INVESTIGATING THE INFLUENCE OF LANDSCAPE DISTURBANCE AND CONNECTIVITY ON HIGH LATITUDE AND ARCTIC AQUATIC SYSTEMS: A PALEOLIMNOLOGICAL APPROACH

by

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Submitted in partial fulfillment of the requirements
for the degree of Master of Environmental Studies

at

Dalhousie University
Halifax, Nova Scotia
November 2020

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ABSTRACT

Connectivity across the terrestrial-aquatic interface drives transport of sediments and nutrients to aquatic systems, a relationship that is significant to historically undisturbed and unproductive lakes. The purpose of this research was to investigate and review disturbance-driven connectivity changes to lakes located within western Scotland and the western Canadian Arctic. The review of existing literature for the paleoenvironmental history of western Scotland revealed the co-linear relationship of climatic and anthropogenic signals within paleo records and provided insights to how they have been dealt with. Specifically, existing records suggest long-term human occupation can result in increased terrestrial-aquatic connectivity that may alter the state of impacted aquatic systems, the literature suggests the integrity of paleoclimate results within areas of known disturbance may be upheld by careful site and proxy selection. The role of landscape disturbance was also investigated in the uplands region of the Mackenzie River Delta, N.W.T., through lacustrine sediment core analyses. The quantitative investigation of two lakes located within a transitional permafrost gradient suggest landscape disturbance confounds temperature reconstructions and increases productivity of nearby aquatic systems, which can alter trophic status and result in biological thresholds being crossed by species once confined to more southernly ranges. Thus, interpretations of biological indicators in areas that are prone to landscape disturbance, particularly under warming climate and high anthropogenic influence conditions, are necessary for detangling the competing signals of climate and disturbance, providing greater confidence to reconstruction results. This research suggests the importance of considerations of landscape disturbance within paleolimnological research and contributes new evidence to our understanding of lake status changes within the western Canadian Arctic.

LIST OF ABBREVIATIONS USED

AM	Additive model
BCE	Before common era
CE	Common era
CO_2	Carbon dioxide
CRS	Constant rate of supply model
DCA	Detrended correspondence analysis
DW_{90}	Dry weight of lacustrine sediment
DW_{550}	Dry weight of lacustrine sediment after combustion at 550^oC
DW_{950}	Dry weight of lacustrine sediment after combustion at 950^oC
GAM	General additive model
GRIP	Greenland Ice Core Project
g^{-1} DW	Grams of dry weight
HC g^{-1} DW	Head capsules per gram of dry weight
KOH	Potassium hydroxide
LOI_{90}	Loss on ignition at 90^oC
LOI_{550}	Loss on ignition at 550^oC
LOI_{950}	Loss on ignition at 950^oC
NGRIP	North Greenland Ice Core Project
N.W.T.	Northwest Territories
O.D.	Ordnance datum
PCA	Principal component analysis
PG3	Patterned ground lake 3; reference lake
PG9	Patterned ground lake 9; thaw polygon lake
TW	Total weight of the sample
WATER	Waterloo Environmental Change Research Laboratory
WA-PLS	Weighted averaging-partial least squares
WESS	Laboratory for Water and Environmental Sustainability Sciences
WC	Water content
WW	Wet weight of lacustrine sediment
W%	%water

^{137}Cs	Caesium-137
^{210}Pb	Lead-210
$\delta^{13}C$	Carbon-13
$\delta^{15}N$	Nitrogen-15
$\delta^{18}O$	Oxygen-18

ACKNOWLEDGEMENTS

A special thank you to my supervisor Dr. Andrew Medeiros who first introduced me to the ever-fascinating field of paleolimnology as an undergrad in 2017, and who had the confidence to entrust me with this project and the willingness to push me to always be better.

My supervisory committee, whom provided unequalled support; Dr. Maarten van Hardenbroek, you introduced me to an entirely different context for paleolimnological research, and you were willing to collaborate across the pond; Dr. Tony Walker, for your immeasurably helpful experience and advice throughout my time at Dal; and Dr. Michelle Adams for your continued support over the past two years.

To MES alumni Ms. Barbara Carleton, the Northern Scientific Training Program, and the Nunavut Arctic College, who's generosity enabled me to peruse this research.

To Anthony Todd, who initially investigated these sediment cores in 2014 for his undergraduate thesis at Wilfrid Laurier University. His thesis provided many insights for me to continue from where he had left off.

Many thanks to the staff and students at the School for Resource and Environmental Studies at Dalhousie University for their unwavering support. In particular to Avi, Krysta, Vicky, Jess, and Emily for both pushing me academically and providing me with true friendship during my time in Nova Scotia; our office will forever be a space where a little work was done, and a lot of fun was had. I'd also like to acknowledge the hard work of the research assistants at the WESS lab, this thesis would not be finished without the dedicated and meticulous work completed by Connor Nishikawa, Sevrenne

Sheppard, Alex Soontiens-Olsen, and Kathleen Hipwell, thanks for the hours sorting dead bugs guys!

A big thank you to Sevrenne Sheppard and Paige Cincio, who were my lifelines during fieldwork and writing, and who have become lifelong friends. Go Team DB!

Finally, thank you to my family; who's unwavering support I could always count on. To Mom and Dad, for always being in my corner and reading everything I sent you, even if you did not fully understand it. To my grandparents for weekly calls that could calm even the most stressful times. To my sister Adrianna for always being my biggest fan. To Jeff, Bonnie, Merren, and Zoey Russell, thank you for making Nova Scotia feel like home. To my partner Robyn, who was there for every single smile and tear along the way; I could not have done it without you as my rock, editor, and counsel, and I am so happy to get to come home to you now.

CHAPTER 1 INTRODUCTION

1.1 Statement of Student Contributions

Chapter design by Alannah Niemeyer, chapter writing by Alannah Niemeyer with editorial contributions from Andrew Medeiros, Tony Walker, Maarten van Hardenbroek van Ammerstol, and Peter Tyedmers.

1.2 Introduction

Disturbance and stress on an environment, either direct or indirect, are known to greatly impact both biotic and abiotic processes (Kokelj et al. 2009a; Bishop et al. 2018). A physical disturbance to an ecosystem results in stress and subsequent disruption to the normal function; examples include but are not limited to, thermal changes, thermokarst activity, nutrient loading, and pollution (Jones et al. 1993; Bennion et al. 2004; Moquin et al. 2014; Koch et al. 2018). Here the intersections of natural and human-induced disturbances that impact aquatic systems are examined, within the contexts of the western Canadian Arctic and western Scotland where remote and uninhabited sites allow for unique investigations.

The Canadian Arctic remains a biome that has been relatively untouched by humans due to sporadic habitation and inaccessibility; however, the Earth's polar regions are one of the most highly affected areas by the indirect impacts of anthropogenic climate change (Post et al. 2009). This susceptibility to the consequences of rapid global climate and environmental change is understood, yet the potential impacts of the consequences are not. In contrast, the high latitude regions of the European North Atlantic have experienced human occupation and influence at increasingly high levels for thousands of years, with recolonization of Scotland estimated to have begun after the retreat of Late Devensian ice sheets (c. 12550-12050 BCE) (Stone & Ballantyne 2006). While Scotland has not experienced the most extensive climate changes as observed in the Arctic, direct impacts have been widespread and long-lasting. One of the primary concerns and gaps of knowledge within both of these regions is the role and impacts of co-linear or secondary variables of disturbance, such as the competing influences of atmospheric warming and allochthonous inputs.

The question of the influence of disturbance on aquatic systems in both the western Canadian Arctic and the northwest Atlantic region will be explored through a review of the paleoenvironmental history of western Scotland, and the examination of primary data from the Mackenzie River Delta uplands region of the Northwest Territories (N.W.T.), Canada. These locations are quite different in geography, anthropogenic impacts, and ecology, yet both allow for exploration of competing influences on local environments. Moreover, the confounding variable of direct terrestrial influences on aquatic systems is known to complicate paleoenvironmental research within the field of limnology (Juggins 2013; Medeiros et al. 2015). Within Scotland long-term human occupation has influenced aquatic systems, such as acidification and eutrophication caused by effluent run-off; while in the western Canadian Arctic climate-induced landscape changes (e.g., retrogressive thaw slumps and patterned ground formation) have rapidly increased connectivity and resulted in habitat transformations within the affected Arctic lakes and ponds (Bennion et al. 2004; Kokelj et al. 2009a; Brooks et al. 2012b; Koch et al. 2018).

A primary goal of this thesis is to add to the field of paleolimnology, concerning the question of the impacts of disturbance on aquatic ecosystems in various regions of Earth. Chapter 2 of this thesis reviews the paleoenvironmental history of Scotland within the context of human influence, landscape alteration, and environmental change; Chapter 3 investigates multiple proxies of paleolimnological evidence from the uplands region of the Mackenzie River Delta, N.W.T.; and finally, Chapter 4 considers knowledge gained from both regions and how it contributes to the future directions of paleolimnological research. Specific focus on the western Canadian Arctic and western Scotland will enable meaningful considerations of the intersections of climate and human influences, and how future paleolimnological research can learn from these unique landscapes.

1.2.1 Overview of the Problem to be Addressed:

Disturbance, and the resulting stress, can have significant impacts on fragile but complex aquatic ecosystems. Hydrological connectivity within a watershed significantly influences aquatic productivity due to transport of constituents; however, this relationship is generally limited within the permafrost regions of the Arctic, while connectivity is typically higher within areas of long-term human settlement due to landscape alterations. In particular, the permafrost landscape surrounding the Mackenzie River, N.W.T., Canada, varies with latitude (Figure 1.1). Permafrost in the Arctic is characteristic; a gradient exists from southern discontinuous (<100m depth) to northern continuous (>500m depth) permafrost, which governs the hydrological cycle of the region (Bond & Carr 2018). In contrast, more southernly regions lack the controlling nature of permafrost and, therefore, have relatively increased connectivity due to both lateral movement and infiltration. For example, western Scotland has experienced both anthropogenic and climate changes over the past 10000 years, which has greatly impacted the surrounding ecosystems (Robinson & Dickson 1988; Jones et al. 1989; Bishop et al. 2018). While the western Canadian Arctic and western Scotland are geographically and historically distinctive, both are regions that have experienced disturbance and have responded in interesting individual manners. The link between these seemingly diverse sites is the influence of multiple stressors, and the consequences on the aquatic systems. Medeiros et al. (2015) examined North American lakes in order to discern the drivers of chironomid assemblage changes, which can mask climate signals within the data; results indicated unproductive lake reconstructions are primarily influenced by temperature changes, yet aquatic systems in areas of transitional landscapes are more likely to be influenced by co-linear or secondary variables. Specifically, the role and influence of co-linear and secondary variables within paleolimnological research is not well understood, and this thesis seeks to increase knowledge of both natural and anthropogenic confounding variables.

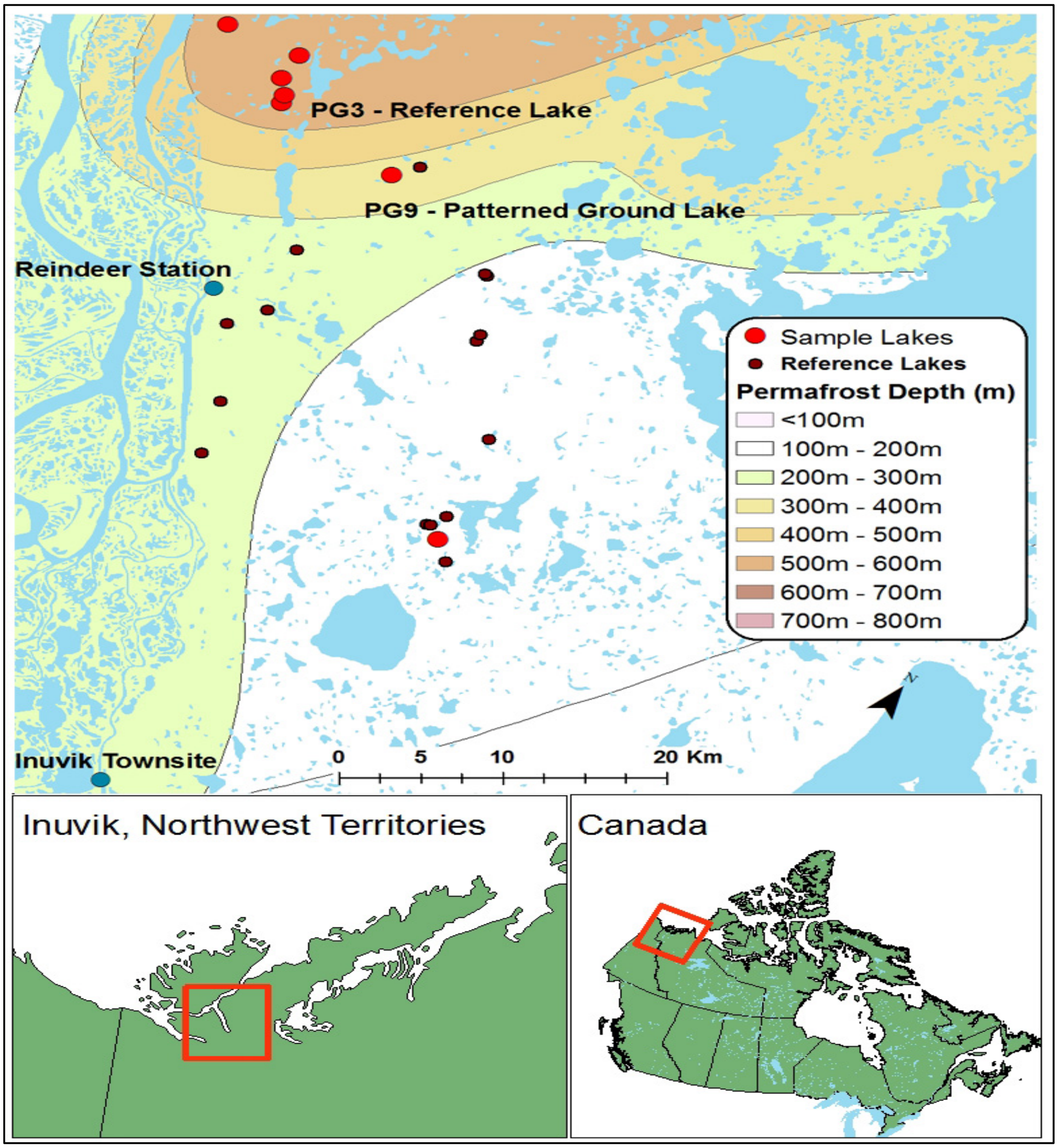

Figure 1.1 Location of the PG lake sites where data was gathered, with the primary sites of Lake PG3 and Lake PG9 labelled. Showing the approximate distribution and thickness of permafrost (Brown et al. 1998; Todd 2014).

1.2.2 Primary Data Research Purpose and Objectives

A central objective of this research is to increase knowledge of changes to lake productivity, as a result of the influence of the terrestrial-aquatic interface, within the Canadian Arctic landscape. The role of the transitional patterned ground landscape will be analyzed to determine if thaw polygon features constitute a significant function in surface and/or near-surface transport of organic matter. Consequently, thaw polygons are proposed to be increasing connectivity by transporting constituents from catchment-mediated processes, such as permafrost degradation, to downslope lakes. Thus, the hypothesis of this study is, lakes with higher connectivity will have greater terrestrial influence and be more productive than lakes with lower connectivity. In order to better understand the relationship between landscape disturbance and terrestrial-aquatic connectivity, this research focuses on how observed productivity in lakes within the Mackenzie River Delta uplands region relate to: a) lake productivity in the southern discontinuous permafrost zone; and b) reconstructions of productivity from lacustrine sediment cores of the study lakes.

Three research objectives will be investigated: (1) Outline surface and/or near surface flow; (2) contrast productivity in highly connected lakes to productivity of lakes with lower connectivity; and (3) identify contemporary productivity relationships and compare observations with reconstructions of historic productivity from lacustrine sediment cores.

Paleolimnological analysis will address these objectives by allowing the investigation of lakes through time. Fieldwork in the Mackenzie River Delta uplands region near Inuvik and Reindeer Station elucidated changes in landscape disturbance across a gradient of permafrost by examining biological indicators (*Chironomidae*) and elemental and isotopic geochemical data. The areas surrounding the Mackenzie River Delta are characterized by thousands of lakes, that are typically small, allowing for inferences between these aquatic bodies that were formed following the Wisconsin glaciation and have experienced similar thermokarst activity since (Pielou 1991; Kokelj et al. 2005). The paleolimnological analysis included sediment cores from two lakes; (1) Lake PG3 reference core (8.4 cm diameter & 38.5 cm deep); and (2) Lake PG9 impacted core (8.4 cm diameter & 14.5 cm deep). Lake PG3 is located within a continuous permafrost zone, while Lake PG9 is located within an area of shallower permafrost that has observed thaw polygon disturbance (Figure 1.1); the comparison of the lake histories elucidate past and contemporary productivity relationships. Thus, examining theses lakes over time provides evidence to either support or disprove the notion that Arctic lake hydrological connectivity is increasing rapidly.

1.3 Literature Review

The Canadian Arctic is an ecosystem experiencing rapid effects of climate change, to date numerous studies have demonstrated support for accelerated warming at the poles of the Earth (Johannsen et al. 2003; Lantz & Kokelj 2008; Liljedahl et al. 2016; Steedman et al. 2017). Future modelling has predicted that annual snowmelt may occur up to two weeks prior than historically observed in the second half of the twenty-first century (Scheepers et al. 2018). Here, I focus on the Mackenzie River Delta region, N.W.T., which is a large river located in northern Canada that flows south-to-north ultimately discharging into the Beaufort Sea, that is strongly impacted by snowmelt. The river regularly floods as a result of melt occurring earlier in the south while the persisting ice in the north dams the river, thereby creating a floodplain (Emmerton et al. 2007). Freshet data from 1966-1984 indicates peak discharge of the Mackenzie at Normal Wells (65°16′52″N, 126°49′53″W) was an average of 12 days prior to the peak discharge at the

East Channel at Inuvik (68° 19' 36.2208" N, 133° 41' 0.0852" W) (Walker et al. 2008a). The Mackenzie River watershed also consists of the Peace-Athabasca River, Great Slave Lake, and Great Bear Lake; therefore, warming effects, which accelerate the hydrological cycle, may have significant consequences for this vast region that is highly connected (Walker et al. 2008b; Griffin et al. 2018). This concern is displayed in the patterned ground (thaw polygon) landscape which occurs with polycyclic behaviour in the transition from discontinuous to continuous permafrost in the Mackenzie River region (Bond & Carr 2018). Additionally, polygon microtopographic changes have been observed to be increasing since the late twentieth century and it has been suggested that projected warming could result in regional scale changes with large implications (e.g., runoff & evapotranspiration alterations) for the hydrological cycle in the Canadian Arctic (Liljedahl et al. 2016; Abolt et al. 2018).

