

**USING FOSSIL CHIRONOMIDS TO INVESTIGATE DISSOLVED OXYGEN IN NEW
BRUNSWICK LAKES EXPERIENCING ALGAL BLOOMS**

BY

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A thesis submitted to the
Department of Geography and Environment
Mount Allison University
in partial fulfillment of the requirements for the
Bachelor of Science degree with Honours
April 21, 2022

Abstract

Lake eutrophication often results from an increase in anthropogenic activities and poses a serious threat to the function and structure of lake ecosystems. In particular, algal blooms are increasing in frequency in low-nutrient lakes that would otherwise not be expected to experience signs of eutrophication. As algal-derived organic matter sinks in the water column, bacteria consumption uses a large amount of dissolved oxygen (DO). When DO levels become low in a lake's hypolimnion, hypoxia can occur, threatening lake health. In this study, 20 low-nutrient New Brunswick lakes were examined for environmental changes using the paleolimnological approach of comparing the relative abundances of invertebrate taxa (chironomids) from "top and bottom" sediment intervals. Lakes were grouped into bloom and reference categories for comparison of measures of water quality and invertebrate bioindicators. Most water quality measures did not differ between categories. Assemblages indicated that there were ecological changes between top and bottom samples of several individual lakes as opposed to consistent differences in assemblage composition between bloom and reference categories. Findings indicate the importance of both direct and indirect monitoring of low-nutrient New Brunswick lakes.

Acknowledgments

I would like to thank my supervisor Dr Joshua Kurek for giving me the opportunity to work under his guidance on this project. I am thankful that he gave me the opportunity to work at ECAB the summer prior to my third year which is when I knew that this was the lab and the mentor, I wanted to do my Honours with. His guidance and confidence in my abilities have allowed me to make strides towards my future goals and careers.

I also would like to extend a large thank you to the other members and students of ECAB. I am lucky to have had Dr Andrew Labaj as a mentor in both the lab and the field. I could not have learned how to conduct efficient and fun field work from anyone better. Meghan Fraser, thank you for not only trusting me with participating in your field work, but for also being a constant source of inspiration and motivation during mine. To Suzan, thank you for all the hard work you put into assisting me processing samples and collecting field measures. To Dr Branaavan Sivarajah, thank you for the guidance and patience while helping me write this thesis, your knowledge and kindness made the daunting process seem much less intimidating.

Thank you to faculty and staff of Mount Allison University, for inspiring me and pushing me to this point in my academic career. Special thank you to Ben Philips and Liza Barney, for giving me so many opportunities. I would not be the person I am today, at the end of my degree, without the time I have spent at Mount A.

Without the support of my friends and family I would be truly lost. To my father David, thank you for keeping me calm when I start to worry and always being a source of laughter. To my mother, Karen, you were the first woman in science I looked up to and thank you for your never-ending interest and support in my research. Thank you to my brother Conor for keeping me humble. To my roommates, Ava, Lauryn, and Hayley, thank you for being an amazing support system. Finally, Michael, you always listened, supported, and pushed me to work my hardest, I am forever grateful to you.

This research could not have been conducted without the financial support from the NB Environmental Trust Fund. Additionally, thank you to the property owners we met in the field that provided access from their properties to several lakes.

Table of Contents

<i>Abstract</i>	2
<i>Acknowledgments</i>	3
<i>List of Figures and Tables</i>	5
<i>Introduction</i>	6
<i>Algal blooms & Eutrophication</i>	6
<i>Importance of Dissolved Oxygen</i>	7
<i>Use of Chironomids as Bioindicators</i>	9
<i>Methods</i>	11
<i>Study Design</i>	11
<i>Field Measures</i>	12
<i>Chironomid Processing and Identification</i>	14
<i>Data Analyses</i>	15
<i>Results</i>	16
<i>Environmental Measures</i>	16
<i>Top-Bottom Analysis</i>	17
<i>Lake Specific Observations</i>	18
<i>Principal Component Analysis</i>	19
<i>Discussion</i>	19
<i>Limnology of New Brunswick Lakes</i>	19
<i>Present Chironomid Assemblages</i>	20
<i>Past and Present Assemblages</i>	21
<i>Conclusion</i>	24
<i>Tables and Figure</i>	30

List of Figures and Tables

Table 1. Select environmental measures of study lakes.

Figure 1. Province of New Brunswick and locations of study lakes assigned to bloom (green squares) and reference (blue circles) groups.

Figure 2. Box plot of select environmental measures of bloom lakes (green) and reference lakes (blue) obtained during the late summer thermal stratification period.

Figure 3. Comparative stratigraphy of top (empty bars) and bottom (filled bars) chironomid assemblages of bloom (green) and reference (blue) lakes. Only select, common taxa are shown and ordered from highest to lowest oxygen optima (Quinlan and Smol, 2001). Organization of lakes along the y-axis is in ascending order of lowest to highest total phosphorus (mg/L) within both groupings.

Figure 4. Principal Component Analysis (PCA) of chironomid assemblages from top and bottom samples of individual lakes. Bloom lakes represented by green (top samples) and empty (bottom samples) circles. Reference lakes represented by blue (top samples) and empty (bottom samples) squares.

Introduction

Algal blooms & Eutrophication

Algal blooms occur annually in lakes around the world and are an essential part for the functioning of freshwater ecosystems. However, intense cyanobacterial algal blooms pose several problems to lake health. Blooms block sunlight from penetrating the water column, deprive aquatic macrophytes and other primary producers of light essential to their growth, and cause degradation of essential habitat for fish and aquatic invertebrates (Paerl & Huisman, 2009). For a cyanobacterial algal bloom to thrive and become a persistent problem, inputs of excess nutrients are the primary cause (Brodersen & Quinlan, 2006a; Hall et al., 1999; Huisman et al., 2018). Some lakes are intrinsically nutrient rich in the absence of human disturbances, therefore cyanobacterial algal blooms occur naturally. However, throughout the Anthropocene cyanobacterial blooms have increased in frequency, intensity, and duration (Carey et al., 2012; Reavie et al., 2006; Taranu et al., 2015; Winter et al., 2011). Cultural eutrophication, the process by which human activities in the catchment exacerbate the input of nutrients to lake ecosystems, has been identified as an important driver of cyanobacterial algal blooms (Schindler 2012; Huisman et al. 2018; Reavie et al., 2006). Examples of cultural eutrophication include run-off of phosphorus based fertilizers from agricultural operations, urban developments of riparian habitat, and waste-water effluent from treatment facilities (Mallin et al., 2006; Stewart et al., 2018). These human activities often involve land-use change and directly and indirectly facilitate the input of two limiting nutrients in particular, nitrogen and phosphorus, which are attributed with being the primary cause of eutrophication and subsequent cyanobacterial blooms (Schindler, 2012). Thus, controlling nutrient inputs is important to managing eutrophication and mitigating cyanobacterial blooms. There is an increasing and urgent need for understanding the mechanisms

of eutrophication and the consequences of intense algal blooms, as our sources of freshwater become more threatened (Carey et al., 2012; Pick, 2016).

