TRACKING LONG-TERM RESPONSES OF CHIRONOMIDS TO HUMAN SETTLEMENT

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ABSTRACT

Anthropogenic stress has altered the ecological integrity of freshwater lakes for millennia. This remains a confounding factor when examining ecological changes prior to human records. Freshwater management attempts to understand human-induced damage that occurred in the past. Here, the applicability of paleolimnological methods to study complex socioecological systems is investigated. Paleolimnology is an essential methodology for informed environmental management using bioindicators to infer missing monitoring data. A systematic map demonstrated that paleolimnological strategies have wide applicability to reconstruct the relationship between humans and freshwater ecosystems. Fossil chironomid heads were then used to reconstruct the impact of humans on the ecological function of Chocolate Lake, N.S. The fossil record revealed a drastic change in ecological state from wetland to temperate lake, which was then impacted from human disturbances, e.g., industrialization and residential development. Paleolimnological studies can show the impacts of climate and human disturbance, making them essential for freshwater resource management.

LIST OF ABBREVIATIONS USED

^{14}C	Carbon-14
^{210}Pb	Lead-210
CE	Common era
Cl^-	Chloride
CRS	Constant rate of supply model
GHGs	Greenhouse gases
HC g_{-1} DW	Head capsules per gram of dry weight
HRM	Halifax Regional Municipality
KOH	Potassium hydroxide
LOI	Loss on ignition
MeHg	Methyl mercury
N. S.	Nova Scotia
TP	Total phosphorus
WESS	Laboratory for Water and Environmental Sustainability Sciences
years BP	Years before present

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CHAPTER 1 INTRODUCTION

1.1 Statement of Student Contributions

Chapter design by Allison Covert, chapter writing by Allison Covert with editorial contributions from Andrew Medeiros.

1.2 Introduction

Human activity and development within watersheds have resulted in considerable impacts on the health and functioning of freshwater ecosystems. A healthy ecosystem can be defined as one that is resilient to ecological stressors, maintaining its ecological structure and function, but also continuing to provide ecosystem services to meet the needs and expectations of society (Meyer 1997). Societies have “taken” from freshwater ecosystems since the earliest human presence, initially using waterways for travel which has since evolved to also include “taking” for managing municipal and industrial wastes, cooling purposes, irrigation, power generation, and for recreation and aesthetic displays (Encyclopaedia Britannica, inc. n.d.). As we have changed the way in which we interact with the environment so have our values towards it. Early human populations for example, relied on freshwater bodies to support their subsistence lifestyle and had an intimate relationship with the ecosystem. Today as we have distanced ourselves from the system, societal values have become embedded in the assessment of ecosystems and has resulted in a subjective perspective of what the desired state of an ecosystem should be (Pollard and Huxham 1998). For example, the need to support larger populations have prioritized large-scale farming practices that have accelerated the deterioration of freshwater ecosystems on a global scale (Hannah et al. 1994). There is a need in today’s society for us to understand how we have impacted freshwater ecosystems before further destruction and irremediable changes take place. To assess our current and future impacts, we first need to understand the past.

Here, paleoenvironmental data demonstrates how human settlement, societal growth, and urbanization has impacted the health of freshwater ecosystems as we continue to live in a human-dominated system. Paleolimnology is the study of the accumulated sediment in inland water basins to understand ecological and environmental change (Frey 1988). Lake histories can be reconstructed as freshwater lakes are susceptible to physical, chemical, and biological changes, making them good sentinels of environmental stressors, such as eutrophication, lake acidification, and climate change (Schindler 2001). Several environmental responses are quantifiable with paleolimnological methods, such as changes in water chemistry, water temperature, and biological indicator composition (Adrian et al. 2009). As such, monitoring changes in community composition of invertebrates, such as chironomids can be important for understanding environmental changes induced by human presence. Paired with sediment dating and historical records, paleolimnological data can be crucial for distinguishing human impacts from natural processes that drive change (Paterson et al. 2020). Ultimately, paleolimnological studies can aid in research related to biodiversity, or assessing changes related to local or regional environmental pollution, or, in the case of this study, tracking long-term environmental change potentially attributable to changes in human presence (Smol 2008).

Paleolimnological techniques can also help us as a society to understand the impact of human development on the health and functioning of ecosystems. A common misconception has existed surrounding the impact that human activities can have on freshwater ecosystems; remote regions have been thought to be unimpacted by anthropogenic activity. Recent research, however, has shown that remote freshwater lakes in the high Arctic have in fact been impacted by early human populations in the region (Douglas et al. 2004). Today, to satisfy the needs of the world's ever-growing human population, extensive anthropogenic pressure has been placed on freshwater lakes and has impacted the ecosystem services they provide to society, pressures such as lakeside development, the application of pesticides and fertilizers, and road salt runoff. Recent urbanization (within the past ~200 years) has reduced the health of freshwater lakes and their capacity of providing ecosystem services (Huot et al. 2019); such as clean water for wildlife, recreational enjoyment, and aesthetic value. Canada in particular, is known for its abundance of freshwater resources, containing 20% of the world's total freshwater, 7% of the world's renewable water (Canada 2018). Nova Scotia alone has over 3000 lakes, with 5% of the land area covered by freshwater bodies including rivers and wetlands (Nova Scotia Museum of Natural History 1996; Beck 2019). These bodies of water are valued for the diverse set of environmental services they provide that have allowed for settlement, the development of regional activities, and economic profitability throughout the history of the province (Beck 2019). Seiler et al. (2001) found a lake view increases home value by approximately 56%. Unfortunately, this value is dependent on the state of the health of the water, and the activities that took place during the industrial era (1800s and 1900s) have seriously degraded the health of freshwater lakes. Human activities, such as the creation of reservoirs by damming, human development along shorelines, and the leaching of pollutants and excess nutrients into the waters have led to polluted water bodies and have depreciated property values across the continent (Seiler et al. 2001; Nguyen-Quang et al. 2016). Furthermore, the adverse anthropogenic stressors acting on freshwater ecosystems have been compounded by natural environmental stressors, such as anthropogenically induced climate warming. It is expected that freshwater bodies will be one of the primary mediums through which climate change impacts are felt (United Nations 2010). The study of freshwater is therefore pivotal to understand the susceptibility and vulnerability of communities who benefit from healthy freshwater systems.

Here, the relationships between environmental change and their impact on society, and the influence of human disturbance on freshwater ecosystems is explored. The first relationship will be demonstrated through the use of a systematic map which reviews the breadth of paleolimnological research that exists on environmental change and its impact on subsistence cultures. This review is important as it highlights the value of the methodology and approach used to examine the second relationship; where the impact of human disturbances will be assessed for the freshwater ecosystem of Chocolate Lake, Nova Scotia (N.S), Canada. An interpretation will be completed of the last 3500 years of Chocolate Lake's paleohistory. The two primary goals of this thesis are to 1) highlight the importance of using paleolimnological methodologies in the study of early human disturbances in Chapter two, and 2) add to the field of paleolimnology in Chapter three through the study of an urban freshwater lake. Finally, Chapter four concludes this thesis by considering how paleolimnological studies concerning human disturbance should become an integral role in freshwater ecosystem management.

1.2.1 Overview of the Problem to be Addressed

A variety of stressors can act on and influence freshwater ecosystems. It is because of this that Chapter two is devoted to reviewing how paleolimnology (the methodology employed in the quantitative investigation, Chapter three) has been used to infer how freshwater ecosystems and subsistence societies have changed throughout history. This review will be the foundation for why paleolimnology was used in Chapter three, as Chapter two highlights the range of topics in which paleolimnological techniques can study in relation to the relationship between freshwater ecosystems and societies. It will also demonstrate how far paleolimnology can accurately date back to, highlight the variety of biological indicators that can be employed, and will support the specific biological indicator that will be used in Chapter three has in fact shown to be successful in reconstructing the impact of humans on freshwater ecosystems. Lastly, it will demonstrate the value of paleolimnological assessments in the realm of remediation and management.

Despite the early human presence of Mi’kma’ki hunter gatherer groups and European settlement in the study region (Halifax, N.S) in 1749 (McCann and Young 2012), there has been a lack of freshwater ecosystem monitoring in the Maritimes. Urban lakes close to Halifax’s city-center in particular have experienced great amounts of urban development along their shorelines. Chocolate Lake, an urban lake just five minutes away from the city-center is an example of this, with few records documenting its history and limited water quality monitoring of E. coli and cyanobacterial blooms (Halifax Regional Municipality 2022). Without long-term monitoring data of the water body, the pre-disturbance state of the lake and the degree of natural versus anthropogenic variability is difficult to know, and therefore it is difficult to know what human activities have and are currently impacting the health and ecological functioning of the lake (Ginn et al. 2008b). This leaves a gap in knowledge concerning future water risks and freshwater ecosystem management, as baseline conditions are fundamental to understand to rehabilitate water bodies and build climate change resilient communities. Now more than ever, with Halifax being the second fastest growing city in the country (Global News 2021) experiencing increased human stressors upon the ecosystem, this information is important to acquire as the world moves into an uncertain future faced with complex interactions and influences of both natural and anthropogenic environmental stressors.

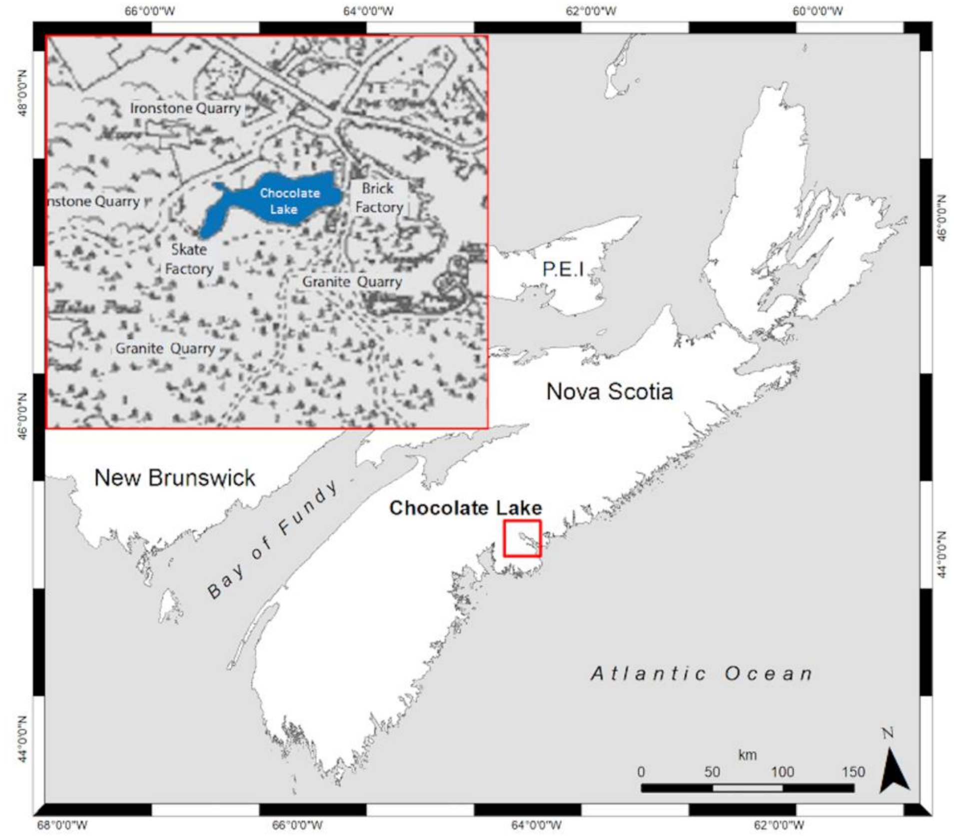

Figure 1.1 Map showing the location of industries surrounding Chocolate Lake during the Late Victorian Period (ca. 1850-1910) and its location in Atlantic Canada (adapted from the Halifax Government of Canada 2011; The Halifax Urban Greenway Association 2019).

1.2.2 Research Purpose and Objectives

The central purpose of this research is to present the utility of paleolimnology in the study of the relationship between environmental change and human disturbance. Highlighting the applicability of this method in reconstructing this relationship will depend on the successful demonstration of two objectives: 1) review the applications of paleolimnology in the literature to understand the range in which it can reconstruct the relationship between changes in environment and human presence/activities in watersheds, and 2) use paleolimnology to evaluate trends in biological indicators to understand how an urban lake in Halifax has undergone ecological changes in the past for management and restoration purposes.

Environmental change has “pushed” and “pulled” at societies throughout history, impacting where people live, how people live, and how people will continue to live (Covert and Medeiros 2021). Paleolimnological techniques are critical in reconstructing environmental changes experienced by human-nature relationships as traditional means of historical review (oral and written records) only provide an account of human adaptation over a timescale of centuries. A systematic map will address the first objective of this thesis by highlighting how paleolimnological studies are essential for extending our knowledge of past environments, and the societies that were supported, at a millennial scale.

Records of human disturbance in the watershed of Chocolate Lake exist; however, there is a lack of detailed records of pre-European settlement which makes it difficult to know how early human activities impacted the lake. This once hunting ground now-turned residential area, as a result of damming the outlet flow, has experienced drastic changes in the amount of human induced stress since European settlement. As a result, it is predicted that there will be changes in biological indicators that can be associated with human activity in the watershed.

Paleolimnological analysis will address the second objective of this thesis by investigating changes in a biological indicator (subfossil remains of the Family Chironomidae) in Chocolate Lake throughout time. This research will be the first to provide a long-term investigation into understanding the consequences human stressors have had on Chocolate Lake. Reconstructing human activity in the watershed will be achieved by evaluating a sediment core from the freshwater lake with chironomid-based analysis. Assemblage composition will provide an understanding of the ecosystem's baseline (original state) and how the ecosystem has changed. A baseline of environmental knowledge is valuable to understand the environmental changes residents of Halifax have observed, such as deaths and disappearances of fish and plant life, and poor quality of the water (algal blooms) (Halifax resident, personal communication, August 2020). A thorough understanding of the lake's ecological history is critical should planners or the community wish to restore Chocolate Lake to its 'natural' ecological state.

As such, it is hypothesized that paleolimnological analysis will prove to be a useful tool for effective management and mitigation against further changes induced by human activities. Two predictions support this hypothesis: 1) analysis of the applications of paleolimnology through the systematic mapping process will indicate reconstructing humans and their impacts is attainable in any region, and 2) analysis of the sediment history of Chocolate Lake will indicate a shift in biological indicators that are responsive to human development over time.

Changes in community composition will allow for the inference of what ecological stressors were/are acting on the lake. The paleolimnological analysis includes the sediment from one sediment core (8.4 cm diameter and 34.5 cm deep) taken at one of the deepest points of the lake. This will be the first study to complete a full paleolimnological analysis and provide an assessment of the impact of human disturbance on Chocolate Lake.

1.3 Literature Review

1.3.1 Human disturbance in watersheds

Human disturbance of nature is said to have altered ecosystems on all continents and in all climatic zones, not only recently, but since our earliest records of human activity (Hannah et al. 1994). Approximately only 52% of Earth's land-area remains undisturbed, as human activities have replaced natural habitats, threatening some major ecosystem types (Hannah et al. 1994). There can be varying degrees of disturbance; however, human disturbance for the purpose of this thesis is defined as any degree of manipulation to either the physical, chemical, and/or biological processes in an ecosystem as a result of human activities (Hannah et al. 1994; United States Environmental Protection Agency 2021).

Human activities to establish and maintain urban settlements have placed stress on freshwater ecosystems, through primary threats to water quality and quantity, such as the creation of reservoirs and the application of fertilizers and pesticides and de-icing salt near waterways (Noble and Basnet 2015). Watershed alterations due to these stressors and land-use changes have been shown to impact natural ecological functioning and result in overall degradation to freshwater bodies (Hilderbrand et al. 2010). Alterations, such as tree removal, road building, construction near shorelines, and the use of fertilizers and pesticides near waterways can impact water bodies as they can lead to, turbid conditions, algal blooms, modification of substrate types, and shifts in trophic structure (United States Environmental Protection Agency 2021). These impacts in turn affect biodiversity. Loss of benthic macroinvertebrate taxa has been shown to occur as a result of development in watersheds and can be related to the amount of impervious surface cover (Hilderbrand et al. 2010). Hilderbrand et al. (2010) demonstrated that the loss of biodiversity as a result of human development in a watershed can be forecasted. For example, unchecked human development in a watershed in Maryland, U.S.A, is forecasted to cause a loss of approximately 60% of benthic macroinvertebrate taxa by the time impervious surface cover reaches 15% of the watershed (Hilderbrand et al. 2010).

Very few undisturbed ecosystems remain today, as human disturbances have influenced the ecological functioning of ecosystems since before even our earliest historical records (Hannah et al. 1994). Since the 1900s, the impact of human disturbance has accelerated. Not only are the harmful impacts of human development disturbing freshwater ecosystems, but these stressors are being compounded by climate change, another human induced stressor (Zandbergen 1998; McDonald et al. 2011). Climate change has induced responses in freshwater lakes, such as changes in stratification and mixing regimes, increased eutrophic events, and shifts in trophic structure (Jean-Phillipe et al. 2020). On average with population growth, roughly 100 million people living in urban centers will experience water shortage under projected climate change scenarios

(McDonald et al. 2011). This statistic will only worsen as by the year 2050, when 67% of the world’s population is predicted to be living in an urban area (United Nations 2011).

1.3.2 Urban development /Urbanization

Humans have practiced urbanization since ancient times. For most of human history, people have lived in nomadic groups as a form of safety and to share the burdens of the subsistence lifestyle. It has only been within the past few centuries with the adoption of agriculture and invention of modern technology that the world has seen a drastic increase in urbanization (Ritchie and Roser 2018). In the year 2020, 55% of the world’s population lived in urban areas; when only 40 years prior (1960), the rural population of the world was twice that of the urban population (Ritchie and Roser 2018).

Urbanization is predicted to continue, bringing with it further environmental degradation (Ren et al. 2014). As cities continue to sprawl, the health and protection of the remaining natural landscapes gain importance within society (Ren et al. 2014). The consequences of urbanization on water quality and wildlife community composition resulting from changes in land use due to urban and agricultural development in the watershed has gained a significant foothold in scientific research (Winter and Duthie 1998; Ren et al. 2014). This field of environmental research now has a large focus on how changes in land use has influenced water quality and wildlife (Smith 2003).

1.3.3 Ecological consequences

Urbanization is accompanied by a variety of threats of human disturbance on freshwater ecosystems, such as the creation of reservoirs, salinization, and nutrient enrichment (Noble and Basnet 2015). These threats, that are present due to land-use change, have been known to have fundamental consequences on water quality and benthic community composition (Winter and Duthie 1998). For example, macroinvertebrate and periphyton communities in Laurel Creek, Ontario, were impacted from agriculture and roadway runoff (Winter and Duthie 1998).

1.3.3.1 Reservoir creation

For thousands of years, the power of flowing water has been harnessed to allow for urban development; the initial purpose being for the prevention of flooding erosion, then for the irrigation of agriculture, and more recently, to store and control water for hydropower (Smith 1971). The creation of dams and thereby man-made lakes, however, has devastating impacts on water quality, wildlife, and food webs as a result of land flooding. This is an extreme manipulation of terrestrial organic matter inputs as flooding results in the decomposition of organic matter that would not have been a natural input to the aquatic system (Paterson et al. 1997).

Flooded landscapes through the creation of reservoirs have several ecological consequences on aquatic ecosystems (Duchemin et al. 1995). The food web in particular, is impacted by the accelerated production and release of methylmercury (MeHg). Flooding creates favourable conditions for bacteria to convert existing mercury in soil and vegetation into the vertebrate neurotoxin MeHg (Hall et al. 2005). Anthropogenic mercury from gold mining activities peaked in N.S. in the late-1800s, increasing mercury concentrations in the natural environment (Clark et al. 2021). Accumulation from human activities compounded by flooding of soil has led to the bioaccumulation of MeHg to dangerous levels in the trophic system (Hall et al. 1998; Paterson et al. 1998; Bodaly et al. 2004). Because Hg is primarily sequestered in the sediment, species that feed on benthic species are more severely impacted by bioaccumulation of MeHg (Châteauvert et al. 2015).

1.3.3.2 Salinization

The health of aquatic ecosystems in the province of N.S. today are also threatened by a lack of infrastructure for dealing with road salt runoff. The rolling hills of the province allow for runoff to be primarily dealt with by allowing it to flow downhill into receiving bodies of water. Without proper storm drainage, the application of road de-icing salt poses a threat to freshwater ecosystems through changes in water chemistry due to increased salinity.

The threat salinization poses on lakes has increased over time as more surfaces become impermeable due to increased levels of urbanization and the use of concrete roadways that reduce soil permeability. The chloride (Cl^-) ion of dissolved road salt is not easily bio-transformed in freshwater ecosystems and can lead to multiple environmental impacts (Hintz et al. 2019), such as: increased conductivity, altered nutrients and carbon levels, reduced oxygen, increased microbial mats, reduced pH, reduced species richness and diversity, and trophic cascades (Winter and Duthie 1998; Kim and Koretsky 2013; Jones et al. 2017; Hintz et al. 2019).

1.3.3.3 Nutrient Enrichment

Eutrophication is a biological response to both natural and anthropogenic induced influxes of growth-limiting nutrients from the landscape to receiving waters (Hasler 1969; Winter and Duthie 1998). Phosphate additions due to human influence in particular, tend to be the driving force behind most cases of lakes becoming eutrophic and reducing water quality, this is known as cultural eutrophication (Hasler 1969; Codd

2000). In rural settings, the leading cause of eutrophication is the application of manure and fertilizers; nutrients can run off land and leach into nearby water bodies, causing growth in free-floating algae under ideal conditions (Hasler 1969). In urban settings, however, eutrophication most often results from the application of fertilizers that runoff from lawns and garden beds of properties located close to shorelines (Codd 2000).

Eutrophication has occurred alongside early human urbanization. Early humans even in remote regions have been shown to induce eutrophication due to subsistence activities. Early Arctic peoples for example, building settlements out of whale carcasses adjacent to freshwater ponds, have caused marked changes in water chemistry and biological response (Douglas et al. 2004). Even today, there is a continuous influx of nutrients leaching from whale bones that influences the ecology of Arctic ponds (Michelutti et al. 2013). As large-scale urbanization has ramped up in recent years so has the occurrence of harmful algal blooms in the freshwater lakes of Nova Scotia (Van Heyst et al. 2022).

1.3.4 Biological indicators of development

Lakes act as excellent sentinels of change in watersheds (Schindler 2009). Generally being at the lowest point of the surrounding landscape, lakes can provide valuable information on how environmental processes respond to changes in their surroundings (Williamson et al. 2009). Whether it be natural or human-induced change, environmental stress can be inferred from biological indicators preserved in the lake sediment, allowing for gaps in environmental monitoring to be filled in (Smol 2008). A variety of biological indicators exist; however, certain indicators are better suited for making inferences about human impacts on the environment. Pollen analysis for example, is often used to demonstrate changes to land cover due to agricultural activities, whereas chironomids are better suited to infer environmental changes in urban environments from stressors, such as the influxes of nutrients and changes in climate (Edwards and Whittington 2001; Luoto 2011).

Other environmental stressors resulting from human development can also influence the composition of chironomid communities from changes in factors, such as lake depth, salinity, pH, and dissolved organic carbon (Walker et al. 2003). Sensitivity to these elements makes chironomids good indicators to provide proxy evidence of both past and present human induced changes, such as those of lake productivity, hypolimnetic anoxia, water depth, and acidification (Walker 2001).

1.4 Research Site

1.4.1 Chocolate Lake

Chocolate Lake is a temperate freshwater lake, underlain with bedrock known as the Cunard Formation, which is comprised of slate and metasiltstone overlain with metasedimentary rock (White et al. 2014). This composition results in a highly susceptible lake, prone to acid rock drainage and human disturbance of the watershed (Waldron et al. 2015). Chocolate Lake is also a receiving body of the Chain of Lakes, whose outlet stream enters the Atlantic Ocean at the Northwest Arm (Scott et al. 2019; Mapcarta n.d.). Located in the Armdale neighbourhood of Halifax (population: 16,502), its 83,508 m^2 catchment has had a relatively high amount of residential development; its population density being 1941% higher than that of the city of Halifax (Ginn et al. 2008a; AreaVibes Inc. 2021). Chocolate Lake has become surrounded by private homes whose property lines end at the shoreline, a Best Western hotel who's parking lot comes extremely close to the water, and finally, a recreational man-made beach area (Province of Nova Scotia 2018). Indeed, Chocolate Lake is one of Halifax's most frequented lakes as it is within walking distance of the city center and provides a recreational area for residents to cool off in during the summer months.

Chocolate Lake holds a rich history of different human activities and disturbances. Around 11, 000 years ago, Nova Scotia saw the retreat of its last glacier which left behind thousands of lakes that take up approximately 5% of the total land surface (~ 2,408km^2) (Davis and Browne 1996). Human occupation also took place approximately 11,000 years ago by Paleo-Indians, followed by a period of abandonment, then approximately 1,000 years ago was re-colonized by First Nations, mainly Mi'kmaq peoples (Davis and Browne 1996). Mi'kmaq people frequented the area (Halifax also known as Kjipuktuk) for centuries prior to European settlement (McDonald 2017). Here, three clans, with an estimated population of 400-600 people (McDonald 2017), spent their summers hunting and fishing along the Northwest Arm where they had a constant supply of freshwater from the streams flowing out to the ocean, including that of Chocolate Lake (McDonald 2017). European settlement (ca. 1769) brought with it significant changes to the region; for one, the British put an end to the Mi'kmaq's nomadic subsistence lifestyle at "Indian Lake" – how Chocolate Lake was once referred to, they also saw their newfound landscape as one full of commercial potential (Watts 1979). European settlers are thought to have the first major impact on the watershed as a result of deforestation and land clearing (Dunnington et al. 2018).

Chocolate Lake’s proximity to the ocean and main port allowed for easy access to shipping goods out of the province, and its outlet stream also provided the opportunity for harnessing the power of flowing water. These ecosystem services led to the establishment of the Hosterman gristmill, located at the end of Chocolate Lakes outlet stream in 1786 (Find a Grave 2012). It was one of only two gristmills in the area, therefore, to meet the demands of a growing population Chocolate Lake was dammed (year unknown) to hold more water for greater production (Watts 1994). In 1820 the province saw the start to the industrial era with coal mining, which was quickly followed by forest clearance, other forms of mining, and the construction of buildings and major roads (Davis and Browne 1996; Dunnington et al. 2018). Around the year 1835, the dam holding back the water at the east end of the lake was raised further, elevating the lake by approximately 12 feet for increased power generation (Province of Nova Scotia 1937). Over the years the lake became a busy manufacturing centre, where the shoreline hosted a chocolate factory (hence the site’s name), a spice and snuff mill, a rolling mill, a skate factory (Figure 3.4), and a nail factory (Regan 1928; The Halifax Urban Greenway Association 2019). In 1844, to supply the growing population of Halifax with drinking water, the city began to source freshwater from nearby lakes including the Chain of Lakes (Halifax Water Commission 1995). Consequently, this impacted water levels downstream in Chocolate Lake and caused issues with industry owners during the summer months due to lake level drawdowns; some mills ended up closing as the city favoured water users (Halifax Water Commission 1995). In 1887, the paint factory burnt down (Province of Nova Scotia 1937), marking the change from industrial activity on the lake to that of residential properties. By the year 1905, upstream of Chocolate Lake, the Chain of Lakes was considered “polluted” and impacted by urbanization in the watershed (Dunnington et al. 2018).

By 1920, four families had settled on the shoreline of Chocolate Lake (Halifax resident, personal communication February 2021). Overtime, those living in Halifax who appreciated the cottage lifestyle of Nova Scotia’s freshwater lakes, began to build year-round homes on Chocolate Lake as it is just on the outskirts of the major city (Watts 1979). Due to its proximity to the city center, Chocolate Lake became very popular for recreational users in the summer months at the man-made beach on the East side of the lake. Even in the winter months Chocolate Lake has been frequented by masses of people. Photos from 1977 exist showing hundreds of Haligonians skating on the frozen lake (Halifax Regional Municipality 2020). In 1960, one of the original homes on the lake was demolished and later developed into a Best Western hotel that stands nine stories tall with a parking lot extending to the very edge of the shoreline (Halifax resident, personal communication February 2021). By 1977 the entire community was residentially developed (Scott et al. 2019). Today, little to no riparian zone exists between Chocolate Lake and the human development that has occurred; the majority of the 50+ residential properties, the hotel, and beach/recreational facility exist within a few meters of the lake with their manicured lawns butting right up against the shoreline; 20 meters (66 feet) is considered an adequate amount of riparian zone (Halifax Water 2022). During the time of initial development around Chocolate Lake septic systems were the only type of infrastructure available for dealing with human waste from homes (Watts 1979). Increasing development in the mid-late twentieth century is expected to have had harmful effects on the ecosystem’s health due to sewage inputs (Rowell et al. 2016).

It was not until around the 1960s that new homes began to be serviced with piping to municipal waste treatment plants (Watts 1979). The construction of major paved roads (1980) has also impacted the lake as the municipality lacks stormwater drains, resulting in road runoff during high rainfall and snowmelt events running directly into the lake, quickly across the impervious parking lots and non-existent riparian zone (Scott et al. 2019; Halifax Water 2021). Global warming also impacts the region and increases the occurrence of these high intensity runoff events (Province of Nova Scotia 2014). Furthermore, Chocolate Lake has more recently experienced algal blooms during the increasingly hot summer months and is well-known as an occasionally contaminated lake that needs to be monitored by the municipality (Miralai et al. 2008). Altogether, these human disturbances can be expected to have had and continue to impact Chocolate Lake today. Rogers and Jones (2018) have studied changes in lake pH in the region and noted that prior to the 1900s, Halifax lakes had a pH of roughly 4.5, but with leaching of domestic waste around the 1970s, the waters became eutrophic and saw a near-neutral pH. Finally, around the 1990s excavation of land in the region highlighted how road construction on similar slate bedrock to Chocolate Lake led to the release of an acidic leachate runoff with a pH of 2.9, resulting in increases in lake acidity (decrease in pH) and consequently, fish die offs (Rogers and Jones 2018). Compared to acidified lakes in the region, however, Chocolate Lake saw no significant decrease in pH and total phosphorus levels (Ginn et al. 2015). An increase in conductivity has occurred in the past 20 years due to the increased use of sodium, chloride, and calcium in the developed areas primarily from the application of de-icing road salt (Clement et al. 2007). A rapid paleolimnological assessment of Chocolate Lake by Rajaratnam (2009) showed a decline in diatom-inferred total phosphorus (TP) since pre-impact period, starting off as mesotrophic during pre-industrial times and more recently becoming oligotrophic. The assessment by Rajaratnam (2009) used diatom assemblages to determine likely stressors acting on Chocolate Lake throughout history are primarily acidification, eutrophication, and climate.