A similarly noteworthy site is Scotland, which has experienced landscape disturbance from direct human occupation that is estimated to have begun during the Lateglacial (Mithen et al. 2015). Due to Scotland's location in the North Atlantic, it experiences marine and atmospheric circulations, with the addition of long-term direct impacts from human occupation. Specifically, the Western Isles of Scotland (hereto referred to as the Hebridean Islands) are of particular interest as they represent the most southern of the North Atlantic archipelagoes and as such exist over a transitional region, from the temperate conditions in the south to the Arctic boundary conditions in the north (Bishop et al. 2018). It is well established that human settlement and colonization, such as farming groups and Norse settlements in the Hebrides has led to environmental changes to the occupied regions (Mercer 1980; Robinson 1983; Storrie, 1983; Robinson &

Dickson 1988; Steven & Dickson 1991; Edwards & Mithen 1995; Bishop et al. 2018). Specifically, archaeological, pollen, and charcoal records support the Hebrides as locations with early evidence of human recolonization following the last glacial maximum; currently the oldest evidence of post-glacial occupation dates to c. 7350-5850 BCE and is from the Inner Hebridean Island of Islay (Mithen et al. 2015). Environmental changes, ranging from initial deglaciation effects to more contemporary concerns of climate warming, are prevalent in this region and provide an opportunity to explore the coupled impacts of climate and human occupation on aquatic systems. The review of paleolimnological climate reconstructions for sites with known long-term human occupation may shed light on the applicability of these methods to other highly impacted systems. Thereby, establishing western Scotland, and the Hebridean Islands, as important sites of interest when considering the influence of terrestrial-aquatic connectivity on aquatic system conditions.

1.3.1 Climate Change at Northern Latitudes

Human induced-climate change is projected to have detrimental effects globally; however, there are current pronounced impacts in the polar regions of the Earth. Specifically, the Arctic has experienced warming at a magnitude greater than double the amount of average temperature change for the non-polar biomes (Anderson et al. 2007; Post et al. 2009). This unique situation of rapid climate change suggests the Arctic may be an indicator of changes to come for other regions of Earth (Post et al. 2009). Other high latitude regions, such as regions of the North Atlantic, are also experiencing the effects of climate change, but at a reduced speed when compared to the Arctic (Tipping et al. 2012; Walker & Lowe 2019). Currently, global alterations to species ranges, reduced ice-cover, increased plant biomass, precipitation variability, permafrost degradation, and increases to duration and average temperature of summers are resulting impacts of warming that have had larger cascading impacts and negative feedback, such as the increasing release of long-stored organic carbon from permafrost due to degradation (Anderson et al. 2007; Andresen & Lougheed 2015; Medeiros et al. 2015; Schuur et al. 2015).

The terrestrial consequences of climate change also influence freshwater systems. Rapid Arctic warming has resulted in increased hydrological connectivity, which impacts productivity, water quality, and water quantity (Andresen & Lougheed 2015). The change to the hydrological cycle of the Arctic also has wider ecosystem effects, as hydrology is a governing factor of life and abiotic processes in the Arctic (Andresen & Lougheed 2015). Rapid climate change impacts the fundamental cycles of the Arctic, which control landscape ecology and biotic elements (e.g., topography, nutrient cycling, and trophic structures).

1.3.2 Deglaciation

The process of deglaciation is gradual and natural; current isostatic adjustment is a result of the Pleistocene glaciations (Adhikari et al. 2018). Glaciations greatly influence the landscape of a region, such as the weight of the ice sheet causing the ground to depress; this process is then reversed following the retreat of the ice sheet (Lemieux et al. 2008). In addition to topography changes, glaciation and subsequent deglaciation also influences hydrology. In particular, isostatic rebound effects topography and hydrology, due to the loss of the depressive ice (Lemieux et al. 2008). Thus, this process alters the environment at the landscape scale and can result in overall large changes, yet this occurs over time at a very slow pace (Lemieux et al. 2008). Consequently, within the decadal and even centurial temporal-scale, rapid geophysical and hydrological changes would not be predicted to occur, indicating that any rapid changes could not be attributed to natural deglaciation processes.

1.3.3 Permafrost

Permafrost is the freezing of water within soil and its maintenance as a solid for at least two consecutive years (Burn 2012). Permafrost develops at depth in the lithosphere due to sequential low temperatures; it can range from sporadic and discontinuous to greater than 1 km deep (Lemieux et al. 2008). In the absence of permafrost or positioned above the permafrost, unfrozen soil is called the active layer, which is biologically available to organisms and allows for transport of water and ions (Liljedahl et al. 2016). Permafrost is a significant feature of the Arctic and sub-Arctic because it strongly influences soil availability, and as a result, controls surface and near-surface flow of water (Lemieux et al. 2008). Moreover, permafrost has also been labelled as a controlling factor of the Arctic landscape; water is only able to travel overland and through the active layer in areas with permafrost present. Consequently, it has been predicted that climate change, and the associated degree of warming within the Arctic, will have a pronounced impact on this controlling factor due to permafrost degradation and the deepening of the active layer (Kokelji et al. 2009a). This is also significant due to permafrost degradation having the capacity to release long-stored ionic material, which could chemically alter the impacted, ion-lacking, active layer and downstream aquatic systems (Kokelji et al. 2009a).

1.3.3.1 Retrogressive Thaw Slumps

Retrogressive Thaw slumps are characterized by a steep headwall and a foot-slope of a lower gradient and form due to thermokarstic activity (Kokelji et al. 2009b; Segal et al. 2016). Thaw slumps are known have polycyclic behaviour, which is described as slump initiation and growth within an area of previous slumping (Lantuit & Pollard 2008; Kokelj et al. 2009b) (Figure 1.2). Thus, thermokarst processes initialize a preliminary thaw slump and then over time the scarred land continues to stabilize and then re-activate. Moreover, this polycyclic behaviour has been demonstrated to occur at a relatively rapid rate, that is, less than a century (Kokelj et al. 2009b). Lantz & Kokelj (2008) found that thaw slump polycyclic behaviour had increased the size of the slump area by 15 % between 1950-1973, and a follow-up 2006 survey concluded that area had increased by an additional 36 %; suggesting that slump behaviour or re-initialization has become more rapid within the past fifty years. Wang et al. (2016) monitored retrogressive thaw slumps near Inuvik, N.W.T., over a three-year period and found the highest annual rates of regression for the period to be 8-15 m. The initial slump and continued slumping behaviour is known to be potentially catastrophic to nearby water bodies; thaw slumps may spill into aquatic systems and have short-term sediment depositional effects, as well as a long-term ionic concentration legacy (Kokelj et al. 2009a; Houben et al. 2016). However, a clear gap in the literature exists in the context of thaw slump impacts on a wider geographic range.

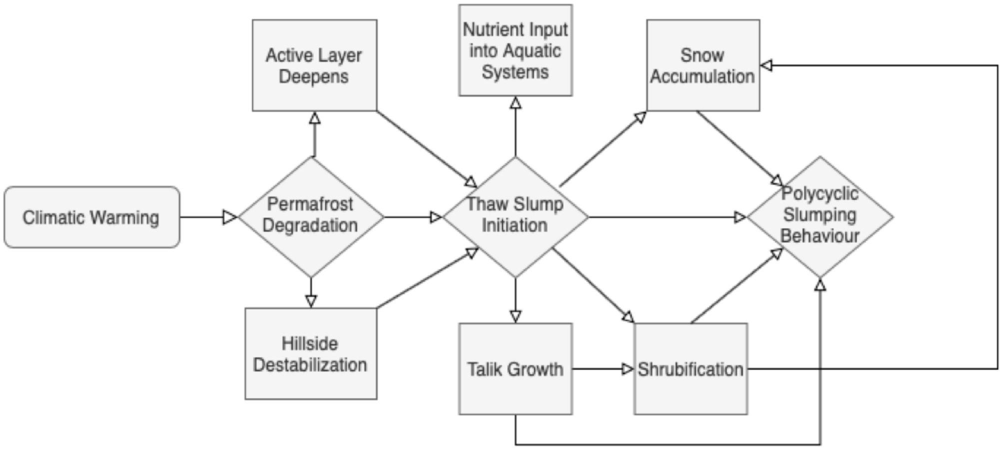

Figure 1.2 Causation diagram describing independent variables related to retrogressive thaw slump initiation and polycyclic behaviour.

1.3.3.2 Thaw Polygons

Thaw polygons are another example of Arctic topography that form through thermokarstic processes. Specifically, thaw polygons are formed as a result of meltwater infiltrating the ground deeply through contraction cracks, which then freeze and, as this process is repeated annually, an ice-wedge is created that displaces the substrate (Liljedahl et al. 2016). Polygons are formed by ice-wedges within the permafrost creating higher elevations which keep water within the area not affected by ice-wedges and/or channel water through lower troughs (Liljedahl et al. 2016; Abolt et al. 2018). While a natural phenomenon, thaw polygon formation has been described as accelerating within areas of discontinuous permafrost, due to the effects of climate change induced warming (Breton et al. 2009). Rapid change has been observed within the context of these polygons; degradation of the polygons has caused lateral expansion of troughs and, consequently, create more connectivity within the landscape (Liljedahl et al. 2016).

Moreover, this degradation has been observed at sites in both the Canadian and Russian Arctic within a decadal time-period (Liljedahl et al. 2016). This heightened connectivity suggests progress towards an increased intensity of the, historically limited, hydrological cycle within the Arctic. Abolt et al. (2018) conducted polygon thermal simulation analyses and concluded with support for deeper troughs causing warmer ice wedge temperatures. Increased high temperature influence as well as larger troughs could create a positive feedback mechanism where warming increases degradation and deeper troughs facilitate greater connectivity.

1.3.3.3 Impacts of Permafrost Degradation

For northern aquatic systems the degradation of permafrost, due to warming, can release ions and nutrients into lake catchments (Lantz & Kokelj 2008). There is also the concern of permafrost degradation causing a release of historically frozen organic carbon into the atmosphere, which results in a feedback relationship where increased warming results in greater carbon release that then intensifies warming (Schuur et al. 2008); while this particular relationship is significant to understanding the context of warming in the Arctic, the specifics are outside of the scope of this thesis. Yet, the release of nutrients from degrading permafrost that settle into aquatic systems can be a problem when it occurs at a rapid rate, due to water bodies within the Arctic typically containing low ionic concentrations (Kokelj et al. 2009a). Moreover, thaw slumping in the southern Mackenzie River region has been observed to be catastrophic to the lakes directly impacted as it causes the release of large amounts of sediment into the water, thereby drastically altering the aquatic chemistry (Kokelji et al. 2009a). The dynamic polygon landscape may allow for surface and near-surface transport of these constituents northward. Liljedahl et al. (2016) conducted a study that suggested ice-wedge degradation can be landscape-wide in various sites of the Canadian Arctic, which results in polygon expansion and greater aquatic connectivity. Therefore, current environmental change in the Arctic is creating warmer conditions, which, conceivably, may increase lateral movement of matter throughout the environment by surface and/or near-surface flow.

1.3.4 Polar Aquatic Systems

Productivity of Arctic lakes has historically been muted due to the large influence of light, specifically ultra-violet (UV) radiation, on lakes and ponds that have a large surface area yet shallow depth, which are commonplace in the Arctic (Mariash et al. 2018). The quantity of dissolved organic carbon (DOC) is a significant contributor to the colour and resulting turbidity of waterbodies; however, the quality of DOC is even more significant (Mariash et al. 2018). Terrestrial (allochthonous) DOC is more coloured than aquatic (autochthonous) DOC (Mariash, et al. 2018). The majority of allochthonous DOC in the Arctic is stored within permafrost (Anderson & Stedmon 2007), which, in the context of climate change, poses the potential to physically alter aquatic ecosystems as permafrost degradation may cause the release of this pigmented allochthonous DOC. Thus, climate change, the resulting warming, and degradation of permafrost could severely alter the physical conditions of aquatic systems, which then have the potential to influence biotic communities. More specifically, increased pigmentation of lakes would suggest high allochthonous DOC input, resulting in decreased harmful influence of UV on producer organisms (eg. phytoplankton). This presents the issue of potentially increased productivity in aquatic systems, which have typically had less light attenuation and greater UV impact. If this alteration is due to climate change, it would be expected to observe rapid changes over recent time.

Consequently, the issue arises from the addition of these typically absent or low-level ions and nutrients into tundra aquatic systems that have the capability to increase productivity, which is possibly due to increasing connectivity within the watershed. As a result, environmental change within the Arctic could create trophic cascade effects (Medeiros & Quinlan 2011). It is pertinent to understand the source and influence of increased constituent inputs and how it may alter the physical, chemical, and ultimately biological composition of aquatic systems. The source of organic matter and the history of primary production are pertinent to understanding the past and current conditions of a lake, all of which can be investigated through stable isotope, C:N ratio, and organic content analysis, with considerations for the added complexity from microbial activity and processes (Hodell & Schelske 1998; Meyers 2003; Torres et al 2012). Yet, increased, or catastrophic, allochthonous inputs may pose a secondary threat to the methods of reconstructing past aquatic systems, as landscape alteration can result in co-linear variables that affect proxy assemblages. As such, the characteristics of the catchment area and basin strongly influence the transport of allochthonous material into polar aquatic systems.

1.3.5 Temperate Aquatic Systems

The temperate zones of the Earth are situated between the polar regions and the tropical areas located nearer to the equator; generally, these areas experience all four seasons and, consequently, tend to have larger annual changes in temperature. These annual changes in temperature typically induces lake mixing in the spring and autumn, while stratification and inverse stratification occur in the summer and winter, respectively (Wetzel 2001). Typically, temperate aquatic systems have complex hydrological cycles and productivity regimes, which are regulated by the biotic and abiotic factors both within and external to the basin. Terrestrial-aquatic connectivity in temperate zones is not as limited as in the Arctic. As such, the precipitation regime, UV penetration, geomorphology, climate, evapotranspiration, and vegetation community surrounding or affecting a freshwater system form some of the complex set of factors influencing the conditions of any given basin.

Temperate zones contain many of the Earth's developed nations, where a high proportion of the population occupies urban areas; for example, in the United States approximately 80% of the entire population live in urbanized settings (Pickett et al. 2011). Demotechnic growth, or the inseparable nature of exponential human population growth and technological advancements (Wetzel 2001), is of particular concern in the temperate regions, thereby, placing stress on aquatic systems from both indirect (e.g., climate change) and direct (e.g., human occupation) sources. In addition, the urbanization of many areas within the temperate zones are linked to increased terrestrial-aquatic connectivity, which influences the hydrological cycle and complex nutrient transport processes. Wahl et al. (1997) investigated drainage and nutrient loading of wetlands from an urbanized stream and a forested stream in the southeastern United States, their results suggest the impacts of urbanization-induced physical changes to the catchment area supported a three times increase in runoff flow and an eleven times increase in N loading in the urbanized stream versus the forested stream. This is of particular concern in the context of pollution and effluent runoff; Brodin & Gransberg (1993) investigated the modern history of Round Loch of Glenhead in southwestern Scotland and found evidence of anthropogenic-caused lake acidification beginning in 1850 CE, with a substantial increase around 1950 CE. Acidification (attributed to atmospheric deposition) negatively impacted the health of the chironomid community, suggesting potential additional effects at higher trophic levels as well (Brodin & Gransberg 1993). Consequently, urbanized and agriculturally developed areas are associated with changes to pathways, volume, and content of surface waters (Newton & McLellan 2015).

1.3.6 Transport of Organic Matter

Movement of organic material and sediment is regulating factor within aquatic ecosystems, sources can be allochthonous (terrestrial) and/or autochthonous (aquatic). Carbon additions dissolved organic carbon (DOC), in particular, can regulate light penetration, primary production, and ultimately alter trophic systems (Mariash et al. 2018). Within the temperate context, human occupation, and subsequent activity, has altered landscapes for agriculture and infrastructure, which has largely resulted in increased terrestrial and aquatic connectivity; for example, the primary threat to European aquatic systems is considered to be nitrogen and phosphorus mobilization from agricultural, industrial, and residential sources (Chique et al. 2018). In the Arctic connectively is quite different than lower latitude regions, the largest movement of both water and the sediment it carries occurs during freshet, which has historically occurred at peak in May-June (Walker et al. 2008a). More recently, surface and near-surface sources of dissolved organic matter, caused by permafrost degradation, release long-stored ions into aquatic systems making these nutrients contemporarily available (Frey et al. 2016). This has been demonstrated within the Arctic by Medeiros & Quinlan (2011), whom found that climate change could be an explanation for the observed alterations to chironomid communities over time at various sites on Bylot Island, Nunavut. Morison et al. (2018) suggested increased air temperature coupled with decreased snowfall and ice formation could support conditions that mobilize organic matter and the bioavailable nutrients within it. In particular, chromophoric carbon has the potential to attenuate light and as a result can alter the turbidity and colour of a lake, due to immediate significant leeching (Griffin et al. 2018). The ability of chromophoric carbon to leech into an aquatic system and alter the physical conditions indicates increasing amounts of bioavailable nutrients can greatly influence the biotic communities found in typically large yet shallow Arctic lakes; within such lakes light and particularly UV radiation are naturally controlling factors for organisms. Thus, the presence of chromophoric carbon in an Arctic lake may inhibit penetration of UV radiation and support greater biological activity. Consequently, knowledge of chromophoric carbon's ability to attenuate light suggests increased productivity within Arctic lakes may be a result of large additions of this ion, originating from southern allochthonous sources, via surface and near-surface transport. Environmental change and subsequent warming can lead to additions of organic matter, and nutrients and ions, which have the potential to critically alter typically unproductive and/or remote Arctic and high elevation aquatic systems.

1.3.7 Productivity

Eutrophication, a classification based on a highly productive oxygen-limiting environment, is a common problem in the current epoch due to terrestrial anthropogenic sources of nutrients infiltrating the natural environment and accumulating in aquatic systems (Brodersen & Quinlan 2006). While greater productivity within an aquatic system can lead to a diversification of flora and fauna species, within the Arctic context this is of concern due to the threat of the loss of unique lake systems, which may ultimately result in biodiversity (Lesack & Marsh 2010). In temperate regions direct anthropogenic nutrient inputs have been the leading driver of eutrophication (Mariash et al. 2018). Typical examples of nutrient enrichment by humans include agricultural practices, discharge of sewage, and general pollution (Pick 2016). Specifically, modernization of agriculture within the 20th and 21st centuries is considered one of the greatest direct drivers of change to the surrounding landscape, through the resulting vegetational, hydrological, and trophic changes (Chique et al. 2018). Britton et al. (2017) investigated wetlands in the uplands of Scotland, finding species richness of herbaceous plants increased, and concluded the mixture of climate change, pollution, and grazing has driven these systems to greater homogeneity since the 1970's. This kind of direct human impact is also observed within the Arctic; Virtanen et al. (2002) analyzed satellite images of the area surrounding the city of Vorkuta, Russia, and found evidence of two impact zones, the first being the most highly polluted in a radius of 150-200 km^2 where lichens were absent, and the second less polluted zone extending 600-900 km^2 with similar but fewer vegetational changes.