Climate Change as a Co-Stressor

Although cultural eutrophication is the primary driver of cyanobacterial algal blooms, climate change has been identified as an important co-stressor (Pick, 2016). Climatic changes can greatly impact lake water temperatures, thermal stratification patterns, and make the pelagic environment favourable for cyanobacterial algal blooms to form and thrive (Huisman et al. 2018; Favot et al. 2019; Daly et al., 2019). Specifically, warmer waters and stronger thermal stratification can provide ideal conditions for buoyancy regulating cyanobacteria over other pelagic algae in nutrient-rich environments (Paerl & Huisman, 2008; Rigosi et al., 2014). Further, increased precipitation extremes can transport more nutrients into lake systems, exacerbating cyanobacterial blooms in lakes (Moss, 2011). The combined effects of land-use change, eutrophication, and climatic changes allow cyanobacterial blooms to develop and persist in a warmer world (Paerl & Huisman, 2008; Moss 2011).

Importance of Dissolved Oxygen

Dissolved oxygen (DO) in hypolimnetic layers of lakes exist in relatively low quantities, making it a critical resource for all organisms that require oxygen during gas exchange (CCME, 1999). Hypolimnetic dissolved oxygen is sensitive to lake functions across seasons and dependant on multiple environmental variables, such as water temperature, mixing regime, water colour, and the balance between photosynthesis and respiration (Broderson and Quinlan 2006).

However, there is a lack in systematic long-term monitoring of DO in most lake ecosystems, despite the importance of DO as a measure of lake health (Quinlan & Smol, 2002).

Cyanobacterial algal blooms can pose a serious threat to levels of DO, which can result in hypoxia or anoxia. Hypoxia is a state in which an aquatic environment is lacking DO to the point where serious consequences to lake health, such as mass die-offs of fish communities or loss of accessible habitat, can occur (Mallin et al., 2006; Paerl & Huisman, 2008). According to the Canadian Council of Ministry of the Environment's water quality guidelines (1999), living organisms in cold water systems require a minimum dissolved oxygen concentration of 6.5mg/L to 9.5mg/L to survive and function. When an algal bloom dies off and begins to sink in the water column, it is consumed by bacteria, which requires a significant amount of DO to decompose and metabolize the bloom. This can result in hypolimnetic layers depleted in DO during the period when a lake is thermally stratified (Little et al., 2000; Mallin et al., 2006). A hypoxic or anoxic environment can promote internal loading of nutrients, such as phosphorus, previously trapped in the sediment, which then adds additional limiting nutrients to the overlying water column and furthers eutrophication of a lake ecosystem (Favot et al., 2019; Paerl & Huisman, 2008; Sivarajah, Simmatis, et al., 2021a). Internal loading of nutrients is a common issue that productive lakes may experience despite management controls aimed to reduce point and non-point source nutrient inputs from the watershed.

Paleolimnology & Top-Bottom Paleolimnological Approach

One of the main challenges with studying water quality and lake health is the lack of long-term monitoring data that extends across years and decades (Smol, 2019). Lakes are great

sentinels of the environment and integrate signals from the atmosphere, catchment, and water column. The interdisciplinary field of paleolimnology uses biological, chemical and physical information preserved in lake sediments to reconstruct past environmental changes (Smol, 2009). The long-term ecological perspectives gained from paleolimnological studies can inform management decisions and help to assess the effectiveness of policies. In studying lake sediment, there is a myriad of analyses, from simple to complex, that can be conducted to yield information on lake health and long-term environmental changes. One common experimental design in paleolimnology is a “top-bottom” approach. A top-bottom approach utilizes sediments from many lakes and focuses on examining top and bottom sediment intervals to create a comparative analysis between past and present lake conditions (Sivarajah et al., 2021b).

Use of Chironomids as Bioindicators

The use of bioindicators, living organisms that are sensitive to environmental conditions and their changes, can be widely applied in the study of lake sediments to examine past and present lake conditions (Quinlan & Smol, 2002). Chironomidae are non-biting midges that through most of their larval stage reside in or near the top layer of lake sediments within the littoral or profundal zone of a lake. The larvae of Chironomidae can be found in most aquatic habitats from the equator to high-latitude regions. Some species are terrestrial, and a few are also found in marine environments. Chironomid larvae show a range of feeding strategies, but most are detritivores or graze on bacteria and algae that colonize benthic substrate (Quinlan & Smol, 2001). With a wide range of taxa, each with their own specific environmental preferences. As a result they can well reflect the surrounding oxygen availability and other key variables (Brodersen & Quinlan, 2006; Kurek et al., 2012; Quinlan & Smol, 2001). Their chitinous head

capsules, form during their larval stage, are often numerous at hundreds of individuals per gram of sediment and well preserved in lake sediment for thousands of years. As lake sediment accumulates through time, identification of fossilized head capsules from various taxa can be used to reconstruct environmental conditions in both modern and past sediment.

Algal Blooms in New Brunswick lakes

Typically, algal blooms are observed in eutrophic lakes, meaning there are already favorable nutrient conditions for cyanobacterial communities to grow (Pick, 2016; Huisman et al. 2018). Cyanobacterial algal blooms have been identified as an important water quality issue impacting some New Brunswick lakes, even though their nutrient status suggests they are oligotrophic to mesotrophic (Daly et al. 2019). The Government of New Brunswick's Office of the Chief Medical Officer of Health (Public Health) maintains an active list of lakes experiencing blue-green algal blooms (Government of New Brunswick, 2011). Out of the provinces ~2500 lakes, this list includes about 20 lakes. However, many New Brunswick lakes are considered low nutrient lakes. This means for eutrophication to occur, other mechanisms of nutrient inputs, such as anthropogenic activities may be the cause (Daly et al., 2019).

