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## The Effects of Warming Temperatures, Fire, and Landscape Change on Lake Production in Mountain Lakes, Alberta, Canada

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Graduate Program in Geography  
A thesis submitted in partial fulfillment of the requirements for the degree in Master of Science  
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THE EFFECTS OF WARMING TEMPERATURES, FIRE, AND LANDSCAPE CHANGE ON  
LAKE PRODUCTION IN MOUNTAIN LAKES, ALBERTA, CANADA

(Thesis Format: Monograph)

by

Amber Elizabeth Gall

Graduate Program in Geography (Environment and Sustainability)

A thesis submitted in partial fulfillment  
of the requirements for the degree of  
Masters of Science

The School of Graduate and Postdoctoral Studies  
The University of Western Ontario  
London, Ontario, Canada

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## Abstract

Many factors could be causing the widespread eutrophication being observed globally, including natural and human factors. In the mountainous regions of Alberta, Canada, warming temperatures, increased fire occurrence, and greater landscape disturbance could increase lake production. To determine the effects of these factors, proxies of lake production preserved in lake sediment records that span the last 1000 years were measured. These records are from two lakes that have not been affected by direct nutrient inputs from human activities; one in Jasper National Park and one from the Hinton area (Alberta). The results highlight that there is little effect of fire or landscape change on lake production, with the exception of the large and widespread fire that occurred in 1889 at Little Trefoil Lake #3. This fire caused a decrease in lake production, possibly due to increased turbidity and reduced light availability. There was a rapid increase in lake production in Little Trefoil Lake #3 and in diatom and chrysophyte production in ZS1 Lake after 1950/1960. These increases may be related to warming temperatures, but this hypothesis is not supported by the absence of change in lake production to earlier periods of warming. My research contributes to our knowledge of the effects of warming temperatures, fire and landscape changes on small lakes in Alberta, Canada, which should help inform management decisions for protecting these sites.

## Keywords

Alberta, diatoms, eutrophication, fire, landscape change, limnology, logging, paleolimnology, sedimentary chlorophyll *a*, and temperature.

## Dedication

*For my parents,  
Joseph and Anne,  
And my friends and those dear to me,  
Without whom none of my success would be possible.*

## Acknowledgments

I would like to express my gratitude to my supervisor, Dr. Katrina Moser, for her support, guidance, and ongoing patience and encouragement throughout my coursework and thesis writing. I also appreciate the opportunity on being a graduate in the Department of Geography, a member of the Lake and Reservoir System (LARS) Research Facility, a.k.a., a LARSian, and the many opportunities to attend conferences in Tampa, Florida, Chicago, Illinois, and Edmonton, Alberta, lab work in Kingston and Calgary, and field work in Jasper and Hinton, Alberta.

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lunch dates a week, you are my best friend, and you will forever be the person I go to throughout life for advice. To my sister Jennie, the forever goofball, you are my partner in crime and have made sure that I take time for myself. I will forever appreciate the extra care you have given me the past few years. When I stayed up too late you forced me to go to bed and start fresh another day. You would always make sure I did something fun on my days off, like go thrift store shopping, drop by the London comic book stores, or have YouTube surfing nights, which has become a tradition. One day we will be on The Amazing Race Canada together, fighting a whole new group of challenges. Whatever we face in life, you and I can conquer them all together.

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# Chapter 1

## 1 Introduction

Eutrophication, defined as nutrient enrichment and its associated symptoms, continues to be ranked as the most common water-quality problem in the world (Schindler, 2006). Symptoms of eutrophication include of algal blooms, which can lead to decreased biodiversity within lakes, taste and odour deterioration of lake water, anoxic deep waters, and fish kills (Carpenter, 2005; Smith & Schindler, 2009; Thienpont et al., 2008). Cultural eutrophication, the addition of nutrients from human sources, has accelerated the rate at which nutrients are entering lakes leading to increased lake production (Smol, 2008). Cultural nutrient sources include agricultural runoff, sewage and industrial discharge, and human-caused changes to landscapes (Smol, 2008). Cultural eutrophication, and its consequences, are expected to increase in the upcoming decades due to increases in population, urbanization run-off, landscape changes, and fertilizer use (Carpenter, 2005; Schindler & Vallentyne, 2008; Smith & Schindler, 2009).

Eutrophication can be measured using estimates of primary production. Primary production refers to the creation of organic matter from CO<sub>2</sub> through photosynthesis (Michelutti et al., 2005), and is largely dependent on the addition of nutrients to lakes, but also the timing and frequency of those additions (Fraterrigo & Downing, 2008). Hereafter, I will use the term “lake production” to mean all primary production occurring in lakes, whether it is by algae or macrophytes. The more algal and plant biomass in a lake the more lake production there is. An increase in limiting nutrients typically results in an increase in lake production, and can ultimately lead to eutrophication.

The “Law of the Minimum” states that the amount that any organism can grow is determined by scarcest resource required for growth (Schindler, 1977). Phosphorus and nitrogen have typically been needed for growth and lake production in aquatic ecosystems and are considered to be “limiting factors” (Schindler, 1977). Since the 1970s, phosphorus has generally been considered to be the limiting nutrient in freshwater systems (Schindler, 1977), but this has recently been challenged, and it has been suggested that in some cases nitrogen can be limiting (Marcarelli & Wurtsbaugh, 2007). Depending on changes of the environmental conditions near a



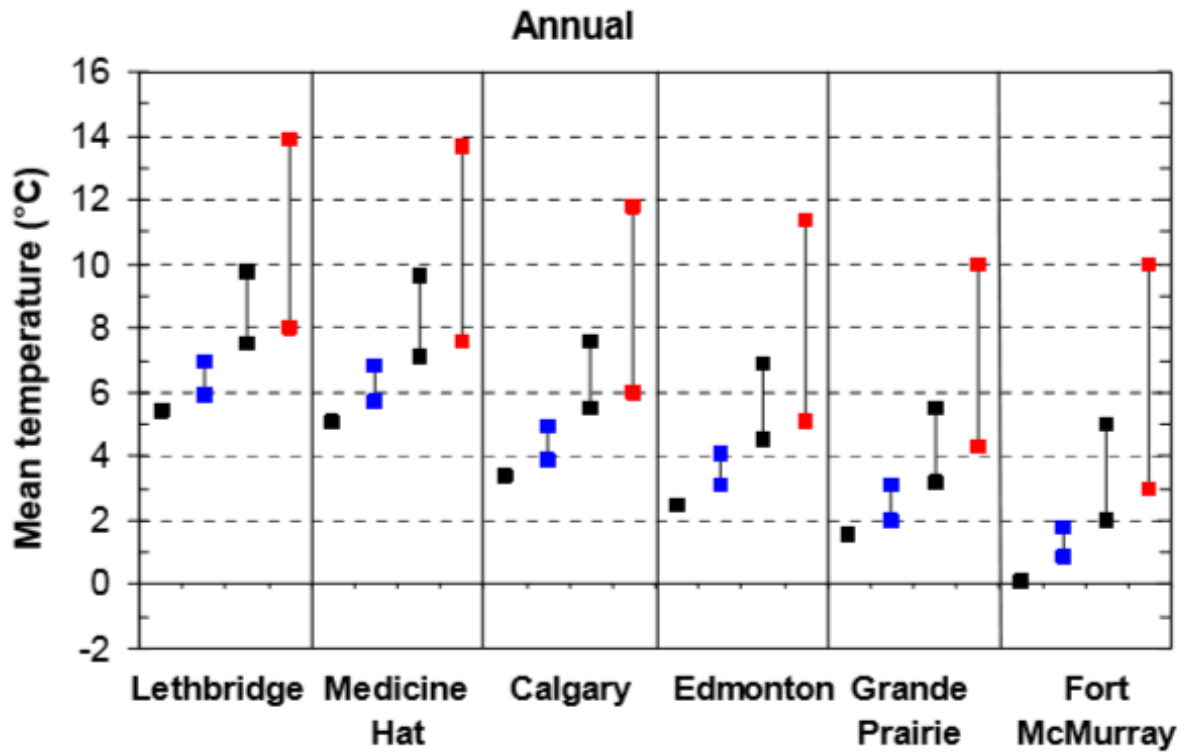
lake, for example, temperature, light, and nutrient concentrations, and the limiting nutrient(s) in the lake, can cause an increase in lake production (Marcarelli & Wurtsbaugh, 2007).

Eutrophication is often the result of direct inputs of nutrients from human activities, for example, land clearance, but also happens as a result of natural processes, for example, wild fire (Wright, 1976). There could lead to increased delivery of nutrients from the catchment to the aquatic system (McColl & Grigal, 1975), although several studies indicate small changes in lake production as a result of changes in nutrient delivery from fire or natural landscape change (Laird, Cumming, & Nordin, 2001; McColl & Grigal, 1977). To test the effect of temperature, fire, and land clearance on lakes, research needs to be done where direct inputs of nutrients are not occurring. These factors potentially play an important role in nutrient delivery to aquatic ecosystems (Carpenter et al., 1998). For many lakes of the Jasper National Park region, there are no direct nutrient inputs and atmospheric deposition is likely low, but climate warming, fire and landscape change are important.

Lake production could also be affected by temperature. The Intergovernmental Panel on Climate Change has observed that over the last 50 years, the global average surface air temperature has increased by about 0.6°C and is projected to increase between 1.4°C and 5.8°C by 2100 (IPCC, 2001.a). Warming temperatures can lead to increased algal production due to a change in the timing of food or nutrient availability or a physiological response to warming temperatures (Reid et al., 1998; Weyhenmeyer, Blenckner, and Pettersson, 1999; Winder & Schindler, 2004).

Based on the different constructed scenarios of climate change, Alberta's annual mean temperature is expected to increase between 3°C and 5°C by 2050 (based on the CCSRNIES AIF1 scenario, which tends to be warmer than the other four scenarios) (Barrow & Yu, 2005). Figure 1 represents the calculated annual mean temperature from the results of the five scenarios. Of the six selected sites in Alberta, Jasper and Hinton are located between Edmonton and Grand Prairie and are following Alberta's overall annual mean temperature projected increase by 2050 (black high-low bars). They are expecting an increase between 4.5°C and 11.5°C by 2080. Combined with warmer temperatures and decreases in precipitation during the warmest months of the year, models for the boreal forest predict that frequency and intensity of forest fire will

increase with climate warming (Schlesinger & Mitchell, 1987).



**Figure 1: Annual mean temperatures (°C) for six different sites in Alberta. The baseline conditions from 1961-1990 (black square), and the scenario ranges: 2020s (blue high-low lines), 2050s (black high-low lines), and the 2080s (red high-low lines) in CE (Barrow & Yu, 2005).**

Although there are clear connections between climate and fire, wildfire occurrence and severity has been greatly affected by human fire policy (Marcoux et al., 2015). After a widespread and intense fire occurred in the Jasper National Park region in 1889 CE, and a series of other smaller but still large fires (Tande, 1979), Jasper National Park hired their first wardens to extinguish wildfires in 1909 (Parks Canada, 2012). In 1913 the Park introduced a fire suppression policy to decrease the intensity and frequency of fire events (Parks Canada, 2012; Tande, 1979). As a result of reduced fires, diversity of the vegetation decreased and became dominated by Lodgepole pine (Amoroso et al., 2011). Forests in Jasper National Park and much of Alberta and British Columbia, have become over-mature, dense, more susceptible to insects and disease, and allowed these forests to become prone to high risk, large wildfires (Amoroso et

al., 2011; Parks Canada, 2012; Parks Canada, 2015). In the late 1980s a prescribed fire program began to try and restore grassland (MacLaren, 2007; Taylor, 2009). The most recent prescribed fires were completed in the spring of 2015. These fires were made to encourage Whitebark Pine growth, to restore Athabasca Valley grasslands, provide higher quality wildlife habitat, to create a barrier against the mountain pine beetle, and to create a strategic firebreak against wildfire spread (Parks, 2015).

Landscape change is also an important factor in Alberta as a result of logging, resulting in possible nutrient loading into lakes. Natural Resources Canada states 87,578 hectares were harvested in Alberta in 2013, equating to a total area of 22,825,000m<sup>3</sup> (Government of Canada, 2015). The Hinton, Alberta region is home to many mining, forestry, and pulp mill companies and facilities, with logging beginning in 1956 (MacLaren, 2007).

The main objective of this research is to determine how climate warming, landscape change, and fire have affected lake production in two Alberta lakes located in the Jasper National Park region. This research addresses two key questions:

**Research Question 1:** What is the relationship between lake production and temperature, known landscape changes (logging), and fire that have occurred in the last 150 to 300 years in two lakes from the Jasper National Park region?

**Research Question 2:** Do the relationships observed in these lakes over the last 150 years persist over the last 1000 years, prior to the period of increased human activity of logging?

To address these questions, paleolimnological techniques that provide a historical perspective will be used. Lake sediments are laid down at the bottom of lakes year after year, often forming a continuous record. Paleolimnology uses the chemical, physical, and biological information preserved in lake sediments to determine past environmental conditions of aquatic systems (Smol, 2008). By dating the lake sediments we can provide a long-term (100s to 1000s of years) record of environmental change. Analyses of short sediment cores (~40cm) that span the last ~300 years will be used to document changes in lake production in two lakes, Little

Trefoil Lake #3 and ZS1 Lake, in the Jasper National Park region. To address the first research question, these records will be compared to Jasper climate station instrumental and dendroclimatological records (Government of Canada, 2012; Luckman & Wilson, 2005), reconstructed fire events (Davis, 2015; Stretch et al., 2015) and known landscape changes to determine links between lake production and these factors. Lake production will be determined using three variables, percentage organics, chlorophyll *a*, which provides a measure of overall lake production in lakes, and biogenic silica, which provides an estimate of production by siliceous algae (i.e., chrysophytes and diatoms). Chrysophytes are photosynthesizing golden algae and diatoms are microscopic unicellular photosynthesizing algae that have siliceous cell walls. Changes in diatom community composition over the past ~300 years will also be used to better understand the specific limnological changes driving the change. Each diatom prefers to live in specific environmental conditions, for example, salinity levels or certain amounts of phosphorus amounts, and therefore a shift in their community composition can help determine the environmental conditions of a lake before and after a shift. To address the second question, the same approach will be used for a longer record from Little Trefoil Lake #3. A sufficiently long core was not available from ZS1 Lake to address the second research question at this lake.

This research will provide knowledge about the factors affecting lake production in Jasper National Park, both before and after European colonization in the early 1800s, and provide information to better inform water managers about the effects of warming temperatures, changing landscapes and fire on lakes. Eighty percent of Alberta's water is located in the northern part of the province, while 80% of the demand is in the south (Government of Alberta, 2010), making all resources in Alberta an asset, including water in the Jasper National Park region. Jasper National Park is a protected wilderness area, and many animals and plants that are disappearing from areas across North America are protected within the park, making protection of water resources and their ecosystems necessary (Parks Canada, 2013).

## 1.1 Literature Review

### 1.1.1 Measures of Lake Production: Percentage Organics, Chlorophyll *a*, Biogenic Silica, and Diatoms

Percentage organics, chlorophyll *a*, and biogenic silica can be used to determine the amounts of lake production and algal growth in lakes. Diatom species and shifts in diatom community compositions can help understand limnological changes. Organic matter in lakes originates from both terrestrial and lake organic matter. Therefore, the percentage of organics in lake sediments can indicate either changes in catchment inputs or lake production (Meyers & Ishiwatari, 1993; Smol, 2008). For example, an increase in lake production could result in an increase in the percentage of organics in lake sediments. An increase in forest cover, however, could also result in an increase in the percentage organics because it would decrease erosion and inputs of inorganics. Therefore, without using other proxies it is difficult to interpret percentage organics, although it is not uncommon to do this (i.e., Munroe, 2007). Typically, the percentage of organic matter can be determined using the loss on ignition method, weighing the sample before and after ignition at 550°C and determining the percent of the weight lost (Dean, 1974; Heiri, Lotter, & Lemcke, 2001).

The percentage of organic matter has been used to determine the effects of logging and fire in other studies. In a study off the coast of Vancouver Island, British Columbia, only one lake out of four showed a gradual decrease in organic matter after logging and an increase once logging ended (Laird et al., 2001). Laird and Cumming (2001) found differing results in the interior of British Columbia. Only one of their six lakes was impacted by logging and had a significant increase in percentage organics, following logging. Using percentage organics with other proxies improves interpretation. For example, knowing the carbon:nitrogen in Otisco Lake, New York, as well as the percentage organics, showed there was a shift from terrestrial organics to lacustrine algae organics after the forests surrounding were clear cut during the 1800s (Bookman et al., 2010).

Another useful proxy for studying lake production is lake water chlorophyll *a*. Chlorophyll *a* is a blue-green pigment found in photosynthesizing organisms, including aquatic plants and algae. Algae are phytoplankton (microscopic plants) that are usually photosynthetic

and aquatic, and have simple reproductive structures without stems, leaves, roots, or vascular tissue (Smol, 2008). Chlorophyll *a* concentrations in lake water are often used as a measure of algal production (Gitelson, 1992). Previous studies have suggested links between lake water chlorophyll *a* and climate, landscape change, and fire. In Wisconsin lakes, low nutrients and chlorophyll *a* were linked to internal lake controls of nutrients related to climate conditions (Baines et al., 2000). The effects of fire and logging on lake production reported were small and short-term. Planas et al. (2000) found chlorophyll *a* in waters of lakes situated in both logged and burnt catchments in the Canadian Shield had more chlorophyll *a* and biomass than in lakes in burned catchments. The increased chlorophyll *a*, however, only persisted for two years after the fire. Other research showed that although nutrients, specifically phosphorus, increased following fires, chlorophyll *a* did not (McEachern et al., 2000). It was suggested that this was because the addition of nutrients were countered by a decrease in light availability.

Chlorophyll *a* also occurs as a fossil pigment that is one portion of the total organic matter in lake sediments, and can be used to track changes in lake production over time (Wolfe et al., 2006). When aquatic plants and algae die, the pigment is contained in the sediment and can be used to measure algal and macrophyte production (Wolfe et al., 2006). This technique can be used to reconstruct lake production in a lake by determining the peak absorbance of chlorophyll *a*, a wavelength range that lies between 650-700nm, from sediments (Michelutti et al., 2010; Wolfe et al., 2006). Michelutti et al. (2010) showed that chlorophyll *a* tracked changes in lake production and can be used to reconstruct past lake production, especially when coupled with other proxy data.

We can also consider lake production changes based on a single algal group, siliceous algae. Diatom and chrysophyte cysts use dissolved silica for their cell structures, so biogenic silica can be used as an indicator of the amount of siliceous microfossil abundance in sediment (Conley, 1988; Krausse, Schelske, & Davis, 1983). The amount of biogenic silica in the sediment is determined using the wet alkaline digestion method (Conley, Schelske, & Stoermer, 1993; DeMaster, 1981).

Diatom and chrysophyte production has been used previously to test relationships between production and warming temperatures, or fire. Moser et al. (2002) used biogenic silica as one of the paleolimnological proxies to show that while total production in a boreal lake increased, the

overall biogenic silica decreased. They suggested that the biogenic silica showed a general decrease from 1830 to 1993 due to an increase in nutrients, as a result of warming temperatures, causing blue-green and green algae to out-compete diatoms and chrysophytes when silica became limited. They also reported no or little change in biogenic silica and other proxies in response to fire events.

Diatoms are the most common type of algae in freshwater systems and because they are often well preserved in lake sediments, are sensitive to environmental change, are taxonomically unique, and found in large numbers, and therefore, provide a useful tool for studying environmental change (Moser et al., 1996; Smol, 2008; Thienpont et al., 2008). Diatoms cells are made of two valves that fit together similarly to a petri dish that are held together by a siliceous band (Round, Crawford, & Mann, 1990). Their size, shape, and ornamentation of the cell walls allow them to be identified to the species or subspecies level, and once identified, can help determine the current and past environmental conditions (reviewed in Moser, 2013).

Diatom species assemblage composition is often controlled by the amount of nutrients in a lake. Bradbury (1988) collected diatoms from sediment traps in Elk Lake, Minnesota during two different years, one that had a colder, wet season, with a long ice cover season, and another during a warmer, dry season, with a shorter ice-cover season. The colder season resulted in reduced nutrient availability, whereas the warmer season resulted in diatoms that represented high phosphorus amounts in Elk Lake. This same study also inferred dry or wet seasons from diatoms that preferred certain nutrient amounts; dry conditions were inferred when diatoms were present that preferred high phosphorus amounts and wet conditions were inferred when diatoms were present that preferred low phosphorus amounts. Other lakes throughout Minnesota found similar diatoms that generally indicate the same climate related connections (Bradbury, 1988). Other studies used diatoms indicative of high nutrient levels to determine how increased erosion rates increased nutrient availability after fires in Baptists Lake, Alberta (Hickman, Schweger, and Klarer, 1990).

### 1.1.2 Potential Links between Warming Temperatures and Lake Production

Research has linked warming temperatures and lake production (Weyhenmeyer et al., 1999; Weyhenmeyer, 2001; Winder & Schindler, 2004). Warming temperatures can reduce ice cover, creating a longer growing season that results in changes in diatom community composition and algal production (Weyhenmeyer, 2001). Growth of phytoplankton during the spring after ice cover is controlled by temperature, turbulence, and thermal stratification (Winder & Schindler, 2004). When lakes have less ice cover, spring seasons favour fast growing diatoms that require nutrients, but not necessarily having light and temperature requirements (Reynolds, 1984). The timing of peak lake production is also affected. Earlier spring seasons can cause phytoplankton blooms to peak, approximately 30 days earlier than 45 years ago (Weyhenmeyer et al., 1999; Weyhenmeyer, 2001). Winder & Schindler (2004) found that the spring water temperatures of Lake Washington have increased since 1962 Common Era (CE). The spring phytoplankton bloom aligned with the earlier spring stratification and warmer temperatures, beginning 20-27 days earlier over the period of 1962-2002.

Research has also linked warming temperatures and algal growth (Douglas, Smol, & Blake, 1994; Lam & Schertzer, 1999; Thienpont et al., 2008). Douglas et al. (1994) found that diatom community composition had changed in Arctic lakes and ponds beginning in the 1800s, but more dramatically after the late 1900s. They showed that with warmer temperatures diatom species diversity increased as the growing season lengthened allowing for greater habitat diversity (Douglas et al., 1994). Similarly, Thienpont et al. (2008) found that the diatom community composition and blue-green algae amounts changed because of reduced ice cover due to increasing temperature trends over the past ~100 years in Lake George, Nova Scotia. Here they suggested that warmer waters may have caused the blue-green algae to be more competitive since they are able to grow faster in warmer waters (Theinpont et al., 2008). Lam and Schertzer (1999) completed research on the Great Lakes and they found that increased temperatures, combined with decreased ice cover, decreases the albedo during the winter and early spring months and increases the amount of solar radiation absorbed by a lake. In 1983, Lake Erie received large heat fluxes in the summer and had higher surface temperatures, contributing to anoxic conditions in the central basin and reduced the water quality (Lam & Schertzer, 1999). Anoxic conditions occur when the organic matter in eutrophic lakes settles to the sediment-water



interface and consumes oxygen (Miller et al., 2012). A study completed by Schindler et al. (2008) on Lac la Biche, Alberta was done to determine what was causing the deterioration of the water quality showed that Lac la Biche was being impacted by nutrients being added to the lake from cottage development, road building, human sewage, and animal manure. However, they suggest that climate warming has the potential to increase the impacts of such cultural eutrophication.

### 1.1.3 Potential Links between Landscape Change, Fire Events, and Lake Production

Early research suggested that fire events and land clearance would increase nutrient inputs to aquatic systems from lakes, potentially increasing lake production (Keenan & Kimmins, 1993; Marks & Bormann, 1972). However, nutrients that become available after forest fires may not reach the lake depending on the soil type, slope, and vegetation surrounding a lake (McColl & Grigal, 1975; McColl & Grigal, 1977; Wright, 1976). McColl and Grigal (1975) found that while runoff increased after a fire in Minnesota due to less forest cover, the amount of phosphorus only increased for one year following the fire and then decreased because much of the phosphorus was taken up by soils and new vegetation surrounding the lake. Wright (1976) studied the phosphorus budget of the same lake, and also found that while fire produced higher concentrations of phosphorus in runoff, this was not found within the lake. McColl and Grigal (1977) studied both unburnt and burnt lake catchments in Minnesota. Again, they found little impact by the fire in aquatic systems and suggested that vegetation growth after the fire could potentially use the nutrients before they reached the lake.

Fires loosens the soil structure and rocks by destroying the plant root structure, increasing water permeability, runoff, and erosion rates (Beaty, 1994). Laird and Cumming (2001) studied lakes whose catchments were impacted by both logged and burnt lakes in British Columbia. Both logged and burnt lakes had higher levels of phosphorus than the reference lakes, but only the burnt lakes had higher amounts of chlorophyll *a*. They also suggested that lakes impacted by fires would have a decrease in sedimentary organics for a short period after the fire due to periods of increased erosion of inorganic matter.

Paterson et al. (1998) looked at whether or not lakes in northwestern Ontario were impacted by forest fires and logging, expecting them to increase catchment erosion, adding more nutrients into lake systems, and changing the chrysophyte cyst composition. The study found very few changes in lakes affected by forest fires or logging, despite over 90% of the forests in the lake catchments were removed (Paterson et al., 1998). The changes that were found were suggested to be related to climate warming and reduced precipitation.

## Chapter 2

### 2 Study Area

#### 2.1 Lake and Watershed Properties

Two lakes with differing types and levels of landscape disturbance within their catchments were selected from Jasper National Park and the Hinton area to determine the impacts of natural causes (fire) and anthropogenic activities (land clearance) on lake production. Smaller lakes with a simple bathymetry were selected to ensure even sedimentation across the basin and complete sediment records. The lakes both had relatively small catchments, although Little Trefoil was smaller than ZS1, so both of these lakes are likely more sensitive to internal lake changes compared to catchment changes (Schindler, 1971) (Table 1). This means that even if these lakes show no response to catchment changes lakes with relatively large catchments may still respond to fire or logging. The location of Little Trefoil Lake #3 (52° 53' 32" North, 118° 3' 33" West) within Jasper National Park means it is protected from direct human activity (Figure 2) and was selected to isolate the effects of fire and warming temperatures on lake production. ZS1 Lake (53° 52' 49" North, 117° 25' 48" West) is approximately 50km north of Hinton, Alberta and 130km east of Little Trefoil Lake #3 (Figure 2). ZS1 Lake was selected to compare to Little Trefoil Lake #3 as it is also affected by fire and shares a similar climate. It is also presently being impacted by human activity, dramatically altering the landscape as a result of logging in the catchment.

