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Understanding long-term environmental change in Lake Carmi, VT using the paleo-diatom record

by
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Undergraduate senior thesis conducted as part of requirements for the Environmental Science Bachelor of Science degree through the Rubenstein School of the Environment and Natural Resources and the Honors College

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Abstract

Vermont lakes are changing rapidly in response to interacting climate and watershed disturbances. Understanding and predicting the biological response to disturbance in these systems is limited by a lack of long-term biological monitoring records. Paleolimnology is a powerful tool that allows us to characterize environmental change over annual to multidecadal timescales through analysis of lake sediments. Lake Carmi, located in Franklin, VT, is a eutrophic lake that receives high inputs of nitrogen and phosphorus from the watershed and frequently experiences cyanobacteria blooms. The lake is an upstream tributary of Missisquoi Bay, Lake Champlain, and is surrounded by land primarily used for agriculture. In order to reconstruct the trajectory of eutrophication in this lake, 10 samples were taken from a sediment core and the paleo-diatom record was analyzed for relative genus and species abundance. As expected, we found increases in taxa, including *Fragilaria crotonensis* and *Aulacoseira granulata*, in the upper section of the core which are associated with high nutrient loads and serve as an indication that the lake has not always been eutrophic as it is today. These and other taxa including *Aulacoseira alpigena* and *Aulacoseira ambigua* demonstrate the lake's response to nutrient loading and physical disturbances in the lake and will be important to monitor in the future to inform the biotic response to nutrient remediation. The sediment diatom community provides insight into how Lake Carmi is responding to nitrogen and phosphorus nutrient loading and is the first step towards understanding its history and future trajectory to inform management decisions.

Introduction and Literature Review

Paleolimnology

Paleolimnology is a branch of the field of limnology that uses the chemical and micro-fossil record in lake sediments to reconstruct the environmental history of lakes over decades to millennia. These chemical and biological indicators serve as proxies from which pre-established relationships to different environmental conditions can be extrapolated (Beck et al., 2016). These conditions include trophic dynamics and water characteristics such as TP, pH, and salinity (Flower and Batterbee 1983, Anderson 1995). Lake variability is reflected in the sediment record and thus paleolimnological methods can reveal the drivers of ecosystem change over extended periods of time (Gauthier et al., 2020), which is especially helpful in cases where human records might not be as extensive or reliable (Dalton et al. 2018).

Diatoms as environmental indicators

Diatoms are a type of algae commonly used as an environmental proxy in paleolimnological studies. Because they have silica cell walls, they persist in lake sediments over long time periods. They have well defined tolerance ranges and autecology, which allows their abundance and community composition in lake sediments to be used to infer past conditions (Julius and Theriot 2010). Different diatom species thrive in different chemical and physical habitats (Rühland et al., 2015) meaning that communities are sensitive to changes in nutrient concentrations in their surrounding environment (Hobbs et al., 2010). A particular lakes' diatom community can indicate environmental conditions such as pH (Flower and Batterbee, 1983), nitrogen concentration (Saros et al., 2012), dissolved oxygen levels (Randall et al., 2019) and past eutrophication patterns (Davidson and Jeppesen, 2013). Ultimately, as diatom community composition changes with environmental conditions over time, their cell walls can remain preserved over thousands of years of sedimentation (Reavie et al., 2014), thus allowing for taxonomic identification (Hobbs et al., 2010). For all these reasons, diatoms are excellent indicators of ecological disturbance and change in lakes (Li et al., 2021, Bradshaw et al. 2006, Flower and Batterbee, 1983).

Examples in the Literature

Diatoms have a wide range of applications in paleolimnology. Understanding community turnover is another function of paleolimnology, such as a study that assessed remote lakes via sediment diatom δ -diversity to assess this turnover longitudinally (Hobbs et al., 2010). Other characteristics can be examined as well; the diatom record at two lakes in Scotland was studied to understand fluctuations in lake acidification over time (Flower and Batterbee. 1983). Sediment core distribution of the species *Aulacoseira granulata* and *Aulacoseira ambigua* were compared in Douhu Lake, Fujian Province, China, and their inverse population growth over time was found to directly reflect global warming trends (Li et al., 2021). The sediment diatom record has also been used to reconstruct a high-resolution record of lake-level change in the Aral Sea over 1600 years (Austin et al. 2007), and to understand historical land use. For example, Dutch agricultural land-use in the 19th century had significant impacts on lake ecology, determined via a pre-existing calibration dataset that correlated diatom assemblages with in-lake TP concentrations (Bradshaw et al. 2006). Similarly, ecological change was modeled over time using sediment diatom

assemblages and shifts in diatom community composition were found to correspond to land-use changes and population growth in the years following 1950 (Wolfe et al., 2001).

