassium dichromate (van der Werff 1956). Cover slips on which a portion of the diatom suspension was dried were mounted on microscope slides with Naphrax®. Specimens were identified and counted under oil immersion objective (1000X) until at least 500 valves had been encountered. Diatoms were identified to species level whenever possible using references which included Patrick and Reimer (1966, 1975), Krammer and Lange-

Table 1. Lake Morphometry, hydrologic type and sampling location of the study lakes.

	Hydrologic Type	Location	Area (ha)	Maximum Depth (m)
Big Silver	Seepage	44.05320° 89.23025°	139	13.7
Deer	Seepage	44. 04256° 89.21638°	6	4.3
Huron	Seepage	44.19461° 89.41721°	16	14.0
Long	Seepage	44.21535° 89.12636°	110	21.6
Pine	Seepage	44.12920° 89.51069°	38	6.4
Pleasant	Seepage	43.9847989.55374°	51	9.1
Round	Seepage	44.16072° 89.16146°	26	5.8
Wilson	Seepage	44.17465° 89.17552°	12	3.7

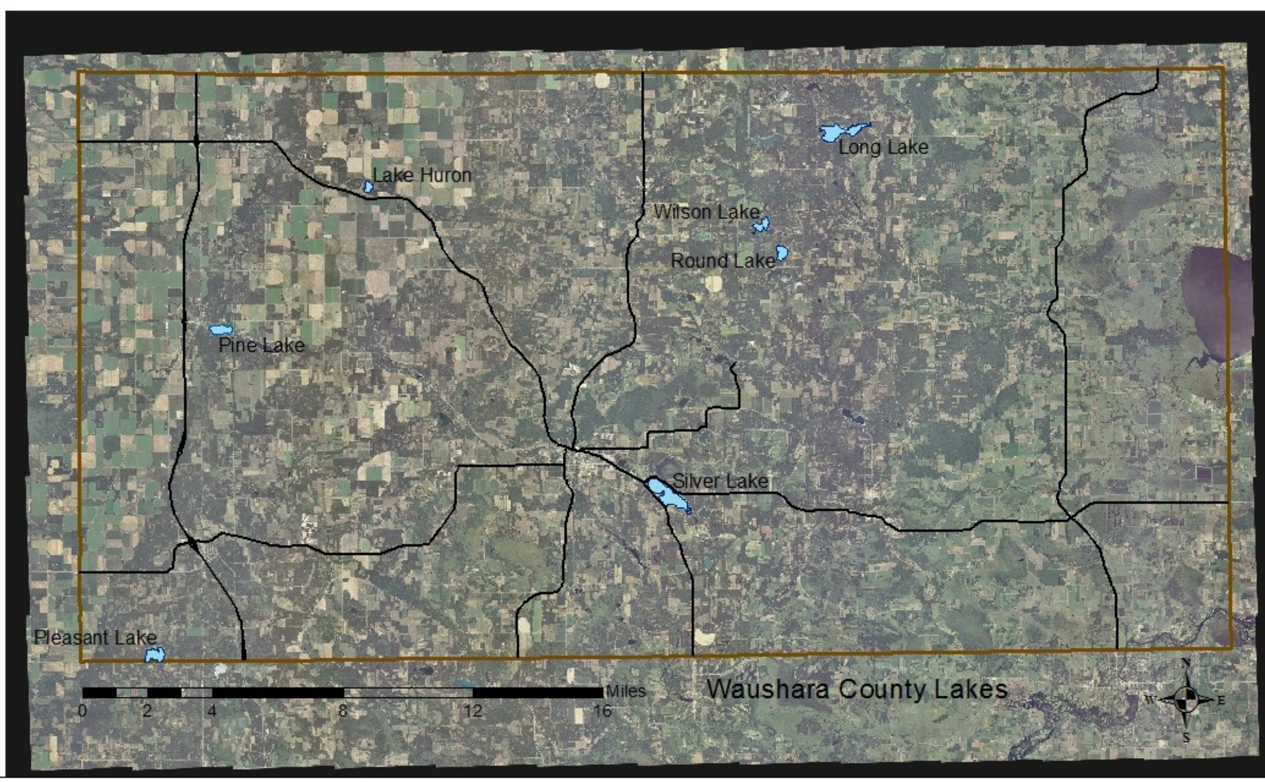

Figure 1. Map of Waushara County showing the study lakes. Deer Lake is not shown on this map as it was sampled as part of another study.

Bertalot (1986, 1988, 1991a,b), Camburn and Charles (2000), Krammer (2000), Lange-Bertalot (2001), and Siver et al. (2005) as well as primary species literature.

Results and Discussion

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 2 shows photographs of diatom species that were common in the sediment cores.