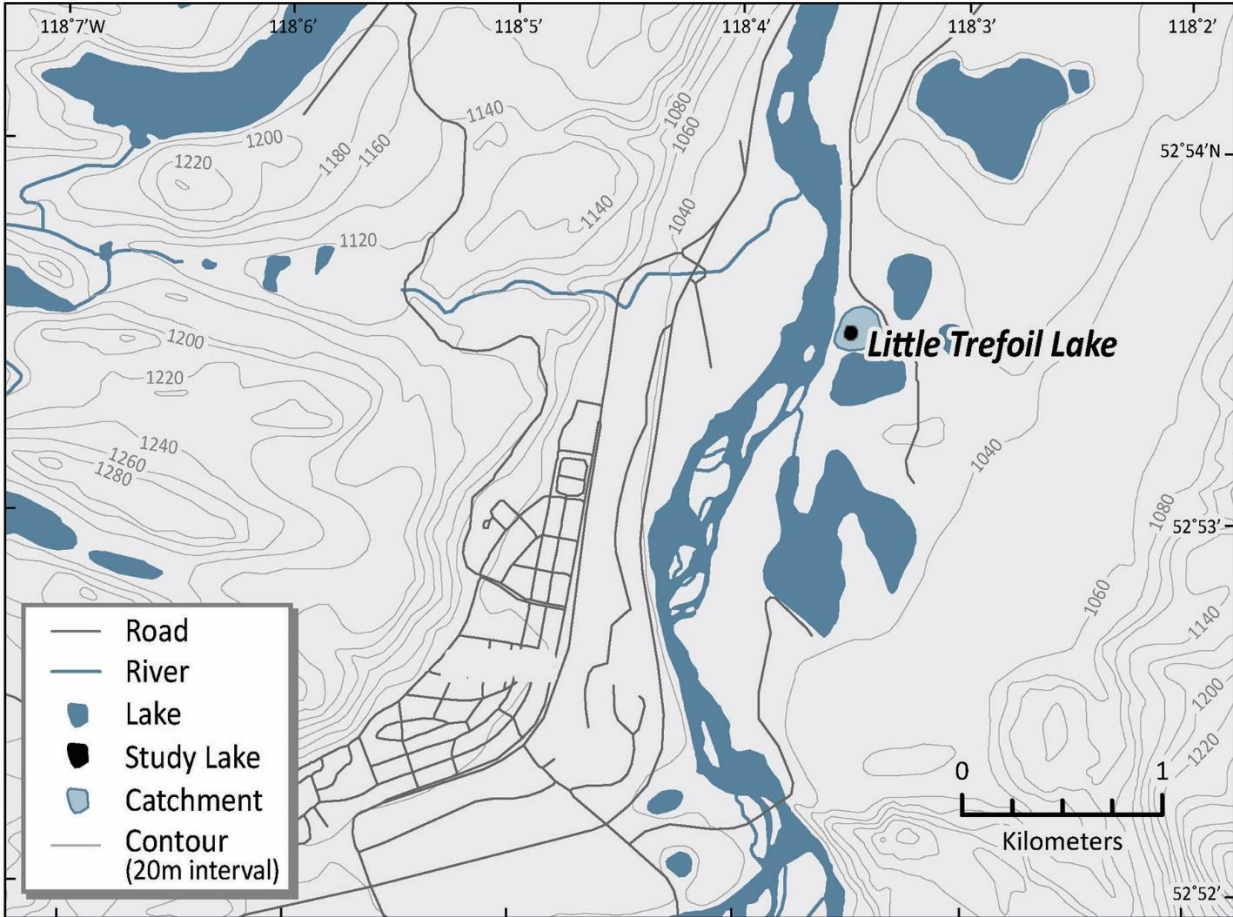
**Table 1: Water chemistry, and lake and watershed properties of Little Trefoil Lake #3 and ZS1 Lake were collected in the summer of 2014. (Unpublished data from the Lake and Reservoir Research Facility).**

	<b>Little Trefoil Lake #3</b>	<b>ZS1 Lake</b>
Latitude	52° 53' 32" North	53° 52' 49" North
Longitude	118° 3' 33" West	117° 25' 48" West
Lake Area (km <sup>2</sup> )	0.004	0.013
Catchment/Lake Area Ratio	9.75	261
Catchment Area (km <sup>2</sup> )	0.039	3.4
Maximum Depth (m)	5.2	4.5
Altitude (m above sea level)	1026	1068
pH	8.6	7.9
Secchi Depth (m)	3.6m	3.7
Surface Temperature (°C)	22.0	15.3
Mean Annual Temperature (°C)	-0.4	1.7
Mean Annual Precipitation (mm)	798	603
Observed Lakewater Colour	Green	Dark brown
Shape	Round	Round
Ammonia (NH <sub>3</sub> ) (µg/L)	<5	17
Chlorophyll <i>a</i> (µg/L)	1.5	1.2
Dissolved Inorganic Carbon (mg/L)	25.1	25.5
Dissolved Organic Carbon (mg/L)	9.3	13.2
Dissolved Silica (SiO <sub>2</sub> ) (mg/L)	5.54	7.9
Nitrate (mg/L)	0.010	0.011
Soluble Reactive Phosphate-Phosphorus (µg/L)	0.2	0.2
Total Nitrogen (µg/L)	717	584
Total Phosphorus (µg/L)	4.8	8.6



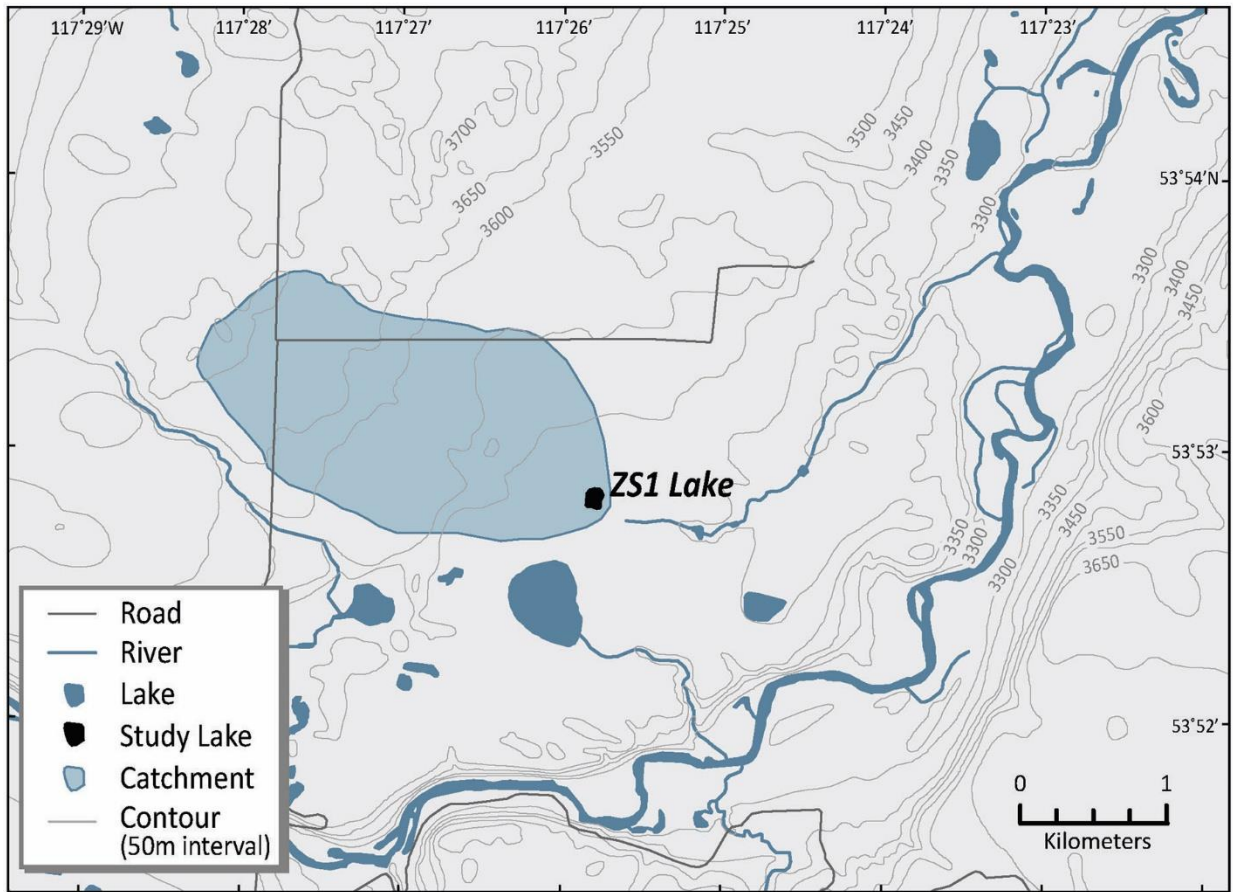
**Figure 2: Map showing locations of study area sites, Little Trefoil #3 and ZS1 Lake, in Alberta, Canada.**

Little Trefoil Lake #3 and ZS1 Lake are both shallow lakes (maximum depth of 5.2m and 4.5m, respectively) without surficial inflows or outflows. Little Trefoil Lake #3 is situated at an elevation of 1026m just east of the Athabasca River, which is about 1m below the lake. The lake and river are separated by a bank that is ~2m. The colour of the lake is an emerald green (Figure 3). ZS1 Lake has an elevation of 1068m above sea level. The colour of the lake is dark brown and the lake is surrounded by a 20-30m wide floating bog (Figure 4). The remaining lake and watershed properties are summarized in Table 1.



**Figure 3: Image, site location, and selected limnological properties of Little Trefoil Lake #3, Jasper, Alberta.**





**Figure 4: Image, site location, and selected limnological properties of ZS1 Lake, Hinton, Alberta.**

## 2.2 Geology

The catchment of Little Trefoil Lake #3 is found in the Front Ranges, in the middle of the Canadian Rocky Mountains. The Front Ranges are to the east of the main range and are characterized by Paleozoic era (544-250 million years ago) pale grey limestone in the Front Ranges (Parks Canada, 2013). The underlying geology of these ranges include sandstone, limestone, shale, and quartzite (Alberta Geology Survey, 2012; Parks Canada, 2013).

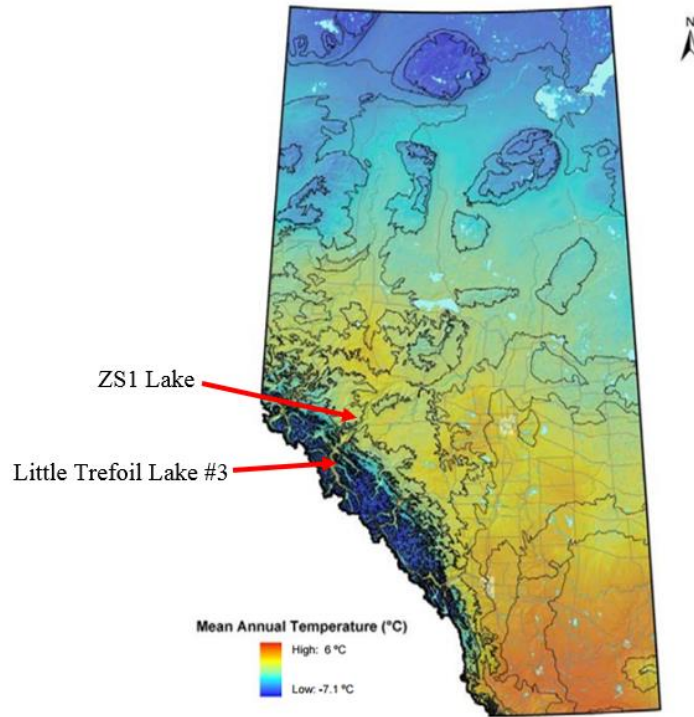
ZS1 Lake's catchment is located in the Alberta foothills. The underlying geology of the area is sandstone and mudstone, covered with glacial till (Alberta Geology Survey, 2012).

## 2.3 Climate

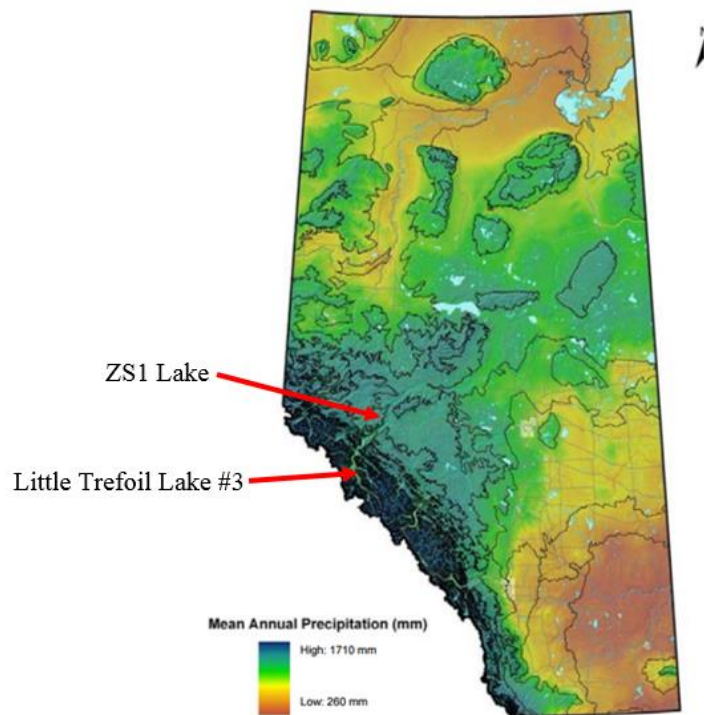
Little Trefoil Lake #3 and ZS1 Lake are located in a continental climate, with long, cold winters and short, warm summers, influenced by elevation and proximity to the Rocky Mountains. The warmest month is July with an average temperature around 22°C and the coolest month is in January with an average temperature around -9°C (Parks Canada, 2015). Winds from the Pacific Ocean influence much of the weather, bringing colder winds and moisture from the west, allowing for a high amount of precipitation in the summer and winter months. The Athabasca Valley also receives colder and drier Arctic winds from the northeast (Parks Canada, 2013).

For the catchment of Little Trefoil Lake #3, the mean annual temperature is -0.4°C and the mean annual precipitation is 798mm (Figure 5 and Figure 6) (Government of Alberta, 2006). For the catchment of ZS1 Lake, the mean annual temperature is 1.7°C and the mean annual precipitation amount is 603mm (Figure 5 and Figure 6) (Government of Alberta, 2006).





**Figure 5: Mean annual temperature across Alberta (°C) (Government of Alberta, 2006).**



**Figure 6: Mean annual precipitation across Alberta (mm) (Government of Alberta, 2006).**

## 2.4 Vegetation and Fire History

Prior to the creation of Jasper National Park in 1907 CE (Taylor, 2009), the vegetation in the Athabasca Valley and surrounding area was open grasslands due to the occurrence of forest fire. The trees in the valley and surrounding mountain sides were diverse, including *Picea glauca* (White spruce), *Picea mariana* (Black spruce), *Pseudotsuga menziesii* var. *glauca* (Rocky Mountain Douglas fir), *Populus tremuloides* (Trembling aspen), and *Pinus contorta* (Lodgepole pine). Little Trefoil Lake #3's catchment experienced a major fire in 1889 CE (Tande, 1979). A ~300 year tree-ring based fire study in Jasper National Park (1665-1971 CE) described the 1889 CE fire event as a major fire (burned more than 500 hectares) and was the largest in the record; 287 scars were found in the Lodgepole pine, and around 338.39km<sup>2</sup> (33,839ha) were burned. The next fire event was five years later in 1894 CE, when only 0.16km<sup>2</sup> burned and one scar was found in the Lodgepole pine. There were also two other major fire events that burnt greater than 100km<sup>2</sup>, one in 1758 and one in 1847, burning 219.42km<sup>2</sup> and 225.45km<sup>2</sup>, respectively (Tande, 1979). The images in Figure 7 represent how the vegetation has changed after fire suppression (1913 CE) was implemented (Luckman & Kavanagh, 2000).

The forests around ZS1 Lake are mostly dominated by Lodgepole Pine and are often similar aged due to forest fires (Government of Alberta, 2006), similar to the catchment of Little Trefoil Lake #3. The largest fires in ZS1 Lake's catchment was in 1808 CE, 1815 CE, and 1917 CE. ZS1 Lake is located in a wetland, surrounded by a floating bog with large amounts of moss, grasses, and sedges. Tamarack and Black Spruce are close to the lake's edge along the north, south, and east sides, with marsh-like conditions on the west edge. Lily pads cover the lakes surface.



**Figure 7: The 1915 CE photo is viewed looking northwest across the Athabasca River, approximately 3km north of Little Trefoil Lake #3. There are patchy grassland areas in the Athabasca Valley and on the low mountain slopes. With no fires since 1915 CE, the 1998 CE image has less open space in the Athabasca Valley and slopes, which is now dominated by Lodgepole Pine coniferous trees. (Luckman & Kavanagh, 2000).**

## Chapter 3

### 3 Research Methods

#### 3.1 Field Methods

##### 3.1.1 Sediment Core Collection and Extrusion

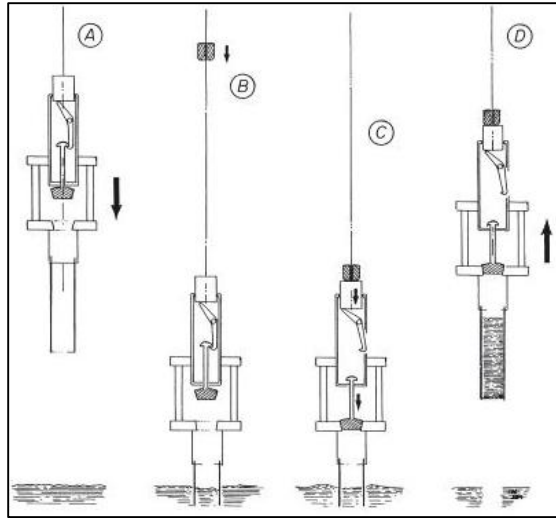
To assess the impacts of natural and anthropogenic landscape change and climate warming on lake production over the last 300 years, as well as determine how this variation compares with a longer 1000 year record, we collected lake sediment cores from two lakes, Little Trefoil Lake #3 and ZSI Lake. In all cases, cores were collected in the middle and deepest area of the lake, which usually is the most representative of the whole lake as sediment accumulates in the middle and is more likely to contain undisturbed sediments (Smol, 2008). A Kajak-Brinkman (KB) gravity corer (Figure 8) (Glew, Smol, & Last, 2001) was used to collect the upper 45cm of sediments from Little Trefoil Lake #3 in 2007 CE. The KB corer was chosen because it can collect up to 60cm of undisturbed sediment and allows for visible inspection of the sediment/water interface, which if undisturbed indicates modern day sediment has been collected (Glew et al., 2001). A second KB gravity corer was used to collect 45 cm of sediment from Little Trefoil Lake #3 in August 2014 CE in order to process diatoms from 2007 to 2014 CE, but also to ensure sufficient sediment for all analyses planned. A Glew vertical extruder (Glew et al., 2001) was used to sub-sample the cores every 0.5cm on site (Figure 9). Sediment was placed in Whirl-Pak<sup>®</sup> bags, stored in a fridge at the Palisades Stewardship Education Centre, shipped to Lake and Reservoir Systems Research (LARS) on ice and then refrigerated at 4°C.

An additional 2.6m of sediment was collected using a modified Livingstone corer (Myrbo & Wright, 2008) in the winter of 2007 CE. A Livingstone corer is able to collect 1m, continuous sections with little disturbance to the sediment (Figure 10) (Glew et al., 2001). The lower sediment cores were packed in plastic wrap and aluminum foil, stored on ice in a cooler, and shipped by plane back to the (LARS) Research Facility at Western University. High resolution photos were taken of the sediment cores collected with the Livingstone corer using the Multi Sensor Core Logger in the LARS lab in order to have an archive of sedimentological changes.

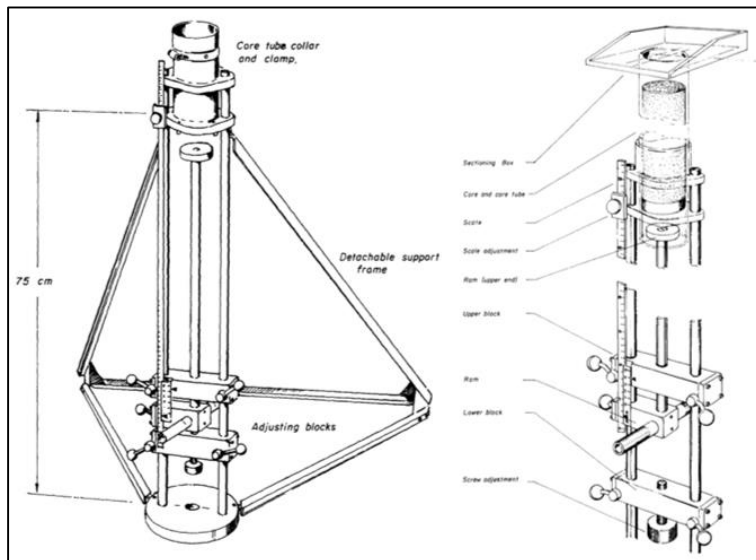
The Livingstone sediment cores were subsampled at LARS at the University of Western Ontario in 2013 CE (at 0.5cm intervals).

The Livingstone core was collected in a way that the top of the core overlapped with the bottom of the gravity core to have a continuous sediment record. Core correlations were made between the gravity and Livingstone cores in Little Trefoil Lake #3. This was done to determine if the changes in production found in the most recent record were related to humans in Jasper, Alberta or if they were present pre-human contact. The correlation allowed for accurate chronologies of the deeper sediments.

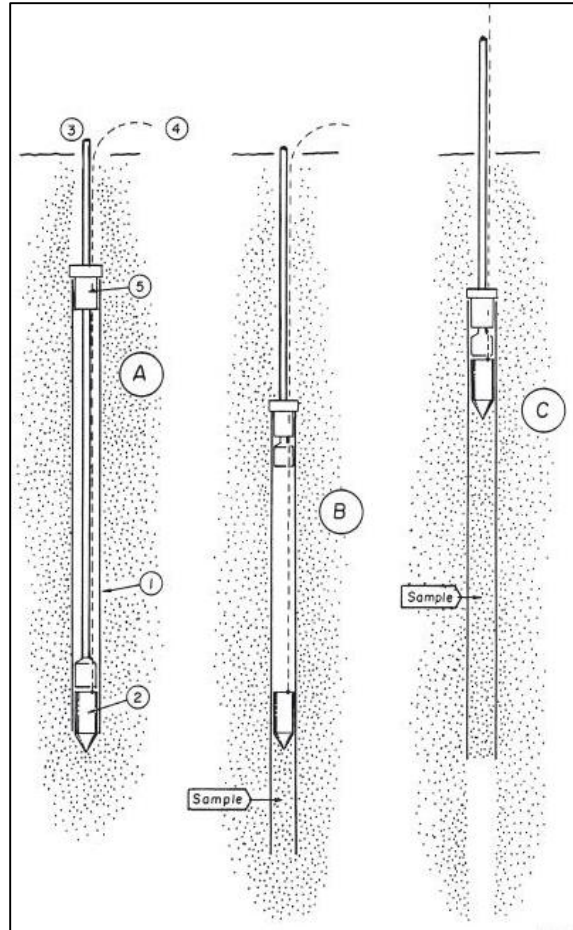
Knowing that the Livingstone core collected from Little Trefoil Lake #3 extended to ~1000 years, a Livingstone corer with a plastic tube attached was also used for ZS1 Lake to collect 1m of sediment to compare to Little Trefoil Lake #3. This core was collected by researchers from the University of Guelph in the summer of 2013 CE. A Glew vertical extruder (Glew et al., 2001) was used to sub-sample the cores every 0.5cm on site (Figure 9) and sediment was placed in Whirl-Pak<sup>®</sup> bags. The sediment bags were stored in a fridge in Alberta, transported in a cooler, and stored in a fridge at 4°C.



**Figure 8: General operation of a messenger-triggered gravity corer. A) Corer lowered through the water column. Water is able to pass through the open core tube during descent. B) Corer enters sediment using its own weight and messenger is released from the surface. C) The messenger strikes the corer and creates a seal. D) Corer is vertically removed to the surface with the sediment sample, and plugged at the bottom. (Glew et al., 2001).**



**Figure 9: Left – General arrangement of the Glew vertical extruder arrangement without Gravity core tube. Right – General arrangement of the Glew vertical extruder during subsampling with extruder tray and sediment core. (Glew, 1988).**



**Figure 10: General operation of a Livingstone-piston corer. A) Lowering, B) Sampling, and C) Removal of core. 1) Core tube, 2) Piston, 3) Drive rods, 4) Piston cable, and 5) Locking drive head. The drive rods are used to push the corer into the sediment and a cable at the surface holds the piston in place (Glew et al., 2001).**

## 3.2 Lab Methods

### 3.2.1 Chronology

Two different dating techniques were used to determine the chronology of Little Trefoil Lake #3,  $^{210}\text{Pb}$  and  $^{14}\text{C}$ .  $^{210}\text{Pb}$  can date sediments from the present to ~150 years.  $^{226}\text{Ra}$  decays in soil to become  $^{222}\text{Rn}$ , which then escapes into the atmosphere and decays to become  $^{210}\text{Pb}$ .  $^{210}\text{Pb}$  eventually makes its way into lake systems and sediments.  $^{210}\text{Pb}$  dating is based on the difference in unsupported and supported  $^{210}\text{Pb}$  in the sediment; the unsupported amount of  $^{210}\text{Pb}$  is produced from outside of the sediment and supported  $^{210}\text{Pb}$  is produced in the sediment. The amount of unsupported  $^{210}\text{Pb}$  will decrease with depth because of radioactive decay. Knowing that  $^{210}\text{Pb}$  has a half-life of 22.26 years and that the decay rate is constant, the age of sediment can be determined by looking at the unsupported  $^{210}\text{Pb}$  at any depth relative to the amount at the surface sediment (De Souza et al., 2012).  $^{210}\text{Pb}$  activity was analyzed in 23 samples from the gravity core using alpha spectroscopy at MyCore Scientific Inc. in Deep River, Ontario (MyCore Scientific Inc., n.d.). Samples were analyzed every 0.5-0.75cm in the top 3cm, 1cm in the top 3-10cm, 1.5cm in the top 10-20cm, and 1.75-2.50 in the top 20-30cm.

Radiocarbon can be used to date sediments from approximately 150 to 50,000 years (Bradley, 1999). Radiocarbon is formed in the atmosphere by shortwave radiation colliding with  $^{14}\text{N}$ , forming  $^{14}\text{C}$  and  $^1\text{H}$ . The production of  $^{14}\text{C}$  in the atmosphere varies depending on cosmic radiation reaching the Earth (Bradley, 1999). During photosynthesis,  $^{14}\text{CO}_2$  is taken up by organic matter. When the organic matter dies the  $^{14}\text{C}$  is incorporated into the sediment. Knowing that the half-life of  $^{14}\text{C}$  is  $5730 \pm 40$  years and it decays back into  $^{14}\text{N}$ , the amount of  $^{14}\text{C}$  can be measured in organic matter to determine the age of the sediment (Bradley, 1999).

For dating purposes, it was initially assumed that the amount of  $^{14}\text{C}$  in the atmosphere is in equilibrium with the amount of  $^{14}\text{C}$  in the  $\text{CO}_2$  reservoirs on Earth and that they have been constant over time. This assumption is now known to be incorrect, so a correction is applied to the  $^{14}\text{C}$  dates to correct the dates for the varying  $^{14}\text{C}$  (Berglund, 1986). Five terrestrial macrofossils (seeds and wood) were dated using  $^{14}\text{C}$  from Little Trefoil Lake #3 using an accelerator mass spectrometer at DirectAMS in Bothell, Washington (DirectAMS, 2013).