In this thesis, chironomid-based paleolimnological approaches, combined with standard water quality monitoring, were used to assess environmental changes and hypolimnetic oxygen dynamics in lakes impacted by algal blooms in New Brunswick. The assessment is complemented with examination of chironomid assemblages and water quality measures from reference lakes where algal blooms have not been observed. Specifically, this thesis aims to address the following questions:

1. Do chironomid assemblages from lakes experiencing recent algal blooms reflect greater changes in assemblages than those of reference lakes?
2. Which lakes and their chironomid assemblages demonstrate the most composition change?
3. What environmental factors explain the observed chironomid assemblage changes?

I predict that chironomid assemblages from bloom lakes will show greater differences than those of reference lakes. Additionally, the current chironomid assemblages of the bloom lakes would indicate poor oxygen concentrations compared to those of the reference lakes. Furthermore, the reference lakes are expected to show little changes between the top and bottom samples. This thesis will contribute to the direct and indirect monitoring of NB lakes and provide some baseline bioindicator measures for future studies.

Methods

Study Design

A total of 20 lakes across New Brunswick were selected following criteria described below (Figure 1). Lakes were categorized into bloom or reference groups. Selected lakes were required to have a maximum depth >5 m, to ensure they underwent thermal stratification and displayed differences in DO levels between the hypolimnion and epilimnion. Most of the study lakes, except Wheaton and Nashwaak, were previously sampled for water quality and sediment cores for other studies (Armstrong and Kurek, 2019; Daly et al., 2019; Kurek et al., 2019). Their location and proximity to urban, industrial, and agricultural areas were also considered, as these

are land-use factors that are often associated with algal blooms. Although land use in each lake's catchment was not estimated as part of this study, lakes typically showed minimal land-use change (i.e. active forestry activities) or only modest development of built infrastructure (i.e. cottages, houses, roads). Bloom lakes were chosen based on Public Health Advisories maintained by the New Brunswick, Office of the Chief Medical Officer of Health. A total of 10 lakes from each category were originally selected, however the status of California Lake was changed to having active algal blooms, resulting in eleven bloom lakes and nine reference lakes (Figure 1). Several lakes, such as Chamcook Lake, Lac Baker, Lac Unique, Yoho Lake, and Lac Caron had developed shorelines, primarily occupied by cottages and residential homesteads.

Field Measures

Lake sediment cores, surface water chemistry and water column profiles were collected throughout the 2021 summer months. Sediment cores were collected from the deepest areas of a lake's basin located using bathymetric maps and a depth sounder. Cores were collected using a Glew (1989) gravity corer. Sectioning of the core was completed on site, at intervals of 0.5 cm, to be used for a "top-bottom" paleolimnological study with chironomid assemblages. The use of a top-bottom approach provides "snapshots" of what may be occurring in a lake as opposed to looking at each section of a core. It is also less time consuming and allows for a larger number of lakes to be examined. The top sediment intervals (~0.0-1.0 cm) represent the modern lake conditions and chironomid assemblages, whereas the bottom sediment intervals represent lake conditions and assemblages from a past point in time, usually recognized as a pre-disturbance or pre-industrial time period (Barrow et al., 2014; Smol 2008). For this study, bottom intervals of the cores likely represent the pre-industrial period in New Brunswick. Several study lakes had

cores that were already dated and thus ages could be assigned to the bottom sediment intervals. For the study lakes that required new sediment cores, sediment intervals >30 cm downcore, were used as they tend to represent conditions that pre-date ~1900 in the region (Daly et al., 2019; Kurek et al., 2019).

Water chemistry sampling consisted of collecting surface water samples and water column measures every one meter with a YSI multi-parameter meter. The measures were taken over a period of approximate 2 weeks in late August 2021. Surface water samples were collected from the coring location of each lake approximately 10 cm below the water's surface. The designated bottles were rinsed thoroughly with lake water three times, filled to their maximum capacity, and capped under the water. All water samples were stored on ice and sent within 48 hr of collection to the Research & Productivity Council (RPC) facility in Moncton, NB. Water samples were analyzed for various analytes such as phosphorus, nitrogen, total organic carbon, colour, and turbidity according to RPC standards.

A YSI with a 20m long cable with probe was deployed at the approximate location where cores were taken in each lake during the visit when water chemistry was collected. Water column measures of temperature (°C), specific conductivity ($\mu\text{s}/\text{cm}$), pH and dissolved oxygen (mg/L), were recorded at intervals of every one meter until the probe reached the bottom of the lake or the maximum length of the cable was reached. Additionally, the air temperature and weather conditions were noted.

Chironomid Processing and Identification

The head capsules of fossil chironomids were analyzed from the top-most sediment intervals and pre-determined bottom sediment intervals of each lake's core. Standard paleolimnological methods were followed to process sediments for fossil chironomid remains (Walker, 2001). Initial processing was conducted with ~1.0 to 2.0g of wet sediments, which were treated with 5% KOH solution at 75°C for 20 minutes. Samples were then rinsed on a 100um sieve, and then remaining sediments on the sieve were transferred into a beaker. Sieved samples were poured into Borogov trays and examined under a dissecting microscope at 35x magnification. Examinations of the trays consisted of doing a set of surface and subsurface scans, followed by a gentle mixing of the tray contents, and then another complete set of surface and subsurface scans. Head capsules were picked carefully and transferred to glass coverslips, with a few drops of deionized water. For each lake a total of ~75 to 100 whole mentum equivalents was aimed for. If a sediment sample did not reach these conditions, more wet sediment was processed. A minimum chironomid count of 50 whole mentum equivalents is considered adequate for assemblage characterization (Larocque, 2001; Quinlan & Smol, 2001). Coverslips were permanently mounted to glass slides using Entellan®.

Chironomid remains from each sample were identified following Brooks et al. (2007) taxonomic guide under a bright-field microscope at magnifications of 200X and 400X. Slides were examined methodically. Taxa were identified primarily by the characteristics of their mentum. This consisted of observing the median tooth/teeth in combination with the characteristics and number of lateral teeth. Additionally, ventromental plates were used to distinguish between taxa. More precise identifications could be made from distinct features such

as shapes and lengths of antennal pedestals, markings on the head capsules or, characteristic of mandibles when present.

Data Analyses

Box plots of select environmental measures from water chemistry sampling (pH, dissolved oxygen (mg/L), water depth (m), surface area (ha), total phosphorus (mg/L), total organic carbon (mg/L), colour (TCU), turbidity (NTU) and change in water temperature (°C)) were created using RStudio (Figure 2). Detailed information on water chemistry and water column measures are provided in Table 1. Hypolimnetic DO values were reported at the values closest to the bottom of each lake except for lakes that were deeper than the 20 m YSI cable (States, Chamcook, Nictau, Walton and Baker). Change in water temperature were reported as the difference in surface water temperatures and the deepest hypolimnetic temperatures.