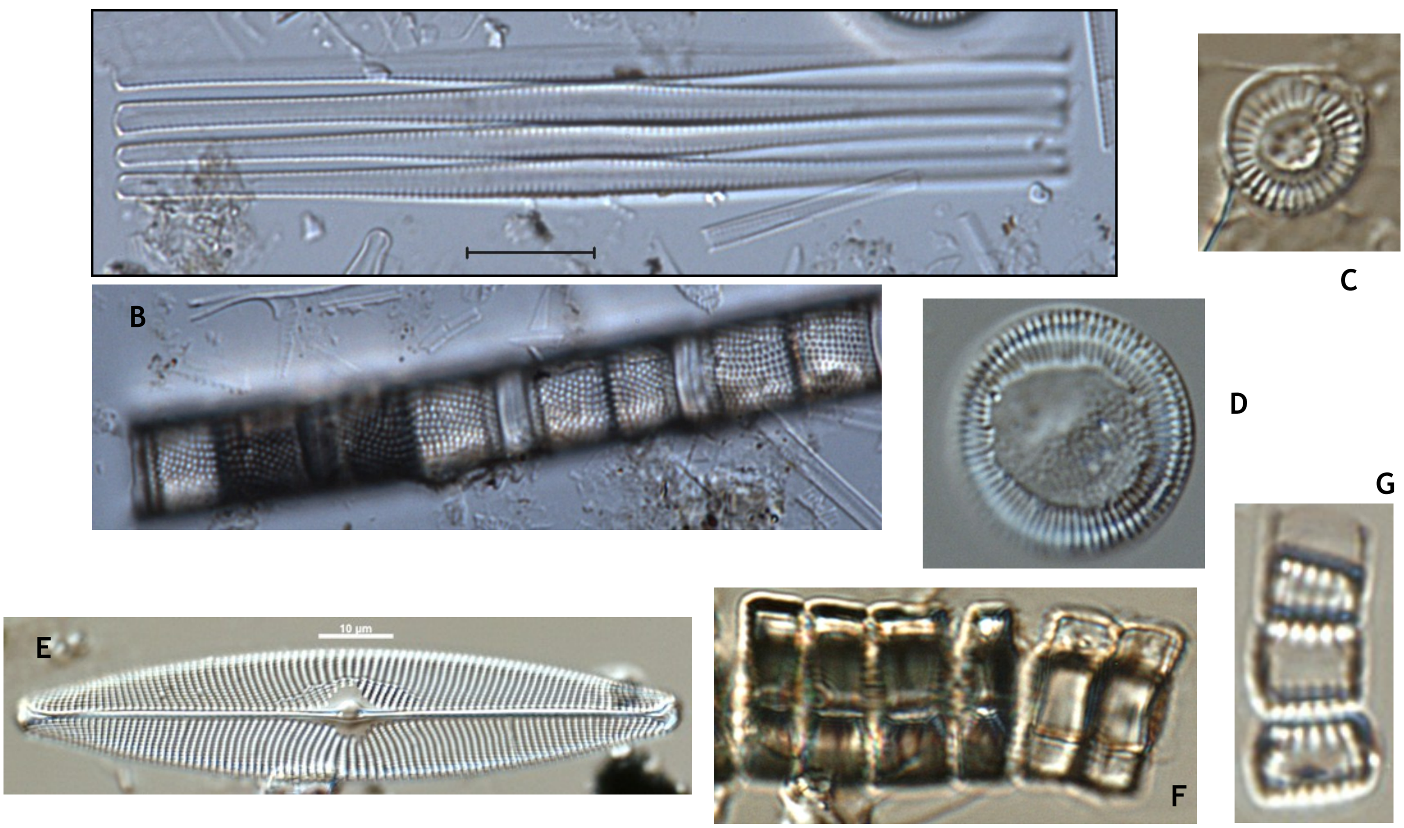

Figure 2. Photomicrographs of the common diatoms found in the sediment cores. The first four diatoms (A) *Fragilaria crotonensis,* (B) *Aulacoseira ambigua*, (C) *Discotella stelligera, and (D) Cyclotella michiganiana* typically are found in open water environments. *Staurosira construens* ((F) and *Staurosira construens* var. *venter (G)* is commonly found attached to substrates such as aquatic plants, other filamentous algae or grow on the sediments and are often associated with higher nutrient concentrations. *Navicula vulpina* (E) grows on aquatic plants and is usually found in low nutrient environments.

All of the lakes are seepage lakes, meaning they have no surface inlets or outlets. These types of lakes generally have lower nutrient concentrations. Water chemistry samples collected and analyzed during the last few years found that these lakes would be classified as mesotrophic based upon their summer phosphorus levels (Table 2). Long (Saxeville) had the lowest phosphorus and chlorophyll concentrations as well as the best water clarity. These levels put this lake

Table 2. Summary of selected water chemical variables from the study lakes. Samples were collected and analyzed by the UW-Stevens Point during the period 2010-12. Secchi disk transparency, phosphorus and chlorophyll are mean values for the summer period while the other variables were sampled less frequently.

	Secchi (m)	Alkalinity (mg L^{-1})	Color (PTU)	pH	Total P (µg L-1)	Total N (µg L^{-1})	Chlorophyll *a* (µg L^{-1})	Chloride (mg L^{-1})
Big Silver	5.3	128	8	8.1	18	700	2.1	12.7
Deer*	2.8	131	10	8.1	18	720	4.5	11.1
Huron	4.0	158	14	8.2	10	1402	1.8	8.5
Long	5.3	134	9	8.2	9	730	1.4	1.7
Pine	3.8	142	26	8.3	16	1088	2.8	5.1
Pleasant	3.0	136	10	8.5	18	858	3.6	1.6
Round	3.4	63	13	7.8	14	780	2.7	1.2
Wilson	2.0	130	29	8.0	19	1270	4.2	14.3

*Only a single sample was collected in July 2012

on the border with oligotrophic. All of these lakes have moderate to high alkalinity values and pH levels are around 8.0. Big Silver, Deer, and Wilson lakes have higher chloride levels, probably the result of the application of salt for ice and snow removal on roadways.

Big Silver Lake

The diatom community at the bottom of the core was dominated by planktonic taxa (Figure 3) which are a type of diatom that are found in the floating in open water. This is not surprising as the lake is relatively deep and of moderate size. The dominant taxa, *Aulacoseira ambigua*, pictured in Figure 1B, is a common diatom in many Upper Midwest lakes. This diatom can exist in a range of phosphorus levels but usually dominate under moderate to low concentrations. At the top of the core the dominant taxa shift to diatoms that grow attached to substrates, e.g. submerged aquatic plants and filamentous soft bodied algae. The taxa richness and diversity are greater in the top sample (Table 3) which supports the suggestion of more macrophytes. With the increase in abundance of macrophytes there are more niches for the diatoms to grow. This increase in diversity with increased nutrients is known as intermediate disturbance hypothesis. This hypothesis suggests that moderate disturbances result in a more diverse community because increased productivity results in more habitats. If the disturbance becomes great enough then richness and diversity decline. The increased richness and diversity is very common in lakes in northern WI that have moderate shoreland development but the watersheds are otherwise forested. This shift suggests that at the present time there are more macrophytes then prior to settlement. This shift also suggests there has been an increase in phosphorus concentrations in recent decades. The increase in phosphorus levels is probably not large or there would a greater shift in planktonic species to eutrophic taxa.