1.5 References

Adrian, R., O’Reilly, C., Zagarese, H., Baines, S., Hessen, D., Keller, W. , … & Winder, M. (2009). Lakes as Sentinels of Climate Change. Limnology and Oceanography, 54(6): 2283-297.

AreaVibes Inc. (2021). Armdale, Halifax, NS Demographics. Retrieved from, https://www.areavibes.com/halifax-ns/armdale/demographics/.

Beck, J. (2019). Nova Scotia. The Canadian Encyclopedia. Retrieved from, https://www.thecanadianencyclopedia.ca/en/article/nova-scotia.

Bodaly, R., Beaty, K., Hendzel, L., Majewski, A., Paterson, M., Rolfhus, K., … & Venkiteswaran, J. (2004). Experimenting with Hydroelectric Reservoirs. Environmental Science & Technology, 38(18): 346A.

Canada, E. (2018). Government of Canada. Retrieved from, https://www.canada.ca/en/environment-climate-change/services/water-overview/frequently-asked-questions.html.

Châteauvert, J., Bulte, G., Poulain, A., Campbell, L., & Blouin-Demers, G. (2015). Dietary reliance on benthic primary production as a predictor of mercury accumulation in freshwater fish and turtles. Water, Air, & Soil Pollution, 226: 337.

Clark, A., Labaj, A., Smol, J., Campbell, L., & Kurek, J. (2021). Arsenic and mercury contamination and complex aquatic bioindicator responses to historical gold mining and modern watershed stressors in urban Nova Scotia, Canada. Science of the Total Environment, 787: 147374. https://doi.org/10.1016/j.scitotenv.2021.147374.

Clement, P., & Gordon, D. (2019). Synoptic Water Quality Study of Selected Halifax-Area Lakes: 2011 Results and Comparison with Previous Surveys. Canadian Technical Report of Fisheries and Aquatic Sciences, 3170.

Codd, G. (2000). Cyanobacterial Toxins, the Perception of Water Quality, and the Prioritisation of Eutrophication Control. Ecological Engineering, 16(1): 51-60.

Covert, A., & Medeiros, A. (2021). Reconstructing the “push” and “pull” of Climate and Its Impacts on Subsistence Cultures Using Paleolimnology. FACETS, 6(1), 2042-2056. doi: 10.1139/facets-2021-0088.

Davis, D., & Browne, R. (1996). The natural history of Nova Scotia. Vol. 2: Theme regions. Nimbus Publishing, Halifax.

Douglas, M., Smol, J., Savelle, J., & Blais, J. (2004). Prehistoric Inuit whalers affected Arctic freshwater ecosystems. Proceedings of the National Academy of Sciences of the United States of America, 101(6): 1613-1617.

Duchemin, E., Lucotte, M., Canuel, R., & Chamberland, A. (1995). Production of the Greenhouse Gases CH4 and CO2 by Hydroelectric Reservoirs of the Boreal Region. Global Biogeochemical Cycles, 9(4): 529-540.

Dunnington, D., Spooner, I., Krkošek, W., Gagnon, G., Cornett, R., Kurek, J., … & Tymstra, D. (2018). Anthropogenic Activity in the Halifax Region, Nova Scotia, Canada, as Recorded by Bulk Geochemistry of Lake Sediments. Lake and Reservoir Management, 34(4): 334-48.

Edwards, K., & Whittington, G. (2001). Lake Sediments, Erosion and Landscape Change during the Holocene in Britain and Ireland. Catena (Giessen), 42(2): 143-73.

Encyclopædia Britannica, inc. (n.d.). Uses and abuses of Lakes. Encyclopædia Britannica. Retrieved from, https://www.britannica.com/science/lake/Uses-and-abuses-of-lakes.

Find a Grave. (2012). John Hosterman. Retrieved from, https://www.findagrave.com/memorial/91110327/john-hosterman.

Frey, D. (1988). What is Paleolimnology? Journal of Paleolimnology, 23:79-96.

Ginn, B., Grace, L., Cumming, B., & Smol, J. (2008a). Tracking Anthropogenic- and Climatic-related Environmental Changes in the Remaining Habitat Lakes of the Endangered Atlantic Whitefish (Coregonus Huntsmani) Using Palaeolimnological Techniques. Aquatic Conservation, 18(7): 1217-1226.

Ginn, B., Rajaratnam, T., Cumming, B., & Smol, J. (2008b). Tracking water quality changes related to human activities in Cape Breton Highlands National Park (Nova Scotia, Canada) using paleolimnological techniques, Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen, 30(2), 242-246. doi:10.1080/03680770.2008.11902118.

Ginn, B., Rajaratnam, T., Cumming, B., & Smol, J. (2015). Establishing realistic management objectives for urban lakes using paleolimnological techniques: an example from Halifax Region (Nova Scotia, Canada). Lake and Reservoir Management, 31(2): 92-108, doi: 10.1080/10402381.2015.1013648.

Global News. (2021). Halifax rated Canada’s second fastest growing municipality. Retrieved from, https://globalnews.ca/news/7588836/halifax-rated-canadas-second-fastest-growing-municipality/.

Halifax Regional Municipality. (2020). Chocolate Lake Beach. Retrieved from, https://www.halifax.ca/parks-recreation/programs-activities/swimming/supervised-beaches-outdoor-pools-splash-pads-0.

Halifax Regional Municipality. (2022). Beaches, outdoor pools, and splash pads. Retrieved from, https://www.halifax.ca/parks-recreation/programs-activities/swimming/supervised-beaches-outdoor-pools-splash-pads.

Halifax resident, personal communication. Retrieved August 2020.

Halifax resident, personal communication. Retrieved February 2020.

Halifax Water. (2021). History of Halifax Water. Retrieved from, https://www.halifaxwater.ca/history-halifax-water.

Halifax Water. (2022). Source Water Protection. Retrieved from, https://www.halifaxwater.ca/protected-water-areas.

Halifax Water Commission. (1995). Downstream: An historical reflection of the Halifax water supply system.

Hall, B., Rosenberg, D., & Wiens, A. (1998). Methyl Mercury in Aquatic Insects from an Experimental Reservoir. Canadian Journal of Fisheries and Aquatic Sciences, 55(9): 2036-2047.

Hall, B., St Louis, V., Rolfhus, K., Bodaly, R., Beaty, K., Paterson, M., & Peech Cherewyk, K. (2005). Impacts of Reservoir Creation on the Biogeochemical Cycling of Methyl Mercury and Total Mercury in Boreal Upland Forests. Ecosystems (New York), 8(3): 248-266.

Hannah, L., Lohse, D., Hutchinson, C., Carr, J., & Lankerani, A. (1994). A Preliminary Inventory of Human Disturbance of World Ecosystems. Ambio, 23(4-5): 246-250.

Hasler, A. (1969). Cultural Eutrophication Is Reversible. Bioscience, 19(5): 425-431.

Hilderbrand, R., Utz, R., Stranko, S., & Raesly, R. (2010). Applying Thresholds to Forecast Potential Biodiversity Loss from Human Development. Journal of the North American Benthological Society, 29(3): 1009-1016.

Hintz, W., & Relyea, R. (2019). A Review of the Species, Community, and Ecosystem Impacts of Road Salt Salinisation in Fresh Waters. Freshwater Biology, 64(6): 1081-1097.

Huot, Y., Brown, C., Potvin, G., Antoniades, D., Baulch, H., Beisner, B., … & Walsh, D. (2019). The NSERC Canadian Lake Pulse Network: A National Assessment of

Lake Health Providing Science for Water Management in a Changing Climate. The Science of the Total Environment, 695: 133668.

Jean-Philippe, J., Anneville, O., Arnaud, F., Baulaz, Y., Bouffard, D., Domaizon, I., … & Weyhenmeyer, G. (2020). Scientists' Warning to Humanity: Rapid Degradation of the World's Large Lakes. Journal of Great Lakes Research, 46(4): 686-702.

Jones, D., Mattes, B., Hintz, W., Schuler, M., Stoler, A., Lind, L., … & Relyea, R. (2017). Investigation of road salts and biotic stressors on freshwater wetland communities. Environmental Pollution, 221, 159– 167.

Kim, S., & Koretsky, C. (2013). Effects of road salt deicers on sediment biogeochemistry. Biogeochemistry, 112: 343– 358. https://doi-org.ezproxy.library.dal.ca/10.1007/s10533-012-9728-x.

Luoto, T. (2011). The Relationship between Water Quality and Chironomid Distribution in Finland—A New Assemblage-based Tool for Assessments of Long-term Nutrient Dynamics. Ecological Indicators, 11(2): 255-262.

Mapcarta. (n.d.). Chocolate lake. Retrieved from, https://mapcarta.com/24189078.

McCann L., & Young, E. (2012). Halifax. The Canadian Encyclopedia. Retrieved from, https://www.thecanadianencyclopedia.ca/en/article/halifax.

McDonald, M. (2017). History of Halifax, a Mi'kmaw perspective. The Nova Scotia Advocate. Retrieved from, https://nsadvocate.org/2017/07/12/history-of-halifax-a-mikmaw-perspective/.

McDonald, R., Green, P., Balk, D., Fekete, B., Revenga, C., Todd, M., & Montgomery, M. (2011). Urban Growth, Climate Change, and Freshwater Availability. Proceedings of the National Academy of Sciences, 108(15): 6312-6317.

Meyer, J. (1997). Stream health: incorporating the human dimension to advance stream ecology. Journal of the North American Benthological Society, 16: 439–447.

Michelutti, N., Mccleary, K., Antoniades, D., Sutherland, P., Blais, J., Douglas, M., & Smol, J. (2013). Using paleolimnology to track the impacts of early Arctic peoples on freshwater ecosystems from southern Baffin Island, Nunavut. Quaternary Science Reviews, 76, 82-95. https://doi.org/10.1016/j.quascirev.2013.06.027.

Miralai, S., Khan, M., & Islam, M. (2008). Replacing artificial additives with natural alternatives. Nature Science and Sustainable Technology Research Progress. Nova Publishers. 45-76.

Nguyen-Quang T., Lieou K., Hushchyna K., Nguyen T., Sharifi Mood N., Nadeem M., … & Hirtle R. (2016). The first step to sketch the spatio-temporal evolution of biochemical and physical parameters involving in the harmful algal blooms (HAB) In Mattatall Lake (Nova Scotia, Canada). Environmental Problems, 1(1), 1-18.

Noble, B., & Basnet, P. (2015). Capacity for Watershed Cumulative Effects Assessment and Management in the South Saskatchewan Watershed, Canada. Canadian Water Resources Journal, 40(2): 187-203.

Nova Scotia Museum of Natural History. (1996). Natural History of Nova Scotia. 1, Topics and Habitats.

Paterson, A., Köster, D., Reavie, E., & Whitmore, T. (2020). Preface: Paleolimnology and Lake Management. Lake and Reservoir Management, 36(3): 205-209.

Paterson, M., Findlay, D., Beaty, K., Findlay, W., Schindler, E., Stainton, M., & McCullough, G. (1997). Changes in the Planktonic Food Web of a New Experimental Reservoir. Canadian Journal of Fisheries and Aquatic Sciences, 54(5): 1088-2102.

Paterson, M., Rudd, J., & St. Louis, V. (1998). Increases in Total and Methylmercury in Zooplankton following Flooding of a Peatland Reservoir. Environmental Science & Technology, 32(24):3868-3874.

Pollard, P., & Huxham, M. (1998). The European Water Framework Directive: A New Era in the Management of Aquatic Ecosystem Health? Aquatic Conservation, 8(6): 773-792.

Province of Nova Scotia. (1937). Report on the Provincial Museum and Science Library for the fiscal year 1935-36. Halifax, NS: King's Printer.

Province of Nova Scotia. (2014). Climate Impacts. Retrieved from, https://climatechange.novascotia.ca/climate-impacts.

Province of Nova Scotia. (2018). Surface Water Quality Monitoring Network. Retrieved from, https://nse.maps.arcgis.com/apps/webappviewer/index.html?id=7ded7a30bef44f848e8a4fc8672c89bd.

Rajaratnam, T. (2009). Assessment of long-term changes in water quality from Halifax region lakes (Nova Scotia, Canada) using paleolimnological techniques. [Master's thesis Queen's University]. Retrieved from, http://hdl.handle.net/1974/5146.

Regan, J. (1928). Sketches and Traditions of the Northwest Arm. (Third Edition).

Ren, L., Cui, E., & Sun, H. (2014). Temporal and Spatial Variations in the Relationship between Urbanization and Water Quality. Environmental Science and Pollution Research International, 21(23): 13646-13655.

Ritchie, H., & Roser, M. (2018). Urbanization. Our World in Data. Retrieved from, https://ourworldindata.org/urbanization.

Rogers, P., & Jones, W. (2018). Applied landscape geochemistry and environmental change in Nova Scotia, Canada. Atlantic Geology, 54.

Rowell, H. Chandler, M., Quinlan, R., Smith, A., Bloomfield, J., Charles, D., & Effler, S. (2016). Quantitative Paleolimnological Inference Models Applied to a High-resolution Biostratigraphic Study of Lake Degradation and Recovery, Onondaga Lake, New York (USA). Journal of Paleolimnology, 55(3): 241-258.

Schindler, D. (2001). The cumulative effects of climate warming and other human stresses on Canadian fresh-waters in the new millennium. Canadian Journal of Fisheries and Aquatic Science, 58: 18-29.

Schindler, D. (2009). Lakes as Sentinels and Integrators for the Effects of Climate Change on Watersheds, Airsheds, and Landscapes. Limnology and Oceanography, 54(6): 2349-2358.

Scott, R., Goulden, T., Letman, M., Hayward, J., & Jamieson, R. (2019). Long-term Evaluation of the Impact of Urbanization on Chloride Levels in Lakes in a Temperate Region. Journal of Environmental Management, 244: 285-93.

Seiler, M., Bond, M., & Seiler, V. (2001). The Impact of World Class Great Lakes Water Views on Residential Property Values. The Appraisal Journal, 69(3): 287-295.

Smith, N. (1971). A History of Dams. London: P. Davies. Print.

Smith, V. (2003). Eutrophication of Freshwater and Coastal Marine Ecosystems a Global Problem. Environmental Science and Pollution Research International, 10(2): 126-139.

Smol, J. (2008). Pollution of lakes and rivers: a paleoenvironmental perspective. Blackwell Publishing Ltd, Malden.

The Halifax Urban Greenway Association. (2019). Other Historic Maps: Halifax City, Late Victorian Period. Retrieved from, http://halifaxurbangreenway.ca/maps/halifax2.gif.

United Nations. (2010). Climate Change Adaptation: The Pivotal Role of Water. Policy and Analytical Briefs. Retrieved from, https://www.unwater.org/publications/climate-change-adaptation-pivotal-role-water/.

United Nations. (2011). World Urbanization Prospects. The 2011 Revision.

United States Environmental Protection Agency. (2021). Indicators: Human Disturbance. Retrieved from, https://www.epa.gov/national-aquatic-resource-surveys/indicators-human-disturbance.

Van Heyst, A., Sinclair, A., & Jamieson, R. (2022). Application of Phosphorus Loading Models to Understand Drivers of Eutrophication in a Complex Rural Lake-watershed System. Journal of Environmental Management, 302: 114010.

Waldron, J., Jamieson, R., Pothier, H., & White, C. (2015). Sedimentary and Tectonic Setting of a Mass-transport Slope Deposit in the Halifax Group, Halifax Peninsula, Nova Scotia, Canada. Atlantic Geology, 51(1): 84.

Walker, I. (2001). Midges: Chironomidae and related Diptera. Tracking Environmental Change Using Lake Sediments Developments in Paleoenvironmental Research, 43–66. doi:10.1007/0-306-47671-1_3.

Walker, I., Levesque, A., Pienitz, R., & Smol, J. (2003). Freshwater Midges of the Yukon and Adjacent Northwest Territories: A New Tool for Reconstructing Beringian Paleoenvironments? Journal of the North American Benthological Society, 22(2): 323-337.

Watts, H. (1979). Beyond the Northwest Arm: A Local History of William's Lake Halifax, Nova Scotia. William's Lake Conservation Company.

Watts, H. (1994). Beyond the Northwest Arm. Halifax, NS: Williams Lake Conservation Company.

White, C., MacDonald, M., & Horne, R. (2014). Bedrock geology map of the Halifax area, NTS 11D/12, Halifax County, Nova Scotia; Nova Scotia Department of Natural Resources, Open File Map ME 2014-010, scale 1:50 000.

Williamson, C., Saros, J., Vincent, W., & Smol, J. (2009). Lakes and Reservoirs as Sentinels, Integrators, and Regulators of Climate Change. Limnology and Oceanography, 54(6): 2273-2282.

Winter, J., & Duthie, H. (1998). Effects of urbanization on water quality, periphyton and invertebrate communities in a Southern Ontario stream. Canadian Water Resources Journal, 23(3): 245-257.

Zandbergen, P. (1998). Urban Watershed Ecological Risk Assessment Using GIS: A Case Study of the Brunette River Watershed in British Columbia, Canada. Journal of Hazardous Materials, 61(1): 163-173.

CHAPTER 2 THE “PUSH” AND “PULL” OF CLIMATE AND HOW ITS IMPACTS ON SUBSISTENCE CULTURES CAN BE RECONSTRUCTED WITH PALEOLIMNOLOGICAL METHODOLOGIES

2.1 Statement of Student Contributions

Chapter design by Allison Covert, chapter writing by Allison Covert with editorial contributions from Andrew Medeiros. Published in the journal FACETS (Dec 9, 2021); Covert, A. E., & Medeiros, A. S. (2021). Reconstructing the “push” and “pull” of climate and its impacts on subsistence cultures using paleolimnology. FACETS, 6(1), 2042-2056. doi: 10.1139/facets-2021-0088.

2.2 Abstract

Climate variability has influenced settlement and cultural activities of human populations for millennia, and our knowledge of the context of environmental drivers of migration can be inferred using paleolimnological techniques. Here, we present a systematic map of literature to understand the breadth of paleolimnological research that exists on environmental change and its impact on subsistence cultures. We aim to illustrate how the “push” and “pull” of climate influenced human society over the late-Holocene. A systematic search found 68 unique relevant studies that discussed topics of human settlement and migration, stressors on the environment, and/or ecological monitoring with respect to changes in climate using paleolimnological methods. We identified three primary themes: where people live, how people live, and how people will continue to live. Most studies took place in North America, within the last decade, and had a focus on diatoms, sediment characteristics, and climate. Topics ranged from reconstructions of changes in climate, human presence, human influence on the environment, subsistence

strategies, and the importance of monitoring. We demonstrate the value of paleolimnological methods in understanding the timing of events, revealing long-term ecological trends, and providing baseline conditions for effective remediation and management purposes.

2.3 Introduction

Changes in the natural environment challenge the resilience of societies, as environmental stress can promote or inhibit adaptation to change (Diamond 2005). Food and livelihood security, in particular, can be threatened by unforeseen and gradual environmental changes that influence cultural health and continuity should adaptation to new conditions not take place within communities (Davies 1993; Newell et al. 2020). Adaptation can be defined as both short-term coping strategies as well as long-term transformations in relation to environmental changes (Davies 1993). Climate change is often a driving force that affects the suitability or practicality of a region that can either "push" human groups to leave some regions, or "pull" them to move to others (Friesen et al. 2020). For example, Carto et al. (2009) suggest large-scale changes in climate during the last glacial cycle created inhospitable conditions in Africa that led to one of the earliest migrations of humans into other regions of the world. Smaller-scale changes in climate can also have "push" and "pull" effects that influence the resilience of cultural practices and the ability to adopt new strategies (Van Aalst et al. 2008); small fluctuations in precipitation, like those observed in Amazonia for example, allowed for the onset of agricultural practices (Bush et al. 2000). The lasting effect from a "push" or "pull" of climate is felt globally and is especially pertinent for northern regions where polar amplification of warming can amplify the influence of climate on cultural development (Wooller et al. 2018; Friesen et al. 2020).

Hunter-gatherer (subsistence) and sharing economies have been a fundamental component of the culture, identity, and sustainability of human society throughout the history of the Pleistocene era (Stutz 2012). Various economies were based on hunting, fishing, and gathering from the land, which is inherently built upon knowledge of weather processes and a resilience to disturbances to the environment. As such, unexpected changes to the environment can impact the core of the sharing economy and its dependent community (Dinero 2013). For example, warming during the time of Late Dorset presence in the Arctic (500-1500 AD) is suggested to have strongly influenced the ability to practice subsistence activities (Temple & Stojanowski 2018). Temple and Stojanowski (2018) suggest a loss in sea ice reduced walrus populations and consequently altered hunting practices and shifted diets. Presently, we are in the midst of observing warming in the Arctic that is fundamentally altering the functionality of the landscape, ecosystem services it supports, and ultimately the activities that can be performed by Northern communities (Williamson et al. 2009). Newell et al. (2020) note the link between health of modern Inuit and health of the landscape, as the ability to hunt and perform cultural activities, is imperative for positive mental health and cultural continuity. Understanding how the Arctic has changed, and may be further affected, is therefore critical to facilitate cultural continuity in a changing environment (Chambers et al. 2004; Newell et al. 2020).

While both oral and written history provides us with an account of adaptation over a timescale of centuries, knowledge of how cultures have been affected by environmental change over millennia is more difficult to ascertain with a conventional historical review. Paleolimnological methods can extend our knowledge of past environments, and the societies that were supported, at a millennial scale. Paleolimnology is a science that relies on indicators deposited in lacustrine sediments through time (Walker 2001) and has successfully been used to understand long-term perspectives of interactions between people and the environment (Brenner et al. 2002). Millennial-scale change is inferred from chemical, physical, and biological indicators (Brenner et al. 2002); giving insight on key climatic periods such as the Mid-Holocene (MH, 6000 years ago) and the Last Glacial Maximum (LGM, 21,000 years ago). Paleolimnological evidence has also complimented archaeological studies (Hadley et al. 2010) that have linked large-scale climate forcing and human migration (Friesen et al. 2020).

As the depositional environment of lakes incorporates aspects of the atmosphere and terrestrial catchment through time, lakes have often been referred to as sentinels of environmental change (Schindler 2009; Williamson et al. 2009). This methodology is therefore a powerful tool that can be used to gain insight into aspects of human societies in regions where lakes exist. Here, we undertake a systematic mapping exercise to identify how paleolimnological studies are valuable in the reconstruction of cultural groups in the face of environmental change. We aim to illustrate the ability for methods in paleolimnology to understand how human society has been influenced, and continues to be influenced, by 1) the “push” and “pull” of climate and its influence on migration (where people live), 2) the “push” and “pull” of climate and its influence on cultural practices (how people live), and 3) cultural adaptation to the “push” and “pull” of climate (how people adapt). We demonstrate the importance of paleolimnological research in tandem with traditional historical reviews for understanding the influence of environmental change.

2.4 Methods

Our research topic was informed by town-hall discussions held with the community of Coral Harbour, Nunavut, on March 15-20, 2019. Through community-led engagement on understanding the influence of climate change on subsistence practices, the need to synthesize and mobilize knowledge behind the influence of climate on human society was identified. We therefore used a systematic mapping approach (Haddaway et al. 2018) to outline and synthesize how methods in paleolimnology are used in research pertaining to the impact of climate change on cultural groups. Trends in the extent, range, and nature of literature were used to identify gaps that exist in the context of research on reconstructing human settlement and subsistence activities. Our systematic process included: 1) the identification of the extent of research associated with both paleolimnology and human activity through a Boolean keyword search, 2) systematically extracting articles relevant to our identified research themes, and 3) summarizing key themes in publications to identify common approaches as well as potential gaps in knowledge.

2.4.1 Search strategy

Three peer-review indexes were used in the systematic mapping process: The Web of Science, PubMed, and Scopus. A string of search terms was generated to capture the research themes (Table 2.1); paleolimnology (paleolimnolog* OR palaeolimnolog*, and pal*limnolog* for search strings in Web of Science), human activity (settle*, migration*, subsist*, hunt*, human activity), climate (climat*), and response (stress*, adapt*). The searches were restricted to articles published between 1990-present. Duplicated results between the three indexes were removed. The search was completed December 12th, 2020, and consistency of decisions were reviewed May 4, 2021.

Table 2.1 Boolean search criteria for peer-reviewed research articles relating to methods in paleolimnology applied to infer subsistence and human migration published and indexed from the Web of Science, Scopus, and PubMed databases since 1990. A total of 148 articles (highlighted in grey) were fully analysed.

Keywords	**Web of Science**	**Scopus**	**PubMed**
paleolimnolog* OR palaeolimnolog* AND settle*	135	191	7
paleolimnolog* OR palaeolimnolog* AND settle* AND adapt*	4	5	0
paleolimnolog* OR palaeolimnolog* AND settle* AND climat* AND stress*	13	11	0
paleolimnolog* OR palaeolimnolog* AND subsist*	5	8	0
paleolimnolog* OR palaeolimnolog* AND hunt*	10	14	3
paleolimnolog* OR palaeolimnolog* AND "human activity"	68	250	3
paleolimnolog* OR palaeolimnolog* AND "human activity" AND adapt*	2	4	0
paleolimnolog* OR palaeolimnolog* AND "human activity" AND climat*AND stress*	2	13	0

Keywords	**Web of Science**	**Scopus**	**PubMed**
paleolimnolog* OR palaeolimnolog* AND migration*	36	66	4
paleolimnolog* OR palaeolimnolog* AND migration* AND climat*	22	31	1

2.4.2 Inclusion Criteria

Inclusion criteria were determined in advance to validate the relevance and eligibility of search results; articles needed to be a primary source and needed to employ methods in paleolimnology. Articles using similar methods (such as paleoecology) were also included as these methodologies are often used in similar contexts. Articles that simply mentioned paleolimnology (or related methods) but did not include it as part of their methodology were not included. Articles were also required to relate to the subthemes of our review (human/subsistence activity, change, resilience, and vulnerability). Lastly, only articles published in English were included.

2.4.3 Article selection process

To select relevant articles, articles were screened for keywords and the inclusion criteria. If the inclusion of paleolimnology or human/subsistence activity was not clear from the title or abstract, the full article was screened for key terms to determine the context. Articles that were found to fit the inclusion criteria and contained content relevant to paleolimnology and human/subsistence activity were included. Excluded articles, and reasons for exclusion, can be found in the supplemental information (Supplementary

Table S1). Initial search and data extraction was done by A. Covert and consistency of decisions was checked by A. Medeiros.

2.4.4 Analysis

The focus of this review was on how paleolimnology has been applied to study components of cultural activities pertaining to the subsistence economy of human populations in the late-Holocene, and to map the range in which this research is covered in the literature. Meta-data was extracted from each article, including the year of publication, region of the study, notable features (themes), and the type of paleolimnological methodology employed. Once the articles from our keyword search were narrowed down to those containing relevant information based on the inclusion criteria and selection process, a keyword query with NVivo 12 PRO was performed. This extracted the top 100 words used in the articles to create a word cloud, as well as identified primary themes represented in the literature. Relevant articles were analysed based on the study's region of interest and year it was published. Some articles were relevant in more than one topic and were placed in multiple categories. Organizing the articles from our keyword search based on content helped understand the context in which this area of research is available in the literature. While this is not a fully complete collection of articles that discuss this area of research, our results can help determine the range of themes that exist in the literature.

2.5 Results

A total of 148 articles were identified using the Boolean search strategy (Table 1) applied to the three selected databases. Only one article was found in the search that was not accessible. Among all search criteria, 45 articles were selected from Web of Science (11 unique), 58 from Scopus (23 unique), and 2 from PubMed (0 unique). 2 articles overlapped between all three databases, and 34 articles overlapped between Web of Science and Scopus. Some articles resulted from more than one combination of key words within a database and were identified in more than one Boolean search process (e.g., Web of Science counted the article by Kusimba (1999) twice, once in results for paleolimnolog* OR palaeolimnolog* AND subsist* and once in results for paleolimnolog* OR palaeolimnolog* AND hunt*). In these instances, articles were only counted once in the total of unique papers. We then applied the article selection and exclusion criteria to these 148 articles, which resulted in 68 unique and relevant articles that included paleolimnological (or similar) methods and subsistence practices (Supplementary Fig. S1).

When sorted by publication date, all articles were found to be published between the year 1996 to present, with noticeable gaps in the years 1997, 1998, and 2000 (Fig. 2.1a). The largest number of articles (10) were published during the year 2020. 43 of the 68 articles, ~63% were published in the last decade (between 2011 and 2020). When sorted by geographic region (Fig. 2.1b), of the 68 articles, one studied Oceania, two studied South America, three studied Central America, seven studied Africa, eight studied Asia, 19 studied Europe, and 28 (41.18%) studied North America. The Canadian Arctic was the most studied region (30% of articles).