Counts of chironomid taxa were expressed as percent relative abundances. Chironomid taxa were grouped following taxonomic organization according to Quinlan and Smol (2002). Once grouped, rare taxa were removed prior to further analysis according to a cut-off of less than 2% in <2 samples. Top and bottom abundances for each common taxa in each lake were represented using a histogram. A principal component analysis (PCA: covariance matrix) was performed on the chironomid assemblage data to summarize the main variation in the assemblages using the “vegan” package in RStudio. The relative abundances of most common chironomid taxa (i.e. taxa occurring in >5% in at least 2 samples) were displayed on a histogram to visualize assemblage change within and between lakes (Figure 3). Top and Bottom PCA axis

1 and 2 site scores were plotted using SigmaPlot to visualize lakes that showed the greatest and least assemblage change through the two time periods examined at each lake (Figure 4).

Results

Environmental Measures

Of the nine reported environmental measures, eight showed little difference between the bloom lakes and reference lakes (Table 1; Figure 2). Average hypolimnetic dissolved oxygen in both lake groupings was relatively low and similar (bloom = 2.05 mg/L, reference = 2.13 mg/L). Overall, the bloom lakes showed more variability in DO measures than the reference lakes. Both the bloom and reference lakes were similar in average maximum water depth. The deepest lake was States Lake (50.3m) and Lac Unique was the shallowest (6.4m). In terms of lake surface area, bloom lakes were generally about three times larger than the reference lakes. The average pH of both the lake categories were circumneutral and similar (bloom pH= 7.8, reference pH= 7.4). The total phosphorus (TP) average of both the lake categories were also similar (bloom TP= 0.011 mg/L, reference TP = 0.007 mg/L). However, the bloom lakes displayed greater variation in TP compared to the reference lakes. Much like the other environmental measures, total organic carbon (TOC) averages for the bloom and reference categories showed little difference (bloom TOC = 3.47 TCU, reference TOC = 3.91 TCU). Turbidity in the bloom lakes showed great variation than that of the reference lakes, but overall, the average turbidity of the two samples groups were similar (bloom turbidity = 1.3 NTU, reference turbidity = 0.57 NTU). The final environmental measure examined, difference in hypolimnetic and surface water temperatures, was the only environmental measure to show a difference between the two lake groups. On average, the bloom lakes showed a change in temperature of 10.4 °C between the

surface water and deepest water depth, whereas the reference lakes showed a greater average change in water temperature at 15.1 °C.

Top-Bottom Analysis

A total 70 chironomid taxa were identified in sediment samples prior to removing rare taxa. Among the bloom lakes, Tanypodinae sp. was found to be the most abundant taxon in both the top and bottom samples (mean top= 14.1%, mean bottom= 13.4%). Among the reference lakes, Tanypodinae sp. was found to be the most abundant taxon in top samples (mean= 11.1%) and *Sergentia coracina* was found to be the most abundant taxon among the bottom samples (mean= 14.3%). Taxon with high oxygen optima such as, *Heterotrissocladius*, *Micropsectra* and *Sergentia coracina*, had varying abundances within both the top and bottom sediment intervals of the bloom and reference lakes. Mean *Heterotrissocladius* from bottom samples of bloom lakes was ~ 8.3% and mean from top samples was ~5.9%. In the reference lakes, the mean from the bottom sediment samples was 10.9% and the mean from the top samples was 8.5%.

Micropsectra abundances in the bloom lakes was low and varied between top and bottom samples, mean bottom = 3.2% and mean top = 1.6%. *Micropsectra* abundance from the reference lakes showed a mean abundance from the bottom samples of 2.3% and that of the top samples of 5.5%. *Sergentia coracina* showed more variation in abundances in the reference lakes compared to the bloom lakes. Mean from the bottom samples was 14.3% and that from the top samples was 7.4%.

Taxa with low oxygen optima, such as *Zalutschia zalutschicola* and *Chironomus*, showed variation in mean abundances between bloom and reference lakes. *Zalutschia zalutschicola*

exhibited variation in abundances between the top and bottom samples of the reference lakes, with means of 3.0% and 0.6%, respectively. *Chironomus* showed similar increase in abundance in both the reference and bloom lake groupings as well. In the bloom lakes, the mean abundance of *Chironomus* in the bottom samples was 4.9% and that of the top samples was 6.1%. In the reference lake groupings, the mean abundance of the bottom samples was 2.0% and that of the top samples was 5.1%.

Lake Specific Observations

Certain lakes displayed large changes in relative abundances between top and bottom samples for several common taxa of interest (Figure 3). Of the bloom lakes, three lakes displayed marked changes between top and bottom samples. Chamcook Lake displayed a decrease in *Tanytarsini* sp. by 23.1% between the bottom sediments and top sediments. Lac Baker displayed a decrease of *Heterotrissocladius* by 18.6% between the bottom and top sediments, as well as an increase of *Chironomus* by 17.4% and a 13.7% increase of *Tanytarsini* sp.. Lac Unique displayed a 18.9% decrease in *Tanypodinae* sp. abundance between the top and bottom samples.

From the reference lakes, Lake Anthony, States Lake and Upsalquitch Lake, displayed the greatest assemblage changes in abundances of certain taxa. Lake Anthony displayed a 31.4% increase in *Micropsectra* and a 43.8% decrease in *Sergentia coracina*. States Lake showed a 34.3% decrease in *Heterotrissocladius* between the bottom and top sediment samples. Finally, Upsalquitch Lake displayed a 28.2% decrease in *Sergentia coracina* abundance between the bottom and top samples.

Principal Component Analysis

Results of the PCA were used to examine the changes in assemblage composition between the top and bottom sediment samples of each lake (Figure 4). Axis 1 accounted for 19% of the variation in the data and Axis 2 accounted for 11%. Visually, most of the top samples from both the bloom and reference lakes were grouped closer together, whereas their corresponding bottom samples were more spread out within the ordination space. Some lakes of note that displayed larger changes in top and bottom samples were Lac Baker, Upsalquitch Lake and Lake Anthony. The top sample of Lac Baker is within the cluster of top samples, however its bottom sample plot far away, indicated a large change had occurred. Upsalquitch Lake displayed a similar trend as Lac Baker, but with a shorter vector between the top and bottom samples. Lake Anthony also displayed a large change between the top and bottom samples, in addition to its negative axis 1 scores.