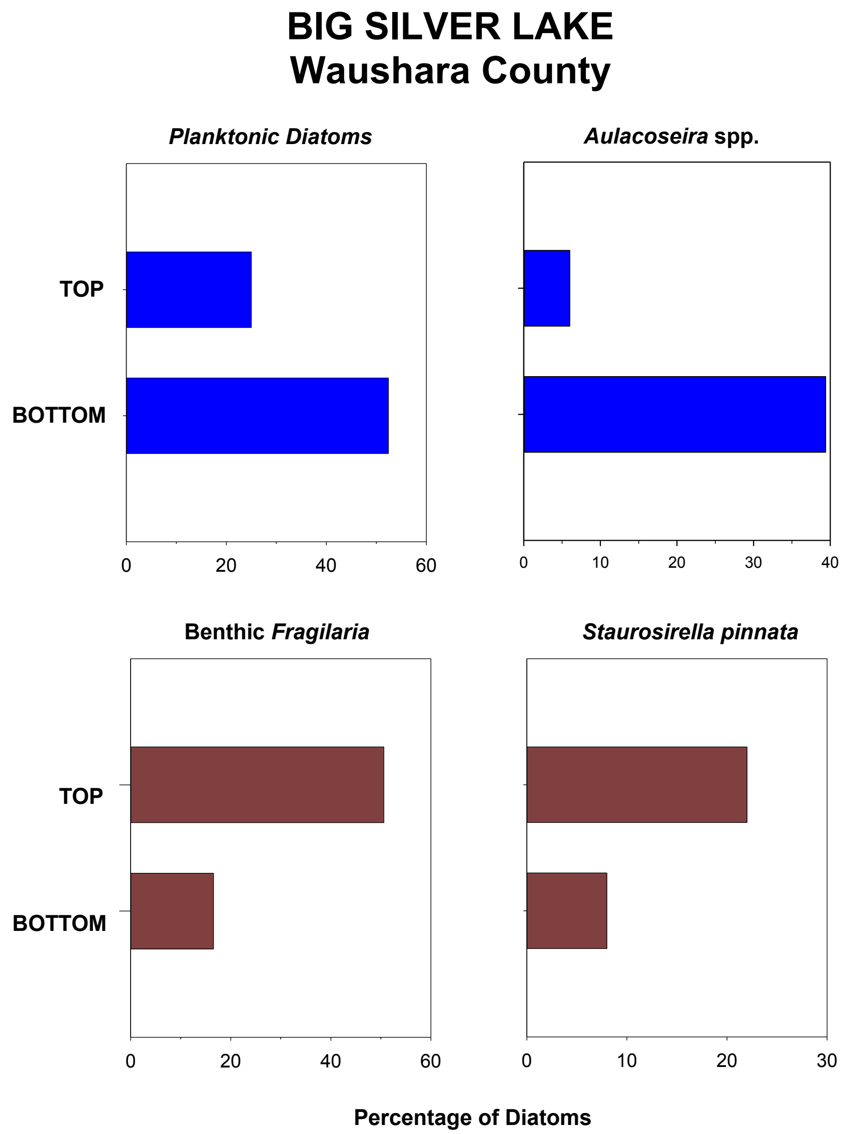

Figure 3. Changes in abundance of important diatoms found at the top and bottom of the sediment core in Big Silver Lake.

Deer Lake

There were almost no planktonic species in either the top or bottom sample in this lake. This reflects the fact that this is a relatively shallow lake and the diatom community is associated with submerged aquatic plants and filamentous algae. The bottom sample is dominated by benthic taxa that indicate low nutrient levels, e.g. Navicula vulpina (Figure 1E), *N. aurora*, and *N. wildii (Lange-Bertalot 2001)* (Figure 4). The diatoms indicate that submerged aquatic plants were common but they were not very dense and phosphorus concentrations in the water were low. In the top sample there were none of these large *Navicula* but instead most of the community was composed of benthic *Fragilaria*. This indicates that nutrient levels have increased to the point where filamentous soft bodied algae are present and the diatoms grow attached to these algae. The degradation of the lake is further suggested by the large decline in species richness (55 to 19) and accompanying decline in diversity (3.23 to 1.03) (Table 3).

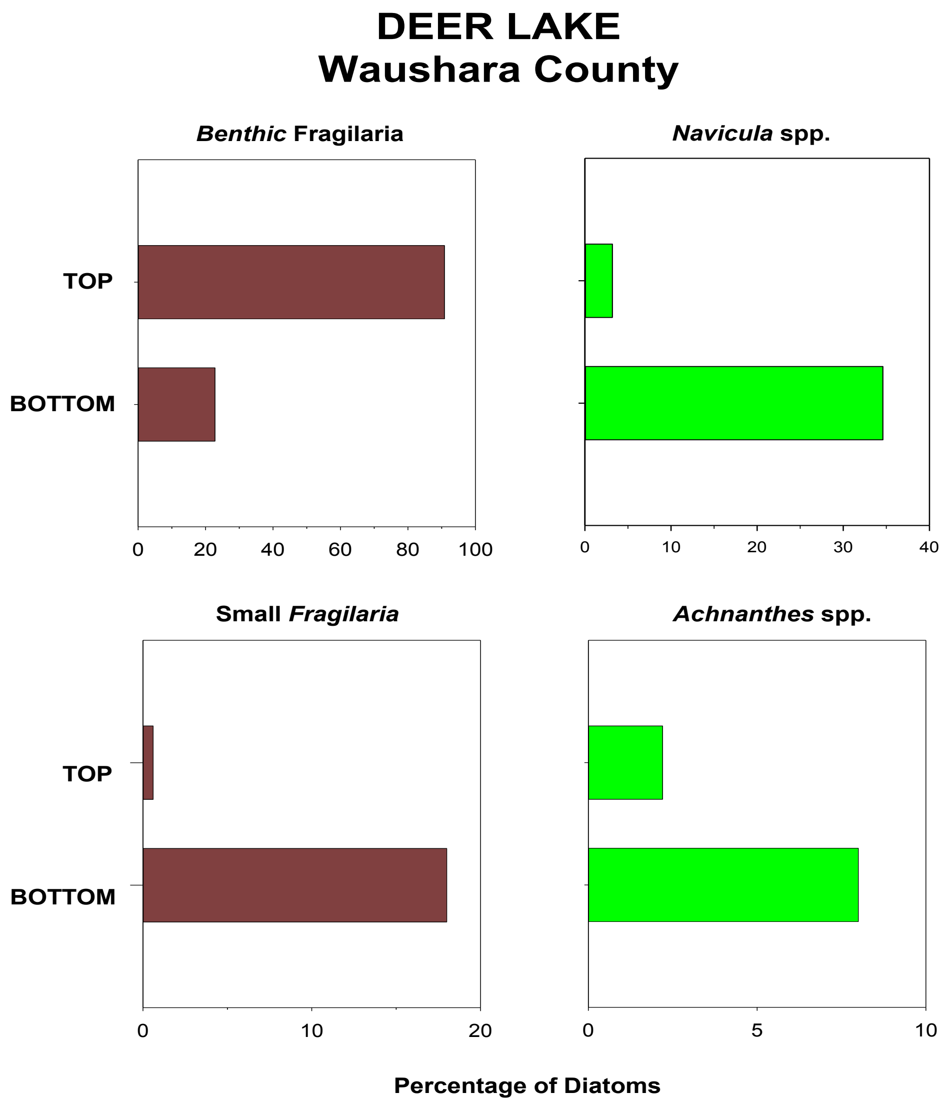

Figure 4. Changes in abundance of important diatoms found at the top and bottom of the sediment core in Deer Lake.