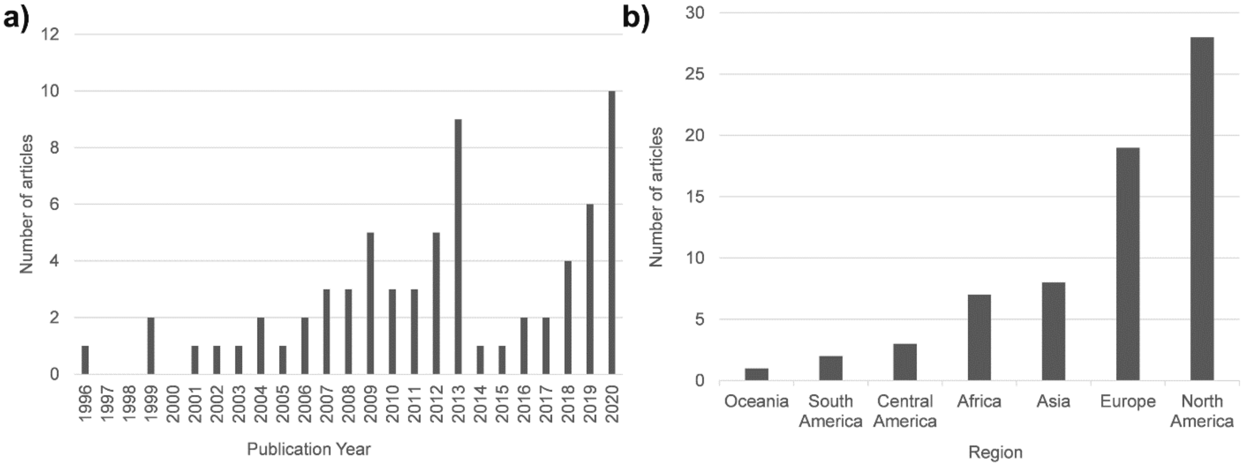

Figure 2.1 The number of relevant articles identified during our systematic review process; a) organized by year of publication, and b) organized by region of study.

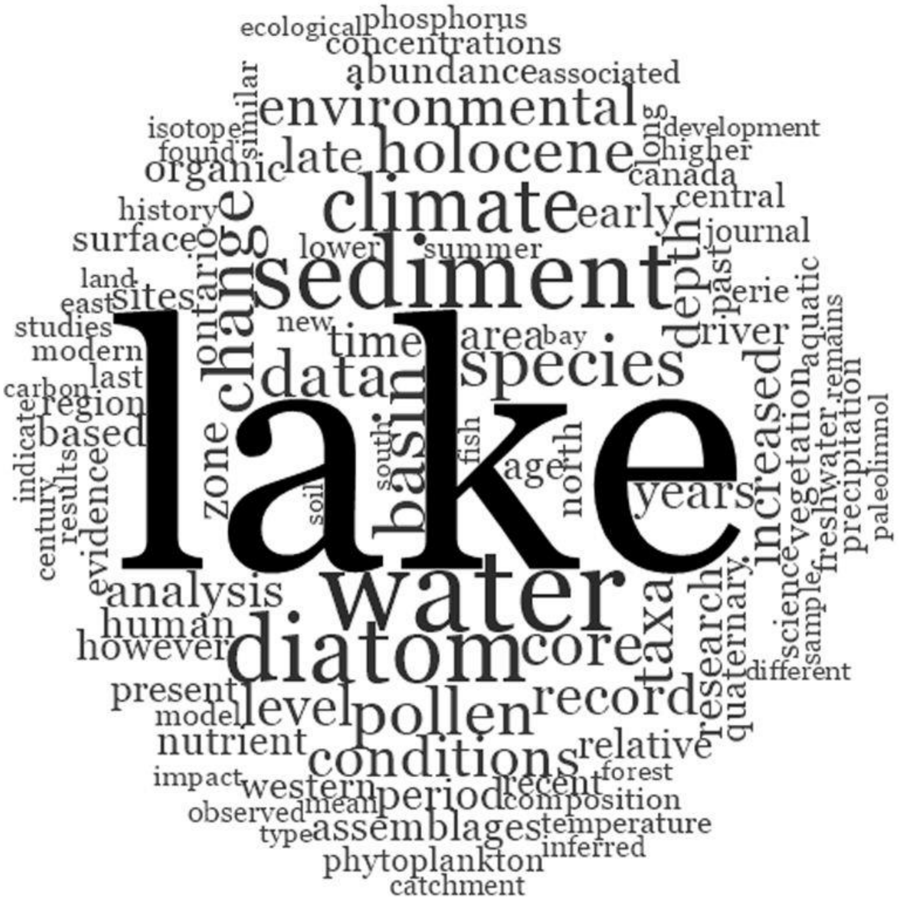

Figure 2.2 Word cloud displaying the top 100 key words (>3 letters) used among relevant articles identified in our systematic mapping process.

Table 2.2 Key themes identified by thematic coding of relevant articles from the systematic mapping process. Themes are organized by primary topic and their subthemes are identified. Note, some papers discussed more than one primary theme as identified in our thematic process.

Theme	**Papers**
Where people live; *The "push" and "pull" of climate over the past millennia*	**56**
Large-scale changes in climate	26
Human occupation	18
Early human migration	12
How people live; *How the "push" and "pull" of climate has influenced culture*	**68**
Ecosystem changes resulting from anthropogenic stressors	36
The impact of both climate and anthropogenic stressors	23
Cultural changes resulting from environmental change	9
How people will continue to live; The use of paleolimnological methods to anticipate impacts	**34**
Water management	23
Wildlife management	6
Vegetation history reconstructions	5

The top 100 keywords (greater than 3 letters) common across the 68 articles identified in our systematic mapping process identified key commonalities between the studies (Fig. 2.2). The 5 most common words used were "lake", "water". "diatom", “sediment”, and “climate”. We then collated three thematic areas to form the scope of our discussion: where people live, how people live, and how people will continue to live (Table 2.2). Studies that focused on “Where people live” included reconstruction of large-scale changes in climate and the effect on human occupation and migration. Studies that focused on “How people live” included reconstructions of changes in ecosystems as a result of subsistence activities, changes in the environment as a result of anthropogenic stressors, impacts of both climate and anthropogenic stressors on human activities, cultural changes due to environmental change, and the onset of new subsistence strategies. Studies that focused on “How people will continue to live” used paleolimnological methodologies to examine water management, wildlife management, and vegetation history reconstructions. A variety of physical, chemical, and biological indicators were used in the studies included in our systematic map (see supplementary information). The majority of articles focused on reconstructing change; climate patterns, human activities, or identifying the need for paleolimnology to examine change in the context of a sustainable future (Fig. 2.3).

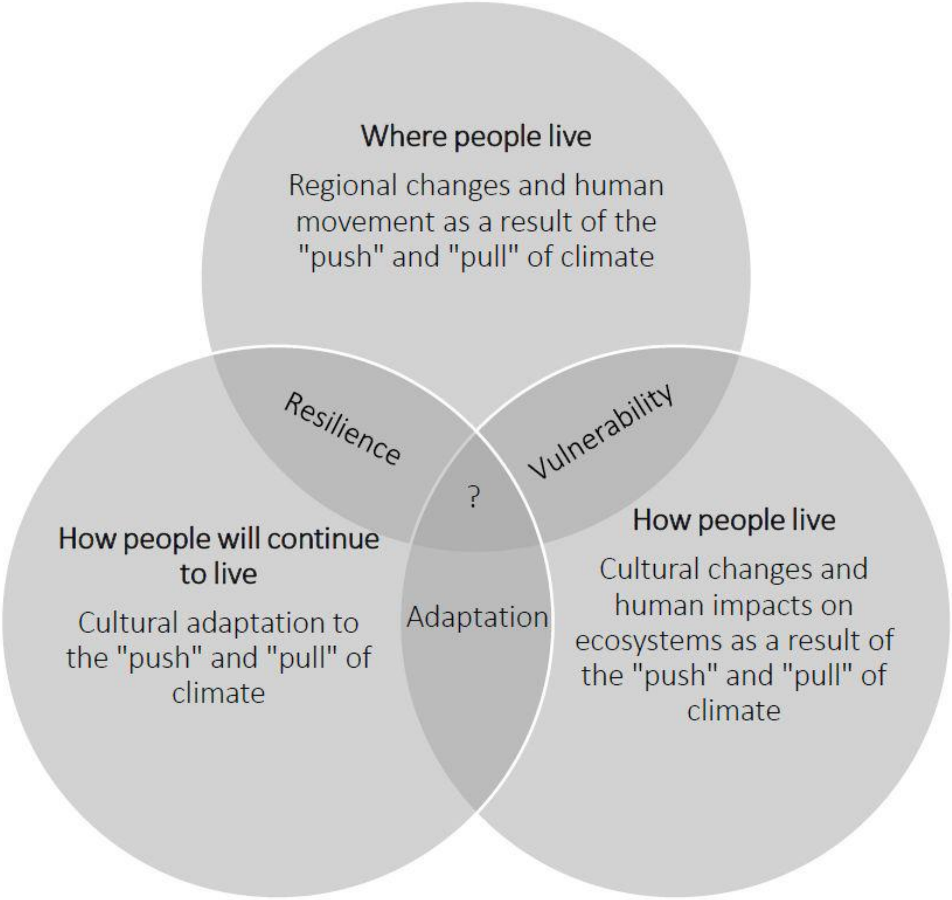

Figure 2.3 Thematic areas identified in the literature that utilize paleolimnological methods to examine how environmental change impacts human society.

2.6 Discussion

Informed by our systematic mapping process, we discuss how paleolimnology, and similar methodologies, have provided context to our knowledge of the "push" and "pull" of climate and its impacts on human society. We focused on articles identified in our results and also highlight future implications, applications, and insights on the use of paleolimnological methodology for increasing our understanding of how climate variability may affect human society in a warming future.

2.6.1 *The "push" and "pull" of climate over the past millennia*

Climate change is a key factor in the spread of human populations across the globe, influencing environments that have predicated the migration of both species and peoples; migration is often an adaptive response to the "push" and "pull" factors of climate (Marr 2015). Large scale changes in climate, such as significant warming and cooling periods, have been well researched through paleo-inferences of isotopic geochemistry and biological indicators in lacustrine sediments (Reheis 1999; Stefanova et al. 2003; Lozhkin and Anderson 2013; Adams et al. 2019). 26 of the relevant 68 articles from our keyword search studied large-scale changes in climate using geochemical and/or biological indicators. Paleoenvironmental reconstruction of glacial change (Vegas-Vilarrúbia et al. 2013), southern oscillation (Rodysill et al. 2012), and hydrologic change (Magyari et al. 2009) all focus on large-scale changes associated to threshold shifts in biological indicators on a millennial scale. Paleolimnological studies have also supported revision of previous estimates of when large-scale changes occurred (Hoelzmann et al. 2001; Wolfe et al. 2012), as well as the amplitude and timing of ecosystem response (Wolfe et al. 1996). This has proven to be important for understanding the impact of climate forcing on biological change, as different biota have different thresholds at which they can tolerate change (Stefanova et al. 2003). Different taxa have differences in their optima and tolerance of environmental conditions in which they operate (Williamson et al. 2009).

While paleolimnological techniques can effectively reconstruct past environments, archaeological evidence is sometimes paired with these inferences to specify the presence of early human populations (Tudryn et al. 2013; Temoltzin et al.

2018). Depending on the subsistence strategies employed, a region's climate is known to influence whether the location is suitable for occupation (Liu et al. 2020), but direct evidence of human occupation is less apparent, especially in studies that deploy a single paleolimnological proxy. Paleolimnology has also been used to help confirm previous human occupation dates that were solely dated using archaeological data (Hoelzmann et al. 2001). While 18 of the 68 articles reviewed discussed human occupation, reconstructing human occupation was often not the main topic of focus. Human occupation was often discussed coincidently alongside other historical environmental information. For example, Schmidt et al. (2019) aimed to reconstruct the onset of stable freshwater conditions on Ruben Island, Japan using multiproxy paleolimnological records, but also discovered the appearance of the earliest settlement of sedentary hunter-gatherer populations (5000-4000 cal. Years BP).

The movement of early humans can largely be tied to environmental changes, especially when a region is no longer fit for occupation. For example, Inuit who rely on seal hunting are required to migrate further North when the sea ice is too thin to be able to safely hunt (Hadley et al. 2010). 12 of the 68 articles from our keyword search discussed human migration, often using paleolimnological techniques along-side archaeological evidence. For example, Hoelzmann et al. (2001) identified four settlement phases around a freshwater in the Eastern Sahara (Africa) during the Holocene epoch using a multi-proxy reconstruction approach of carbonates, oxygen and carbon isotopes, and diatoms, paired with the dates of stone tool remains. The chemical composition of the sediment core allowed for the inference of lake stages throughout history and provided context for why groups settled and abandoned the region in cycles. Indeed, several studies reconstructed the timing of human migration by inferring the timing of abandonment (Hoelzmann et al. 2001; Filippelli et al. 2010; Temoltzin et al. 2018). For example, Filippelli et al. (2010) inferred abandonment of a once-continuous human occupation from the recovery of vegetation at the site.

2.6.2 *How the "push" and "pull" of climate has influenced culture*

A common theme in the field of paleolimnology is how anthropogenic stressors, such as the arrival of settlers or increased human development in lake basins, have led to ecological changes. Climate is often an integral component of understanding ecological stress, as climate factors can influence both the environment as well as human society (Todgham and Stillman 2013). We found that topics relating to how human society was influenced in relation to climate was more commonly covered in the literature than studies relating to where people lived (Table 2). 36 articles from our keyword search discussed how people lived and the impacts that they had on the environment. Indigenous cultures in the Canadian Arctic, in particular, have received large amounts of recent attention. This is not unexpected as climate change is significantly impacting the cultural continuity of the indigenous peoples of the Canadian Arctic (primarily Inuit) and the sustainability of their subsistence-sharing economy (Hadley et al. 2010; Michelutti et al. 2013). Paleolimnology can also identify impacts by subsistence/anthropogenic stressors in what were once thought to be pristine environments (Zawiska et al. 2013). For example, whaling camps by Thule Inuit impacted the water quality and ecology of high Arctic lakes as a result of constructing their settlements from nutrient rich whale bones that over time leached nitrogen into freshwater bodies, altering their chemical composition (Douglas et al. 2004). The Thule society's impact continues be evident despite these lakes having been abandoned centuries ago due to the legacy of nutrient enrichment that continues to leach into the water at these sites (Douglas et al. 2004).

Freshwater lakes are under threat globally from both natural and anthropogenic stress (Mills et al. 2017). As these systems are important for both cultural and subsistence practices, the environment (climate) can have a large influence on settlement and migration. 23 articles from our keyword search discussed the impact of both climate and anthropogenic stress on subsistence lifestyles. For example, lake-level is often associated with climate, which can influence agricultural practices as well as the presence of subsistence prey (Sedov et al. 2010). Paleolimnological inferences have documented examples of human society that transitioned from a low-impact nomadic lifestyle to a high-impact and overly consumptive sedentary lifestyle. These transitions frequently depend on the magnitude of the "push" or "pull" of climate on the ecosystem or ecological services that cultural activities depend on and the timing of climate events (Junginer and Trauth 2013). Water collection, hunting, fishing, gathering, and agriculture are all environment dependent, and adaptations to these practices are frequently tied to changes in climate, and more recently, technological advancements. While migration is a common response to environmental stress (Shaw 2016), adaptation or the transition to different subsistence practices was discussed in 9 articles (Table 2). For example, Feeser et al. (2015) described the transition to animal husbandry inferred with the use of pollen during the Neolithic epoch (7000–4000 BP).

2.6.3 The use of paleolimnological methods to anticipate impacts

The context of how lakes have changed from their natural or pre-disturbed state provides key information for remediation projects and the creation of freshwater management plans. As such, paleolimnology can ultimately be considered an effective tool to achieve environmental sustainability (Saulnier-Talbot 2006). Environmental managers are better able to understand the trajectory of ecosystem change with a baseline context of the pre-disturbance state. This knowledge can then be applied to the management of ecosystem services that communities are reliant upon (Sullivan and Charles 1994). The use of paleolimnology to qualify freshwater sustainability was a common theme discussed in the literature, with 23 articles discussing the application of paleolimnological methods in the realm of water management. Popular themes identified focused on the influence of anthropogenic activities and how they have modified lake catchments (Magyari et al. 2009; Shaw Chraïbi et al. 2014), as well as changes in ecological status since the industrial revolution (Kirilova et al. 2009).

The reconstruction of lake trophic structure can be a determining factor for inferences on the population dynamics of wildlife, especially where census data does not exist for a species (Hargan et al. 2019). Similar to the migration of humans, the migration of sensitive species can be tracked through paleolimnological inferences of limnological conditions (Hobbs and Wolfe 2008). 6 articles from our keyword search discussed the application of paleolimnological methodologies in the realm of wildlife management. A reoccurring theme in these articles was reconstructing limnological conditions to assess and track how habitat conditions of endangered fish species have changed in freshwater lakes (Selbie et al. 2007; Ginn et al. 2008a). As ecotones are expected to shift with an anthropogenic warming, employing paleolimnological techniques will be very valuable to understand wildlife population shifts and to better protect species against habitat threats. Ultimately, the history behind the evolution of natural systems is crucial for assessing conservation priorities (Zawiska et al. 2013).

While pollen analysis is commonly used in paleolimnological reconstructions, studies that specifically focus on changes in vegetation that may influence human society were less commonly found in the literature. 5 of the 68 articles in our study focused on the application of paleolimnological methodologies for identifying the onset of new species (e.g., the introduction of invasive species), and/or changes in climate and post-glacial hydrologic change with respect to vegetation cover. Paleolimnological methodologies are also useful to simply reconstruct changes in the dominant types of vegetation (Zhilich et al. 2017), which can ultimately provide reference conditions of a region for restoration projects to keep in mind.

2.6.4 New approaches in paleolimnological assessment of the Anthropocene

The use of emerging techniques with an interdisciplinary focus, as well as transdisciplinary methods, have expanded our knowledge of human settlement. For example, the inclusion of zooarchaeological archives along with an analysis of lipid biomarkers and isotopic geochemistry of sediments allowed Connolly et al. (2019) to infer human settlement locations back to the Paleolithic (late Pliocene) era, providing evidence of some of the very first sites of human occupation. Indeed, as Smol (1990) noted, paleolimnology as a method in the realm of aquatic sciences has substantially advanced; we can still see that this holds as true in 2020 as it did in 1990. The number of publications on reconstructing subsistence cultures has increased dramatically in recent years (Fig. 1a). While our systematic mapping approach captured some new and novel approaches (such as Connolly et al. 2019), we undoubtedly missed studies that may have made inferences from lacustrine sediments using different methods deploying different terminology. For example, advances in fecal biomarkers (Guillemot et al. 2015; Zocatelli et al. 2017) and sedimentary DNA (Domaizon et al. 2017) have opened new and interesting opportunities for investigating long-term influences of humans on the environment. Yet, our systematic approach did not capture these studies, as they did not include keywords associated with paleolimnology. Studies that are either primarily driven by an archaeological focus (e.g., Zocatelli et al. 2017), or based on former lacustrine sediment archives (Labarca et al. 2020) are particularly difficult to capture in a review of paleolimnological approaches; while they use lacustrine archives, they do so in a unique way for a completely different discipline. Indeed, our systematic map of literature notes that while paleolimnology can be used to infer the influence of climate on subsistence cultures, these inferences are often only made in a direct way when a combination of discipline-specific methods are deployed (e.g., archaeological evidence). The future of paleolimnological research may actually reside in the ability for researchers to have an interdisciplinary focus and combine innovative approaches to reconstruct past environments.

2.7 Conclusion

We found 68 articles that demonstrated the usefulness of paleolimnological methodologies in reconstructing subsistence lifestyles throughout history using a systematic mapping process. Three key themes were identified and further organized by subtheme: the “push” and “pull” of climate over the past millennia; large-scale changes in climate, human occupation, and early human migration, how the “push” and “pull” of climate has influenced culture; ecosystem changes resulting from anthropogenic stressors, the impact of both climate and anthropogenic stressors, and cultural changes resulting from environmental change, and the use of paleolimnological methods to anticipate impacts; water management, wildlife management, and vegetation history reconstructions.

Our review revealed that a comprehensive collection of literature exists that demonstrates paleolimnological methods are an effective tool at providing insight into how climate has influenced aspects of the subsistence culture. 95% of the relevant articles from our systemic mapping process were published in this past decade. This suggests that the employment of paleolimnological techniques has become more common in subsistence-related research. These records have changed our perception of subsistence cultures and our transition to modern day techniques. Paleolimnological methods can also aid in the understanding of the timing of events and baseline / reference conditions for water bodies, wildlife populations, and vegetation types. This knowledge is crucial for effective remediation and management. Of the 10 articles published in the year 2020, all studies explored a unique research scope and topic; a common characteristic found was that paleolimnological methods provide quantitative context for past environments based on physical data. We note that our systematic mapping process has likely missed key studies that use unique and novel approaches, especially those that deploy transdisciplinary approaches to understanding past environments. Ultimately, the future of paleolimnological research likely lies with interdisciplinary research focused on understanding how past societies were either resilient or adaptable to environmental change. This knowledge is essential should we wish to achieve environmental sustainability while we continue to be “pushed” and “pulled” by climate.

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2.9 Authors Contributions and Conflict of Interest

A.S. Medeiros was principal investigator and conceived of the study. A. Covert completed the systematic mapping process, extracted data, and completed all reporting. A. Medeiros reviewed and checked results for consistency. Both A. Covert and A. Medeiros contributed to writing the manuscript draft. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

2.10 Data Accessibility

All articles identified, selected, excluded, and thematically coded in this systematic process are outlined in the supplemental information.

2.11 Supplemental Information

Supplemental information for Supplementary Table S1and Supplementary Figure S1 can be found on the FACETS website at https://www.facetsjournal.com/doi/10.1139/facets-2021-0088, Doi: 10.1139/facets-2021-0088. Supplementary Table S1caption: A complete table of data extracted from relevant papers for review analysis. Supplementary Figure S1caption: A ROSES flow diagram for systematic map (version 1.0) to record the selection process of articles based on the variations of search terms seen in Table 2.1. (Haddaway et al. 2017).

2.11 References

Adams, J., Peng, Y., Rose, N., Shchetnikov, A., & Mackay, A. (2019). Diatom community responses to long-term multiple stressors at Lake Gusinoye, Siberia. Geo: Geography and Environment, 6(1). https://doi.org/10.1002/geo2.72.

Bramburger, A., Reavie, E., Sgro G., Estepp, L., Shaw Chraïbi, V., & Pillsbury, R. (2020). Size matters: diatom establishment and extirpation timing in the Laurentian Great Lakes has been influenced by cell size. Journal of Plankton Research, 42(3): 255–264. https://doi.org/10.1093/plankt/fbaa013.

Brenner, M., Rosenmeier, M., Hodell, D., & Curtis, H. (2002). Paleolimnology of the Maya Lowlands: Long–term perspectives on interactions among climate, environment, and humans. Ancient Mesoamerica, 13(1); 141-157. https://doi.org/10.1017/s0956536102131063.

Bush, M., Miller, M., De Oliveira, P., & Colinvaux, P. (2000). Two histories of environmental change and human disturbance in eastern lowland Amazonia. Holocene (Sevenoaks), 10(5): 543-553. https://doi.org/10.1191/095968300672647521.

Carto, S., Weaver, A., Hetherington, R., Yin, L., & Wiebe, E. (2009). Out of Africa and into an ice age: On the role of global climate change in the late Pleistocene migration of early modern humans out of Africa. Journal of Human Evolution, 56(2): 139-151. https://doi.org/10.1016/j.jhevol.2008.09.004.

Chambers, K., Corbett, J., Keller, C., & Wood, C. (2004). Indigenous Knowledge, Mapping, and GIS: A Diffusion of Innovation Perspective. Cartographica, 39(3): 19-31. https://doi.org/10.3138/n752-n693-180t-n843.

Connolly, R., Jambrina-Enríquez, M., Herrera-Herrera, A., Vidal-Matutano, P., Fagoaga, A., Marquina-Blasco, R., … & Mallol, C. (2019). A multiproxy record of palaeoenvironmental conditions at the Middle Palaeolithic site of Abric del Pastor (Eastern Iberia). Quaternary Science Reviews, 1(225). https://doi.org/10.1016/j.quascirev.2019.106023.

Davies, S. (1993). Are Coping Strategies a Cop Out? IDS Bulletin, 24(4): 60-72. https://doi.org/10.1111/j.1759-5436.1993.mp24004007.x.

Diamond, J. (2005). Collapse: How societies choose to fail or succeed. Penguin, New York, 586.

Dinero, S. (2013). Indigenous perspectives of climate change and its effects upon subsistence activities in the Arctic: The case of the Nets'aii Gwich'in. GeoJournal, 78(1): 117-137. https://doi.org/10.1007/s10708-011-9424-8.

Domaizon, I., Winegardner, A., Capo, E., Gauthier, J., & Gregory-Eaves, I. (2017). DNA-based methods in paleolimnology: new opportunities for investigating long-term dynamics of lacustrine biodiversity. Journal of Paleolimnology, 58(1): 1-21. https://doi.org/10.1007/s10933-017-9958-y.

Douglas, M., Smol, J., Savelle, J., & Blais, J. (2004). Prehistoric Inuit whalers affected Arctic freshwater ecosystems. Proceedings of the National Academy of Sciences of the United States of America, 101(6): 1613-1617. https://doi.org/10.1073/pnas.0307570100.

Feeser, I., Dörfler, W., Czymzik, M., & Dreibrodt, S. (2016). A mid-Holocene annually laminated sediment sequence from Lake Woserin: The role of climate and environmental change for cultural development during the Neolithic in Northern Germany. Holocene (Sevenoaks), 26(6): 947-963. https://doi.org/10.1177/0959683615622550.

Filippelli, G., Souch, M., Horn, C., & Newkirk, S. (2010). The pre-Colombian footprint on terrestrial nutrient cycling in Costa Rica: Insights from phosphorus in a lake sediment record. Journal of Paleolimnology, 43(4): 843-856. https://doi.org/10.1007/s10933-009-9372-1.

Friesen, T., Finkelstein, S., & Medeiros A. (2020). Climate variability of the Common Era (AD 1 – 2000) in the eastern North American Arctic: Impacts on human migrations. Quaternary International, 549: 142-154. https://doi.org/10.1016/j.quaint.2019.06.002.

Frisch, D., Morton, P., Culver, B., Edlund, M., Jeyasingh, P., & Weider, L. (2017). Paleogenetic records of Daphnia pulicaria in two North American lakes reveal the impact of cultural eutrophication. Global Change Biology, 23(2): 708-718. https://doi.org/10.1111/gcb.13445.

Ginn, B., Grace, L., Cumming, B., & Smol, J. (2008). Tracking anthropogenic- and climatic-related environmental changes in the remaining habitat lakes of the endangered Atlantic whitefish (Coregonus huntsman) using palaeolimnological techniques. Aquatic Conservation: Marine and Freshwater Ecosystems, 18(7): 1217-1226. https://doi.org/10.1002/aqc.934.

Guillemot, T., Zocatelli, R., Bichet, V., Jacob, J., Massa, C., Le Milbeau, C., ... & Gauthier, E. (2015). Evolution of pastoralism in Southern Greenland during the last two millennia reconstructed from bile acids and coprophilous fungal spores in lacustrine sediments. Organic Geochemistry, 81: 40-44. https://doi.org/10.1016/j.orggeochem.2015.01.012.

Haddaway, N., Macura, B., Whaley, P., & Pullin, A. (2018). ROSES Reporting standards for Systematic Evidence Syntheses: pro forma, flow-diagram and descriptive summary of the plan and conduct of environmental systematic reviews and systematic maps. Environmental Evidence, 7(1): 1-8. https://doi.org/10.1186/s13750-018-0121-7.

Hadley, K., Douglas, M., Blais, J., & Smol, J. (2010). Nutrient enrichment in the High Arctic associated with Thule Inuit whalers: A paleolimnological investigation from Ellesmere Island (Nunavut, Canada). Hydrobiologia, 649(1): 129-138. https://doi.org/10.1007/s10750-010-0235-6.

Hargan, K., Gilchrist, H., Clyde, N., Iverson, S., Forbes, M., Kimpe, L., … & Blais, J. (2019). Multicentury perspective assessing the sustainability of the historical harvest of seaducks. Proceedings of the National Academy of Sciences of the United States of America, 116(17): 8425-8430. https://doi.org/10.1073/pnas.1814057116.

Hobbs, W., & Wolfe, A. (2008). Recent paleolimnology of three lakes in the Fraser River Basin (BC, Canada): No response to the collapse of sockeye salmon stocks following the Hells Gate landslides. Journal of Paleolimnology, 40(1): 295-308. https://doi.org/10.1007/s10933-007-9161-7.

Hoelzmann, P., Keding, B., Berke, H., Kröpelin, S., & Kruse, H. (2001). Environmental change and archaeology: Lake evolution and human occupation in the Eastern Sahara during the Holocene. Palaeogeography, Palaeoclimatology, Palaeoecology, 169(3): 193-217. https://doi.org/10.1016/s0031-0182(01)00211-5.

Hofmann, A., Geist, J., Nowotny, L., & Raeder, U. (2020). Depth-distribution of lake benthic diatom assemblages in relation to light availability and substrate: Implications for paleolimnological studies. Journal of Paleolimnology, 64(3): 315-334. https://doi.org/10.1007/s10933-020-00139-9.

Holmes, J., Jones, R., Nicolas Haas, J., McDermott, F., Molloy, K., & O’Connell, M. (2007). Multi-proxy evidence for Holocene lake-level and salinity changes at An Loch Mór, a coastal lake on the Aran Islands, Western Ireland. Quaternary Science Reviews, 26(19): 2438-2462. https://doi.org/10.1016/j.quascirev.2007.06.020.

Horta, L., Marcos, M., Sacchi, M., Bozzuto, D., Georgieff, S., Mancini, M., & Civalero, M. (2019). Paleogeographic and paleoenvironmental evolution in northwestern Santa Cruz (Argentina), and its influence on human occupation dynamics during the late Pleistocene- early Holocene. Palaeogeography, Palaeoclimatology, Palaeoecology, 516: 44-53. https://doi.org/10.1016/j.palaeo.2018.11.037.

Jones, R., Marshall, J., Fisher, E., Hatton, J., Patrick, C., Anderson, K., Bedford, A., & Oldfield, F. (2011). Controls on lake level in the early to mid-Holocene, Hawes Water, Lancashire, UK. Holocene (Sevenoaks), 21(7): 1061-1072. https://doi.org/10.1177/0959683611400455.

Junginger, A., & Trauth, M. (2013). Hydrological constraints of paleo-Lake Suguta in the Northern Kenya Rift during the African Humid Period (15–5kaBP). Global and Planetary Change, 111: 174-188. https://doi.org/10.1016/j.gloplacha.2013.09.005.

Kirilova, E., Heiri, O., Enters, D., Cremer, H., Lotter, A., Zolitschka, B., & Hubener, T. (2009). Climate-induced changes in the trophic status of a Central European lake. Journal of Limnology, 68(1): 71-82. https://doi.org/10.1016/0033-5894(87)90010-x.

