

**Paleolimnological Investigation of Gilmour Bay,
Chandos Lake, Ontario:
FINAL REPORT
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EXECUTIVE SUMMARY

Land use changes and human-caused climate warming potentially degrade the water quality of lakes. ***This study uses paleolimnology to determine whether the water quality of Gilmour Bay, Chandos Lake, Ontario, has changed since European settlement to present day, particularly considering the effects of changing land use and warming temperatures.*** Land use changes, including land clearance for lumber and settlement, as well as expanding development and associated septic systems, can increase the amount of nutrients transported and delivered from the land to the lake. Increased nutrient concentrations in lakes can lead to an increase in algal production. These changes are referred to as eutrophication, and can result in a loss of recreation, changes in taste and odour of waters, oxygen depletion, and fish kills. Warming temperatures are another factor that has been shown to increase algal production and reduce water quality, but the mechanisms linking warming and algal production are complex.

This research uses sedimentary chlorophyll *a* and biogenic silica as indicators of overall algal and diatom production, respectively. Diatoms are one type of algae that are often a major component of primary production in lakes. Changes in diatom community composition were used to determine and track changes in water quality in Gilmour Bay.

The results show that Gilmour Bay has changed markedly in the last 175 years and particularly in the last 30 years. The records presented here show that the Gilmour Bay ecosystem response to a combination of environmental stressors is complex, and disentangling the response to individual stressors is difficult. What is clear from our research is that the Gilmour Bay ecosystem is sensitive to both landscape changes and warming temperatures.

Four main periods of change were determined based on changes in diatom community composition. The first period spans from 1850 to 1913, which is coincident with a period of land clearance. Logging would have peaked in the late 1800s, and surveys show that much of the forests had been removed by 1913. This period is also characterized by gradually warming temperatures and earlier ice out dates. Diatom community composition indicates that thermal stratification in Gilmour Bay during this time was relatively strong and nutrient concentrations were low. Both algal and diatom production increased likely in response to warmer temperatures and longer growing seasons.

The second period spans from 1913 to 1940 when logging had ended and farms in the area were mostly abandoned. Temperatures increased slightly. Diatom community composition indicates that Gilmour Bay became more transparent and better mixed. This occurred as forests re-established, which would decrease erosion and turbidity and increase lakewater transparency. There is no indication of increased nutrients in the diatom record and overall algal production decreases.

The third period extends from 1940 to 1987. The land around Gilmour Bay was increasingly used for recreation and cottage development beginning in the 1940s. Diatom community composition shows that nutrient concentrations, particularly phosphorus, increased during this time. Chlorophyll *a* indicates a coincident increase in overall algal production, although diatom production decreases. Increased nutrients generally lead to increased algal production. The reduction in diatom production may be in response to cooling temperatures and later ice out dates at this time, which may have reduced some of the effects of increased nutrients. There is also a decrease in the abundance of benthic and epiphytic diatoms, which may indicate a loss of aquatic plants and diatom habitat in the shallow waters. Removal of aquatic plants to improve swimming and boating opportunities can occur with development.

The most recent period extends from 1987 to 2014. This zone is marked by continued development around the lake and rapidly warming temperatures. These changes have led to an increase in thermal stratification, decreased epilimnetic nutrient concentrations and increased algal production. Our paleolimnological study is supported by recent measurements of water chemistry that show anoxia and increased hypolimnetic and reduced epilimnetic phosphorus. In Gilmour Bay increased algal production is occurring rapidly despite decreasing phosphorus concentrations in the surface waters.

The results from this study indicate that the water quality of Gilmour Bay has changed since settlement by Europeans. Although we have not yet completed similar analyses in the rest of Chandos Lake, based on research by Hollingshead (2017) we would expect similar changes to be occurring throughout the lake. The magnitude of changes at other Chandos Lake sites may be different, but we anticipate the direction of change to be similar. To mitigate increasing algal production stewards of Chandos Lake need to be vigilant about reducing delivery of nutrients from the land to the lake. Best strategies include maintaining and repairing sewage septic systems, maintaining a vegetated buffer of at least 30m between the lake and land, and protecting natural shoreline and aquatic vegetation. Further paleolimnological analyses and high temporal resolution monitoring can provide a greater understanding of the changes reported.

GLOSSARY

Anoxia – conditions characterized by little to no oxygen

Benthic – used to describe algae or diatoms living in or on the sediment of the lake

Biogenic silica – biologically produced silica; in the case of Gilmour Bay it is a good indication of diatom production

Chlorophyll *a* – a pigment used by plants and algae for photosynthesis. Chlorophyll *a* and its derivatives are preserved in lake sediment and provide a proxy of overall algal production in a lake

Deep chlorophyll maximum – in some lakes when nutrients are limited in the surface waters, algae will take advantage of nutrients found deeper near the thermocline. Sometimes this results in a chlorophyll *a* maximum below the epilimnion

Diatoms – microscopic, single-celled algae characterized by a cell wall composed of opaline silica. Diatoms are comprised of two valves that together make a frustule. The cell walls are well-preserved in lake sediments. There are well over 12,000 species described, and each species is unique and can be identified to species or sub-species level. They are ubiquitous, but sensitive to their environment. They, therefore, are excellent indicators of environmental change.

Epilimnion – the upper, well-mixed layer of a lake that is in contact with the atmosphere

Epiphytic – describes algae and diatoms that live on aquatic plants

Eutrophication – results when increasing levels of nutrients result in increased algal production. This can lead to many other problems including changes in taste and odour of the water, algal blooms, decreased oxygen levels, fish kills, and sometimes toxins associated with algal blooms.

Hypolimnion – the bottom layers of water that are cut-off from surface waters and the atmosphere. Lake water can become stratified into layers when temperature differences between the surface water and lower waters are great enough to cause density differences that prevent mixing of lake waters. This is referred to as **thermal stratification**.

Littoral – refers to the part of the lake connected to the shoreline. This zone extends out into the lake to the region where light can no longer reach the bottom.

²¹⁰Pb – a radioactive isotope that can be used to date sediments less than ~150 years old. Its half-life (i.e., the amount of time for half of the ²¹⁰Pb to have decayed) is 22 years.

Paleolimnology – the study of “ancient” lakes. Paleolimnologists use fossils and geochemical signals preserved in lake sediments to determine conditions of past environments. In lakes sediments are laid down year-after-year, layer-after-layer. These sediments can be dated using a variety of methods and fossil and geochemical and biogeochemical signals preserved in the sediments can be used to infer past environmental conditions. Lakes are particularly useful for studying environmental change as they preserve information from the lake, the atmosphere and the catchment.

Pelagic – refers to the open water zone of the lake.

Planktonic – refers to algae and diatoms that live in the open water of a lake.

Thermal Stratification – occurs when temperature differences between the surface and bottom waters of a lake result in density differences that are sufficiently great to prevent mixing of waters.

Thermocline – the depth at which the temperature is changing fastest with increasing depth.

Thycoplanktonic – refers to diatoms that spend part of their life cycle in the open water zone and part in the near shore environment

INTRODUCTION

The purpose of this study is to determine if there have been detectable changes in the lake water quality of Gilmour Bay, Chandos Lake, Ontario, since European settlement of the area. If changes are detected, a second purpose is to determine the cause of those changes.

The water quality and ecosystems of many lakes worldwide have changed in response to climate warming and human activities, including land clearance, agriculture, sewage, and industry (Smol, 2008). Often there are multiple factors driving changes in water quality and it is difficult to determine the specific cause of these changes, and whether the change is unusual and outside natural variability (Hawryshyn et al., 2012). Previous research indicates that land clearance transfers nutrients and sediments from the land to the lake, which can increase nutrient concentrations (Bradbury, 1986; Hall and Smol, 1993; Hall et al., 1999). Several studies have suggested that warming temperatures will increase the length of the growing season and therefore algal production (Paerl, 2014), but could also increase thermal stability and decrease in-lake circulation and cycling of nutrients (Rühland et al., 2008; 2015). Disentangling the effects of these various factors is complex. Making the task even more challenging is that in North America long-term monitoring of lake ecosystems rarely extends more than several decades, which limits our ability to detect when lake water quality changed, the direction of change, and what is driving detected changes (Smol, 2008). Yet, such information is critical to determine effective management to protect these ecosystems and water resources.

Paleolimnology is important because it provides long-term (100s to 1000s of years) records of water quality using archives preserved in lake sediments (i.e., “mud” that has accumulated at the bottom of a lake). Lake sediments are comprised of materials originating from the land surrounding the lake, the atmosphere and the lake itself. These materials accumulate at the bottom of the lake layer-after-layer, year-after-year, providing a long-term record of environmental change. The lake sediments are comprised of many different materials, including biological remains, geochemical and biochemical signals, which can be thought of as “fingerprints” of past environmental conditions. Paleolimnologists can analyze these “fingerprints” to determine past water quality. There are many different “fingerprints” that paleolimnologists can use to determine how lakes have changed overtime, but one of the most frequently used are diatoms. Diatoms are single-celled algae that are characterized by a cell wall composed of biogenic silica, which is called a frustule. Diatom frustules are well preserved in lake mud and can be identified to species or sub-species level. Each diatom species has specific ecological requirements, so by analyzing diatom assemblages much can be learned about past water quality. Sedimentary chlorophyll *a* can be used to track changes in overall algal production and biogenic silica can be used to track changes in diatom production.