Huron Lake

Similar to Big Silver Lake, the diatom community is dominated by planktonic diatoms in the bottom sample (Figure 5). As with Big Silver, the dominant diatom is *A. ambigua*. Unlike Big Silver, at the top of the core planktonic diatoms still dominate the diatom community. There is a shift in the dominant taxa from *A. ambigua* to *Cyclotella michiganiana* and *Discotella stelligera*. *C. michiganiana* grows in the metalimnion and thus needs good water clarity. In the top sample *Cyclotella comensis* was found at a moderate abundance. This diatom is an invasive from northern Europe. It was first detected in North America in the 1950s (Stormer 1993, 1998). This diatom has been found in sediments deposited since 1950 in the Great Lakes (Stoermer et al. 1985; 1990; 1993) as well as inland lakes in northern lower Michigan (Fritz et al. 1993; Wolin and Stoermer 2005) and northern Wisconsin (Garrison 2005a,b; Garrison 2013). The diatom *C. comensis* typically is found growing in the open water in the middle part of the water column. This means that this taxa is found in lakes with good water clarity but elevated nutrient levels in the deeper waters. Studies indicate that this diatom responds to increased phosphorus and nitrogen levels (Schelske et al. 1972; Wolin and Stoermer 2005).

Table 3. Taxa richness and diversity for the study lakes.

Lake		Richness	Diversity
Big Silver	Top	63	2.95
	Bottom	43	2.46
Deer	Top	19	1.03
	Bottom	55	3.23
Huron	Top	48	2.97
	Bottom	32	1.69
Long (Saxeville)	Top	20	0.97
	Middle	56	2.60
	Bottom	34	1.98
Pine (Hancock)	Top	16	1.69
	Bottom	29	2.08
Pleasant	Top	14	1.33
	Middle	28	2.03
	Bottom	21	1.77
Round	Top	23	1.57
	Bottom	61	2.87
Wilson	Top	37	1.99
	Bottom	28	1.74

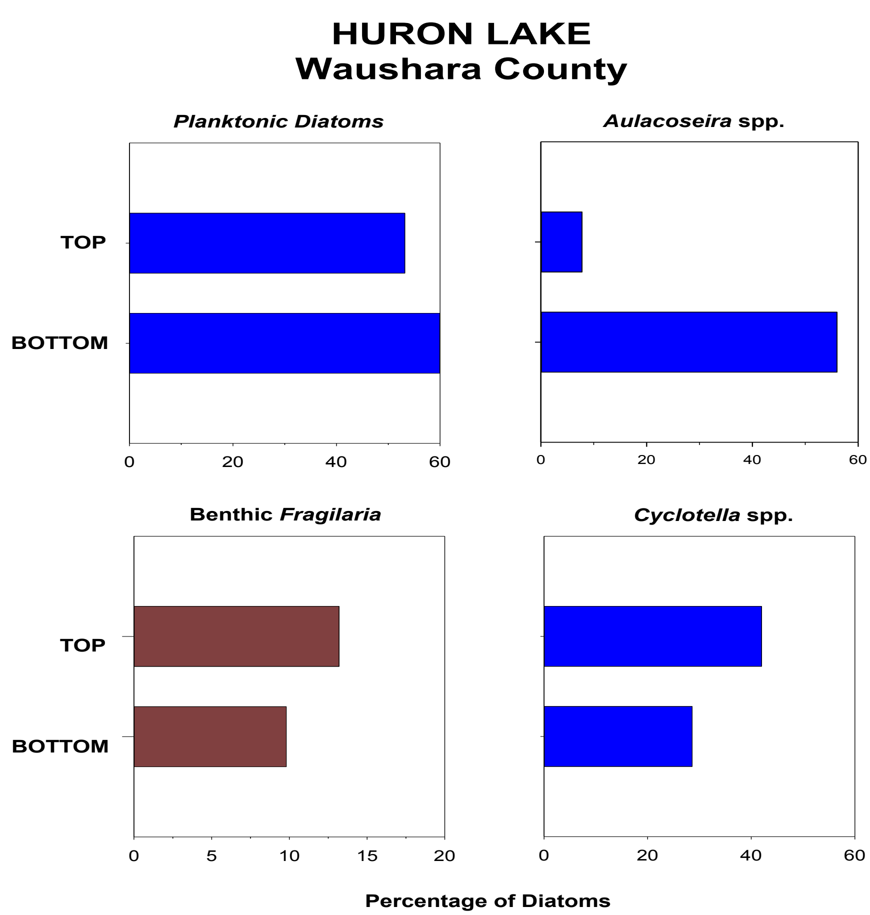

Figure 5. Changes in abundance of important diatoms found at the top and bottom of the sediment core in Huron Lake. *Cyclotella* spp. includes *Cyclotella* and *Discotella* species.