Korosi, J., Ginn, B., Cumming, B., & Smol, J. (2013). Establishing past environmental conditions and tracking long-term environmental change in the Canadian Maritime provinces using lake sediments. Environmental Reviews, 21(1): 15-27. https://doi.org/10.1139/er-2012-0041.

Kusimba, S. (1999). The Early Later Stone Age in East Africa: Excavations and Lithic Assemblages from Lukenya Hill. African Archaeological Review, 18(2): 165-200. https://doi.org/10.1006/jaar.1998.0335.

Labarca, R., González-Guarda, E., Lizama-Catalán, Á., Villavicencio, N. A., Alarcón-Muñoz, J., Suazo-Lara, F., ... & Buldrini, K. (2020). Taguatagua 1: New insights into the late Pleistocene fauna, paleoenvironment, and human subsistence in a unique lacustrine context in central Chile. Quaternary Science Reviews, 238: 106282. https://doi.org/10.1016/j.quascirev.2020.106282.

Lewis, C., Cameron, F., Anderson, M., Heil, G., & Gareau, D. (2012). Lake levels in the Erie Basin of the Laurentian Great Lakes. Journal of Paleolimnology, 47(3): 493-511. https://doi.org/10.1007/s10933-012-9578-5.

Liu, X., Hu, J., Shi, W., Chen, H., Liang, X., & Li, M. (2020). Stratigraphy and its environmental implications of the Late Pleistocene Shuidonggou Formation in the western Ordos Block, North China. Geological Journal, 55(11): 7359-7370. https://doi.org/10.1002/gj.3972/v2/response1.

Lozhkin, A., & Anderson, P. (2013). Late Quaternary lake records from the Anadyr Lowland, Central Chukotka (Russia). Quaternary Science Reviews, 68: 1-16. https://doi.org/10.1016/j.quascirev.2013.02.007.

López-Valcárcel, M., Parra, G., & Del Arco, A. (2021). Environmental Disturbance History Undermines Population Responses to Cope with Anthropogenic and Environmental Stressors. Chemosphere (Oxford), 262: 128373. https://doi.org/10.1016/j.chemosphere.2020.128373.

Magyari, E., Buczkó, K., Jakab, G., Braun, M., Pál, Z., Karátson, D., & Pap, I. (2009). Palaeolimnology of the last crater lake in the Eastern Carpathian Mountains: A multiproxy study of Holocene hydrological changes. Hydrobiologia, 631(1): 29-63. https://doi.org/10.1007/978-90-481-3387-1_3.

Marr, B. (2015). Review of: Migration and Climate Change. Canadian Studies in Population, 42(1-2): 170. https://doi.org/10.25336/p6mw3p.

Michelutti, N., Mccleary, K., Antoniades, D., Sutherland, P., Blais, J., … & Smol, J. (2013). Using paleolimnology to track the impacts of early Arctic peoples on freshwater ecosystems from southern Baffin Island, Nunavut. Quaternary Science Reviews, 76: 82-95. https://doi.org/10.1016/j.quascirev.2013.06.027.

Mills, K., Schillereff, D., Saulnier-Talbot, É., Gell, P., Anderson, N. J., Arnaud, F., … & Moorhouse, H. (2017). Deciphering long-term records of natural variability and human impact as recorded in lake sediments: A palaeolimnological puzzle. Wiley Interdisciplinary Reviews: Water, 4, e1195. https://doi.org/10.1002/wat2.1195.

Murnaghan, S., Taylor, D., Jennings, E., Dalton, C., Olaya-Bosch, K., & O'Dwyer, B. (2012). Middle to late Holocene environmental changes in western Ireland inferred from fluctuations in preservation of biological variables in lake sediment. Journal of Paleolimnology, 48(2): 433-448. https://doi.org/10.1007/s10933-012-9620-7.

Nelligan, C., Jeziorski, A., Rühland, K., Paterson, A., Meyer-Jacob, C., & Smol, J. (2019). A multibasin comparison of historical water quality trends in Lake Manitou, Ontario, a provincially significant lake trout lake. Lake and Reservoir Management, 36(3): 243–259. https://doi.org/10.1080/10402381.2019.1659889.

Newell, S., Dion, M., & Doubleday, N. (2020). Cultural continuity and Inuit health in Arctic Canada. Journal of Epidemiology and Community Health (1979), 74(1): 64-70. https://doi.org/10.1136/jech-2018-211856.

Reheis, M. (1999). Highest Pluvial-Lake Shorelines and Pleistocene Climate of the Western Great Basin. Quaternary Research, 52(2): 196-205. https://doi.org/10.1006/qres.1999.2064.

Saulnier-Talbot, É. (2016). Paleolimnology as a tool to achieve environmental sustainability in the Anthropocene: An overview. Geosciences, 6(2): 26.

Schindler, D. (2009). Lakes as sentinels and integrators for the effects of climate change on watersheds, airsheds, and landscapes. Limnology and Oceanography, 54(6): 2349-358. https://doi.org/10.4319/lo.2009.54.6_part_2.2349.

Schmidt, M., Leipe, C., Becker, F., Goslar, T., Hoelzmann, P., Mingram, J., … & Tarasov, P. (2019). A multi-proxy palaeolimnological record of the last 16,600 years from coastal Lake Kushu in northern Japan. Palaeogeography, Palaeoclimatology, Palaeoecology, 514: 613-626. https://doi.org/10.1016/j.palaeo.2018.11.010.

Sedov, S., Lozano-García, S., Solleiro-Rebolledo, E., Mcclung de Tapia, E., Ortega-Guerrero, B., & Sosa-Nájera, S. (2010). Tepexpan revisited: A multiple proxy of local environmental changes in relation to human occupation from a paleolake shore section in Central Mexico. Geomorphology (Amsterdam, Netherlands), 122(3): 309-322. https://doi.org/10.1016/j.geomorph.2009.09.003.

Selbie, D., Lewis, B., Smol, J., & Finney, B. (2007). Long-Term Population Dynamics of the Endangered Snake River Sockeye Salmon: Evidence of Past Influences on Stock Decline and Impediments to Recovery. Transactions of the American Fisheries Society (1900), 136(3): 800-821. https://doi.org/10.1577/t06-100.1.

Shaw, A. (2016). Drivers of Animal Migration and Implications in Changing Environments. Evolutionary Ecology, 30(6): 991-1007. https://doi.org/10.1007/s10682-016-9860-5.

Shaw Chraïbi, V., Kireta, A., Reavie, E., Cai, M., & Brown, T. (2014). A paleolimnological assessment of human impacts on Lake Superior. Journal of Great Lakes Research, 40(4): 886-897. https://doi.org/10.1016/j.jglr.2014.09.016.

Slate, J., Johnson, E., & Moore, T. (2013). Impact of pre-Columbian agriculture, climate change, and tectonic activity inferred from a 5,700-year paleolimnological record from Lake Nicaragua. Journal of Paleolimnology, 50(1): 139-149. https://doi.org/10.1007/s10933-013-9709-7.

Smol, J. (2008). Pollution of lakes and rivers: a paleoenvironmental perspective. John Wiley & Sons. 396.

Stefanova, I., Ognjanova-Rumenova, N., Hofmann, W., & Ammann, B. (2003). Late Glacial and Holocene environmental history of the Pirin Mountains (SW Bulgaria): A paleolimnological study of Lake Dalgoto (2310 m). Journal of Paleolimnology, 30(1): 95-111. https://doi.org/10.1191/0959683603hl597rp.

Stutz, A. (2012). Culture and Politics, Behavior and Biology: Seeking Synthesis among Fragmentary Anthropological Perspectives on Hunter-Gatherers. Reviews in Anthropology, 41(1): 23-69. https://doi.org/10.1080/00938157.2012.649183.

Sullivan, T., & Charles, D. (1994). The Feasibility and Utility of a Paleolimnology/paleoclimate Data Cooperative for North America. Journal of Paleolimnology, 10(3): 265-73. https://doi.org/10.1007/bf00684036.

Temoltzin-Loranca, Y., Velez, M., Moreno, E., & Escobar, J. (2018). Late Holocene environmental change in Lake Boquete and its watershed human or natural causes? Boletín De La Sociedad Geológica Mexicana, 70(1): 121-131. https://doi.org/10.18268/bsgm2018v70n1a7.

Temple, D. & Stojanowski, C. (2018). Hunter-gatherer Adaptation and Resilience: A Bioarchaeological Perspective. Cambridge University Press. https://doi.org/10.1017/9781316941256.

Tierney, J., & Russell, J. (2007). Abrupt climate change in southeast tropical Africa influenced by Indian monsoon variability and ITCZ migration. Geophysical Research Letters, 34(15). https://doi.org/10.1029/2007gl029508.

Todgham, A., & Stillman, J. (2013). Physiological Responses to Shifts in Multiple Environmental Stressors. Integrative and Comparative Biology, 53(4): 539-44. https://doi.org/10.1093/icb/ict086.

Tudryn, A., Tucholka, P., Özgûr, N., Gibert, E., Elitok, O., Kamaci, Z., … & Platevoet, B. (2013). A 2300-year record of environmental change from SW Anatolia, Lake Burdur, Turkey. Journal of Paleolimnology, 49(4): 647-662. https://doi.org/10.1007/s10933-013-9682-1.

Tütken, T., Vennemann, T., Janz, H., & Heizmann, E. (2006). Palaeoenvironment and palaeoclimate of the Middle Miocene lake in the Steinheim basin, SW Germany: A reconstruction from C, O, and Sr isotopes of fossil remains. Palaeogeography, Palaeoclimatology, Palaeoecology, 241(3): 457-491. https://doi.org/10.1016/j.palaeo.2006.04.007.

Van Aalst, M., Cannon, T., & Burton, I. (2008). Community level adaptation to climate change: The potential role of participatory community risk assessment. Global Environmental Change, 18(1): 165-179. https://doi.org/10.1016/j.gloenvcha.2007.06.002.

Vegas-Vilarrúbia, T., González-Sampériz, P., Morellón, M., Gil-Romera, G., Pérez-Sanz, A., & Valero-Garcés, B. (2013). Diatom and vegetation responses to Late Glacial and Early Holocene climate changes at Lake Estanya (Southern Pyrenees, NE Spain). Palaeogeography, Palaeoclimatology, Palaeoecology, 392(C): 335-349. https://doi.org/10.1016/j.palaeo.2013.09.011.

Walker, I. (2001). Midges: Chironomidae and Related Diptera. Tracking Environmental Change Using Lake Sediments Developments in Paleoenvironmental Research, 4: 43–66. https://doi.org/10.1007/0-306-47671-1_3.

Williamson, C., Saros, J., Warwick, V., & Smol, J. (2009). Lakes and Reservoirs as Sentinels, Integrators, and Regulators of Climate Change. Limnology and Oceanography, 54(6): 2273-2282. https://doi.org/10.4319/lo.2009.54.6_part_2.2273.

Wolfe, B., Edwards, T., Aravena, R., & MacDonald, G. (1996). Rapid Holocene hydrologic change along boreal treeline revealed by δ13C and δ18O in organic lake sediments, Northwest Territories, Canada. Journal of Paleolimnology, 15(2): 171-181. https://doi.org/10.1007/bf00196779.

Wolfe, B., Hall, R., Edwards, T., & Johnston, J. (2012). Developing temporal hydroecological perspectives to inform stewardship of a northern floodplain landscape subject to multiple stressors: Paleolimnological investigations of the Peace–Athabasca Delta. Environmental Reviews, 20(3): 191-210. https://doi.org/10.1139/a2012-008.

Zawiska, I., Zawisza, E., Woszczyk, M., Szeroczyńska, K., Spychalski, W., & Correa-Metrio, A. (2013). Cladocera and geochemical evidence from sediment cores show trophic changes in Polish dystrophic lakes. Hydrobiologia, 715(1): 181-193. https://doi.org/10.1007/s10750-013-1482-0.

Zhang, C., Zhao, C., Zhang, H., Zhang, X., & Shen, J. (2020). Western Pacific Ocean influences on monsoon precipitation in the southwestern Chinese Loess Plateau since the mid-Holocene. Climate Dynamics, 54(5-6): 3121-3134. https://doi.org/10.1007/s00382-020-05159-9.

Zhilich, S., Rudaya, N., Krivonogov, S., Nazarova, L., & Pozdnyakov, D. (2017). Environmental dynamics of the Baraba forest-steppe (Siberia) over the last 8000 years and their impact on the types of economic life of the population. Quaternary Science Reviews, 163: 152-161. https://doi.org/10.1016/j.quascirev.2017.03.022.

Zocatelli, R., Lavrieux, M., Guillemot, T., Chassiot, L., Le Milbeau, C., & Jacob, J. (2017). Fecal biomarker imprints as indicators of past human land uses: Source distinction and preservation potential in archaeological and natural archives. Journal of Archaeological Science, 81: 79-89. https://doi.org/10.1016/j.jas.2017.03.010.

CHAPTER 3 UNDERSTANDING THE INFLUENCE OF DEVELOPMENT ON CHOCOLATE LAKE, NOVA SCOTIA

3.1 Statement of Student Contribution

Study design by Allison Covert and Andrew Medeiros, limnological data collection by Allison Covert, Andrew Medeiros, and Kathleen Hipwell, chapter writing by Allison Covert with editorial contributions by Andrew Medeiros.

3.2 Abstract

Freshwater ecosystems in proximity to urban centres are often impacted by a combination of local and regional anthropogenic stressors. Urban environments can experience changes due to climate change, surface water acidification, nutrient inputs, and winter deicing salt inputs. For the Halifax Regional Municipality (HRM), surveys of water quality over the last several decades have identified concerns regarding acidification, salinity, and nutrients due to industrial activity, human development, and atmospheric deposition. Local concerns have also added to these concerns for environments that hold recreational value, such as Chocolate Lake. In this chapter, how human disturbance in HRM has impacted the health and ecological functioning of Chocolate Lake is explored through a paleolimnological study of chironomids (Diptera: Chironomidae). The findings of this study established the baseline condition of Chocolate Lake to have been a shallow wetland environment ~3100 years BP. Based on shifts in chironomids assemblages observed in the sediment record influences from industrialization, residential development, and the application of chemicals in the watershed over the last millennia are inferred. The findings of this study are important for informed lake management, to

support lake managers and decision makers in establishing realistic remediation targets and identifying stressors that need to be addressed.

3.3 Introduction

The province of Nova Scotia has experienced rapid growth and development since the industrial revolution that has relied on freshwater systems as a basis of socioeconomic growth. Through a resource-based economy, the province's industrial growth rate exceeded all of the other provinces in eastern Canada during the years 1881 and 1891 (Acheson 1972). Atlantic communities traditionally exported lumber, fish, and ships, and between the years 1880-1890 Nova Scotia's industrial output increased 66% (Acheson 1972). This growth originated from cities with railroad centres and traditional Atlantic ports such as that of Halifax and brought with it a host of environmental impacts for the community including watershed development, nutrient inputs, and climate change (Acheson 1972).

Human disturbances negatively affect wildlife and aquatic communities, as well as the ecosystem services societies benefit from a waterbody (United States Environmental Protection Agency 2021). Throughout history, Halifax has benefited from the use of ecosystem services of its local freshwater environments. However, the use of freshwater ecosystems for human benefit has led to diminished ecological value (Chu and Karr 2016) through a range of activities, including deforestation for land development, flooding as a result of damming, and algal blooms due to nutrient enrichment (Ruddiman et al. 2015). The intensity of human disturbances has increased since the industrial revolution, starting around mid-1800, when the world's largely rural agrarian society transitioned into an urban industrialized society (Humphries and Schneider 2019). The shorelines of nearby lakes became more developed for vacation and residential properties and increasing amounts of water needed to be extracted to service the growing urban population.

Nova Scotia’s resource extraction industry (coal and gold mining) has been shown to have impacted water bodies across the province through both local and long-range atmospheric deposition of anthropogenic mercury and sulphates (Arctic Monitoring and Assessment Programme/United Nations Environment Programme 2018; Roberts et al. 2019). These disturbances have been shown to result in adverse impacts to wildlife through the bioaccumulation of contaminants and the acidification of HRM lakes (Ginn et al. 2007; Roberts et al. 2019). Despite legislations enacted to reduce industry emission levels, the already acid sensitive lakes in Halifax continue to be impacted today, as aquatic communities across all trophic levels such as, plankton, benthic species, fish, and birds have been shown to be impacted by changes in pH (Vaughan et al. 1982; Nocera and Taylor 1998; Jeffries et al. 2000; Ginn et al 2007; Korosi et al. 2013; Kurek et al. 2012). Large scale operations, such as quarries and manufacturing centres, such as mills and factories, have been a significant disturbance on the ecology and functioning of freshwater lakes in HRM (Regan 1928; The Halifax Urban Greenway Association 2019). The creation of millponds to harness energy for the production industry was also a prevalent human disturbance that led to flooding of watersheds that impacted the health of the province’s aquatic systems (Gwynn 1998). Flooding can lead to the erosion of shorelines and consequently induce the mobilization of mercury from the soil that bioaccumulates in the trophic system, having devastating consequences on the health of local wildlife (Spencer et al. 2011).

Understanding the complexities of socioecological systems, the relationship between humans and ecosystems, requires knowledge of both the past and present (Briggs et al. 2006). Without historical records of the original or pre-disturbance state of a water body and the activities and stressors that have been impacting the system, the degree of natural versus anthropogenic variability is difficult to know (Ginn et al. 2008a). Hence, the impact of human activities remains largely unknown in how and to what extent they have impacted the health and functioning of lakes (Ginn et al. 2008a). This leaves a gap in knowledge concerning future water risks and freshwater ecosystem management, as baseline conditions are fundamental to understand to rehabilitate water bodies and build climate change resilience in shoreline communities. This information is important to acquire as the world moves into an uncertain future faced with complex interactions and influences of both natural and anthropogenic environmental stressors.

Informed management via paleolimnological data is required to offer conclusions on changes in water quality which is essential for HRM to carry out their Regional Municipal Planning Strategy. The city’s strategy aims to have a “balanced approach to development [with] established targets for directing housing growth over the life of the Regional Plan (2006-2031)” (HRM 2014). The strategy is based on growth scenarios of HRM and considers how human development will impact the environment (HRM 2014, page). It aims to “direct [settlement and] growth so as to balance property rights and lifestyle opportunities with responsible […] environmental management” (HRM 2014). Unfortunately, Atlantic Canada lacks detailed historical limnological records which will prove difficult to achieve the goal of further human development with responsible environmental management. Anthropogenic activities have impacted most of the lakes in HRM, especially those within well-developed watersheds, with acid precipitation, increased nutrients, silt, and road salt identified as some of the major pollutants (Clement et al. 2007). Should HRM wish to understand and have targets for managing the quantity and quality of freshwater resources in response to human stressors, resource managers and city planners must first gain a reference point to understand patterns and vulnerability through paleolimnological study.

Several paleolimnological studies conducted in Nova Scotia exist in the literature (Kerekes et al. 1984; Ginn et al. 2008a; Kurek et al. 2012; Korosi et al. 2013; Ginn et al 2015). Many of these studies investigated the influence of human activities on freshwater bodies to provide insight into topics of concerns, such as how changes in acidic deposition and nutrient status will impact fisheries management, conservation efforts, and catchment development (Ginn et al. 2008a; Kurek et al. 2012; Korosi et al. 2013). Diatoms have been predominantly used as the bioindicator in Nova Scotia, a province threatened by sulphate emissions, as they are well-suited for making inferences regarding changes in pH. Furthermore, for Halifax in particular, top-bottom sampling techniques have primarily been conducted, as opposed to full chronological studies, to gather a quick comparison between pre-industrial (~ pre-1850) and present-day conditions (Rajaratnam 2009; Ginn et al 2015). As such, there is a gap in the literature in regards to complete stratigraphical analyses of freshwater lakes in Halifax, also completed with the chironomid bioindicator to investigate productivity and temperature changes.

Here, the presence and patterns of human disturbances in the Halifax region are inferred by completing a biostratigraphic analysis of chironomid assemblage changes from sediment cores collected from Chocolate Lake. Chocolate Lake is a well-frequented lake just outside of Halifax’s city-center. Ecological change is inferred through shifts in chironomid assemblages in response to human disturbances through the use of paleolimnology techniques, by (1) establishing baseline ecological conditions and (2) inferring causes of ecosystem stress. The results of this study will attempt to provide HRM planners with quantitative inferences of how local human activities and development along the shoreline have impacted the freshwater resource. This is important information for the effective management of the ecosystem as this information can be used for the projection of future water conditions to predict whether the lake will become more hostile in a warming and more populated future (Dunnington et al. 2018). The results will also facilitate HRM in their goal of recommending strategies and methods to adapt stormwater management and in preparing a monitoring protocol that ensures objectives for maintaining water quality are met (Halifax Regional Municipality 2014).

3.4 Study Area

Chocolate Lake located five minutes west of Halifax’s city-center in Armdale, N. S. (44.38° N, 63.38° W) was sampled in September 2020 (Figure 3.1). Chocolate lake has a surface area of 7.1 ha, a maximum depth of 12 m, and an 83,508 m^2 catchment area (Figure 3.3). It plays a major role in the hydrological network of the surrounding watershed, collecting stormwater runoff during high-runoff events. Chocolate Lake also receives inputs from 2 major roadways (St Margaret’s Bay Rd and Herring Cove Rd), from residential properties, and from the parking lot of a major hotel. It is also the receiving body of the Chain of Lakes which then drains into an outlet stream that enters the Atlantic Ocean at the Northwest Arm (Scott et al. 2019; Mapcarta n.d.).

Chocolate Lake transitioned from mesotrophic conditions (prior to human disturbance, ~ pre-1850) to oligotrophic (Ginn et al. 2015). Today, algal blooms threaten the water quality in the summer months and cause unsafe conditions for recreational users; the municipality now regularly tests the lake’s E. coli and cyanobacteria levels (Halifax Regional Municipality 2020; 2021). Probable stressors at play in the catchment are the influx of nutrients from lawn fertilizer and garden pesticide runoff, road salt runoff, and chemical runoff from the hotel and residential properties. Climate warming of the region is most likely also a compounding factor influencing eutrophication in the lake (Smith 2003).

Other changes in the ecological state of Chocolate Lake have been noted by the residents, such as the death and the disappearance of fish and vegetation (Halifax resident, personal communication, August 2020). Climate change could also be a factor influencing the wildlife of Chocolate Lake (Ginn et al. 2008a). However, the lake is surrounded by significant roadways therefore salt inputs from road deicing salt runoff should also be considered as an ecological stressor influencing the health and functioning of the ecosystem.

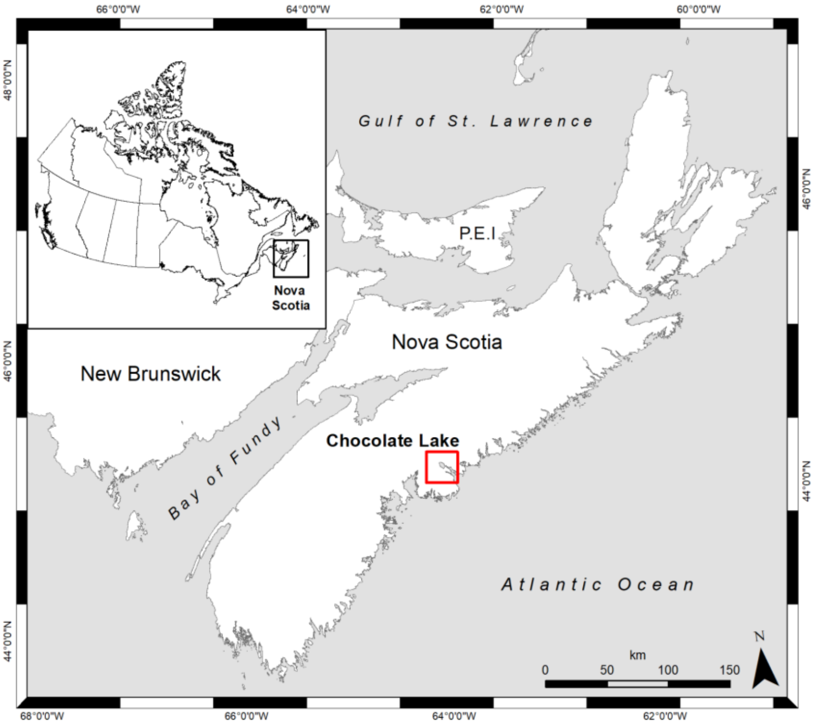

Figure 3.1 Location of the study site Chocolate Lake, Nova Scotia, Canada (Government of Canada 2011).

Figure 3.2 Bathymetric map (depth in metres) of the study site, Chocolate Lake (Government of Nova Scotia, 1983; Google Maps 2022). Coring sites indicated by red squares.

3.5 Methods

3.5.1 Field Methods

Two sediment cores were collected from the deepest region (12-13 m) of Chocolate Lake using a Uwitec gravity corer with an 8.4 cm diameter. The first core totalled 34.5 cm in length, while the second core totalled 25.5 cm in length. The cores were sectioned at the lake in 0.5-cm intervals, placed in a Whirl-Pack ® bag, then transported in a cooler and stored at 4°C for processing.

3.5.2 Laboratory analysis

The first Chocolate Lake core chronology was established using alpha ^{210}Pb and ^{14}C dating techniques completed at the University of Ottawa's AMS lab. Chronos Scientific Ltd. completed the ^{210}Pb spectrometry with the Constant Rate of Supply (CRS) model (Appleby 2001). ^{14}C radiocarbon calibration was performed using OxCal v4.4 (Bronk Ramsey 2009) and the IntCal20 calibration curve (Reimer et al. 2020) completed by the University of Ottawa. To determine organic and carbonate content throughout the core, weight loss-on-ignition (LOI) analysis was carried out following methods defined by Heiri et al. (2001).

Following standard methods (Walker 2001), sediments from the first Chocolate Lake core were processed for subfossil chironomids at Dalhousie University in the Laboratory for Water and Environmental Sustainability Sciences (WESS). The first core (34.5 cm) was analyzed every 0.5 cm interval from the basal interval to 5 cm, after which every 1 cm interval was analyzed to 10 cm, finally every 2 cm interval was analyzed to 34 cm. Each sample was treated with potassium hydroxide (KOH) at 75°C for 30 min, stirring once halfway through, to deflocculate the sediment. Residues were sifted using nested 212 and 106 µm sieves, then washed with 95% ethanol. Subfossil chironomids were sifted and enumerated at least three times from the deflocculated and washed sediment with the use of a dissecting microscope to ensure a 95% capture rate of chironomid heads capsules for each sample. A minimum of 50 head capsules from each interval were collected as per recommended methods (Quinlan and Smol 2001). Should 50 heads not be collected, more sediment was subsampled until 50 or more was attained. The collected specimens were then permanently mounted on glass slides using Entellen® then identified using a Stereo microscope to the lowest possible taxonomic resolution with the use of Oliver and Roussel (1983), Wiederholm (1983), Coffman and Ferrington (1984), and Epler (2001).

3.5.3 Numerical methods

Data analysis was completed using R statistical software v.3.6.0 (R Core Team 2019). Chironomid production, referred to as total chironomid abundance, was calculated for each depth interval of Chocolate Lake using the enumerated head capsules per gram of dry weight (HC g_{-1} DW). Relative abundance for chironomid taxa was also calculated as the percentage of identifiable chironomid head capsules in a sample (see supplemental); taxa with <2% relative abundance was considered rare and were removed from further analysis. Taxa, represented by relative abundance, were plotted stratigraphically by depth and time with zones of significant chironomid abundance change depicted by horizontal lines. The broken stick model (bstick) was applied to a constrained hierarchal cluster analysis (chclust) and found 4 significant zones of change. Principal components analysis (PCA) was completed to outline trends within chironomid community assemblages over time (see supplemental) and plotted using the function timetrack in the R package ‘analogue’ (Simpson 2007). This analysis was used to reduce the dimensionality of the large dataset and display dominant trends among the taxa. The data were limited to taxa greater than 2% relative abundance, and a square-root transformation was applied to the dataset to stabilize variance. Rarefaction analysis (Figure S1) was used to quantify the paleolimnological richness of each sample where E(Tn) is the number of chironomid taxa in n heads in each sample for n=50 (Birks and Line 1992, Bennett and Willis 2001).

3.6 Results

3.6.1 Age-Depth Models

The age-depth model to establish the chronology of the core (Figure 3.3) was created based on nine ^{210}Pb, and six ^{14}C measurements from 3 bulk sediment samples near the bottom of the core. ^{14}C dates were calibrated using the weighted average of the probability distributions, then averaged to apply a linear interpolation between the ^{210}Pb and ^{14}C dates. The level of unsupported ^{210}Pb activity decreased from 0.594 to 0.073 Bq/g between 1.5 – 11.0 cm; the lowermost five samples were below background. A CRS model was used to estimate the age of each interval from 1.5 – 11.0 cm, and linear interpolation, based on the ^{14}C calibrated date of 3114.73 years BP at 34.5 cm, was used for the intervals from 11.5 – 34.5 cm. Organic content (LOI_{550}) (Figure 3.4) largely reflects the chironomid production for the system, where Chocolate Lake exhibits a variable amount of production throughout the core, peaking in organic content at the oldest part of the core (Figure 3.5).

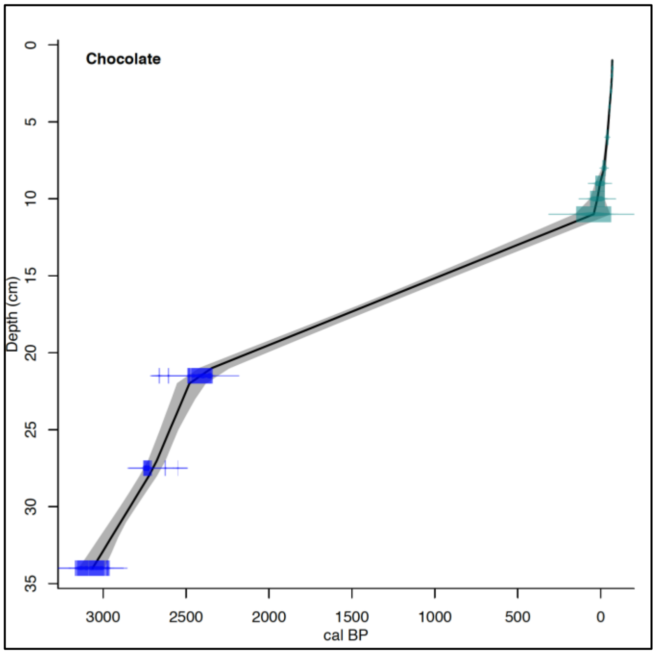

Figure 3.3 Sediment core chronology for Chocolate Lake based on ^{210}Pb (teal) and ^{14}C-inferred (blue) dates and the linear interpolation.