Terrestrial plants are used for radiocarbon dating because they use atmospheric CO<sub>2</sub> for tissue building and the decay of carbon begins soon after their death. Using terrestrial plants avoids problems of old carbon that can be in the dissolved inorganic carbon (DIC) component of lake water as a result of underlying carbonate rocks (MacDonald, Beukens, & Kieser, 1991). This <sup>14</sup>C-depleted DIC is taken up by aquatic plants and algae resulting in ages that are too old. Terrestrial macrofossils are transported to the deeper parts of the lake where coring occurs and provide the age of the sediment increment they are located in (Glew et al., 2001). Unfortunately, no terrestrial macrofossils were found in the ZS1 Lake core, making <sup>14</sup>C dating not an option.

A statistical computing and graphics program, R, was used to create dating models for both Little Trefoil Lake #3 and ZS1 Lake (R Development Core Team, 2013). Bacon, an age-depth modelling program that is a free, open-sourced software based on Bayesian statistics, and can be run in R, was used to determine dates for each sampled lake depth (Blaauw and Christen, 2011). Bacon divides the core depths entered into the program into thin vertical sections, and through millions of Markov Chain Monte Carlo iterations, it estimates an accumulation rate for each of those sections (in years/cm). Bayesian statistics are able to combine unknown variables by assigning probability distributions with known sample data, allowing for complex calculations and creating outputs for exact values, rather than large approximations. This is valuable for determining specific dates for specific depths. Markov Chain Monte Carlo uses the slice-sampling in Bacon, allowing for Bayesian statistics to create the specific date/depth outputs for large amounts of data (a specific date for each 0.1cm for 310cm, creating an output of 3,100 dates) (Blaauw and Christen, 2011). Bacon uses IntCal13 for terrestrial northern hemisphere material to calculate dates from inputted uncalibrated radiocarbon dates (Blaauw & Christen, 2011). Combining the entered <sup>210</sup>Pb and uncalibrated radiocarbon dates, Bacon assumes that the accumulation rate is linear between each date and that if there was a large change, it would occur suddenly and exactly at the depths entered with the dates. The accumulation rates then form the age-depth model and the program creates a .text file with a minimum, maximum, medium, and weighted mean age for every depth (Blaauw and Christen, 2011).

### 3.2.2 Loss-on-Ignition

The loss-on-ignition (LOI) technique was used to determine the percentage organics and inorganics of lake sediments; an increase in organic content in the sediment can be evidence of increased production. As sediment samples must be dried and crushed with mortar and pestle during the LOI process, the already measured, dried, crushed, and sieved samples from the chlorophyll *a* were used. These samples were placed in a pre-weighed ceramic crucible, weighed, dried at 100°C for one hour in a muffle furnace and reweighed for the dry weight (to make sure no moisture was added to the chlorophyll *a* samples). The samples were heated again to 550°C for one hour and reweighed. The difference between this weight and the previous weight at 100°C is the amount of organic material that was burned off and was expressed as a percentage (Dean, 1974). This technique was selected because it provides accurate results, is inexpensive, and is considered fast when large numbers of samples need to be analyzed (Dean, 1974; Heiri et al., 2001).

The following equation was used to determine the percentage organics:

$$\% \text{ Organics} = \left( \frac{\text{Dry Weight (g)}(100^\circ\text{C}) - \text{Dry Weight (g)}(550^\circ\text{C})}{\text{Dry Weight (g)}(100^\circ\text{C})} \right) * 100$$

The following equation was used to determine the percentage inorganics:

$$\% \text{ Inorganics} = \left( \frac{\text{Dry Weight (g)}(550^\circ\text{C})}{\text{Dry weight (g)}(100^\circ\text{C})} \right) * 100$$

### 3.2.3 Chlorophyll *a*

Chlorophyll *a* is a blue-green pigment found in photosynthesizing organisms. When these organisms die, they can accumulate in lake sediments and the pigment becomes part of the sediment. Visible-near infrared reflectance (VNIR) was used to measure the amount of chlorophyll *a* in each sediment sample (Michelutti et al., 2012). VNIR provides a rapid, inexpensive, and non-destructive technique for measuring past sedimentary lake production (Michelutti et al., 2012). Infrared radiation is passed through each sediment sample to determine an absorbance spectrum for different wavelengths (Khoshhesab, 2012). The peak absorbance of chlorophyll *a* lies between 650-700 wavelength (nm) (Michelutti et al., 2010; Wolfe et al., 2006).

To prepare samples for VNIR, 1-2cm<sup>3</sup> were measured at every 0.5cm interval and freeze-dried in a Triad Freeze Drier for twenty-four hours, crushed with a mortar and pestle, and sieved (<125µm). This process removes moisture and ensures even sediment size distribution, so that these two variables do not affect the spectral signal (Michelutti et al., 2010). The sieved sample was placed in glass scintillation vials, covering the bottom of the vial with sediment. VNIR spectrometry was done at the Paleoecological Environment Assessment and Research Laboratory (PEARL) in Kingston, Ontario. The amount of inferred chlorophyll *a* concentration was calculated using this equation (Michelutti et al., 2012):

$$\text{Inferred chlorophyll } a = (0.0919 * \text{peak area (650 - 700nm)}) + 0.0011$$

To ensure the changes observed in the chlorophyll *a* record were real and not the result of changes in sedimentation rates or inorganic inputs, I also calculated chlorophyll *a* as a flux rate and as a percent of organics, respectively, for both Little Trefoil Lake #3 and ZS1 Lake.

### 3.2.4 Biogenic Silica

Diatoms are often the dominant algal group in freshwater lake ecosystems, often contributing to half of the lake production (Smol, 2008). There are thousands of species with different environmental tolerances and the assemblages change quickly in response to environmental shifts (Smol, 2008). Diatoms often account for half of the natural production in lakes and use silica for growth and as a component of their cell walls (Conley, 1988). Following death, the dissolved silica in diatoms settles in the sediment. Biogenic silica (BSi) is often used as an indicator of the amount of siliceous microfossil abundance in sediment and was used to reconstruct changes in diatom and chrysophyte production.

The amount of biogenic silica in the sediment was determined using the wet alkaline digestion method (DeMaster, 1981). A 1% sodium carbonate solution ( $\text{Na}_2\text{CO}_3$ ) was added to polypropylene bottles containing 20mg of sediment (for silica-poor sediments) from the prepared chlorophyll *a* samples for 4 hours in an 85°C shaker water bath. After 2, 3, and 4 hours, the samples were removed from the water bath and placed on ice packs to stop the silica reaction. A micropipette set to 1mL removed sample from the bottles and was placed into its corresponding 15mL test tube. Each sample received 3.2mL of 0.06 N hydrochloric acid and 10mL of Epure Water, and was capped, mixed, and placed in the refrigerator. The bottles returned to the shaker bath at the end of each 2, 3, and 4 hour interval. The reasoning behind taking sample extractions at the 2, 3, and 4 hour intervals is because biogenic silica dissolves within 2 hours and clay and mineral silica is leached at a slower rate. The amount of biogenic silica compared to clay and mineral silica can be calculated as the y-intercept of a regression line (clay silica at a time of 0) of weight percent silica versus extraction time (DeMaster, 1981).

The samples were run in the spectrophotometer within 24 hours. On the second day, 0.64mL of the sample is placed in a cuvette with 0.84mL ammonium molybdate, 0.64mL oxalic acid, and 0.84mL ascorbic acid. The combination of these reagents with the sample causes the solution in the cuvette to turn a blue colour. The intensity of blue depends on the amount of silica in the sample and can be measured at a 660nm wavelength on the spectrophotometer. The BSi should be measured in the samples after 5 minutes but before 15 minutes to receive an accurate silica reading. Each cuvette was cleaned with Epure water and wiped with a Kimwipe between

runs for more reliable results; fingerprints, watermarks, or streaks on the outside of the cuvette can absorb or reflect light and can provide inaccurate results (DeMaster, 1981).

Chrysophyte cysts and diatoms were enumerated in selected samples (see Appendix D for diatom samples). The cysts:diatoms ratio was calculated to determine how representative the biogenic silica was of diatoms. The equation used was:

$$Cysts: Diatoms = \frac{Cysts}{Cysts + \left(\frac{Diatom Valves}{2}\right)} * 100$$

### 3.2.5 Diatoms

Diatoms are unicellular photosynthesizing organisms that are sensitive to changes in nutrient concentrations and were looked at to examine if changes in their community composition aligned with changes in the environment. Diatom samples from Little Trefoil Lake #3 were processed following Battarbee, Carvalho, and Juggins (2001) to remove calcium carbonate and organics. At 1.0cm intervals and up to a depth of 45cm, approximately 0.4-1.0 g of sediment was treated with 15mL of 10% hydrochloric acid to remove the calcium carbonates. The samples were left for 24 hours before being aspirated and washed with E-pure water in a fume hood. Sulphuric and nitric acid were then added to the samples to remove organics and isolate the silica. After another 24 hours, the samples were mixed and placed in a hot water bath of 85°C for 2 hours, mixing after the one hour mark to increase the reaction rate. Once removed from the hot water bath the samples were mixed and allowed to cool for another 24 hours. Samples were aspirated to remove the acids and washed with E-pure water until neutralized, resulting in a siliceous slurry that was used for diatom analysis (Battarbee et al., 2001).

To mount the diatom slurries onto slides, a slide warmer and cover slips were cleaned with 10% ethyl alcohol and wiped with Kimwipes. Test tubes were cleaned out well with E-pure water to remove the chances of contamination from anyone who may have used them before or from fingerprints. A different pipette was used for each diatom sample, placing a subsample in a test tube and approximately 10mL of E-pure water to dilute the slurry. Each dilution is placed on a different cover slip until four dilutions are made per sample, labelled A (least diluted) to D (most diluted). This process is repeated, making sure to use a new pipette and test tube for each diatom sample. For each cover slip placed on the slide warmer, its location was mapped on a

diagram to not confuse the four dilutions of each individual sample. The slide warmer was set to a low temperature, covered, and the aliquots evaporated on their respective cover slips over 24 hours (Ruhland et al., 1999). After the 24 hours, they were permanently mounted on glass microscope slides using a drop of Naphrax<sup>®</sup>, a mounting medium with a high refractive index (at least 1.74) (Ruhland et al., 1999).

Approximately 500 diatom valves were counted and identified to species level per sample along a minimum of half of one horizontal transect across each slide. A Leica<sup>®</sup> E-600 light microscope was used at 1000x magnification (under oil immersion) and diatoms were identified (Cumming et al., 1995). Upon the identification of each diatom, a photo with a stamped ruler scale was taken with Northern Eclipse, an image analysis software program (EMPIX Imaging Inc., 2015). Photos of the diatoms are located in the diatom species plates below.

To better understand the diatom species data, Principal Component Analysis (PCA) and stratigraphy plots were created for Little Trefoil Lake #3 using CANOCO version 4.5 and C2 for Windows. PCA plots were created to determine the relationships between the diatom species. All of the species data input into CANOCO were square-root transformed to have all data weighted the same.

### 3.2.6 Core Correlation

Owing to availability of long cores from Little Trefoil #3, but not ZS1 Lake, only long-term lake production in Little Trefoil #3 was determined for the last ~1000 years. A Livingstone corer, which allows collection of sediments in 1m intervals, and a gravity corer were used to collect sediments in overlapping sections. Therefore, it was necessary to determine exactly where the overlap between cores occurred to have temporal continuity and ensure accurate ages were assigned to different sediment intervals.

Chlorophyll *a* and percentage organics are analyzed at greater temporal resolution compared to biogenic silica because by the time the biogenic silica was measured there was not always sufficient sample available, and also because the biogenic silica method is time-consuming. Therefore, chlorophyll *a* and percentage organics records were used to match the Livingstone sediment core to the gravity core of Little Trefoil Lake #3 by visual inspection and

comparison of the main patterns in each core. Figure 29 and Figure 30 in Appendix B further explain the core correlation.

### 3.3 Historical Description of Little Trefoil Lake #3's Region

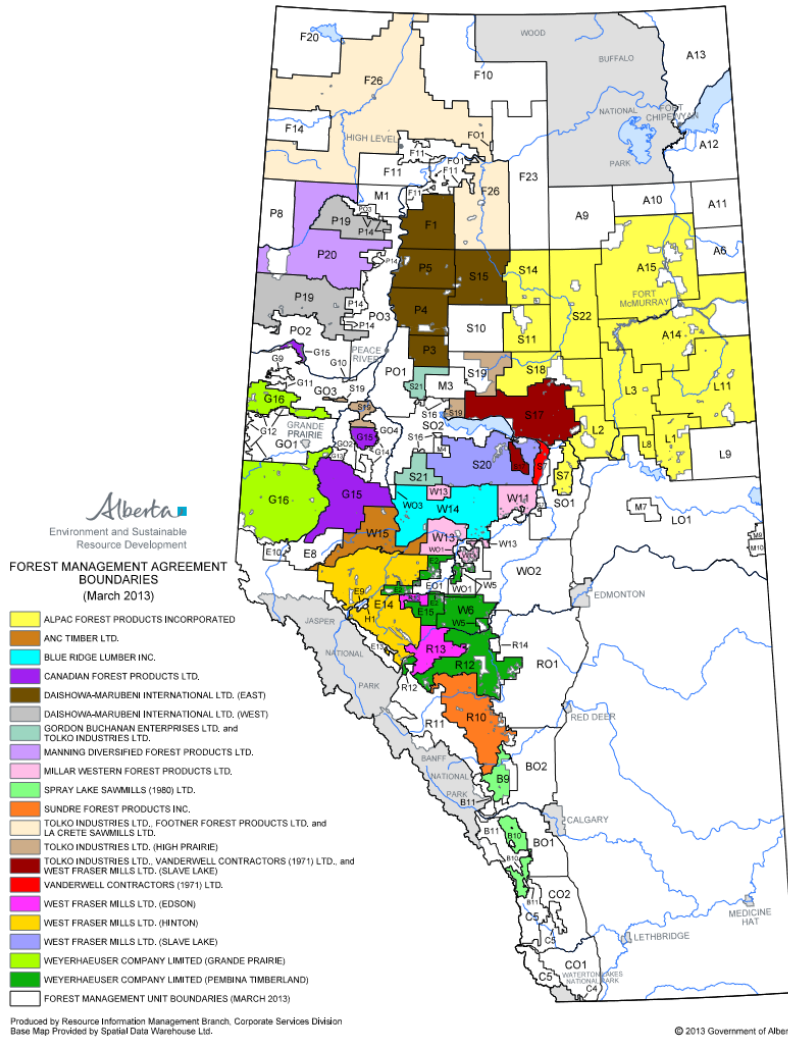
History of landscape change for Jasper and Hinton, Alberta are available from the Government of Canada, Parks Canada, and a written history of Jasper (Government of Canada, 2015; Parks Canada, 2015; Taylor, 2009). Little Trefoil Lake #3's catchment is small (0.038 km<sup>2</sup>) and many of the events that occurred in Jasper did not happen in the catchment. In 1811 CE, the region surrounding Little Trefoil Lake #3 was explored by David Thompson, an explorer with the North West Company. Two years later, the North West Company built the first Jasper House for fur traders to bring mail, supplies, and furs, and merged with the Hudson's Bay Company in 1821 CE (Parks Canada, 2014).

In 1909 CE, Jasper National Park was established and railroad construction began; railways were built from 1909 CE and completed in 1912 CE, building stations at 20 mile intervals and one at the eastern entrance to Jasper Park (Taylor, 2009). There was major growth in Jasper in the 1920s; railways expanded, Jasper Park Lodge opened in 1922 CE just south of Little Trefoil Lake #3, and the number of tourists and the need for more churches, banks, and other facilities increased. A new trestle bridge was built over the Athabasca River in 1935 CE, just north of Little Trefoil Lake #3. This bridge created a new entrance to Jasper Park Lodge, connected by a road that runs along the east edge of Little Trefoil Lake #3, separating those travelling through Jasper and those going specifically to the Lodge (Taylor, 2009). The Lodge burned down in 1952 CE but was quickly rebuilt (Parks Canada, 2014). New highways were built from 1950-1960s and Maligne Road was opened in 1970 CE, allowing more traffic along the trestle bridge. The Jasper National Park Annual Report from 2014 CE states that the number of tourists in Jasper National Park was 2,301,575 and the population of Jasper, Alberta was 4,051 (Parks Canada, 2014).

### 3.4 Historical Description of ZS1 Lake's Region

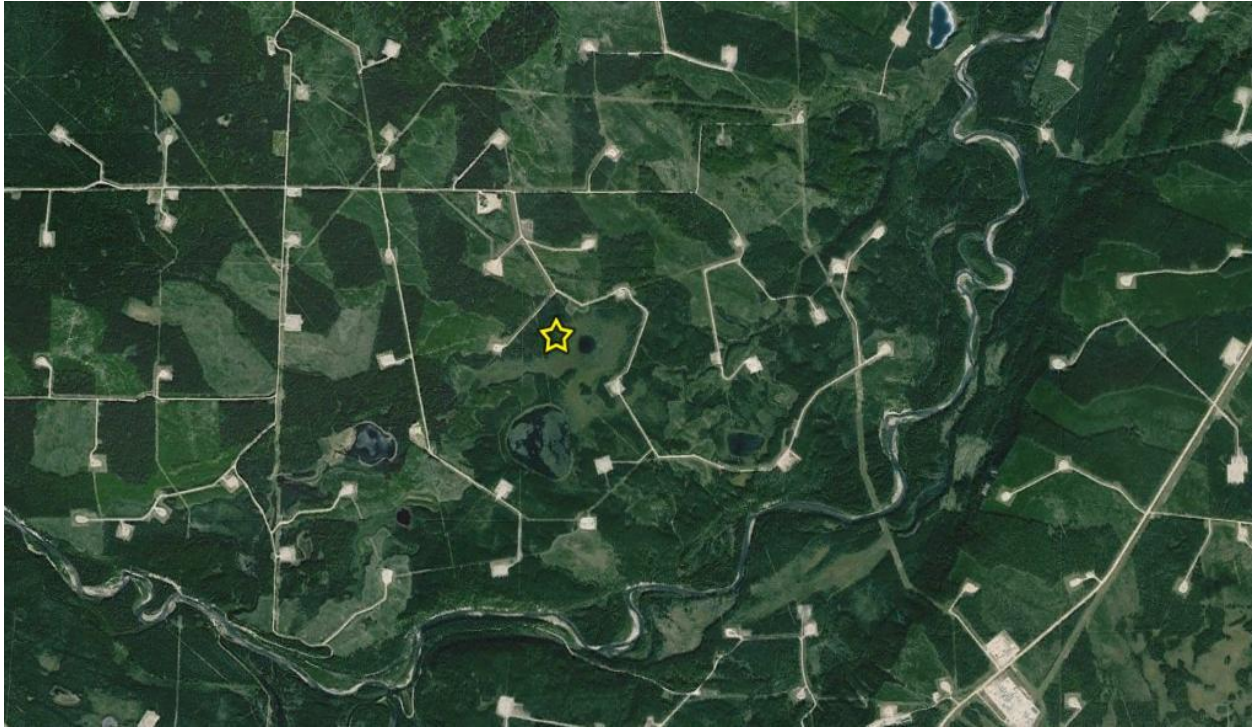
The landscape change nearby ZS1 Lake has been more recent than at Little Trefoil Lake #3. West Fraser Mills Ltd. is a North American integrated wood products company that holds a Forest Management Agreement (FMA) in Alberta for 988,630 hectares, of which 715,341 hectares is available for timber harvesting (Figure 11) (Government of Alberta, 2015). Company holders of FMAs must manage the forests they occupy to provide long-term, sustainable yields by planning and reforestation after harvest; companies must reforest within two years. During land clearance these companies must also consider watersheds, wildlife, and the environment, as well as accept communication with public in the area they are occupying (Government of Alberta, 2015). Hinton Wood Products started logging operations in the FMA in 1956 CE (MacLaren, 2007).





**Figure 11: Forest Management Agreement Boundaries as of March 2013 CE. The West Fraser Mills Ltd. in Hinton is located in E14 (Government of Alberta, 2015).**

West Fraser Mills Ltd. has four Forest Management Agreement locations in Alberta, one located in the vicinity of Hinton and including ZS1 Lake. The FMA duration is from May 1, 2008 CE to April 30, 2028 CE, and their main facility is a bleached pulp mill and lumber sawmill located at Hinton. The land surrounding ZS1 Lake is included in the FMA and is presently being altered by land clearance activities (Figure 12).



**Figure 12: Image of land clearance surrounding ZS1 Lake (yellow star) by West Fraser Mills Ltd. (Google, 2013).**

### 3.5 Historical Data

The proxies that represent lake production (percentage organics, chlorophyll *a*, and biogenic silica) and diatom community compositions were compared to records of landscape change, fire and temperature. Homogenized monthly mean temperature data was available from Environment Canada for the Jasper, Alberta climate station (Government of Canada, 2012). Due to missing temperature data (more than four months per year), the mean annual temperature record for Jasper, Alberta begins in 1936 and extends to 2015 CE. In order to see the effects of temperature in the lake ecosystems, a 5-year running mean was calculated to compare to the high-resolution temporal proxy data, including chlorophyll *a*, biogenic silica, and diatoms. For data before 1936 CE, the regional curve standardisation (RCS) 2004 tree-ring series was used to determine mean summer annual temperatures for the average behaviour of trees in the region, dating back to 950 CE (Luckman & Wilson, 2005). The RCS2004 is based on a regional scale of four grid squares near the Columbia Icefields (51°45'-52°45'N by 116°23'-117°52'W) located just southeast of Jasper, and provided mean summer and maximum summer temperatures (Luckman & Wilson, 2005). This data set has a lower frequency than the Jasper station temperature data and on average is cooler, but aligns with glacial advance in the area, and was therefore used for warm or cool temperature trends in Little Trefoil Lake #3's history. Winter and spring temperatures are relevant for lake ice cover and growing season lengths, especially winter temperatures (Ruhland, Paterson, & Smol, 2008), which are significant for diatom and algal production, and therefore the Jasper climate station annual temperatures will be used in comparison to the mean summer tree-ring temperature data.

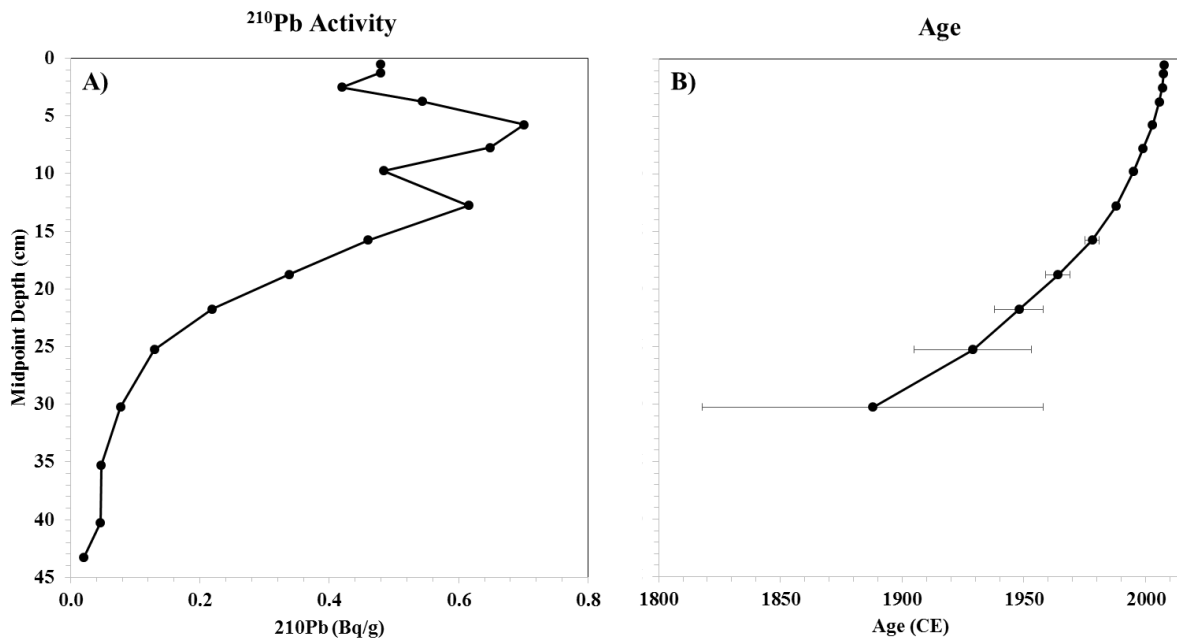
Fire charcoal accumulation and fire peak data was also available for Little Trefoil Lake #3 (Davis, 2015) and ZS1 Lake (Stretch et al., 2015), and was used to determine how chlorophyll *a*, diatoms, and biogenic silica respond to fire events. Fire peaks were based on the macrofossil charcoal accumulation counts that were above the threshold amount of charcoal in Little Trefoil Lake #3.

## Chapter 4

### 4 Results

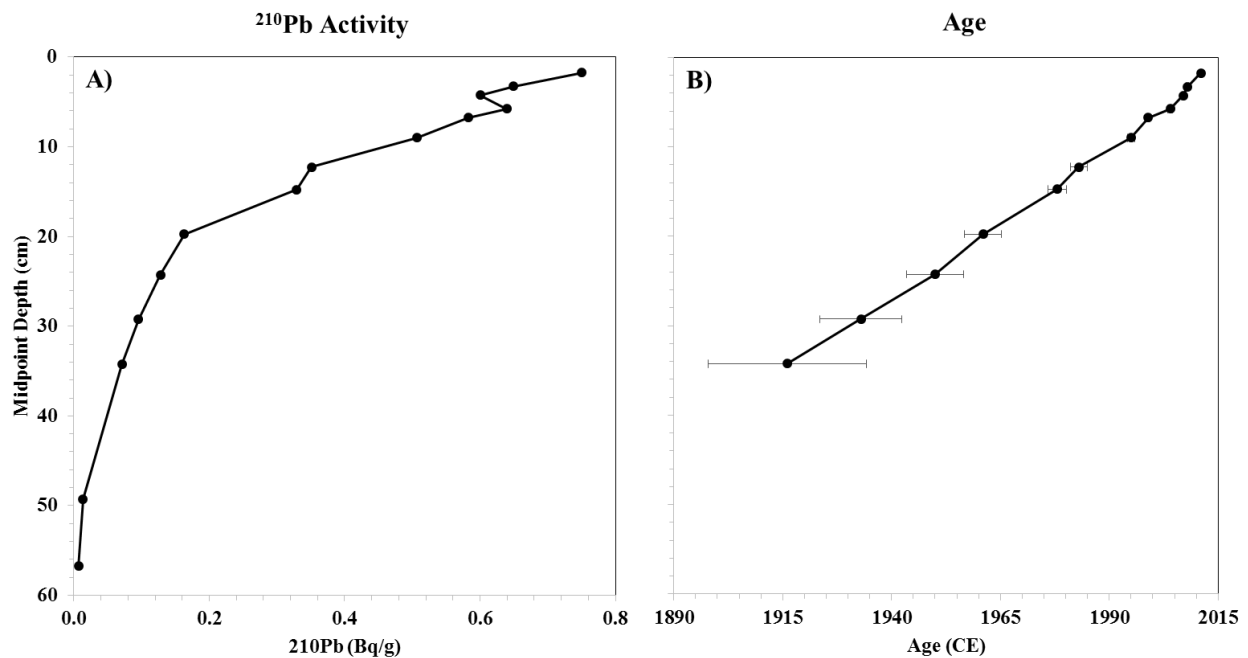
#### 4.1 Chronology

The  $^{210}\text{Pb}$  activity profile (Figure 13A) in Little Trefoil Lake #3 follows the expected exponential decline with increasing depth (Binford, 1990). At a depth of 35cm the amount of  $^{210}\text{Pb}$  activity stabilizes at approximately 0.45 Bq/g, indicating that only supported  $^{210}\text{Pb}$  remains in the lake sediment. Sediment ages determined using  $^{210}\text{Pb}$  are based on the amount of unsupported  $^{210}\text{Pb}$  in the lake sediments. The  $^{210}\text{Pb}$  chronology indicates that the sediment from the top of the core to 30 cm represents ~120 years (Figure 13B). The standard deviation (1 STD) of the dates increases with depth as  $^{210}\text{Pb}$  concentrations become low (Figure 13 B and Table 2).