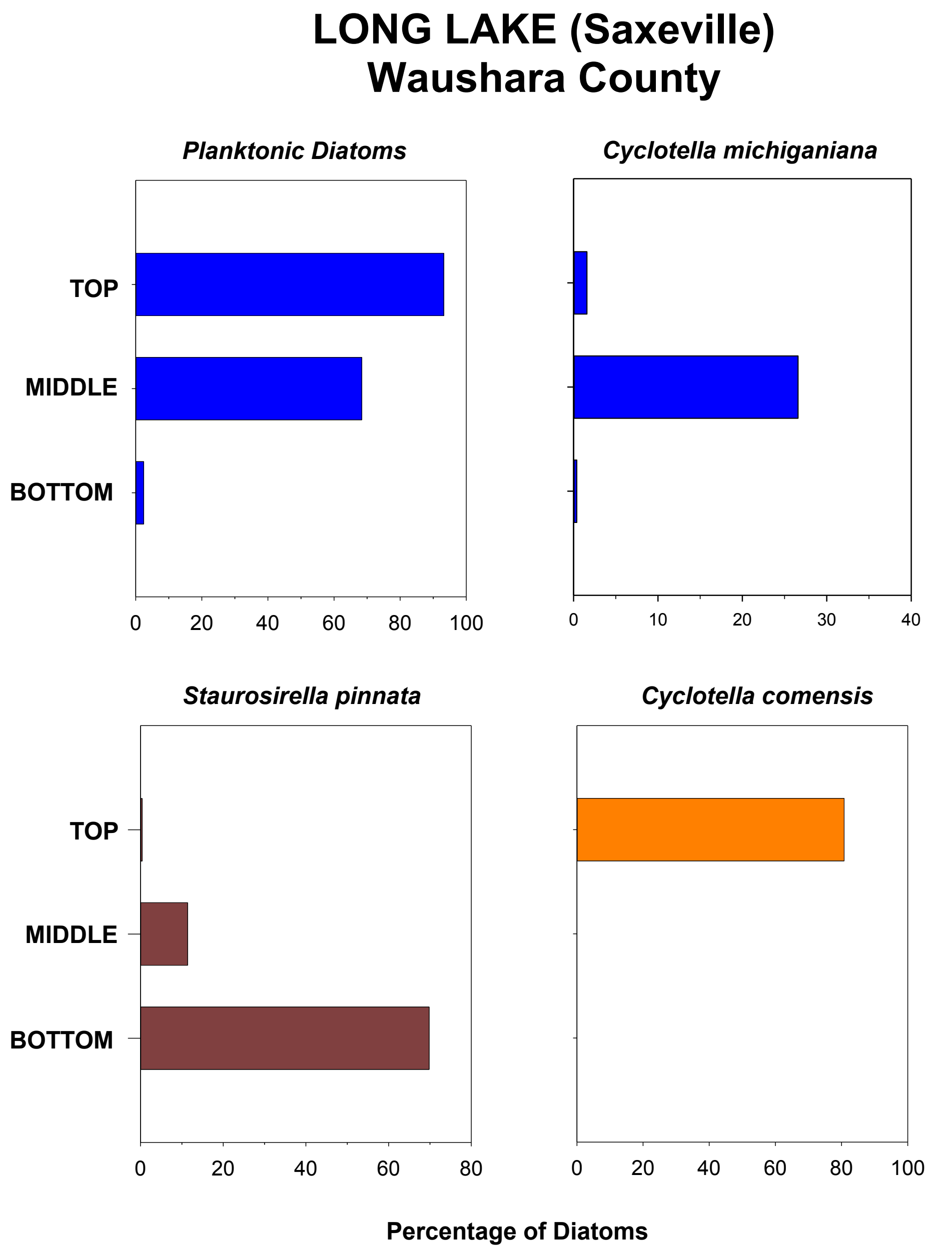

Figure 6. Changes in abundance of important diatoms found at the top and bottom of the sediment core in Long Lake. Three depths were analyzed in this core because the high dominance of *C. comensis* in the top sample made it difficult to fully understand the historical changes in this lake.

There are a few more benthic *Fragilaria* in the top sample which suggests there may have been a small increase in submerged aquatic plants and filamentous algae but it is much smaller than in Big Silver. This is indicated by a small increase in taxa richness and diversity (Table 3). Phosphorus concentrations probably have increased only a small amount.

Long Lake

Even though Long Lake is a large, deep lake, the bottom sample is dominated by the benthic diatom *Staurosirella pinnata* (Figure 6). This often is associated with filamentous algae and is an indicator of higher phosphorus levels. This diatom is also known to grow on bottom sediments and has been found two southeastern WI marl lakes at sediment depths prior to European settlement (Garrison and Wakeman 2000). It was hypothesized that in these types of lake, very clear water allows light to reach a significant part of the bottom sediments allowing this diatom dominates the community.

The dominant diatom in the top sample was *C. comensis*, the invasive diatom found in Huron Lake. Unlike Huron Lake, this diatom was found in very high numbers in Long Lake. In order to gain a better understanding of changes that occurred in the lake prior to the abundance of C. comensis, a sample in the upper middle part of the core was examined. In this section the dominant diatoms were planktonic taxa. By this time nutrients had increased enough that water clarity had declined and the planktonic diatom, *C. michiganiana* ,was an important part of the community. Since this diatom grows in the mid-level of the water column, water clarity was good at this time. This change in the diatom community from *S. pinnata* to *C. michiganiana* was also observed in the southeastern WI marl lakes mentioned earlier (Garrison and Wakeman 2000).

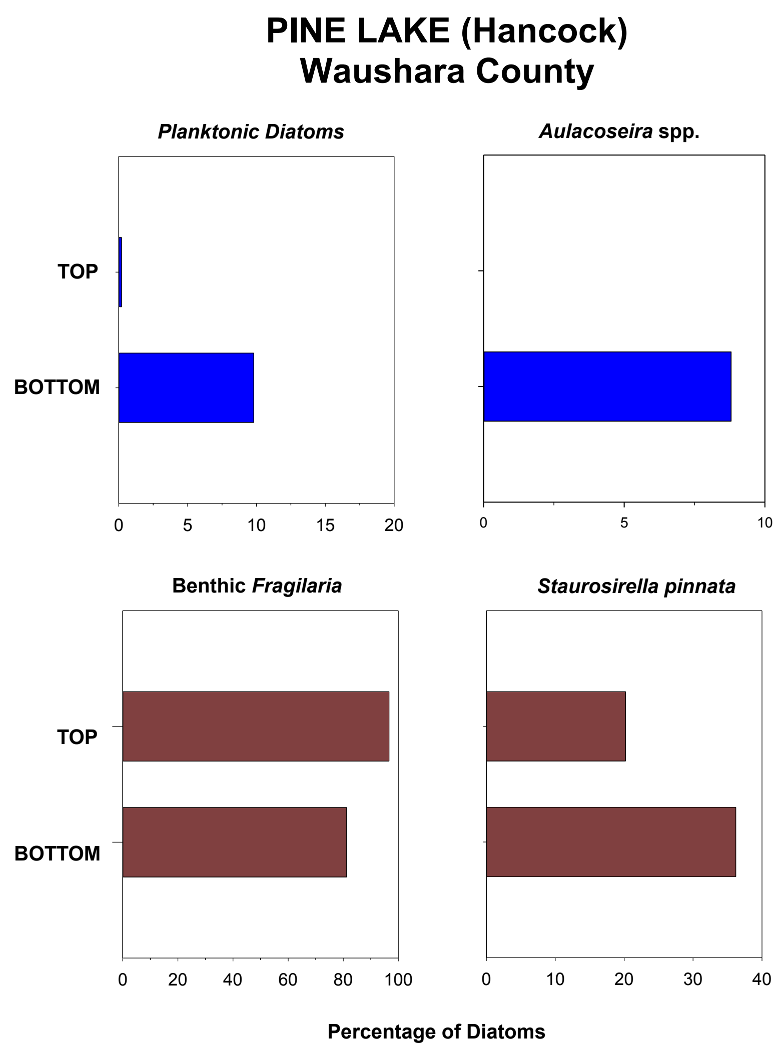

Figure 7. Changes in abundance of important diatoms found at the top and bottom of the sediment core in Pine Lake.