A previous report used diatoms and a top/bottom approach at three sites in Chandos Lake (Hollingshead, 2017). A top/bottom approach compares indicators in the upper 0-1cm (present-day) of sediment to the lowermost sediments 25-40 cm (typically pre-European conditions) (Cumming et al., 1992). The previous report documented a change in diatom community composition between the top and bottom samples at the three sites in Chandos Lake. This change was interpreted as an increase in nutrient concentrations and increased thermal stability (Hollingshead, 2017). Because the analysis only compared two samples at each site, it was not possible to say when the changes occurred or why they occurred. The present study analyzes samples throughout the longest core collected by Hollingshead (from Gilmour Bay), and determines changes related to water quality, including nutrient concentrations and algal production. Diatom community composition provides information about nutrient concentrations, and chlorophyll *a* and biogenic silica provide information about how algal and diatom

production have changed. The records determined from the sediment cores will be compared to historical climate data and a history of land use change to see whether there are similarities in timing of changes in lake water quality and land use and climate change. ***The overall goal of this project is to provide the Chandos Lake Property Owner Association (CLPOA) with scientific data that can help effectively protect this lake.***

STUDY AREA

Chandos Lake is located just east of the town of Apsley and north of Peterborough in the township of North Kawartha, Ontario, Canada (Figure 1), and its location and general morphology are listed in Table 1. Along with the main part of the lake, there are three main bays: West Bay, South Bay, and Gilmour Bay. The primary focus of this study is Gilmour Bay (Figure 2). Chandos Township forms part of the Laurentian peneplain of the Precambrian Shield (Shaw, 1962). Gilmour Bay is underlain by the Apsley gneiss and rocks of the Loon Lake pluton, including monzonites, granodiorite gneiss and diorite-gabbro (Heaman et al., 1982). Deposits of iron, copper, and uranium have been found in the township (Shaw, 1962). The lake was created by glacial scour from the retreat of the Pleistocene glaciation (Shaw, 1962), and the surrounding terrain is mainly low rounded hills with swampy areas and poor drainage. Chandos Lake is in the Atlantic watershed and the largest lake in the Crowe River watershed. Most of the nearby smaller lakes and ponds (~20) drain into Chandos Lake (Shaw, 1962). Chandos Lake is fed by springs, and drains north into the Crowe River (CLPOA, 2016; Shaw, 1962).

Table 1: Lake and watershed properties of Chandos Lake.

Properties	Chandos Lake
Latitude, Longitude	44°49'30"N, 77°58'30"W
Maximum Depth (m)	48
Surface Water Area (ha)	1400
Water Catchment Area (km ²)	1387
Altitude (m above sea level)	310

The average annual air temperature from 1985-2015 within the Peterborough region was measured to be 7.1 °C (Lafleur, 2015). The number of ice out days at Lake Scucog, a lake close to Chandos (Figure 2), ranged from 75-109 days from 1985-2015. Chandos Lake is within Great Lakes/St. Lawrence forest region, comprised of a mix of deciduous and coniferous trees (Natural Resources Canada, 2017). Based on Hollingshead's (2017) water chemistry results, all three bays (including Gilmour Bay) within Chandos Lake are mesotrophic (Table 2). Previous reports also show that Chandos Lake is stratified in the summer, and that Gilmour Bay is anoxic in the summer (Hollingshead, 2017). Anoxia results in elevated levels of nutrients in the hypolimnion (Table 2).



Figure 1: Aerial view of Chandos Lake (Google Earth, 2016), including County Roads 504 and 620 encircling the lake. The red star shows Gilmour Bay.



Figure 2: The bathymetry of Gilmour Bay including the coring location (red star). Contour lines represent 10 ft intervals beginning at 0 ft along the shoreline. Revised from The Angler's Atlas (2007). The red star shows our coring site.

Table 2. Limnological properties of the epilimnion (E) and hypolimnion (H) for different sections of the lake including total phosphorus (P), total nitrogen (N), Secchi depth (m) and dissolved silica (mg/L). Trophic status was determined using classifications found in Wetzel (2001), which uses total phosphorus (P), total nitrogen (N), chlorophyll *a* concentration and Secchi depth.

Lake	Total P (ug/L)		Total N (ug/L)		Secchi Depth (m)	Dissolved Silica (mg/L)		Trophic Status
	E	H	E	H		E	H	
South Bay East	9	10	319	325	11.4	0.93	2.20	Mesotrophic
South Bay West	5	13	269	320	10.7	0.94	2.41	Mesotrophic
Gilmour Bay	7	140	277	1150	10.8	0.70	2.77	Mesotrophic

METHODS

Historical and Climate Data

Various historical archives were consulted to determine the land use history of Gilmour Bay and Chandos Lake. The historical sources ranged from terrain maps, fire maps, watershed surveys, past satellite maps, scientific reports and historical books. Air temperature data and ice out days were obtained through historical temperature measurements that were recorded by Environment Canada and Trent University and obtained from Dr. Pete Lafleur, Trent University. The data is a compilation of data from several weather stations in the Peterborough and Kawartha area (Lafleur and Adams, 2009). Ice out days for Lake Scugog were supplied by Hvidsten (2017), former owner and editor of Port Perry Star. Data for Chandos Lake is from Burgess (2017), a local Chandos Lake resident. All of this data is available from the Chandossier website, a website run by a community with water quality interests in Chandos Lake (<https://chandossier.com/>).

Sediment Core Collection and Extrusion

A Kajak-Brinkmann (KB) gravity corer (Glew et al., 2001) (6.5 cm internal tube diameter) (Figure 3) was used to collect three sediment cores: South Bay east (sediment record collected 28 cm depth), Gilmour Bay (sediment record collected 41.5 cm depth), and South Bay west (sediment record collected 35 cm depth) (Table 3; Figure 4) from Chandos Lake on August 23-24, 2014 by Ms. Kelly Hollingshead. Although three cores were collected, only the Gilmour Bay core was analyzed for this study. Each core was retrieved from the deepest part of three different sections of the lake, which is the most appropriate coring site to ensure the most continuous, undisturbed, representative sediment record of the entire lake (Smol, 2008). To minimize stratigraphic disturbance, sediment cores were sectioned at continuous 0.5 cm intervals immediately after collection using a vertical extruder in the field (Figure 5). Subsamples were placed into Whirl-Pak® bags and stored at 4°C until further processing. The scraper was cleaned with Chandos Lake surface water between each interval.

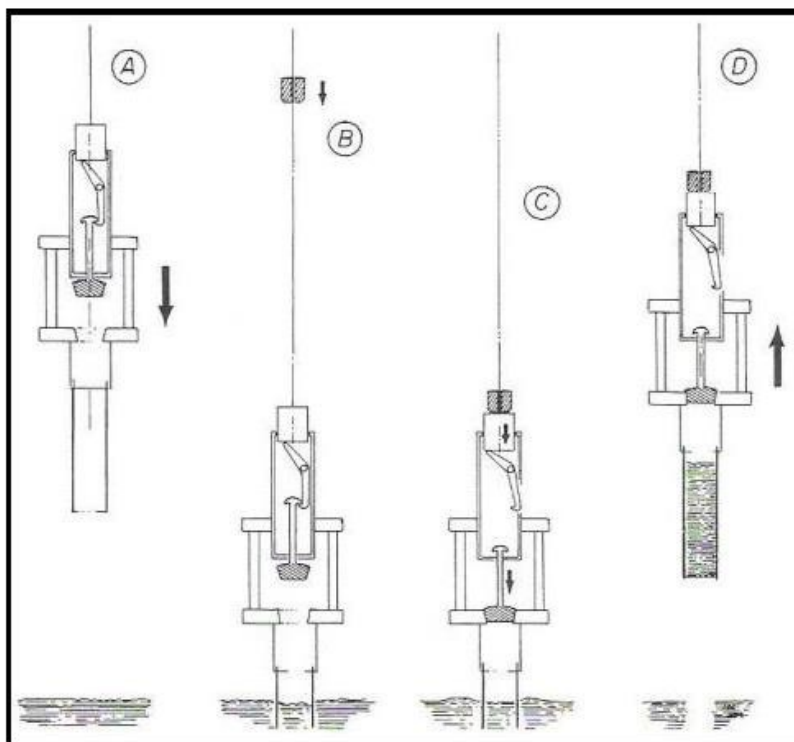


Figure 3: General operation of a messenger-triggered gravity corer. (A) Corer lowered through water column: (B) corer centers the sediment and trigger is released from the surface: (C) trigger hits the corer and forms a seal: (D) corer is vertically removed to obtain sample (Glew *et al.*, 2001; Smol, 2008).