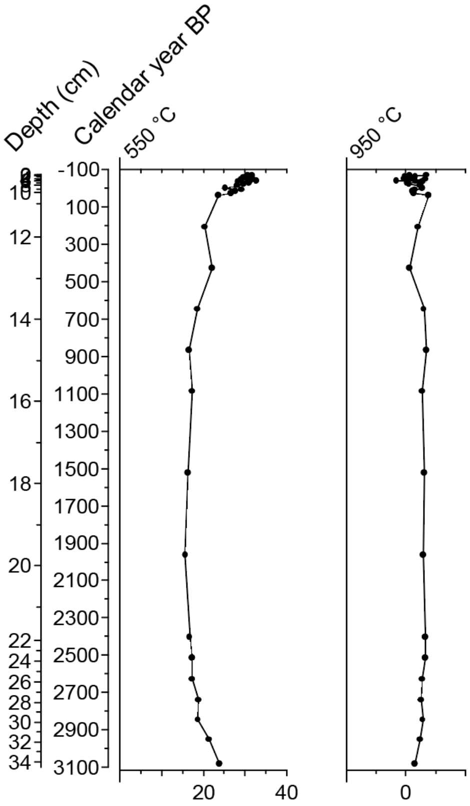

Figure 3.4 Loss on ignition data (% organic matter) for Chocolate Lake (0.5 – 26.0 cm) plotted against age (Calendar year BP) and depth (cm) downcore.

3.6.2 Water Quality Records

Inferences of community assemblage changes in Zone 4 of Chocolate Lake are accompanied by water quality records collected by Clement et al. (2007) (Table 3.1). These records were collected over a 30-year period in the years 1980, 1991, 2000, and 2011 for multiple lakes in Nova Scotia including Chocolate Lake (Clement et al. 2007). While this study does not date back very far in the core, it can help infer recent changes. Notable changes in Chocolate Lake's water quality from the study were: pH has recently become more neutral, conductivity has increased throughout history, Cl^- concentrations have increased, total nitrogen has decreased, and TP spiked in 1991 (Clement et al. 2007).

Table 3.1 Water quality variables in Chocolate Lake over 30 years collected by Clement et al. (2007).

Water quality variable	Unit	1980	1991	2000	2011
Average surface water temperature	(°C)	7	7.6	7	5
pH		5.4	4.7	6.7	5.2
Conductivity	(µS/cm)	450	550	500	620
Average sodium concentrations	(mg/L)	70	80	75	73
Average calcium concentrations	(mg/L)	13	11	12	14
Average magnesium concentrations	(mg/L)	2	2.4	1.7	1.5
Average potassium concentrations	(mg/L)	1.5	1.5	0.9	1.3
Average aluminium concentrations	(mg/L)	N/A	2.30	0.20	0.05
Average chloride concentrations	(mg/L)	110	130	125	135
Average sulphate concentrations	(mg SO4/L)	34	48	26	21
Water quality variable	**Unit**	**1980**	**1991**	**2000**	**2011**

Water quality variable	**Unit**	**1980**	**1991**	**2000**	**2011**
Average alkalinity	(mg CaCO3/L)	1	N/A	2	7
Average ammonia concentrations	(mg N/L)	0.08	0.03	0.02	0.02
Average nitrate concentrations	(mg N/L)	0.21	0.24	0.22	0.25
Average phosphate concentrations	(mg P/L)	0	0.001	0.001	0.001
Average silicate concentrations	(mg Si/L)	0.75	N/A	0.16	0.21
Average total nitrogen (TN)	(mg/L)	0.38	0.35	0.26	0.33
Average total phosphorus (TP)	(mg/L)	0.001	0.250	0.001	0.032
Average chlorophyll a concentrations	(µg/L)	N/A	0.040	0.015	0.010
Average dissolved organic carbon concentrations	(mg C/L)	N/A	N/A	0.8	2.1

3.6.3 Chironomid Assemblages

A total of 2069.5 chironomid head capsules were extracted from the sediment of the core of Chocolate Lake. A total of 163 samples with 76 different chironomid taxa were examined (head capsules per interval: average = 71; median = 65; and range = 51-118.5). Chocolate Lake had an average total abundance of 1457 chironomid head capsules per gram of dry weight (HC g_{-1} DW). Trends in abundance fluctuated throughout the core from 334.94 to 3000.12 HC g_{-1} DW, having the lowest total abundance around the middle and top of the core and peaking in abundance at the oldest interval (Figure 3.5). Zones of “significant” shifts in chironomid abundance were determined using the broken-stick-model applied to a constrained cluster analysis (Figure 3.7); analysis found four significant zones occurred at approximately the years: 2300 years BP, 1400 years BP, and 1943 common era (CE).

Zone 1: 3100 - 2300 years Before Present (BP)

Within Zone 1, 3100 to 2300 years BP, the dominant taxa (>6.3% abundance) were: Chironomus, Cladopelma, Dicrotendipes nervosus-type, Procladius, Psectrocladius psilopterus-type, Tanytarsus mendax-type, and Tanytarsus pallidicornis-type. This zone had the highest average accumulation of chironomids head capsules (productivity) of 73 heads and a taxonomic richness 31. Of the dominant taxa in this zone, Dicrotendipes nervosus-type and Tanytarsus pallidicornis-type had decreasing trends, 9.8 – 2.3% and 15.6 – 1.8% respectively. Conversely, there were increasing trends of Chironomus (0-19.8%), Procladius (3.9 - 15.6%), Psectrocladius psilopterus -type (1.0 - 7.8%), and Tanytarsus mendax-type (0 - 13.9%).

Zone 2: 2300 -1400 years BP

Zone 2 was represented by high relative abundances of: Chironomus, Dicrotendipes nervosus-type, Procladius, Psectrocladius psilopterus -type, Tanytarsus mendax-type, Tanytarsus pallidicornis -type, and Zaltuschia lingulata pauca -type. Productivity and taxonomic richness were lower compared to Zone 1, with an average accumulation of 60.0 heads and a taxonomic richness of 33. Psectrocladius sordidellus -type, which was not present in Zone 1, increased from 0 – 1.6%. Seven taxa present in Zone 1 declined to 0% relative abundance: Cryptochironomus, Harnischia, Labrundinia, Parakiefferiella type A, Sergentia, Stempellina, and Tribelos. Of the dominant taxa present, Chironomus, Tanytarsus pallidicornis-type, and Zaltuschia lingulata pauca -type had decreasing trends; from 6.5 – 1.6%, 6.5 – 1.6%, and 7.3 – 1.6%, respectively. Conversely, there were increasing trends of Dicrotendipes nervosus-type (8.2 - 13.5%), Procladius (4.9 - 6.7%), Psectrocladius psilopterus-type (7.3 - 8.4%), and Tanytarsus mendax-type (3.2 - 9.3%).

Zone 3: 1400 - 100 years BP

The dominant taxa of Zone 3 were: Chironomus, Dicrotendipes nervosus-type, Procladius, Psectrocladius psilopterus -type, Tanytarsus mendax-type, Tanytarsus pallidicornis-type, and Zaltuschia lingulata pauca-type. Productivity increased slightly from an average accumulation of 60.0 heads in Zone 2 to 66 heads. Taxonomic richness saw a small decline (from 33 to 22) after 1300 years BP, then a steady increase (from 22 to 26) after 1100 years BP. Harnischia, which was not present in Zone 2, reappeared in this zone at ~ 600 years BP. Three taxa declined to 0% and were not present during this period: Glypotendipes pallens-type, Parachironomus varvus-type, and Tanytarsus chinyensis-type. Of the dominant taxa in this zone, the following taxa had decreasing trends, Chironomus (20.9 – 10.9%), Dicrotendipes nervosus (10.6 – 4.7%), Procladius (6.6 – 3.8%), Tanytarsini undiff (5.7 – 1.3%), and Tanytarsus pallidicornis (11.9 – 4.0%). Conversely, there were increasing trends of Psectrocladius psilopterus (5.3 - 18.3%), Tanytarsus mendax (0 - 7.8%), and Zaltuschia lingulata pauca (6.6 - 14.2%).

Zone 4: 100 years BP – 2020 CE

Within Zone 4 dominant taxa were: Chironomus, Dicrotendipes nervosus-type, Heterotrissocladius marcidus -type, Pentaneurini, Phaenospectra type-A, Polypedillum, Procladius, Psectrocladius psilopterus -type, Tanytarsus mendax-type, Tanytarsus pallidicornis-type, and Zaltuschia lingulata pauca (Figure 3.6). Heterotrissocladius marcidus-type, Phaenospectra type-A, and Polypedillum appeared in this zone. Productivity and taxonomic richness increased in this zone, with an average accumulation of 72.3 heads and a taxonomic richness of 25.2. Productivity and taxonomic richness fluctuated throughout the zone but peaked around the year 2002. Two taxa, Glypotendipes pallens and Labrundinia, declined to 0% and were not found present during this period. Of the dominant taxa in this zone, the following taxa had decreasing trends, Chironomus (22.6 – 4.4%), Pentaneurini (9.4 – 0%), Phaenospectra type-A (7.4 – 0%), Polypedillum Psectrocladius psilopterus -type (21.6 –7.4%), and Tanytarsus mendax-type (7.7 – 0%). Conversely, there were increasing trends of Dicrotendipes nervosus-type (1.8 - 12.7%), Heterotrissocladius marcidus -type (0.5 - 13.4%), Procladius (0 - 7.2%), Tanytarsus pallidicornis -type (0 - 11.1%), and Zaltuschia lingulata pauca (6.0 - 21.5%).

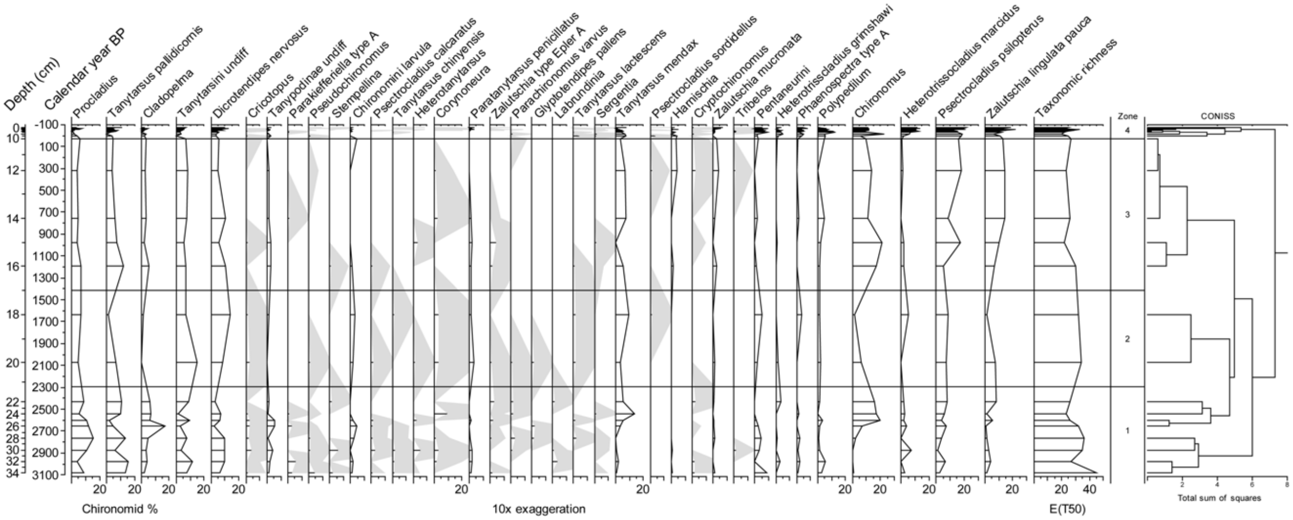

Figure 3.5 Biostratigraphy of abundance (HC g^{-1} DW) plotted against estimated ^{210}Pb linear extrapolation age for Chocolate Lake. CONISS zonation represented by the clustering on the right. Grey background highlighting small changes in taxa abundance with a 10x exaggeration.

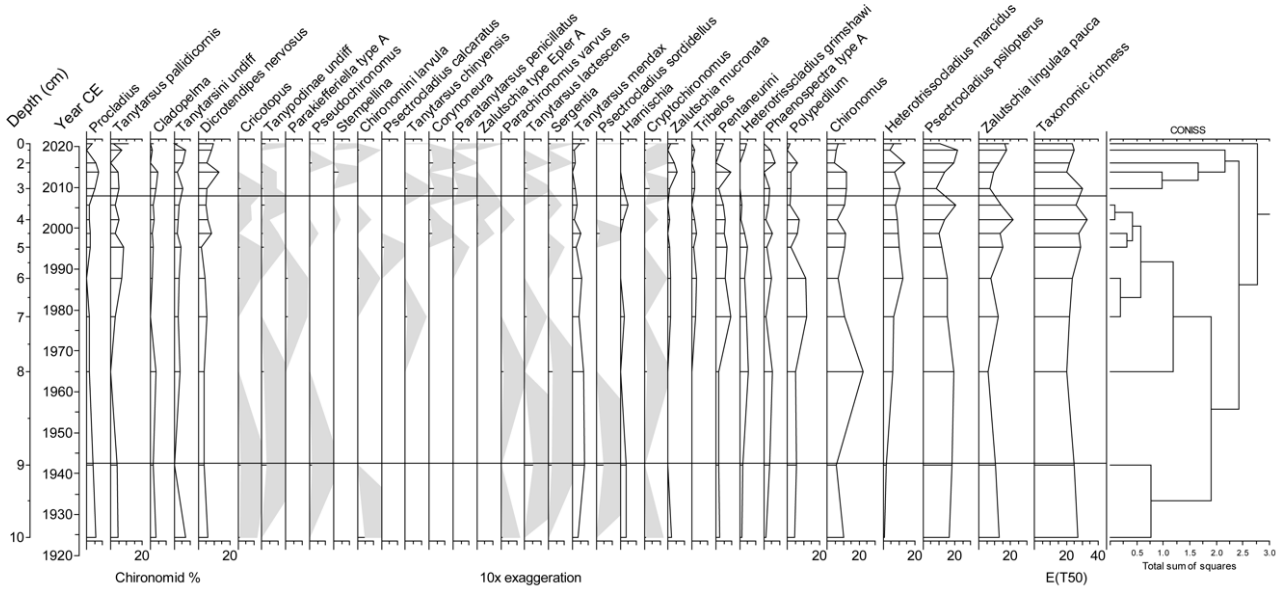

Figure 3.6 Biostratigraphy of abundance (HC g^{-1} DW) plotted against estimated ^{210}Pb linear extrapolation age for Chocolate Lake for Zone 4.

3.7 Discussion

3.7.1 Ecological inferences

While previous studies inferred that Chocolate Lake transitioned from mesotrophic conditions (pre-1850) to more oligotrophic conditions in the present due to human activities, little is known about the context or history of inferred stress (Clement et al. 2007; Ginn et al. 2015). Ginn et al. (2015) and Clement et al. (2007) both examined TP and pH changes in Nova Scotian lakes through top-bottom paleolimnological analyses (diatoms) and water quality surveys from the past 31 years, respectively. These studies allowed for a snapshot of whether 'present' conditions are similar to the past but gives no context to why or when those changes may have occurred. Here, I attempt to contextualize the history of the environment of Chocolate Lake through time with inferences made from biostratigraphic shifts in chironomids assemblages.

Zone 1: 3100 - 2300 years Before Present (years BP)

The oldest section of the core (Zone 1) dates to ~3100 years BP and provides inferences of Chocolate Lake during the Holocene era. While this period occurred prior to European settlement in Nova Scotia (1769) the influence of Mi'kmaq people is possible (Watts 1979; McDonald 2017). Dominant taxa occurring in this zone, Chironomus, Cladopelma, Dicrotendipes nervosus-type, Procladius, and Tanytarsus pallidicornis-type are commonly associated with slow-flowing bodies of water, muddy substrates, mesotrophic conditions, and organic-rich sediments, respectively (Moller Pillot and Buskens 1990; Brodin and Gransberg 1993; Manaaki Whenua 2021; Brooks et al. 2007; Wilson and Gajewski 2004). Although rare, Glypotendipes pallens, a wood mining taxon commonly associated with permanent stagnant and overgrown water bodies was also present (Antczak-Orlewska et al. 2021). Altogether, the presence of these taxa suggest Chocolate Lake may have had shallower wetland habitat during this period. Furthermore, Parachironomus varvus -type found in this zone supports this inference as it is a taxon commonly associated with standing waters and macrophytes (Hofmann 1984; Buskens 1987; Brodersen et al. 2001). Acidophilic taxa, taxa indicative of an environment with low pH, Glypotendipes pallens-type, Heterotanytarsus, and Psectrocladius calcaratus -type also peaked in this zone (~ 2700 years BP) indicating a possible trend of acidic conditions in this environment at that time (Brodin 1986; Kurek et al. 2012).

Zone 2: 2300 -1400 years BP

Zone 2 was also prior to European settlement. Chironomid assemblages had a significant change during this period, where new taxa became dominant in abundance with the ecological preferences indicating a deepening of the body of water. Psectrocladius psilopterus-type, Tanytarsus mendax-type, and Zaltuschia lingulata pauca -type became dominant during this period and are commonly associated with having the ecological preference for streams, ponds, and humic/dystrophic lakes with abundant algae or aquatic plants (Brundin 1949; Manaaki Whenua 2021; Ekrem et al. 2003; Medeiros and Quinlan 2011). The disappearance of Labrundinia, Stempellina, and Tribelos, which are associated with shallow systems, support this inference (Brundin 1949; Fittkau & Roback 1983; Pinder & Reiss 1983), and suggests this zone is transitioning away from a shallow wetland environment to a larger body of water. The disappearance of Glypotendipes pallens-type and Labrundinia, taxa commonly associated with macrophytes and mesotrophic lakes, respectively (Brodin 1982; Fittkau & Roback 1983; Brodin 1986; Buskens 1987; Vallenduuk 1999; Brodersen et al. 2001) suggests the body of water is transitioning away from a mesotrophic environment. Furthermore, the steady increase of Heterotrissocladius grimshawi -type, a depth indicator taxon (Brooks et al. 2007), supports this inference as it would suggest the environment was deepening around the beginning of this zone.

Zone 3: 1400 - 100 years BP

Zone 3 provides ecological information of Chocolate Lake during the Medieval Warm Period (770 – 1070 years BP) of the Holocene, including the time of European settlement (1769) in Nova Scotia (McCann and Young 2012). Numerical zonation of chironomid assemblages demonstrates a significant change in the chironomid community. The presence of Psectrocladius psilopterus -type, a taxon commonly associated with having the ecological preferences for temperate lakes (Brundin 1949) suggests that during this time Chocolate Lake, first a wetland-turned-pond, had deepened into a lake. The disappearance of Parachironomus varvus -type also supports the inference of this zone becoming a lake as this taxon is commonly found in the littoral zone of standing waters (Hofmann, 1984).

The chironomid community also demonstrated evidence of human disturbance during this zone. Chironomus (anthracinus -type), a taxon commonly associated with the presence of elevated nutrients and low oxygen levels (Quinlan and Smol 2001), occurred at its maximum abundance in this zone. The presence of this taxon could suggest the presence of humans and the onset of human disturbance on the ecosystem of Chocolate Lake. Then post-1769, the steady increase in Chironomus could have been due European land settlement which required burning to clear the land of trees. Finally, there is record of the dam at the outlet of Chocolate Lake being raised ~1835 CE to increase reservoir capacity and downstream power generation for the gristmill; however, the chironomid community does not seem to reveal any sign of ecological change due to increased lake levels.

Zone 4: 100 years BP – Present (2020)

Zone 4 provides ecological information of Chocolate Lake during the last century. Between the years 1940 – 1985 CE, the major peak in abundance of Chironomus (5.8 – 22.6%), a human disturbance indicator taxon - a common indicator of deforestation, sewage inputs, and salinity increases (Manaaki Whenua 2021; Belyakov et al. 2019), allows us to make an inference about human activity during this time. Municipal records also show the first major wave of residential development occurred along the shoreline around this time (1920) (ViewPoint 2022), becoming completely developed by 1977 CE, with 8 km of two-lane roadway being built by 1981 (Scott et al. 2019). As such, I can infer that human activity had an impact on the ecology of Chocolate Lake as result of property construction and road runoff inputs into the lake. The continuous high abundance of Chironomus throughout the zone could also correspond to the presence of residential properties and their resulting inputs of human waste into the lake (Helson et al. 2006). The decrease in Chironomus post-1965 could highlight the timing of diverting human waste via the use of sewage systems rather than into the neighbouring environment (Helson et al. 2006). The increase in Cryptochironomus also post-1965, a taxon associated with very poor water quality due to high organic pollution (Hilsenhoff 1966), supports the inference of this zone experiencing stress-related conditions as a result of human activity.

Furthermore, this zone saw sharp increases in Corynoneura and Polypedilum that are commonly associated with algae and macrophytes around the year 2000 CE (Manaaki Whenua 2021; Brodin & Gransberg 1993; Brodin 1982; Brodin 1986; Klink 2002). Paired with the increases in Harnischia, a taxon associated with eutrophic lakes (Brooks et al. 2001), the presence of these taxa could suggest that during the 2000’s high input events of limiting nutrients may have occurred from human activities such as the application of chemical lawn fertilizer, leading to increased levels of primary production or increased human-induced eutrophic conditions (Zhang et al. 2010). Chironomus, a taxon tolerant of eutrophic and anoxic conditions (Brooks et al. 2007) followed similar distribution trends of these taxa, as such, supporting this inference where eutrophic conditions may have occurred.

Several taxa indicative of productivity (found in environments abundant with macrophytes): Dicrotendipes nervosus, Parachironomus varvus, Pseudochironomus, and

Zalutschia mucronata, decreased between the years 1980 – 2000 CE, then increased post-2000 CE. This trend suggests the lake became less productive between the years 1980 – 2000 CE then saw more macrophyte growth in more recent years. Clement et al. (2007) also found high TP conditions around these years: water quality testing showed eutrophic conditions in 1991 and mesotrophic conditions in 2011. Finally, increases in abundance of Harnischia and Parachironomus varvus -type, taxa associated with a high pH environment (Buskens 1987), took place around the years 1970 and 2000 CE, indicating a possible trend of pH recovery to less acidic conditions.

3.7.2 Lake Management

The province of Nova Scotia has focused its freshwater management resources on the assessment of the impact of acid deposition. Paleolimnological studies have proven to be useful for informed management for issues of surface water acidification in HRM through the observation of trends in diatoms associated with specific gradients in pH (Delorme et al. 1984; Duthie 1989; Ginn et al. 2007a). However, monitoring of pH recovery continues to be the management focus due to the complexities resulting from the low buffering capacity of the regions bedrock (Gerber et al. 2008; Rajaratnam 2009) despite cultural eutrophication also being a major issue facing the quality of Halifax's freshwater lakes (Korosi et al. 2013). While certain bioindicators are better equipped for inferring certain environmental changes, data from various types of biostratigraphic analysis should be acquired and considered by lake managers to establish baseline ecological conditions and infer causes of ecosystem stress based on quantified data.

Despite two top-bottom paleolimnological studies having been conducted to assess limnological changes in Chocolate Lake (Rajaratnam 2009; Ginn et al. 2015), the progression of how lakes have responded to centuries of human-induced changes are currently not known. Here, this knowledge gap is addressed with a complete stratigraphical analysis to provide the baseline context of the system as well as the progression of change over several millennia. Top-bottom studies can only speculate when observed changes in the environment occurred and can only provide a general statement of change (e.g., the transition from mesotrophic to oligotrophic conditions). The inferences from this study fill in long-term monitoring gaps of biological responses to the environment.

While chironomids are not the most appropriate bioindicator for inferring pH changes, this study is useful as it validates but also questions the findings of Ginn et al. (2015) and Rajaratnam (2009). Top-bottom analyses of Chocolate Lake by Ginn et al. (2015) and Rajaratnam (2009) used diatoms to reconstruct limnological changes and found Chocolate Lake has become more acidic (0.5 pH units) since “pre-disturbance” ~ pre-1850 CE (Rajaratnam 2009; Ginn et al. 2015). Our study found the chironomid assemblages showed a more complex response to environmental changes in Chocolate Lake over time than what Ginn et al. (2015) and Rajaratnam (2009) proposed. The dated sediment core revealed that acidophilic taxa, taxa associated with acidic environments, were present not only in the most recent zone (as suggested by Ginn et al. (2015) and Rajaratnam (2009)), but also in the older zones, in some cases in higher abundances (Figure 3.5). Heterotanytarsus, Procladius, and Psectrocladius calcaratus peaked in abundance in Zone 1 ~ 2900 years BP: Heterotanytarsus at 5.34%, Procladius at 15.64%, Psectrocladius calcaratus at 3.21%. Conversely, the following acidophilic taxa peaked in Zone 4: Sergentia peaked at 2.61% ~ 1935 CE and Tribelos peaked at 3.11% ~ 1901 CE.

As such, I infer conditions conducive to acidophilic taxa were present during both the wetland phase of Chocolate Lake and the "post-disturbance" period as defined by Ginn et al. (2015) and Rajaratnam (2009). It is difficult to make any further comparisons between our findings and those of the top-bottom diatom studies as their sediment is not dated and does not assess trends through time. The general water quality records collected by Clement et al. (2007) further informs lake management for Chocolate Lake as it has recorded pH fluctuating during their 31 years of collection. Continuous and more frequent water quality testing and a complete paleolimnological study using diatoms as the bioindicator to assess long term trends could help determine how the pH of Chocolate Lake has changed and if recovery is occurring.

The biostratigraphic analysis shows Chocolate Lake has had a complex ecological history as it transitioned from a shallow wetland environment, likely with a lower pH than today, to a temperate mesotrophic lake. The paleolimnological perspective is essential for defining ecological changes and is therefore essential that complete biostratigraphical studies should continue to be conducted to examine trends in other limnological properties. For example, a complete stratigraphical analysis of diatom assemblages in Chocolate Lake would fill in knowledge gaps in Ginn et al. (2015) and Rajaratnam (2009)'s studies. Furthermore, additional monitoring should continue to be conducted into the future as more drastic and different stressors may begin to impact the functioning of Chocolate Lake, such as, climate change (Ginn et al. 2015). Cladocera for example, an order of crustacean zooplankton, could be used as a bioindicator to reconstruct ecotoxicological changes in Chocolate Lake to assess whether the numerous industries that once existed along the lake have left any environmental legacies

(Leppanen 2018). Collectively, a variety of biostratigraphical studies should aid in establishing insightful management objectives and more accurately distinguish between causes of ecosystem stress in this environment that experiences complex interacting stressors.

Managers can now establish accurate management baselines and targets to work towards as changes in chironomid assemblages allowed us to infer natural variability in the productive state of the system; baseline conditions ~3100 years BP are suspected to have been a wetland which then transitioned to a lake ~ 1400 years BP. The data also demonstrates the lake's vulnerability to human development in the watershed. Shifts in chironomid assemblages tended to correlate with the timing of major human activities such as, the first major phase of residential development around the lake and the use of proper sewage systems. Because chironomids are the most appropriate bioindicator for inferring productivity changes (Brodersen and Quinlan 2006), one can be confident using this study as a jumping off point for the continued monitoring of nutrient inputs and eutrophic events in Chocolate Lake.

3.8 Conclusion

Ecological changes in Chocolate Lake, a recreational urban lake in HRM, have been attributed to acid deposition and the consequent decrease in pH (Rajaratnam 2009; Ginn et al. 2015). To gather a more comprehensive assessment of the impact of human development on the ecological status of Chocolate Lake a biostratigraphical study using chironomids was conducted as they are excellent bioindicators of lake trophic status (nutrient loading, eutrophication) (Brodersen and Quinlan 2006) and are most appropriate for addressing the community’s concerns that are common with productivity issues. The abundance changes of taxa revealed three key insights into the baseline ecological conditions of Chocolate Lake and causes of ecosystem stress: (1) the chironomid community conveys a transition from an acidic wetland environment to a temperate lake susceptible to eutrophic events; (2) the chironomid community reflects environmental change is induced by human presence and construction in the watershed; and (3) the chironomid community reflects societal norms/practices could be responsible for impacting productivity in the lake (sewage systems, fertilizer application).

While Chocolate Lake may pale in comparison to the level of human disturbance experienced by other urban lakes surrounded by active industrial activity and high levels of human development (i.e., The Great Lakes), it provides important evidence of a concerning threat within Atlantic Canada of excess nutrient loading as a result of human presence, which is only expected to increase in HRM (Inniss 2022). Should HRM wish to effectively manage Chocolate Lake and other freshwater resources in the region in the face of increasing human pressure, managers and decision-makers should incorporate this study’s results into their plan for two reasons, (1) for setting realistic recovery targets, and (2) for long-term monitoring that will support future work. As such, this quantitative data is essential for satisfying Regional Municipal Planning Strategy with responsible environmental management, allowing for residential growth while balancing lifestyle opportunities through healthy ecosystems (Halifax Regional Municipality 2014), in Chocolate Lake’s case, restoring a healthy environment in which recreational activities can continue for the community. In closing, as large-scale environmental conditions continue to worsen and populations continue to increase in the future, this study will contribute to understanding the socioecological complexities between Chocolate Lake and the residents of HRM and highlight human stressors that need to be addressed to achieve sustainable communities and restore healthy ecological functioning of the lake.

3.9 References

Acheson, T. (1972). The National Policy and the Industrialization of the Maritimes, 1880-1910. Acadiensis, 1(2): 3-28.

Antczak-Orlewska, O., Płóciennik, M., Sobczyk, R., Okupny, D., Stachowicz-Rybka, R., Rzodkiewicz, M., … & Kittel, P. (2021). Chironomidae Morphological Types and Functional Feeding Groups as a Habitat Complexity Vestige. Frontiers in Ecology and Evolution, (8).