Carbon-to-Nitrogen Ratios as a Research Tool

Decades of research have informed the use of diatoms as an archive of past lake conditions (Anderson 1995). Diatoms are excellent indicators of lake productivity and anthropogenic eutrophication (Tezuka 1989; Niell 1976). The carbon to nitrogen ratio (C:N) fluctuates based on nutrient cycling in the lake, decreasing during periods of high productivity and increasing with a decline in productivity (Niell 1976). These ratios are a reliable tool to infer disturbance and historic nutrient loading in lakes (Kaushal and Binford, 1999), as algae blooms, a common effect of nutrient loading, result in high productivity levels. A C:N analysis was performed on the Lake Carmi core by M.S. student Kaleb Jones and was a key factor in determining areas of interest in the core, a technique that is found in other paleolimnological studies (Smol 2009). C:N as a tool to understand lake productivity is particularly useful in cases of eutrophic lakes and algal blooms. The literature confirms decreases in C:N values are associated with increased algal productivity (Levine et al, 2012) and nutrient input (Wengrat et al., 2019). Consistent with climate trends, decreases are expected C:N over time in the years following 1950 (Levine et al., 2012).

Connection to Transfer Functions

While some variables such as C and N can be measured directly in lake sediments, others such as phosphorus (P) cannot be measured reliably due to diagenesis. When this is the case, transfer functions are created to model relationships between individual diatom taxa and specific environmental conditions, such as P, pH, water clarity, or chloride (Anderson 1995). Before a transfer function can be created, a thorough data collection of diatom species composition across a gradient of lakes is needed; when paired with land-use history, connections can be made between diatom-inferred lake conditions and past human activity (Smol 2002, Koster and Pienitz 2006). In 1994, phosphorus concentrations were reconstructed using a transfer function in shallow, eutrophic lakes in England (Bennion, 1994). Transfer functions have only grown in use since then. Recently, and closer to the region of interest, Reavie et al. (2014) focused on the Laurentian Great Lakes correlated TP concentrations with diatom community assemblages by using a transfer function. Diatom community composition from a lake core provides the key data needed to create a transfer function (Davies et al., 2002, Werner and Smol, 2005).

Lake Carmi, Franklin, VT

The focus of this study is Lake Carmi, located in Franklin County, Northwest Vermont. The town of Franklin was first settled by colonizing Europeans in 1789. In the mid-1800s, a dam was constructed at the lake's outlet to support local industry; this dam was rebuilt in 1970 and exists to this day (Unpublished data contributed by Kaleb Jones). The land-use in the Lake Carmi watershed follows a history typical for Vermont. Once Europeans arrived, clear-cutting of trees for agriculture began; for the subsequent 200 years, the land continued to be settled and the shoreline developed (Unpublished data contributed by Kaleb Jones).

The lake is eutrophic (Gerhardt 2017) due to decades of agricultural nitrogen and phosphorus loading (Holdren et al., 2018). Current lake watershed management is focused on sustainable land use and reducing nutrient loads to tributaries, which has seen some success. Due to substantial phosphorus now stored in sediments, however, in-lake mitigation is also needed to minimize harmful algal blooms caused and internal phosphorus loading (Holdren et al., 2018). In 2019, the State of Vermont installed an aeration system in the bottom of the lake, with the intent of oxygenating bottom waters and suppressing the lakes' internal phosphorus loading (Schroth et al., 2019). The goal of my thesis work is to document the history of eutrophication in the paleolimnological diatom record by identifying species that are indicators of nitrogen and phosphorus enrichment. In the future, these data will be integrated into a transfer function to reconstruct historic phosphorus concentrations (Reavie et al 2014; Bradshaw 2006). This project will analyze samples from a 31cm core from Lake Carmi spanning the pre-industrial era to the present, and to begin the process of understanding diatom community composition, allowing for a deeper understanding of the history of Lake Carmi.