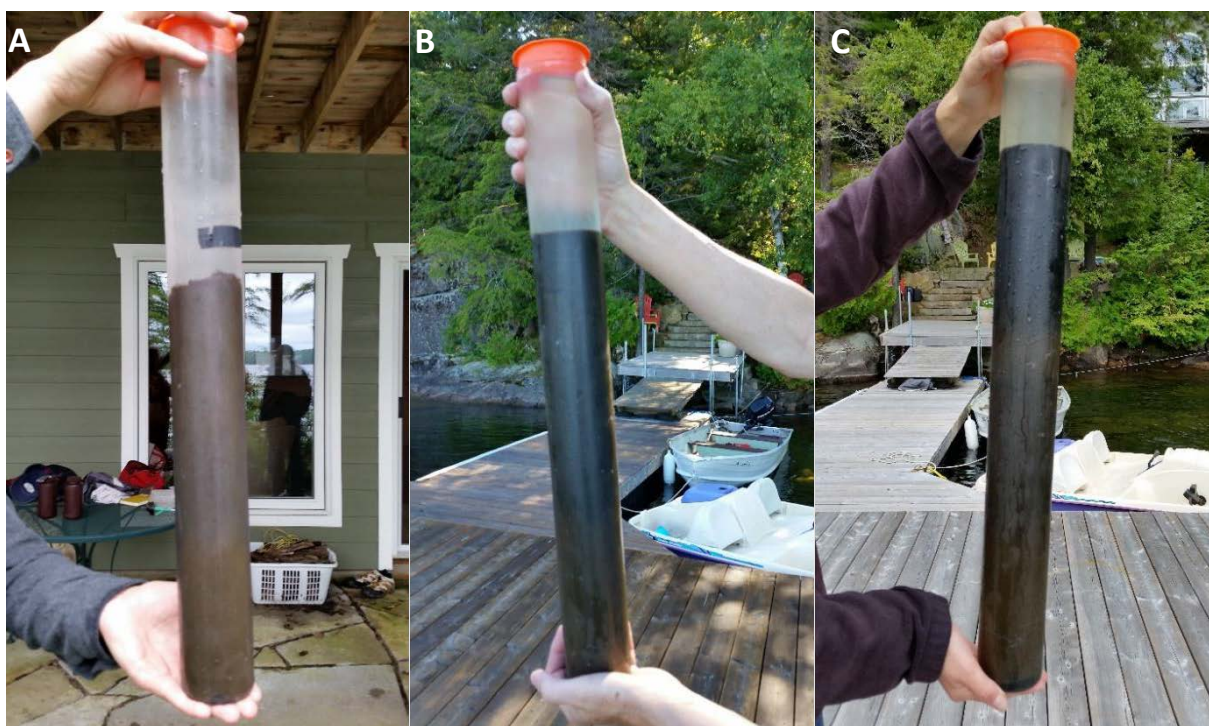


Figure 4: Photographs of Chandos Lake cores: A) South Bay east, B) South Bay west, and C) Gilmour Bay, respectively.

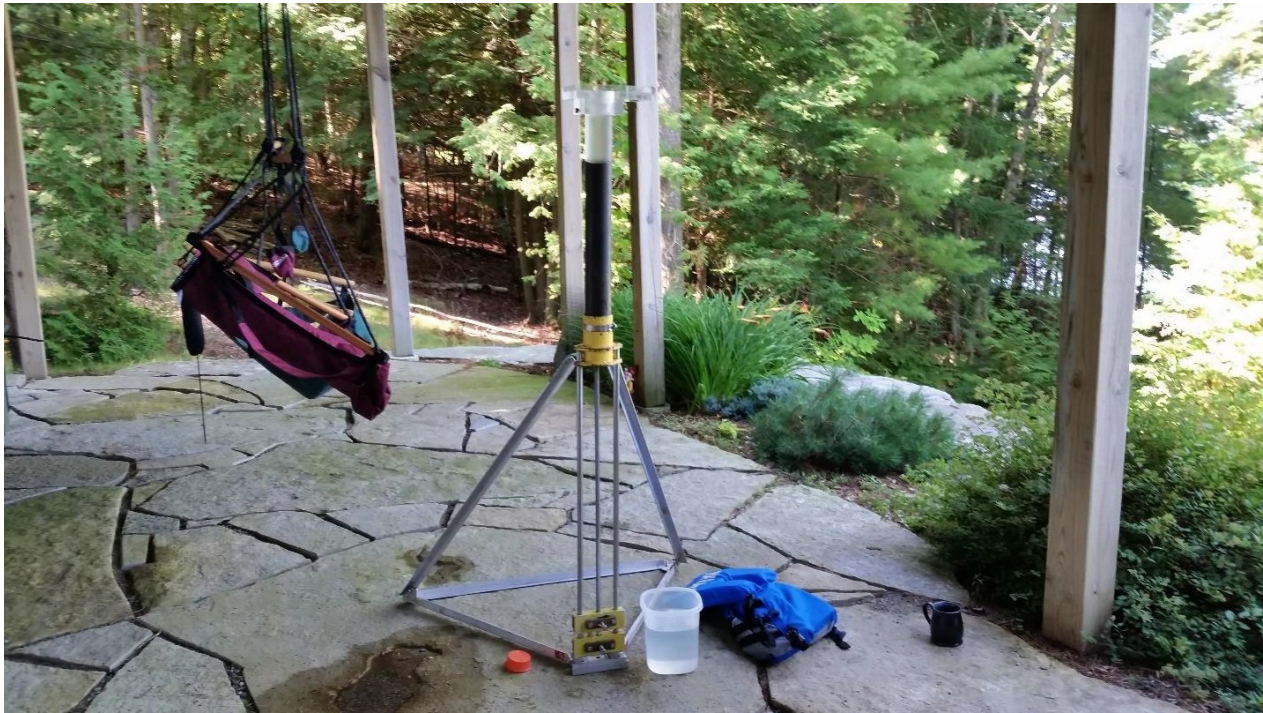


Figure 5: South Bay west sediment core in extruder ready for sectioning in the field.

Table 3: Core depths for each analysis.

Lake	Top Sample (cm)	Bottom Sample (cm)
South Bay east	0 – 0.5	27.5 – 28.0
South Bay west	0 – 0.5	34.5 – 35.0
Gilmour Bay	0 – 0.5	41.0 – 41.5

For each sample, 7 cm³ of wet sediment was prepared. These samples were used for ²¹⁰Pb dating, chlorophyll *a* and biogenic silica analysis. Wet sediments were frozen in a freezer for 24 hours and placed in a freeze-dryer, *Labconco Triad*. This process removed the water from the wet sediments. After freeze drying, dry samples were pulverized with the use of a mortar and pestle and then sieved through a 125 um mesh to homogenize samples for further analyses. Since the analysis of chlorophyll *a* and biogenic silica involved the use of a spectroscope, homogenization of samples is required to minimize particle size interference with the spectral signal (Michelutti et al., 2005; 2010). An additional subsample of 1 cm³ was sampled for diatom/chrysophyte analysis.

²¹⁰Pb Dating

²¹⁰Pb analysis is necessary to determine the ages of the sediments. Sediment dates provide the years when changes in total algal and diatom production and diatom community composition has occurred. ²¹⁰Pb is a naturally occurring intermediate isotope from the ²³⁸U series. It has a half-life of 22 years and enters sediments through precipitation (Cornett et al., 1984). ²¹⁰Pb can accumulate in sediments as unsupported ²¹⁰Pb and background ²¹⁰Pb. Unsupported ²¹⁰Pb refers to the ²¹⁰Pb derived from the atmosphere, whereas background ²¹⁰Pb is derived from the underlying bedrock. By estimating and isolating the amount of unsupported ²¹⁰Pb, the age of the sediments can be estimated using the radioactive decay law (Appleby,

2001). An alpha spectroscope was used to indirectly measure ^{210}Pb concentrations by the wavelengths emitted through its daughter isotope ^{210}Po . This method is favourable as the wavelengths emitted directly through ^{210}Pb are difficult to measure (Appleby, 2001). Seventeen samples (Appendix A) were sent in December 2017 to MyCore (MyCore Scientific Inc., 2017), Ontario for ^{210}Pb dating analysis. ^{210}Pb dating analysis is not required for every interval as key sample intervals throughout the core can be dated and then ages interpolated based on the ages of the dated sediment layers.

Sedimentary Chlorophyll *a* Analysis (Overall Algal Production)

Chlorophyll *a* is a pigment present in all photosynthetic organisms, including algae and diatoms (Smol, 2008). By determining the sedimentary chlorophyll *a* levels from sediment records, past algal production can be estimated. Based on research conducted by Michelutti et al. (2010), the optimal absorbance peak for measuring chlorophyll *a* is 675 nm. Chlorophyll *a* and its derivatives were measured using visible reflectance spectroscopy. A spectroscope, *Rapid Content Analyzer*, was used at the *Paleoecological Environmental Assessment and Research Laboratory* at Queen's University November 2017 to obtain the absorbance values. Forty-one selected samples were dried and grinded and assessed with a full spectral range (400-2500 nm) by the *Rapid Content Analyzer*. The absorbance values were converted to chlorophyll *a* concentration by calculating the area under the peak between 650-700 nm. An equation derived from Michelutti et al. (2010) was used to determine the concentration.

$$\text{Chlorophyll } a + \text{derivatives} = 0.0919 \times \text{peak area } 650\text{-}700 \text{ nm} + 0.0011$$

The raw chlorophyll *a* concentration values were used to determine chlorophyll *a* flux, which is how quickly chlorophyll *a* accumulated in the sediment. Chlorophyll *a* flux accounts for changes in the concentration values caused by variations in sedimentation rates rather than real changes in chlorophyll *a* concentration. The sedimentation rates were determined from ^{210}Pb analysis, and chlorophyll *a* flux was determined by multiplying the chlorophyll *a* concentration by the sedimentation rate.