Discussion

Limnology of New Brunswick Lakes

There was overall little difference between both the bloom and reference lake categories in terms of the environmental measures. Although there is little comparison that can be made between the two groups there are some inferences that can be made as to what the condition of these lake groupings are. Both the lake grouping had low average DO concentrations (bloom = 2.05mg/L, reference = 2.13 mg/L), and though this does not indicate a difference between the lake groupings, this does indicated the both experience DO levels below the minimum tolerable concentrations for most living organisms (CCME, 1999). It is important to note that the hypolimnetic DO of five lakes could not be measured accurately due to their max depth being

greater than the length of the YSI cable (Table 1). It was expected that the bloom lakes would have higher total phosphorus concentrations than that of the reference lakes. Oligotrophic lakes, such as the ones in this study, typically maintain a range of 0.004-0.010 mg/L of TP, however if concentrations exceed these levels, there can be cause for concern (CCME, 2004). The average total phosphorus of the bloom lakes category was slightly more elevated (0.011 mg/L) than that of the reference lakes category (0.006 mg/L). Both these average measures are just on the edge of the “healthy” TP concentration. Furthermore, low DO concentrations in the deep water of lakes, can lead to the internal loading of phosphorus (Carey et al., 2008; Favot et al., 2019). Therefore, since the DO concentrations of both lake categories are low, to the point here they are in a state of hypoxia and possibly anoxia, there could be further inputs of phosphorus from the sediments.

Present Chironomid Assemblages

Presence and absence of profundal taxa can provide insight into lake conditions, especially in the profundal zone. There are profundal taxa such as *Heterotrissocladius* and *Micropsectra* that have high oxygen requirements and there are taxa with low oxygen requirements such as *Chironomus* (Meriläinen et al., 2001). Presence and absence of these taxa can depict the hypolimnetic DO availability of a lake (Kurek et al., 2012; Quinlan & Smol, 2002). There are certain taxa that stand out in the data set (Figure 3). Firstly, *Heterotrissocladius*, a profundal taxa with a high oxygen requirement (Quinlan & Smol, 2002), does not display a large difference, between the two groupings. Average abundance of *Heterotrissocladius*, in the bloom lakes, 5.9%, is lower than that of the reference lakes, 8.5%. Although this does not indicate a large difference, the abundance of *Heterotrissocladius* within the reference lakes is

slightly higher, indicating a more favorable environment for this taxon. *Micropsectra* did display a difference between the bloom and reference group. Average abundance in reference lakes was 5.5% and that of the bloom lakes was 1.6%. This indicates that the current profundal environment in reference lakes is better suited for *Micropsectra*.

Taxa such as *Chironomus* and *Zalutschia zalutschicola* displayed smaller differences between the two lake groupings. Average abundance of *Chironomus* in the bloom lakes (6.1%) was greater than that of the reference lakes (5.1%). As for *Zalutschia zalutschicola*, the bloom lakes had a larger average abundance (3.0%) in the top samples as opposed to the average abundance of the reference top samples (0.1%). In Figure 3, the abundance of *Zalutschia zalutschicola*, is mostly accounted for in Lake Yoho and Lake Wheaton, two bloom lakes. The conclusion that can be drawn from these findings is that despite there being a decrease in abundance of profundal taxa that are high oxygen optimum taxa, and an increase in profundal taxa with low oxygen optima, the differences between the groupings are minor.

Past and Present Assemblages

There are two chironomid taxa that stand out from the rest of the data set when looking at the differences between top and bottom samples that are indicators of lake health, particularly DO availability. The first being *Heterotrissocladius*, which is associated with high oxygen concentrations (Quinlan & Smol, 2002). In the bloom lakes *Heterotrissocladius* average abundance decreased from 8.3% to 5.9% between the bottom and top samples. A similar decrease was observed in the reference lakes, as the average abundance decreased from 10.9% to 8.5%. The second prominent taxa, *Chironomus*, observed to be indicative of environmental

change, increased in both the lake groupings. In the bloom lakes, the average abundance of *Chironomus* increased from 4.9% to 6.1% between the bottom and tops, and in the reference lakes the abundance increased from 2.0% to 5.1%. These findings suggest that both the bloom and reference lakes are experiencing similar environmental changes in chironomid habitat, specifically profundal habitat.

In the overall data set, lake specific observation is important. For example, an increase in *Zalutschia zalutschicola*, is observed in Lake Yoho and Lake Wheaton. Both these lakes are in the bloom grouping, and do not display any other large taxon changes between top and bottom samples. A possible explanation for the increase in *Zalutschia zalutschicola*, would be the low hypolimnetic DO concentration both lakes are experiencing (Yoho=0.11 mg/L, Wheaton=0.04 mg/L). However, it is acknowledged that multiple environmental factors likely influence the abundance of benthic invertebrates (Brodersen & Quinlan, 2006b).

Changes in chironomid assemblages are similar between bloom and reference lakes. However, lakes such as Lac Baker and Lake Anthony, had large vectors between their top and bottom samples (Figure 4). This suggests that these lakes have experienced more environmental change than other lakes. For example, Lac Baker, showed a large decrease in *Heterotrissocladius* abundance between its bottom and top samples and a large increase in *Chironomus* abundance (Figure 3). Both taxa are indicators of environmental changes in lake health, suggesting that the lake is undergoing eutrophication (Meriläinen et al., 2001). Lac Baker has a developed shoreline, consisting of a public park, public beach, residence and cottages. The total phosphorus concentration of the lake, 0.01 mg/L, is just on the cusp of the “healthy” TP range determined by

the CCME (2004) and the DO concentration at 20m depth, is already below the minimum tolerable concentration determined by the CCME (1999). The environmental measures combined with the intense anthropogenic use of the lake could explain the differences observed in abundances of *Heterotrissocladius* and *Chironomus*. Both direct and indirect monitoring data suggest that Lac Baker has experienced low DO availability.