Taxa richness and diversity are highest in the middle section compared with the top and bottom which is consistent with the intermediate disturbance hypothesis. The low diversity at the top is common when an ecosystem is heavily impacted by an invasive species.

Pine Lake

Similar to Deer Lake, the bottom and top samples of Pine Lake are dominated by benthic diatoms (Figure 7). There are a few planktonic diatoms in the bottom sample unlike Deer Lake which reflects the slightly deeper maximum depth of Pine Lake. The dominant diatoms in the bottom sample are benthic *Fragilaria* which often are associated with submerged aquatic plants and filamentous soft bodied algae. Even though an important species is *S. pinnata* the abundance of other benthic *Fragilaria* suggests that historically there were abundant macrophytes. In the top sample there were almost no planktonic diatoms indicating higher nutrients concentrations at the present time. The reduction in taxa richness and diversity (Table 3) also indicates an increase in nutrients.

Pleasant Lake

Even though Pleasant Lake is relatively deep, the dominant diatoms were benthic taxa (Figure 8). There were slightly more planktonic taxa in the bottom sample but there is little change between the top and bottom samples. Because of the possibility that the dominance of small *Fragilaria* at the bottom of the core might have indicated excellent water clarity, an upper middle sample was examined. The community was similar in both samples. While it is possible that the dominance of small *Fragilaria* in the middle sample also signals excellent water quality, I think it is more likely that the diatom community has not changed much in the last 150 years because the lake's ecosystem has not significantly changed. The lowest taxa richness and diversity is at the top of the core and this suggests that phosphorus levels may have increased slightly.

Round Lake

In the bottom sample the dominant diatoms were benthic taxa but there were also a significant amount of planktonic diatoms (Figure 9). The most common planktonic taxa was *A. ambigua* which was present historically in most of the other lakes. The bottom sample also had some *N. vulpina* which are found growing on submerged aquatic vegetation when phosphorus concentrations are low. The taxa richness and diversity are also higher in the bottom sample (Table 3) suggesting that there was a rich macrophyte community and nutrient levels were low. In the top sample there were almost no planktonic taxa and the community was dominated by benthic *Fragilaria*. This suggests that nutrient levels have increased and while macrophytes are still common, there is a greater abundance of soft bodied filamentous algae. The taxa richness in the top sample is almost one third that in the bottom sample indicating that the lake's ecosystem has degraded.

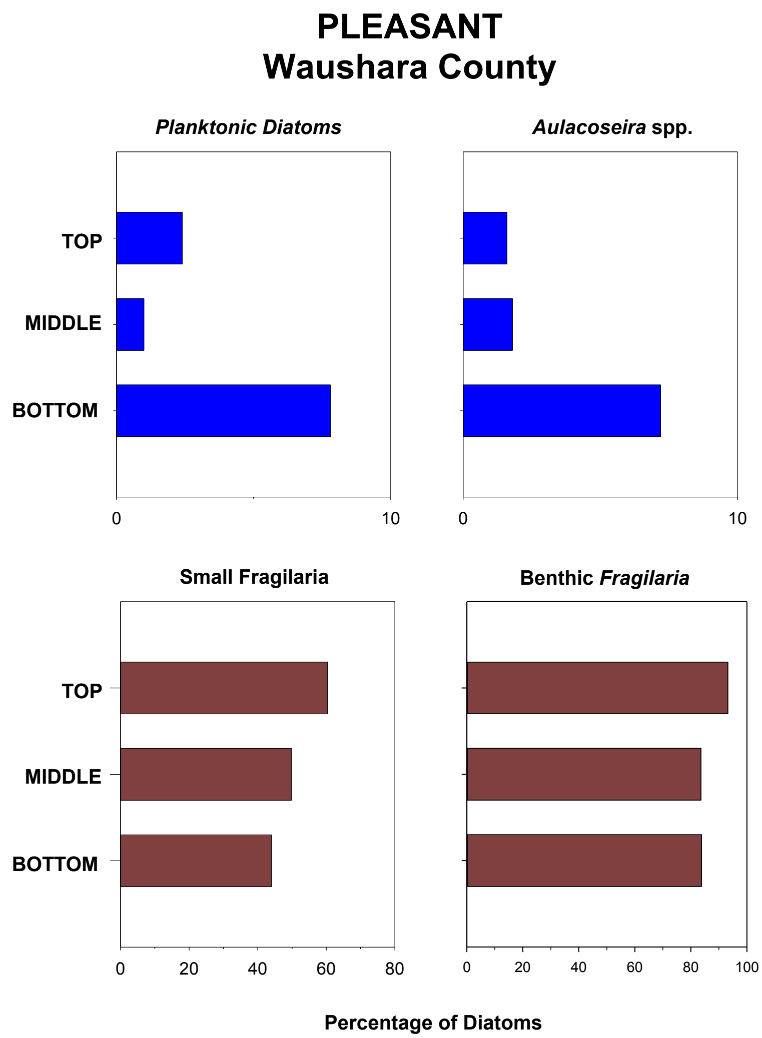

Figure 8. Changes in abundance of important diatoms found at the top and bottom of the sediment core in Pleasant Lake.

Wilson Lake

The dominant diatoms in the bottom and top of the core are benthic taxa (Figure 10). This reflects the relative shallow depth of the lake. Historically the dominant taxa are benthic *Fragilaria* which suggests that the historical phosphorus were higher compared with Deer and Round lakes. The bottom sample of Wilson Lake does not contain any of the large *Navicula* found in Deer and Round lakes which further suggests higher nutrient levels. The higher nutrients indicated at the bottom of the core may be because the lake is shallower than Deer and Round lakes. Similar to Pleasant Lake, the diatom community suggests that there has been little change in Wilson Lake during the last 150 years.

Data Analysis

In order to better understand how much the lakes have changed from historical times, a multivariate statistical analysis, detrended correspondence analysis (DCA), was performed on the diatom communities in the top and bottom samples of the study lakes (CANOCO 4.5 software, ter Braak and Smilauer 2002). The greater the separation between the bottom and top samples, the more the lake is different at the present time compared with its historical ecosystem.