Biogenic Silica (Diatom Production)

Biogenic silica analysis was used to determine diatom production. Biogenic silica was measured at the Lake and Reservoir Systems (LARS) Research Facility, Western University using the wet alkaline extraction method (DeMaster, 1979). This method is preferred over others because it is a time efficient method and provides accurate results (DeMaster, 1979). Selected grinded and dried sediments were leached into polypropylene bottles containing 1 % sodium carbonate for 4 hours at 85 °C. It has been shown that 1 % sodium carbonate is the optimal concentration to dissolve biogenic silica within 2 hours while minimizing the dissolution of silica derived from minerals and other clastic material (DeMaster, 1979; Conley, 1988). The slurries were subsampled using a micropipette after 2, 3 and 4 hours. The concentration of biogenic silica in each subsample at time 2, 3 and 4 hours was determined through the formation of blue silicomolybdate colour complex and analyzing the wavelength range of 480-490 nm with a spectroscope. To determine the concentration of dissolved silica in each hourly sample, a calibration of absorbance values for eleven known silica standards were used. A regression line is fit, and the equation of this line was used to estimate the biogenic silica concentrations of samples from the absorbance values. Biogenic silica from diatoms and chrysophytes dissolves completely within 2 hours whereas silica from clastic material dissolves at a slower rate. Therefore, the subsample results will represent silica from both biogenic and clastic sources. The concentration of biogenic silica was calculated as the y-intercept of the regression line of weight % silicon (Si) versus extraction time. Afterwards, biogenic silica concentrations were converted into biogenic silica flux. Biogenic silica flux accounts for changes in the raw weighted biogenic silica values caused by variations in

sedimentation rates. The sedimentation rates were determined from ^{210}Pb analysis and biogenic silica flux was determined by multiplying biogenic silica weighted values by the sedimentation rate.

Diatom Sample Preparation and Analysis

Sediment samples from Gilmour Bay were prepared for diatom analysis in the Lake and Reservoir Systems (LARS) Research Facility at the University of Western Ontario following standard procedures reported in Battarbee *et al.*, (2001). At least 450 diatom valves (Pappas and Stoermer, 1996) were identified and enumerated to species level under oil immersion (1000x magnification) using a Leica® E-600 light microscope equipped with Nomarski DIC optics. To ensure a representative and reproducible sample, each count ended at precisely halfway or at the end of the transect. Diatom identification to the lowest taxonomic level possible (species or variety) was based primarily on Krammer and Lange-Bertalot (1986, 1988, 1991a, b). Chrysophcean cysts were also counted, but not identified, on each slide enumerated for diatoms. Digital photographs of all dominant taxa were taken using a Retiqua® black and white digital camera.

Data Analysis and Presentation

Stratigraphic plots of chlorophyll *a* flux and biogenic silica flux were compared to climate data using the software program C2 (Juggins, 2007), a program for the analysis and visualization of ecological and paleoenvironmental data. All data was smoothed using a LOESS function with a span of 0.3 and an iteration of 10 to better observe the main trends. Comparisons between plots was done by visual inspection.

In order to better understand changes in diatom assemblages through time, the diatom assemblages identified were plotted in C2 (Juggins, 2017). Only dominant diatom taxa (i.e., those taxa that exceeded 1% relative abundance in at least three samples (Wilson *et al.*, 1994) were considered in the data analyses. The percentage of each diatom taxon was calculated using the total number of individuals of each taxon divided by the total number of all diatoms in the sample. Diatom species were grouped as planktonic (free floating), thycoplanktonic (living part of their life cycle in the open water and part in the littoral zone) or benthic (living on and in the sediments). The planktonic *Fragilaria* species were in long chains or broken and the *Cyclotella* species were small creating difficulty distinguishing between species without a Scanning Electron Microscope; therefore, on the diatom stratigraphy, the *Fragilaria* complex represents *Fragilaria cf. tenera* and *Fragilaria cf. crotonensis* and *Cyclotella stelligera* and *C. pseudostelligera* have been grouped together. To simplify the diatom data, principal components analysis (PCA), an indirect gradient analysis, was used in the program C2. The sample scores on the first three axes were plotted against time to compare to the chlorophyll *a*, biogenic silica and climate data.

RESULTS

The History of Chandos Lake

Although the Kawartha Lakes region has been occupied by people for thousands of years (Brunger, 2009), the focus of this study is on human impacts in the last 200 years. Based on the review of several historical documents, three main periods of land use change were determined. The first is a period of significant land clearance and spans from the mid-1800s to 1910. Although European settlement in Peterborough began as early as 1818 (Howe and White, 1913); settlement in the Chandos area only began in the early 1860s (Cole, 1989). Logging in the Kawartha Lakes area went hand-in-hand with settlement. In the Kawartha Lake region logging peaked between 1860 and 1870 (Brunger, 2009), but because Chandos is further north and more isolated from trade centers, logging may have been delayed. The earliest records we found indicated logging

beginning in the Chandos area by 1874 (Cole, 1989). At that time the Rathburn Lumber Company purchased over 2000 acres of land for timber within the Chandos Township (Cole, 1989). However, by the early 1900s much of the Chandos area had been logged. A report from 1913 indicates that 68% of the Chandos township had been logged (Howe and White, 1913). Because the land around Chandos township was not good for farming, settlers to this area probably relied on logging to help make a living, so when most of the trees had been removed, these farmers were often forced to leave (Howe and White, 1913). The second period from 1910 to 1950 is marked by a decreasing population and perhaps modest forest recovery (Brunger, 2009). After the Second World War, Period 3 began. Beginning in 1945, people began to establish cottages and homes near Chandos Lake (Cole, 1989). The natural aesthetics of Chandos Lake continued to attract new cottagers, exponentially increasing the establishment of cottages and homes near Chandos Lake (Table 3). By 1945, there were 150 cottages; today, there are 1200 cottages and homes along the shorelines of Chandos Lake (Ministry of the Environment, 1972; Cole, 1989; Chandossier, 2017).

Table 4. Historical events summarized. Generalized major events are listed as Period 1, 2, 3. Year and activity summarize when each specific land clearing or cottage establishments occurred.

TIME PERIOD	YEAR	ACTIVITY
Period 1: Land clearance (1860-1910)	1860	European settlers arrive in Chandos Township
	1874-1877	Major lumbering activities occur within Chandos Township
	1913	68% of the forested area surveyed in Chandos Township has been logged
Period 2: Reduction in settlement and land clearance (1910-1945)	1910-1930	As lumbering potential declines, farms are abandoned and populations decrease
	1930	End of the logging era
	1945-1949	Cottage settlements begin, 150 cottages
Period 3: Cottagers and homes increase (1945-Present)	1961	635 cottages
	1972	820 cottages
	2010	1200 cottages

Climate Data and Trends

A graph comparing annual, summer and winter temperatures and the number of ice out days show climate trends (Figure 6). All three temperature records show roughly the same trends, so only annual temperatures will be used for the rest of the analyses. Based on the temperature records, three periods are delineated (Figure 6). The first extends from the 1860 CE – 1935 CE and is characterized by warming. The second period begins in 1935 CE – 1980 CE and is characterized by relatively stable to slightly cooler temperatures (Figure 6). After 1980 CE, a rapid warming is observed. Only a short record of ice out is available for Chandos Lake, but it is very similar to Lake Scugog (Figure 6). As expected, ice out dates are earlier when temperatures are warmer.