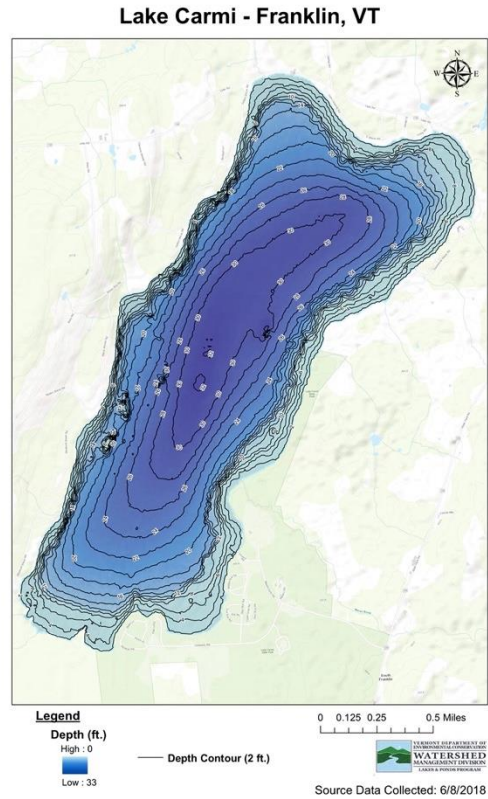


Figure 1. Bathymetric map of Lake Carmi, VT. Vermont Department of Environmental Conservation.

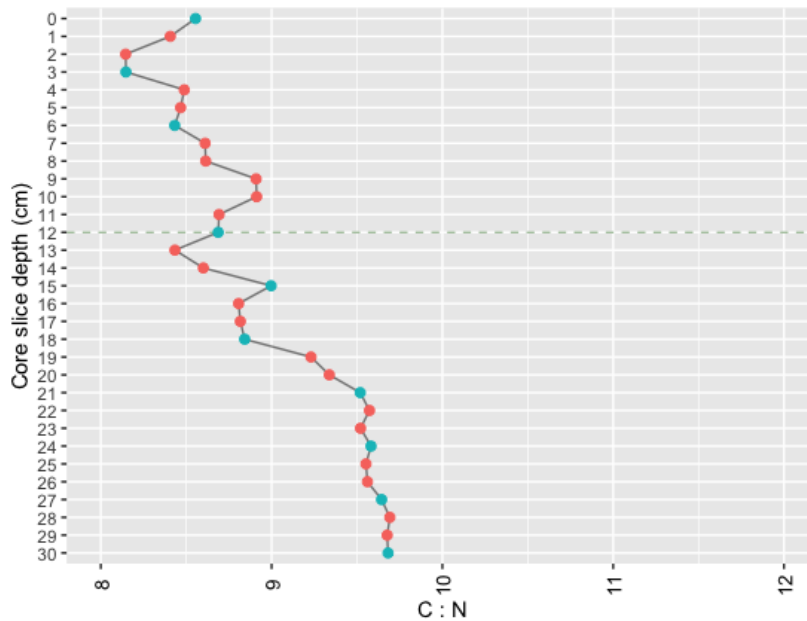


Figure 2. Measured C:N ratio in the Lake Carmi sediment core used to select samples of interest for diatom analysis.

Sample #	Depth Used (cm)
1	0
2	3
3	4
4	6
5	13
6	15
7	18
8	21
9	25
10	30

Table 1. Sample number in relation to the depth of the sediment core it represents. Data provided by M.S. student Kaleb Jones and Dr. Andrea Lini.

Methods

Sediment core collection

To collect this data from Lake Carmi, a sediment core was collected by Dr. Andrea Lini and Kaleb Jones on October 12, 2020 at the deepest point in the lake using a UWITEC gravity corer with an inner diameter of 6 cm. Lake depth was determined using bathymetric maps from the Vermont DEC. On site, depth was determined using a 100ft weighted measuring tape. The core was sectioned in centimeters, weighed, frozen, and placed in a Labconco Freezone 6 freeze-drier until dry. The desiccated samples were then weighed and ground into powder. Of 30 sections, samples of interest were chosen at inflection points on the C:N graph of the core. These are depicted in red in Figure 2; of these, 10 samples were ultimately analyzed.

Sample digestion

Following a method modified from Reimer (1966), 0.010g of freeze-dried sediment was weighed into a 150mL beaker. 20 mL 68-70% HNO₃ was added to each sample. Samples 1-6 and two blanks sat in the 20mL HNO₃ for five days before being boiled at a hot plate setting of 140°C for one hour. This measure was decided to be more time-consuming than necessary (but would not affect the digestion’s efficacy), and samples 7-12 were boiled in HNO₃ at a hot plate setting of approximately

120°C. The samples and blanks were all rinsed with the same protocol: HNO₃ was aspirated to 30 mL and DI added to 140 mL. Each rinse aspirated the supernatant to 30 mL and added DI back to 140 mL. Samples were allowed to settle at least 6 hours before the next rinse; each sample was rinsed 6 times (except sample 3 which was rinsed 7 times).