In contrast, more indirect anthropogenic influences have been linked to increased productivity within some regions of the Arctic due to far proximity to human influence. Climate change induced warming is predicted to stimulate greater Artic productivity; yet, this increase may also be heightened by alterations to nutrient fluxes (Przytulska et al. 2017). Taranu et al. (2015) conducted a paleolimnological analysis of subarctic lakes and concluded that cyanobacteria have significantly increased since the end of the eighteenth century, and also that the rate of increase of these organisms has become increasingly more rapid since World War II. Schindler (1977) famously provided ecosystem-scale evidence to demonstrate that nutrient loading, in particular phosphorus but also nitrogen and carbon, control the growth of phytoplankton. This long history on the subject of algal blooms and eutrophication, even within an Arctic context, provide strong evidence that increased productivity within an aquatic system suggests nutrient loading from a source. Thus, lakes with greater connectivity to the terrestrial, and wider aquatic ecosystems could be more productive than those which are less connected and as a result receive less input.

1.3.8 Chironomidae

Bioindicators are used to infer the health of an ecosystem. In particular, *Chironomidae* (chironomids) are useful bioindicators as the longest aspect of the life-cycle is the larval-stage, which is when they are benthic-dwelling invertebrates (Oliver & Roussel 1983). Additionally, this family is useful due to abundance, as chironomids are ubiquitous within the Arctic and can make up greater than 50 % of the diversity of species within a waterbody (Oliver & Roussel 1983). In the paleolimnological context this notion is supported by Walker (2001), who found that subfossils of the *Chironomidae* family are found in greater abundance than any other in the order *Diptera*. Lang et al. (2010) notes that unlike other proxies, such as pollen, chironomid larvae exist completely *in situ* and, therefore, reflect the impacts and changes to the immediate environment. Specifically, chironomids are effective agents for paleolimnology due to the rigid chitinous head capsules that do not decay, but instead remain within sediments over time in large quantities (Brodersen & Quinlan 2006). These head capsules can be found in large quantities in an incredibly small volume of sediment, which, consequently, allows for the construction of a relatively high temporal resolution stratigraphy (Walker & Lowe 2019).

Chironomids are known to be sensitive to environmental changes, including alterations to temperature and nutrients within the aquatic system (Luoto et al. 2016). In particular, factors external to a lake system are of primary concern due to the impacts of changing air and ground temperatures, as well as nutrient additions on *in situ* variables (e.g., water temperature, dissolved oxygen, food availability, & habitat) (Walker 2001). In the context of monitoring changes of productivity due to increased terrestrial inputs, chironomids are especially useful due to the sensitivity of the taxon. Chironomid larvae have a range of diets from grazers to predators, however, a similarity among the taxon is that a key source of the diet is detritus, both allochthonous and autochthonous (Oliver & Roussel 1983; Luoto et al. 2016). Therefore, changes that alter the amount of detritus in the system could lead to community-level responses in diversity and abundance of chironomids. Additionally, chironomids are an effective choice as a bioindicator because the larvae maintain an important role within the aquatic biotic community; that is, chironomids are known to be a significant source of food within freshwater systems, as well as to be significant to biogeochemical cycles (eg. carbon cycle) due to the consumption and processing of detritus and other organics (Luoto et al. 2016). Thus, due to abundance, sensitivity, and a prominent role in the ecosystem, using the subfossilized head capsules of chironomid larvae is accepted as an effective bioindicator.

The identification of the subfossilized head capsules of chironomids is predominantly based upon morphology such as the mentum, ventromental plates, and in some cases by pedestals, spurs, and mandibles (Walker 2001; Walker 2006). The mentum is the primary distinguishing feature between chironomid taxa, which is located on the anterior ventral margin of the head, where the number and sizing of median and lateral teeth is typically utilized to differentiate species and sub-families (Figure 1.3). Taxonomic keys are significant to the differentiation between taxa and were utilized throughout the analysis of chironomids for this thesis, to ensure consistent identifications (Brooks et al. 2007).

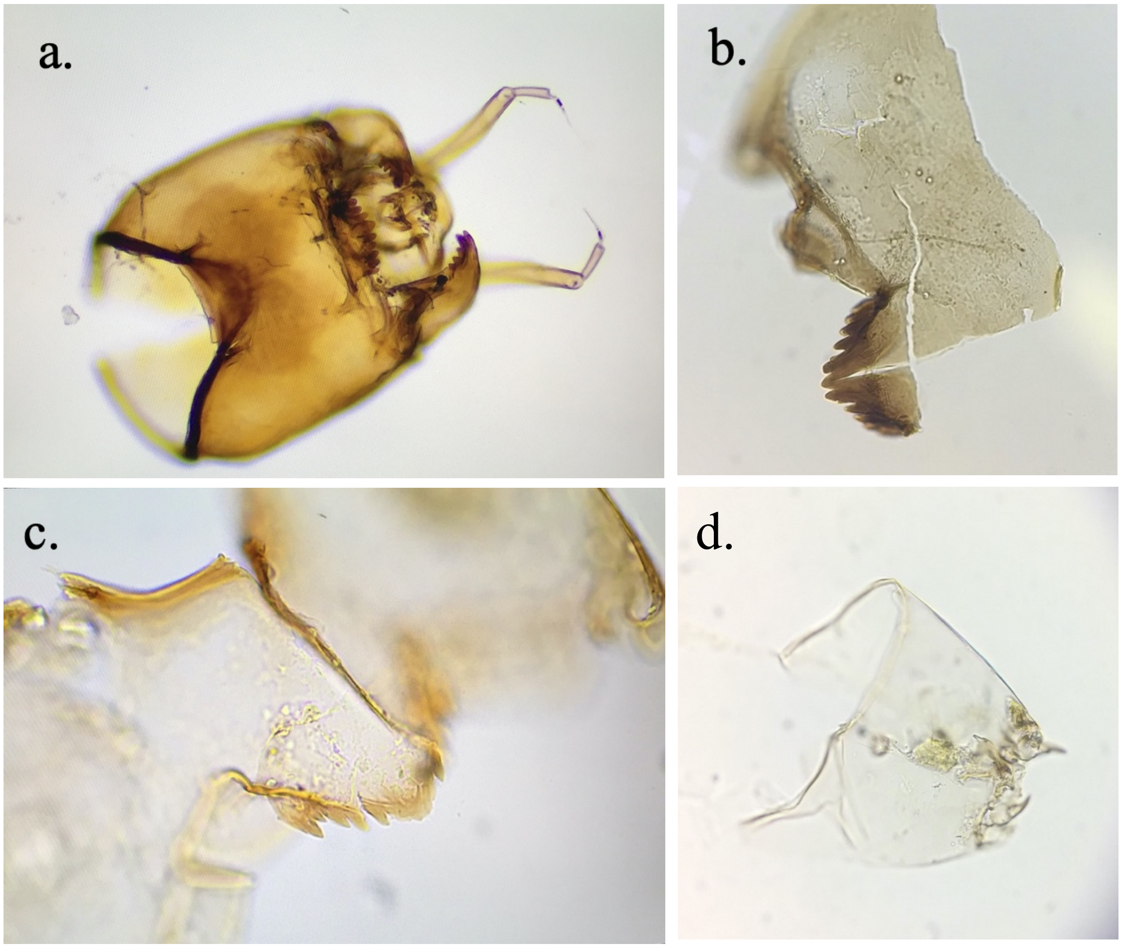

Figure 1.3 Examples of chironomid taxa showing distinct morphologies; a). *Paratanytarsus pencillatus*-type (*Tanytarsini*), b). *Cricotopus intersectus*-type (*Orthocladiinae*), c). *Cladopelma* (*Chironomini*), and d). *Procladius* (*Tanypodinae*).

1.4 Research Sites

1.4.1 The Mackenzie River

The Mackenzie River is the largest river within the North American portion of the Arctic; the river annually transports 330 km^3 of fresh water, along with 127 Mt of terrestrial sediment into the Beaufort Sea (O'Brien et al. 2006; Walker et al. 2008b). Peak discharge typically occurs May-June, and then continually decreases until Autumn; yet, an investigation of the four largest rivers draining into the Arctic Ocean (i.e., Lena, Mackenzie, Ob, and Yenisei) suggest earlier freshet onset between 1980-2009 (Ahmed et al. 2020).

1.4.2 Mackenzie River Delta Uplands Region

The Mackenzie Delta uplands region is considered to be at the transition between the northern reaches of treeline and the beginning of tundra; as such it is a region that greatly varies, with a mix of landscapes as well as flora and fauna (Palmer et al. 2012). Burn & Kokelj (2009) describe the contemporary state of the landscape; the southern portion is dominated by shrubbery while the more northward areas are marked with sedges and shorter shrubs. The area previously had glacial influence from the Laurentide ice sheet, which covered the region until Holocene retreat approximately 10000 years ago (Pielou 1992). Thus, the area has been experiencing isostatic rebound for the entirety of the current epoch. The region has been characterized by permafrost presence since Illinoian glaciation, when persisting climatic conditions resulted in the formation of permafrost, and more recently permafrost thickness has been influenced by mean ground temperatures and the glacial legacy of the area (Burn 1994; Burn & Kokelj 2009). Currently, the uplands region permafrost depth ranges from >700 to <100 m (Burn 1994; Burn & Kokelj 2009).

1.4.3 Lake PG3

Lake PG3 is located within the upland continuous permafrost region of the Mackenzie Delta, northwest of Reindeer Station, N.W.T. (coordinates being 68.8396 ^{o}N, 134.2795

°W). Furthermore, permafrost mapping indicates PG3 is located within an area of approximately 500-600 m of permafrost depth (Figure 1.1) (Todd 2014). As such this lake was designated as reference lake, as it was hypothesized that it would have less terrestrial flux than lakes located in areas with a lower permafrost depth, due to the known lack of permafrost degradation in the surrounding landscape (Figure 3.3).

1.4.4 Lake PG9

Lake PG9 is also located within the Mackenzie Delta region; however, it lies within an area of shallower permafrost than PG3 with approximate depth being 300-400 m (Figure 1.1) (Todd 2014). Specifically, PG9 is located at the coordinates 68.8135 °N, 134.0317 °W, which is northwest of Reindeer Station. Aerial photographs from 1950, 1975, and 2013 indicate visible thermokarst activity in the area surrounding the lake, which is expected to have increased evidence of terrestrial flux (Figure 3.2).

1.4.5 Western Scotland

Western Scotland exhibits varying landscapes, from the rugged highlands to the sloping valleys. The area is one of the most western regions of Northern Europe and has a climate primarily shaped by the surrounding north Atlantic Ocean. The Hebridean Islands consist of a group of bounded systems that are the most southern of the North Atlantic archipelagoes, which experience a wide range of environmental conditions; temperate in the southern portion while the more northern islands exist at the Arctic boundary (Bishop et al. 2018).

1.4.6 Arran

The Isle of Arran is one of the Inner Hebridean Islands, located off the southwest coast of mainland Scotland (55° 34' 39.1656" N, 5° 12' 36.918" W). The island is of interest due to its transitional landscape; the northern and southern regions of the island vary greatly from one set of environmental conditions to another differing set. Steven and Dickson (1991) describe the northern areas as highlands (peaking at 974 m O.D.) with steep glaciated valleys; while, in contrast, the southern portion is characterized by low and rolling hills. Evidence of human recolonization after the Lateglacial suggests settlement occurred primarily in the southern regions, where the terrain was more easily traversed than the mountainous north (Robinson 1983; Steven & Dickson 1991). This landscape and human occupation distribution may provide an opportunity to research the co-linear variables of climate and anthropogenic impacts on aquatic systems.

1.4.7 Jura

The Isle of Jura is an Inner Hebridean Island located off the west coast of mainland Scotland (55° 53' 58.0884" N, 5° 56' 30.3792" W). The location, between the mainland of Scotland and Islay, situated Jura as an area of high human activity. For example, stone rings found on Jura have been dated to c. 6244 BCE, which is the oldest evidence of stone structures within Scotland, and additionally archaeological and paleoenvironmental evidence suggests extensive human activity of the island since the Mesolithic period (Mercer 1972; Mercer 1980; Storrie 1983; Edwards & Mithen 1995). Prolonged and intensifying human occupation since the Mesolithic period indicates Jura has experienced the direct impacts of human settlement for approximately the past 10000 years, and as such, it is an area of great interest within the context of co-linear variable paleoenvironmental research.

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CHAPTER 2 A REVIEW OF THE PALEOENVIRONMENTAL HISTORY OF WESTERN SCOTLAND: METHODS OF UNDERSTANDING THE INTERSECTION OF LATE-HOLOCENE ENVIRONMENTAL CHANGES AND HUMAN IMPACTS

2.1 Statement of Student Contributions

Review design by Alannah Niemeyer and Maarten van Hardenbroek van Ammerstol, chapter writing by Alannah Niemeyer with editorial contributions from Maarten van Hardenbroek van Ammerstol and Andrew Medeiros.

2.2 Abstract

The histories of environmental change and human occupation in western Scotland were explored through reviewing existing literature, by outlining climate variability and human occupation with reflections of the purposes of the paleoenvironmental proxies used to investigate each. Paleoenvironmental and archaeological evidence of human recolonization of Scotland after deglaciation suggests the Inner Hebridean Islands as areas of early and intense human activity. The impacts of human activity on the environment can be both direct and indirect, and it is often difficult to disentangle the relative importance of humans and climate when reconstructing past environments. We specifically investigate the Inner Hebridean Islands, such as the islands of Arran and Jura, which exhibit varying environmental and geographic conditions and high levels of human activity since the Mesolithic (Jura) and Neolithic (Arran) periods. Archaeological and paleoenvironmental evidence suggest human activity was often focused at lowland and coastal areas, while anthropogenic influences are much rarer at higher elevation. We

present this as a unique opportunity to produce independent climate records within areas of prolonged human occupation, yet with only very limited direct impact from human activities.

2.3 Introduction

Natural climate change throughout the Holocene has long been thought of as gradual (e.g., millennial), yet recent evidence suggests changes taking place at much shorter timescales (e.g., centennial) with a rapid pace previously not considered (Tipping et al. 2012; Walker & Lowe 2019). The observation of rapid change over shorter timescales would undoubtably have affected prehistoric human societies, exceeding a threshold (e.g., temperature thresholds) can have global impacts that can transform societies through the necessity of adaptation to changing conditions (Alley et al. 2003; Niemeyer et al. 2005; Holmes et al. 2011) Yet, Tipping et al. (2012) found the existing Scottish paleoenvironmental records and archaeological evidence did not allow for any significant testing of new hypotheses concerning the relationship between natural changes and human influence. Scottish reconstructions of Holocene climate variability are difficult to obtain due to the widespread and prolonged influence of human occupation (Saville & Wickham-Jones 2012; Tipping et al. 2012). Subsequently, if this clear knowledge gap is addressed it may elucidate the relationship between prehistoric societies and environmental changes in western Scotland, which could provide insight and context to archaeological evidence and could inform future adaptation to a world that is currently experiencing rapid warming.

One of the main principals of understanding past environments is the geological law of superposition, where the sequence of deposition will reflect an accurate chronology (youngest to oldest) of the environmental conditions at the time of a particular layer. In an ideal system, the principal of uniformitarianism would suggest that the processes that govern deposition would be the same in the past as well as the present.

Since deposition to lakes and bogs adhere to these principles, lake and peat sediments are often used as ‘storybooks of the past’, whereby chemical, physical, and biological indicators preserved in sediments can be used to provide insights to past environmental conditions of the site under consideration (Mayle et al. 1997; Brooks & Birks 2000; Lang et al. 2010; Walker & Lowe 2019; Engels et al. 2020). In particular, the nature of the allochthonous inputs that flow into lakes is strongly controlled by the characteristics and configuration of the drainage basin (Chique et al. 2018). The composition of the organic and inorganic materials within lacustrine sediments is therefore highly impacted by any environmental stressors in a lake’s catchment including the presence of humans, which may alter sedimentary nutrient levels through activities such as agriculture.

In order to disentangle natural and anthropogenic signals in paleoenvironmental records, a combination of proxy indicators is often required. Typically utilized proxies include pollen, plant macrofossils, charcoal, diatoms (siliceous algae), Chironomidae (chironomids), and Coleoptera (beetles) (Walker & Lowe 2019). Changes to the proxies are induced by various natural and anthropogenic signals; for example, chironomids are typically used to reconstruct July temperature (Birks et al. 1990; Eggermont & Heiri 2012), while diatoms have been widely used to reconstruct pH and nutrients (Jones et al. 1989; Birks et al. 1990; Battarbee et al. 2012). However, the entanglement of human and natural influences throughout the common era have created a challenge for proxy interpretation and signal tracing, which must be taken into account (Simpson & Anderson, 2009; Battarbee et al. 2012; McKeown et al. 2019).

The Inner Hebridean Islands, located along the western coast of Scotland, represent a potentially significant area of interest to understand how environmental change may have affected prehistoric human settlement, as the islands are a transitional landscape that has a long history of human activity. The Inner Hebrides have undergone landscape changes, such as the alterations to forest cover since at least the Mesolithic period (Bishop et al. 2018), as well as the landscape variances between locations on a single island (Steven & Dickson 1991); here, we use ‘transitional landscapes’ to describe such areas in which there is a change from one set of environmental conditions to another differing set of conditions over time and/or space. In relation to understanding the interactions of human and natural influences on an environment, transitional landscapes may provide a unique opportunity to disentangle these signals. The Inner Hebrides are noted to have some of the earliest evidence of prehistoric human occupation, including evidence of lithics, cave use, bone, pollen, and charcoal (Mercer 1980; Robinson 1983; Storrie 1983; Hardy & Wickham-Jones 2009; Saville & Wickham-Jones 2012). As such, the islands present a unique potential to understand the interference between natural environmental changes and those caused by human occupation and activity. The Scottish Archaeological Research Framework (ScARF) detailed extensive evidence of Mesolithic hunter-gatherer activity on the Inner Hebrides (Saville & Wickham-Jones 2012), of which we focus on archaeological sites that can potentially illustrate the recolonization of western Scotland after the Last Glacial maximum (Figure 2.1). For example, the first known stone structures (i.e., stone rings) within Scotland are dated to c. 6244 BCE and are found on the island of Jura (Mercer 1980). Additionally, extensive pollen and charcoal evidence of human activity during the Mesolithic period are found at the Machrie Moor site of the island of Arran (Robinson 1983). Arran has few coastal Mesolithic archaeological sites, while the southern regions have many documented sites with evidence of human activity (Steven & Dickson 1991). Thus, this area presents a unique opportunity to examine both natural environmental change and human impacts in Scotland over the past ~6000 years. Moreover, evidence suggests that on the Outer Hebridean Islands, were some of the first areas to transition to Neolithic agricultural-based societies within Scotland (c. 3800-3600 BCE) (Bishop et al. 2018), which provides regional context to a time-scale of anthropogenic development (e.g., settlement & agriculture) and may illuminate the impacts of both human activity and climate variability throughout Scotland's prehistory. Consequently, focus on this distinctive region may present a unique potential to understand the interference between natural environmental changes and those caused by human occupation and activity, if we are able to detangle the boundary between what is natural and what is anthropogenic.