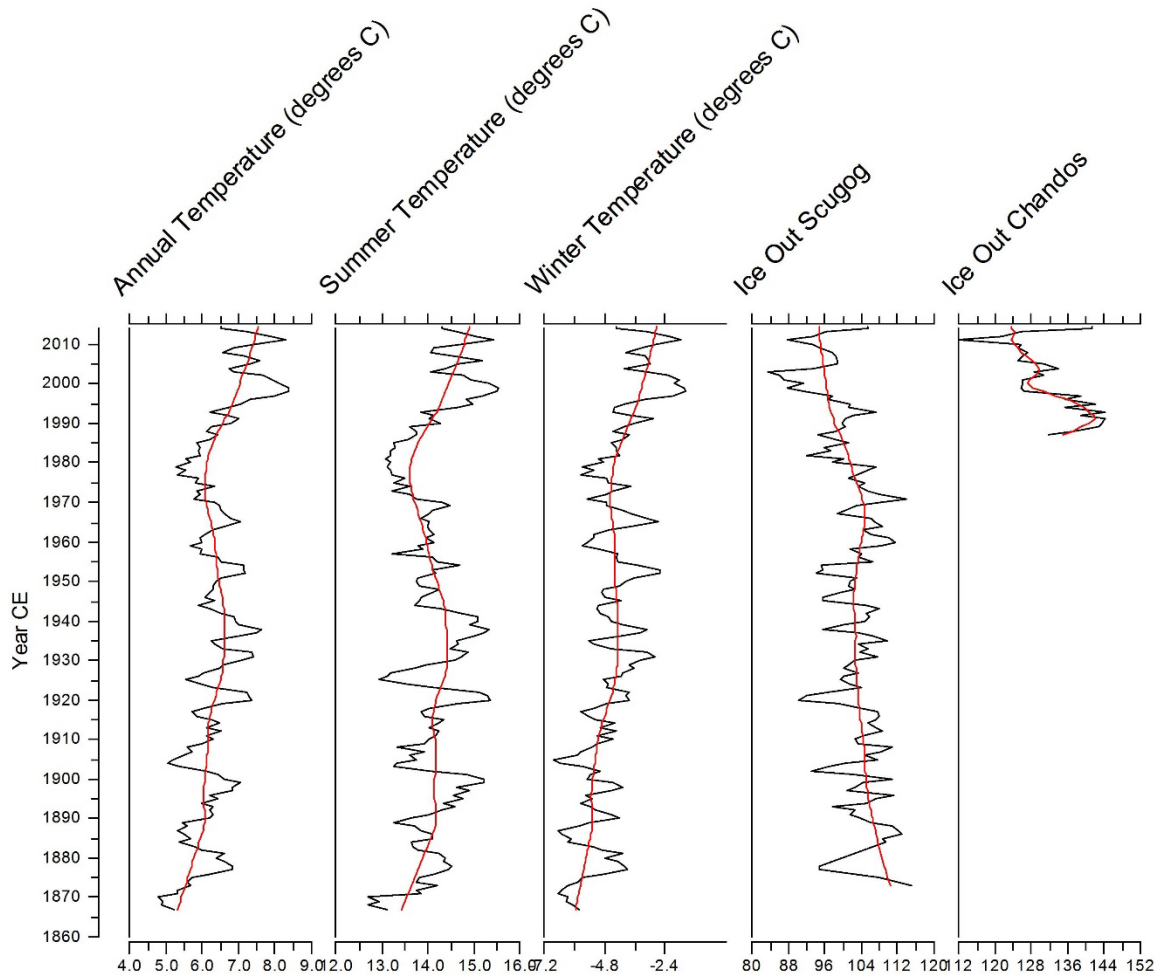


Figure 6. Climate data composed of annual, summer and winter air temperatures within the Peterborough area 1866-2016 in degrees Celsius (Lafleur, 2015). The data is a compilation of data from several weather stations in the Peterborough and Kawartha area (Lafleur and Adams, 2009). Ice out data represent the number of days of ice cover since January 1st on Lake Scugog and Chandos Lake. Data from Lake Scugog was collected from 1873-2017 (Hvidsten, 2017; 1999). Data from Chandos Lake was collected from 1985-2016 (Burgess, 2017). The red lines are a Loess smoothing function to reduce noise and make the data sets more comparable.

Core Description and Chronology

The top part of the core (0 – 15 cm) from Gilmour Bay was composed of dark brown organics. From 18 - 36 cm the sediments were comprised of medium brown organics. The bottom of the core (38 – 41 cm) was composed of light brown organics (Hollingshead, 2017). The amount of unsupported ^{210}Pb exponentially decreases from the top of the core to the bottom of the core (Figure 7a). The estimated age of sediment samples based on ^{210}Pb analysis is shown in Figure 7b. The basal age of the sediment core retrieved from Gilmour Bay is 1859 CE, which means that the sediment record does not extend to periods prior to European arrival, so the baseline (pre- disturbance) conditions remain unknown. Earlier sediments could be retrieved using alternative coring methods.

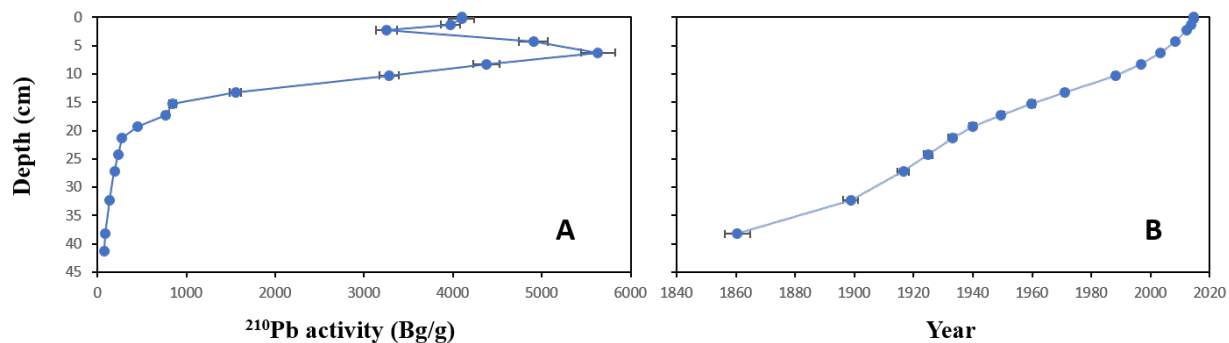


Figure 7. A) Unsupported ^{210}Pb activity (Bg/g) against sediment depth, Gilmour Bay. B) Using the constant rate of supply (CRS) model, the age of the sediment intervals were estimated. Error bars in both A) and B) represent uncertainty.

Chlorophyll *a* (algal production) and Biogenic Silica (diatom production)

Chlorophyll *a* flux generally tracks land clearance patterns, although chlorophyll *a* increases markedly with recent warming (Figure 8 and 9). Chlorophyll *a* increased from 1860 – 1913, the period of land clearance and deforestation (Figure 8). From 1913 - 1945 when forests were re-establishing, chlorophyll *a* decreases. From 1945 until 1987 chlorophyll *a* increases slightly. After 1987 chlorophyll *a* increases rapidly to the present (Figure 8 and 9). This is a period of increasing numbers of cottages, but also warming temperatures.

Biogenic silica flux levels do not align to land use change as clearly as chlorophyll *a* (Figure 8 and 9). Although biogenic silica flux follows land clearance patterns in the earliest part of the record, increasing between 1860 and 1913, it more closely follows temperature trends and continues to increase until 1935, at which point it decreases following decreasing temperature trends (Figure 8 and 9). Biogenic silica does not increase with the recent warming, but measurements in the upper 10cm of sediment may be misleading owing to anoxic conditions in the hypolimnion (Table 4), which would cause dissolution of silica in the upper sediments.

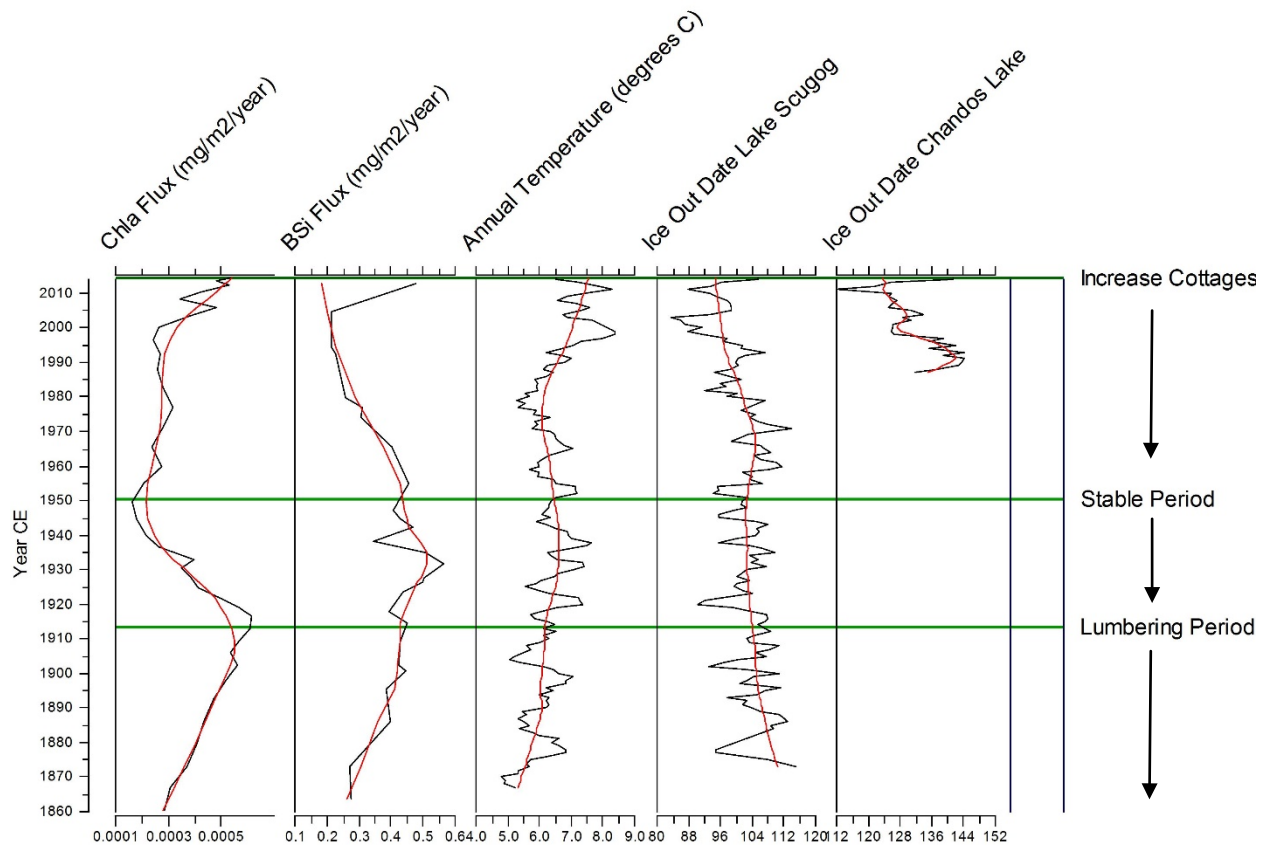


Figure 8. Chlorophyll *a* flux (Chla Flux) was used to represent algal production. Biogenic silica flux (BSi Flux) was used to represent diatom production. Both sedimentary chlorophyll *a* and BSi flux levels were compared to annual air temperatures from the Peterborough area, and ice out dates from Lake Scugog and Chandos Lake. Ice out dates represent the number of days ice cover is present on the body of water since January 1st. For more information see Figure 6. The three land use periods are identified as the green lines. The red lines are a Loess smoothing function to reduce noise and make the data sets more comparable.