Lake Anthony, like many of the other reference lakes and bloom lakes, has a low DO concentration. However, it displays a large change in several key taxa between its top and bottom sediment samples. Additionally, assemblage composition of Lake Anthony is different from those of the other lakes in both categories. The taxa that are indicative of these differences, *Micropsectra* and *Sergentia coracina*, are displaying contradicting results. There is a large increase in the abundance of *Micropsectra*, from 5.1% to 36.5%, between the bottom and top samples. *Sergentia coracina*, is decreasing between the bottom and top samples, 56.3% to 12.5%. Typically, the presence of both these taxa are indicators of high DO availability (Brodersen & Quinlan, 2006b; Kurek et al., 2012). The increase in *Micropsectra* would be indicative of improving DO availability but that is contradicted by the decrease in *Sergentia coracina*. One possible explanation could be that there is another ecological factor influencing *Sergentia coracina*. However, relative abundance data makes it a challenge to determine which taxon is increasing and decreasing. *Micropsectra* presumably is not affected in the same way by environmental change as *Sergentia coracina*, given their different ecology. This suggests that Lake Anthony's environmental changes and differences in chironomid assemblages are not only influenced by loss of oxygen. Meriläinen et al., (2001) consider increasing *Sergentia coracina* abundances to indicate more pollution in a lake and subsequent eutrophication.

Conclusion

The nature of this water quality and paleolimnological research is exploratory. The overall aim was to build understanding of long-term environmental changes within low-nutrient New Brunswick lakes. Overall, the water quality and paleolimnological data indicates that there is not much consistent difference between the bloom lakes and reference lakes. Both lake categories experience low hypolimnetic DO concentrations in late summer. Findings from chironomid assemblages support this environmental observation. However, several taxa, such as *Heterotrissocladius* and *Chironomus*, show differences in abundance between the lake categories that are may be indicative of environmental change and differencing DO availability. Lake specific difference are obvious, as several blooms and reference lakes reflect environmental changes based on their assemblage compositions. Furthermore, focused downcore studies of the lakes that showed the greatest assemblage changes could help to determine the environmental causes and timings of these assemblage shifts.

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Tables and Figure

Table 1. Select environmental measures of study lakes.

Category	Lake	Surface Area ha	Max. Water Depth m	Δ Water Temperature $^{\circ}\text{C}$	TP mg/L	TOC mg/L	Colour TCU	pH	Turbidity NTU	Dissolved Oxygen mg/L
BLOOM	Chamcook*	338.6	41.9	15.3	0.006	2.6	5	7.6	0.3	8.9
BLOOM	Wheaton	104.0	11.9	6.5	0.012	3.7	5	7.6	3.9	0.04
BLOOM	Yoho	126.0	13.7	5.4	0.005	3.1	5	7.2	0.4	0.11
BLOOM	Harvey	684.2	13.6	4.1	0.007	4.4	14	7.2	0.3	3.05
BLOOM	Unique	121.2	6.4	3.8	0.022	4.7	7	8.6	3.9	1.64
BLOOM	Caron	41.2	14.2	17.2	0.005	1.7	5	8	0.3	0.26
BLOOM	Nashwaak	112.0	8.5	9.0	0.021	9.1	79	7.5	0.9	0.14
BLOOM	Baker*	546.2	38.1	17.0	0.01	2.4	5	7.9	0.4	5.58
BLOOM	Bathurst	178.4	7.3	7.2	0.02	4.2	9	9	2.5	0.08
BLOOM	Nictau*	197.7	22.6	15.4	0.009	2.5	7	7.8	0.5	2.7
BLOOM	California	45.0	11.5	13.6	0.009	2.8	5	7.8	0.9	0.07
REF	Anthony	29.8	12.8	14.1	0.003	2.8	5	7.3	0.3	1.5
REF	States*	74.2	50.3	16.8	0.006	1.6	5	8.1	0.2	11.4
REF	Upsalquitch	69.1	15.2	16.8	0.012	2.5	6	7.6	0.5	2.73
REF	First	447.8	16.8	11.8	0.004	2.3	5	8.5	0.4	0.23
REF	Pink Rock	3.0	19.8	17.0	0.015	8.8	94	5.7	2.2	1.04
REF	Walton*	23.3	22.8	15.9	0.002	2.3	5	7.2	0.4	0.92
REF	Middle									
REF	Peaked	14.4	9.8	19.3	0.007	7.4	24	7.5	0.5	0.15
REF	Sinclair	45.6	8.5	10.8	0.004	4.9	27	7.4	0.3	0.17
REF	Goodwin	21.5	7.6	14.1	0.006	2.6	5	7.5	0.4	1.07

* Maximum depths deeper than YSI cable length.