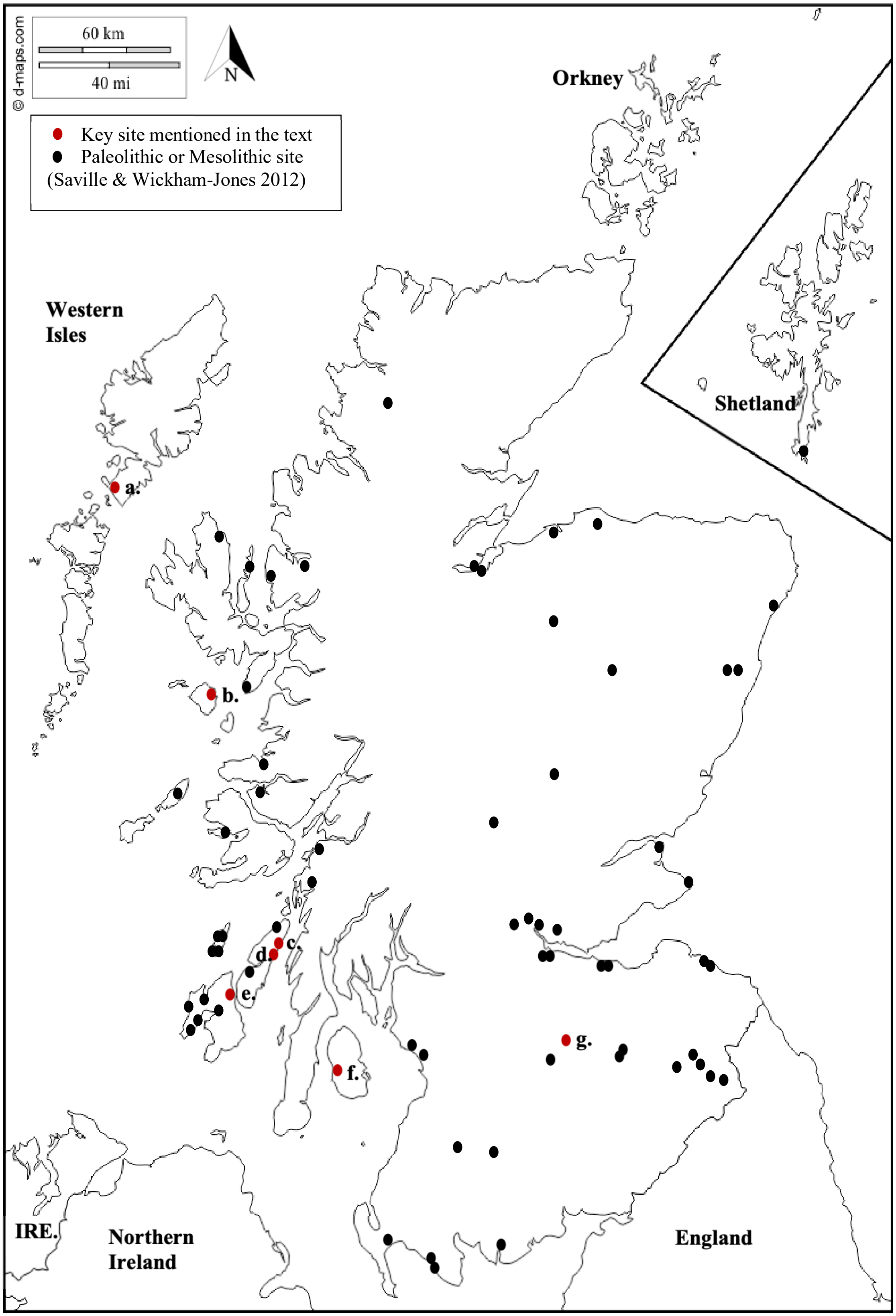
© d-maps.com
60 km
40 mi
N
● Key site mentioned in the text
● Paleolithic or Mesolithic site
(Saville & Wickham-Jones 2012)
Orkney
Western Isles
Shetland
a.
b.
c.
d.
e.
f.
g.
IRE.
Northern Ireland
England

Figure 2.1 Selected archaeological sites of Scotland that illustrate early Scottish recolonization, while demonstrating the potential regional influences of the Atlantic Ocean as well as local impacts from prolonged human occupation. This region is of interest due to the relatively high concentration of prehistoric archaeological sites (Saville & Wickham-Jones 2012), and lack of many high-resolution paleoenvironmental records. Here, key sites discussed in the text include; a.) Northton, Harris (Gregory et al. 2005); b.) Kinloch, Rùm (Wickham-Jones 1990); c.) Lealt Bay, Jura (Mercer 1972); d.) Lussa Wood, Jura (Mercer 1980); e.) Rubha Port an t-Seilich, Islay (Mithen et al. 2015); f.) Machrie Moor, Arran (Robinson 1983); and g.) Howburn Farm, mainland Scotland (Ballin et al. 2010).

Scotland experiences the culmination of marine, terrestrial, and atmospheric climatic processes in the North Atlantic region, as it is situated on the fringe of the Atlantic Ocean. During the Holocene the North Atlantic thermohaline circulation, meltwater flux from deglaciation, and solar variability are all considered driving forces of regional environmental changes; all of these factors are interconnected, for example during the Younger Dryas increases in solar radiation contributed to deglaciation that then caused meltwater fluxes from Hudson Bay and Greenland into the North Atlantic Ocean, ultimately impacting the thermohaline circulation (Debret et al. 2009; Brooks et al. 2012b). While well-known regional trends are useful for interpretations, Brooks et al. (2012b) have suggested that a regional application of less established paleoenvironmental research may not be applicable as they found local variations within studies from Greenland, Norway, and Scotland. Thus, direct focus on a study region, such as the Hebrides, allows for an understanding of the interactions of the co-linear variables of climate and humans at a meaningful high-resolution. Specifically, co-linear variables refer to the entanglement of human and natural signals within the paleoenvironmental record; sites that have a long history of human occupation are often difficult to obtain records from that show climate signals without any human interference. Bennion et al.

(2004) note that low-elevation shallow lakes are particularly susceptible to human impacts within Scotland, and therefore complicate research seeking climate signals that are not impacted by prehistoric human activity. Jones et al. (1993) support the previous argument, as they indicate alpine lakes are less susceptible to anthropogenic land-use, such as the impacts of livestock grazing. Additionally, Thompson et al. (2005) discuss the importance of remote aquatic systems as time-capsules of natural climate variability, due to reduced direct anthropogenic influence. Thus, the specific focus of this review is concerned with the Inner Hebridean Islands (e.g., Arran and Jura), as these sites have extensive evidence of human occupation since the Mesolithic period, and lakes with small catchments that are located in areas of high elevation have been identified. As such, these sites suggest potential locations with historically low human impacts due to limited accessibility. Lacustrine proxy reconstructions from sites with low levels of human activity, yet a long history of human occupation, may offer insights to the influence of climate variability during the Holocene. To address the suitability and necessity of paleoenvironmental research on closing the knowledge gap concerning late Holocene landscape changes related to natural and human impacts on the environment, we specifically; 1) review environmental change experienced throughout prehistoric Scotland, 2) outline the known history of human occupation and impacts on the Inner Hebridean Islands (e.g., Arran and Jura), and 3) review of the methods of paleoenvironmental inquiry with a critical examination of how co-linear variables discussed may be elucidated in the context of human settlement of Scotland. These examinations make no pretence of being exhaustive, rather they serve the purpose of presenting the image of changes the region has experienced while highlighting the Inner

Hebridean Islands as sites of interest. Consequently, this review of the paleoenvironmental and archaeological histories of western Scotland serves as an important piece of literature that fills the knowledge gap concerning how rapid environmental change during the late Holocene has influenced prehistoric human settlements, which is then expanded upon to ultimately create a greater understanding of the methods needed to detangle co-linear variables within chronological records.

2.4 Climate Variability During Scotland's Prehistory

The position of Scotland within the north-east of the Atlantic Ocean means it is highly sensitive to long-range climate cycling which, when coupled with the relatively long history of human occupation, suggests large impacts of climate on human populations in the region (Tipping et al. 2012). This argument has been supported by existing prehistoric climate and vegetation records, and archaeological evidence of long-term human presence (Figures 2.2 & 2.3). Tipping et al. (2012) is also an advocate for future research in Scotland on the basis of a paucity of Scottish records, and the possible risk of interpreting data from adjacent regions as a reference for Scotland. For example, Brooks et al. (2012b) examined Lateglacial and early Holocene air temperature reconstructions which utilized chironomids as a proxy but was forced to calibrate the record with a Norwegian dataset due to the absence of a modern set from Scotland. The use of the Norwegian set to calibrate Scottish records is not harmful to the results of the study, such as its successful application at Whitrig Bog due to the expected parallel temperature ranges of the modern Norwegian set and the Lateglacial to Holocene transition in

Scotland (Brooks 2006). Yet, greater strength and confidence in the conclusions could be achieved if more geographically relevant data was available.

Scotland experiences regional and local influences on climate; regional impacts are sourced from atmospheric transport, solar variability, deglaciation, and the marine circulation (e.g., the North Atlantic thermohaline circulation), while in contrast local influences include direct and indirect anthropogenic activity (e.g., agriculture) as well as hydrology and weather (e.g., the local precipitation regime). Due to the large-scale regional influences experienced by Scotland, considerations of surrounding areas can be useful in the absence of Scottish records. However, the need for site-specific research cannot be ignored and is supported by Coope & Lemdahl (1995) who conclude, through analyses of coleopteran records, that climatic variations in Northern Europe are varied in both space and time (Figure 2.2).

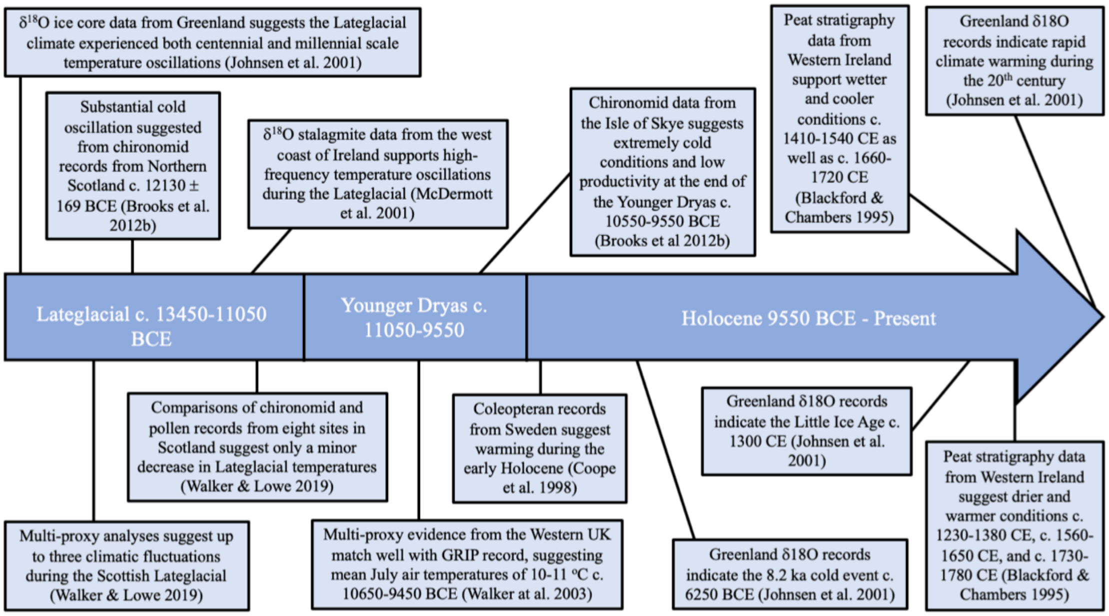

Figure 2.2 Broad timeline of climate variability within Scotland and the wider Northern European region, featuring evidence mentioned within the text. The divisions of time are based upon Scottish records from the ScARF reports (Saville & Wickham-Jones 2012).

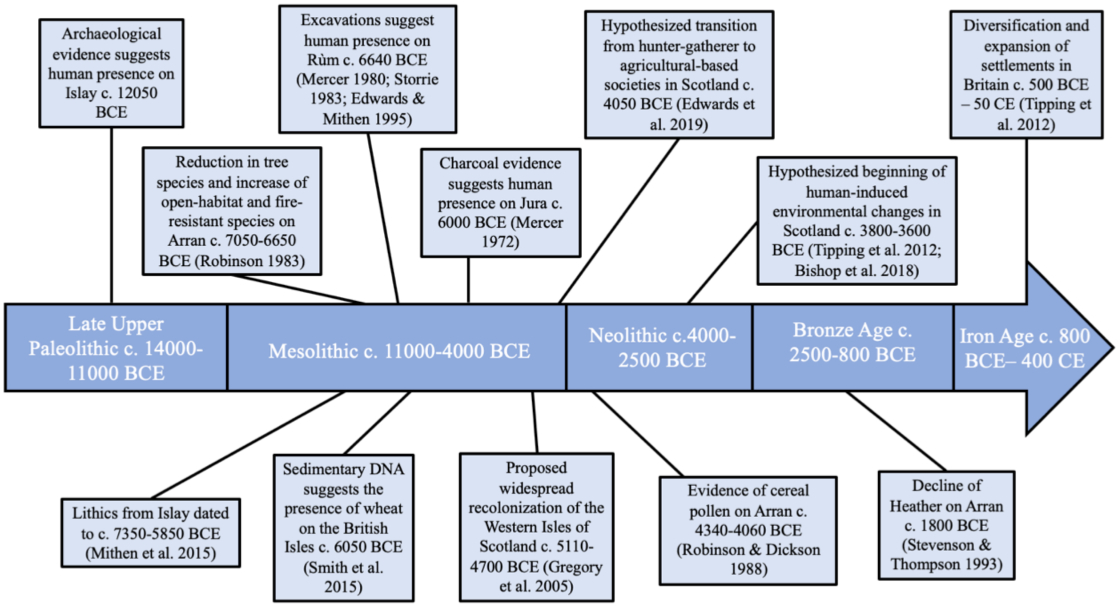

Figure 2.3 Broad timeline of primary points of human recolonization of Scotland after deglaciation, featuring evidence mentioned within the text. The divisions of time are based upon Scottish records from the ScARF reports (Saville & Wickham-Jones 2012).

2.4.1 Lateglacial

Some of the most significant climate data available for the North Atlantic region comes from the Greenland Ice Core Project (GRIP). Records of ice cores from Greenland utilize oxygen analysis ($\delta^{18}O$), borehole temperature profiles, and Monte Carlo Simulation methods in order to reconstruct Lateglacial and Holocene temperatures (Johnsen et al. 1972; Dansgaard et al. 1982; Dansgaard et al. 1993; Grootes et al. 1993; Johnsen et al. 2001). $\delta^{18}O$ data suggests the Lateglacial experienced both centennial and millennial scale temperature oscillations with a strong signal of temperature inversions (Johnsen et al. 2001). Within the context of Ireland, McDermott et al. (2001) investigated the timescale of climatic oscillations in the North Atlantic region through $\delta^{18}O$ analysis of a stalagmite from the west coast of Ireland; concluding that variations in $\delta^{18}O$ support high frequency (i.e., centennial scale) regional oscillations that may have greater influence on the region than low frequency events. While regionally relevant, McDermott et al. (2001) is also significant as there are no $\delta^{18}O$ analyses within the local Scottish context, as such this study serves as one of the most geographically applicable high-resolution reconstruction of Holocene climate variability. Additionally, a substantial cold oscillation during the Lateglacial (c. 12,130 ± 169 BCE) is recorded in chironomid-inferred temperatures from Scotland, which also matched with the GRIP and North Greenland Ice Core Project (NGRIP) ice core records (Brooks et al. 2012b). This provides some support for comparability between North Atlantic records, mostly likely due to large-scale atmospheric and oceanic cycling within the region, such as the North Atlantic Thermohaline. However, Walker & Lowe (2019) compared eight Scottish and English chironomid and pollen records and found notable deviations between the local UK and the regional Greenland records. For example, a minor decrease in Lateglacial Interstadial temperatures was noted, which contrasts with the lasting decrease observed in the Greenland $\delta^{18}O$ records (Walker & Lowe, 2019). Additionally, high-resolution chironomid and $\delta^{18}O$ data (Matthews et al. 2011; Brooks et al 2012b; Candy et al. 2016) suggest the possibility of up to three climatic fluctuations during the Scottish Lateglacial Interstadial, namely mild ice-free conditions c. 12050 BCE, which is followed by two colder oscillations that broadly match the GI-1d and GI-1b records from Greenland (Walker & Lowe, 2019). Consequently, there is significance in the role of local records to ultimately determine the state of climate variability throughout time; as such, a greater understanding of how the regional natural climatic fluctuations relate to local variability on Hebrides would require site-specific records.

2.4.2 Younger Dryas

The Younger Dryas Stadial (c. 11050-9550 BCE) ended as the Holocene began and, therefore, serves as one of the final barriers to human recolonization of Scotland due to the rapid return to a glacial climate before the sudden warming of the Holocene allowed for human settlement (Figures 2.2 & 2.3) (Hubbard 1999; Saville & Wickham-Jones 2012; Tipping et al 2012). For Scotland, the Younger Dryas is typically accepted as a time of colder temperatures than observed today with records suggesting an overall decrease of 8 ^{o}C from the Lateglacial (c. 13450-11050 BCE) (Saville & Wickham-Jones 2012). This period was accompanied by the formation and advancement of an ice sheet in the highland regions of western Scotland with a central ice cap and peripheral ice fields, which then experienced rapid deglaciation due to increasingly warming temperatures at the beginning of the Holocene (Hubbard 1999; Golledge 2010).