Slide preparation

To prepare for permanent slide mounting, the samples following the final rinse were aspirated to the final volume of ~15 mL (1-6) and ~20 mL (7-12), which is acceptable given the study's focus on diatom community composition and not species density. The samples were then agitated and then 1 mL was pipetted onto a coverslip (Figure 3). Two coverslips were made for each sample, including the 3 blanks. The coverslips dried overnight, and then were heated at hot plate setting 4 for approximately 10 minutes. 1mL Naphrax was used as a binding agent. The slides were heated for approximately 5 minutes, with light pressure being applied after removal to discourage gas bubble formation.

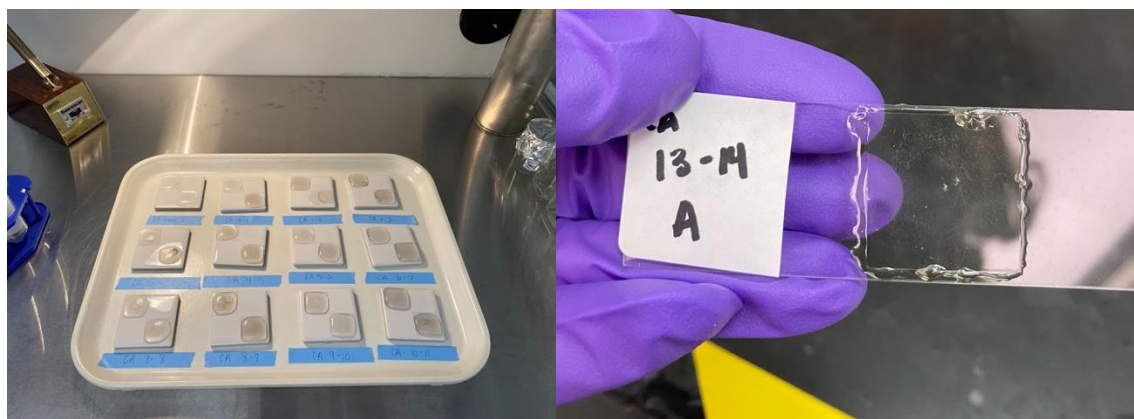


Figure 3. (left) Temporary slides of sediment and solvent drying; (right) a final prepared slide.

Diatom identification and quantification

300 valves were identified in each sample using the Diatoms of the US website (diatoms.org). Each sample was counted on a Leica compound microscope at 1000x magnification using an oil immersion lens. Each transect coordinate location on the scope was recorded during the counting process to avoid re-counting. Diatoms were identified to the lowest taxonomic resolution possible and identifications were quality control checked by M.S. student Ismar Biberovic and Dr. Morales-Williams.

Statistical analysis and visualization

Statistical analysis was performed using the R software using packages tidyverse, analogue, gridExtra and pacman.

Results

Key Findings

Several different *Aulacoseira* species were dominant throughout the core, regardless of depth. *Aulacoseira ambigua* remained consistently abundant throughout the depth of the core, while *Aulacoseira granulata* was dominant in the upper (most recent) part of the core, and *Aulacoseira ambigua* was more abundant with depth (Figures 4 and 5). A graph of lead % in the core plotted by M.S. student Kaleb Jones indicates a peak of Pb at ~13cm into the core, which is known to be associated with the years 1960-1970. Thus, distributions above 13cm can be inferred to be post-1970, and those below as before 1960.

Lindavia sp. also increased with depth, as did *Stephanodiscus* sp., while *Fragilaria crotonensis* decreased in abundance as depth increased (Figure 4). *Navicula* sp. showed a moderate increase while *Pseudostaurosira* sp. showed a more dramatic increase as core depth increased (Figure 6). Other rare genera (<0.5% relative abundance) including *Cocconeis*, *Diploneis*, *Eunotia* and *Tabellaria* showed a change in abundance over the length of the core (Figure 7).