**Figure 13: A)  $^{210}\text{Pb}$  activity (Bq/g dry wt.) and B) age (CE) with errors (error bars represent one standard deviation above and below the date) against midpoint depth (cm) for Little Trefoil Lake #3. Data for these two plots is provided in Appendix A.**

The  $^{210}\text{Pb}$  activity profile (Figure 14A) for ZS1 Lake also generally follows the expected exponential decline curve (Binford, 1990). At a depth of 49cm, the amount of  $^{210}\text{Pb}$  activity becomes constant at 0.010 Bq/g, indicating that the  $^{210}\text{Pb}$  activity below this depth is only from supported  $^{210}\text{Pb}$ . The  $^{210}\text{Pb}$  chronology (Figure 14B) indicates that the upper 34cm of sediment at ZS1 Lake represents ~95 years. The standard deviation (STD) errors of ZS1 Lake are smaller than those of Little Trefoil Lake #3, but also increase with depth (Figure 14 and Appendix A).

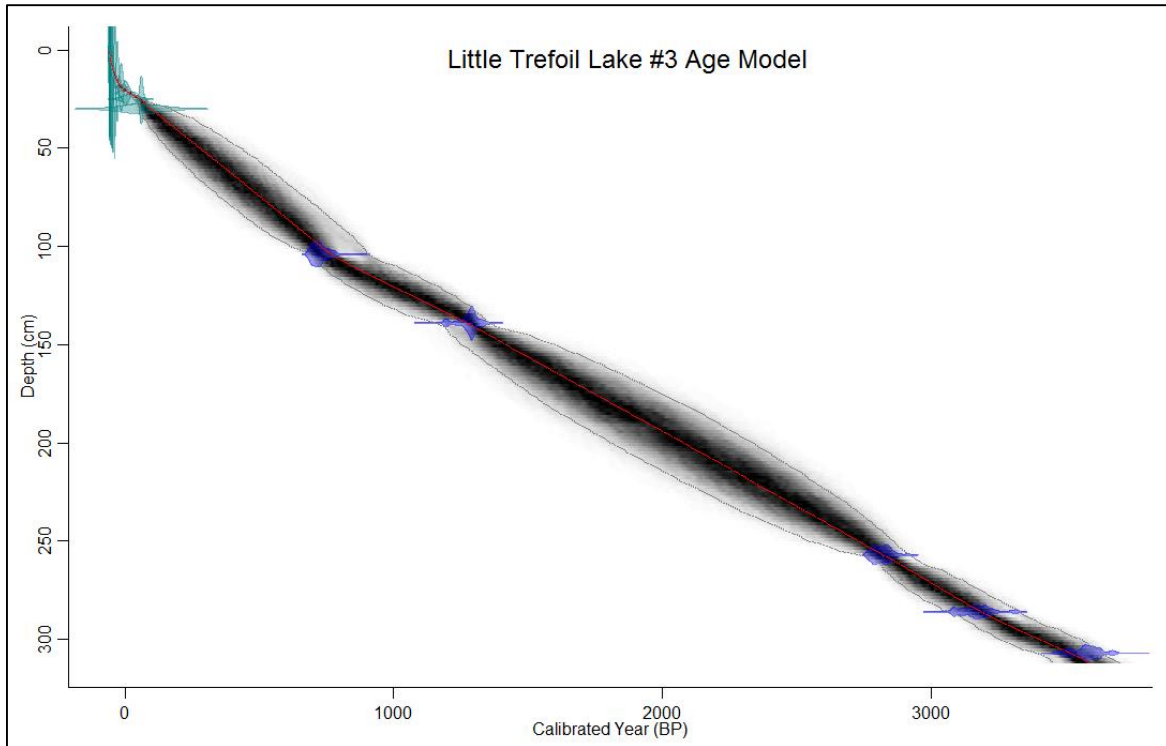


**Figure 14: A)  $^{210}\text{Pb}$  activity (Bq/g dry wt.) and B) age (CE) with errors (STD in years) against midpoint depth (cm) for ZS1 Lake. See Appendix A for data.**

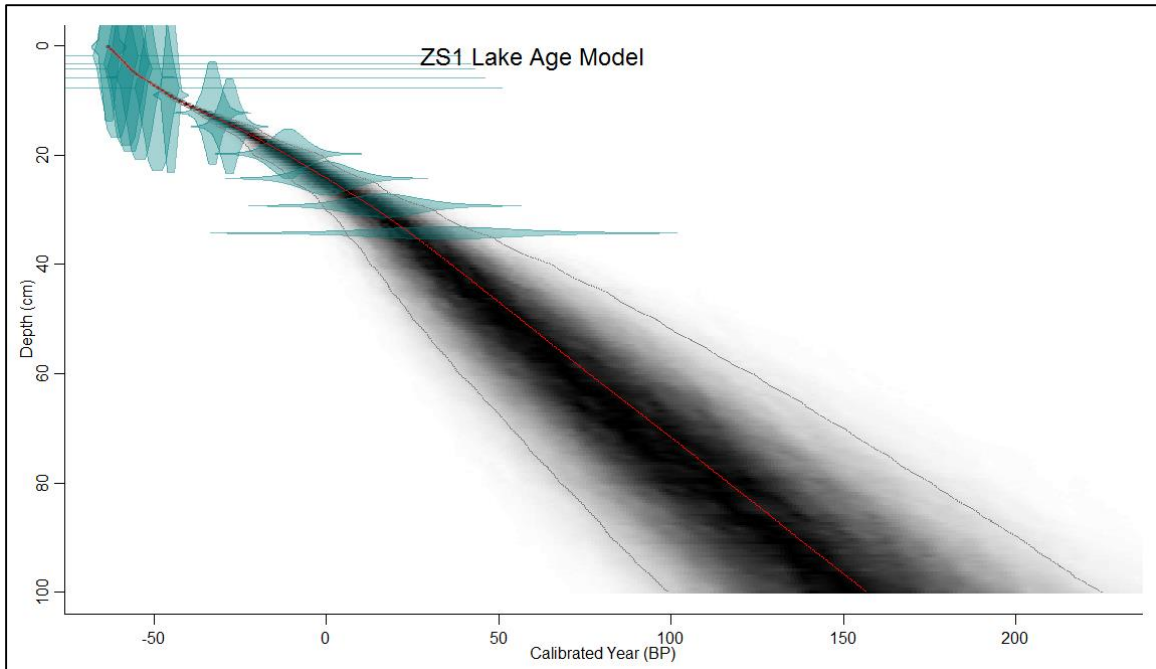
Radiocarbon dating ( $^{14}\text{C}$ ) was also used to determine the ages of sediments in Little Trefoil Lake #3. Table 2 shows that the radiocarbon dates range from 810 years BP (99cm) to 3341 years BP (302cm). To determine a chronology for the sediments from Little Trefoil Lake #3 Bacon (a package in R) was used (Blaauw & Christen, 2011), and the resulting age-depth model is shown (Figure 15). Unfortunately, no suitable terrestrial materials were found for  $^{14}\text{C}$  dating, so the  $^{210}\text{Pb}$  dates were used in Bacon to extend the chronology to the base of the core from ZS1 Lake (Figure 16).

**Table 2:  $^{14}\text{C}$  dates obtained from AMS Direct for Little Trefoil Lake #3. The radiocarbon date is reported as age prior to 1950, but is not calibrated. Dates were calibrated within the Bacon program, which uses the IntCal13 program (Stuvier & Polach, 1977).**

<b>Core 07-JP-02</b>	<b>Sample Type</b>	<b>Depth (cm)</b>	<b>Weight (mg)</b>	<b><math>\delta^{13}\text{C}</math> (per mil)</b>	<b>Radiocarbon Age (BP)</b>	<b>1<math>\sigma</math> Error</b>
1A	Conifer stem	99.8-100.3	29.1	-24.9	810	31
1B	Conifer stem	134.8-135.5	41.8	-26.6	1360	35
1C	Seed capsule	252.4-253.0	41.3	-22.7	2718	29
1C	Woody Stem	281.7-282.9	101.2	-37.9	2991	28
1C	Woody Stem	302.5-303.1	32	-25.4	3341	32



**Figure 15: Little Trefoil Lake #3 age-depth model. This plot shows the resulting age vs depth plot. The transparent green data points represent the  $^{210}\text{Pb}$  data and the transparent blue data points represent the calibrated  $^{14}\text{C}$  data. The darker grey lines indicate the calendar years, the grey stripped lines show the 95% confidence intervals, and the red curve shows the best model used for the weighted mean age for each depth (Blaauw & Christen, 2011).**



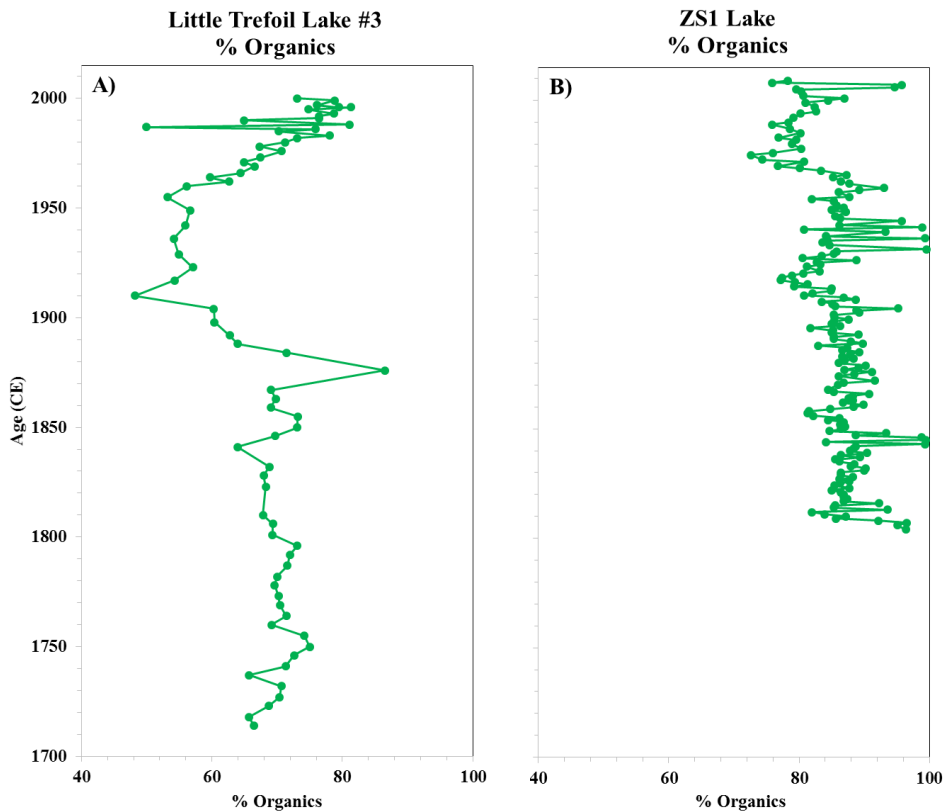
**Figure 16: ZS1 Lake age-depth model (Bacon package in R). This plot shows the resulting age vs depth plot. The transparent green data points represent the  $^{210}\text{Pb}$  data and the transparent blue data points represent the calibrated  $^{14}\text{C}$  data. The darker grey lines indicate the calendar years, the grey stripped lines show the 95% confidence intervals, and the red curve shows the best model used for the weighted mean age for each depth (Blaauw & Christen, 2011).**



## 4.2 Short-Term Records

### 4.2.1 Percentage Organics

Overall, the percent of organics in ZS1 Lake is greater and the values are less variable than in Little Trefoil Lake #3 (Figure 17). The trends in the percentage organics between the two lakes are different. The percentage organics in Little Trefoil Lake #3 are stable from 1714 to 1860 CE. After ~1860 to ~1900 CE there is a rapid decrease in percentage organics, and low values persist until ~1950 CE, when they increase to the present. In ZS1 Lake the percentage organics are stable from 1800-1900 CE, when they increase until 1950 CE. From 1960 to 1975 CE, there is a decrease from 93% to 72% organics, which is followed by a subtle increase to the present.

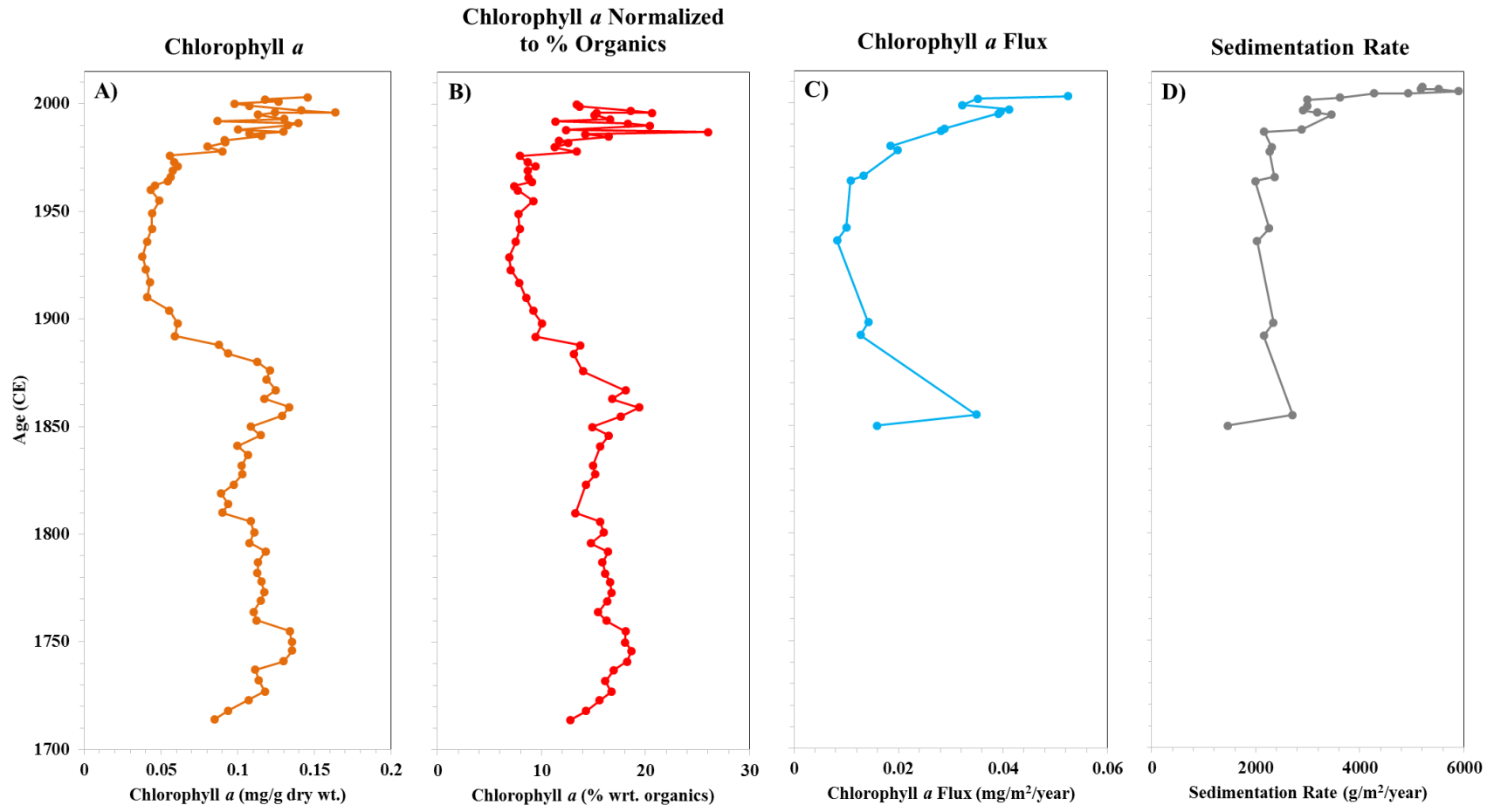


**Figure 17: A) Little Trefoil Lake #3 percentage organics and B) ZS1 Lake percentage organics against age (CE).**

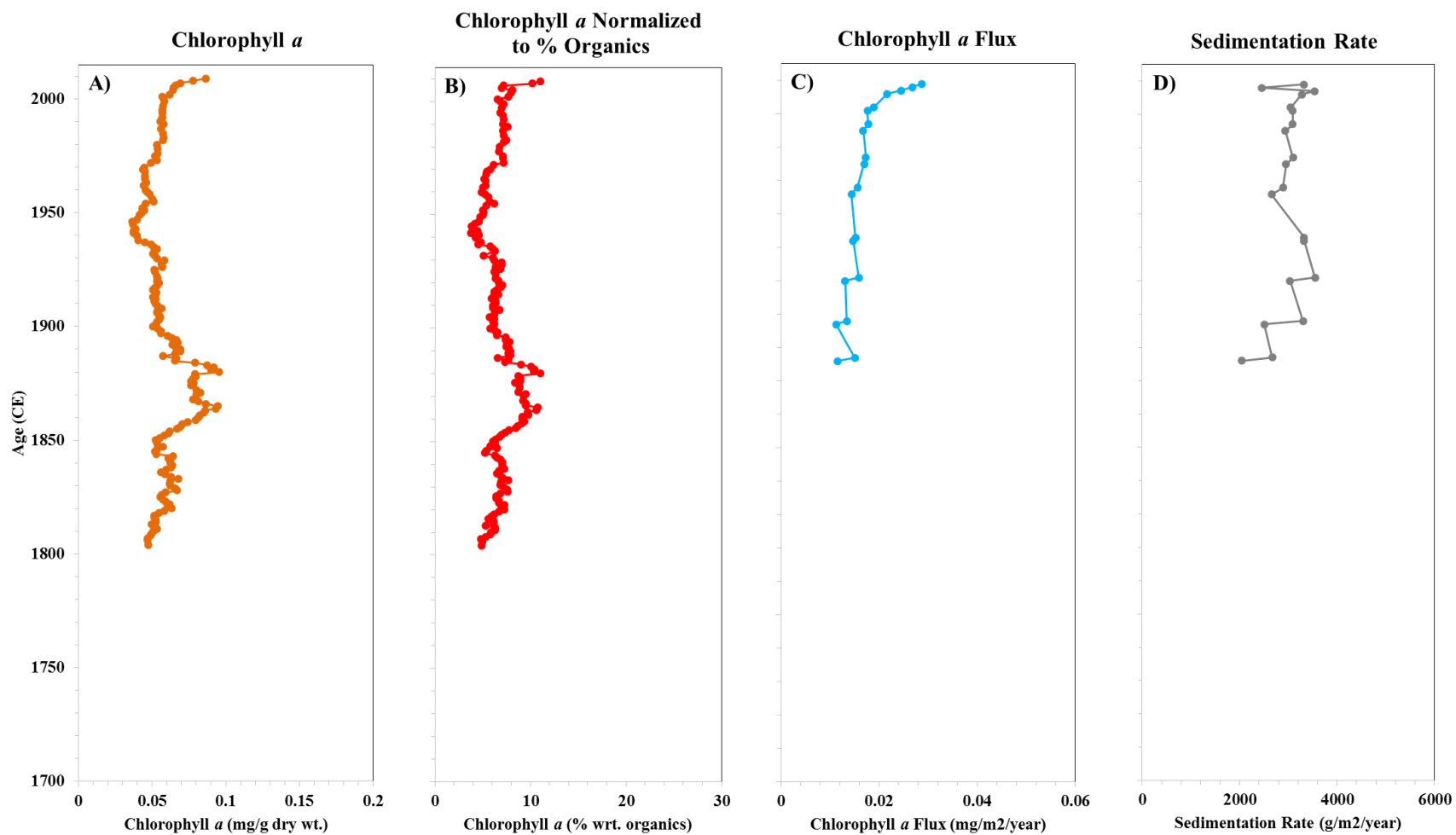
#### 4.2.2 Chlorophyll *a* and Sedimentation Rate

The trends in chlorophyll *a* in Little Trefoil Lake #3 are similar to the trends in organics (Figure 17 and Figure 18). Chlorophyll *a* was consistent from 1714 to 1850 CE (Figure 18). This stable period was followed by a decrease in chlorophyll *a* from 1876 to 1910 CE. From ~1910 values remain low until ~1960 CE when the values increase until the top of the gravity core (2007 CE), when maximum chlorophyll *a* values are recorded. Chlorophyll *a* can be diluted by either increased inorganic deposition or increased sedimentation rates. To determine whether the chlorophyll *a* represented algal production or the dilutions, chlorophyll *a* values were normalized to organic values and chlorophyll *a* flux (the rate of chlorophyll *a* flow in g/m<sup>2</sup>/year) was calculated, respectively. Normalized chlorophyll *a* and chlorophyll *a* flux showed similar trends to chlorophyll *a* meaning the changes observed are representing the chlorophyll *a* from algal production (Figure 18). The dramatic decrease in sedimentation rate at the top of the core is because the bottom part is compacted.

The chlorophyll *a* in ZS1 Lake is relatively consistent compared to the chlorophyll *a* in Little Trefoil Lake #3 (Figure 18 and Figure 19). There is an increase in chlorophyll *a* from 1851 to 1865 CE that is similar in timing to an increase in Little Trefoil Lake #3 from 1850 to 1859 CE. There is also a slight increase beginning in ~1950 CE to the present that matches the increase in Little Trefoil Lake #3 beginning ~1960 until 2007 CE. The chlorophyll *a* (normalized to percentage organics) and chlorophyll *a* flux trends are the same as the chlorophyll *a* data.



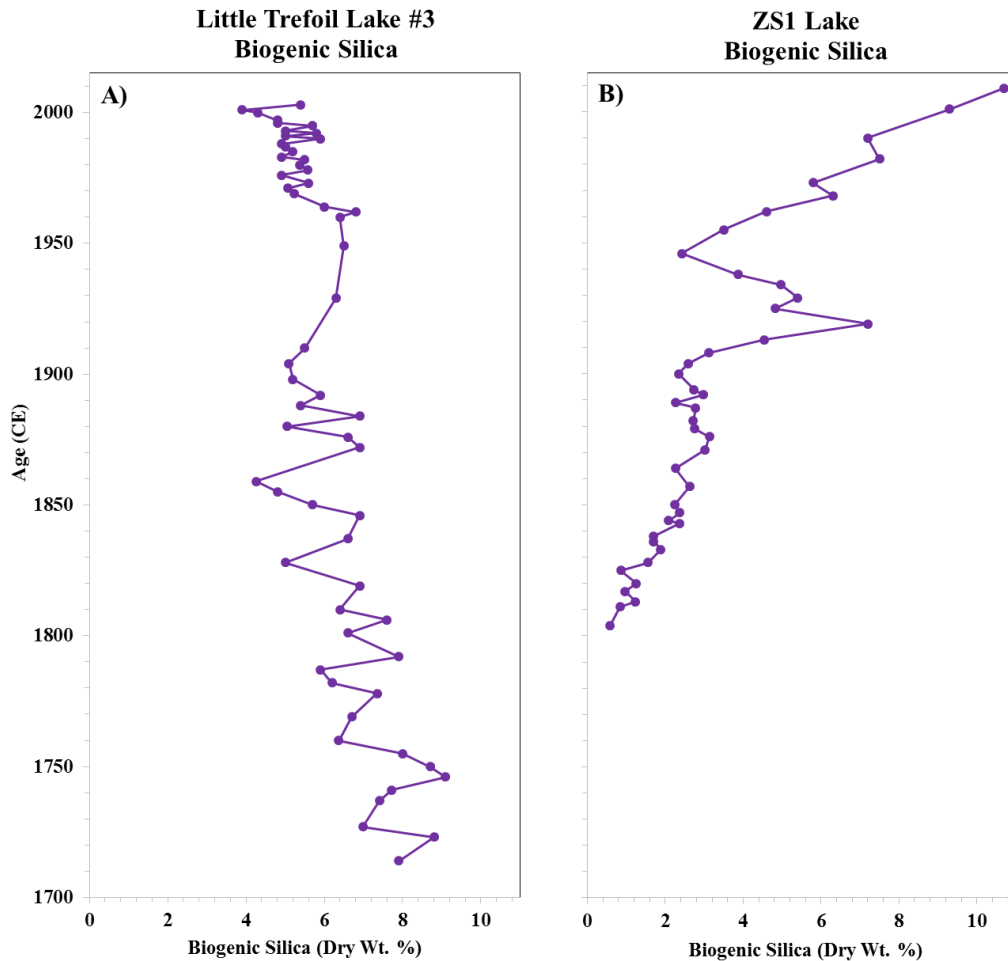
**Figure 18: A) Chlorophyll *a* (mg/g dry wt.), B) percent chlorophyll *a* normalized to organics (% wrt organics), C) chlorophyll *a* flux (mg/m<sup>2</sup>/year), and D) sedimentation rate (g/m<sup>2</sup>/year) against age (CE) for Little Trefoil Lake #3.**



**Figure 19: A) Chlorophyll *a* (mg/g dry wt.), B) percent chlorophyll *a* organics (% wrt organics), C) chlorophyll *a* flux (mg/m<sup>2</sup>/year), and D) sedimentation rate (g/m<sup>2</sup>/year) against age (CE) for ZS1 Lake.**

### 4.2.3 Biogenic Silica

The biogenic silica in Little Trefoil Lake #3 generally shows an opposite trend to ZS1 Lake's biogenic silica (Figure 20). Although noisy, the biogenic silica in Little Trefoil Lake #3 shows a general, gradual decrease from 1714 to 2003 CE and the biogenic silica shows a general and more rapid increase from 1804 to 2009 CE.