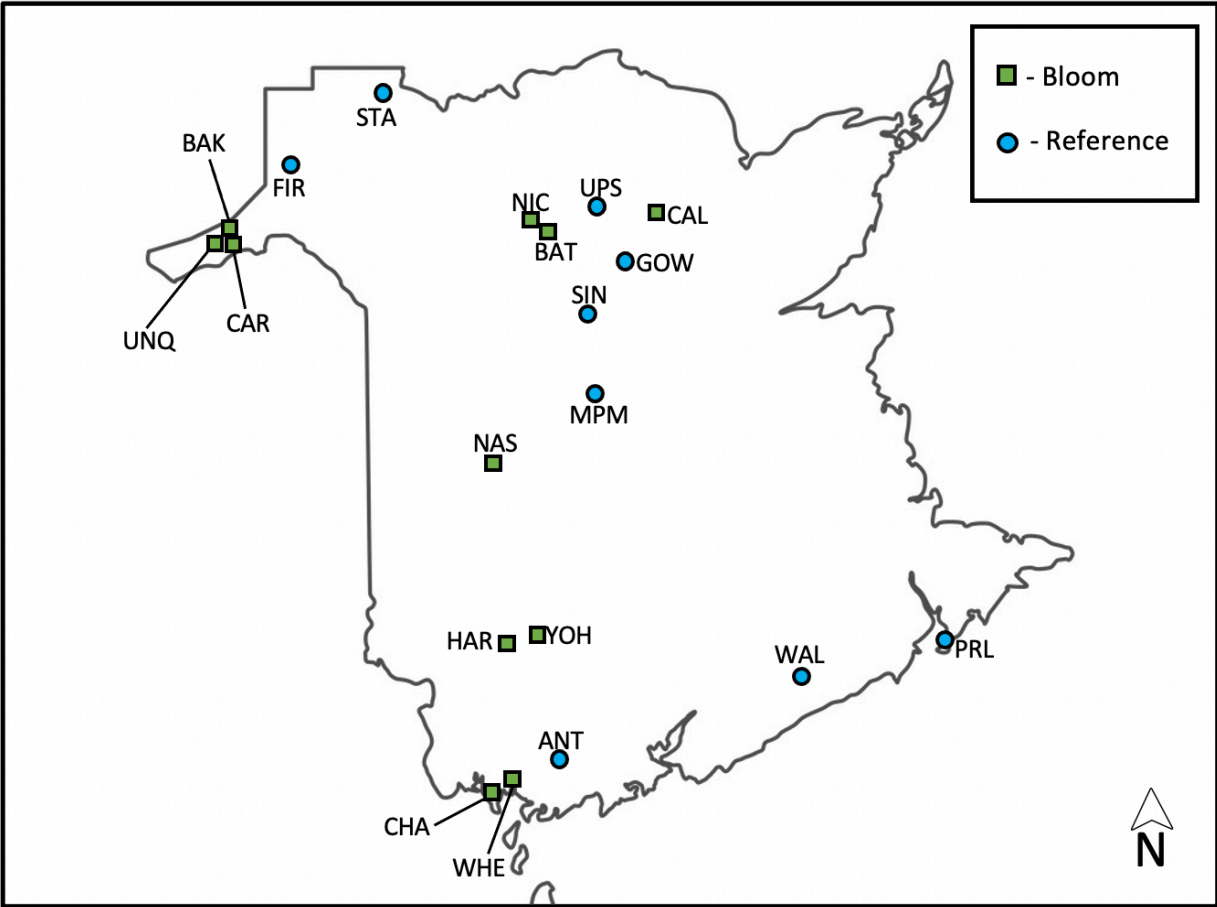


Figure 1. Province of New Brunswick and locations of study lakes assigned to bloom (green squares) and reference (blue circles) groups.

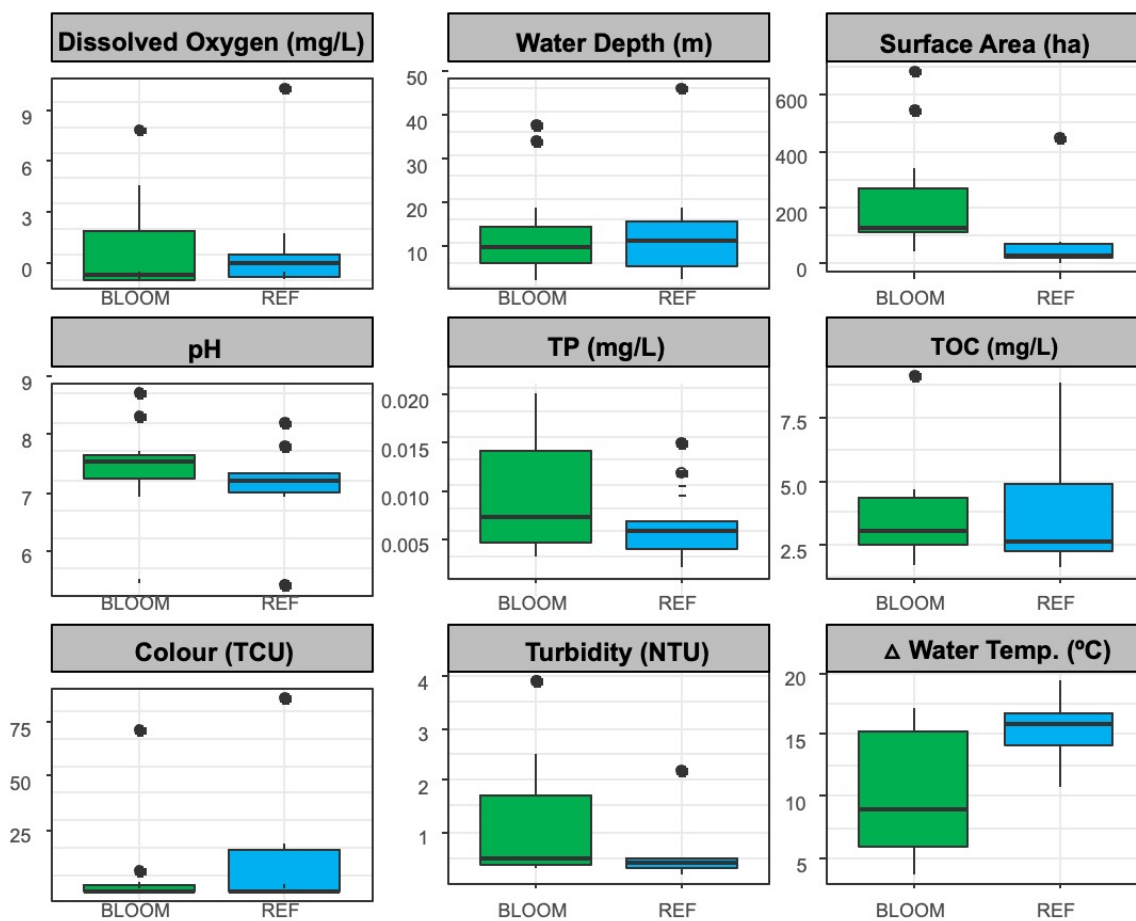


Figure 2. Box plot of select environmental measures of bloom lakes (green) and reference lakes (blue) obtained during the late summer thermal stratification period.