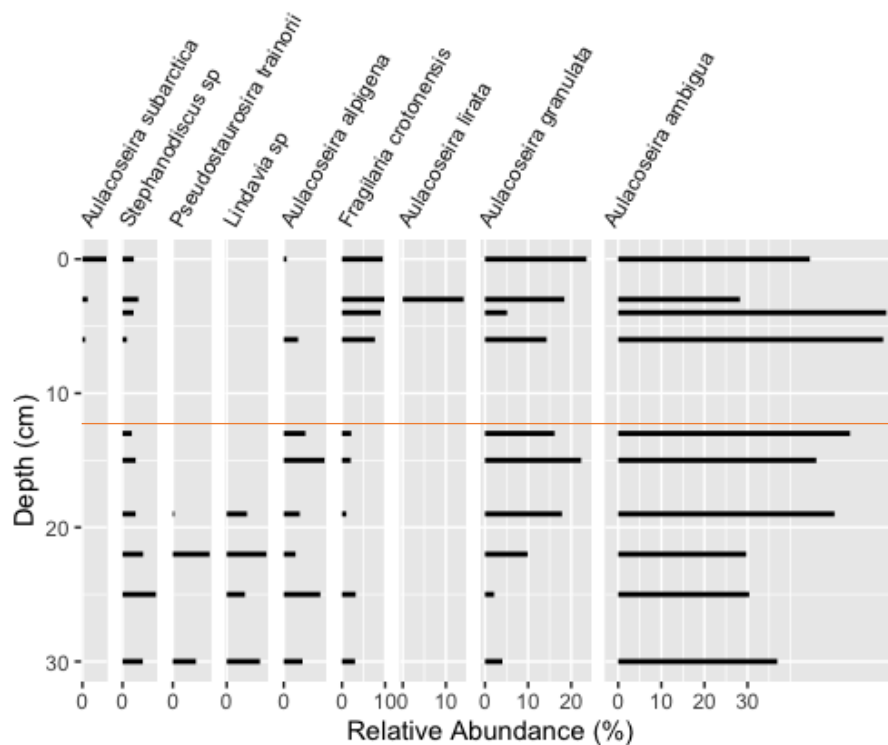


Figure 4. Taxa with 5% or more relative abundance per sample. The red line represents approximately the 1960-1970 decade.

Preliminary results filtering the data by relative abundances of 5% or higher (Figure 4) demonstrate strong *Aulacoseira* sp. presence and diversity. The presence of *Aulacoseira* throughout the distribution of the core generated interest in a plot examining just *Aulacoseira* species (Figure 5).

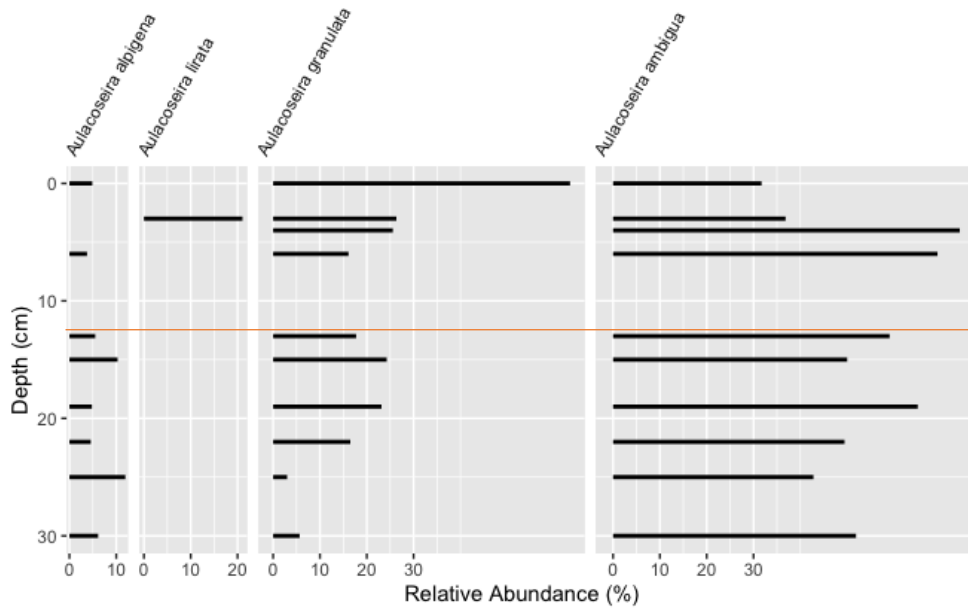


Figure 5. *Aulacoseira* species above 5% abundance.