Appleby, P. (2001). Chronostratigraphic techniques in recent sediments. In: "Tracking Environmental Change Using Lake Sediments. Volume 2: Physical and Chemical Techniques", Developments in Paleoenvironmental Research. Last WM and Smol JP (eds). Kluwer Academic Publishers: Dordrecht, 171-203.

Arctic Monitoring and Assessment Programme/United Nations Environment Programme. (2018). Global Mercury Assessment, UNEP Chemicals Branch, Geneva, Switzerland, 1-81.

Belyakov, V., Anufriieva, E., Bazhora, A., & Shadrin, N. (2019). Effect of Salinity on Chironomid Larvae (Diptera, Chironomidae) in Hypersaline Lakes of Crimea. Biology Bulletin of the Russian Academy of Sciences 45(10): 1211-218.

Bennett, K., &Willis, K. (2001). Pollen. In: Smol, J., Birks, H., and W. Last. Tracking Environmental Change Using Lake Sediments, 3: 5–32.

Birks, H., & Line, J. (1992). The use of rarefaction analysis for estimating palynological richness from Quaternary pollen-analytical data. The Holocene, 2: 1-10.

Briggs, J., Spielmann, K., Schaafsma, H., Kintigh, K., Kruse, M., Morehouse, K., & Schollmeyer, K. (2006). Why Ecology Needs Archaeologists and Archaeology Needs Ecologists. Frontiers in Ecology and the Environment, 4(4): 180-188.

Brodersen, K., & Quinlan, R. (2006) Midges as Palaeoindicators of Lake Productivity, Eutrophication and Hypolimnetic Oxygen. Quaternary Science Reviews, 25(15): 1995-2012.

Brodersen, K., Odgaard, B., Vestergaard, O., & Anderson, N. (2001). Chironomid stratigraphy in the shallow and eutrophic Lake Søbygaard, Denmark: chironomid-marcrophyte co-occurrence. Freshwater Biology, 46: 253-267.

Brodin, Y. (1982). Paleoecological studies of the recent development of Lake Vãxjösjön. IV. Interpretation of the eutrophic process through the analysis of subfossil chironomids. Archiv für Hyrdobiologie, 93: 313-326.

Brodin, Y. (1986). The postglacial history of Lake Flarken, southern Sweden, interpreted from subfossil insect remains. Internationale Revue der Gesamten Hydrobiologie, 71: 371-432.

Brodin, Y., & Gransberg, M. (1993). Responses of insects, especially Chironomidae (Diptera), and mites to 130 years of acidification in a Scottish lake. Hydrobiologia, 250: 201-212.

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon 51: 337–360.

Brooks, S., Bennion, H., & Birks, J. (2001). Tracing lake trophic history with a chironomid-toal phosphorus inference model. Freshwater Biology, 46(4): 513-533. https://doi.org/10.1046/j.1365-2427.2001.00684.x.

Brooks, S., Langdon, P., & Heiri, O. (2007). The identification and use of Palaearctic Chironomidae larvae in palaeoecology. London: Quaternary Research Association.

Brundin, L. (1949). Chironomiden und andere Bodentiere der südschwedischen Urgebirgseen. Ein Beitrag zur Kenntnis der bodenfaunistischen Charakterzüge schwedischer oligotropher Seen. Report of the Institute of Freshwater Research, Srottningholm, 30: 1-914.

Buskens, R. (1987). The Chironomid assemblages in shallow lentic waters differing in acidity, buffering capacity and trophic level in the Netherlands. Entomologica Scandinavica Supplement, 29: 217-224.

Chu, E., & Karr, J. (2016). Environmental Impact: Concept, Consequences, Measurement. Reference Module in Life Sciences. doi: 10.1016/B978-0-12-809633-8.02380-3.

Clement, P., & Gordon, D. (2019). Synoptic Water Quality Study of Selected Halifax-Area Lakes: 2011 Results and Comparison with Previous Surveys. Canadian Technical Report of Fisheries and Aquatic Sciences, 3170.

Coffman, W., & Ferrington, L. (1984). An introduction to the aquatic insects of North America. Chironomidae, 2: 551–643.

Delorme, L., Esterby, S., & Duthie, H. (1984). Prehistoric pH trends in Kejimkujik Lake, Nova Scotia. Intl. Revue ges. Hydrobiol, 69: 41-55.

Dunnington, D., Spooner, I., Krkošek, W., Gagnon, G., Cornett, R., Kurek, J., … & Tymstra, D. (2018). Anthropogenic Activity in the Halifax Region, Nova Scotia, Canada, as Recorded by Bulk Geochemistry of Lake Sediments. Lake and Reservoir Management, 34(4): 334-348.

Duthie, H. (1989). Diatom-inferred pH history of Kejimkujik Lake, Nova Scotia: A reinterpretation. Water, Air, Soil Poll, 46: 317-322.

Ekrem, T. (2003). Towards a phylogeny of Tanytarsus van der Wulp. Is morphology alone sufficient to reconstruct the genealogical relationships between species in Chironomidae (Diptera)? Insect Systematics & Evolution 34: 199-219.

Epler, J. (2001). Identification Manual for the Larval Chironomidae (Diptera) of North and South Carolina. North Carolina Department of Environment and Natural Resrources Division of Water Quality, 7, 159.

Fittakau, E., & Roback, S. (1983). The larvae of the Tanypodinae (Diptera: Chironomidae) of the Holarctic region – keys and diagnoses. Entomologica Scandinavica Supplement, 19: 33-110.

Gerber, A., Ginn, B., Whitfield, C., Dillon, P., Cumming, B., & Smol, J. (2008). Glasgow Lake: an early-warning sentinel of lake acidification in Cape Breton Highlands National Park (Nova Scotia, Canada). Hydrobiologia, 614: 299-307.

Ginn, B., Cumming, B., & Smol, J. (2007). Assessing PH Changes since Pre-industrial times in 51 Low-alkalinity Lakes in Nova Scotia, Canada. Canadian Journal of Fisheries and Aquatic Sciences, 64(8): 1043-1054.

Ginn, B., Rajaratnam, T., Cumming, B., & Smol, J. (2008). Tracking water quality changes related to human activities in Cape Breton Highlands National Park (Nova Scotia, Canada) using paleolimnological techniques, Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen, 30(2): 242-246.

Ginn, B., Rajaratnam, T., Cumming, B., & Smol, J. (2015). Establishing realistic management objectives for urban lakes using paleolimnological techniques: an example from Halifax Region (Nova Scotia, Canada). Lake and Reservoir Management, 31(2): 92-108, doi: 10.1080/10402381.2015.1013648.

Google Maps. (2022). Chocolate Lake, Halifax, N.S. Retrieved from, https://www.google.com/maps/d/u/0/edit?hl=en&mid=1Mo_vh85bthwpUJjpTYOlpBemFci3VzLp&ll=44.63844579548565%2C-63.62379040647093&z=17.

Government of Canada. (2011). Province and Territory Cartographic Boundary Files, Census, Dataset. Retrieved from, http://www12.statcan.gc.ca/census-recensement/2011/geo/bound-limit/files-fichiers/gpr_000b11a_e.zip.

Government of Nova Scotia. (1983). Chocolate Lake Survey. Retrieved from the Inland Fisheries Division.

Gwyn, J. (1998). Excessive expectations: Maritime commerce and the economic development of Nova Scotia, 1740-1870. McGill-Queen's Press-MQUP, 4.

Halifax Regional Municipality. (2014). Regional Municipal Planning Strategy. Retrieved from, https://www.halifax.ca/sites/default/files/documents/city-hall/boards-committees-commissions/170712rwab911ref-pres.pdf.

Halifax Regional Municipality. (2020). Harmful Algae Blooms. Retrieved from, https://www.halifax.ca/about-halifax/energy-environment/lakes-rivers/harmful-algae-blooms.

Halifax Regional Municipality. (2021). Case 22890: Land Use By-Law amendment for 48 and 50 Old Sambro Road, Halifax. Retrieved from, https://www.halifax.ca/sites/default/files/documents/city-hall/community-councils/211116hwcc1311pres.pdf.

Halifax resident, personal communication. Retrieved August 2020.

Heiri, O., Lotter, A., & Lemcke, G. (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. Journal of Paleolimnology, 25: 101-110. doi:10.1023/A:1008119611481.

Helson, J., Williams, D., & Turner, D. (2006). Larval Chironomid Community Organization in Four Tropical Rivers: Human Impacts and Longitudinal Zonation. Hydrobiologia, 559(1): 413-31.

Hilsenhoff, W. (1966). The biology of Chironomus plumosus in Lake Winnebago, Wisconsin. Annals of the Entomological Society of America, 59: 465-473.

Hofmann, W. (1984). Stratigraphic subfossiler Cladocera (Crustacea) und Chironomidae (Diptera) in zwei Sedimentprofilen des Meerfelder Maares. Courier Forschungs Insitut Senckenberg, 65: 67-80.

Humphries, J., & Schneider, B. (2019). Spinning the Industrial Revolution. The Economic History Review, 72(1): 126-155.

Inniss, A. (2022). Halifax’s downtown population growing at fastest pace in Canada. The Signal. Retrieved from, https://signalhfx.ca/halifaxs-downtown-population-growing-at-fastest-pace-in-canada/.

Jeffries, D., Lam, D., Wong, I., & Moran, M. (2000). Assessment of Changes in Lake PH in Southeastern Canada Arising from Present Levels and Expected Reductions in Acidic Deposition. Canadian Journal of Fisheries and Aquatic Sciences, 57(S2): 40-49.

Kerekes, J., B. Freedman, G. Howell, & Clifford, P. (1984). Comparison of the Characteristics of an Acidic Eutrophic, and an Acidic Oligotrophic Lake Near Halifax, Nova Scotia. Water Quality Research Journal, 19(1): 1-10.

Klink, A. (2002). Determineersleutel voor de larven van de in Nederland voorkomende soorten Polypedillum. STOWA conceptuitgave, 18.

Korosi, J., Ginn, B., Cumming, B., & Smol, J. (2013) Establishing past Environmental Conditions and Tracking Long-term Environmental Change in the Canadian Maritime Provinces Using Lake Sediments. Environmental Reviews 21(1): 15-27.

Kurek, J., Lawlor, L., Cumming, B., & Smol, J. (2012). Long-term oxygen conditions assessed using chironomid assemblages in brook trout lakes from Nova Scotia, Canada. Lake and Reservoir Management, 28(3), 177-188. doi: 10.1080/07438141.2012.692462.

Leppanen, J. (2018). An Overview of Cladoceran Studies Conducted in Mine Water Impacted Lakes. International Aquatic Research, 10(3): 207-221.

Manaaki Whenua. (2021). Chironomid midge (Tanytarsini). Retrieved from, https://www.landcareresearch.co.nz/tools-and-resources/identification/freshwater-invertebrates-guide/identification-guide-what-freshwater-invertebrate-is-this/no-jointed-legs/true-fly-larvae/midges/chironomid-midge-tanytarsini/.

Mapcarta. (n.d.). Chocolate lake. Retrieved from, https://mapcarta.com/24189078.

McCann L., & Young, E. (2012). Halifax. The Canadian Encyclopedia. Retrieved from https://www.thecanadianencyclopedia.ca/en/article/halifax.

McDonald, M. (2017). History of Halifax, a Mi'kmaw perspective. The Nova Scotia Advocate. Retrieved from https://nsadvocate.org/2017/07/12/history-of-halifax-a-mikmaw-perspective/.

Medeiros, A., & Quinlan, R. (2011). The distribution of the Chironomidae (Insecta: Diptera) along multiple environmental gradients in lakes and ponds of the eastern Canadian Arctic. Canadian Journal of Fisheries and Aquatic Sciences, 68: 1511–1527. Doi:10.1139/f2011-076.

Moller Pillot, H., & Buskens, R. (1990). De larven der Nederlandse Chironomidae. Autoecologie en verspreiding. Nederlandse Faunistische Mededelingen 1c: 1-87.

Nocera, J., & Taylor, P. (1998). In Situ Behavioral Response of Common Loons Associated with Elevated Mercury (Hg) Exposure. Conservation Ecology, 2(2): 10.

Oliver, D., & Roussel, M. (1983). The insects and arachnids of Canada, Part 11: The genera of larval midges of Canada – Diptera: Chironomidae. Publication 1746, Agriculture Canada, Ottawa, Ont.

Pinder, L., & Reiss, F. (1983). The larvae of Chironominae (Diptera: Chironomidae) of the Holarctic region. Keys and diagnoses. Entomologica Scandinavica Supplement, 19: 293-435.

Quinlan, R., & Smol, J. (2001). Setting minimum head capsule abundance and taxa deletion criteria in chironomid-based inference models. Journal of Paleolimnology, 26: 327-342.

R Core Team. (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from, https://www.R-project.org/.

Rajaratnam, T. (2009). Assessment of long-term changes in water quality from Halifax region lakes (Nova Scotia, Canada) using paleolimnological techniques. [Master's thesis Queen's University]. Retrieved from, http://hdl.handle.net/1974/5146.

Regan, J. (1928). Sketches and Traditions of the Northwest Arm. (Third Edition).

Reimer, P., Austin, W., Bard, E., Bayliss, A., Blackwell, P., … & Talamo S. (2020). The Intcal20 northern hemisphere radiocarbon age calibration curve (0-55 cal kBP). Radiocarbon, 62(4): 725-757.

Roberts, S., Kirk, J., Wiklund, J., Muir, D., Yang, F., Gleason, A., & Lawson, G. (2019). Mercury and Metal(loid) Deposition to Remote Nova Scotia Lakes from Both Local and Distant Sources. The Science of the Total Environment, 675: 192-202.

Ruddiman, W., Ellis, E., Kaplan, J., & Fuller, D. (2015). Defining the epoch we live in. Science, 348(6230): 38-39. DOI: 10.1126/science.aaa7297.

Scott, R., Goulden, T., Letman, M., Hayward, J., & Jamieson, R. (2019). Long-term Evaluation of the Impact of Urbanization on Chloride Levels in Lakes in a Temperate Region. Journal of Environmental Management 244: 285-293.

Simpson, G. (2007). Analogue methods in paleoecology: using the analogue package. Journal of Statistical Software, 22. doi:10.18637/jss.v022.i02.

Smith, V. (2003). Eutrophication of Freshwater and Coastal Marine Ecosystems a Global Problem. Environmental Science and Pollution Research International, 10(2): 126-139.

Spencer, S., Shutler, D., & O'Brien, M. (2011). Correlates of Mercury in Female River Otters (Lontra Canadensis) from Nova Scotia, Canada. Environmental Toxicology and Chemistry, 30(8): 1879-884.

The Halifax Urban Greenway Association (2019). Other Historic Maps: Halifax City, Late Victorian Period. Retrieved from, http://halifaxurbangreenway.ca/maps/halifax2.gif.

United States Environmental Protection Agency. (2021). Indicators: Human Disturbance. Retrieved from, https://www.epa.gov/national-aquatic-resource-surveys/indicators-human-disturbance.

Valenduuk, H. (1999). Key to the larvae of Glyptotendipes (Diptera: Chironomidae) in Western Europe. Schijndel. 51.

Vaughan, H., Underwood, J., & Ogden, G. (1982). Acidification of Nova Scotia Lakes I: Response of Diatom Assemblages in the Halifax Area. Water, Air, and Soil Pollution, 18(1-3): 353-361.

Viewpoint. (2022). Retrieved from, https://www.viewpoint.ca/map#eyJzdW1tYXJ5Ijp7InByb3BlcnR5Ijp7InBpZCI6IjAwMjIzMjE0IiwiY2xhc3NfaWQiOiIxIn0sInR5cGUiOmZhbHNlfSwibWFwIjp7Inpvb20iOjE4LCJjZW50ZXIiOnsibGF0Ijo0NC42Mzk3ODI3NDgxMDE0MiwibG5nIjotNjMuNjIyMjgzMTc1MDIyNjZ9fX0=.

Walker, I. 2001. Midges: Chironomidae and Related Diptera. Tracking Environmental Change Using Lake Sediments Developments in Paleoenvironmental Research, 4: 43–66. https://doi.org/10.1007/0-306-47671-1_3.

Watts, H. (1979). Beyond the Northwest Arm: A Local History of William’s Lake Halifax, Nova Scotia. William’s Lake Conservation Company.

Wiederholm, T. (ed.). (1983). Chironomidae of the Holarctic region. Keys and diagnoses. Part 1. Larvae. Entomologica Scandinavica Supplement, 19: 1-457.

Wilson, S., & Gajewski, K. (2004). Modern Chironomid Assemblages and Their Relationship to Physical and Chemical Variables in Southwest Yukon and Northern British Columbia Lakes. Arctic, Antarctic, and Alpine Research, 36(4): 446-555.

Zhang, E., Liu, E., Jones, R., Langdon, P., Yang, X., & Shen, J. (2010). A 150-year Record of Recent Changes in Human Activity and Eutrophication of Lake Wushan from the Middle Reach of the Yangze River, China. Journal of Limnology 69(2): 235-241.

CHAPTER 4 CONCLUSION

4.1 Statement of Student Contribution

Chapter design by Allison Covert, chapter writing by Allison Covert with editorial contributions from Andrew Medeiros.

4.2 Introduction

Human presence in watersheds all around the world has been shown to have had significant impacts on the structure and functioning of freshwater ecosystems. Chapter two reviewed with a systematic map how the paleolimnological methodology has been applied to study socioecological relationships worldwide, reconstructing the impact of the "push" and "pull" of climate and its influence on society and how society has learned to adapt, while primary data research was conducted in Chapter three to understand the impact of human development on the health and functioning of an ecosystem in a relatively highly developed neighbourhood near an urban center. Altogether, the results of the review and primary data research chapter satisfied the original hypothesis proving paleolimnological analysis is a useful tool for societies to effectively manage freshwater resources and mitigate against further changes induced by human activities.

4.3 The "push" and "pull" of climate and how it's impacts on subsistence cultures can be reconstructed with paleolimnological methodologies: Key Insights

Chapter two successfully demonstrated with a systematic map the range in which paleolimnological methodologies exist in the literature and the importance of using paleolimnological methodologies in the study of early human disturbances. This search showed paleolimnology is capable of reconstructing environmental change all over the world, with a variety of bioindicators, and up to the millennial scale. This chapter also summarized the many dimensions of research in which paleolimnological strategies can be applied to understanding socioecological relationships including, the impact of the "push" and "pull" of climate on where people live, how people live, and how people adapt to environmental change. Ultimately, this chapter affirmed the choice in methods for analyzing the socioecological relationship in Chapter three and provided examples of similar research that has been conducted using paleolimnology.

Chapter two is important for understanding the value of paleolimnological studies as the world is currently in a period of climate warming that is fundamentally altering the functionality of landscapes (Williamson et al. 2009) making it essential to understand how environmental changes have altered societies in the past for today's society in order to be resilient and adaptable to environmental change. The systematic map review of existing paleolimnological studies found 68 articles that fit the inclusion criteria, demonstrating the usefulness of paleolimnology quantifying change and reconstructing subsistence lifestyles and their relationship with changing environments up to the millennial-scale through the analysis of trends in chemical, physical, and biological indicators (Brenner et al. 2002; Fordham et al. 2020).

This review was discussed by three primary themes found in the literature:

1) ***the "push" and "pull" of climate and its influence on migration (where people live).***

This theme was further organized by subtheme: the "push" and "pull" of climate over the past millennia; large-scale changes in climate, human occupation, and early human migration. The search found 26 paleolimnological studies used a variety of indicators to reconstruct change relating to these topics and in some cases were able to revise estimates of when large-scale changes occurred (Hoelzmann et al. 2001; Wolfe et al. 2012), as well as the amplitude and timing of ecosystem response (Wolfe et al. 1996). Early human occupation and migrations were also discovered from these reconstructions of climate, going to show just how widely applicable paleolimnological studies can be.

2) ***the "push" and "pull" of climate and its influence on cultural practices (how*** **people live)***.*

This second theme was discussed in 36 (more than half) of the articles and highlighted the importance paleolimnological studies play in revealing cultural history. Some paleolimnological reconstructions have even demonstrated the impact of cultural activities on what were once thought by to be pristine environments (Zawiska et al. 2013). Studies also showed the influence in which the environment (climate) can have on the ability of peoples to settle in a certain region and the lifestyle in which they engage in (Sedov et al. 2010; Junginer and Trauth 2013).

3) cultural adaptation to the "push" and "pull" of climate (how people adapt).

The third and final theme was discussed in 23 of the articles discussing the application of paleolimnological methods in the realm of water and wildlife management. These paleolimnological studies provide key information for remediation and management projects - how lakes have changed from their baseline or pre-disturbed state. The history behind the evolution of natural systems is crucial for assessing conservation priorities (Zawiska et al. 2013). Popular themes identified by the search focused on the influence of anthropogenic activities and how they have modified lake catchments (Magyari et al.

2009; Shaw Chraïbi et al. 2014), as well as changes in ecological status such as trophic structure since the industrial revolution (Kirilova et al. 2009; Hargan et al. 2019). Ultimately, these studies demonstrate the value of paleolimnological methods in understanding the timing of events, revealing long-term ecological trends, and providing baseline conditions for effective remediation and management purposes.

4.4 Human disturbance and urban lakes in Halifax, Nova Scotia: Key insights

Chapter three adds to the field of paleolimnology through the study of Chocolate Lake, an urban freshwater lake in Halifax, N.S. Urban lakes can be difficult to manage without historical context of their natural state and exposure to stressors. This chapter shows Chocolate Lake, a well-frequented lake by Haligonians at the centre of a highly developed community has had a rather interesting relationship with human presence throughout history. A complete paleolimnological reconstruction was conducted using chironomids, making this the first complete biostratigraphical analysis to assess how human disturbances have impacted the health and ecological functioning of the lake.

Urban lakes in Atlantic Canada, including Chocolate Lake, have been subjected to multiple human disturbances, making it difficult for remediation efforts to be effectively carried out. The analysis of Chocolate Lake’s sediment core highlights the effectiveness of paleolimnological methodologies in the assessment of freshwater ecosystems in Halifax, N.S., revealing the impact of human stressors on the ecological functioning of freshwater lakes, specifically via shifts in biological indicators that are responsive to nutrient enrichment. All in all, this chapter demonstrates a useful method for gathering data to inform lake management for the mitigation against further changes induced by human activities. The successful demonstration of the applicability of this methodology involved realizing two research objectives:

Research Objective #1: Establish baseline ecological conditions of Chocolate Lake.

The biostratigraphic analysis shows Chocolate Lake has had a complex ecological history. Chironomid assemblages present in the oldest part of the core (what is considered to be Chocolate Lake's baseline state), ~3100 years BP, were indicative of as a highly productive wetland environment. Taxa associated with slow-flowing bodies of water, muddy substrates, mesotrophic conditions, organic-rich sediments, and considered to be wood-miners were abundant. This is dramatically different from the body of water that is Chocolate Lake today. Thousands of years later, the lake has transitioned to a periodically eutrophic, temperate lake.

Research Objective #2: Infer causes of ecosystem stress experienced by Chocolate Lake

Changes in chironomid assemblages since European settlement (1769) in Chocolate Lake can be associated with a variety of human induced stressors. Based on the timing of changes and records of human activities within the vicinity of the lake activities, such as residential development, human waste inputs, fertilizer application, road salt application, and atmospheric acid deposition, it is suspected these are all probable stressors to have impacted the health and functioning of the lake. However, because the study employed the use of chironomids as the bioindicator, one can only be confident about the inferences made regarding productivity changes in the lake (Walker 2001). As such, further studies need to be conducted to distinguish between the multiple stressors that have been synergistically impacting Chocolate Lake throughout history. For example, paleolimnological studies employing Cladocera (ecotoxicological bioindicator) could explore whether industrial activity along the shorelines have had and/or continue to have an impact on the ecological functioning of Chocolate Lake.

4.5 Final Thoughts and Future Directions

Although a large collection of paleolimnological studies investigating the relationship between humans and the environment exist in the literature, Atlantic Canada remains relatively unexplored in terms of how humans have impacted and altered the region throughout history. This thesis shows paleolimnological data can identify baseline ecological conditions of freshwater ecosystems, and when paired with historical records, provides insight into how human activities have impacted their ecological health and functioning and in turn impact the functioning of society. This type of research provides valuable information for policy makers and resource managers in which they can use to not only contextualize the impact of their efforts in long-term monitoring plans and rehabilitation projects but also to set realistic management targets.

The province of Nova Scotia would also benefit from additional paleolimnological studies to investigate the impact human activities from their rich history of natural resource extraction has had on their freshwater resources in other regions of the province. The ecological knowledge gained would, for example benefit the sport fishing industry and angling-associated revenue of the province as paleolimnological data will aid in conservation efforts of sensitive brook trout habitat (Kurek et al. 2012). Chocolate Lake would also benefit from more (complete) paleolimnological analyses as multiple studies generate stronger conclusions (Gustafsson 2017). Direction for freshwater management has become clearer from our primary data research chapter that focused primarily on how human stressors have influenced the productivity of the lake, however productivity is not the only limnological aspect that needs to be assessed should the community of Chocolate Lake's concerns be addressed. Studies of lakes located relatively close to Chocolate Lake, that likely experienced similar human disturbances, could also be beneficial as they could potentially infer the impact of stressors that in these findings were muted by the effect of compounding stressors. Consequently, more studies would provide greater context and a more comprehensive outlook of human disturbances in the region. Furthermore, paleolimnological studies employing alternative bioindicators would also expand our knowledge of the region and strengthen the inferences made from this method.

Finally, because paleolimnology provides baseline ecological conditions in which policy makers and resource managers can work towards, data from more studies like that of this thesis would allow for insight into whether a remediation project is even worthwhile. For Chocolate Lake, the goal of remediation will not likely be restoring it to its baseline shallow water state as a result of societal values of the ecosystem; this study will however still provide guidance. Hilderbrand et al. (2010) discuss threshold responses of ecosystems in cases where further human development and growth is inevitable. They reason that in some cases, if human disturbance has already impacted an ecosystem beyond its ecological threshold perhaps it's more pragmatic to protect systems that can still be rehabilitated (Hilderbrand et al. 2010). In an ideal world however, paleolimnological studies would be conducted regardless of a system's ecological state and in all regions to gain insight into the complexities of society’s relationship with the environment and assist in globally responsible and effective freshwater resource management.

4.6 References

Brenner, M., Rosenmeier, M., Hodell, D., & Curtis, H. (2002). Paleolimnology of the Maya Lowlands: Long–term perspectives on interactions among climate, environment, and humans. Ancient Mesoamerica, 13(1): 141-157. https://doi.org/10.1017/s0956536102131063.

Fordham, D., Jackson, S., Brown, S., Huntley, B., Brook, B., Dahl-Jensen, D. &, D. Nogues- Bravo. (2020). Using paleo-archives to safeguard biodiversity under climate change. Science (New York, N.Y.), 369. doi:10.1126/science.abc5654.

Gustafsson, J. (2017). Single case studies vs. multiple case studies: A comparative study. Academy of Business, Engineering and Science Halmstad University. Retrieved from, https://www.diva-portal.org/smash/get/diva2:1064378/FULLTEXT01.pdf.

Hargan, K., Gilchrist, H., Clyde, N., Iverson, S., Forbes, M., Kimpe, L., … & Blais, J. (2019). Multicentury perspective assessing the sustainability of the historical harvest of seaducks. Proceedings of the National Academy of Sciences of the United States of America, 116(17): 8425-8430. https://doi.org/10.1073/pnas.1814057116.

Hilderbrand, R., Utz, R., Stranko, S., & Raesly, R. (2010). Applying Thresholds to Forecast Potential Biodiversity Loss from Human Development. Journal of the North American Benthological Society 29(3): 1009-016.

Hoelzmann, P., Keding, B., Berke, H., Kröpelin, S., & Kruse, H. (2001). Environmental change and archaeology: Lake evolution and human occupation in the Eastern Sahara during the Holocene. Palaeogeography, Palaeoclimatology, Palaeoecology, 169(3): 193-217. https://doi.org/10.1016/s0031-0182(01)00211-5.

Junginger, A., & Trauth, M. (2013). Hydrological constraints of paleo-Lake Suguta in the Northern Kenya Rift during the African Humid Period (15–5kaBP). Global and Planetary Change, 111: 174-188. https://doi.org/10.1016/j.gloplacha.2013.09.005.

Kirilova, E., Heiri, O., Enters, D., Cremer, H., Lotter, A., Zolitschka, B., & Hubener, T. (2009). Climate-induced changes in the trophic status of a Central European lake. Journal of Limnology, 68(1): 71-82. https://doi.org/10.1016/0033-5894(87)90010-x.

Kurek, J., Lawlor, L., Cumming, B., & Smol, J. (2012). Long-term oxygen conditions assessed using chironomid assemblages in brook trout lakes from Nova Scotia, Canada. Lake and Reservoir Management, 28(3): 177-88.

Magyari, E., Buczkó, K., Jakab, G., Braun, M., Pál, Z., Karátson, D., & Pap, I. (2009). Palaeolimnology of the last crater lake in the Eastern Carpathian Mountains: A multiproxy study of Holocene hydrological changes. Hydrobiologia, 631(1): 29-63. https://doi.org/10.1007/978-90-481-3387-1_3.

Sedov, S., Lozano-García, S., Solleiro-Rebolledo, E., Mcclung de Tapia, E., Ortega-Guerrero, B., & Sosa-Nájera, S. (2010). Tepexpan revisited: A multiple proxy of local environmental changes in relation to human occupation from a paleolake shore section in Central Mexico. Geomorphology (Amsterdam, Netherlands), 122(3): 309-322. https://doi.org/10.1016/j.geomorph.2009.09.003.

Shaw Chraïbi, V., Kireta, A., Reavie, E., Cai, M., & Brown, T. (2014). A paleolimnological assessment of human impacts on Lake Superior. Journal of Great Lakes Research, 40(4): 886-897. https://doi.org/10.1016/j.jglr.2014.09.016.

Walker, I. (2001). Midges: Chironomidae and related Diptera. Tracking Environmental Change Using Lake Sediments Developments in Paleoenvironmental Research, 43–66. doi:10.1007/0-306-47671-1_3.