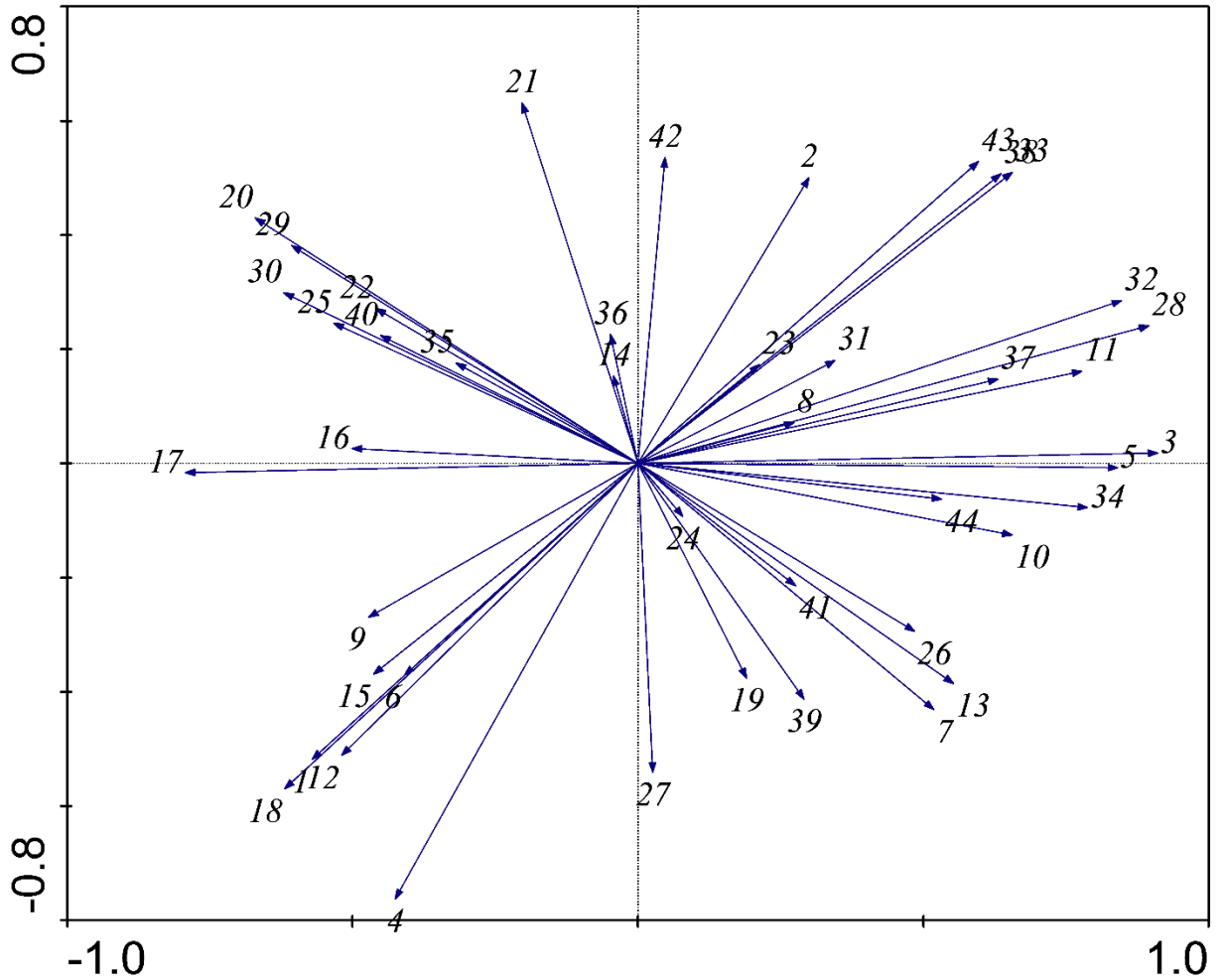
**Figure 20: A) Little Trefoil Lake #3 biogenic silica (reported as weight percentage of dried sediment) against age (CE), B) ZS1 Lake biogenic silica (is reported as weight percentage of dried sediment) against age (CE).**

#### 4.2.4 Diatoms from Little Trefoil Lake #3

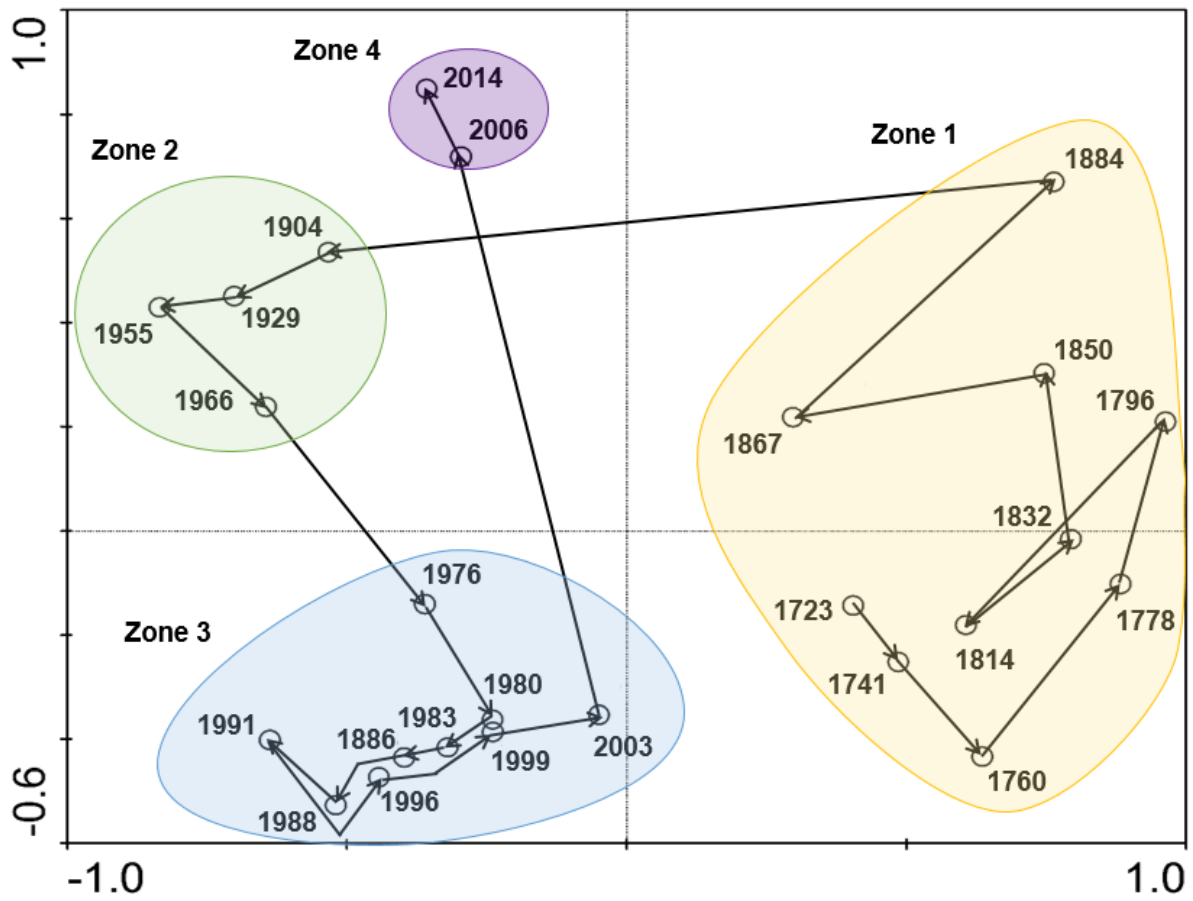
The diatom data used in the principal components analysis is provided in the diatom stratigraphies in Appendix E. The eigenvalue for axis one in the Principal Component Analysis (PCA) is 0.33. The eigenvalue for axis two is much less (0.17) and is not discussed further. Each arrow in the PCA plot (Figure 21) represents a different diatom species living in Little Trefoil Lake #3. Longer arrows that have a small angle with an axis show diatom species that are influential in determining the position of that axis. The ecology of groups of diatoms aligned with the axes can be used to help determine possible environmental variables being represented by that axis. Samples that plot close to the ends of arrows are characterized by high proportions of this species. (Moser, Smol, & MacDonald, 2004; ter Braak, 1986).

The diatoms that are most negatively correlated to axis one are *Denticula elegans* (16) and *Denticula kuetzingii* (17) and the diatoms most positively correlated to axis one are *Amphora libyca* (3), *Caloneis silicula* (5), *Cymbella delicatula* (10), *Cymbella ehrenbergii* (11), *Navicula pupula* (34), and *Stephanodiscus parvus* (44) (Figure 21). Figure 22 represents how the diatom community composition has changed in Little Trefoil Lake #3 from 1723 to 2014 CE. The closer samples plot to each other the more similar the diatom species assemblages are in those samples. Samples that plot far from each other are less similar. Distinct changes in diatom community composition are observed in Figure 22, and also in the diatom stratigraphy in Appendix E. The diatom species assemblages from 1723 to 1884 CE (Zone 1) are similar in terms of diatoms that are positively correlated to axis one. The community composition changes between ~1884 and 1904 CE, and between 1904 and 1966 CE (Zone 2) is characterized by higher abundances of diatoms that are negatively correlated to axis one including, small *Fragilaria* species (20, 22, 25) and *Navicula cryptotenella* (29), *Navicula cryptotenella* fo. 1 PISCES (30), *Navicula radiosa* (35), and *Nitzschia palea* (40) and lower abundances of diatoms positively correlated with axis one, including *Cyclotella bodanica* (7), *Cymbella minuta* (13), *Gomphonema acuminatum* (26), *Navicula aurora* (28), *N. oblonga* (34) and *Nitzschia. radiculara* (41). This time period is also characterized by a large decrease in chlorophyll *a* and percent organics (Figure 17 and Figure 18). The diatom community composition changes between 1966 and 1976 CE, and between 1976 to 2003 CE (Zone 3) is characterized by increased abundances of diatoms negatively correlated to axis 2 including *Brachysira vitrea* (4), *Cymbella microcephala* (12), *C. minuta* (13), and

*Nitzschia fonticola* (39). Following 2003 (Zone 4) the diatom community composition becomes more similar to what it was between 1904 and 1966 CE.



**Figure 21: Little Trefoil Lake #3 diatom Principal Component Analysis (PCA) plot with diatom species represented by numbered arrows. The legend for the numbers are found in the Appendix D, Table 5.**



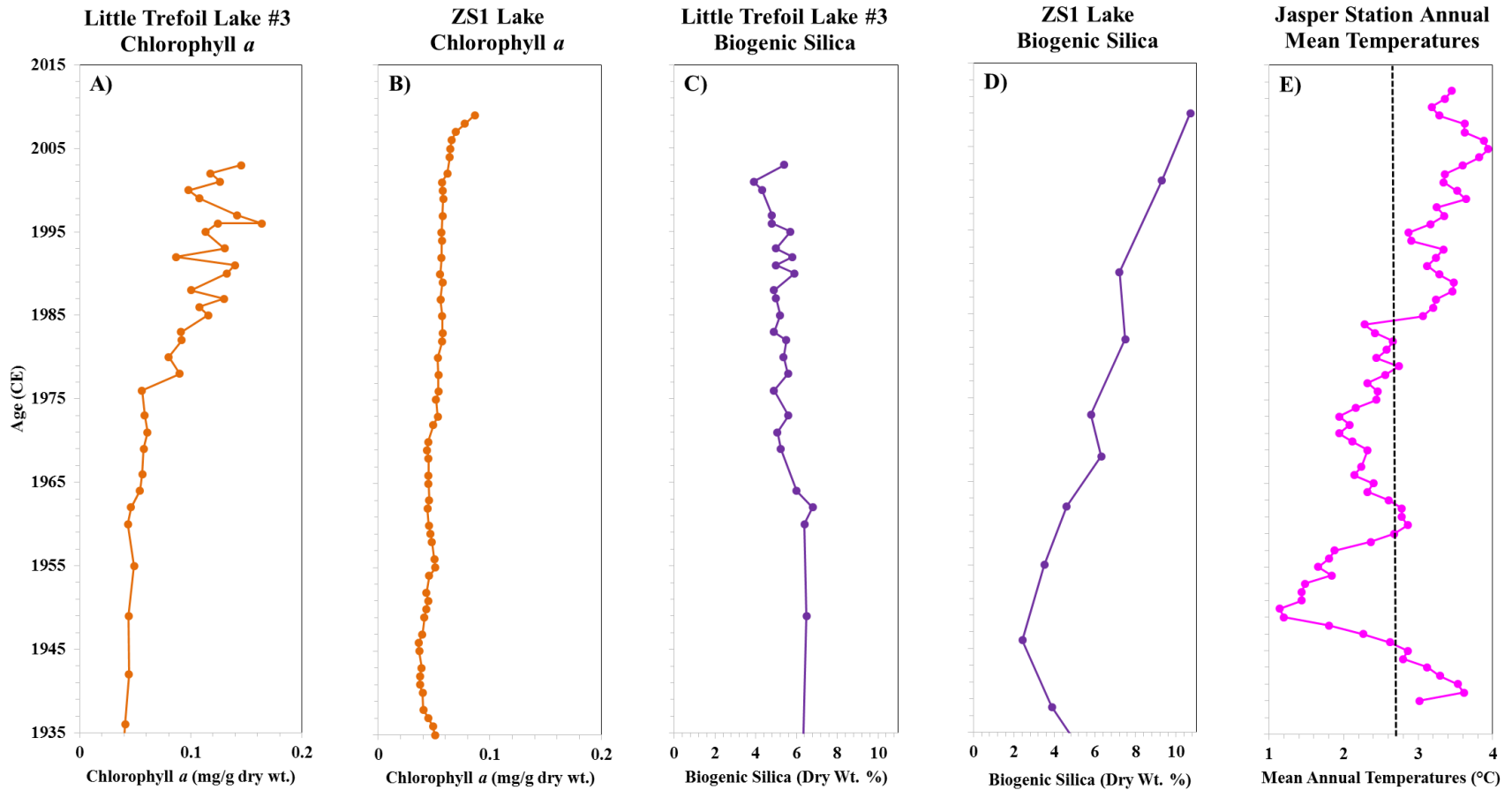
**Figure 22: Diatom sample Principal Component Analysis (PCA) plot showing samples that are denoted by their respective age (CE).**



## 4.3 How do Proxy Records Compare to Temperature, Fire, and Landscape Change?

### 4.3.1 Records of Lake Production (Chlorophyll *a* and Biogenic Silica) compared to the Instrumental Temperature Record

The instrumental temperature record shows a steady increase from ~1950 CE onwards, but is not above the mean (1946-1983 CE) until 1985 CE (Figure 23). The only similarities between the lake production records and the instrumental temperature record occurs after 1960 and 1950 CE when chlorophyll *a* at Little Trefoil Lake #3 and biogenic silica at ZS1 Lake increase, tracking the increasingly warm temperatures. Interestingly, biogenic silica at Little Trefoil Lake #3 decreases during this time period.

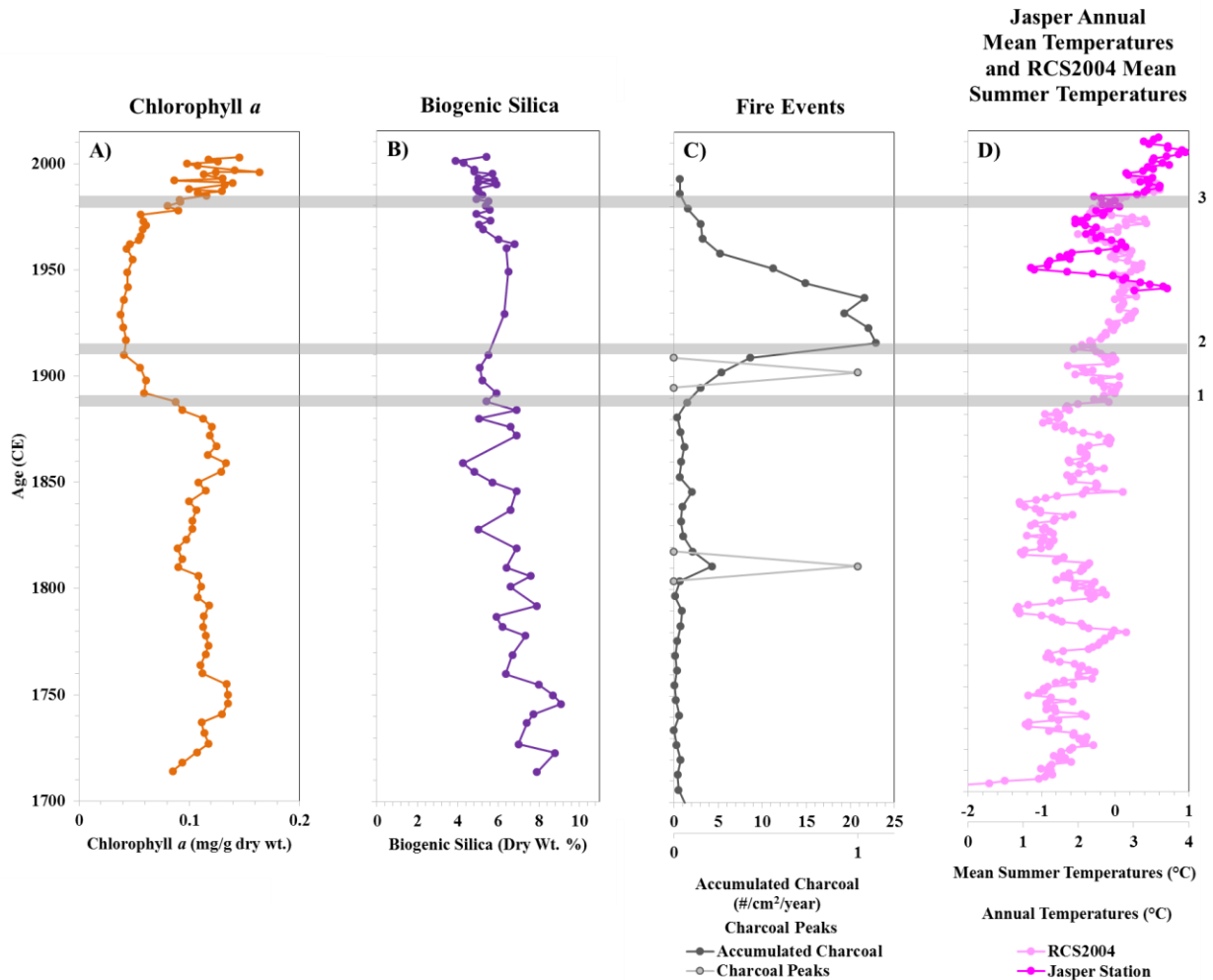


**Figure 23: Little Trefoil Lake #3 A) chlorophyll *a* (mg/g dry wt.), B) ZS1 Lake chlorophyll *a* (mg/g dry wt.), C) Little Trefoil Lake #3 biogenic silica (reported as weight percentage of dried sediment), D) ZS1 Lake biogenic silica (reported as weight percentage of dried sediment), and E) Mean annual Jasper climate station temperature (°C) (5-year running mean) against age (CE). The dashed line represents the mean (2.7°C) of the Jasper climate station temperature data.**

#### 4.3.2 Records of Lake Production Compared to Tree Ring Record of Temperature, Landscape Change, and Fire

Although the previous data suggests a link between recent (i.e., after 1950 CE) warming and increasing chlorophyll *a*, comparison between mean summer temperature determined from tree ring data (Luckman & Wilson, 2005) and chlorophyll *a* do not support this link prior to 1950 CE at either Little Trefoil #3 or ZS1 Lake (Figure 24) .

After the largest fire event in Jasper in 1889 CE (Tande, 1979) there is a large decrease in chlorophyll *a*, the PC1 sample scores, and the cyst:diatom ratio (Figure 24 and Figure 25), and an increase in biogenic silica. After 1965 CE when the charcoal accumulation decreased to normal amounts in the lake, the chlorophyll *a* and the PC1 sample scores began to increase, and the biogenic silica to decrease.



**Figure 24: Little Trefoil Lake #3 A) chlorophyll *a* (mg/g dry wt.), B) biogenic silica (reported as weight percentage of dried sediment), C) accumulated charcoal and fire events (Davis, 2015), and D) Jasper annual mean temperatures and RCS2004 mean summer temperatures (°C) (Luckman & Wilson, 2005) (5-year running mean) against age (CE).**

The dashed line represents the means (2.7°C) of the Jasper climate station and (-0.53°C) of mean summer RCS2004. The grey bars represent landscape changes: 1) 1889 CE - Largest fire on record, 2) 1913 CE - Fire suppression method began, and 3) 1980 CE - Jasper National Park prescribed fire program began (MacLaren, 2007).

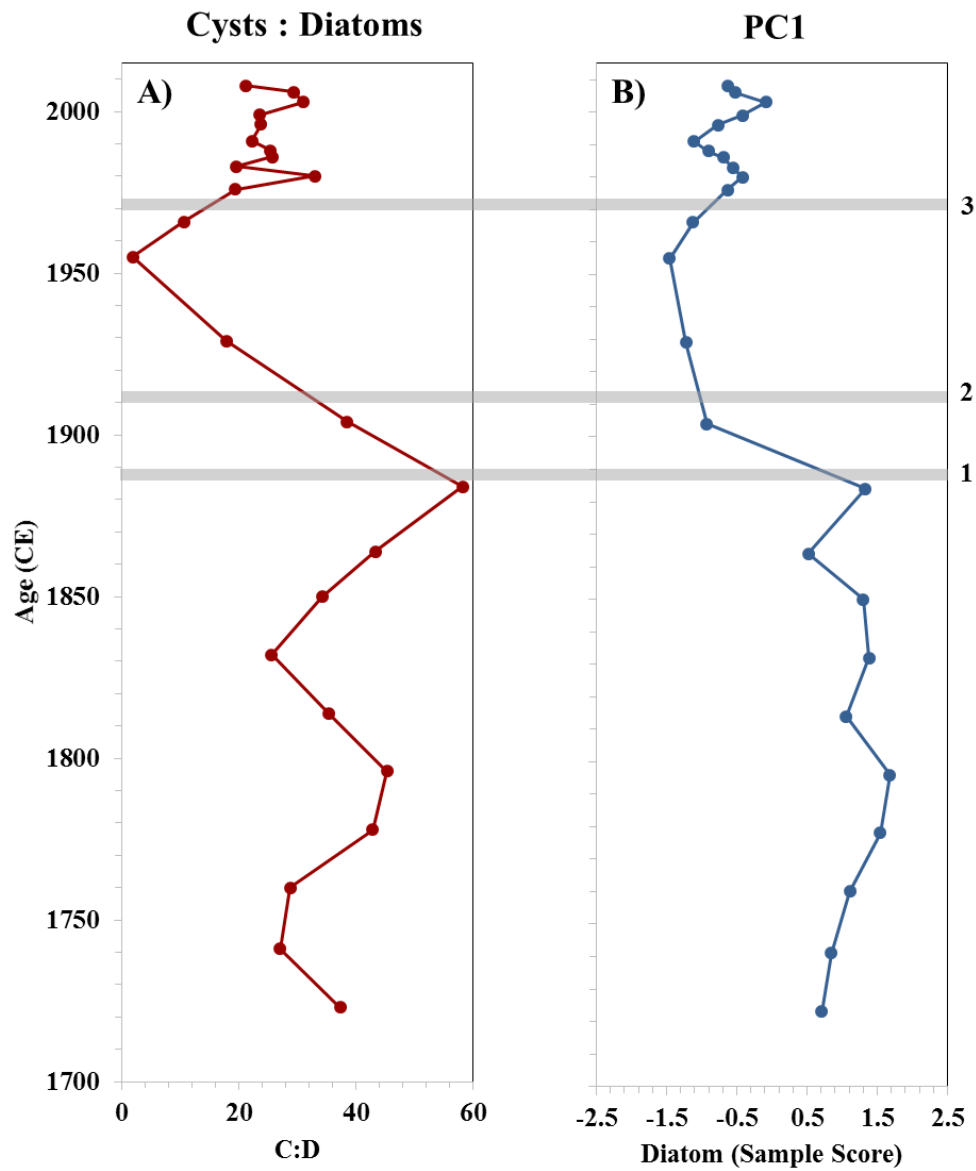
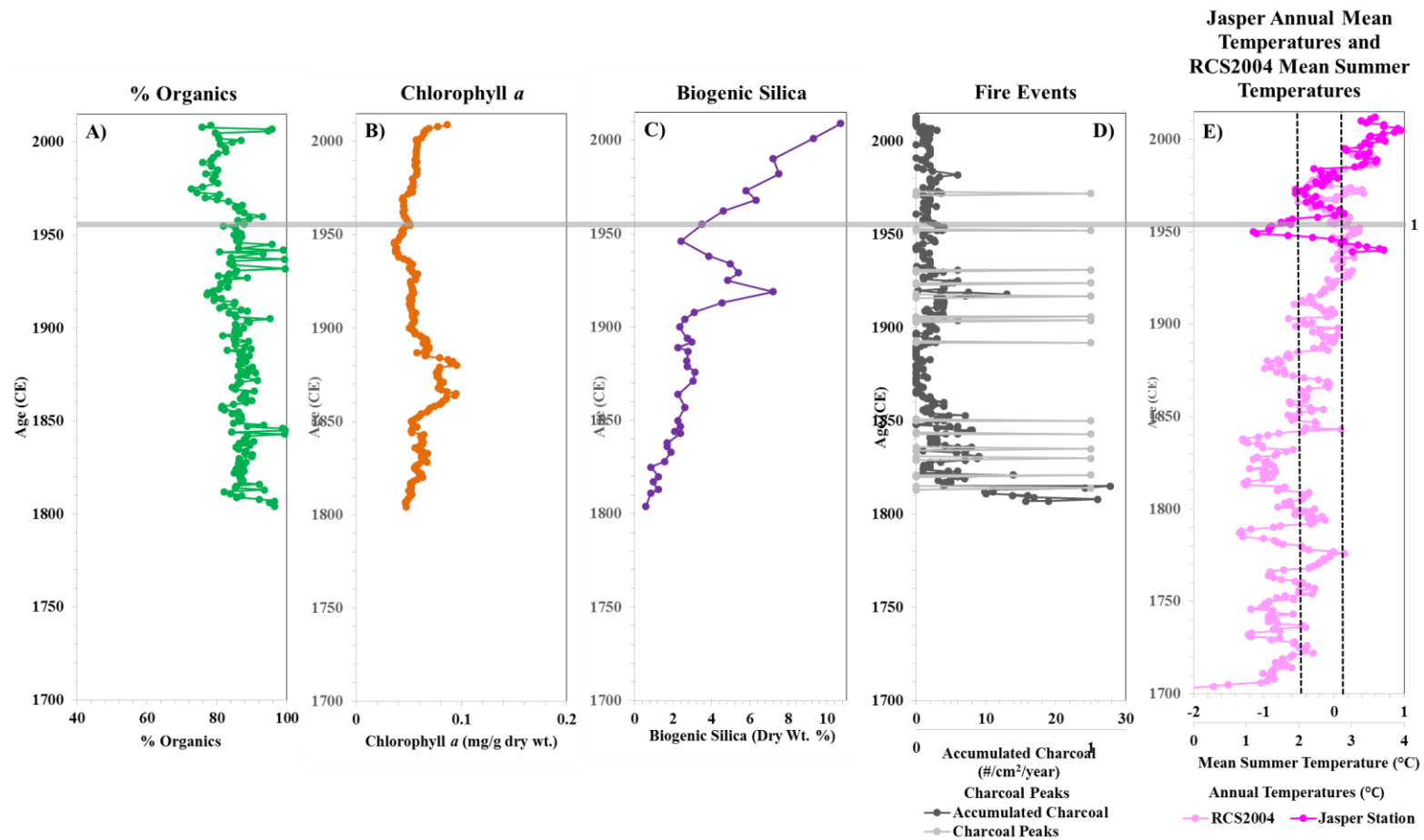


Figure 25: Little Trefoil Lake #3 A) cysts:diatoms ratio and B) diatom PCA one sample scores.

### 4.3.3 ZS1 Lake

The only proxy from ZS1 Lake that follow the trends in the mean summer temperatures determined from tree ring data (Luckman & Wilson, 2005) is biogenic silica (Figure 26). The amount of charcoal in ZS1 Lake has stayed consistent throughout the fire history, with the largest fires in 1808, 1814, and 1917 CE (Figure 26D). The number of fires decrease after 1950 CE, the same time that temperature warming increases and the biogenic silica begins to increase at a faster rate. The decrease in fire is linked to reduced fuel as a result of logging, and also potentially fire suppression.