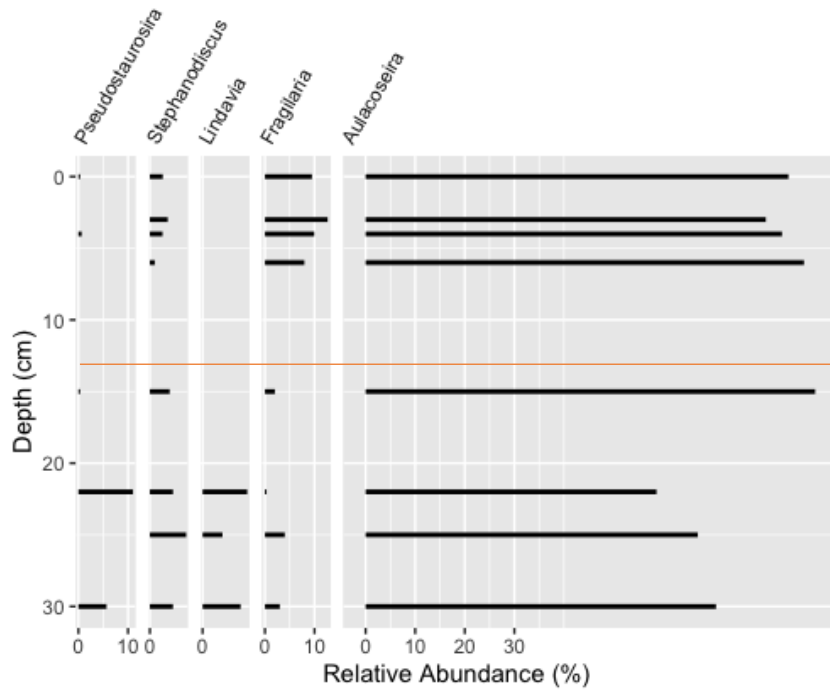


Figure 6. Relative abundance above 5% grouped by genus.

Figure 6 shows that along with *Aulacoseira*, the most common genera were *Pseudostaurosira*, *Fragilaria*, *Stephanodiscus*, and *Lindavia*.

A plot was created looking at the genera with abundances lower than 0.5% (Figure 7), as a way to get a sense of overall community composition aside from the most abundant taxa. Here, genera such as *Cocconeis*, *Diploneis*, *Tabellaria*, *Eunotia*, *Navicula* and *Planorbulidium* can be seen as making up a small portion of the diatom community in the sediment.

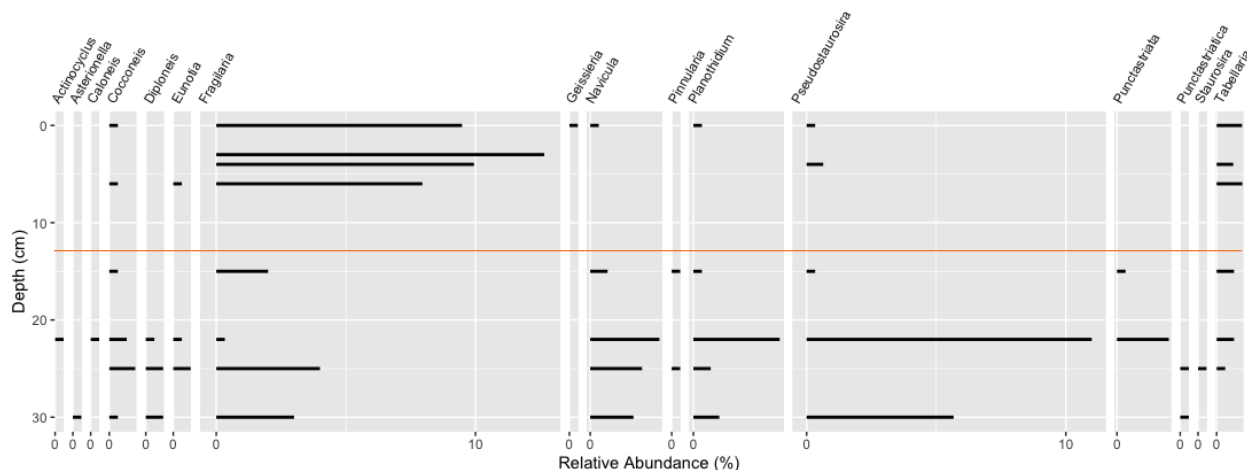


Figure 7. Genera with relative abundance lower than 0.5% per sample.

Discussion

Our results align with other Northeast and Midwestern lakes with similar agricultural land-use histories and challenges with nutrient loading. *Aulacoseira ambigua* has been previously associated with eutrophic conditions (Terasmaa et al., 2013), and physical disturbance (Wolin and Stoermer, 2005). *Fragilaria crotonensis* is thought to be associated with an increase in annual temperatures (Bradbury et al. 2002) and increased nitrate conditions (Wolin and Stoermer, 2005). Studies at Lower Herring Lake, Michigan, reflected similar trends of *Aulacoseira ambigua* dominance and a strong presence of *Fragilaria crotonensis* in the upper sections of the core before decreasing with depth (Wolin and Stoermer, 2005). Similar to the results of this study, in Pasqua Lake, Saskatchewan, Canada, *Aulacoseira granulata* has been found to increase after disturbance associated with European settlement periods. *Aulacoseira granulata* is also associated with eutrophic conditions (Hall et al., 1999). *Aulacoseira alpigena* has been found to be connected to lake mixing (Dalton et al., 2018) to decrease in the presence of TP (Yang et al., 2008), and to generally prefer oligotrophic lakes (Leira et al., 2015). This would support the decrease in *Aulacoseira alpigena* post-1970, given the increase of nutrient inputs and other anthropogenic influences on the watershed.