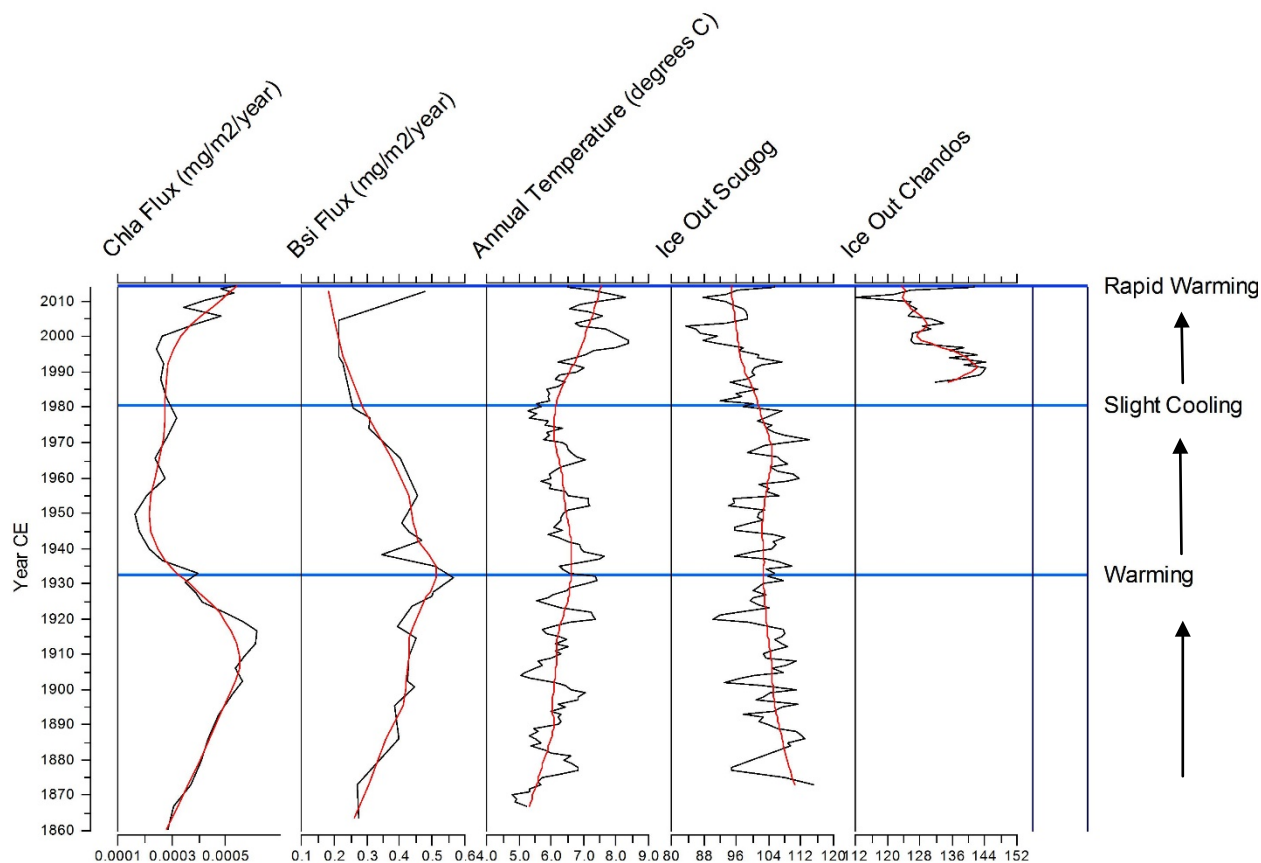


Figure 9. Chlorophyll *a* flux (Chla Flux) was used to represent algal production. Biogenic silica flux (BSi Flux) was used to represent diatom production. Both sedimentary chlorophyll *a* and BSi flux levels were compared to annual air temperatures from Peterborough, ice out dates from Lake Scugog and Chandos Lake. Ice out dates represent the number of days ice cover is present on the body of water since January 1st. For more information see Figure 6. Three climate periods are identified by the blue lines. The red lines are a Loess smoothing function to reduce noise and make the data sets more comparable.

Diatoms

Approximately 130 different diatom species were identified, although many were in abundances less than 1% and identified in less than three samples. These diatom species are not included in the analysis for this report. The diatom community composition changes markedly in the last 150 years in Gilmour Bay (Figure 10). Four distinct zones (time periods) were determined by visual inspection of the changes in diatom community composition (Figure 10). All zones are characterized by high abundances (>70%) of diatoms living in the open water. Zone 1 spans from 1850 to 1913 and is comprised mainly of small *Cyclotella stelligera/pseudostelligra* diatoms, which typically indicate low nutrients. Zone 2 extends from 1913 to 1940 and is similar to zone 1 except that *Aulocoseira subarctica* are more abundant. *A. subarctica* are also typical of lower nutrients, but are heavily silicified and require turbulence to stay in the photic zone where there is sufficient light for photosynthesis.

There are several similarities between zone 1 and 2. *Cyclotella* species, including *C. michiganiana* and *C. invisitatus*, which are also typical of lower nutrients, are common. Chrysophyte stomatocysts, which are often indicators of more oligotrophic (i.e., nutrient poor) conditions are also most abundant in these zones. Zone 1 and 2 contain the highest abundances (>20%) of benthic diatoms. These diatoms include mainly small benthic

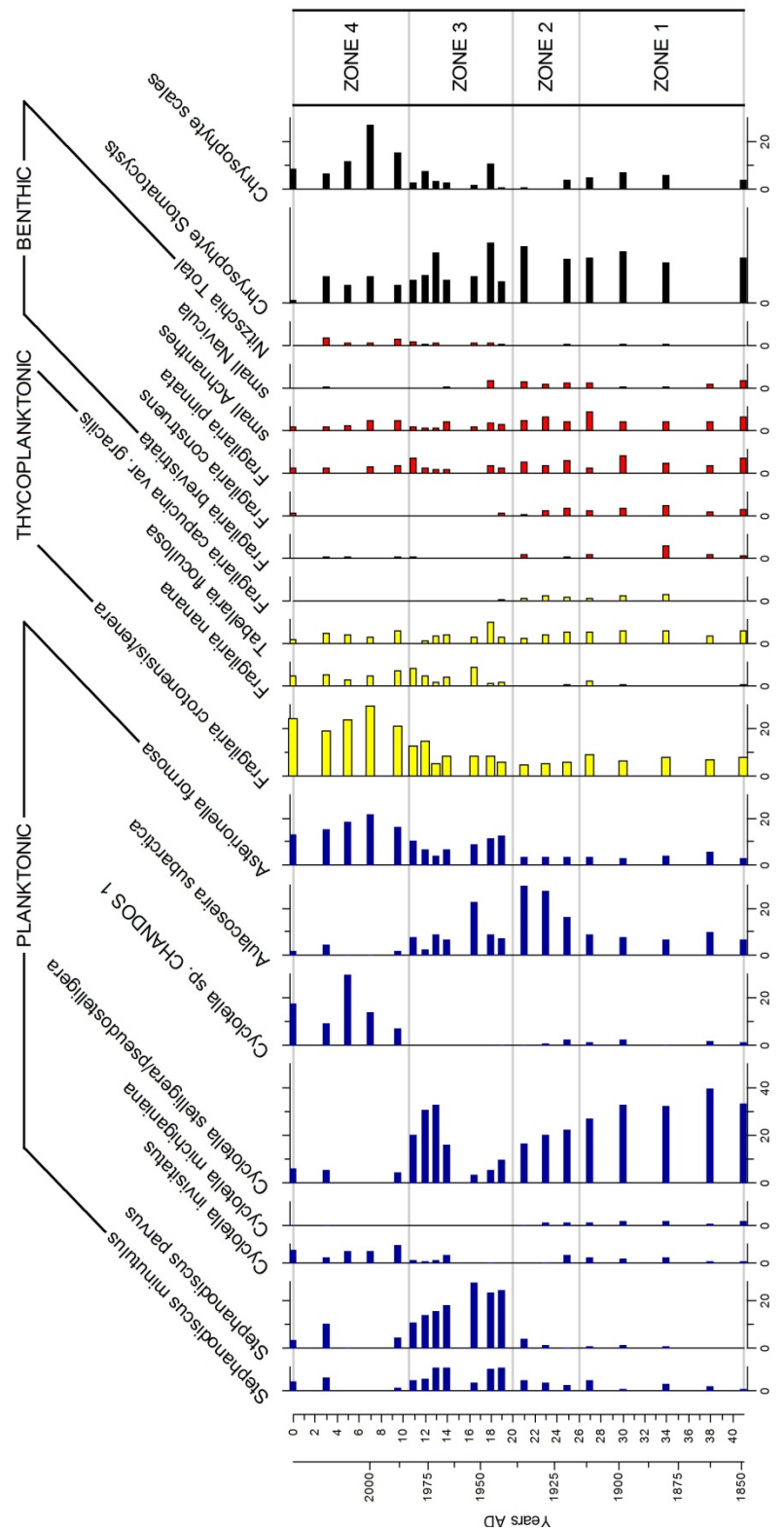


Figure 10: Diatom Stratigraphy. This plot shows changes in the abundance of diatom species over time. Each column represents a different diatom taxa. Only key species are illustrated. The x axis represents abundance and the y axis represents both depth and time.