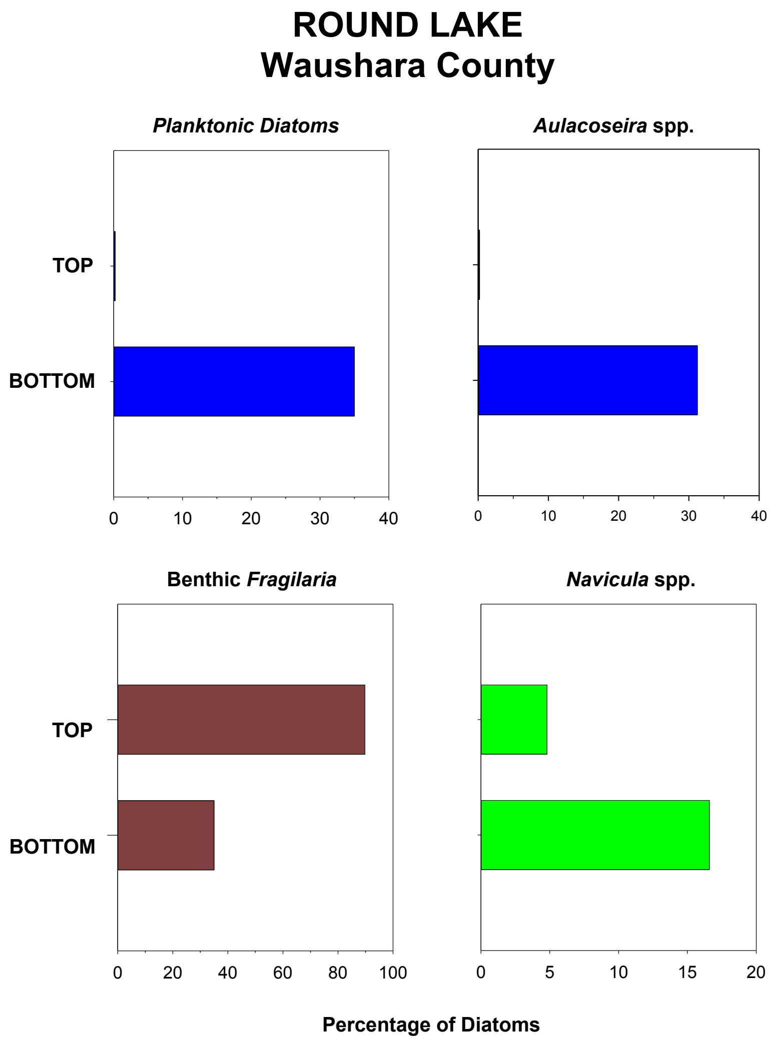

Figure 9. Changes in abundance of important diatoms found at the top and bottom of the sediment core in Round Lake.

The lakes that showed the greatest change are Deer and Long lakes (Figure 11). The lakes with the least change in the diatom community were Pleasant and Wilson lakes. With this analysis it is not possible to know for sure what environmental conditions are most influencing the shift in the placement of the samples on the graph but we can hypothesize what the main factors are. It is not clear what the horizontal axis indicates but most of the shift is in the direction of the vertical axis. The vertical axis probably indicates increasing amounts of benthic filamentous algae and increased macrophyte growth which is associated with increased phosphorus concentrations. A shift from bottom to top, e.g. Deer, indicates an increase in plants and filamentous soft bodied algae. The remainder of the lakes show some change from the bottom to the top but on a smaller scale than Long or Deer lakes.

Weighted averaging calibration and reconstruction (Birks et al., 1990) were used to infer historical water column total phosphorus (TP) in the sediment core. A training set was developed from 52 Wisconsin lakes. The 52 lakes training set is based on lakes with total phosphorus values from 3 to 30 µg L^{-1}. Training set species and environmental data were analyzed using weighted average regression software (C2; Juggins 2003) to calculate TP optima for 128 taxa in the training set. The resulting transfer functions (bootstrapped 999 cycles $r^2 = 0.79$, $P < 0.05$) were subsequently applied with weighted averaging calibration to the fossil diatom assemblages (Birks et al., 1990, Juggins, 2003). Initial TP esti-

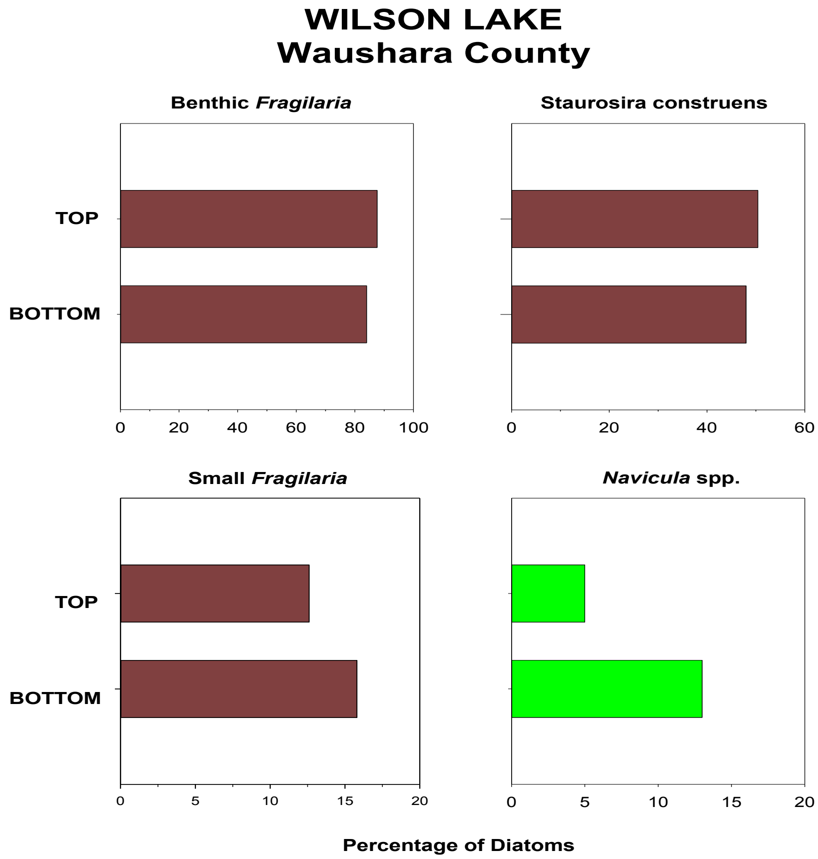

Figure 10. Changes in abundance of important diatoms found at the top and bottom of the sediment core in Wilson Lake.