**Figure 26: ZS1 Lake A) percentage organics, B) chlorophyll *a* (mg/g dry wt.), C) biogenic silica (reported as weight percentage of dried sediment), D) accumulated charcoal and fire events (Stretch et al., 2015), and E) Jasper annual mean temperatures and RCS2004 mean summer temperatures (°C) (Luckman & Wilson, 2005) (5-year running mean) against age (CE). The dashed line represents the means (2.7°C) of the Jasper climate station and (-0.53°C) of mean summer RCS2004. The grey bar represents landscape change: 1) Logging began in 1956 CE (MacLaren, 2007).**

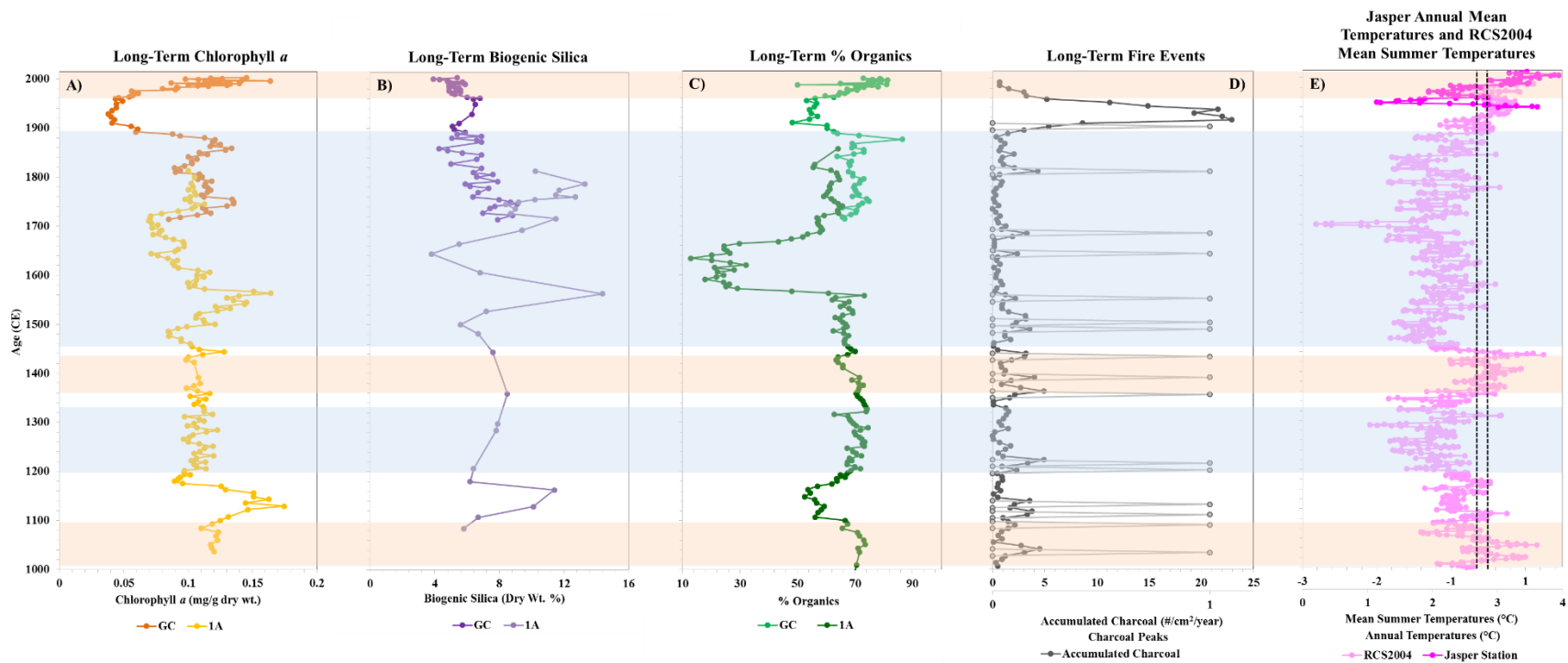
## 4.4 Long-Term Record: How the Last 100 Years compare to the Last 1000 Years

### 4.4.1 Chlorophyll *a*, Biogenic Silica, Percentage Organics, Compared to Temperature and Fire Events

As noted previously, in the most recent part of the record the biogenic silica shows opposite trends to the chlorophyll *a* record (Figure 24). However, prior to 1706 CE, chlorophyll *a* and biogenic silica (Figure 24) follow the same trends with two peaks, one between 1084 and 1180 CE and one between 1518 and 1600 CE. Chlorophyll *a* in comparison to the percentage organics was similar from 1714 CE to the present, but does not always follow the same trends prior to 1704 CE. For example, the peak in chlorophyll *a* and biogenic silica observed between 1084 and 1180 CE is not observed in the percentage organics. Instead, there is a drop in the percentage organics.

It was noted that in the recent part of the record, chlorophyll *a* and the percentage organics increase in response to the most recent warming, with temperatures following an increasing trend beginning in 1950 and above the mean of 2.7°C since 1985 CE. A comparison of previous warm periods identified using tree rings (Luckman & Wilson (2005) to chlorophyll *a* and percentage organics does not show this relationship (Figure 27). Similarly, the large decrease in chlorophyll *a*, percentage organics, a shift in diatom community composition, and an increase in the relative amount of diatoms to cysts following the documented widespread and large fire of 1889 CE is not observed to occur with previous fires (Figure 27).





**Figure 27: Little Trefoil Lake #3 Lake long-term A) chlorophyll *a* (mg/g dry wt.), B) biogenic silica (reported as weight percentage of dried sediment), C) percentage organics, D) accumulated charcoal and fire events (Davis, 2014), and E) Jasper annual mean temperatures and RCS2004 mean summer temperatures (°C) (Luckman & Wilson, 2005) (5-year running mean) against age (CE). The dashed line represents the means (2.7°C) of the Jasper climate station and (-0.53°C) of mean summer RCS2004. The blue and orange bars represent cold and warm periods (Luckman & Wilson, 2005). See notes in the methods and Appendix B for how core correlation was done.**

## Chapter 5

### 5 Discussion

#### 5.1 Is there a Link between Lake Production and Temperature?

The Canadian Rockies have had a 1.5°C increase in mean annual temperatures over the last century (Luckman and Kavanagh, 2000). Based on available temperature data from the Jasper climate station, temperatures in Jasper, Alberta have increased from 1949 to 2000 CE, with temperatures above the mean after 1985 CE. For the most recent decades (~1950 to present) chlorophyll *a* and the percentage organics in Little Trefoil Lake #3 increased rapidly (Figure 24), tracking increasing temperatures. Several studies have suggested that increasing temperatures will reduce ice cover, increase light, and extend the growing season, therefore increasing lake production (Adrian, Wilhelm, & Gerten, 2006; Ruhland & Smol, 2005; Ruhland et al., 2008; Winder & Schindler, 2004). Other research has shown that warmer temperatures can strengthen thermal stratification, which could increase nutrient availability during overturn (Moser et al., 2002) or reduce lake depth and increase cycling of nutrients from the hypolimnion to the epilimnion during the growing season (Ruhland et al., 2008). Warming temperatures may cause lower lake levels, reduce water flows, and increase water residence times and nutrient retention, and can contribute to eutrophication (Schindler, 2006).

However, climate changes occur over large areas, so if climate change is the main driver of recent changes, we might expect to see similar changes in chlorophyll *a* in ZS1 Lake, but we only see small increase in chlorophyll *a* in ZS1 Lake from 1945 to 2009 CE. This could reflect a difference in these two lakes' sensitivity to warming temperatures. The two lakes are very similar in all respects (Table 1), except catchment area (Table 1, Figure 3, and Figure 4). ZS1 Lake has a much larger catchment, which could make it more sensitive to catchment changes and less sensitive to in-lake temperature effects. However, ZS1 Lake has an extensive wetland, approximately extending 0.13km (127m) along the edges of the lake, with floating aquatic vegetation around it, which might also buffer any effects from the catchment increasing its sensitivity (Figure 28). This wetland could also be the main source of organics and chlorophyll *a*

in the lake sediments, and if unchanged in the recent past could mask any in-lake changes. Wetlands can act as a buffer, absorbing sediment, nutrients, slowing water runoff, and reducing the chance that nutrients can reach ZS1 Lake (Klemas, 2014). The generally higher and less variable percentage organics would support a more consistent organic source, such as the wetland. To test this idea we could determine C:N or  $\delta^{13}\text{C}$  values of N-alkanes (Meyers & Ishiwatari, 1993), which would give us an idea of the source of organics.



**Figure 28: Moss, grasses, and sedges surrounding ZS1 Lake, with Tamarack and Black Spruce further in the catchment.**

We can also consider the biogenic silica record at ZS1 Lake, which does show a marked increase from 1946 to the present (Figure 23). While chlorophyll *a* at ZS1 Lake has not changed recently, the biogenic silica is following the temperature trends (Figure 26). Biogenic silica is a measure of siliceous algal production, which can comprise both diatoms and chrysophytes, and in a lake with a significant wetland, such as ZS1 Lake, the biogenic silica may be a more clear indication of in-lake production. For example, McKay, Kaufman, and Michelutii (2008) showed that biogenic silica increased with increasing temperature over the last 2,000 years in Hallet Lake in Alaska. By extending growing season and increasing nutrients during overturn, warming

temperatures could increase diatom production (Ruhland & Smol, 2005) Interestingly, this trend in biogenic silica is not observed at Little Trefoil Lake #3; in fact, biogenic silica decreases beginning ~1714 to present. Schelske and Stoermer (1971) states that silica depletion in a lake can limit diatom production, decreasing the amount of biogenic silica. An increase in nitrogen and phosphorus enrichment can deplete silica, which is slow to regenerate in water and limits diatom growth. This leaves more nutrients available for blue-green algae. Moser et al., (2002) also measured decreasing biogenic silica from 1830 CE onwards. They suggested that when there is an increase in nutrients, blue-green and green algae, and chrysophyte cysts can outcompete diatoms as a result of silica-limitation. In this scenario, production would then increase but the biogenic silica would decrease.

When comparing the chlorophyll *a* data from 1700 CE to the present from Little Trefoil Lake #3 to the RCS2004 modeled temperature, there is nothing in the temperature record around 1876 CE that would explain the change in chlorophyll *a* and percentage organics from relatively consistent to rapidly decreasing (Figure 24). There was a dry period from 1929-1931 CE, associated with a large drought in the western North America (Watson & Luckman, 2004), and the RCS2004 temperatures were above the mean after ~1880 CE. Dry-warm periods can decrease the amount of runoff into lakes (Paterson et al., 1998), and therefore nutrients to the lake, which may explain the low percentage organics and chlorophyll *a* after 1910 CE until ~1960 CE.

Although there seems to be a positive relationship between temperature and chlorophyll *a* in Little Trefoil Lake #3 after 1970 CE, temperature was not solely affecting chlorophyll *a* and percentage organics before this date. If warming temperatures were the driving factor causing changes in in-lake production, then we would expect increased lake production when temperatures have previously warmed, but this is not the case (Figure 24). Previous warm periods identified using tree rings are not characterized by increases in lake production (Figure 27). It is possible that previous warming was insufficient to cause any change in lake production.

Scheffer and Carpenter (2003) suggest that gradual changes in temperature might have small effects on lakes until a critical temperature is reached and then lakes cross a “threshold” and enter a new regime. All temperatures from 1985 to 2012 CE of the Jasper climate station data are greater than the annual instrumental mean of 2.7°C, and 2005 CE is the warmest

temperature on record. It is possible that a threshold temperature has been reached in Little Trefoil Lake #3 and this may explain why percentage organics and chlorophyll *a* increase at such a fast rate after 1976 CE, aligning with Anthropogenic warming. To test this, a current tree-ring reconstructed temperature record could be used to replace the Jasper climate station data. This record could be compared to the RCS2004 temperature record and determine if the last few decades from 1985-2012 are unusually warm and whether a threshold temperature has been reached.

## 5.2 Is there a Link to Changes in the Lake Ecosystem, Landscape Change, and Fire?

Logging and forest fires are expected to cause an increase in the amounts of nutrients and sediment into lakes, affecting nutrient and light availability, and therefore lake production (Planas et al., 2000). There have been numerous fires in Little Trefoil Lake #3's history, with the number of fires decreasing after 1913 CE due to fire suppression enforced by Jasper National Park (Parks Canada, 2012; Tande, 1979). The largest fire on record was in 1889 CE (Tande, 1979), causing large amounts of charcoal to enter the lake system until 1937 CE (Figure 24). This large fire also coincides with the large decrease in chlorophyll *a* and increase in biogenic silica. General previous research has shown that fire has little effect on lake ecosystems (Laird & Cumming, 2001; McColl & Grigal, 1975; McColl & Grigal, 1977; Paterson et al., 1998; Wright, 1976), and when there is an effect it usually persists for only a few years (Planas et al., 2000). Moreover, most research has suggested that fire would increase nutrients, and therefore lake production, but the opposite is observed here. However, this fire was unusual as it was widespread in the region and burnt 21% of Jasper National Park with at least 50% around the Jasper town site burned (Luckman & Kavanagh, 2000; Tande, 1979). Fire scars were also found in British Columbia for the 1889 fire (Amoroso et al., 2011). One possibility, is that this fire affected algal production via light rather than nutrients. It is possible that the duration and intensity of this fire, coincident with road building and transport of building supplies, led to increased erosion that limited light. Previous research has shown that the increase in suspended solids from volcanic ash and glacier clay, similar to the charcoal and ash from the large 1889 CE

fire (Figure 23), can decrease the amount of light, affecting community compositions in lakes (Modenutti et al., 2012). McEachern et al. (2000) showed that algae in lakes impacted by fire in their catchments were light limited. An elevated level of inorganic suspended solids after the fire reducing the transparency and limited plant growth. The amounts of dissolved organic carbon also increased after fire events, reducing the amount of light availability as the transparencies decreased in burnt lake catchments (McEachern et al., 2000).

I tested this idea using diatom and chrysophyte analysis. The PCA sample scores on the first axis show trends similar to the chlorophyll *a* and percentage organics in Little Trefoil Lake #3 (Figure 24 and Figure 25). Although there is limited ecological information on the diatom species identified, the first PCA axis likely represents a change in lake habitats available to diatoms. The diatoms that are most negatively correlated to axis one (positively related to the time of fire) are *Denticula elegans* (16) and *Denticula kuetzingii* (17), which are epilithic (Stoermer & Smol, 2001). This time period is also characterized by greater abundances of small epipsammic *Fragilaria* species (20, 22, 25) and *Navicula cryptotenella* (29), *Navicula cryptotenella* fo. 1 PISCES (30), *Navicula radiosa* (35), and *Nitzschia palea* (40), which live attached to hard substrates (Friel, Finkelstein, & Davis, 2014; MacDonald et al., 1991) and lower abundances of planktonic *Cyclotella bodanica* (7) and *Stephanodiscus parvus* (44) and epiphytic *Amphora libyca* (3), *Cymbella minuta* (13), *Cymbella delicatula* (10) and *Cymbella ehrenbergii* (Round et al., 1990). A switch from epiphytic to epipsammic and epilithic diatoms signals a loss of aquatic plants, which would disappear with reduced light and a reduction in the littoral zone habitat. Lower abundances of planktonic diatoms, particularly *Cyclotella bodanica*, a heavily silicified diatom, would also indicate lower light conditions. Sampling of modern aquatic plants, rocks and sediments in Little Trefoil Lake #3 would provide better information on habitat preference of these diatoms.

Chrysophytes have been used as indicators of clear, nutrient-poor waters (Lotter, Birks, Hofmann, and Marchetto, 1998; Paterson, Betts-Piper, Smol, & Zeeb, 2003). The cysts in Little Trefoil Lake #3 decrease when the chlorophyll *a* and percentage organics decreased beginning around 1890-1900 CE, indicating that the lake may have shifted to more nutrients but because of turbidity from the 1889 fire CE, the production decreased.

Another possible factor that may have increased dust is land changes in the Little Trefoil Lake #3 area. Although the Jasper Park Lodge, roads, and the trestle bridge are not located in the catchment of Little Trefoil Lake #3, they are in close proximity and it is possible that the building of the Lodge that opened in 1922, moving of the supplies along a road just east of Little Trefoil Lake #3, and the road construction could have caused dust to enter the lake (VanCuren, Pederson, Lashgari, Dolislager, & McCauley, 2012). This construction and associated landscape changes between 1922 and 1960, could have resulted in the observed period of constantly low levels of chlorophyll *a* and percentage organics (Figure 24). Dust has the ability to decrease clarity in a lake (Zhu, Kuhns, Gillies, & Gertler, 2014). The dust from the construction, combined with the charcoal and the ash from the 1889 fire, could have exasperated the light availability in Little Trefoil Lake #3.

The percentage organics, chlorophyll *a*, and biogenic silica do not appear to respond to the largest fires in 1808 and 1815 CE of ZS1 Lake's record or any other fire event in the lake. Carcaillet, Richard, Asnong, Capece, and Bergeron (2006) were unable to find any link between the amount of charcoal in their lakes and the percentage organics to determine the severity of the fires within their catchment. They suggest that if there is a thick covering of mosses surrounding a lake, which is the case surrounding ZS1 Lake, that layer can protect against erosion and may mute the signal.

### 5.3 The Athabasca River

Little Trefoil Lake #3 is located only a few metres away from the Athabasca River and another possible explanation to the decrease in chlorophyll *a*, percentage organics, and chrysophyte cysts between ~1870 and 1910 CE is flooding of the river into Little Trefoil Lake #3. A study by Hay et al. (1997) looked at the diatoms found within lakes nearby the Mackenzie River, in the Northwest Territories, Canada. During flooding the lakes that are found within the Mackenzie River's floodplain had similar diatoms to the river, including *Asterionella formosa*, *Aulacoseira islandica*, *Fragiliaria ulna*, and *Nitzschia acicularis*. Reference lakes that did not get flooded had the following diatoms: *Achnanthes minutissima*, *Cocconeis placentula*, *Cymbella microcephala*, *Gomphonema acuminatum*, *G. angustum*, *G. minutum*, and *Rhoicosphenia*

*abbreviate*. These diatoms can only persist in lakes with little disturbance (Hay et al., 1997). The diatoms found in the floodplains of the Mackenzie River are not found in Little Trefoil Lake #3 and of the seven diatoms found in the non-flood lakes, Little Trefoil Lake #3 has five, *Achnanthes minutissima*, *Cocconeis placentula* (not found to be significant), *Cymbella microcephala*, *Gomphonema acuminatum*, and *G. angustum*. Due to the diatom community composition similarities between the non-floodplain lakes and Little Trefoil Lake #3, flooding of the Athabasca River into Little Trefoil Lake #3 is not considered likely. To test this thoroughly, however, diatoms from the Athabasca River should be determined or sediment grain size analyses completed.



## 5.4 Future Work

1. To determine if the higher temperatures observed in the Jasper climate station are unusually warm locally from 1985-2012 and whether a threshold temperature has been reached, the Jasper climate station data and the tree-ring reconstructed temperature record must be made more comparable to one another.
2. Determine carbon:nitrogen and or  $\delta^{13}\text{C}$  values of N-alkanes from ZS1 Lake sediments. This information would determine whether organics were mainly terrestrial or aquatic, which would allow me to test the importance of wetland contributions to sediment organics to better understand the consistent chlorophyll *a* and organic values in ZS1 Lake.
3. The current record of the ZS1 Lake from 1804 to 2004 CE would benefit from a longer record in percentage organics, chlorophyll *a*, and biogenic silica to see if any of the earlier changes recorded at Little Trefoil Lake #3 also occur in ZS1 Lake, which would suggest a regional factor, such as climate, driving the changes. This would require acquiring several more meters of sediments using a Livingstone coring device.
4. An analysis completed at more lakes in the region of Jasper National Park of similar size to Little Trefoil Lake #3 would be beneficial to compare if the effects of the 1889 fire and recent climate change are widespread. Having a control lake, not effected by fire or human land use, would also help understand the change between ~1880 and 2003 CE in Little Trefoil Lake #3.
5. Additional higher resolution diatom work could help to better understand changes in chlorophyll *a* and biogenic silica at Little Trefoil Lake #3. Diatom data prior to 1714 CE in Little Trefoil Lake #3 could provide a better understanding of the factors driving changes.

## Chapter 6

### 6 Conclusion

The research presented in this thesis supports the following conclusions:

- The Canadian Rocky Mountains has seen a 1.5°C increase in mean annual temperatures over the last century, with the warmest temperatures occurring in the last 20-30 years. From 1970 CE to the present, Little Trefoil Lake #3 has seen an increase in production as represented by increased percentage organics and chlorophyll *a* at a faster rate than anytime previously. A rapid rise in temperature would result in less ice cover, a longer growing season, changes in thermal stratification and potentially more available nutrients, having the potential to increase lake production. Given the Intergovernmental Panel on Climate Change projections of an increase of 1.4°C to 5.8°C of global temperatures, and similar increases expected in Alberta, by 2100 CE, algal production is expected to continue to increase, at least until other factors, such as nutrients, become limiting.
- The biogenic silica in Little Trefoil Lake #3 has decreased in contrast to the increasing percentage organics and chlorophyll *a*, therefore negatively tracking the temperature records. With an increase in temperature, blue-green and green algae can outcompete diatoms if silica becomes limiting as diatom populations increase, which is possible given the underlying limestone bedrock.
- If the recent changes in lake production at Little Trefoil Lake #3 are climate-driven, we would expect to see similar changes at ZS1 Lake, but we do not see this. At ZS1 Lake, the percentage organics and chlorophyll *a* have been relatively similar throughout its record. ZS1 Lake's catchment is larger in area compared to Little Trefoil Lake #3 and therefore may not be as sensitive to climactic changes. ZS1 Lake is also surrounded by wetland vegetation, which may be the main source of organics to ZS1 Lake, and therefore mute any signal in chlorophyll *a* and percentage organics caused by climate change.

- The intensity of the 1889 CE fire in Little Trefoil Lake #3 resulted in higher amounts of charcoal amounts than in the fire record, associated with a decrease in percentage organics, chlorophyll *a*, and cysts:diatoms. The amount of charcoal, ash, and dust could have decreased the amount of light availability and reduced lake production.
- Earlier in the Little Trefoil Lake #3's fire record, there were series of smaller fires where the charcoal amounts increased but nowhere to the extent of the 1889 CE fire. Smaller fires have been known to increase the amounts of nutrients in lakes for around a 5 year period after fires. This was also seen in Little Trefoil Lake #3; the chlorophyll *a* amounts increased for a period of five-ten years after the smaller fires.

## 6.1 Implications of Research

This research has implications for how lakes in Alberta will respond to warming temperatures. With predictions for increased temperatures, drier summers, and more severe and intense fires, the findings in this paper will give the Government of Alberta, Jasper National Park, forestry companies in Hinton, and others who manage water and the environment in the Jasper Park region more knowledge on how to protect these important resources. Possible changes Jasper National Park can impliment to reduce impacts of large fires on lake production is reduce how prone forests are to intense fires. Jasper Natioanl Park is already trying to accomplish this by scheduling prescribed fires. The long-term record in Little Trefoil Lake #3 and ZS1 Lake have been somewhat constant with very few changes, with Little Trefoi Lake #3 showing the largest impacts occurred within the past 150 years, the Anthropocene. This suggests that lakes in Jasper National Park are not isolated from human disturbances despite being located within a protected wilderness, indicating that these ecosystems need to be protected.

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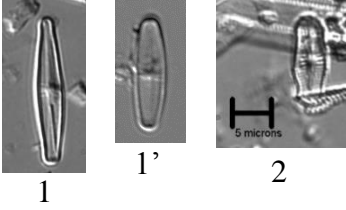
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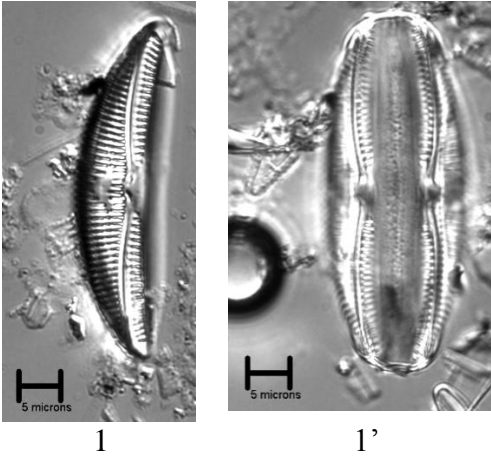
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1: *Achnanthes minutissima*  
2: *A. rosenstockii*



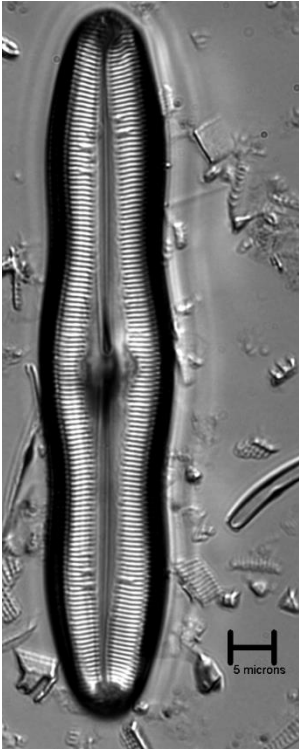
1: *Amphora libyca*



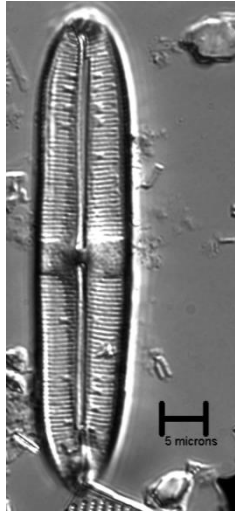
1: *Brachysira vitrea*

**Plate 1.** *Achnanthes*, *Amphora*, and *Brachysira* species.



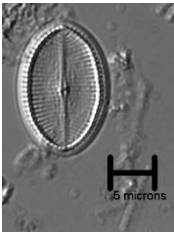


1



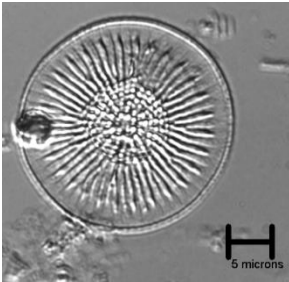
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1: *Caloneis silicula*

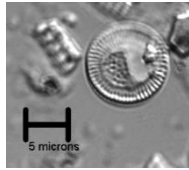


1

1: *Cocconeis placentula* var. *euglypta*



1

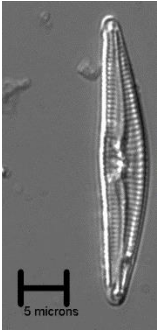


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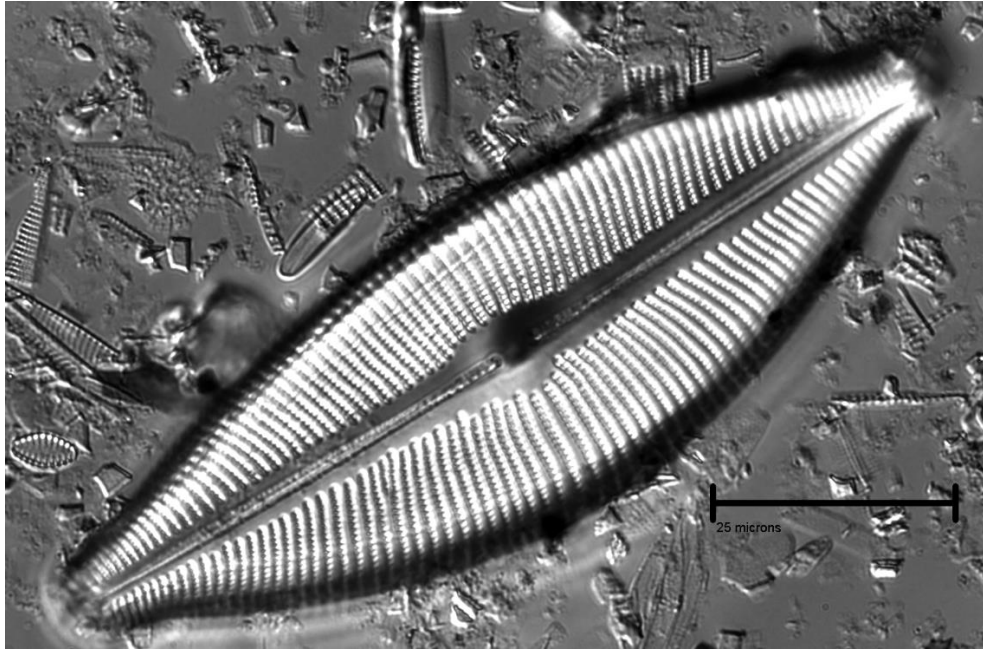
1: *Cyclotella bodanica*

2: *C. michiganiana*

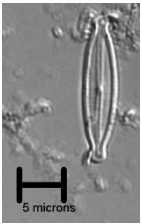
**Plate 2.** *Caloneis*, *Cocconeis*, and *Cyclotella* species.