Beyond the most dominant genera, there are other trends of interest. *Pseudostaurosira sp.* has been found to tolerate low light conditions and ice cover (Dalton et al., 2018). This genus is abundant in the pre-1960 section of the core (Figure 7). In Lake Champlain, the lake has frozen over less and less and has been melting sooner (Lake Champlain Committee). The distribution of *Pseudostaurosira* could be indicating a similar trend at Lake Carmi, wherein historically the lake could have iced over more frequently and for longer periods of time.

Tabellaria flocculosa has been found to be indicative of eutrophication (Lotter et al., 1998). This aligns with other eutrophic-indicating taxa distribution in the core.

Cocconeis sp., an epiphytic diatom genus, is associated with lower nutrient levels and often found growing on filamentous, macrophytic algae like *Cladophora sp.* (Brugam and Munoz, 2018). Its distribution is consistent with other data in that its abundance is greater pre-1960 than in post-1970. *Eunotia spp.* are also abundant in lower nutrient concentrations (Jacques et al., 2015); additionally, both *Eunotia* and *Cocconeis sp.* are known to be tolerant of low-pH environments (DeNicola 2000). In our study, these two genera shared similar distributions (Figure 7). Indicative of the specificity of diatoms to their environment, *Tabellaria* has also been noted to be associated with acidification (McGowan et al. 2017) and yet is distributed inversely to *Cocconeis* and *Eunotia* – suggesting more study at Lake Carmi will be needed to fully assess diatom community composition and patterns of distribution.

Asterionella formosa is notably absent from all but one of the samples. Given the association between this species and eutrophication and anthropogenic disturbance (Wolin and Stoermer, 2005, Meriläinen et al., 2000), this is a surprising result. There might be more to the story as Lake Carmi is nitrogen-limited, and *Asterionella formosa* has been found to decline in population with a shift to N-limitation (Lehman and Sandgren, 1978). This could provide a key into understanding Lake Carmi’s history with N-limitation in the past, but more research is needed for a definitive conclusion.

Furthermore, *Stephanodiscus sp.* is also associated with eutrophic conditions in lakes (Terasmaa et al., 2013) and yet was lower in abundance post-1970, with greater populations at the bottom. Similarly, *Navicula sp.* is a diatom often associated with high nutrient levels (Burt et al., 2013), which makes its lack of abundance near the top of the core intriguing. However, it is a primarily benthic taxa, so it may have decreased due to turbidity and light limitation with increasing eutrophication. There does not appear to be a strong conclusion as to the relationship between *Lindavia* and conditions such as turbidity and phosphorus concentrations (Kireta et al., 2019), though several species of this genus were recently reclassified from the genus *Cyclotella*, so more research on autecology under the previous classification is needed.

Taxon	Lake Conditions
<i>Aulacoseira ambigua</i>	Eutrophic Physical disturbance
<i>Aulacoseira granulata</i>	Post-European disturbance Eutrophic
<i>Fragilaria crotonensis</i>	Temperature increases Nitrate increases
<i>Aulacoseira alpigena</i>	Lake mixing Low TP Oligotrophic
<i>Pseudostaurosira sp.</i>	Low light Ice cover
<i>Tabellaria sp.</i>	Eutrophic
<i>Cocconeis sp.</i>	Low nutrient levels Low pH
<i>Eunotia sp</i>	Low nutrient levels Low pH
<i>Stephanodiscus sp.</i>	Eutrophic
<i>Navicula sp.</i>	High nutrient levels
<i>Asterionella formosa</i>	Eutrophic Anthropogenic disturbance

Table 2. Diatom taxa mentioned in discussion and associated lake conditions.