Williamson, C., Saros, J., Vincent, W., & Smol, J. (2009). Lakes and Reservoirs as Sentinels, Integrators, and Regulators of Climate Change. Limnology and Oceanography, 54(6): 2273-2282.

Wolfe, B., Edwards, T., Aravena, R., & MacDonald, G. (1996). Rapid Holocene hydrologic change along boreal treeline revealed by δ13C and δ18O in organic lake sediments, Northwest Territories, Canada. Journal of Paleolimnology, 15(2): 171-181. https://doi.org/10.1007/bf00196779.

Wolfe, B., Hall, R., Edwards, T., & Johnston, J. (2012). Developing temporal hydroecological perspectives to inform stewardship of a northern floodplain landscape subject to multiple stressors: Paleolimnological investigations of the Peace–Athabasca Delta. Environmental Reviews, 20(3): 191-210. https://doi.org/10.1139/a2012-008.

Zawiska, I., Zawisza, E., Woszczyk, M., Szeroczyńska, K., Spychalski, W., & Correa-Metrio, A. (2013). Cladocera and geochemical evidence from sediment cores show trophic changes in Polish dystrophic lakes. Hydrobiologia, 715(1): 181-193. https://doi.org/10.1007/s10750-013-1482-0.

REFERENCES

Acheson, T. (1972). The National Policy and the Industrialization of the Maritimes, 1880-1910. Acadiensis, 1(2): 3-28.

Adams, J., Peng, Y., Rose, N., Shchetnikov, A., & Mackay, A. (2019). Diatom community responses to long-term multiple stressors at Lake Gusinoye, Siberia. Geo: Geography and Environment, 6(1). https://doi.org/10.1002/geo2.72.

Adrian, R., O'Reilly, C., Zagarese, H., Baines, S., Hessen, D., Keller, W., ... & Winder, M. (2009). Lakes as Sentinels of Climate Change. Limnology and Oceanography, 54(6): 2283-297.

Antczak-Orlewska, O., Płóciennik, M., Sobczyk, R., Okupny, D., Stachowicz-Rybka, R., Rzodkiewicz, M., … and Kittel, P. (2021). Chironomidae Morphological Types and Functional Feeding Groups as a Habitat Complexity Vestige. Frontiers in Ecology and Evolution, 8.

Appleby, P. (2001). Chronostratigraphic techniques in recent sediments. In: Tracking Environmental Change Using Lake Sediments. Volume 2: Physical and Chemical Techniques, Developments in Paleoenvironmental Research. Last WM and Smol JP (eds). Kluwer Academic Publishers: Dordrecht, 171-203.

Arctic Monitoring and Assessment Programme/United Nations Environment Programme. (2018). Global Mercury Assessment, UNEP Chemicals Branch, Geneva, Switzerland, 1-81.

AreaVibes Inc. (2021). Armdale, Halifax, NS Demographics. Retrieved from, https://www.areavibes.com/halifax-ns/armdale/demographics/.

Beck, J. (2019). Nova Scotia. The Canadian Encyclopedia. Retrieved from, https://www.thecanadianencyclopedia.ca/en/article/nova-scotia.

Belyakov, V., Anufriieva, E., Bazhora, A., & Shadrin, N. (2019). Effect of Salinity on Chironomid Larvae (Diptera, Chironomidae) in Hypersaline Lakes of Crimea. Biology Bulletin of the Russian Academy of Sciences, 45(10): 1211-218.

Bennett, K., & Willis, K. (2001). Pollen. In: Smol, J., Birks, H., and W. Last. Tracking Environmental Change Using Lake Sediments, 3: 5–32.

Birks, H., & Line, J. (1992). The use of rarefaction analysis for estimating palynological richness from Quaternary pollen-analytical data. The Holocene, 2: 1-10.

Bodaly, R., Beaty, K., Hendzel, L., Majewski, A., Paterson, M., Rolfhus, K., & Venkiteswaran, J. (2004). Experimenting with Hydroelectric Reservoirs. Environmental Science & Technology, 38(18): 346A.

Bramburger, A., Reavie, E., Sgro G., Estepp, L., Shaw Chraïbi, V., & Pillsbury, R. (2020). Size matters: diatom establishment and extirpation timing in the Laurentian Great Lakes has been influenced by cell size. Journal of Plankton Research, 42(3): 255–264. https://doi.org/10.1093/plankt/fbaa013.

Brenner, M., Rosenmeier, M., Hodell, D., & Curtis, H. (2002). Paleolimnology of the Maya Lowlands: Long–term perspectives on interactions among climate, environment, and humans. Ancient Mesoamerica, 13(1): 141-157. https://doi.org/10.1017/s0956536102131063.

Briggs, J., Spielmann, K., Schaafsma, H., Kintigh, K., Kruse, M., Morehouse, K., & Schollmeyer, K. (2006). Why Ecology Needs Archaeologists and Archaeology Needs Ecologists. Frontiers in Ecology and the Environment, 4(4): 180-188.

Brodersen, K., & Quinlan, R. (2006) Midges as Palaeoindicators of Lake Productivity, Eutrophication and Hypolimnetic Oxygen. Quaternary Science Reviews, 25(15): 1995-2012.

Brodersen, K., Odgaard, B., Vestergaard, O., & Anderson, N. (2001). Chironomid stratigraphy in the shallow and eutrophic Lake Søbygaard, Denmark: chironomid-marcrophyte co-occurrence. Freshwater Biology, 46: 253-267.

Brodin, Y. (1982). Paleoecological studies of the recent development of Lake Vãxjösjön. IV. Interpretation of the eutrophic process through the analysis of subfossil chironomids. Archiv für Hyrdobiologie, 93: 313-326.

Brodin, Y. (1986). The postglacial history of Lake Flarken, southern Sweden, interpreted from subfossil insect remains. Internationale Revue der Gesamten Hydrobiologie, 71: 371-432.

Brodin, Y., & Gransberg, M. (1993). Responses of insects, especially Chironomidae (Diptera), and mites to 130 years of acidification in a Scottish lake. Hydrobiologia, 250: 201-212.

Bronk Ramsey, C. (2009). Bayesian analysis of radiocarbon dates. Radiocarbon, 51: 337–360.

Brooks, S., Bennion, H., & Birks, J. (2001). Tracing lake trophic history with a chironomid-toal phosphorus inference model. Freshwater Biology, 46(4): 513-533. https://doi.org/10.1046/j.1365-2427.2001.00684.x.

Brooks, S., Langdon, P., & Heiri, O. (2007). The identification and use of Palaearctic Chironomidae larvae in palaeoecology. London: Quaternary Research Association.

Brundin, L. (1949). Chironomiden und andere Bodentiere der südschwedischen Urgebirgseen. Ein Beitrag zur Kenntnis der bodenfaunistischen Charakterzüge schwedischer oligotropher Seen. Report of the Institute of Freshwater Research, Srottningholm, 30: 1-914.

Bush, M., Miller, M., De Oliveira, P., & Colinvaux, P. (2000). Two histories of environmental change and human disturbance in eastern lowland Amazonia. Holocene (Sevenoaks), 10(5): 543-553. https://doi.org/10.1191/095968300672647521.

Buskens, R. (1987). The Chironomid assemblages in shallow lentic waters differing in acidity, buffering capacity and trophic level in the Netherlands. Entomologica Scandinavica Supplement, 29: 217-224.

Canada, E. (2018). Government of Canada. Retrieved from, https://www.canada.ca/en/environment-climate-change/services/water-overview/frequently-asked-questions.html.

Carto, S., Weaver, A., Hetherington, R., Yin, L., & Wiebe, E. (2009). Out of Africa and into an ice age: On the role of global climate change in the late Pleistocene migration of early modern humans out of Africa. Journal of Human Evolution, 56(2): 139-151. https://doi.org/10.1016/j.jhevol.2008.09.004.

Chambers, K., Corbett, J., Keller, C., & Wood, C. (2004). Indigenous Knowledge, Mapping, and GIS: A Diffusion of Innovation Perspective. Cartographica, 39(3): 19-31. https://doi.org/10.3138/n752-n693-180t-n843.

Châteauvert, J., Bulte, G., Poulain, A., Campbell, L., &. Blouin-Demers, G. (2015). Dietary reliance on benthic primary production as a predictor of mercury accumulation in freshwater fish and turtles. Water, Air, & Soil Pollution, 226: 337.

Chu, E., & Karr, J. (2016). Environmental Impact: Concept, Consequences, Measurement. Reference Module in Life Sciences. doi: 10.1016/B978-0-12-809633-8.02380-3.

Clark, A., Labaj, A., Smol, J., Campbell, L., & Kurek, J. (2021). Arsenic and mercury contamination and complex aquatic bioindicator responses to historical gold mining and modern watershed stressors in urban Nova Scotia, Canada. Science of the Total Environment, 787: 147374. https://doi.org/10.1016/j.scitotenv.2021.147374.

Clement, P., & Gordon, D. (2019). Synoptic Water Quality Study of Selected Halifax-Area Lakes: 2011 Results and Comparison with Previous Surveys. Canadian Technical Report of Fisheries and Aquatic Sciences, 3170.

Codd, G. (2000). Cyanobacterial Toxins, the Perception of Water Quality, and the Prioritisation of Eutrophication Control. Ecological Engineering, 16(1): 51-60.

Coffman, W., & Ferrington, L. (1984). An introduction to the aquatic insects of North America. Chironomidae, 2: 551–643.

Connolly, R., Jambrina-Enríquez, M., Herrera-Herrera, A., Vidal-Matutano, P., Fagoaga, A., Marquina-Blasco, R., … & Mallol, C. (2019). A multiproxy record of palaeoenvironmental conditions at the Middle Palaeolithic site of Abric del Pastor (Eastern Iberia). Quaternary Science Reviews, 1(225). https://doi.org/10.1016/j.quascirev.2019.106023.

Covert, A., & Medeiros, A. (2021). Reconstructing the “push” and “pull” of Climate and Its Impacts on Subsistence Cultures Using Paleolimnology. FACETS, 6(1): 2042-2056. doi: 10.1139/facets-2021-0088.

Davies, S. (1993). Are Coping Strategies a Cop Out? IDS Bulletin, 24(4): 60-72. https://doi.org/10.1111/j.1759-5436.1993.mp24004007.x.

Davis, D., & Browne, R. (1996). The natural history of Nova Scotia. Vol. 2: Theme regions. Nimbus Publishing, Halifax.

Delorme, L., Esterby, S., & Duthie, H. (1984). Prehistoric pH trends in Kejimkujik Lake, Nova Scotia. Intl. Revue ges. Hydrobiol, 69: 41-55.

Diamond, J. (2005). Collapse: How societies choose to fail or succeed. Penguin, New York, 586.

Dinero, S. (2013). Indigenous perspectives of climate change and its effects upon subsistence activities in the Arctic: The case of the Nets'aii Gwich'in. GeoJournal, 78(1), 117-137. https://doi.org/10.1007/s10708-011-9424-8.

Domaizon, I., Winegardner, A., Capo, E., Gauthier, J., & Gregory-Eaves, I. (2017). DNA-based methods in paleolimnology: new opportunities for investigating long-term dynamics of lacustrine biodiversity. Journal of Paleolimnology, 58(1): 1-21. https://doi.org/10.1007/s10933-017-9958-y.

Douglas, M., Smol, J., Savelle, J., & Blais, J. (2004). Prehistoric Inuit whalers affected Arctic freshwater ecosystems. Proceedings of the National Academy of Sciences of the United States of America, 101(6): 1613-1617.

Duchemin, E., Lucotte, M., Canuel, R., &. Chamberland, A. (1995). Production of the Greenhouse Gases CH4 and CO2 by Hydroelectric Reservoirs of the Boreal Region. Global Biogeochemical Cycles, 9(4): 529-540.

Dunnington, D., Spooner, I., Krkošek, W., Gagnon, G., Cornett, R., Kurek, J., … & Tymstra, D. (2018). Anthropogenic Activity in the Halifax Region, Nova Scotia, Canada, as Recorded by Bulk Geochemistry of Lake Sediments. Lake and Reservoir Management, 34(4): 334-48.

Duthie, H. (1989). Diatom-inferred pH history of Kejimkujik Lake, Nova Scotia: A reinterpretation. Water, Air, Soil Poll, 46: 317-322.

Edwards, K., & Whittington, G. (2001). Lake Sediments, Erosion and Landscape Change during the Holocene in Britain and Ireland. Catena (Giessen), 42(2): 143-173.

Ekrem, T. (2003). Towards a phylogeny of Tanytarsus van der Wulp. Is morphology alone sufficient to reconstruct the genealogical relationships between species in Chironomidae (Diptera)? Insect Systematics & Evolution, 34: 199-219.

Encyclopædia Britannica, inc. (n.d.). Uses and abuses of Lakes. Encyclopædia Britannica. Retrieved from, https://www.britannica.com/science/lake/Uses-and-abuses-of-lakes.

Epler, J. (2001). Identification Manual for the Larval Chironomidae (Diptera) of North and South Carolina. North Carolina Department of Environment and Natural Resrources Division of Water Quality, 7: 159.

Feeser, I., Dörfler, W., Czymzik, M., & Dreibrodt, S. (2016). A mid-Holocene annually laminated sediment sequence from Lake Woserin: The role of climate and environmental change for cultural development during the Neolithic in Northern Germany. Holocene (Sevenoaks), 26(6): 947-963. https://doi.org/10.1177/0959683615622550.

Filippelli, G., Souch, M., Horn, C., & Newkirk, S. (2010). The pre-Colombian footprint on terrestrial nutrient cycling in Costa Rica: Insights from phosphorus in a lake sediment record. Journal of Paleolimnology, 43(4): 843-856. https://doi.org/10.1007/s10933-009-9372-1.

Find a Grave. (2012). John Hosterman. Retrieved from, https://www.findagrave.com/memorial/91110327/john-hosterman.

Fittakau, E., & Roback, S. (1983). The larvae of the Tanypodinae (Diptera: Chironomidae) of the Holarctic region – keys and diagnoses. Entomologica Scandinavica Supplement, 19: 33-110.

Fordham, D., Jackson, S., Brown, S., Huntley, B., Brook, B., Dahl-Jensen, D. &, Nogues-Bravo, D. (2020). Using paleo-archives to safeguard biodiversity under climate change. Science (New York, N.Y.), 369. doi:10.1126/science.abc5654.

Frey, D. (1988). What is Paleolimnology? Journal of Paleolimnology, 23: 79-96.

Friesen, T., Finkelstein, S., & Medeiros A. (2020). Climate variability of the Common Era (AD 1 – 2000) in the eastern North American Arctic: Impacts on human migrations. Quaternary International, 549: 142-154. https://doi.org/10.1016/j.quaint.2019.06.002.

Frisch, D., Morton, P., Culver, B., Edlund, M., Jeyasingh, P., & Weider, L. (2017). Paleogenetic records of Daphnia pulicaria in two North American lakes reveal the impact of cultural eutrophication. Global Change Biology, 23(2): 708-718. https://doi.org/10.1111/gcb.13445.

Gerber, A., Ginn, B., Whitfield, C., Dillon, P., Cumming, B., & Smol, J. (2008). Glasgow Lake: an early-warning sentinel of lake acidification in Cape Breton Highlands National Park (Nova Scotia, Canada). Hydrobiologia, 614: 299-307.

Ginn, B., Cumming, B., & Smol, J. (2007). Assessing PH Changes since Pre-industrial times in 51 Low-alkalinity Lakes in Nova Scotia, Canada." Canadian Journal of Fisheries and Aquatic Sciences, 64(8): 1043-1054.

Ginn, B., Grace, L., Cumming, B., & Smol, J. (2008). Tracking Anthropogenic- and Climatic-related Environmental Changes in the Remaining Habitat Lakes of the Endangered Atlantic Whitefish (Coregonus Huntsmani) Using Palaeolimnological Techniques. Aquatic Conservation, 18(7): 1217-1226.

Ginn, B., Rajaratnam, T., Cumming, B., & Smol, J. (2008). Tracking water quality changes related to human activities in Cape Breton Highlands National Park (Nova Scotia, Canada) using paleolimnological techniques, Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen, 30(2): 242-246. doi:10.1080/03680770.2008.11902118.

Ginn, B., Rajaratnam, T., Cumming, B., & Smol, J. (2015). Establishing realistic management objectives for urban lakes using paleolimnological techniques: an example from Halifax Region (Nova Scotia, Canada). Lake and Reservoir Management, 31(2): 92-108, doi: 10.1080/10402381.2015.1013648.

Global News. (2021). Halifax rated Canada’s second fastest growing municipality. Retrieved from, https://globalnews.ca/news/7588836/halifax-rated-canadas-second-fastest-growing-municipality/.

Google Maps. (2022). Chocolate Lake, Halifax, N.S. Retrieved from, https://www.google.com/maps/d/u/0/edit?hl=en&mid=1Mo_vh85bthwpUJjpTYOlpBemFci3VzLp&ll=44.63844579548565%2C-63.62379040647093&z=17.

Government of Canada. (2011). Province and Territory Cartographic Boundary Files, Census, Dataset. Retrieved from, http://www12.statcan.gc.ca/census-recensement/2011/geo/bound-limit/files-fichiers/gpr_000b11a_e.zip.

Government of Nova Scotia. (1983). Chocolate Lake Survey. Retrieved from the Inland Fisheries Division.

Guillemot, T., Zocatelli, R., Bichet, V., Jacob, J., Massa, C., Le Milbeau, C., ... & Gauthier, E. (2015). Evolution of pastoralism in Southern Greenland during the last two millennia reconstructed from bile acids and coprophilous fungal spores in lacustrine sediments. Organic Geochemistry, 81: 40-44. https://doi.org/10.1016/j.orggeochem.2015.01.012

Gustafsson, J. (2017). Single case studies vs. multiple case studies: A comparative study. Academy of Business, Engineering and Science Halmstad University. Retrieved from, https://www.diva-portal.org/smash/get/diva2:1064378/FULLTEXT01.pdf.

Gwyn, J. (1998). Excessive expectations: Maritime commerce and the economic development of Nova Scotia, 1740-1870. McGill-Queen's Press-MQUP.

Haddaway, N., Macura, B., Whaley, P., & Pullin, A. (2017). ROSES for Systematic Map Protocols. Version 1.0. https://10.6084/m9.figshare.5897284.

Haddaway, N., Macura, B., Whaley, P., & Pullin, A. (2018). ROSES Reporting standards for Systematic Evidence Syntheses: pro forma, flow-diagram and descriptive summary of the plan and conduct of environmental systematic reviews and systematic maps. Environmental Evidence, 7(1): 1-8. https://doi.org/10.1186/s13750-018-0121-7.

Hadley, K., Douglas, M., Blais, J., & Smol, J. (2010). Nutrient enrichment in the High Arctic associated with Thule Inuit whalers: A paleolimnological investigation from Ellesmere Island (Nunavut, Canada). Hydrobiologia, 649(1): 129-138. https://doi.org/10.1007/s10750-010-0235-6.

Halifax Regional Municipality. (2014). Regional Municipal Planning Strategy. Retrieved from, https://www.halifax.ca/sites/default/files/documents/city-hall/boards-committees-commissions/170712rwab911ref-pres.pdf.

Halifax Regional Municipality. (2020). Featured Archival Photographs: Skating parties – Chocolate Lake. Retrieval code: 102-106-2-27.10.

Halifax Regional Municipality. (2020). Harmful Algae Blooms. Retrieved from, https://www.halifax.ca/about-halifax/energy-environment/lakes-rivers/harmful-algae-blooms.

Halifax Regional Municipality. (2021). Case 22890: Land Use By-Law amendment for 48 and 50 Old Sambro Road, Halifax. Retrieved from, https://www.halifax.ca/sites/default/files/documents/city-hall/community-councils/211116hwcc1311pres.pdf.

Halifax Regional Municipality. (2021). Chocolate Lake Beach. Retrieved from, https://www.halifax.ca/parks-recreation/programs-activities/swimming/supervised-beaches-outdoor-pools-splash-pads-0.

Halifax Regional Municipality. (2022). Beaches, outdoor pools, and splash pads. Retrieved from, https://www.halifax.ca/parks-recreation/programs-activities/swimming/supervised-beaches-outdoor-pools-splash-pads.

Halifax resident, personal communication. Retrieved August 2020.

Halifax resident, personal communication. Retrieved February 2020.

Halifax Water. (2021). History of Halifax Water. Retrieved from, https://www.halifaxwater.ca/history-halifax-water.

Halifax Water. (2022). Source Water Protection. Retrieved from, https://www.halifaxwater.ca/protected-water-areas.

Halifax Water Commission. (1995). Downstream: An historical reflection of the Halifax water supply system.

Hall, B., Rosenberg, D., & Wiens, A. (1998). Methyl Mercury in Aquatic Insects from an Experimental Reservoir. Canadian Journal of Fisheries and Aquatic Sciences, 55(9): 2036-2047.

Hall, B., St Louis, V., Rolfhus, K., Bodaly, R., Beaty, K., Paterson, M., & Peech Cherewyk, K. (2005). Impacts of Reservoir Creation on the Biogeochemical Cycling of Methyl Mercury and Total Mercury in Boreal Upland Forests. Ecosystems (New York), 8(3): 248-266.

Hannah, L., Lohse, D., Hutchinson, C., Carr, J., & Lankerani, A. (1994). A Preliminary Inventory of Human Disturbance of World Ecosystems. Ambio, 23(4-5): 246-250.

Hargan, K., Gilchrist, H., Clyde, N., Iverson, S., Forbes, M., Kimpe, L., … & Blais, J. (2019). Multicentury perspective assessing the sustainability of the historical harvest of seaducks. Proceedings of the National Academy of Sciences of the United States of America, 116(17): 8425-8430. https://doi.org/10.1073/pnas.1814057116.

Hasler, A. (1969). Cultural Eutrophication Is Reversible. Bioscience, 19(5): 425-431.

Heiri, O., Lotter, A., & Lemcke, G. (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: Reproducibility and comparability of results. Journal of Paleolimnology, 25: 101-110. doi:10.1023/A:1008119611481.

Helson, J., Williams, D., & Turner, D. (2006). Larval Chironomid Community Organization in Four Tropical Rivers: Human Impacts and Longitudinal Zonation. Hydrobiologia, 559(1): 413-31.

Hilderbrand, R., Utz, R., Stranko, S., & Raesly, R. (2010). Applying Thresholds to Forecast Potential Biodiversity Loss from Human Development. Journal of the North American Benthological Society, 29(3): 1009-1016.

Hilsenhoff, W. (1966). The biology of Chironomus plumosus in Lake Winnebago, Wisconsin. Annals of the Entomological Society of America, 59: 465-473.

Hintz, W., & Relyea, R. (2019). A Review of the Species, Community, and Ecosystem Impacts of Road Salt Salinisation in Fresh Waters. Freshwater Biology, 64(6): 1081-1097.

Hobbs, W., & Wolfe, A. (2008). Recent paleolimnology of three lakes in the Fraser River Basin (BC, Canada): No response to the collapse of sockeye salmon stocks following the Hells Gate landslides. Journal of Paleolimnology, 40(1): 295-308. https://doi.org/10.1007/s10933-007-9161-7.

Hoelzmann, P., Keding, B., Berke, H., Kröpelin, S., & Kruse, H. (2001). Environmental change and archaeology: Lake evolution and human occupation in the Eastern Sahara during the Holocene. Palaeogeography, Palaeoclimatology, Palaeoecology, 169(3): 193-217. https://doi.org/10.1016/s0031-0182(01)00211-5.

Hofmann, A., Geist, J., Nowotny, L., & Raeder, U. (2020). Depth-distribution of lake benthic diatom assemblages in relation to light availability and substrate: Implications for paleolimnological studies. Journal of Paleolimnology, 64(3): 315-334. https://doi.org/10.1007/s10933-020-00139-9.

Hofmann, W. (1984). Stratigraphic subfossiler Cladocera (Crustacea) und Chironomidae (Diptera) in zwei Sedimentprofilen des Meerfelder Maares. Courier Forschungs Insitut Senckenberg, 65: 67-80.

Holmes, J., Jones, R., Nicolas Haas, J., McDermott, F., Molloy, K., & O'Connell, M. (2007). Multi-proxy evidence for Holocene lake-level and salinity changes at An Loch Mór, a coastal lake on the Aran Islands, Western Ireland. Quaternary Science Reviews, 26(19): 2438-2462. https://doi.org/10.1016/j.quascirev.2007.06.020.

Horta, L., Marcos, M., Sacchi, M., Bozzuto, D., Georgieff, S., Mancini, M., & Civalero, M. (2019). Paleogeographic and paleoenvironmental evolution in northwestern Santa Cruz (Argentina), and its influence on human occupation dynamics during the late Pleistocene- early Holocene. Palaeogeography, Palaeoclimatology, Palaeoecology, 516: 44-53. https://doi.org/10.1016/j.palaeo.2018.11.037.

Humphries, J., & Schneider, B. (2019). Spinning the Industrial Revolution. The Economic History Review, 72(1): 126-155.

Huot, Y., Brown, C., Potvin, G., Antoniades, D., Baulch, H., Beisner, B., … & Walsh, D. (2019). The NSERC Canadian Lake Pulse Network: A National Assessment of Lake Health Providing Science for Water Management in a Changing Climate. The Science of the Total Environment, 695: 133668.

Inniss, A. (2022). Halifax's downtown population growing at fastest pace in Canada. The Signal. Retrieved from, https://signalhfx.ca/halifaxs-downtown-population-growing-at-fastest-pace-in-canada/.

Jean-Philippe, J., Anneville, O., Arnaud, F., Baulaz, Y., Bouffard, D., Domaizon, I., … & Weyhenmeyer, G. (2020). Scientists' Warning to Humanity: Rapid Degradation of the World's Large Lakes. Journal of Great Lakes Research, 46(4): 686-702.

Jeffries, D., Lam, D., Wong, I., & Moran, M. (2000). Assessment of Changes in Lake PH in Southeastern Canada Arising from Present Levels and Expected Reductions in Acidic Deposition. Canadian Journal of Fisheries and Aquatic Sciences, 57(S2): 40-49.

Jones, D., Mattes, B., Hintz, W., Schuler, M., Stoler, A., Lind, L., … & Relyea, R. (2017). Investigation of road salts and biotic stressors on freshwater wetland communities. Environmental Pollution, 221: 159– 167.

Jones, R., Marshall, J., Fisher, E., Hatton, J., Patrick, C., Anderson, K., Bedford, A., & Oldfield, F. (2011). Controls on lake level in the early to mid-Holocene, Hawes Water, Lancashire, UK. Holocene (Sevenoaks), 21(7): 1061-1072. https://doi.org/10.1177/0959683611400455.

Junginger, A., & Trauth, M. (2013). Hydrological constraints of paleo-Lake Suguta in the Northern Kenya Rift during the African Humid Period (15–5kaBP). Global and Planetary Change, 111: 174-188. https://doi.org/10.1016/j.gloplacha.2013.09.005.

Kerekes, J., B. Freedman, G. Howell, & Clifford, P. (1984). Comparison of the Characteristics of an Acidic Eutrophic, and an Acidic Oligotrophic Lake Near Halifax, Nova Scotia. Water Quality Research Journal, 19(1): 1-10.

Kim, S., & Koretsky, C. (2013). Effects of road salt deicers on sediment biogeochemistry. Biogeochemistry, 112: 343– 358. https://doi-org.ezproxy.library.dal.ca/10.1007/s10533-012-9728-x.

Kirilova, E., Heiri, O., Enters, D., Cremer, H., Lotter, A., Zolitschka, B., & Hubener, T. (2009). Climate-induced changes in the trophic status of a Central European lake. Journal of Limnology, 68(1): 71-82. https://doi.org/10.1016/0033-5894(87)90010-x.

Klink, A. (2002). Determineersleutel voor de larven van de in Nederland voorkomende soorten Polypedillum. STOWA conceptuitgave, 18.

Korosi, J., Ginn, B., Cumming, B., & Smol, J. (2013). Establishing past environmental conditions and tracking long-term environmental change in the Canadian Maritime provinces using lake sediments. Environmental Reviews, 21(1): 15-27. https://doi.org/10.1139/er-2012-0041.

Kurek, J., Lawlor, L., Cumming, B., & Smol, J. (2012). Long-term oxygen conditions assessed using chironomid assemblages in brook trout lakes from Nova Scotia, Canada. Lake and Reservoir Management, 28(3): 177-188, doi: 10.1080/07438141.2012.692462.

Kusimba, S. (1999). The Early Later Stone Age in East Africa: Excavations and Lithic Assemblages from Lukenya Hill. African Archaeological Review, 18(2): 165-200. https://doi.org/10.1006/jaar.1998.0335.

Labarca, R., González-Guarda, E., Lizama-Catalán, Á., Villavicencio, N. A., Alarcón-Muñoz, J., Suazo-Lara, F., ... & Buldrini, K. (2020). Taguatagua 1: New insights into the late Pleistocene fauna, paleoenvironment, and human subsistence in a unique lacustrine context in central Chile. Quaternary Science Reviews, 238: 106282. https://doi.org/10.1016/j.quascirev.2020.106282

Leppanen, J. (2018). An Overview of Cladoceran Studies Conducted in Mine Water Impacted Lakes. International Aquatic Research, 10(3): 207-221.

Lewis, C., Cameron, F., Anderson, M., Heil, G., & Gareau, D. (2012). Lake levels in the Erie Basin of the Laurentian Great Lakes. Journal of Paleolimnology, 47(3): 493-511. https://doi.org/10.1007/s10933-012-9578-5.

Liu, X., Hu, J., Shi, W., Chen, H., Liang, X., & Li, M. (2020). Stratigraphy and its environmental implications of the Late Pleistocene Shuidonggou Formation in the western Ordos Block, North China. Geological Journal, 55(11): 7359-7370. https://doi.org/10.1002/gj.3972/v2/response1.

López-Valcárcel, M., Parra, G., & Del Arco, A. (2021). Environmental Disturbance History Undermines Population Responses to Cope with Anthropogenic and Environmental Stressors. Chemosphere (Oxford), 262: 128373. https://doi.org/10.1016/j.chemosphere.2020.128373.

Lozhkin, A., & Anderson, P. (2013). Late Quaternary lake records from the Anadyr Lowland, Central Chukotka (Russia). Quaternary Science Reviews, 68: 1-16. https://doi.org/10.1016/j.quascirev.2013.02.007.