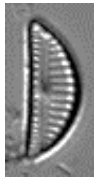
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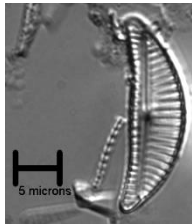
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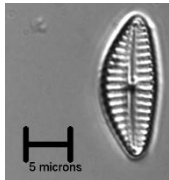
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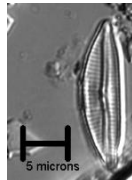
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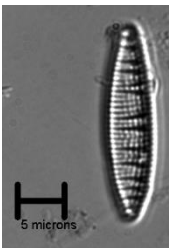


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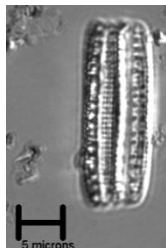


6

- 1: *Cymbella delicatula*
- 2: *C. ehrenbergii*
- 3: *C. microcephala*
- 4: *C. minuta*
- 5: *C. muelleri*
- 6: *C. sp.* 1 PISCES



1



2

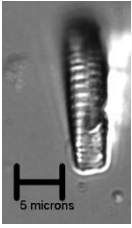
- 1: *Denticula elegans*
- 2: *D. kuetzingii*



1

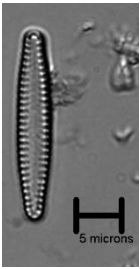
- 1: *Diatoma moniliformis*

**Plate 3.** *Cymbella*, *Denticula*, and *Diatoma* species.

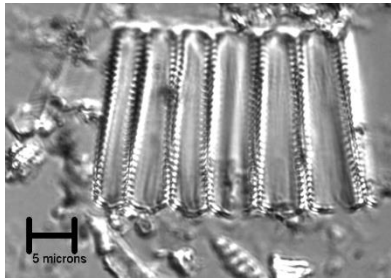


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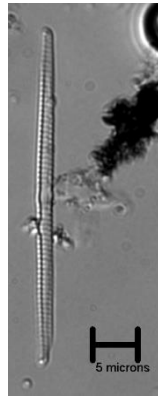
1: *Eunotia*



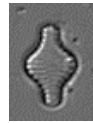
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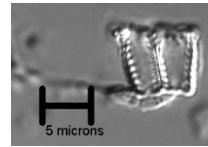
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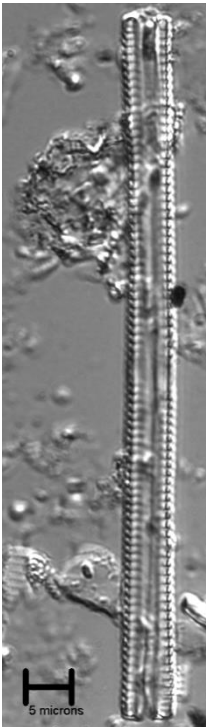
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3



4



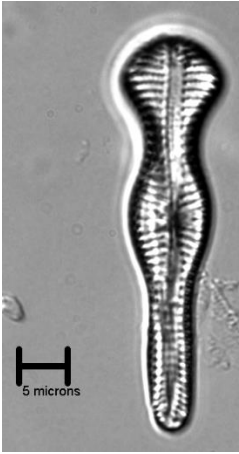
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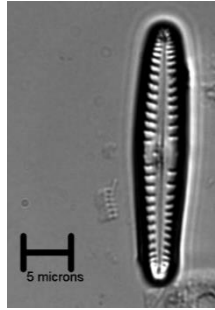
6

- 1: *Fragilaria brevistriata*
- 2: *F. cf. tenera*
- 3: *F. construens*
- 4: *F. construens* var. *venter*
- 5: *F. fasciculata*
- 6: *F. pinnata*

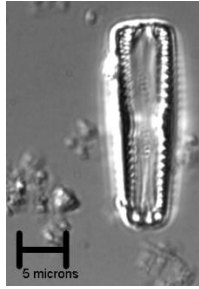
Plate 4. *Eunotia* and *Fragilaria* species.



1

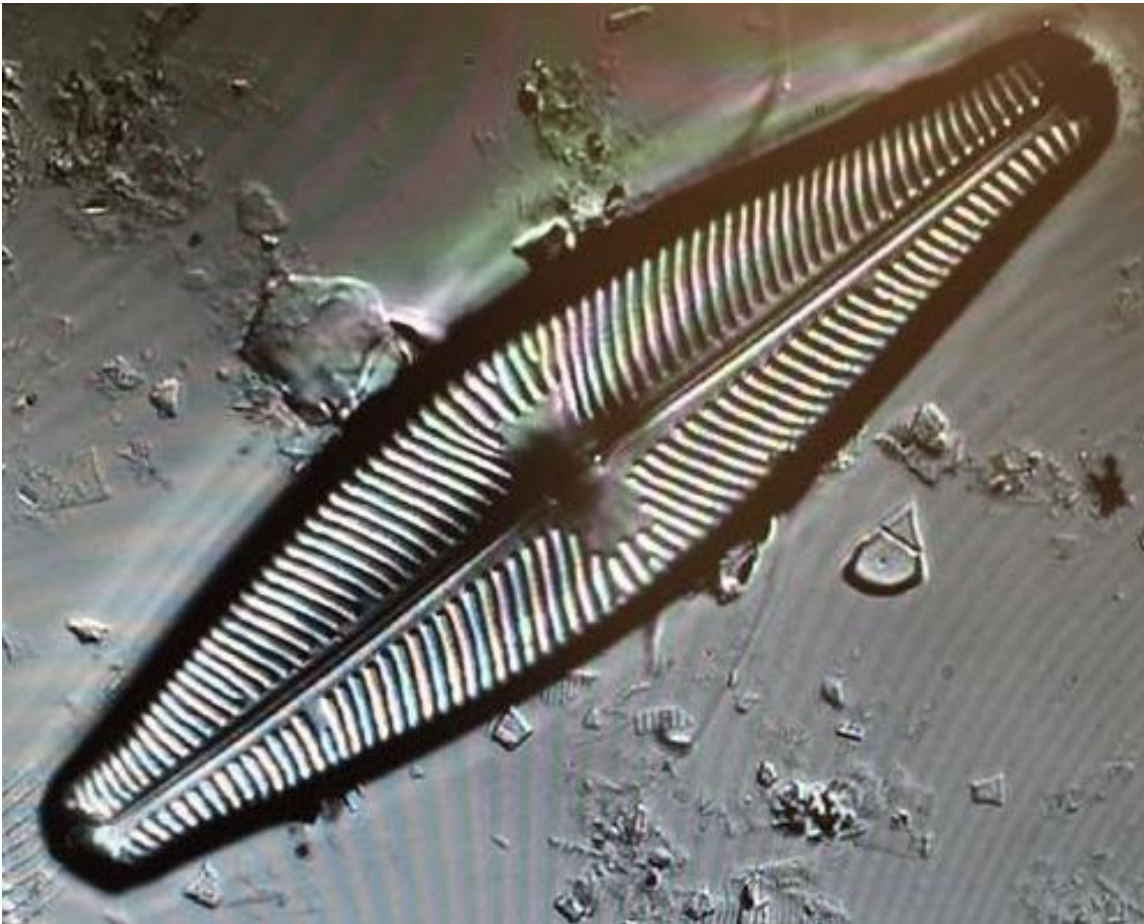


2



2'

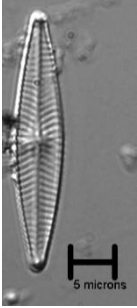
1: *Gomphonema acuminatum*  
2: *G. angustum*



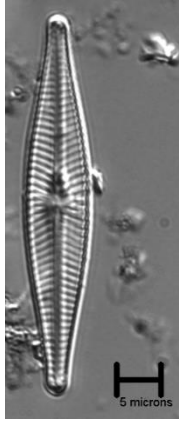
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1: *Navicula aurora*

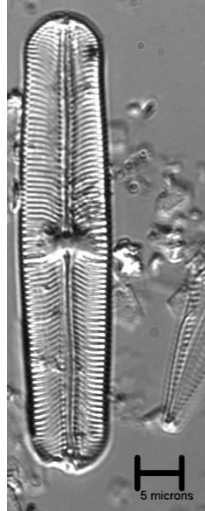
Plate 5. *Gomphonema* and *Navicula* species.



2

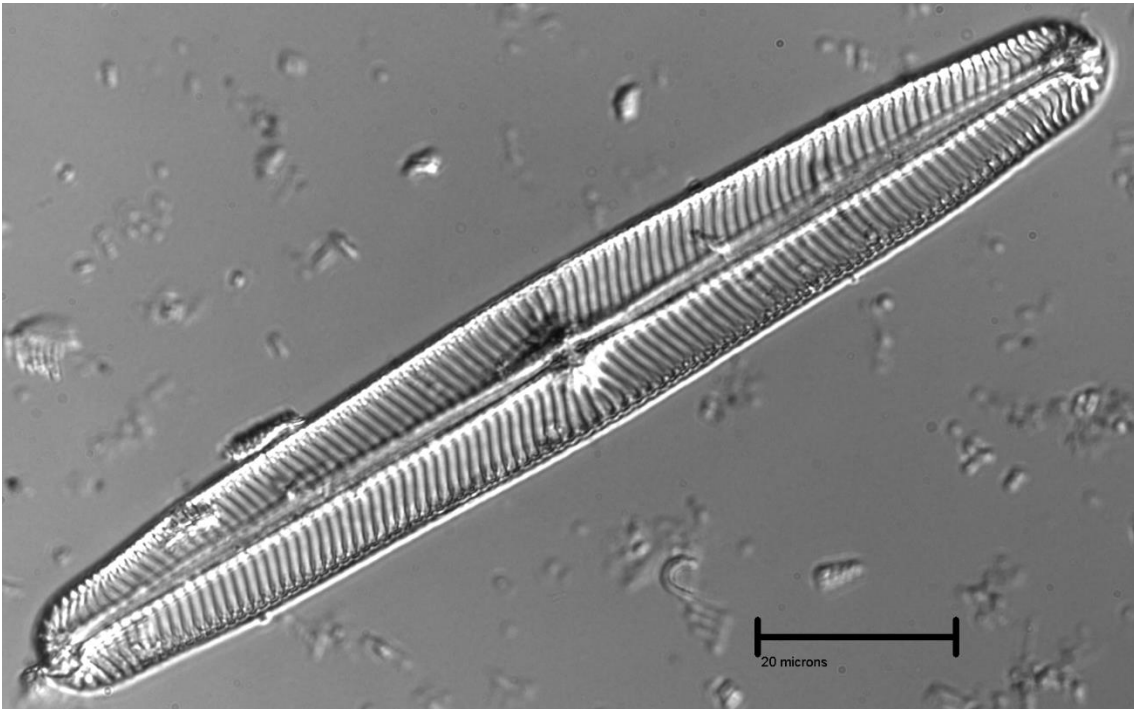


3



4

- 2: *Navicula cryptotenella*
- 3: *N. cryptotenella* fo. 1 PISCES
- 4: *N. laevissima*
- 5: *N. oblonga*
- 6: *N. pupula*
- 7: *N. radiosa*
- 8: *N. vulpina*
- 9: *N. tuscula*



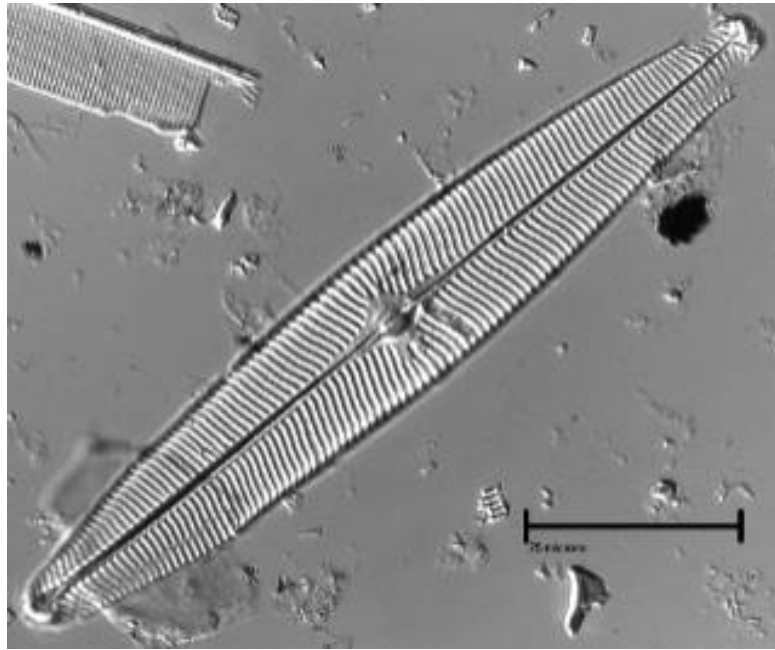
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**Plate 6.** *Navicula* species.

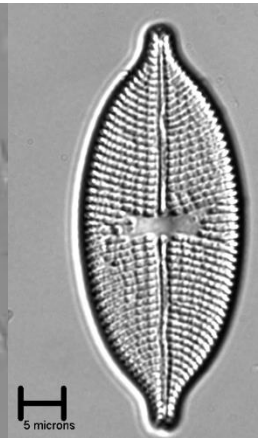




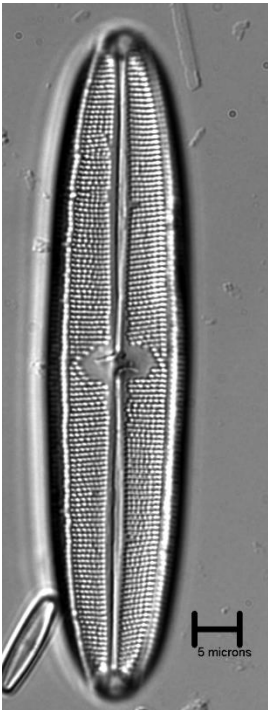
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7



8

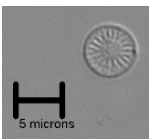
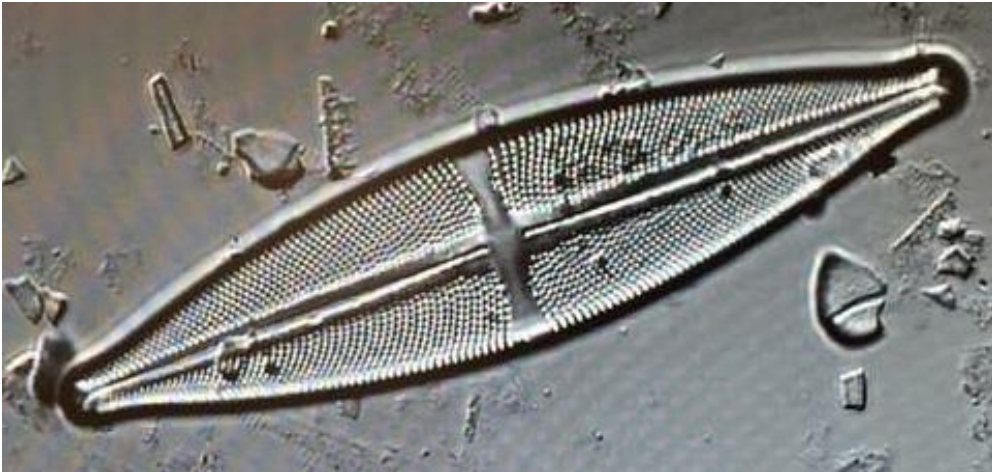
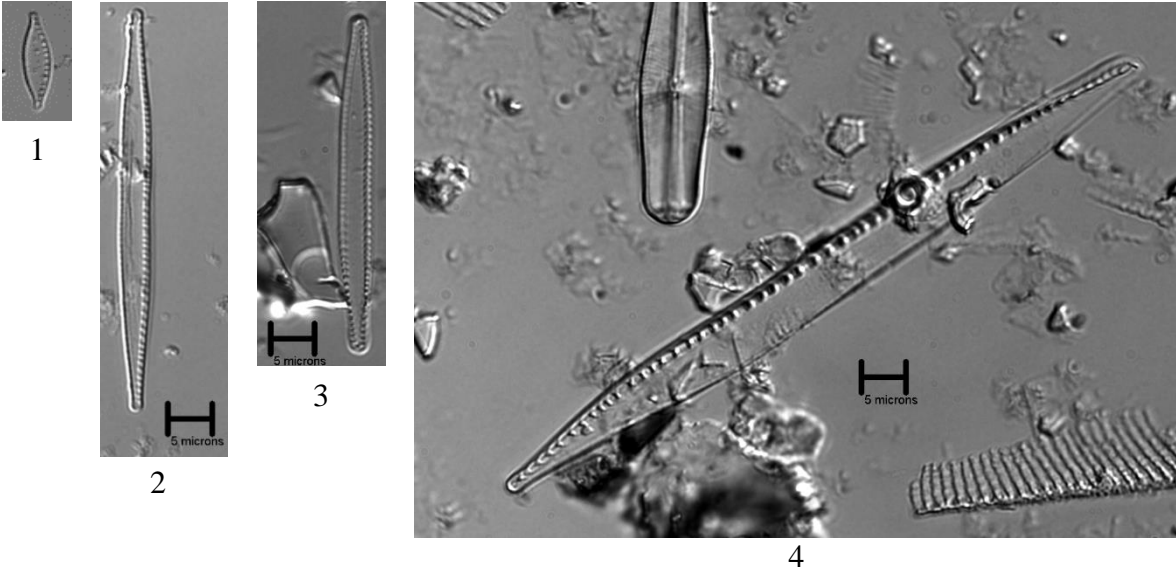


1

- 6: *Navicula pupula*
- 7: *N. vulpina*
- 8: *N. tuscula*

1: *Neidium ampliatus*

**Plate 7.** *Navicula* and *Neidium* species.



1

1: *Nitzschia fonticola*

2: *N. palea*

3: *N. radicula*

4: *N. recta*

1

1: *Stauroneis phoenicenteron*

1: *Stephanodiscus parvus*

**Plate 8.** *Nitzschia*, *Stauroneis*, and *Stephanodiscus* species.

## Appendices

Appendix A: MyCore  $^{210}\text{Pb}$  information for Little Trefoil Lake #3 and ZS1 Lake.

**Table 3:  $^{210}\text{Pb}$  in Little Trefoil Lake #3 for the gravity core (GC).**

<b>Core 07-JP-02</b>	<b>Sample Type</b>	<b>Depth (cm)</b>	<b><math>^{210}\text{Pb}</math> (Bq/g)</b>	<b><math>^{210}\text{Pb}</math> Age (CE)</b>	<b>STD (in years)</b>
GC	Sediment	0-1	0.480	2007.6	0
GC	Sediment	1-1.5	0.480	2007.4	0
GC	Sediment	2-3	0.419	2006.8	0
GC	Sediment	3.5-4	0.544	2005.6	0
GC	Sediment	5.5-6	0.701	2002.8	0
GC	Sediment	7.5-8	0.649	1999	1
GC	Sediment	9.5-10	0.484	1995	1
GC	Sediment	12.5-13	0.615	1988	1
GC	Sediment	15.5-16	0.460	1978	3
GC	Sediment	18.5-19	0.338	1964	5
GC	Sediment	21.5-22	0.219	1948	10
GC	Sediment	25-25.5	0.130	1929	24
GC	Sediment	30-30.5	0.077	1888	70
GC	Sediment	35-35.5	0.047	Background	Background
GC	Sediment	40-40.5	0.046	Background	Background
GC	Sediment	43-43.5	0.020	Background	Background

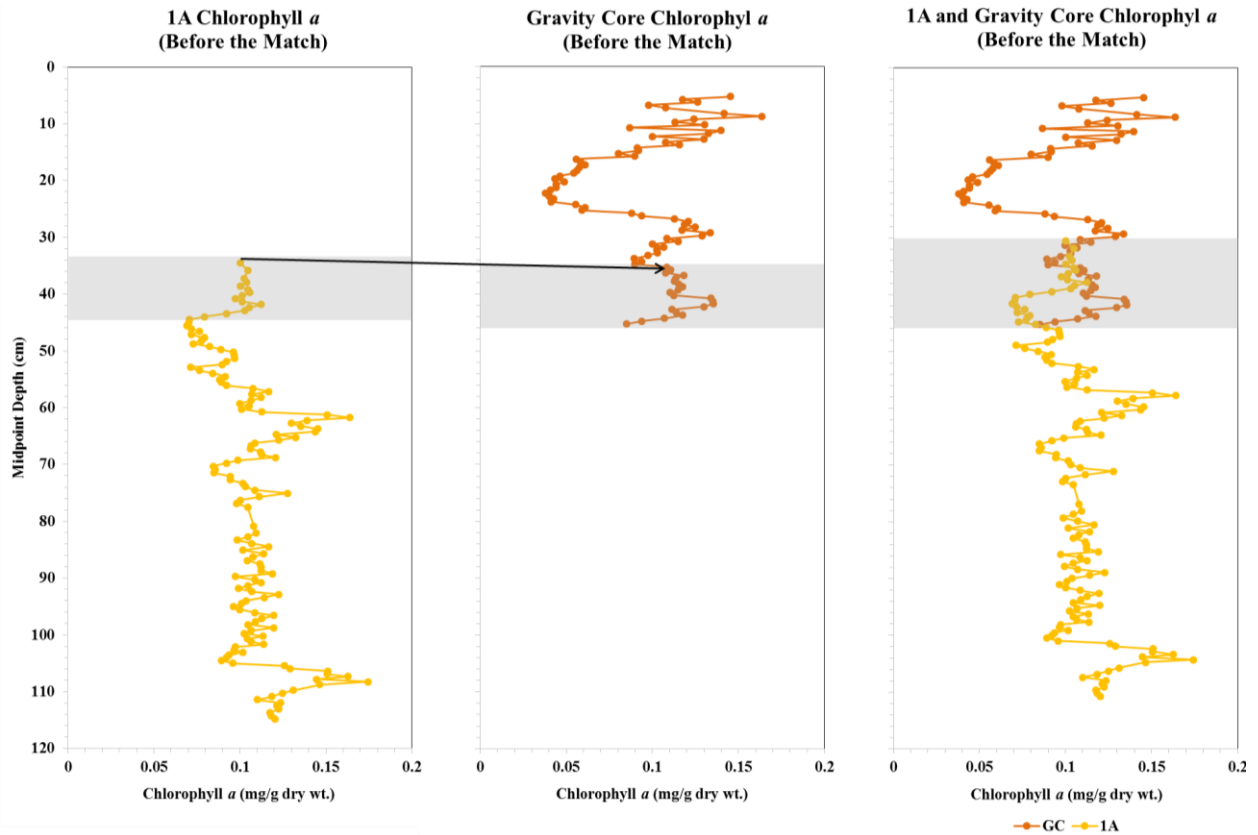


**Table 4:  $^{210}\text{Pb}$  in ZS1 Lake.**

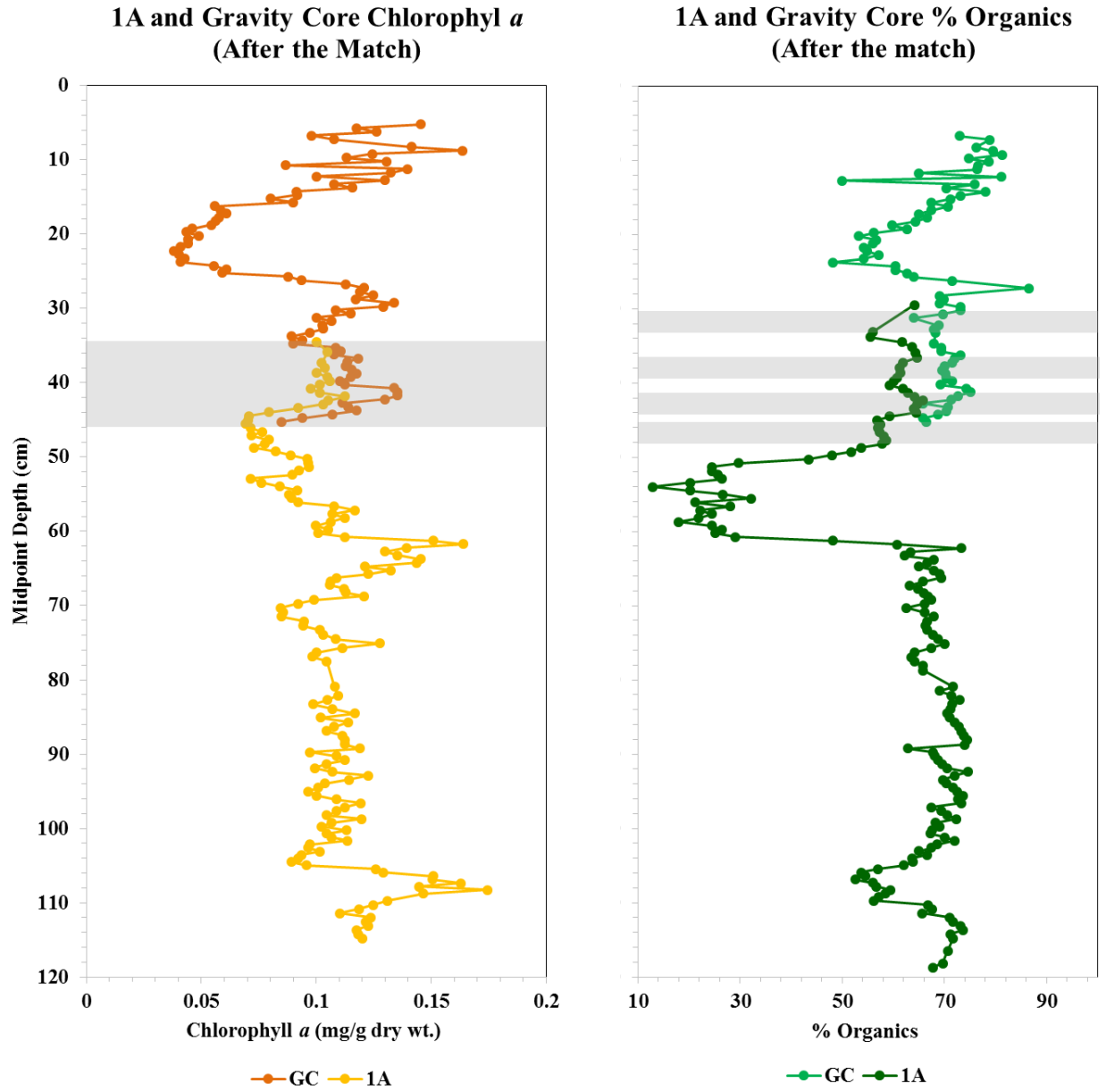
<b>Core 13-ZS1</b>	<b>Sample Type</b>	<b>Depth (cm)</b>	<b><math>^{210}\text{Pb}</math> (Bq/g)</b>	<b><math>^{210}\text{Pb}</math> Age (CE)</b>	<b>STD (in years)</b>
13-ZS1	Sediment	1.5-2.0	0.750	2011	0.2
13-ZS1	Sediment	3.0-3.5	0.649	2008	0.3
13-ZS1	Sediment	4-4.5	0.601	2007	0.3
13-ZS1	Sediment	5-6.5	0.639	2004	0.6
13-ZS1	Sediment	6.5-7	0.582	1999	0.6
13-ZS1	Sediment	8.5-9.5	0.507	1995	0.8
13-ZS1	Sediment	12-12.5	0.351	1983	1.9
13-ZS1	Sediment	14.5-15	0.329	1978	2.1
13-ZS1	Sediment	19.5-20	0.163	1961	4.3
13-ZS1	Sediment	24-24.5	0.128	1950	6.6
13-ZS1	Sediment	29-29.5	0.095	1933	9.4
13-ZS1	Sediment	34-34.5	0.071	1916	18.2
13-ZS1	Sediment	49-49.5	0.013	Background	Background
13-ZS1	Sediment	56.5-57	0.007	Background	Background

Appendix B: Little Trefoil Lake #3 core correlation between the chlorophyll *a* in the gravity core and 1A livingstone core. The percentage organics was used to check the match made with the chlorophyll *a*.