On an entire-core scale, it is worth noting the C:N ratio (Figure 2) is relatively low at the bottom of the core (Levine et al., 2012) and then continues to decrease. This indicates that Lake Carmi's eutrophic state is not a new development. This paints an interesting picture with the diatom assemblages, given the marked increase in nutrient-indicator species such as *Fragilaria crotonensis*, *Aulacoseira granulata*, and *Tabellaria sp.* These assemblages suggest a more drastic change in nutrient loading. Putting these two results together indicates that Lake Carmi has been nutrient-rich for approximately 100 years or more; when paired with diatom assemblage patterns, it indicates perhaps an increase in anthropogenic nutrient inputs to the lake. Potential causes could be increases in fertilizer volume or concentration due to the demands of the agriculture industry, and an increase in impervious surfaces in the surrounding watershed that would result in more nutrients entering the lake. Lake Carmi also receives nutrients from internal loading. This internal loading could be aggravated in recent decades with more internal disturbance from recreational activities or, more likely, the construction of dams.

Implications

Our data show that the diatom community in Lake Carmi has responded to long-term changes in nutrient loading. Furthermore, results reflect that the history of the lake can be reliably tracked in the paleo-diatom record. Changes over time, especially those with *Aulacoseira granulata* and *Fragilaria crotonensis* (but also *Tabellaria*), demonstrate the lake's eutrophication has become more extreme, or amplified, over time. There is also potential for factors beyond nutrient concentrations to be understood from the paleo-diatom record, whether that is ice cover trends or pH.

If the aeration system continues to operate, an expected change could be an increase in *Stephanodiscus sp.*, as extended periods of circulation to a lake bottom has been found to promote blooms of this genus (Bradbury et al. 2002). With *Aulacoseira ambigua* in particular, it will be an indication of how much disturbance the aeration system causes, since the species is found to decrease with anthropogenic influence on a landscape, yet increases with physical disturbance (i.e., turbidity), such as the kind that an aeration system could create (Wolin and Stoermer, 2005). Given that the species has been declining in the upper section of the core, watching its behavior in the future would be a key indicator of the disturbance level of the aeration system.

Study Limitations

The upper levels of the core have been disturbed in recent years due to the installation of the aeration system. Thus, between 0 and 10cm, the species distribution is less likely to be identified as they were originally deposited. However, as depth increases, species distribution becomes more reliable and changes are apparent.

Conclusions and Future Research

Conclusion

This study addressed the questions, 1. What species comprise the diatom community composition in the sediment of Lake Carmi, and 2. How this knowledge can inform our understanding of the lake within the context of eutrophication?

The diatom community in the sediment of Lake Carmi is heavily dominated by *Aulacoseira* spp.; however, there is still a diverse though lower in abundance community comprised of species such as *Stephanodiscus* sp., *Lindavia* sp., *Fragilaria crotonensis*, and *Pseudostaurosira* sp., among others. In the upper part of the core, this community reflects the recent increases in eutrophication and lake disturbance in more recent years that are likely also fueling cyanobacteria blooms that challenge public and ecological health each summer. Furthermore, the change in composition over the depth of the core illustrates that while the land-use history of the land surrounding Lake Carmi has long been agricultural and the lake shows signs of nutrient loading prior to 1960, anthropogenic changes have occurred since earlier settlements that have caused the noted increase in eutrophication in recent decades.

The diatom community at Lake Carmi is a reliable metric in understanding and predicting changes in the lake over time. Lake Carmi been eutrophic and experiencing frequent cyanobacteria blooms for nearly a generation (Polhamus, 2018); however, this record shows it was not always this way. More study of the paleo-diatom record will increase knowledge of other conditions, such as ice cover, pH, and TP, and with greater detail.

Future Research

As referenced in the introduction, transfer functions are the next step to fully reconstructing past lake conditions at Lake Carmi. This transfer function would allow for a more detailed assessment of nutrients such as phosphorus and nitrogen over the history of the lake encapsulated in the sediment core. To create the transfer function, the remaining 18 core sections from Lake Carmi should be digested and preserved in permanent slides for diatom taxonomic identification and counting, giving a thorough depiction of species change over the length of the core. Furthermore, to allow for greater temporal accuracy, dating the sediment of the core with radioactive isotopes such as Pb-210 would allow to place the changes of community composition along a more specific timeline that can then be correlated with changes in land-use. These steps will allow for a fuller picture of Lake Carmi that will only better serve management decisions.

Summary

Unlike Lake Champlain, there is a lack of long-term records of Lake Carmi. Paleolimnology represents a reliable approach to understanding the lake's history. The findings of this study are the beginning of developing a detailed record of the lake's past conditions. This is important as the lake continues to experience the results of heavy nutrient loading and eutrophication. It is the hope of this study that greater knowledge of Lake Carmi can influence management decisions that will improve the health of the lake.

Acknowledgements

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