Luoto, T. (2011). The Relationship between Water Quality and Chironomid Distribution in Finland—A New Assemblage-based Tool for Assessments of Long-term Nutrient Dynamics. Ecological Indicators, 11(2): 255-262.

Magyari, E., Buczkó, K., Jakab, G., Braun, M., Pál, Z., Karátson, D., & Pap, I. (2009). Palaeolimnology of the last crater lake in the Eastern Carpathian Mountains: A multiproxy study of Holocene hydrological changes. Hydrobiologia, 631(1): 29-63. https://doi.org/10.1007/978-90-481-3387-1_3.

Manaaki Whenua. (2021). Chironomid midge (Tanytarsini). Retrieved from, https://www.landcareresearch.co.nz/tools-and-resources/identification/freshwater-invertebrates-guide/identification-guide-what-freshwater-invertebrate-is-this/no-jointed-legs/true-fly-larvae/midges/chironomid-midge-tanytarsini/.

Mapcarta. (n.d.). Chocolate lake. Retrieved from, https://mapcarta.com/24189078.

Marr, B. (2015). Review of: Migration and Climate Change. Canadian Studies in Population, 42(1-2): 170. https://doi.org/10.25336/p6mw3p.

McCann L., & Young, E. (2012). Halifax. The Canadian Encyclopedia. Retrieved from, https://www.thecanadianencyclopedia.ca/en/article/halifax.

McDonald, M. (2017). History of Halifax, a Mi'kmaw perspective. The Nova Scotia Advocate. Retrieved from, https://nsadvocate.org/2017/07/12/history-of-halifax-a-mikmaw-perspective/.

Medeiros, A., & Quinlan, R. (2011). The distribution of the Chironomidae (Insecta: Diptera) along multiple environmental gradients in lakes and ponds of the eastern Canadian Arctic. Canadian Journal of Fisheries and Aquatic Sciences, 68: 1511–1527. doi:10.1139/f2011-076.

Meyer, J. (1997). Stream health: incorporating the human dimension to advance stream ecology. Journal of the North American Benthological Society, 16: 439–447.

McCann L., & Young, E. (2012). Halifax. The Canadian Encyclopedia. Retrieved from https://www.thecanadianencyclopedia.ca/en/article/halifax.

McDonald, M. (2017). History of Halifax, a Mi'kmaw perspective. The Nova Scotia Advocate. Retrieved from https://nsadvocate.org/2017/07/12/history-of-halifax-a-mikmaw-perspective/.

McDonald, R., Green, P., Balk, D., Fekete, B., Revenga, C., Todd, M., & Montgomery, M. (2011). Urban Growth, Climate Change, and Freshwater Availability. Proceedings of the National Academy of Sciences, 108(15): 6312-6317.

Medeiros, A., & Quinlan, R. (2011). The distribution of the Chironomidae (Insecta: Diptera) along multiple environmental gradients in lakes and ponds of the eastern Canadian Arctic. Canadian Journal of Fisheries and Aquatic Sciences, 68: 1511–1527. doi:10.1139/f2011-076.

Meyer, J. (1997). Stream health: incorporating the human dimension to advance stream ecology. Journal of the North American Benthological Society, 16: 439–447.

Michelutti, N., Mccleary, K., Antoniades, D., Sutherland, P., Blais, J., Douglas, M., & Smol, J. (2013). Using paleolimnology to track the impacts of early Arctic peoples on freshwater ecosystems from southern Baffin Island, Nunavut. Quaternary Science Reviews, 76: 82-95. https://doi.org/10.1016/j.quascirev.2013.06.027.

Mills, K., Schillereff, D., Saulnier-Talbot, É., Gell, P., Anderson, N. J., Arnaud, F., … & Moorhouse, H. (2017). Deciphering long-term records of natural variability and human impact as recorded in lake sediments: A palaeolimnological puzzle. Wiley Interdisciplinary Reviews: Water, 4, e1195. https://doi.org/10.1002/wat2.1195.

Miralai, S., Khan, M., & Islam, M. (2008). Replacing artificial additives with natural alternatives. Nature Science and Sustainable Technology Research Progress. Nova Publishers, 45-76.

Moller Pillot, H., & Buskens, R. (1990). De larven der Nederlandse Chironomidae. Autoecologie en verspreiding. Nederlandse Faunistische Mededelingen 1c: 1-87.

Murnaghan, S., Taylor, D., Jennings, E., Dalton, C., Olaya-Bosch, K., & O'Dwyer, B. (2012). Middle to late Holocene environmental changes in western Ireland inferred from fluctuations in preservation of biological variables in lake sediment. Journal of Paleolimnology, 48(2): 433-448. https://doi.org/10.1007/s10933-012-9620-7.

Nelligan, C., Jeziorski, A., Rühland, K., Paterson, A., Meyer-Jacob, C., & Smol, J. (2019). A multibasin comparison of historical water quality trends in Lake Manitou, Ontario, a provincially significant lake trout lake. Lake and Reservoir Management, 36(3): 243–259. https://doi.org/10.1080/10402381.2019.1659889.

Newell, S., Dion, M., & Doubleday, N. (2020). Cultural continuity and Inuit health in Arctic Canada. Journal of Epidemiology and Community Health (1979), 74(1): 64-70. https://doi.org/10.1136/jech-2018-211856.

Nguyen-Quang T., Lieou K., Hushchyna K., Nguyen T., Sharifi Mood N., Nadeem M., McLellan K., Murdymootoo K., Merks E., & Hirtle R. (2016). The first step to sketch the spatio-temporal evolution of biochemical and physical parameters involving in the harmful algal blooms (HAB) In Mattatall Lake (Nova Scotia, Canada). Environmental Problems, 1(1): 1-18.

Noble, B., & Basnet, P. (2015). Capacity for Watershed Cumulative Effects Assessment and Management in the South Saskatchewan Watershed, Canada. Canadian Water Resources Journal, 40(2): 187-203.

Nocera, J., & Taylor, P. (1998). In Situ Behavioral Response of Common Loons Associated with Elevated Mercury (Hg) Exposure. Conservation Ecology, 2(2): 10.

Nova Scotia Museum of Natural History. (1996). Natural History of Nova Scotia. Vol. (1), Topics and Habitats.

Oliver, D., & Roussel, M. (1983). The insects and arachnids of Canada, Part 11: The genera of larval midges of Canada – Diptera: Chironomidae. Publication 1746, Agriculture Canada, Ottawa, Ont.

Paterson, A., Köster, D., Reavie, E., & Whitmore, T. (2020). Preface: Paleolimnology and Lake Management. Lake and Reservoir Management, 36(3): 205-209.

Paterson, M., Findlay, D., Beaty, K., Findlay, W., Schindler, E., Stainton, M., & McCullough, G. (1997). Changes in the Planktonic Food Web of a New Experimental Reservoir. Canadian Journal of Fisheries and Aquatic Sciences, 54(5): 1088-2102.

Paterson, M., Rudd, J., & St. Louis, V. (1998). Increases in Total and Methylmercury in Zooplankton following Flooding of a Peatland Reservoir. Environmental Science & Technology, 32(24): 3868-3874.

Pinder, L., & Reiss, F. (1983). The larvae of Chironominae (Diptera: Chironomidae) of the Holarctic region. Keys and diagnoses. Entomologica Scandinavica Supplement, 19: 293-435.

Pollard, P., & Huxham, M. (1998). The European Water Framework Directive: A New Era in the Management of Aquatic Ecosystem Health? Aquatic Conservation, 8(6): 773-792.

Province of Nova Scotia. (1937). Report on the Provincial Museum and Science Library for the fiscal year 1935-36. Halifax, NS: King's Printer.

Province of Nova Scotia. (2014). Climate Impacts. Retrieved from, https://climatechange.novascotia.ca/climate-impacts.

Province of Nova Scotia. (2018). Surface Water Quality Monitoring Network. Retrieved from, https://nse.maps.arcgis.com/apps/webappviewer/index.html?id=7ded7a30bef44f848e8a4fc8672c89bd.

Quinlan, R., & Smol, J. (2001). Setting minimum head capsule abundance and taxa deletion criteria in chironomid-based inference models. Journal of Paleolimnology, 26: 327-342.

R Core Team. (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from, https://www.R-project.org/.

Rajaratnam, T. (2009). Assessment of long-term changes in water quality from Halifax region lakes (Nova Scotia, Canada) using paleolimnological techniques. [Master's thesis Queen's University]. Retrieved from, http://hdl.handle.net/1974/5146.

Regan, J. (1928). Sketches and Traditions of the Northwest Arm. (Third Edition).

Reheis, M. (1999). Highest Pluvial-Lake Shorelines and Pleistocene Climate of the Western Great Basin. Quaternary Research, 52(2): 196-205. https://doi.org/10.1006/qres.1999.2064.

Reimer, P., Austin, W., Bard, E., Bayliss, A., Blackwell, P., … & Talamo S. (2020). The Intcal20 northern hemisphere radiocarbon age calibration curve (0-55 cal kBP). Radiocarbon, 62(4): 725-757.

Ren, L., Cui, E., & Sun, H. (2014). Temporal and Spatial Variations in the Relationship between Urbanization and Water Quality. Environmental Science and Pollution Research International, 21(23): 13646-13655.

Ritchie, H., & Roser, M. (2018). Urbanization. Our World in Data. Retrieved from, https://ourworldindata.org/urbanization.

Roberts, S., Kirk, J., Wiklund, J., Muir, D., Yang, F., Gleason, A., & Lawson, G. (2019). Mercury and Metal(loid) Deposition to Remote Nova Scotia Lakes from Both Local and Distant Sources. The Science of the Total Environment, 675: 192-202.

Rogers, P., & Jones, W. (2018). Applied landscape geochemistry and environmental change in Nova Scotia, Canada. Atlantic Geology, 54.

Rowell, H. Chandler, M., Quinlan, R., Smith, A., Bloomfield, J., Charles, D., & Effler, S. (2016). Quantitative Paleolimnological Inference Models Applied to a High-resolution Biostratigraphic Study of Lake Degradation and Recovery, Onondaga Lake, New York (USA). Journal of Paleolimnology, 55(3): 241-258.

Ruddiman, W., Ellis, E., Kaplan, J., & Fuller, D. (2015). Defining the epoch we live in. Science, 348(6230): 38-39. doi: 10.1126/science.aaa7297.

Saulnier-Talbot, É. (2016). Paleolimnology as a tool to achieve environmental sustainability in the Anthropocene: An overview. Geosciences, 6(2): 26.

Schindler, D. (2001). The cumulative effects of climate warming and other human stresses on Canadian fresh-waters in the new millennium. Canadian Journal of Fisheries and Aquatic Science, 58: 18-29.

Schindler, D. (2009). Lakes as Sentinels and Integrators for the Effects of Climate Change on Watersheds, Airsheds, and Landscapes. Limnology and Oceanography, 54(6): 2349-2358.

Schmidt, M., Leipe, C., Becker, F., Goslar, T., Hoelzmann, P., Mingram, J., … & Tarasov, P. (2019). A multi-proxy palaeolimnological record of the last 16,600 years from coastal Lake Kushu in northern Japan. Palaeogeography, Palaeoclimatology, Palaeoecology, 514: 613-626. https://doi.org/10.1016/j.palaeo.2018.11.010.

Scott, R., Goulden, T., Letman, M., Hayward, J., & Jamieson, R. (2019). Long-term Evaluation of the Impact of Urbanization on Chloride Levels in Lakes in a Temperate Region. Journal of Environmental Management 244: 285-93.

Sedov, S., Lozano-García, S., Solleiro-Rebolledo, E., Mcclung de Tapia, E., Ortega-Guerrero, B., & Sosa-Nájera, S. (2010). Tepexpan revisited: A multiple proxy of local environmental changes in relation to human occupation from a paleolake shore section in Central Mexico. Geomorphology (Amsterdam, Netherlands), 122(3): 309-322. https://doi.org/10.1016/j.geomorph.2009.09.003.

Seiler, M., Bond, M., & Seiler, V. (2001). The Impact of World Class Great Lakes Water Views on Residential Property Values. The Appraisal Journal, 69(3): 287-295.

Selbie, D., Lewis, B., Smol, J., & Finney, B. (2007). Long-Term Population Dynamics of the Endangered Snake River Sockeye Salmon: Evidence of Past Influences on Stock Decline and Impediments to Recovery. Transactions of the American Fisheries Society (1900), 136(3): 800-821. https://doi.org/10.1577/t06-100.1.

Shaw, A. (2016). Drivers of Animal Migration and Implications in Changing Environments. Evolutionary Ecology, 30(6): 991-1007. https://doi.org/10.1007/s10682-016-9860-5.

Shaw Chraïbi, V., Kireta, A., Reavie, E., Cai, M., & Brown, T. (2014). A paleolimnological assessment of human impacts on Lake Superior. Journal of Great Lakes Research, 40(4): 886-897. https://doi.org/10.1016/j.jglr.2014.09.016.

Simpson, G. (2007). Analogue methods in paleoecology: using the analogue package. Journal of Statistical Software, 22. doi:10.18637/jss.v022.i02.

Slate, J., Johnson, E., & Moore, T. (2013). Impact of pre-Columbian agriculture, climate change, and tectonic activity inferred from a 5,700-year paleolimnological record from Lake Nicaragua. Journal of Paleolimnology, 50(1): 139-149. https://doi.org/10.1007/s10933-013-9709-7.

Smith, N. (1971). A History of Dams. London: P. Davies. Print.

Smith, V. (2003). Eutrophication of Freshwater and Coastal Marine Ecosystems a Global Problem. Environmental Science and Pollution Research International, 10(2): 126-139.

Smol, J. (2008). Pollution of lakes and rivers: a paleoenvironmental perspective. Blackwell Publishing Ltd, Malden.

Spencer, S., Shutler, D., & O'Brien, M. (2011). Correlates of Mercury in Female River Otters (Lontra Canadensis) from Nova Scotia, Canada. Environmental Toxicology and Chemistry, 30(8): 1879-884.

Stefanova, I., Ognjanova-Rumenova, N., Hofmann, W., & Ammann, B. (2003). Late Glacial and Holocene environmental history of the Pirin Mountains (SW Bulgaria): A paleolimnological study of Lake Dalgoto (2310 m). Journal of Paleolimnology, 30(1): 95-111. https://doi.org/10.1191/0959683603hl597rp.

Stutz, A. (2012). Culture and Politics, Behavior and Biology: Seeking Synthesis among Fragmentary Anthropological Perspectives on Hunter-Gatherers. Reviews in Anthropology, 41(1): 23-69. https://doi.org/10.1080/00938157.2012.649183.

Sullivan, T., & Charles, D. (1994). The Feasibility and Utility of a Paleolimnology/paleoclimate Data Cooperative for North America. Journal of Paleolimnology, 10(3): 265-73. https://doi.org/10.1007/bf00684036.

Temoltzin-Loranca, Y., Velez, M., Moreno, E., & Escobar, J. (2018). Late Holocene environmental change in Lake Boquete and its watershed human or natural causes? Boletín De La Sociedad Geológica Mexicana, 70(1): 121-131. https://doi.org/10.18268/bsgm2018v70n1a7.

Temple, D., & Stojanowski, C. (2018). Hunter-gatherer Adaptation and Resilience: A Bioarchaeological Perspective. Cambridge University Press. https://doi.org/10.1017/9781316941256.

The Halifax Urban Greenway Association. (2019). Other Historic Maps: Halifax City, Late Victorian Period. Retrieved from, http://halifaxurbangreenway.ca/maps/halifax2.gif.

Tierney, J., & Russell, J. (2007). Abrupt climate change in southeast tropical Africa influenced by Indian monsoon variability and ITCZ migration. Geophysical Research Letters, 34(15). https://doi.org/10.1029/2007gl029508.

Todgham, A., & Stillman, J. (2013). Physiological Responses to Shifts in Multiple Environmental Stressors. Integrative and Comparative Biology, 53(4): 539-44. https://doi.org/10.1093/icb/ict086.

Tudryn, A., Tucholka, P., Özgûr, N., Gibert, E., Elitok, O., Kamaci, Z., Massault, M., Poisson, A., & Platevoet, B. (2013). A 2300-year record of environmental change from SW Anatolia, Lake Burdur, Turkey. Journal of Paleolimnology, 49(4): 647-662. https://doi.org/10.1007/s10933-013-9682-1.

Tütken, T., Vennemann, T., Janz, H., & Heizmann, E. (2006). Palaeoenvironment and palaeoclimate of the Middle Miocene lake in the Steinheim basin, SW Germany: A reconstruction from C, O, and Sr isotopes of fossil remains. Palaeogeography, Palaeoclimatology, Palaeoecology, 241(3): 457-491. https://doi.org/10.1016/j.palaeo.2006.04.007.

United Nations. (2010). Climate Change Adaptation: The Pivotal Role of Water. Policy and Analytical Briefs. Retrieved from, https://www.unwater.org/publications/climate-change-adaptation-pivotal-role-water/.

United Nations. (2011). World Urbanization Prospects. The 2011 Revision.

United States Environmental Protection Agency. (2021). Indicators: Human Disturbance. Retrieved from, https://www.epa.gov/national-aquatic-resource-surveys/indicators-human-disturbance.

Valenduuk, H. (1999). Key to the larvae of Glyptotendipes (Diptera: Chironomidae) in Western Europe. Schijndel. 51.

Van Aalst, M., Cannon, T., & Burton, I. (2008). Community level adaptation to climate change: The potential role of participatory community risk assessment. Global Environmental Change, 18(1): 165-179. https://doi.org/10.1016/j.gloenvcha.2007.06.002.

Van Heyst, A., Sinclair, A., & Jamieson, R. (2022). Application of Phosphorus Loading Models to Understand Drivers of Eutrophication in a Complex Rural Lake-watershed System. Journal of Environmental Management, 302: 114010.

Vaughan, H., Underwood, J., & Ogden, G. (1982). Acidification of Nova Scotia Lakes I: Response of Diatom Assemblages in the Halifax Area. Water, Air, and Soil Pollution, 18(1-3): 353-361.

Vegas-Vilarrúbia, T., González-Sampériz, P., Morellón, M., Gil-Romera, G., Pérez-Sanz, A., & Valero-Garcés, B. (2013). Diatom and vegetation responses to Late Glacial and Early Holocene climate changes at Lake Estanya (Southern Pyrenees, NE Spain). Palaeogeography, Palaeoclimatology, Palaeoecology, 392(C): 335-349. https://doi.org/10.1016/j.palaeo.2013.09.011.

Viewpoint. (2022). Retrieved from, https://www.viewpoint.ca/map#eyJzdW1tYXJ5Ijp7InByb3BlcnR5Ijp7InBpZCI6IjAwMjIzMjE0IiwiY2xhc3NfaWQiOiIxIn0sInR5cGUiOmZhbHNlfSwibWFwIjp7Inpvb20iOjE4LCJjZW50ZXIiOnsibGF0Ijo0NC42Mzk3ODI3NDgxMDE0MiwibG5nIjotNjMuNjIyMjgzMTc1MDIyNjZ9fX0=.

Waldron, J., Jamieson, R., Pothier, H., & White, C. (2015). Sedimentary and Tectonic Setting of a Mass-transport Slope Deposit in the Halifax Group, Halifax Peninsula, Nova Scotia, Canada. Atlantic Geology, 51(1): 84.

Walker, I. (2001). Midges: Chironomidae and related Diptera. Tracking Environmental Change Using Lake Sediments Developments in Paleoenvironmental Research, 43–66. doi:10.1007/0-306-47671-1_3.

Walker, I., Levesque, A., Pienitz, R., & Smol, J. (2003). Freshwater Midges of the Yukon and Adjacent Northwest Territories: A New Tool for Reconstructing Beringian Paleoenvironments? Journal of the North American Benthological Society, 22(2): 323-337.

Watts, H. (1979). Beyond the Northwest Arm: A Local History of William's Lake Halifax, Nova Scotia. William's Lake Conservation Company.

Watts, H. (1994). Beyond the Northwest Arm. Halifax, NS: Williams Lake Conservation Company.

White, C., MacDonald, M., & Horne, R. (2014). Bedrock geology map of the Halifax area, NTS 11D/12, Halifax County, Nova Scotia; Nova Scotia Department of Natural Resources, Open File Map ME 2014-010, scale 1:50 000.

Wiederholm, T. (ed.). (1983). Chironomidae of the Holarctic region. Keys and diagnoses. Part 1. Larvae. Entomologica Scandinavica Supplement, 19: 1-457.

Williamson, C., Saros, J., Vincent, W., & Smol, J. (2009). Lakes and Reservoirs as Sentinels, Integrators, and Regulators of Climate Change. Limnology and Oceanography, 54(6): 2273-2282.

Wilson, S., & Gajewski, K. (2004). Modern Chironomid Assemblages and Their Relationship to Physical and Chemical Variables in Southwest Yukon and Northern British Columbia Lakes. Arctic, Antarctic, and Alpine Research, 36(4): 446-555.

Winter, J., & Duthie, H. (1998). Effects of urbanization on water quality, periphyton and invertebrate communities in a Southern Ontario stream. Canadian Water Resources Journal, 23(3): 245-257.

Wolfe, B., Edwards, T., Aravena, R., & MacDonald, G. (1996). Rapid Holocene hydrologic change along boreal treeline revealed by δ13C and δ18O in organic lake sediments, Northwest Territories, Canada. Journal of Paleolimnology, 15(2): 171-181. https://doi.org/10.1007/bf00196779.

Wolfe, B., Hall, R., Edwards, T., & Johnston, J. (2012). Developing temporal hydroecological perspectives to inform stewardship of a northern floodplain landscape subject to multiple stressors: Paleolimnological investigations of the Peace–Athabasca Delta. Environmental Reviews, 20(3): 191-210. https://doi.org/10.1139/a2012-008.

Zandbergen, P. (1998). Urban Watershed Ecological Risk Assessment Using GIS: A Case Study of the Brunette River Watershed in British Columbia, Canada. Journal of Hazardous Materials, 61(1): 163-173.

Zawiska, I., Zawisza, E., Woszczyk, M., Szeroczyńska, K., Spychalski, W., & Correa-Metrio, A. (2013). Cladocera and geochemical evidence from sediment cores show trophic changes in Polish dystrophic lakes. Hydrobiologia, 715(1): 181-193. https://doi.org/10.1007/s10750-013-1482-0.

Zhang, C., Zhao, C., Zhang, H., Zhang, X., & Shen, J. (2020). Western Pacific Ocean influences on monsoon precipitation in the southwestern Chinese Loess Plateau since the mid-Holocene. Climate Dynamics, 54(5-6): 3121-3134. https://doi.org/10.1007/s00382-020-05159-9.

Zhang, E., Liu, E., Jones, R., Langdon, P., Yang, X., & Shen, J. (2010). A 150-year Record of Recent Changes in Human Activity and Eutrophication of Lake Wushan from the Middle Reach of the Yangze River, China. Journal of Limnology 69(2): 235-241.

Zhilich, S., Rudaya, N., Krivonogov, S., Nazarova, L., & Pozdnyakov, D. (2017). Environmental dynamics of the Baraba forest-steppe (Siberia) over the last 8000 years and their impact on the types of economic life of the population. Quaternary Science Reviews, 163: 152-161. https://doi.org/10.1016/j.quascirev.2017.03.022.

Zocatelli, R., Lavrieux, M., Guillemot, T., Chassiot, L., Le Milbeau, C., & Jacob, J. (2017). Fecal biomarker imprints as indicators of past human land uses: Source distinction and preservation potential in archaeological and natural archives. Journal of Archaeological Science, 81: 79-89. https://doi.org/10.1016/j.jas.2017.03.010.

APPENDIX: SUPPLEMENTARY MATERIALS FOR UNDERSTANDING THE PALEOLIMNOLOGICAL ANALYSIS OF CHOCOLATE LAKE

S.1 Statement of Student Contributions

Study design by Allison Covert and Andrew Medeiros, supplemental material writing by Allison Covert.

S.2 Introduction

Chocolate Lake, Armdale, N.S. was studied using paleolimnological techniques to understand the impact of human disturbance on long-term change experienced by a freshwater ecosystem. The analysis of chironomid subfossils was applied to a sediment core from Chocolate Lake. Here, additional information of chironomid abundance, and lake characteristics are presented.

S.3 Chocolate Lake Chironomid Production

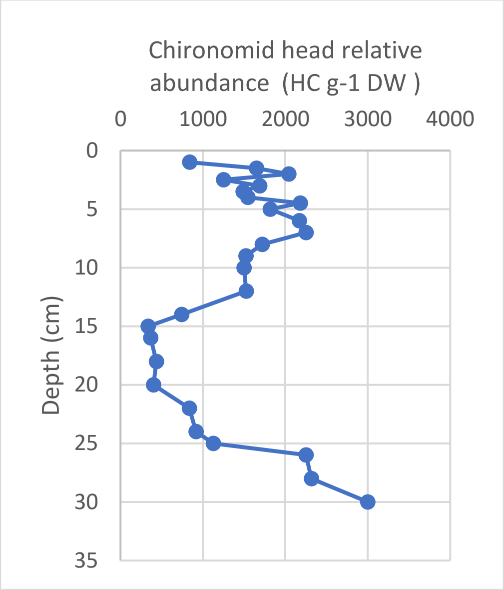

Figure S1. Relative abundance (HC g^{-1} DW) of chironomid heads throughout Chocolate Lake's core.

S.4 Lake Characteristics

Sedimentary stratigraphy

Rarefaction data demonstrating richness fluctuated between 20 – 45, peaking at 34.0 cm and reaching the lowest at 2.5 cm and 8.0 cm. The PCA outlined trends within chironomid community assemblages by coordinate placement of the core samples through time, with axes PC1 and PC2 representing 50.6 and 11.35% of the variation, respectively. Loss on ignition (LOI) data, %Organics (550) and %Carbonates (950), in Chocolate Lake fluctuate synchronously throughout the core (Figure S2). The %Organics ranged from 15.66 to 32.68, remaining <20 between 7.5 – 34.0 cm then peaking at 5.5 cm. The %Carbonates ranged from 0 to 3.78, peaking at 10.5 cm and reaching the lowest at 2 cm.

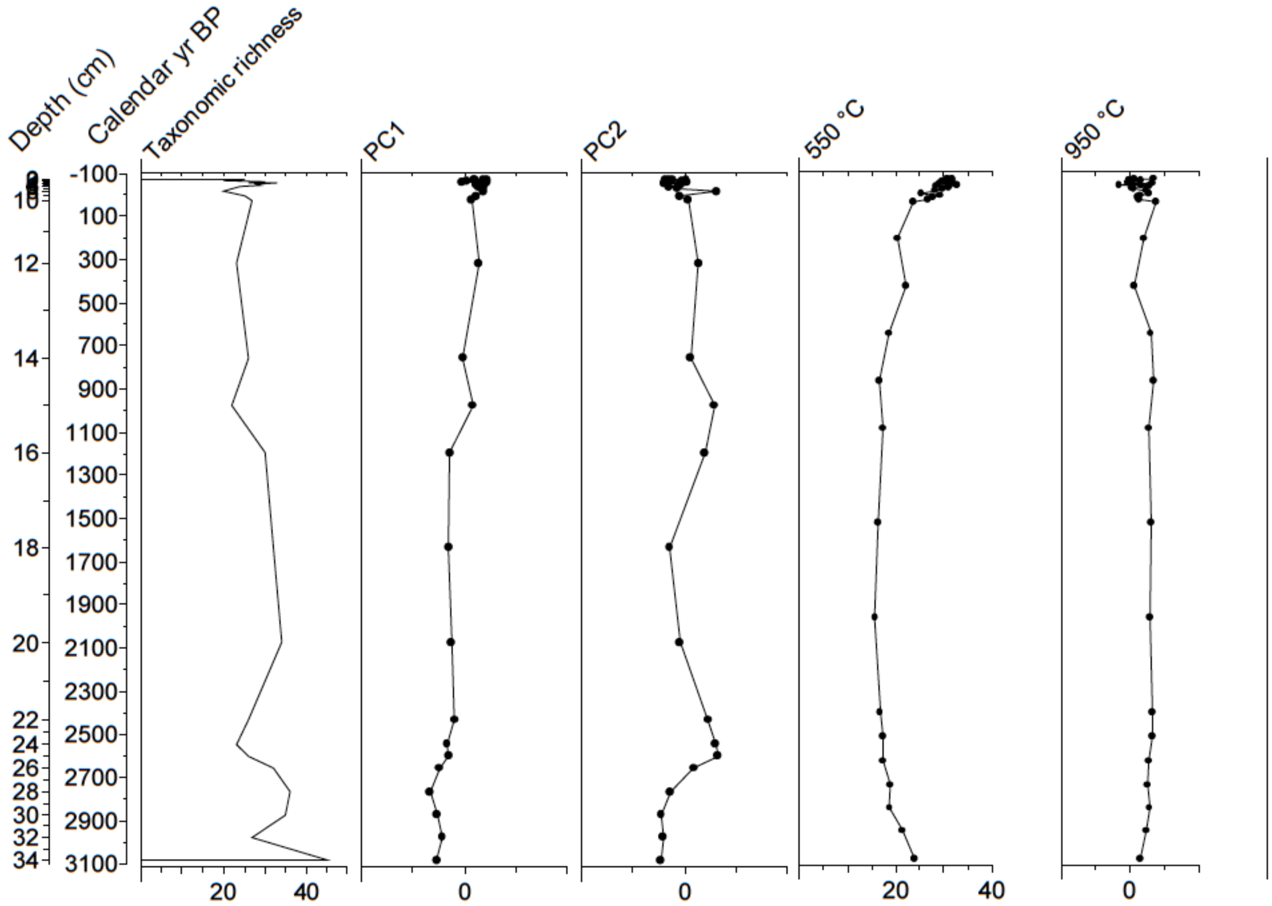

Figure S2. Rarefaction diversity (richness), PCA 1 (50.6%), PCA 2 (11.35%), LOI 550, and LOI 950 data of Chocolate Lakes sediment core.

S.7 References

Haddaway, N., Macura, B., Whaley, P., & Pullin, A. (2017). ROSES for Systematic Map Protocols. Version 1.0. https://10.6084/m9.figshare.5897284.