Fragilaria taxa and small *Achnanthes* and *Navicula* species. Also, although not shown in the figures, large pennate diatoms are more common. This may indicate that there was either more littoral habitat or more diverse littoral habitat compared to later periods.

Zone 3 begins at 1940 and extends to 1987. Both the small *Cyclotella* and *Aulacoseira* species decrease and *Stephanodiscus parvus* and *S. minutulus* increase. *Stephanodiscus* species indicate increased phosphorus. Other diatoms that also do well with increased phosphorus, including *Asterionella formosa* and *Fragilaria nanana*, also increase. Small *Fragilaria*, *Achnanthes* and *Navicula* all decrease and large pennate diatoms become more rare. *Nitzschia* species become more common.

The uppermost zone, zone 4, extends from 1987 to 2014, the year the core was collected. This zone is characterized by the near disappearance of *Stephanodiscus* and *Aulacoseira* and increases in *Cyclotella* sp. CHANDOS 1 and *Fragilaria crotonensis/tenera* complex. Similar changes have been interpreted to indicate that mixing of lakewaters is decreasing.

Principal components analysis was used to reduce the large diatom data set into three plots (Figure 11). The first principal component axis represents *Cyclotella* species with positive values indicating greater abundances of *Cyclotella* sp. CHANDOS 1 and negative values *C. stelligera/pseudostelligera*. Based on similarities between the trend in PCA axis 1 plot and temperature this axis may roughly represent temperature or variables related to temperature (e.g., thermal stratification or ice out). The second axis reflects changes in phosphorus with positive values indicating more phosphorus and negative values indicating less phosphorus. The third axis reflects turbulence with negative values indicating more turbulence and positive values indicating less turbulence. Based on this interpretation of the PCA axes, the first zone was characterized by cool temperatures, increasing but relatively low nutrients and moderate turbulence. The second diatom zone is characterized by slightly warming temperatures, increasing phosphorus and increasing turbulence. The third zone has relatively stable temperatures, high phosphorus, and decreasing turbulence. The fourth zone is characterized by rapid warming, reduced phosphorus and moderate turbulence.

Taxonomic Notes

The *Cyclotella* species occurring in the upper part of the core is not *Cyclotella stelligera/pseudostelligera*. It looks similar to *Cyclotella comensis* identified in Reavie and Kireta (2015), but could include more than one species as there is considerable variation in morphology and size. Although these diatoms are generally small (<10um) they are larger than the *Cyclotella* species identified in zone 4, although this should be quantified. Scanning electron microscopy should be used to better differentiate the *Cyclotella* species observed in Gilmour Bay, which would provide more ecological information and understanding of the changes observed in the sediment record. As in other studies *Fragilaria crotonensis* and *F. tenera* have been grouped together as there is considerable gradation in morphology within this group. There are many species of small (often <5um) *Achnanthes* and *Navicula* at Gilmour Bay, which are difficult to identify. Although best attempts were made to differentiate these species they have been grouped to the genus level until further work can be done.

DISCUSSION

Effects of Land Use and Climate Change on Overall Algal and Diatom Production

The Lumber Period and Slow Warming (1850 to 1913)

The first diatom zone is coincident with the period of lumbering (Table 4). By the end of this period much of the forest had been removed. Chlorophyll *a*, which represents overall algal production, and biogenic silica, which indicates diatom production, both increase during this time, an indication of increasing nutrient loads from the lake catchment to the lake. Algal and diatom production are controlled by many factors, including nutrient (mainly nitrogen and phosphorus) and light availability, temperature, grazing pressures and others,

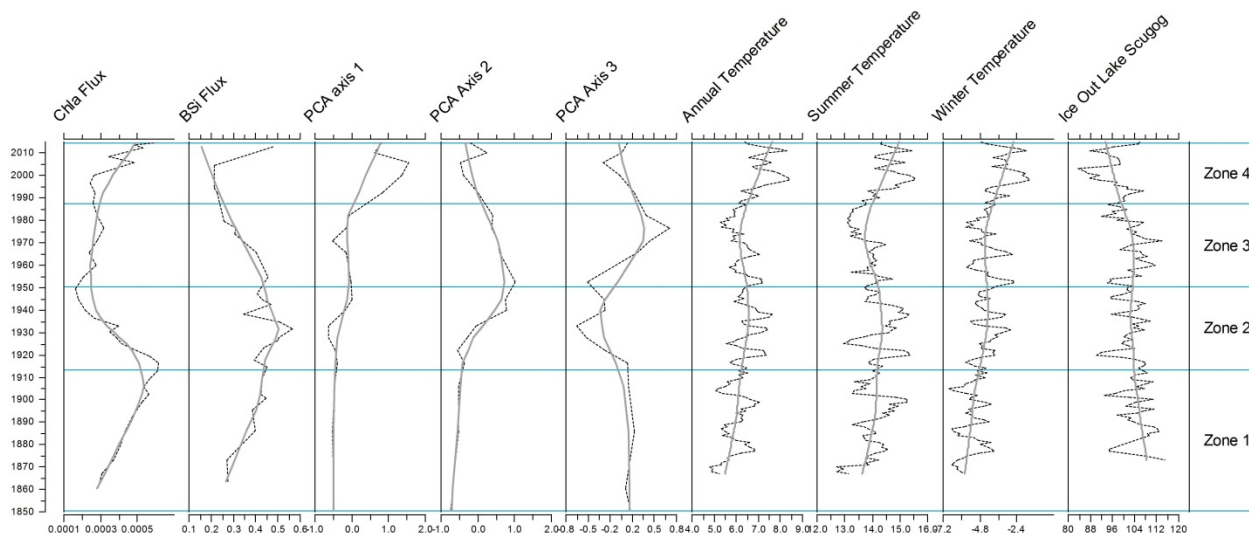


Figure 11: Summary Figure. PCA 1, 2 and 3 are summaries of the diatom data. PCA 1 reflects changes related to temperature (+ values indicate warmer temperatures), PCA 2 shows phosphorus surface water concentrations (+ values indicate increase phosphorus), and PCA 3 is turbulence or mixing (- values indicate more mixing).

but it is well known that algal production increases when nutrients increase (Schindler, 1970). Previous research has shown that land clearance and deforestation contribute to increased soil erosion and the transportation of nutrients from the land to lakes and streams (Hall and Smol, 1993; Kjerfve, 1997; Otu et al., 2011). Delivery of these nutrients would be greatest in the spring with snow melt.

The most abundant diatom in zone 1 is the small *Cyclotella stelligera/pseudostelligera*. These diatoms typically indicate low nutrients and strong thermal stratification (Rühland et al., 2008; Rühland et al., 2015). Along with landscape changes, temperatures were slowly warming and the timing of ice out was becoming earlier. These climatic changes could have increased thermal stratification and lowered nutrients, particularly in summer, allowing this small diatom to thrive during summer.

Reduced Land Use and Slow Warming (1913-1940)

Logging had probably ended ~1910 and most farms were abandoned (Table 4). This period was, therefore, likely when forest re-establishment and re-stabilization of soils began. This would have led to less nutrients, sediments and dissolved organic carbon being transported from the land to the lake. Thus, water transparency increased allowing light and heating to occur to greater depth. The increase in *Aulacoseira*, a heavily silicified diatom that requires turbulence to stay in the photic zone, indicates more light and mixing. Increased winds also could have contributed to the increase in *Aulacoseira*. Chlorophyll *a* decreased and biogenic silica increased. Increased mixing is generally thought to increase diatom and algal production, but only diatom production increases during this time. A past study showed warmer temperatures resulted in higher diatom production (Schelske, 1999). Another study concluded that warmer temperatures reduced the duration of ice cover, which results in an extended growing period, and therefore increased diatom production (Weckström et al., 2016). It is unclear why algal production would decline instead of increasing.

Increased Land Use and Slow Warming (1940-1987)

Starting in the 1940s people began to build cottages and the population and development around Chandos Lake has steadily increased to the present (Table 4). The main change in diatoms was an increase in *Stephanodiscus minutulus* and *S. parvus*, which both indicate increased nutrients (eutrophic conditions), particularly phosphorus (Stoermer and Håkansson, 1984; Reavie and Kireta, 2015). The increase in *Stephanodiscus* species is accompanied by an increase in *Asterionella formosa*, which is also an indication of

increased nutrients, particularly nitrogen (Saros et al., 2005). Cottage establishment is often coupled with urban sewage runoff, which contributes nitrogen and phosphorus to nearby lakes and leads to increased algal production (Hall and Smol, 1999). Septic systems in Shield lake regions can be a key source of nutrients because the weeping beds are often inefficient fairly soon after construction because roots fill the beds and there is limited soil depth to absorb the nutrients. In addition, the establishment of domestic waste disposal sites within the catchment of Chandos Lake could have resulted in nutrient rich runoff during heavy precipitation (Ministry of the Environment, 1972). This zone is also marked by a decrease in the abundance of diatoms living in the littoral zone and increase in abundance of open water diatoms. This could be in response to increased nutrients (Hall and Smol, 1999), or it could be the result of aquatic plants being harvested for recreation. Aquatic plants are frequently removed to increase boating and swimming enjoyment.