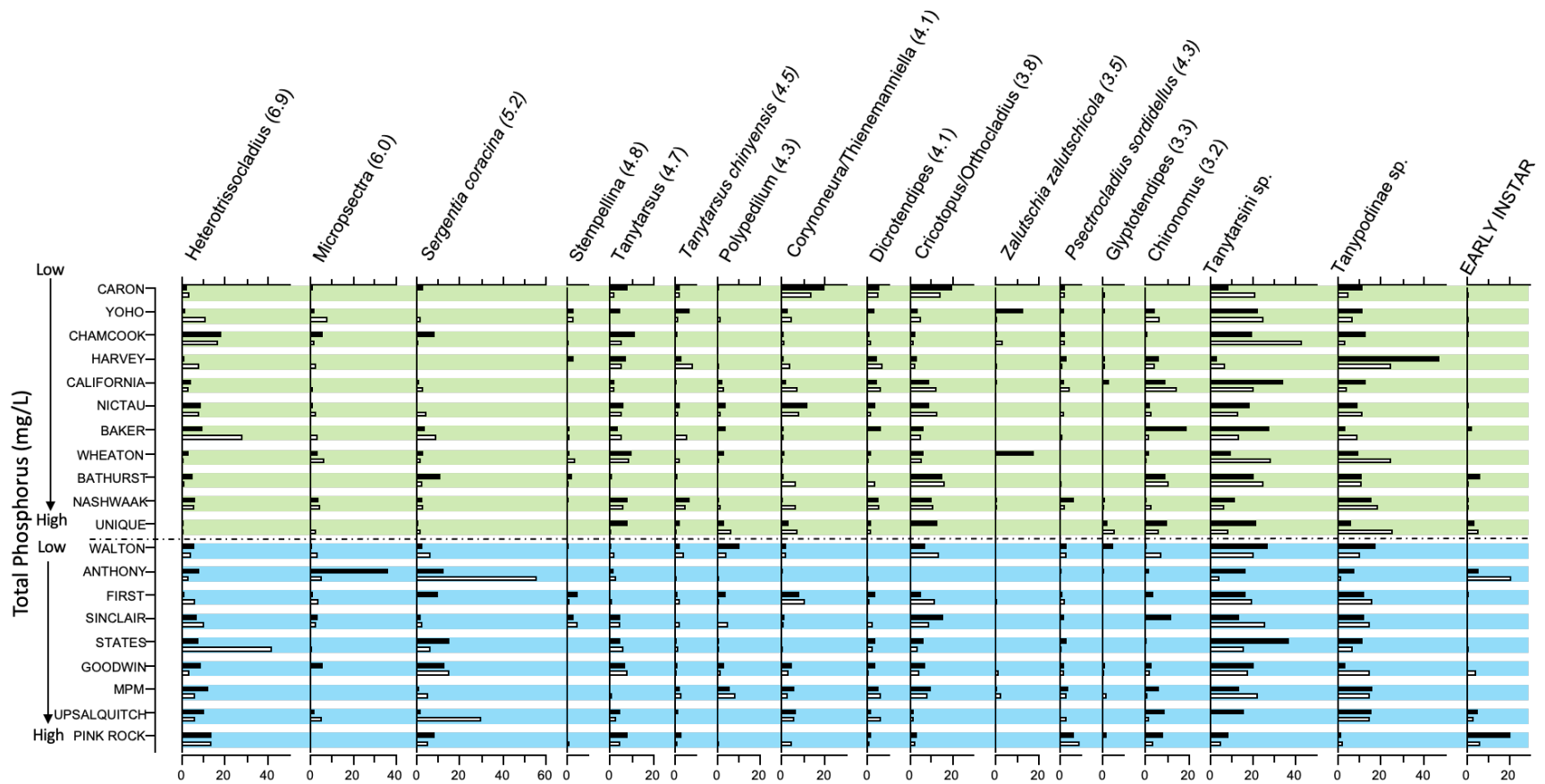


Figure 3. Comparative stratigraphy of top (empty bars) and bottom (filled bars) chironomid assemblages of bloom (green) and reference (blue) lakes. Only select, common taxa are shown and ordered from highest to lowest oxygen optima (Quinlan & Smol, 2002). Organization of lakes along the y-axis is in ascending order of lowest to highest total phosphorus (mg/L) within both groupings.

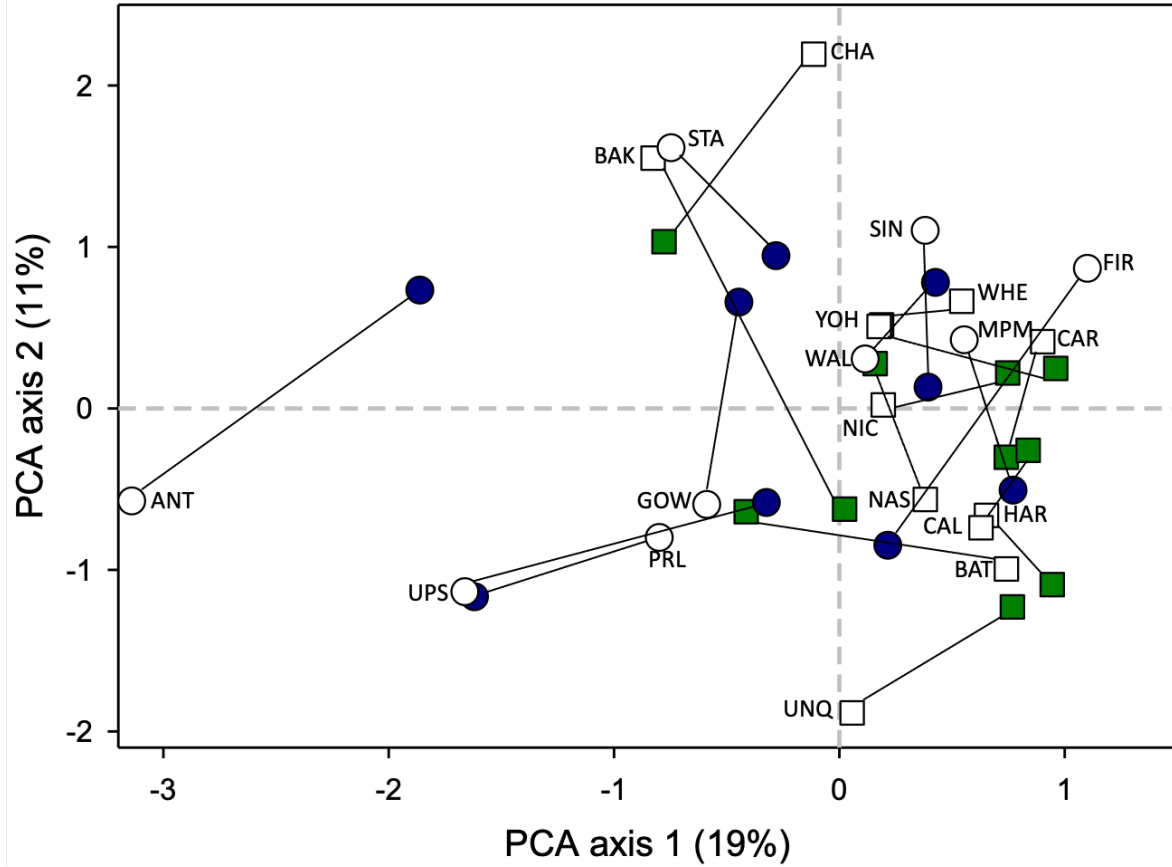


Figure 4. Principal Component Analysis (PCA) of chironomid assemblages from top and bottom samples of individual lakes. Bloom lakes represented by green (top samples) and empty (bottom samples) circles. Reference lakes represented by blue (top samples) and empty (bottom samples) squares.