Our knowledge of the Holocene in Scotland is enhanced by research using paleolimnological techniques. For example, a multi-proxy study conducted in the western UK comparing itself to the GRIP record indicated a decline in temperatures, with mean July air temperatures estimated at 10-11 ^{o}C between 12600-11400 cal yr BP c. 10650-9450 BCE (Walker et al. 2003). Using chironomid-inferred temperature modeling within the highlands of Scotland, Brooks et al. (2012b) found indicators of extremely cold (3-5 ^{o}C) and low productivity conditions on the Isle of Skye at the end of the Younger Dryas (c. 10,550-9,550 BCE), which was then followed by rapid warming and increases to productivity during the early Holocene at both study sites. A multi-proxy study conducted in the western UK comparing itself to the GRIP record indicates a possible decline in temperatures, with mean July air temperatures estimated at 10-11 °C between 12600-11400 cal yr BP c. 10650-9450 BCE (Walker et al. 2003). The western UK, GRIP, and Scottish records correspond relatively well and strengthen the hypothesis of a relatively cool Younger Dryas prior to Holocene warming. Reconstructions using paleolimnology established intense climate variability of prehistoric western Scotland, particularly within the highland regions that would have been a barrier to human occupation.

2.4.3 Holocene

$\delta^{18}O$ records from Greenland indicate climate signals for rapid temperature oscillations in the early Holocene, the 8.2 ka cold event, the Little Ice Age (c. 1550-1850 CE), and climate warming during the 20th century (Johnsen et al. 2001); while more recent tree-ring and speleothem data provide evidence for a warm period known as the Medieval Climate Anomaly (c. 1100-1400 CE) (Trouet et al. 2009; Rydval et al. 2017). Regionally the Holocene saw early high-frequency temperature fluctuations with increased warming compared to the previous period, with cold events near the mid Holocene, and ultimately rapid warming in recent history (Figure 2.2). This is regionally supported by coleopteran records from Sweden, which have shown resemblance to other northern European records, that indicate rapid warming during the early Holocene (Coope et al. 1998). Additionally, a comparison between chironomid and bog-surface-wetness records from northern England also suggest the mid to late Holocene was characterized by a cooler and wetter climate than previously observed at the centennial to millennial scale (Barber et al. 2013). Results from a western Ireland peat stratigraphy (humification) study also suggests a general trend of an oscillating proxy climate record within the later Holocene; where wetter (cooler) conditions are indicated in the periods of 1410-1540 CE, and 1660-1720 CE, while drier (warmer) conditions are indicated for the periods of 1230-1380 CE, 1560-1650 CE, and 1730-1780 CE; additionally, these periods are supported by other existing records (e.g., the Little Ice Age) (Blackford & Chambers 1995). This characterization of the Holocene climate regime in the North Atlantic is supported by Tipping et al. (2012) whom describe episodic variations in temperature with rapid changes on centennial timescales. While general trends have been accepted as applicable to all of Scotland, site-specific influences cannot be overstated, and as such, determining the extent and timing of changes during the Holocene requires an exploration of local records. In order to achieve an examination of later Holocene climate variability specific to Scotland, records must be from sites with little to no human activity (e.g., remote, high elevation sites), otherwise the impacts of the long history of anthropogenic settlement in the region may override results relating to climate signals.

2.5 Scottish Colonization and Human Influences on the Environment

An exploration of both archaeological and paleoenvironmental evidence of early recolonization, the transition to agricultural-based societies, and later Holocene settlement are important considerations that allow local exploration of the extent to which anthropogenic influences impact local environmental change (Figure 2.3). Tipping et al. (2012), through examination of Scottish prehistory climate (c. 4000 cal BCE to c. 50 cal

CE), found connections between Holocene rapid climate change and the response of humans; consequently, it serves as an important review to bridge the work of paleoenvironmental and archaeological research. Building upon this important intersection of paleoenvironmental research and archaeological exploration we seek to broadly outline significant sites of human evidence in order to contextualize the long-term history of human occupation in western Scotland (Figures 2.1 & 2.3).

2.5.1 Early Recolonization and Impacts

Postglacial Scottish recolonization has a long history of human impact, likely beginning during the Lateglacial (13450-11050 BCE). Some of the earliest evidence of occupation belongs to the Inner Hebridean Islands; the earliest being lithics found on Islay along with charcoal and animal bone evidence, all of which dated to the Lateglacial (c. 7350-5850 BCE) (Mithen et al. 2015). Mercer (1980) claimed to have found tanged points on the island of Jura that suggest a Lateglacial occupation; but others have refuted this claim due to the rolled and broken nature of the artefacts (Edwards & Mithen, 1995). However, excavations on the island of Rùm discovered Mesolithic artefacts dated to c. 6640 BCE, while other sites dated to a similar time can be found on Jura (Mercer 1980; Storrie 1983; Edwards & Mithen 1995). Thus, the nature of archaeological discovery requires multiple independent excavations in order to reliably establish human presence. As such, archaeological midden discoveries with charred hazelnut remnants provide evidence to support pollen records that suggest larger Mesolithic colonization of the Western Isles of Scotland occurred c. 5110-4700 BCE (Gregory et al. 2005). Specifically, pollen and charcoal evidence from Machrie Moor, the island of Arran, suggest a Mesolithic human population, with a relatively high level of activity intensity maintained throughout prehistory (Robinson 1983). Charcoal evidence from a stone hearth on Jura is dated to c. 6000 BCE, which also suggests a human presence during the Mesolithic period (Mercer 1972). Some of the strongest evidence, supported by archaeological artefacts, radiocarbon dating, and known cultural history, is from Islay where it is has recently been indicated that there was a human presence c. 12050 BCE (Walker & Lowe 2019). Despite the somewhat contradictory conclusions concerning specific timing of re-introduction, the Hebrides have multiple examples of independent records and excavations that suggest evidence of Mesolithic populations, which support hunter-gatherer activity in the region before the transition to the Neolithic Period.

2.5.2 Agriculture and Land-Use

The transition from hunter-gatherer (Mesolithic) to agriculture-based (Neolithic) societies is argued, based on the presence of cereal pollen, to have occurred after c. 4050 BCE within the UK (Edwards et al. 2019). However, recent evidence based on sedimentary DNA suggests a presence of wheat in the British Isles c. 6050 BCE, which is possibly due to trade, and implies the existence of oceanic trade within Europe (Smith et al. 2015). While the true nature of the transition is not fully understood, evidence suggests strong Mesolithic-Neolithic human influence and land-use within the UK, which ultimately leads to established agriculture-based communities.

For Scotland, it is typically agreed that human-induced environmental changes began during the Neolithic period (c. 3800-3600 BCE) due to the introduction of agriculture resulting in deforestation (Tipping et al. 2012); yet others suggest woodlands may have survived much longer, with a prolonged lag effect (Bishop et al. 2018). Consequently, the true impact of humans on the decline of woodlands on the Scottish islands is not certain. Robinson & Dickson (1988) claim to have found the earliest evidence of cereal pollen at Machrie Moor, Arran, dated to c. 5375 yr BP (c. 4340-4060 BCE). Bishop et al. (2018) also concluded the explosion of agriculture in Scotland began by some of the earliest farmers settling in the Western Isles. As such, multiple sets of independent evidence support a relatively early transition to agricultural-based societies on the Hebrides. In the case of land-use and forest clearing Robinson (1983) suggests Mesolithic populations on Arran had a large impact on the vegetation of the island, as pollen evidence supports a reduction of tree species and an increase of open-habitat and fire-resistant species. The reduction of tree species is of particular interest as at the time (c. 7900 radiocarbon yr BP [c. 7050-6650 BCE]) the extent of the post-glacial forest is considered to be near maximum; yet, at Machrie Moor tree species pollen constituted less than 50 % of the total taxa (Robinson 1983). However, this conclusion should not be treated as absolute, as the absence or decrease of tree species' pollen has been described as possibly misleading through comparisons with plant macrofossils that have provided support for the presence of trees in regions with little pollen evidence (Tipping 1991). Thus, evidence from Machrie Moor on Arran may support the influence of Mesolithic humans on the landscape. However, these conclusions of tree decline on Arran are based only on pollen records and may not appropriately represent the true nature of tree distribution; the addition of other independent proxies could strengthen these results.

2.5.3 Contemporary Considerations

The later Holocene (specifically c. 500 BCE to c. 50 CE) is characterized by the expansion and diversification of settlements in Britain (Figure 2.3) (Tipping, 2012). Late Holocene lacustrine pollen analysis from Arran found a steady decline of heather species beginning c. 1800 BCE (Stevenson & Thompson 1993). Stevenson & Thompson (1993) hypothesize that this relatively recent Holocene landscape change is caused by grazing and burning intensity increasing, with contemporary anthropogenic climate change exacerbating the changes rather than initiating them. As such it has long been accepted that humans possess the ability to affect the Earth's climatic regimes, with pronounced impacts in recent decades, yet the intricacies of the interaction of climate and direct human influence seem to be much more complex and require high-resolution investigation.

2.6 Scottish Climate Variability Proxy Reconstructions

Within the Scottish context proxy records serve a vital role of determining past environmental conditions through reconstructions. Chironomids, pollen, plant macrofossils, coleopteran fossils, and diatoms are typically selected as proxies used to reconstruct environmental and climatic variability throughout time. Effective proxy reconstructions of climate variability are necessary, particularly within the context of the Hebrides in Scotland as the long history of human occupation can serve as a confounding variable, thereby making independent climate records of reference or pristine sites vital to understanding climate variability during the expansion of human populations throughout the Holocene. Significant examples of reconstructions throughout Scotland will be explored for their purpose, strength of results, and possible challenges; specific uses of proxies include, reconstructing past air temperatures, interpreting changes in vegetation, and understanding changes in water quality (Table 2.1).

Table 2.1 A selection of the various proxy reconstructions from Scotland and Northern Europe, presented within the contexts of climate variability, landscape and land-use changes, and human influence on the environment.

Proxy Indicator(s)	Reference	Region	Main Theme of the Reconstruction	Time Period
Charcoal & Pollen	Froyd 2006	Scottish Highland lakes: Loch an Amair, Dubh-Lochan, Lochan na h-Inghinn, Reidh-Lochan	Fire regime and land-use changes	Holocene with ages ranging from c. 12300 BCE- 1200 CE
Chironomids	Brooks et al. 2012b	Lakes from western and eastern Scotland: Loch Ashik, Isle of Skye, and Loch Garten, Abernethy Forest	Air temperature	Lateglacial and early-Holocene
Chironomids	Brooks & Birks 2000	Whitrig Bog, Southeast Scotland	Air temperature	Lateglacial
Chironomids	Engels et al. 2020	837 lakes within the Northern Hemisphere	Air temperature	Last Glacial-interglacial transition (c. 13050-9050 BCE
Chironomids	Lang et al. 2010	Five lake sites in north-west England; Hawes Water, Little Hawes Water, Urswick Tarn, Cunswick Tarn, and Sunbiggin Tarn	Climate reconstructions	Lateglacial and early Holocene
Chironomids	Potito et al. 2014	50 lakes in western Ireland	Air temperature	Modern
Chironomids & Pollen	Chique et al. 2018	Lough Muckno, northeast Ireland	Eutrophication	Late Holocene (c. 1790-2013 CE)
Coleopteran	Coope & Lemdahl 1995	Northern Europe; Britain, Norway, Poland, and Sweden	Air temperature	Lateglacial
Coleopteran	Coope et al. 1998	77 sites across Northern Europe	Climate reconstructions	Last Glacial-Holocene transition (c. 12050-7050 BCE)

Coleopteran	Elias & Matthews 2014	Four sites in the British Isles; St. Bees, Cumbria; Gransmoor, East Yorkshire; Glanllyau, North Wales; and Llanilid, South Wales	Air temperature	Lateglacial- early Holocene (c. 12950-8550 BCE)
Coleopteran, Pollen, & Plant Macrofossils	Walker et al. 2003	Llanilid, South Wales,	Air temperature	Lateglacial- early Holocene (c. 13050-8050 BCE)
Diatoms	Bennion et al. 2004	26 lakes across Scotland	Eutrophication	Late Holocene (c. 1850-1999 CE)
Diatoms	Jones et al. 1993	Five lakes in the Cairngorm and Lochnagar areas of Scotland	Acidification	Late Holocene (c. 1868-1986 CE)
Diatoms & Pollen	Pennington et al. 1972	11 lakes in northern Scotland	Water quality	Lateglacial-Holocene
Diatoms & Pollen	Jones et al. 1989	Round Loch of Glenhead, southwest Scotland	Acidification	Lateglacial-Holocene (c. 7750 BCE- 1984 CE)
Pollen	Stevenson & Tompson 1993	28 Lakes in upland Britain and Ireland	Land-use changes	Late Holocene (c. 1400-1988 CE)
Pollen	Robinson & Dickson 1988	Machrie Moor, Arran, Scotland	Vegetation and land-use reconstruction	Holocene (c. 8050 BCE-1450 CE)
Pollen	Tipping 1991	Pulpit Hill, Oban, western Scotland	Vegetation changes and climate reconstruction	Lateglacial
Pollen, Charcoal, & Plant Macrofossils	Bishop et al. 2018	Western Isles of Scotland	Landscape changes	Neolithic-early Bronze Age

Pollen, Charcoal, & Plant Macrofossils	Edwards & Mithen 1995	Hebridean Islands of Western Scotland	Human colonization	Holocene (c. 10480-5050 CE)
Pollen & Plant Macrofossils	Mayle et al. 1997	Whitrig Bog, southeast Scotland	Vegetation and landscape changes	Lateglacial

2.6.1 Interpreting Past Air Temperature

One of the primary indicators of climate variability over time is the estimation and modelling of air temperatures based on proxy records (Table 2.1). Chironomids, coleopteran, pollen, and plant macrofossils are noted for sensitivity to environmental factors, including temperature, which provides a useful indicator of temperature changes over time through the identification and enumeration of specimens within a sediment record (Mayle et al. 1997; Luoto et al. 2016; Engels et al. 2020).

A comparison of a chironomid inferred mean July air temperature record from Whitrig Bog, Scotland, with the GRIP δ^{18}O reconstruction suggests a substantial similarity; specifically the records suggests thermal oscillations during the Lateglacial followed by a decrease of approximately 3.7 °C during the Younger Dryas, until an ultimate rapid increase of temperature at the beginning of the Holocene (Brooks & Birks 2000). Comparisons between coleopteran records and the Greenland ice cores demonstrate the same high-frequency changes in global temperatures (Coope et al. 1998; Elias 2013; Elias & Mathews 2014). However, Brooks & Birks (2000) compared several Lateglacial Scottish proxy records and determined the coleopteran climate reconstruction only broadly matched other records, while, in contrast, chironomid and plant macrofossil temperature data were much more similar to existing records. Thus, the use of coleopteran records in conjunction with additional proxies can provide a temperature reconstruction with increased confidence, yet barriers of expertise and suitability (e.g., coleopteran analysis requires great amounts of material) within Scotland still exist (Walker & Lowe 2019). Specific thermal regimes can also be ascertained through proxy reconstructions; Mayle et al. (1997) found birch tree pollen at Whitrig Bog, and while it lacks specific dating it was found within the second deepest Lateglacial zone of the chronology, which is well below the intermediate c. 8980-8210 BCE date of the peat core. Despite a lack of birch tree macrofossils from the zone weakening the evidence, if birch woodlands were present at the time the mean July air temperatures at Whitrig Bog must have been greater than 10 °C as that is the known lower temperature threshold for the species (Mayle et al. 1997). Thus, proxy reconstructions can be capable of both coarse and fine estimations of past temperatures, which is significant as they can be useful as an indicator of prehistoric climate variability that is independent of human activity.

A method to attempt to combat the issue of site-specific variations is the use of multiple records (multi-parameter reconstructions) from a specific geographic area, which may allow for increased probability of high-resolution results. Brooks et al. (2012b) investigated Scottish early Holocene air temperatures through analyses of chironomids from Loch Ashik, Isle of Skye, and Loch Garten, Abernathy Forest, which found similarities between the temperature oscillations at the sites but also noted differences caused by site-specific conditions. For this reason, Tipping (1991) examined two cores from Pulpit Hill, Scotland, using the pollen proxy method, and noted the significance of multiple sequences when determining the presence of climatic fluctuations or oscillations, which can also be enhanced by the addition of supplementary proxies (e.g., plant macrofossils). Similarly, Lang et al. (2010) demonstrated the importance of the use of multiple records through analyses of five lakes in northwest England, where slight differences in the Lateglacial climate records are attributed to local geography and the characteristics of each lake catchment, although a clear pattern emerges that is similar in all five records. Eggermont & Heiri (2012) note that while temperature is known to be one of the main influences on chironomid taxa distribution, additional variables (e.g., pollution and nutrient loading) can also impact communities, particularly in shallow lakes. Similarly, Stevenson & Thompson (1993) comment that a common challenge with pollen records is the uncertainty of the source, that is, the inability to determine if pollen samples are site-specific or rather carried from farther distances. Moreover, this long-range transportation characteristic of pollen records is argued to unnaturally inflate temperature records if not considered with other independent proxies, like chironomids or plant macrofossils (Brooks & Birks 2000). Charcoal analyses often face a similar challenge; Edwards & Mithen (1995) describe how wind transport might have affected charcoal records on the Inner Hebridean Island of Islay, but Froyd (2006) indicates that this can be circumvented by distinguishing macroscopic charcoal remains, which are too heavy for wind transport and are much more likely to represent a local source. These studies establish the significance of local influences on proxy indicators and the increased confidence in results that comes from multiple proxy-reconstructions within a site; the influence of site-specific environmental conditions on proxy indicators is a significant variable when considering the value of reconstructions. Consequently, this supports multiple sites to be considered within the context of understanding the intersections of climate variability and long-term human occupation.

2.6.2 Vegetation Changes

Reconstructions of past vegetation communities surrounding lacustrine catchments can offer insights to past environmental conditions (Table 2.1). Pollen analyses methods, consisting of enumeration and identification of pollen to model woodland decline, were utilized to investigate changes in forest cover on the Hebrides, which are noted to have relatively open landscapes at present, but which supported expansive birch and hazel forests during the Mesolithic period (Bishop et al. 2018). Edwards & Mithen (1995) also suggest an expansion of birch and hazel woodlands c. 9120 BCE based on increasing pollen levels within the sediment record from Loch a'Bhogaidh, western Islay. Similarly, Mayle et al. (1997) analyzed pollen and plant macrofossil records from Whitrig Bog in Southeast Scotland to determine Lateglacial landscape and vegetation changes; a succession of the landscape was determined, with the transition from a barren environment to rich birch forest with juniper scrubland (c. 11050-9050 BCE), which was then followed by the colder conditions of the Younger Dryas causing an expansion of Arctic and alpine vegetation. Pollen as a proxy for vegetation changes was also used by Jones et al. (1989), who examined Round Loch of Glenhead, southwest Scotland, and found indications of at least six distinct pollen assemblage zones throughout the Holocene with a noticeable increase in anthropogenic disturbance indicator species during the later Holocene (c. 3450-2250 BCE). Consequently, the agreement between these independent paleoenvironmental proxy reconstructions of vegetational histories in Scotland demonstrate the reliability and strength of their results in relation to environmental changes.