A depth of 36.25cm in Livingstone core 1A was matched to 40.25cm in the gravity core (Appendix B, Figure 29), a difference of 4cm. Therefore, a correction of 4cm was added to 1A. Once the addition of 4cm was made on 1A, the percentage organics data was used to make sure the chlorophyll *a* match was sound (Appendix B, Figure 30). There were four data points in the 1A percentage organics that matched similarly to the percentage organics in the gravity core to support the chlorophyll *a* match; 1A 29.50cm matched with the gravity core 30.3cm, 36.58cm to 36.3cm, 40.3cm to 40.3cm, and 45.6cm to 45.3cm.



**Figure 29: The gravity core (GC) and 1A chlorophyll *a* (mg/g dry wt.) against the midpoint depth (cm) before the cores were matched in Little Trefoil Lake #3.**



**Figure 30: Matched Little Trefoil Lake #3 a) gravity core (GC) and 1A chlorophyll *a* (mg/g dry wt.), and b) percentage organics against the midpoint depth (cm).**

## Appendix C: Core correlation for diatom community composition.

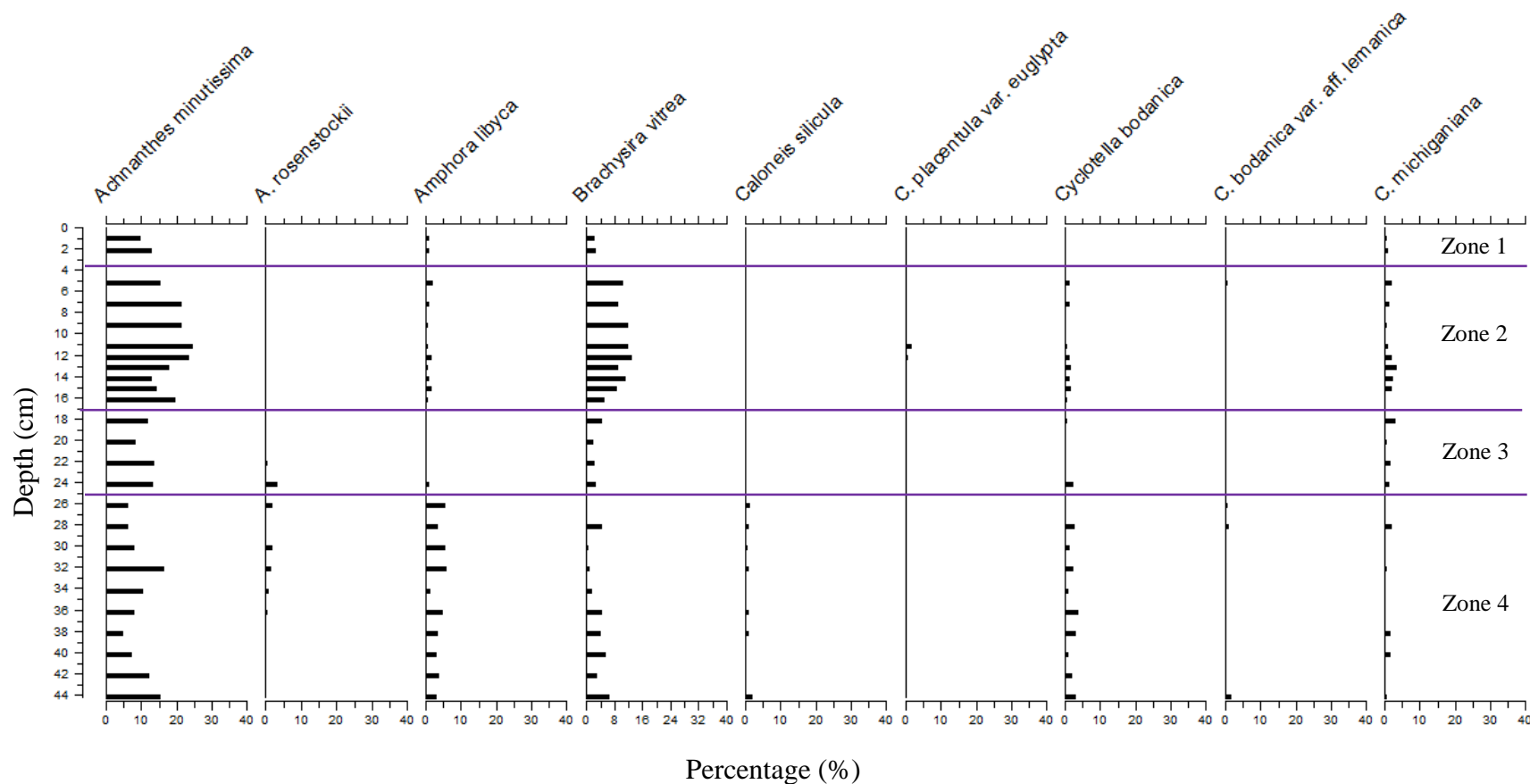
The additional Little Trefoil Lake #3 gravity core collected in the summer of 2014 CE was used to have the most recent seven years of diatom data to add to the top of the gravity core collected in 2007 CE. Diatom slides were made for samples at 1cm, 4cm, 8cm, 16cm, 20cm and 24cm in the 2014 CE core in order to match to the 2007 CE core. The diatom *Fragilaria cf. tenera* in 1cm and 4cm samples in 2014 CE, had percentages of 18 and 30, respectively. This diatom was not significant in the 2007 CE core, with maximum percentages of two, meaning samples 1cm and 4cm of 2014 CE were between 2007 CE and 2014 CE. *Fragilaria pinnata* only appeared in the 2014 CE core at 20cm and 24cm, with percentages of four to six. This diatom only appeared in the 2007 CE core between 18cm and 22cm at percentages of four to 10, indicating that the cores must match in this area. Based on these matches, the diatom data from 1cm and 4cm of 2014 CE were added to the top of the 2007 CE diatom data at 0.5cm and 2.50cm.

Appendix D: Legend for the number representation of significant diatoms for Figure 21.

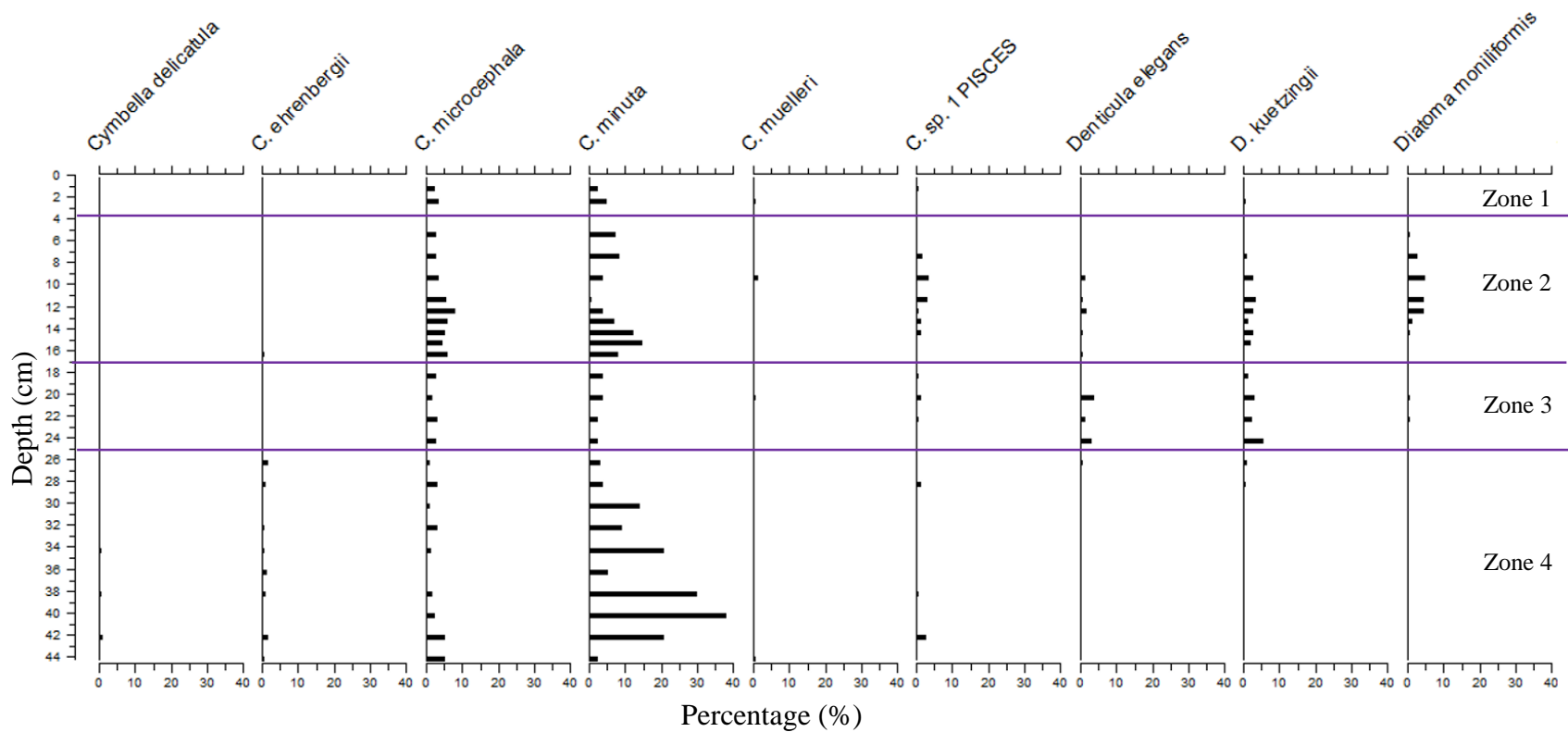
**Table 5: Legend for the number representation of diatom species in Figure 21.**

<b>Legend for Figure 21</b>	<b>Diatom</b>	<b>Legend for Figure 21</b>	<b>Diatom</b>
1	<i>Achnanthes minutissima</i>	23	<i>F. construens</i> var. <i>venter</i>
2	<i>A. rosenstockii</i>	24	<i>F. fasciculata</i>
3	<i>Amphora libyca</i>	25	<i>F. pinnata</i>
4	<i>Brachysira vitrea</i>	26	<i>Gomphonema acuminatum</i>
5	<i>Caloneis silicula</i>	27	<i>G. angustum</i>
6	<i>Cocconeis placentula</i> var. <i>euglypta</i>	28	<i>Navicula aurora</i>
7	<i>Cyclotella bodanica</i>	29	<i>N. cryptotenella</i>
8	<i>C. bodanica</i> var. aff. <i>lemanica</i>	30	<i>N. cryptotenella</i> fo. 1 PISCES
9	<i>C. michiganiana</i>	31	<i>N. explanata</i>
10	<i>Cymbella delicatula</i>	32	<i>N. laevisissima</i>
11	<i>C. ehrenbergii</i>	33	<i>N. oblonga</i>
12	<i>C. microcephala</i>	34	<i>N. pupula</i>
13	<i>C. minuta</i>	35	<i>N. radiosa</i>
14	<i>C. muelleri</i>	36	<i>N. vulpina</i>
15	<i>C. sp. 1 PISCES</i>	37	<i>N. tuscula</i>
16	<i>Denticula elegans</i>	38	<i>Neidium ampliatum</i>
17	<i>D. kuetzingii</i>	39	<i>Nitzschia fonticola</i>
18	<i>Diatoma moniliformis</i>	40	<i>N. palea</i>
19	<i>Eunotia</i>	41	<i>N. radricula</i>
20	<i>Fragilaria brevistriata</i>	42	<i>N. recta</i>
21	<i>F. cf. tenera</i>	43	<i>Stauroneis phoenicenteron</i>
22	<i>F. construens</i>	44	<i>Stephanodiscus parvus</i>

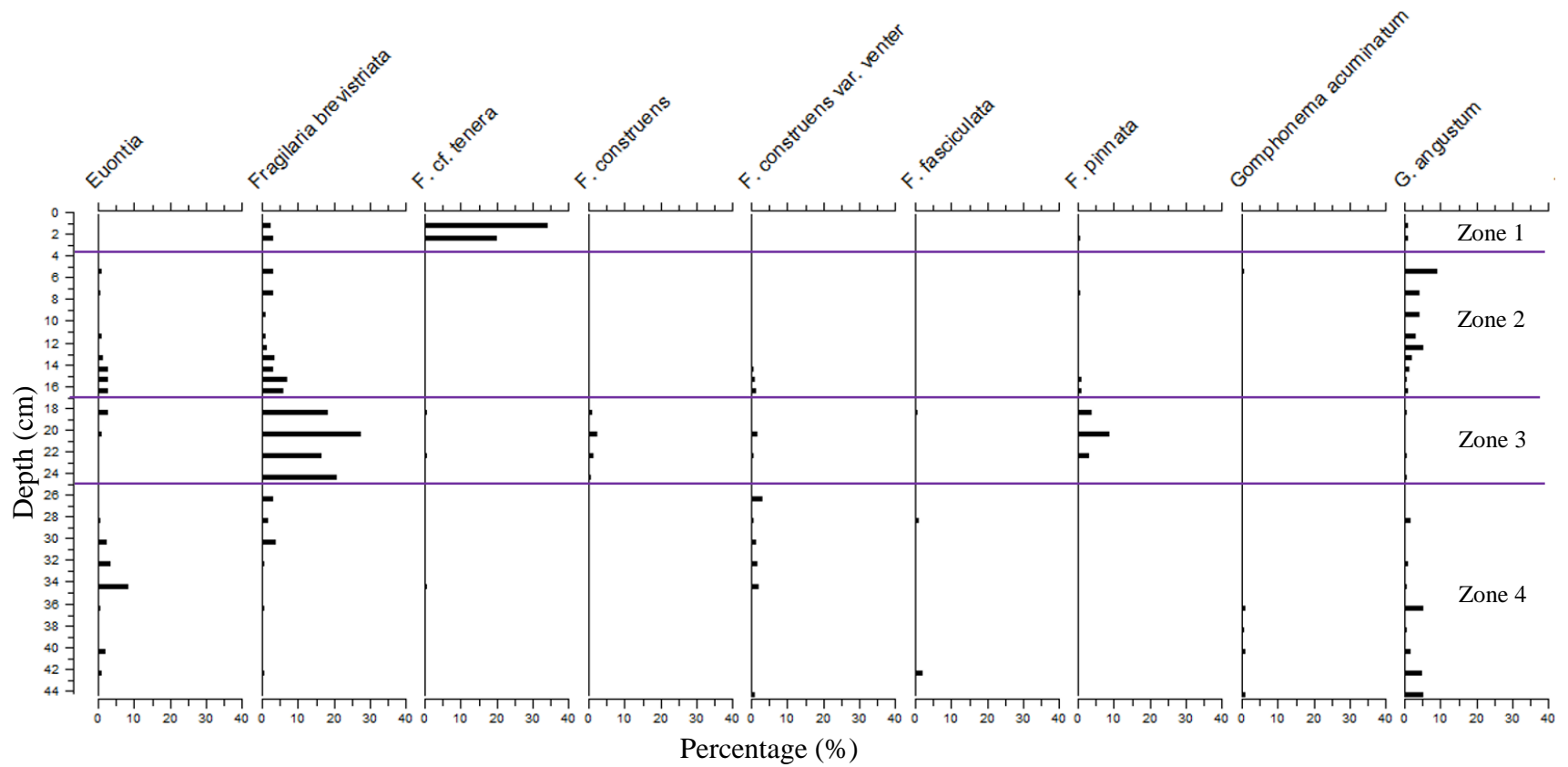
Appendix E: Diatoms stratigraphy plots for Little Trefoil Lake #3 from 0 to 44cm.



**Figure 31: Diatom stratigraphy (0-40%), including *Achnanthes minutissima*, *A. rosenstockii*, *Amphora libyca*, *Brachysira vitrea*, *Caloneis silicula*, *Cocconeis placentula* var. *euglypta*, *Cyclotella bodanica*, *C. bodanica* var. aff. *lemanica*, and *C. michiganiana* against depth (cm). The zones are based on changes in the PCA diatom community composition in Figure 22.**

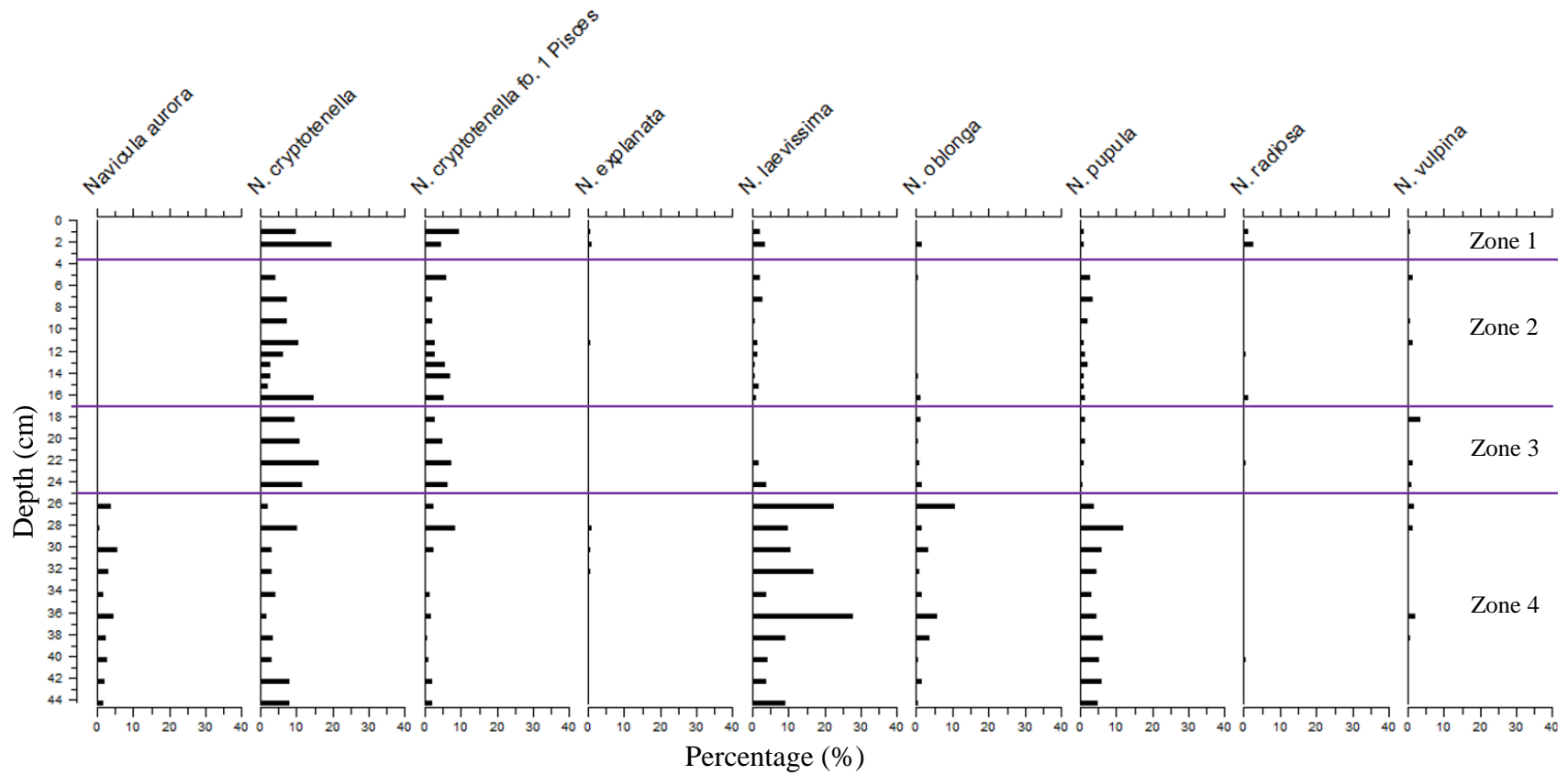


**Figure 32: Diatom stratigraphy (0-40%), including *Cymbella delicatula*, *C. ehrenbergii*, *C. microcephala*, *C. minuta*, *C. muelleri*, *C. sp. 1 PISCES*, *Denticula elegans*, *D. kuetzingii*, and *Diatoma moniliformis* against depth (cm). The zones are based on changes in the PCA diatom community composition in Figure 22.**

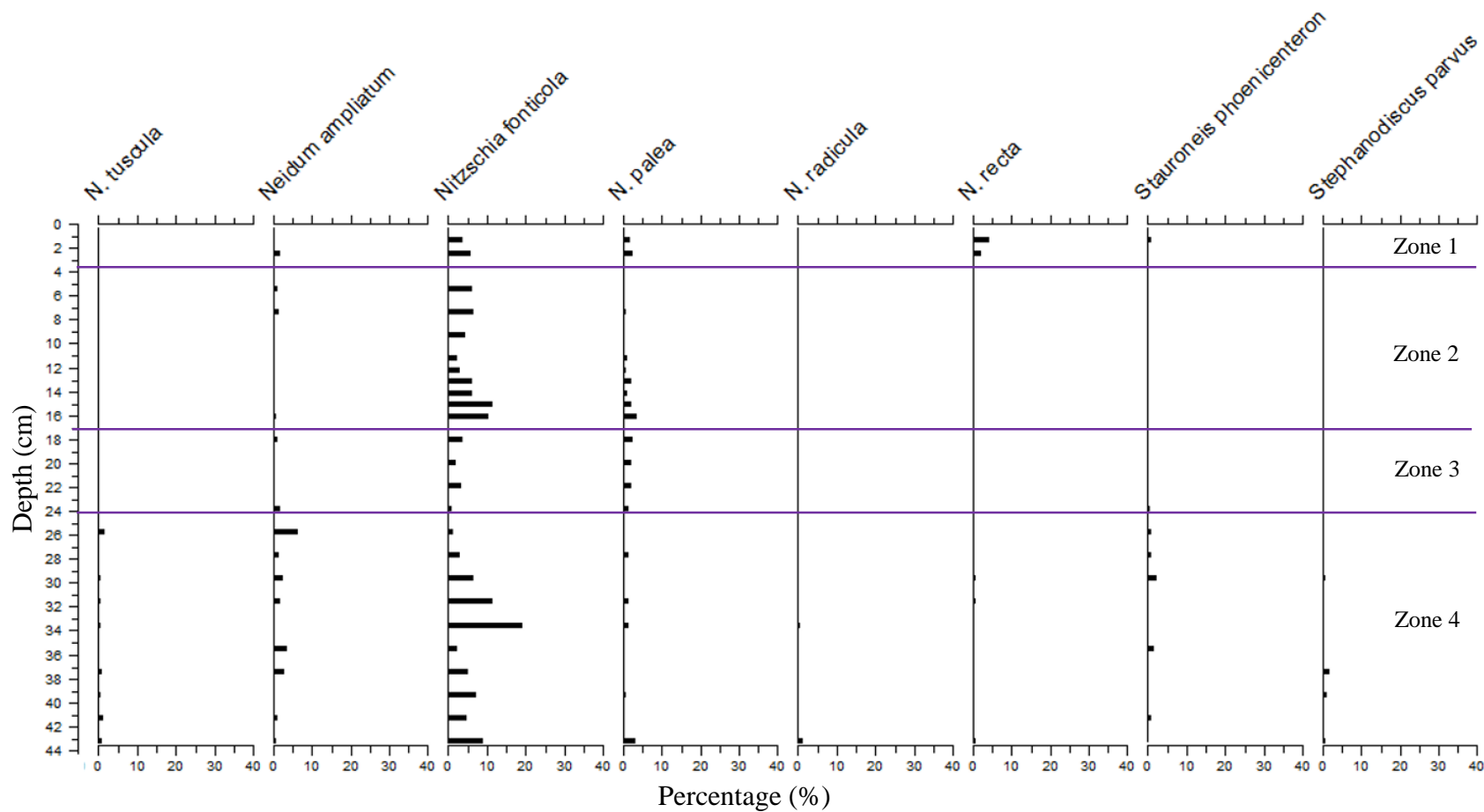


**Figure 33: Diatom stratigraphy (0-40%), including *Eunotia*, *Fragilariopsis brevistriata*, *F. cf. tenera*, *F. construens*, *F. construens var. venter*, *F. pinnata*, *Gomphonema acuminatum*, and *G. angustum* against depth (cm). The zones are based on changes in the PCA diatom community composition in Figure 22.**





**Figure 34: Diatom stratigraphy (0-40%), including *Navicula aurora*, *N. cryptotenella*, *N. cryptotenella* fo. 1 PISCES, *N. explanata*, *N. laevissima*, *N. oblonga*, *N. pupula*, *N. radiosa*, and *N. vulpina* against depth (cm). The zones are based on changes in the PCA diatom community composition in Figure 22.**



**Figure 35: Diatom stratigraphy (0-40%), including *N. tuscula*, *Neidium ampliatum*, *Nitzschia fonticola*, *N. palea*, *N. radiculata*, *N. recta*, *Stauroneis phoenicenteron*, and *Stephanodiscus parvus* against depth (cm). The zones are based on changes in the PCA diatom community composition in Figure 22.**

# Curriculum Vitae

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