The increase in nutrients would also be expected to lead to increased sedimentary chlorophyll *a* and algal production during this time. Chlorophyll *a* does increase slightly, likely in response to increased nutrients, but biogenic silica declines. This may be related to changing climate conditions. From 1940-1980 the Peterborough area experienced slight cooling. Past research shows cooler temperatures are associated with decreases in diatom production (McFadden et al., 2004; Camill et al., 2012). This is because colder temperatures mean longer ice cover and therefore a shorter growing season for diatoms (McFadden et al., 2004). Although the main changes observed during this period reflect cottage development, climate factors may also have played a role.

Recent and Rapid Warming 1987 to Present

Chlorophyll *a* increases throughout this period, but the increase in chlorophyll *a* beginning in 1990 is rapid. Warming temperatures may play an important role in the recent observed changes at Gilmour Bay. From 1980 to the present time, the Peterborough area experienced rapid warming and the ice out date becomes earlier (Figure 6). Overall algal production, indicated by chlorophyll *a*, has previously been reported to increase with warming temperatures (Michelutti et al., 2005). Past research has shown that increasing temperatures lead to earlier ice-out, which results in higher algal production as nutrients and growing seasons are available for longer periods of time (Weckström et al., 2016). So, the increase in chlorophyll *a* beginning in 1950 CE may be the result of increased cottages and aging septic systems, but the more recent and rapid increase is also related to recent warming.

This zone is marked by an increase in *Cyclotella* sp. CHANDOS 1. This diatom looks similar to *Cyclotella comensis*, but scanning electron microscopy is required to confirm this. *C. comensis* is found in nutrient- poor lakes (Werner and Smol, 2006; Saros and Anderson, 2014; Reavie and Kireta, 2015) and has also been found living in the deep chlorophyll layer during summer where it can access nutrients available from periodic upwelling of hypolimnetic waters (Bramburger and Reavie, 2016). The change in *C. sp. CHANDOS 1* is accompanied by increases in *Fragilaria crotonensis* and further increases in *Asterionella formosa*, two diatoms that often form spring blooms (Lund, 1952; McKnight et al., 1990). Similar changes to those reported here are also occurring in many other Ontario lakes and have been attributed to warming temperatures resulting in a longer ice free season increasing the duration and strength of thermal stratification (Rühland et al., 2015; Sivarajah et al., 2018). Our measurements show that Gilmour Bay is presently well stratified in summer and that the hypolimnion is anoxic with high levels of phosphorus (Table 2; Hollingshead, 2017). Supporting this interpretation are measurements of decreasing phosphorus levels in the epilimnion since 2002 (Figure 12).

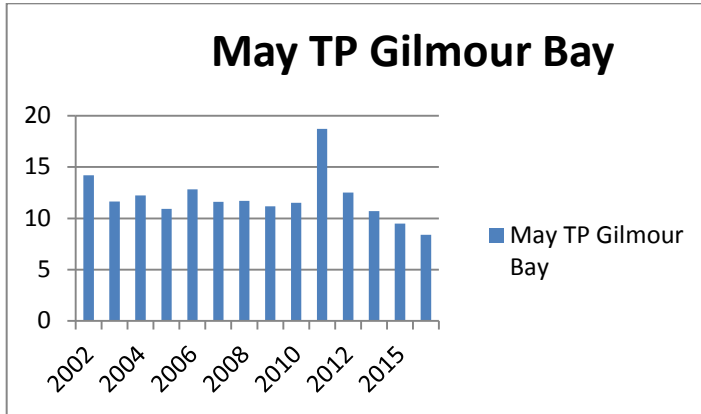


Figure 12: Total Phosphorus in May in Gilmour Bay. Data from Kawartha Lake Partner Program.

If epilimnetic nutrients are decreasing then why is algal production increasing? This could be because algae taxa that are better adapted to warming temperatures and low nutrients are increasing. For example, blue green algae are particularly well adapted to warm waters and have developed a wide array of physiological adaptations to periodic nutrient deplete conditions (Paerl, 2014). In the MOE (1986) report on Chandos Lake the dominant algal type reported in Gilmour Bay was *Anabena*, a bloom-forming blue green algae. It is also interesting to note that during this time biogenic silica decreases. This could indicate that diatoms are being outcompeted by other algae, but it could also indicate a preservation problem in the upper sediments. A key assumption made in equating sedimentary records of biogenic silica to diatom production is that dissolution of diatom valves in the sediments and water column are constant overtime (Cohen, 2003). It is possible that this is not the case in the upper sediments of Gilmour Bay. Chandos Lake, and Gilmour Bay especially, are presently strongly stratified and in Gilmour Bay dissolved silica is 4X greater in the hypolimnion than the epilimnion (Table 2); indicating that silica is being dissolved from the sediments. In a relatively deep lake like Chandos Lake, an increase in thermal stratification can reduce oxygen and change redox conditions in the hypolimnion leading to conditions more conducive to dissolution of silica (Cohen, 2003).

Comparison of these findings with previous research on Chandos Lake further indicates that the conditions reported warrant future monitoring and concern. A report published in 1986 on water samples collected in 1981/1982 shows that total phosphorus concentrations in the epilimnion were 17ug/L (this is higher than the 7ug/L reported here), but in the hypolimnion were 69ug/L (half of the 140ug/L reported here). Surface water chlorophyll *a*, a measure of overall algal production, is shown to have stayed constant (2.37ug/L measured today compared to 2.40 compared in 1981/1982), however, this may be because the increased production observed in the sediment record is occurring at the thermocline below where sampling has been done.

Recommendations for future work and ways to protect Gilmour Bay

This research indicates that Gilmour Bay has changed significantly and several times in the last 175 years. These changes are tied to land use changes and climate variability, although other factors may also contribute. The most recent changes are strongly linked to warming temperatures. The research indicates several next steps:

1. Determine whether the changes identified in Gilmour Bay, which is relatively protected from winds and mixing compared to the rest of the lake, are representative of other parts of the lake. We already have two other cores from South Bay. Similar analyses could be done on these cores to determine whether the changes reported here are spatially consistent.
2. Collect and analyze a longer record in order to determine pre-disturbance conditions. This would provide a baseline to compare the changes that have occurred over the last 175 years to determine

how far out of natural variability the lake now is and provide a target for conservation efforts.

3. Conduct modern day sampling of algal communities in Chandos Lake to determine changes since the sampling in the early 1980s and whether there is a deep chlorophyll maximum. Such analysis would also provide additional ecological information about the *Cyclotella* species observed in the upper part of the sediment record. For example, does this species live in surface waters or at the thermocline.
4. A number of additional paleolimnological analyses would provide more information about the observed changes at Chandos Lake including:
 - a. Cyanobacteria (blue green algae) akinetes preserved in the sedimentary record could be used to track changes in the abundance of blue green algae over time to determine whether they are increasing in Chandos Lake.
 - b. Sub-fossil chironomids preserved in the sediment record could be used to track changes in oxygen levels over time to determine how much oxygen levels have changed. This would also help to better constrain our understanding of changes in thermal stratification.
5. Collect sediment cores from the littoral zone to determine changes that have occurred in shallow water habitats in response to warming temperatures and invasive plant species (e.g., *Myriophyllum spicatum* (Eurasian watermilfoil)). Comparison of these records to deep water records can also provide information on the role of aquatic plants with regard to nutrient loads to the open water zone of the lake.

To protect Chandos Lake from increased algal production and the possibility of algal blooms three approaches should be followed:

- 1) Do everything you can to encourage your government to reduce carbon emissions. Reducing carbon emissions will reduce greenhouse gases in the atmosphere and help to curb global warming. Warming temperatures are changing lake ecosystems and water quality across Ontario and globally (Rühland et al., 2015), and Chandos Lake is no exception.
- 2) Do everything you can to reduce nutrient inputs into Chandos Lake.
 - a. Update old septic systems.
 - b. Keep new development well back from the lake and any inflows to the lake. The MNR and MOE recommends a setback of at least 30m, but the literature shows that this value is a minimum to protect the physical, chemical and biological integrity (Sweeney and Newbold, 2014). Other research suggests that buffers may need to be as much as 130m depending on the vegetation and soil type (Cao et al., 2018).
 - c. Ensure healthy natural terrestrial vegetation in the 30m setback. Healthy aquatic vegetation also helps reduce nutrients to the open water.
- 3) Set up an active monitoring system. Tracking your changing lake is critical to knowing when the lake is going outside of natural conditions.

CONCLUSION

Our results indicate that Gilmour Bay water quality has been affected by the interaction of multiple land use changes over the last 175 years. Although we have not done similar analyses in the rest of Chandos Lake, based on research by Hollingshead (2017), we would expect similar changes at other sites on Chandos Lake. Adding to the complexity of the response of Gilmour Bay to anthropogenic stressors has been climate variation, particularly recent and rapid warming. Four periods of change were identified in the diatom record that coincided with changes in land use and climate and indicated marked changes in water quality at Gilmour Bay. Warming temperatures are playing an important role in the present water quality, and point to the need for ongoing monitoring of Chandos Lake.

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