Plant macrofossils serve as a strong source of evidence as the method is accepted as a reflection of the immediate vegetation, lacking the previously stated uncertainty of transportation that is linked with pollen records (Brooks & Birks 2000). Tipping (1991) also argues for the importance of plant macrofossil data in relation to pollen records through the example of tree pollen, where a review of multiple studies from the UK, such as pollen and macrofossil records from Ballaugh, Isle of Man, revealed that low tree pollen percentages did not necessarily indicate a lack of trees as macrofossil evidence of tree species was also found. Thus, the reconstructions of past vegetational communities using plant macrofossils found within the strata, indicate local presence as long-range dispersal is unlikely. Thus, macrofossils are preferably used as an additional line of proxy evidence to strengthen the confidence in local presence and abundance of past vegetation as well as other proxy reconstructions.

2.6.3 Water Quality Changes

Another line of evidence examined through paleoenvironmental proxies is changes to the water quality within a lake, which can be difficult to obtain natural records from as the degree of anthropogenic impacts versus climate influences are not easily detangled. However, high elevation remote lakes can help eliminate the noise within reconstructions. Jones et al. (1993) examined five northern Scotland alpine sites with no direct human influence using diatom analyses and found a clear atmospheric acidification signal that began during the mid 19th century. Specifically, three of the alpine lakes indicated acidification (0.5-0.8 pH unit change) beginning between c. 1842-1885 CE, while the fourth lake indicated early (pre-19th century) acidification that remained constant (pH 5.0) until the present day, the fifth lake also supported severe acidification (pH decline of 6.4-4.9) but was unable to be dated (Jones et al. 1993). Diatoms have also been used to reconstruct Lateglacial and early Holocene pH of Round Loch of Glenhead in southwest Scotland; results suggest this lake was acidic (pH 5.3-5.9) until c. 2050 BCE, which demonstrates the investigative potential of diatom analysis in the context of uncovering pre-industrial natural influences and changes lakes may experience (Jones & Stevenson 1980; Jones et al. 1989). These examples of drastic changes in pH may also result in changes to the chironomid assemblage that are not related to nutrient content alterations. Moreover, these results were surprising and considered an outlier for the British Isles, which were typically alkaline at that time, and thereby serve as an example of the need for local research to enable greater understanding of Lateglacial and Holocene environmental conditions (Jones & Stevenson 1980; Jones et al. 1989). Pre-recolonization (Lateglacial-early Holocene) records are valuable to reconstructing water quality, while within the context of Scotland, highlands and alpine lakes can be useful to examine natural trajectories with minimal direct anthropogenic influence.

2.7 Scottish Proxy Reconstructions of Human Recolonization

Pollen analyses have been described as positively associated with detecting evidence of prehistoric human settlement due to the continuous nature of the pollen record; thereby providing a relatively broad picture of human occupation over time at a specific site (Edwards & Mithen 1995). Notably, one of the most effective uses for proxy reconstructions of human activity is to couple the record with archaeological evidence, which can remedy persisting challenges in each field of study (e.g., the unknown origin of pollen in lacustrine sediments and understanding the climate and environmental changes past societies experienced), through the comparison of independent lines of evidence, subsequently strengthening the results and conclusions of both. Tipping et al. (2012) exemplify this argument through their review of human reactions to rapid climate change, which advocates to bridge the gap between paleoenvironmental and archaeological evidence. In the context of the Hebridean Islands' long history of human occupation since deglaciation, paleoenvironmental records capable of discerning anthropogenic signals can be used in areas of known long-term occupation to understand the intersection of human activity and climate variability; anthropogenic caused land-use and environmental changes (e.g., agriculture, burning, and nutrient loading) will all be explored in the following sections.

2.7.1 Anthropogenic Land-use and Agriculture Changes

One of the primary relationships utilized to interpret proxy reconstructions in relation to human activity is landscape changes and evidence of agriculture. In fact, human activity within a region with prolonged human occupation, such as Scotland, can often cause noise within a reconstruction, that if ignored may weaken the overall conclusions. Edwards et al. (2019) describes the uncertainty of Scottish charcoal analyses from the Mesolithic-Neolithic transition, where the decline of charcoal evidence has been attributed to wetter conditions, yet that hypothesis fails to consider the interactions of the rise of agriculture with forest decline and increased land-use and control by prehistoric populations. Thus, considerations of the impacts of human activity on the surrounding landscape are vital. Plant macrofossil and charcoal evidence from Neolithic sites located in the northern reaches of the Hebridean Island of Lewis provide insights to the relationship between prehistoric humans and the decline of woodlands; cereal cultivation is hypothesized to have been restricted to a permanent plot of land and would therefore not result in widespread deforestation (Bishop et al. 2018). Additionally, plant macrofossil records can indicate more precise conclusions such as evidence that Neolithic humans at the site primarily utilized small branches of deciduous trees for fuel, while larger pieces of timber were consumed as building materials (Bishop et al. 2018). Subsequently, detailed proxy reconstructions of human activities and influence on the environment serve the purpose of contextualizing results and allowing greater understanding of the mechanisms behind the changes observed within sedimentary records.

2.7.2 Lacustrine Water Quality Changes

Within Scotland, the use of diatoms as environmental indicators was pioneered during the 1970's through a multi-parameter study that reconstructed the histories of 11 lakes (Pennington et al. 1972). The significance of diatoms lay within the ability to understand the quality of the aquatic system through diatom responses to variables such as pH, nutrients, chloride, and calcium, which often vary due to direct human activity (Pennington et al. 1972). Building upon that work, the development of lake histories for Scottish sites would allow for a unique picture of the nutrient and chemical changes within the immediate catchments, which can be linked to the impacts of human's activities. This would create a history of human influence for a particular system that can be used to contextualize the results and conclusions of other independent records, especially climate variability reconstructions. For example, the known long-term human presence in Scotland should be detectable through the changes to diatom communities from possible terrestrial inputs such as effluent and agricultural run-off; this is typically achieved through diatom transfer functions that reconstruct total phosphorus concentrations for catchments (Bennion et al. 2004). A study of Scottish lakes found 19 of the 26 lacustrine diatom reconstructions suggested increased phosphorus levels than previously observed, which was hypothesized to be due to the shallow nature of the lakes as well as their proximity to towns causing a possibility of nutrient loading from runoff (Bennion et al. 2004). Water quality reconstructions, therefore, are effective indicators of nearby human activity, and conversely may also indicate a lack of human influence on lakes; as such it is an important purpose of proxy records that would indeed be applicable to areas of enduring human occupation.

2.8 Proxy Records and Co-Linear Variables

One of the greatest challenges facing the reliability of proxy records is the difficulty of interpretation due to confounding natural and anthropogenic variables. A primary concern then becomes how to disentangle the proxy data and effectively understand the driving forces behind the observed changes (Juggins 2013). Within the context of the Northern Hemisphere, and specifically Scotland, multiple driving forces are consistently acting upon the landscape, and these impacts can differ in both space and time due to the previously discussed variation of both natural and anthropogenic influences across localities. Robinson & Dickson (1988) conducted a multi-proxy investigation of the natural history of Arran, using valley peat records from Machrie Moor, which examined changes in relation to both climate variability and human activity and remains one of the most temporally extensive studies of Hebridean vegetational history, in relation to both natural and human influences, as it presents a continuous record c. 8050 BCE – 1450 CE. This peat record from Machrie Moor is classified as a 'basin mire' and is located in the southwest of Arran, which is an area with a long history of high anthropogenic influence due to its proximity to the coast and relatively flat landscape; as such, this continuous record must be interpreted within the context of intense human activity and, therefore, reflects anthropogenic signals (e.g., agriculture) (Robinson & Dickson 1988). The influence of agriculture was considered one of the most prominent factors that confounds climate signals; this is due to the known relationship of farming resulting in nutrient runoff that then enters the aquatic environment and can lead to eutrophication, which effectively alters the environment and is then reflected in the proxy reconstruction (Chique et al. 2018). Chique et al. (2018) utilized pollen and chironomids to develop a high-resolution reconstruction of Lough Muckno, Ireland, which observed the interactions of increasing agricultural intensity and ecological conditions in the catchment; results suggest 19th century agriculture techniques instigated the transformation of a meso-eutrophic lake ecosystem to hyper-eutrophic under contemporary pastoral-management. Here, linkages between chironomid taxa and pollen taxa are used to infer and strengthen conclusions of landscape changes, such as the relationship between increases to pollutant tolerant chironomids and grass pollen suggesting an expansion of pastoral agriculture (Chique et al. 2018). Specifically, the primary use of chironomids is to reconstruct July air temperatures yet in systems affected by eutrophication, such as the previously described example, the climate signals of the chironomids become unreliable due to disruptions from nutrient impacts on the community assemblage (Chique et al. 2018). While this study is outside of the designated Scottish geographic region, the use of both chironomids and pollen emphasize the significance of multi-proxy studies in order to effectively assess the complex relationship between climate variability, human influence, and landscape changes.

However, multi-proxy research is only one component of dealing with confounding variables within paleoenvironmental records; statistical analyses and modelling of data may also serve as a key to functionally address the issues of co-linear variables. Simpson & Anderson (2009) discuss this problem at length, highlighting the importance of statistical modelling within the context of this issue; they argue the variance of primary and secondary drivers of environmental change within the Northern Hemisphere requires additive models (AM) to effectively uncover the amplitude and timing of climate as a primary driver of changes within paleoenvironmental data. AM utilize a sum of arbitrary smooth functions for the variables in order to present the relationship between the co-linear variables and the response as modelled by the data itself rather than existing functions (e.g., linear) (Simpson & Anderson 2009). An examination of existing data from Loch Coire, Scotland, demonstrated the advantages of the AM technique, as the results largely agreed with the primary research (Pla et al. 2009) but AM uncovered subtle changes in diatom assemblages were linked to climate variability, which the effects of could be compared in magnitude (Simpson & Anderson 2009). No model is perfect, and AM do have associated challenges (e.g., the model complicates forecasting), however, this method can function as a path forward through the challenge of confounding co-linear variables.

2.8.1 Future Directions

This review has examined research that utilizes the most prevalent proxies for paleoenvironmental research within Scotland, outlining the purpose of each in relation to climate variability and human activity signals, as well as the prevailing challenges impacting the confidence of the reconstructions. Yet, many other methods exist and are emerging as powerful proxies for environmental and anthropogenic induced environmental changes over time.

The transition from hunter-gatherer society to agricultural within Scotland is not fully understood, yet the application of sedimentary DNA may serve as a method to fill this knowledge gap. Sedimentary DNA is a relatively new method of sediment core analysis, which examines ancient DNA of plant and animals to create reconstructions of flora and fauna throughout time (Haile et al. 2007; Smith et al. 2015; Sjögren et al. 2016). The power of this proxy lies within the fact that it is possible to create high-resolution reconstructions of past environments from trace amounts of ancient DNA, where macroscopic and even microscopic remains are absent (Willerslev et al. 2003). One of the greatest strengths of sedimentary DNA lies in vegetation records. For example, Sjögren et al (2016) found that vegetation reconstructed from sedimentary DNA matched excellently with a well-documented 20th century plantation of exotic vegetation in southwest Scotland. A possible challenge is the threat of DNA leaching within the strata causing muddling of chronologies, however several studies have concluded no evidence of leaching (Haile et al. 2007; Epp et al. 2015; Sjögren et al. 2016). Yet, with such a new method it will be necessary to be aware of such possibilities as the proxy continuous to be refined. The applicability of sedimentary DNA to cores from Scotland could serve as a powerful and precise method of vegetational and land-use reconstruction.

An additional line of emerging sediment analysis is the analysis of molecules specific to humans and domesticated animals. Faecal sterols and bile acids, specifically recent innovations in detection and estimation of ratios between different molecules have enabled a finer grain of resolution to species level (Harrault et al. 2019). For example, previous research has been able to only distinguish between herbivore, pig, and human faecal matter, yet recent steroid analysis has allowed for higher-resolution taxonomic results (Prost et al. 2017). One of the most relevant applications of faecal sterol analysis at future study sites is the possibility of determining direct human presence. Argiriadis et al. (2018) conducted research investigating human impacts on New Zealand's South Island, where faecal sterols were partnered with charcoal and pollen proxies, among others, which unequivocally linked human presence and land-cover vegetational changes during the late Holocene. The significance of the possibilities of this method may provide a distinct technique for determining true human influence and either supporting or not supporting inferential evidence of human impacts from other less conclusive proxies. Consequently, faecal sterols may serve as a pivotal component of disentangling climate and anthropogenic signals within proxy records, and as such should be of interest within Scotland where the issue of climate and human signals mixing is prevalent.

The existing prevailing proxies outlined in the previous sections also remain relevant in light of emerging methods, as the value and purpose of the various proxy reconstructions have been explored and established within the context of Scotland. For example, if chironomid records are accompanied by additional proxy reconstructions, such as pollen and diatoms, the detangling of climate variability and human signals are made easier. However, the significance of the selection of sites with little human impact, from regions with notably high human influence, cannot be overstated and will allow for the reconstruction climate variability without or with minimal interference from human activity.

2.9 Conclusion

The exploration of existing archaeological and paleoenvironmental records from the western coast of Scotland, along with some records from the surrounding Atlantic region, established the relationship between human settlement and environmental controls within Scotland during its prehistory. Scotland has experienced climatic cycling throughout the Lateglacial and even more so into the Holocene, with both regional (e.g., atmospheric cycling) and local impacts (e.g., agriculture). Through this review Scotland is presented as an area where the co-linear variables of anthropogenic activity and climate variability can be explored simultaneously. The natural climatic and human recolonization histories of Scotland were broadly outlined and effectively demonstrate the prolonged entanglement of these influences over the Scottish landscape (Figures 2.2 & 2.3).

The importance of the selection of sites with little human impact from regions with notably high human influence was discussed throughout the review; existing literature demonstrates the confounding nature of direct human influence in relation to climate signals, as well as the barriers to human occupation in the highland regions of Scotland that prevented colonization (Robinson & Dickson 1988; Jones et al. 1993; Hubbard 1999; Golledge 2010; Chique et al. 2018). Moreover, this selection was shown to be vital for the reconstruction of climate variability in the Hebrides throughout the later Holocene, as the Islands experienced a relatively early transition from hunter-gatherer Mesolithic populations to farming Neolithic communities. Specifically, the land-use history of the Hebridean Islands are of interest in relation to proxy analyses of climate variability; as existing research suggests the islands have a long history of human occupation and, subsequent, impacts to the local environments, which creates a unique opportunity to examine reference climate signals from the uninhabited highland areas of these islands where historically high anthropogenic impacts have been experienced in the lowlands.

The suitability of various proxy reconstruction methods was established through a review of existing records, with additional considerations of emerging proxies (e.g., sedimentary DNA and faecal sterols). We found the most effective reconstructions of both past climate and human influences utilized a multi-proxy approach, such as combinations of chironomid inferred air temperature, pollen and plant macrofossil inferred vegetational changes, charcoal inferred human activity/presence, and diatom inferred water quality changes (Jones et al. 1989; Chique et al. 2018; Bishop et al. 2018). The statistical technique of AM was also explored in the context of its potential capability to address confounding co-linear variables through examining the relationship between drivers of change and the observed proxy response (Simpson & Anderson 2009). These methods and techniques of paleoenvironmental inquiry, coupled with intentional site selections, may provide a path forward for research of climatic impacts and landscape change in regions with prolonged human occupation. While not exhaustive, this review does emphasize the importance of multiple lines of evidence when considering reconstructions of past climate; archaeological data, relevant site selections, and paleoenvironmental proxy reconstructions act as vital components when investigating past human activity and environmental changes within a region or locality.

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CHAPTER 3 UNDERSTANDING THE INFLUENCE OF THAW POLYGONS ON PRODUCTIVITY OF ARCTIC LAKES

3.1 Statement of Student Contribution

Study design by Alannah Niemeyer and Andrew Medeiros, limnological data collection by Andrew Medeiros, chironomid data analysis by Alannah Niemeyer, elemental and isotopic geochemical analysis and lake chronologies were conducted by Anthony Todd under the supervision of Brent Wolfe, chapter writing by Alannah Niemeyer with editorial contributions from Andrew Medeiros, Maarten van Hardenbroek van Ammerstol, and Brent Wolfe.

3.2 Abstract

Gradients of hydrological connectivity within the Western Canadian Arctic typically follow zones of permafrost depth, due to warming-induced permafrost degradation and disturbance. Recent warming is known to increase the rate of permafrost disturbance, which has implications for aquatic systems due to the resulting changes to overland and subsurface flow of water and subsequent transport of sediments. Here, we explore the influence of increasing hydrological connectivity on aquatic productivity through a multi-parameter paleolimnological study of two lakes located in the uplands region of the Mackenzie River, near Inuvik. N.W.T. We contrast a lake where there has been little evidence of permafrost degradation in the surrounding area (Lake PG3) to one that has multiple connections to the terrestrial landscape through a network of thaw polygons in the lake catchment (Lake PG9). Comparisons of biological indicators (chironomids) and

geochemistry reveal divergent lake histories since ~1700 CE. The chironomid assemblage of Lake PG3 followed a temperature gradient, with a warming signal evident since ~1850 CE. While the chironomid assemblage of Lake PG9 was found to primarily respond to nutrient availability and changes in habitat, likely as a result of increasing hydrological connectivity to the landscape. Rapid assemblage and habitat change along with a prominent increase in chironomid abundance were observed at Lake PG9 following ~1983 CE, following a shift to greater source inputs from the terrestrial environment as indicated by both high C:N ratios (>15) and low $\delta^{13}C$ values (towards -30‰). Increased aquatic productivity for the period following high allochthonous additions (~1983-2014 CE) is supported by decreased C:N ratios and rapidly increasing organic content (LOI_{550}). The increased aquatic production pose challenges to chironomid-inferred July air temperature reconstructions, where analogue mismatches can occur due to shifts in dominance of indicators that are orthogonal to the temperature gradient. Thus, caution should be used when interpreting temperature reconstructions from areas impacted by permafrost disturbance.

3.3 Introduction

Arctic aquatic systems are sensitive to permafrost landscape disturbance, as the potential influx of sediments and nutrients from increased hydrological connectivity can alter the existing *in situ* production; however, this relationship is generally limited within the continuous permafrost regions of the Arctic (Koch et al. 2018). Permafrost, the maintained frozen state of water and soil at depth, controls soil availability in the active (unfrozen) upper layer and, thus, limits the surface and near-surface flow of water (Lemieux et al. 2008; Burn 2012). Degradation of permafrost has the potential to alter hydrological connectivity, which may cause ecosystem stress and have cascading impacts for Arctic aquatic systems.