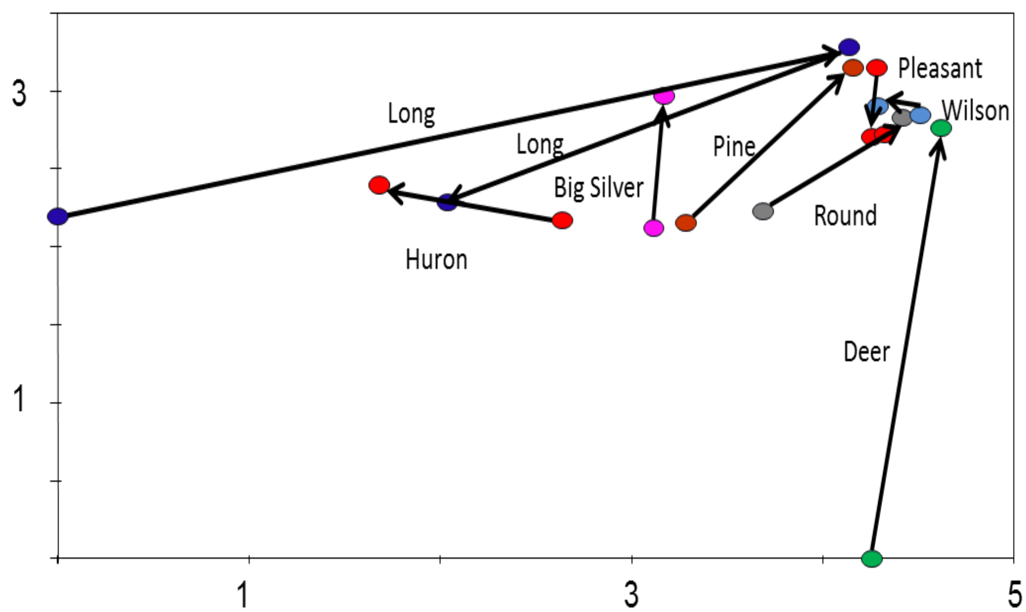

Figure 11. Discriminant correspondence analysis (DCA) for the diatom communities in the study lakes. The further apart the samples are the more dissimilar they are. Deer and Long lakes are the most different between the top and bottom samples while Pleasant and Wilson lakes show little change over time.

mates from weighted averaging regression were corrected using inverse deshrinking. Bootstrapped error estimates are based on initial log transformed data with the TP log error being 0.1407.

The results of the weighted averaging modeling accurately predicted the present day phosphorus concentrations in all of the lakes. The historical inferred phosphorus concentrations are similar for all the lakes ranging from 12-16 µg L^{-1} (Table 4). These concentrations are the same as most other seepage lakes in Wisconsin (Garrison et al. 2008). Most the lakes have experienced little on no increase in phosphorus concentrations. The lakes with the greatest increase in phosphorus are Deer and Pine lakes. These lakes have experienced an increase of 4-5 µg L^{-1}. Although the model appeared to work well for Long Lake, predicting a modern concentration of 8 µg L^{-1} which is nearly the same as the measured value of 9 µg L^{-1} (Table 2), the presence of the invasive diatom *C. comensis* may adversely affect the modeling results. It is unlikely that the phosphorus levels at the present time are lower than historical values. It is more likely that the historical phosphorus concentration was probably around 6-7 µg L^{-1} and phosphorus levels have increased around 2-3 µg L^{-1}. Estimating an accurate historical phosphorus concentration is complicated by the dominance of the benthic diatom *S. pinnata*. While this often is found under higher phosphorus levels, it is likely that in this lake it signals very good water clarity and low phosphorus concentrations.

Table 4. Diatom inferred summer mean phosphorus concentrations.

Lake		**Summer Phosphorus (µg L^{-1})**
Big Silver	Top	14
	Bottom	13
Deer	Top	17
	Bottom	13
Huron	Top	13
	Bottom	14
Long (Saxeville)	Top	8
	Middle	14
	Bottom	12
Pine (Hancock)	Top	20
	Bottom	15
Pleasant	Top	14
	Middle	13
	Bottom	14
Round	Top	14
	Bottom	15
Wilson	Top	16
	Bottom	16

Although phosphorus concentrations have increased a small amount or not at all in these lakes, there have been significant changes in the habitat of the lakes. Most of the lakes have more submerged aquatic plants and a greater expanse of filamentous soft bodied algae. This is especially true for Deer Lake. Long Lake has also experienced a decline in water clarity although phosphorus concentrations have only increased about 2 µg L^{-1}. Numerous other paleolimnological studies on lakes in northern WI have shown that lakes with shoreland development have experienced little change in phosphorus but significant changes in habitat. Borman (2007) found that in northwestern Wisconsin the macrophyte community often changed in seepage lakes, from one dominated by low growing plants to a community dominated by larger macrophytes, as a result of shoreline development. The structure of the macrophyte community changes because the increased runoff of sediment during construction on the shoreline enables the establishment of the larger plants. With the larger plants there is much more surface area available on which diatoms and other periphytic algae are able to grow. This appears to have occurred in many of the lakes in this study. With the increase in aquatic plants there is more surface area for attached algae to grow. While macrophytes obtain most of their phosphorus from sediments the attached algae obtain most of their nutrients from the water column. Consequently there is little increase in measured phosphorus levels because it is incorporated into the algae.

Summary

The lake that that experienced the greatest change from presettlement conditions was Deer Lake. This lake transitioned from a low nutrient with moderate submerged aquatic vegetation to a present day system where plants are much more abundant and there is a fair amount of filamentous soft bodied algae. The present day diatom community in Long Lake is dominated by the invasive diatom *Cyclotella comensis* which is native to northern Europe. This diatom was also found in Huron Lake but in much lower abundance. Only Deer and Pine (Hancock) lakes have experienced significant increased concentrations of phosphorus during the last 150 years. The historical phosphorus concentration in these lakes ranged from 12 to 16 µg L^{-1} which is similar to many other seepage lakes in Wisconsin.

Nearly all of the lakes have experienced a significant change in habitat with shoreland development. Many other lakes in central and northern Wisconsin have seen similar impacts from shoreland development. Although this study is not designed to document degradation of habitat on shore that other studies have found is common, this study does show that with development there often is increased growth of macrophytes and filamentous algae. The periphyton attached to these communities acts as a buffer to inputs of nutrients from shoreland runoff by incorporating nutrients into their plant tissues. Other studies in Wisconsin have shown that if nutrient runoff increases sufficiently, this buffer is overwhelmed and increased phosphorus levels occur in the open water of the lake (Garrison and Wakeman 2000). These Waushara County lakes are typical of many Wisconsin seepage lakes with shoreland development in that they have experienced limited increased concentrations of phosphorus but large changes in habitat during the last century.

Acknowledgments

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