Recently, retrogressive thaw slumps have become commonplace in regions of discontinuous permafrost. Retrogressive thaw slumps have typically been observed on hillsides next to water bodies (Lantz & Kokelj 2008), which can have large impacts to Arctic trophic systems (Moquin et al. 2014). Arctic regions also commonly feature a landscape of patterned ground (also referred to as thaw polygons or ice-wedge polygons within the literature), typically found in transitional areas of permafrost, which alter topography by creating ridges and troughs that may infill with water and channel its movement across the environment (Steedman et al. 2017). Notably, recent rapid warming within the Arctic, up to three times that observed elsewhere on Earth, has resulted in acceleration of the formation of both retrogressive thaw slumps and patterned ground (Post et al. 2009; Schuur et al. 2015; Segal et al. 2016; Wolter et al. 2018). Lacelle et al. (2015) analyzed Landsat imagery of the Peel Plateau for the period of 1985 to 2011 CE, finding evidence to support a positive relationship between increasing precipitation (rain) and increasing retrogressive thaw slump size. Indeed, recent warming and increased precipitation within the Mackenzie River Delta region act as drivers of thermokarst activity and subsequently permafrost degradation. Polygon microtopographic changes near Prudhoe Bay, Alaska, were investigated by Abolt et al. (2018), who found that projected warming scenarios could lead to regional landscape changes that may severely alter hydrological regime of tundra environments. Additionally, permafrost degradation can result in a transition from low-centred polygons that are associated with muted runoff to high-centred polygons which facilitate greater than twice the runoff previously observed (Liljedahl et al. 2012). The combination of these concerning trends may result is cascading impacts, such as changing species ranges, which would alter the existing states of the Arctic ecosystem (Smol et al. 2005). Increased and rapid permafrost degradation can result in immediate and direct impacts to aquatic systems; yet, the indirect influence of rapid warming, increased precipitation, and the resulting landscape disturbance on geographically-isolated aquatic systems is not well-understood.

Rapid warming and a shifting hydrological cycle in the Canadian Arctic are of keen interest, as historically reduced levels of connectivity and limited nutrient availability have led to Arctic aquatic systems characterized by low ionic concentrations (Kokelj et al. 2009a). In particular, Arctic and boreal permafrost contains large quantities of long-stored organic carbon, estimated to contain one third of the global terrestrial budget, from the accumulation of plants and animals within the frozen ground over time (Koch et al. 2013; Schuur et al. 2015). Retrogressive thaw slumps allow for immediate catastrophic release of organic carbon, while increased patterned ground creates greater channelization that supports amplified overland flow to carry the newly released constituents (e.g., particulate and dissolved nutrients, and ions) to otherwise geographically distant aquatic systems (Kokelj et al. 2009b; Liljedahl et al. 2016). The consequences of these inputs to lake systems can cause abrupt and cascading responses from biota, such as inducing alterations to the Chironomidae (chironomid) larvae community assemblage (Moquin et al. 2014). Chironomids are commonly used as bioindicators of environmental change through time due to known responses to variables such as temperature (Quinlan et al. 2005; Walker & Cwynar 2006; Upiter et al. 2014), nutrients (Brooks et al. 2001; Moquin et al. 2014; Medeiros et al. 2015), depth (Rosenberg et al. 2004; Barley et al. 2006), and dissolved oxygen (Brodersen & Quinlan 2006; Walker 2006). The ubiquitous nature of chironomids within aquatic systems, in particular, establishes this family as prominent proxies of paleo-climate reconstruction. Oliver & Roussel (1983) note that greater than 50 % of species diversity in a lake can consist of chironomids, while similarly Walker (2001) states the family comprises the largest proportion of subfossilized biota from the order *Diptera* within lacustrine sediment records.

The uplands region of the Mackenzie River Delta, Northwest Territories (N.W.T.), is considered a transitional area where the boreal forest meets tundra and discontinuous permafrost gives way to the permafrost-rich continuous zone (Palmer et al. 2012). Landscape disturbances, such as retrogressive thaw slumps and thaw polygons, have been commonplace within this region and are suggested to be increasing in frequency (Lantz & Kokelj 2008; Kokelj et al 2009b; Moquin et al. 2014; Lacelle et al. 2019). This unique region is of keen interest as the rapid flux of the landscape allows for paleolimnological investigation of aquatic systems locally situated yet ecologically distinct. Indeed, biota abundance within the lakes of the region surrounding Inuvik, N.W.T., are known to differ based on proximity to permafrost disturbance (Moquin et al. 2014). Yet, the complex relationship of permafrost degradation and lake productivity over time, through channels of increased terrestrial-aquatic connectivity, remains an area in need of investigation to further detangle the past and present changes (Kokelj et al. 2009b; Moquin et al. 2014; Todd 2014; Medeiros et al. 2015).

Here, we contrast a reference lake with limited hydrological connectivity to a lake that has extensive patterned ground formations in its catchment (Figure 3.1). Through paleolimnological assessment of sediment cores from these two systems, we compare subfossil chironomid assemblages to organic carbon and nitrogen elemental and isotopic geochemical data to assess changes in aquatic productivity across gradients of catchment-mediated inputs. These records are evaluated for individual assemblage changes over time which is then supported by comparison of the two systems, allowing for insight into the influence of terrestrial-aquatic interface connectivity on chironomid community assemblages in relation to aquatic productivity. The role of competing variables (e.g., climate vs. terrestrial influence), which has been shown to influence chironomid temperature reconstructions (Medeiros et al. 2015), are also considered within the context of landscape disturbance. Examining the paleo-chironomid communities and abiotic variables of these two lakes permitted investigation of the three objectives of this research: (1) outline landscape changes over time; (2) contrast productivity in a highly connected lake to productivity of a lake with lower connectivity; and (3) identify contemporary paleo-temperature reconstruction challenges in relation to high terrestrial-aquatic connectivity. Thus, this study serves as an opportunity to explore the influence of increased terrestrial-aquatic connectivity and secondary gradients on chironomid-based paleo-temperature reconstruction.

3.4 Study Areas

Two lakes located in the uplands region of the Mackenzie Delta in the N.W.T., Canada, were sampled in July 2013 (Figure 3.1). The area is transitional with variable depth of permafrost and extent of treeline (Palmer et al. 2012). Lake PG9 is designated as the impacted patterned ground lake as visual evidence since 1950 CE supports an increasingly connected aquatic system (Figure 3.2). Lake PG3 was sampled as a reference lake, observed to have limited observable patterned ground in its immediate catchment (Figure 3.3). The PG3 reference lake has a larger surface area and depth (13.9 ha & >2.0 m) than Lake PG9 (0.2 ha & <2 m); while depth is known to influence chironomids, water level changes between the lakes would need to be at least three times as large to produce statistically significant differences (Walker 2001). The study lakes are located within different permafrost terrain, as Lake PG3 (68.8396 °N, 134.2795 °W) is located within an area of continuous permafrost with 500-600 m of depth, while Lake PG9 (68.8135 °N, 134.0317 °W) is located within a transitional zone with 300-400 m of permafrost (Figure 3.1) (Brown et al. 1998; Todd 2014). The location and surrounding catchment of each lake are essential to take into consideration in relation to the paleolimnological data as landscape disturbance may significantly alter the hydrology of a region over time (Burn & Kokelj 2009; Grosse et al. 2011). Using these sites with varying permafrost depths enables comparison between the biotic and abiotic conditions of lakes, through time, with differing levels of terrestrial influence and disturbance.

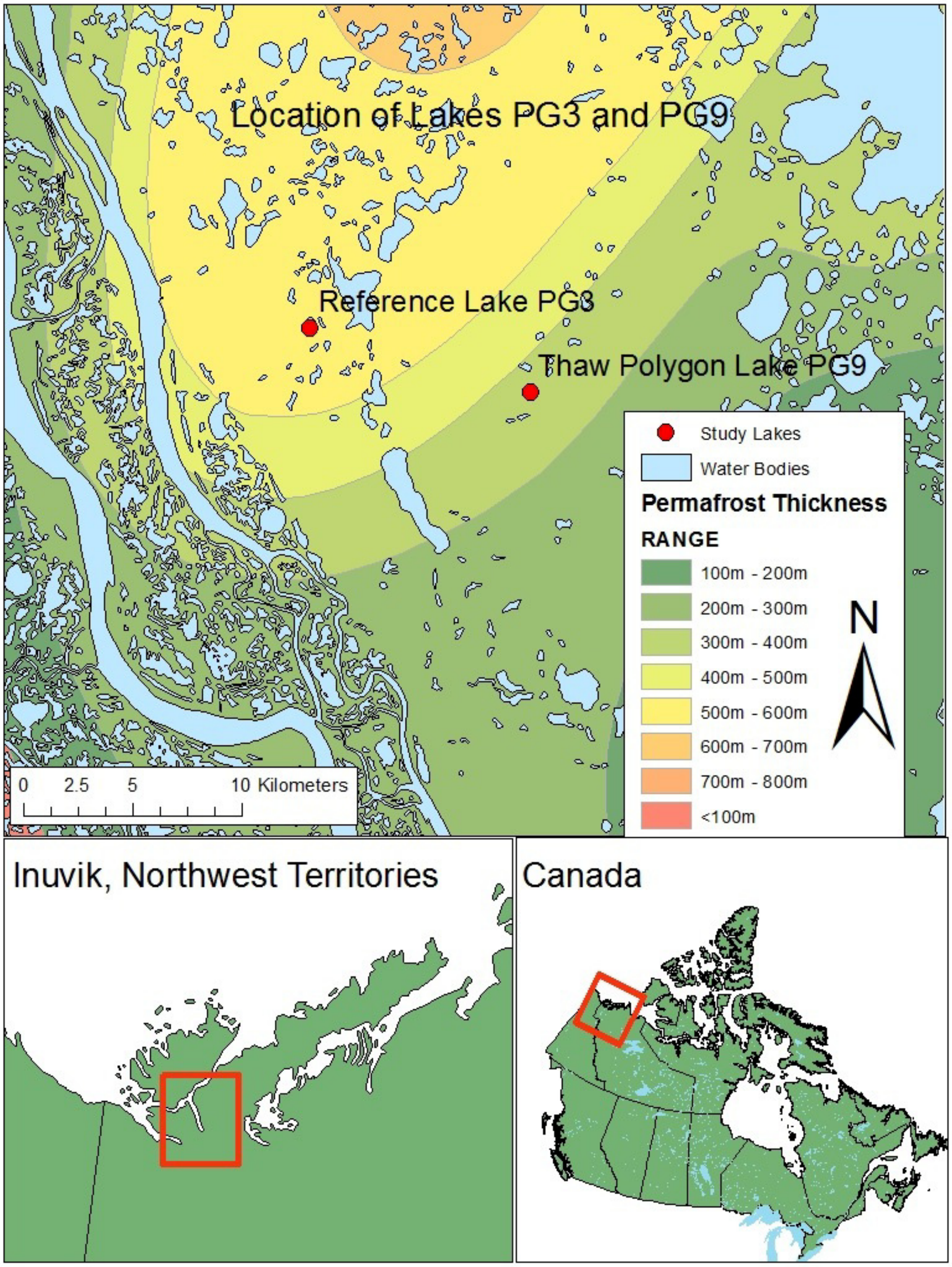

Figure 3.1 Location of Lake PG3 and Lake PG9 sites where data was gathered, with the approximate distribution and thickness of permafrost (Brown et al. 1998; Todd 2014).

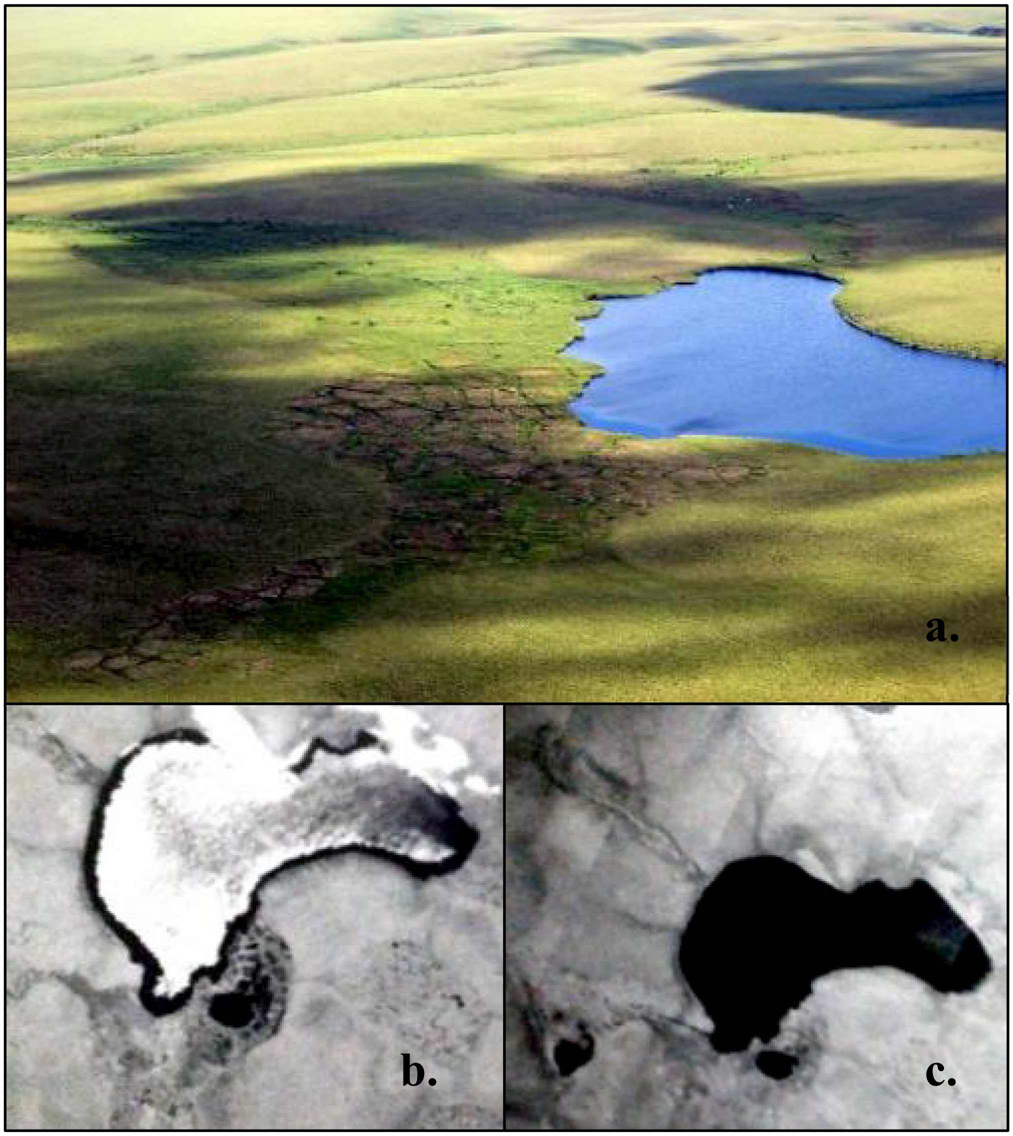

Figure 3.2 Thaw polygon lake (PG9) aerial photographs. a.) Lake PG9 with substantial patterned ground (2013 CE). b.) Lake PG9 with some patterned ground in the surrounding area (1975 CE). c.) Lake PG9 with little patterned ground (1950 CE).

Figure 3.3 Reference lake (PG3) aerial photograph, showing limited patterned ground in the surrounding catchment area for a.) 2013 CE, b.) 1975 CE, and c.) 1950 CE.

3.5 Methods

3.5.1 Field Methods

Sediment cores were collected from the mid-basin of each lake using a Uwitec gravity corer with an 8.4 cm diameter; the Lake PG3 core totalled 38.5 cm in length, while the Lake PG9 core totalled 14.5 cm in length. Each core was sectioned at 0.5 cm intervals, placed in a Whirl-Pak® bag, and transported in a cooler to be stored at 4°C for laboratory processing. On-site environmental metrics, including epilimnetic water temperature (°C), dissolved oxygen (mg/L), conductivity (μs/m), pH, and depth (m), were collected at each lake using a YSI multi-parameter probe (Supplemental table S1).

3.5.2 Chironomid Processing

Sediments were processed for subfossil chironomids at Dalhousie University in the Laboratory for Water and Environmental Sustainability Sciences (WESS) following standard methods (Walker 2001). The Lake PG3 sediment core (38.5 cm) was analyzed for chironomids at every other cm from the basal interval until 4.5 cm, after which every 0.5 cm interval was examined. The PG9 sediment core (14.5 cm) was analyzed at every 1.0 cm interval from the basal sample until 2.5 cm, after which each 0.5 cm interval was examined. Each sample was treated with potassium hydroxide (KOH) at 75 °C for 30 minutes, with periodic stirring, to deflocculate the sediment. Residues were then sifted using 106 μm and 212 μm nested sieves and washed with 95% ethanol. For each sample, subfossil chironomids were sifted and enumerated with the use of a dissecting microscope at least three times to ensure a 95 % capture rate of all chironomid head capsules within the sample. The extracted specimens were then permanently mounted on glass slides using Entellen® and identified using an Olympus SZ61 Stereo microscope. Following Quinlan and Smol (2001), a minimum of 50 head capsules were recovered from each interval and identified using Brooks et al. (2007) and Medeiros & Quinlan (2011). Chironomid production was calculated for each interval of Lake PG3 and Lake PG9 as head capsules per gram of dry weight (HC g^{-1} DW). Organic and carbonate content of sediment intervals from both Lake PG3 and Lake PG9 were estimated using weight loss on ignition (LOI), following methods defined by Heiri et al. (2001).

3.5.3 Elemental and Isotopic Geochemistry Analyses

Following Wolfe et al. (2001), analysis of organic carbon and nitrogen elemental and isotopic content were conducted on each interval of the sediment cores from both lakes. Carbonates were removed with a 10 % hydrogen chloride (HCl) solution rinse. This process was repeated until the sediments reached neutral pH. A fin-grain fraction subsample was collected by passing freeze-dried samples through a 500 µm sieve; the subsamples were then sent to the University of Waterloo Environmental Isotope Laboratory, where elemental and stable isotope analyses were completed. Following convention, the stables isotopes are reported with respect to the Vienna-Pee Dee Belemnite (VPDB) (carbon) and atmospheric (AIR) (nitrogen) standards as δ-notation in per mil.

3.5.4 ^{210}Pb and ^{137}Cs Dating

Each lake core chronology was determined using the Constant Rate of Supply (CRS) model for ^{210}Pb with gamma ray spectrometry (Appleby et al. 1986; Appleby 2001), at the Waterloo Environmental Change Research Laboratory (WATER), University of Waterloo, ON (Sanchez-Cabeza et al. 2000; Todd 2014). ^{137}Cs was analyzed for each core and compared to known fallout peaks in 1963 caused by the atmospheric testing of nuclear weapons (Walling & Qingping 1992; Todd 2014; Pulley et al. 2018).

3.5.5 Quantitative Analyses of Chironomid and Geochemical Data

Raw chironomid abundance (hereto referred to as abundance) was calculated for each interval of both Lake PG3 and Lake PG9 using the enumerated head capsules per gram of dry weight (HC g^{-1} DW). Chironomid data for Lake PG3 and Lake PG9 were analyzed using the R statistical language v3.6.2 (R Core Team 2019) with the package rioja v0.9-21 (Juggins 2017). Zones of significant shifts in chironomid abundance were determined using the broken stick model (bstick) applied to a constrained hierarchal cluster analysis (chclust). The Lake PG3 broken stick model suggests seven to eight significant zones, while the constrained cluster analysis identified four significant zones. Analysis of Lake PG9 data using the broken stick model found two to three significant zones, while the constrained cluster analysis established three significant zones. The relative abundance of taxa was also calculated (see supplemental). Only data meeting the requirement of >2 % relative abundance were included in our analyses. Chironomid data were plotted against depth and time, with zones of significant abundance shifts illustrated by dashed lines. Elemental and isotopic data were also plotted in a biostratigraphy of each lake using the R software.

3.5.6 Paleo-Temperature Reconstructions

Paleo-temperature reconstructions were developed for both Lake PG3 and Lake PG9 using the Fortin et al. (2015) calibration dataset and transfer function model, in the R statistical language v3.6.2 (R Core Team 2019). The Fortin et al. (2015) calibration set was selected due to the applicability of the region and the large size that included modern analogues of historic taxa; the dataset includes 434 lakes from across Canada and Alaska, where the systems are diverse ranging from the high Arctic to more temperate regions. Taxa data of Lake PG3 and Lake PG9 were Hellinger transformed, where taxa were weighted according to abundance. The chironomid inferred July air temperature reconstruction for each lake was bootstrapped weighted average partial least squares (WA-PLS) (Braak & Juggins 1993) with 9999 bootstraps to cross-validate the model.

Squared-chord distance for Lake PG9 showed good analogues for the entire record (supplemental Figure S7), while analysis of Lake PG3 data showed the majority of subfossil samples (16 of 26 samples) had good analogues with some fair and a few poor (supplemental Figure S8). Squared residual distance tests revealed similar results with all Lake PG9 data being a good fit the inference model, while Lake PG3 had some subfossil data fit good, fair, and poorly (supplemental Figures S9 & S10).

3.6 Results

3.6.1 Age-Depth Models

^{210}Pb content in Lake PG3 demonstrated a stable declining trend down the record, with an initial value of 433.2 Bq/kg at 0.5 cm and ending with 39.0 Bq/kg at 24 cm (Figure 3.4). ^{210}Pb background was reached at 24 cm, which was modelled as 1860 CE using CRS. The model was also supported by the ^{137}Cs peak of 162.7 Bq/kg at 13.75 cm, corresponding to 1963 CE. Interval ages after 24.0 cm were estimated through linear extrapolation, where the basal interval of 38.5 cm gave a date of 1700 CE.

The Lake PG9 ^{210}Pb record had a decreasing trend from an initial inferred value of 258.5 Bq/kg at 0.5 cm, with the exception of a minor increase to 260.3 Bq/kg at 1.5 cm (Figure 3.5). ^{210}Pb background was achieved at 8.0 cm with 38.3 Bq/kg, which agreed with the CRS modelled date of 1902 CE. ^{137}Cs concentration peaked at 5.75 cm with 61.6 Bq/kg, which also agreed well with the CRS modelled chronology. Below 8.0 cm the chronology was estimated using linear extrapolation, where the basal date of 1618 CE is expected for the depth of 14.5 cm.

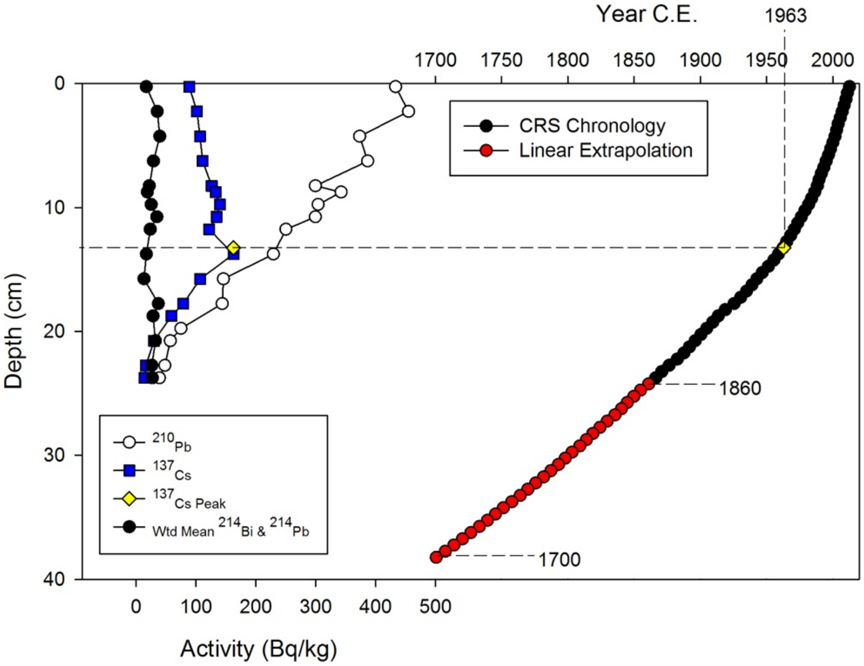

Figure 3.4 Sediment core chronology for Lake PG3 (Todd 2014).

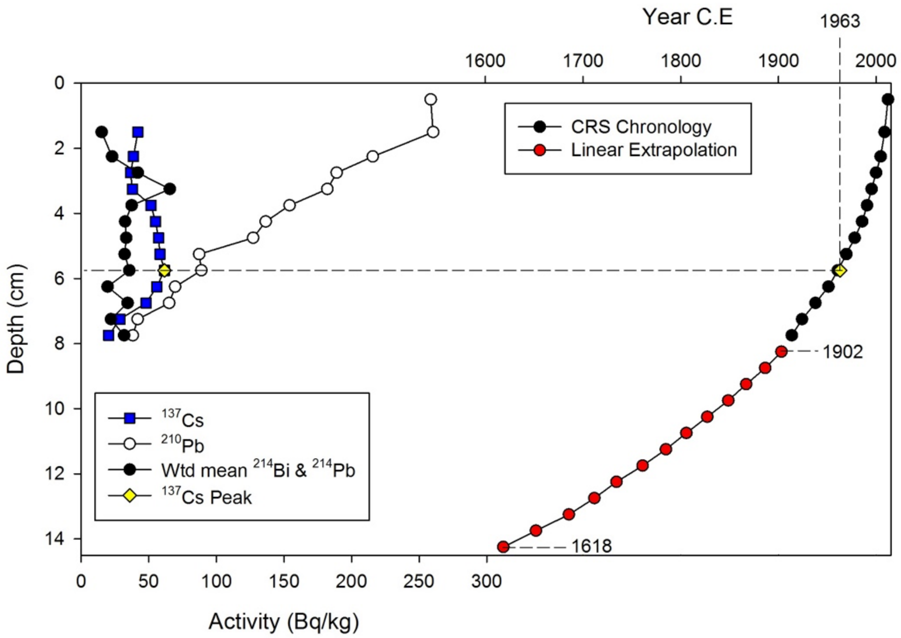

Figure 3.5 Sediment core chronology for Lake PG9 (Todd 2014).

3.6.2 Chironomid Descriptions

Greater than 3000 subfossilized chironomid head capsules were extracted from 0.5 cm intervals of the Lake PG3 and Lake PG9 lacustrine sediment cores. A total of 26 samples with 97 taxa groups were examined from Lake PG3 (head capsules per sample average= 67; median = 60; & range= 50-117), while 17 samples with 70 taxa groups were examined from Lake PG9 (head capsules per sample average= 126; median= 123; & range= 50-262). The abundance differed greatly between the lakes, with Lake PG3 having an average total abundance of 6.79 HC g^{-1} DW whereas Lake PG9 total average abundance was 21.35 HC g^{-1} DW. Moreover, trends in abundance for each lake diverged; Lake PG3 abundance consistently fluctuated within a range of 338.19-1096.47 HC g^{-1} DW, while Lake PG9 abundance displayed an overall positive trend with a range of 174.06-4099.21 HC g^{-1} DW. The mean chironomid production demonstrated stark differences as well. Lake PG3 average production was 625.46 HC g^{-1} DW, while Lake PG9 was 1377.96 HC g^{-1} DW.

Diversity and abundance were calculated for both Lake PG3 and Lake PG9. Many shifts appeared in the diversity analysis of each lake, as calculated by constrained cluster analysis and the broken stick model; yet, greater changes were observed within the abundance data. As such, diversity will not be considered within the primary results, rather in the supplementary chapter. Shifts within the Lake PG3 abundance biostratigraphy were observed at core depths of 20.5 cm (~1902 CE), 2.5 cm (~2006 CE), and 1.5 cm (~2009 CE); significant zones were observed at 4.5 cm (~1983 CE) and 1.5 cm (~2008) for Lake PG9 (Figure 3.6).

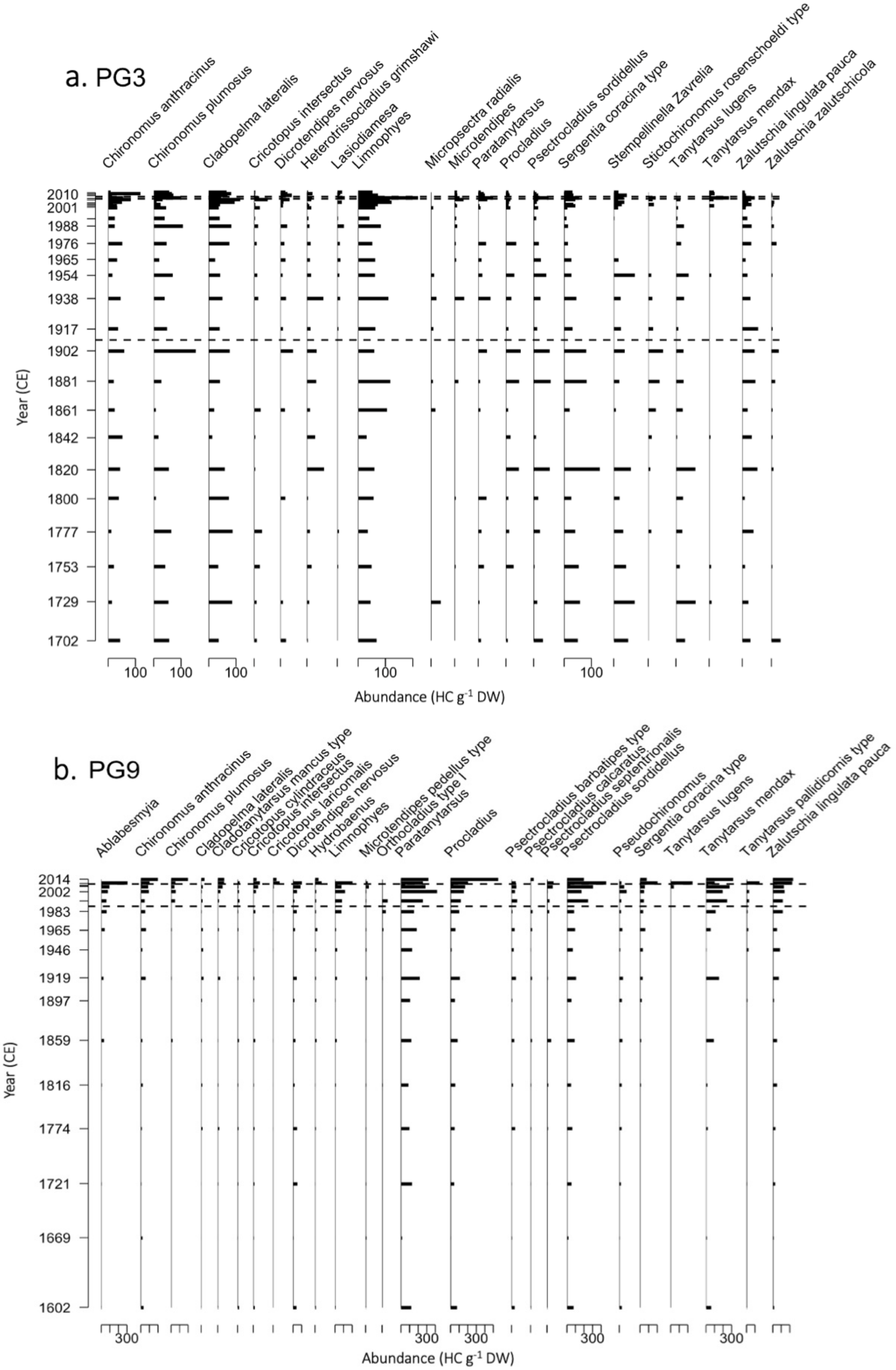
a. PG3
Chironomus anthracinus
Chironomus plumosus
Cladopelma lateralis
Cricotopus intersectus
Dicrotendipes nervosus
Heterotrissocladius grimshawi
Lasiodiamesa
Limnophyes
Micropsectra radialis
Microtendipes
Paratanytarsus
Procladius
Psectrocladius sordidellus
Sergentia coracina type
Stempellinella Zavrelia
Stictochironomus rosenschoeldi type
Tanytarsus lugens
Tanytarsus mendax
Zalutschia lingulata pauca
Zalutschia zalutschicola
Year (CE)
2010
2001
1988
1976
1965
1954
1938
1917
1902
1881
1861
1842
1820
1800
1777
1753
1729
1702
100
100
100
100
100
Abundance (HC g^{-1} DW)
b. PG9
Ablabesmyia
Chironomus anthracinus
Chironomus plumosus
Cladopelma lateralis
Cladotanytarsus mancus type
Cricotopus cylindraceus
Cricotopus intersectus
Cricotopus laricomalis
Dicrotendipes nervosus
Hydrobaenus
Limnophyes
Microtendipes pedellus type
Orthocladius type I
Paratanytarsus
Procladius
Psectrocladius barbatipes type
Psectrocladius calcaratus
Psectrocladius septentrionalis
Psectrocladius sordidellus
Pseudochironomus
Sergentia coracina type
Tanytarsus lugens
Tanytarsus mendax
Tanytarsus pallidicornis type
Zalutschia lingulata pauca
Year (CE)
2014
2002
1983
1965
1946
1919
1897
1859
1816
1774
1721
1669
1602
300
300
300
300
300
Abundance (HC g^{-1} DW)

Figure 3.6 Biostratigraphy of abundance (HC g^{-1} DW) plotted against estimated ^{210}Pb linear extrapolation age for reference Lake PG3 (a.) and thaw polygon Lake PG9 (b.).

3.6.3 The Influence of Landscape Connectivity

The period of ~1702-1902 CE for Lake PG3 and ~1602-1897 CE for Lake PG9 demonstrates negligible changes in δ^{13}C values (Figures 3.7 & 3.8). Isotopic nitrogen data suggests the period of ~1702-1902 CE for Lake PG3 is characterized by a decreasing trend in δ^{15}N (2.27-1.16 ‰). The δ^{15}N trend of the early intervals of Lake PG9 (~1602-1897 CE) indicate two peaks; first, the content increases from -0.42 ‰ at ~1602 CE to 0.17 ‰ at ~1720 CE; second, there is a large decrease after the first peak, with -0.55 ‰ at ~1774 CE, followed by an increase until the next peak of 0.25 ‰ at ~1816 CE after which the δ^{15}N values decrease to -0.26 ‰ at ~1897 CE. The C:N ratio of Lake PG9 for the 17th and 18th centuries are characterized by fluctuations. The peak C:N ratio of 17.3 occurs at the basal interval of Lake PG9 (~1602 CE) and is then followed by decreases until ~1721 CE (15.6), after which the value increases to 16.3 by ~1774 CE. The 18th century of Lake PG3 is marked by a small C:N ratio peak of 14.5 at ~1753 CE, overall having similar values observed for the same period in Lake PG9. The period of ~1816-1919 CE for Lake PG9 is characterized by an initial increase to the C:N ratio reaching 15.8 at ~1897 CE, followed by a decrease to 15.0 at ~1919 CE. For Lake PG3, C:N ratios throughout the 1800s (~1800-1881 CE) exhibit a slight curve, where the peak occurs at ~1843 CE with 16.1.

The majority of the 20th century (~1897-2002 CE) is characterized by general decreases to the δ^{13}C of both Lake PG3 and Lake PG9, coupled with an increasing trend for δ^{15}N in Lake PG9 and relative stability for Lake PG3. The period of ~1897-1993 CE for Lake PG9 shows a consistent $\delta^{13}C$ decreasing trend (-28.27 ‰ to -28.91 ‰), while Lake PG3 generally decreases from -29.47 ‰ (~1902 CE) to -30.33 ‰ (~2001 CE). The $\delta^{15}N$ values differ greatly between the reference and impacted lakes, with Lake PG3 having approximately twice the $\delta^{15}N$ content observed in Lake PG9. The %N content of Lake PG3 reflects relative stability throughout the 20th century, ranging between 2.22-2.48 %; while Lake PG9 %N values for the same period suggest similar stability ranging from 1.73-2.05 %. Notably, the %N content varies between the lakes, with Lake PG3 demonstrating relatively higher values than those observed within the Lake PG9 record. The 20th century of PG9 is marked by increasing organic matter, LOI_{550} values grew by ~9 %. Since ~1902 CE Lake PG3 $\%C_{org}$ fluctuated between the core peak of 40.32 % at ~1970 CE and a low of 34.32 % at ~1995 CE. The C:N ratio for Lake PG9 peaks in the middle of the 20th century (~1965 CE) with 16.88, while the surrounding intervals range from 14.71-16.02. The Lake PG3 C:N ratio, in contrast, exhibits a clear decreasing trend (16.8-14.3) for the entire period (~1902-2001 CE).

The remaining ~50 years of the PG9 record demonstrate a marked decrease in the C:N ratio after a peak of 16.9 at ~1965 CE, which is followed by the eventual lowest point of the entire core at ~2014 CE with 13.7. Zones 2 & 3 of Lake PG9 (~1993-2014 CE) see a trend of decreasing C:N ratio values (~15.0-13.7) coupled with generally increasing $\delta^{15}N$ in the range of ~0.1-0.5 ‰. The %N content of Lake PG9 also displayed rapid increases since ~1965 CE (1.73 to 2.39 %). Similarly, Lake PG3 C:N ratio values gradually decline to values ranging from 14.3-15.3 after ~1965 CE; while the %N content of Lake PG3 also increased over the same period (2.38 to 2.49 %), yet at a reduced rate when compared to Lake PG9. The lowest $\delta^{13}C$ values of each core are found within the

21st century; Lake PG9 δ13C content decreases to -29.22 ‰ at ~2008 CE, while Lake PG3 values decrease to -30.33 ‰ at ~2000 CE. The δ13C content then slightly increases in both records following ~2008 CE, Lake PG9 increases to -28.94 ‰ ~2014 CE, while Lake PG3 climbs to -29.85 ~2009 CE.

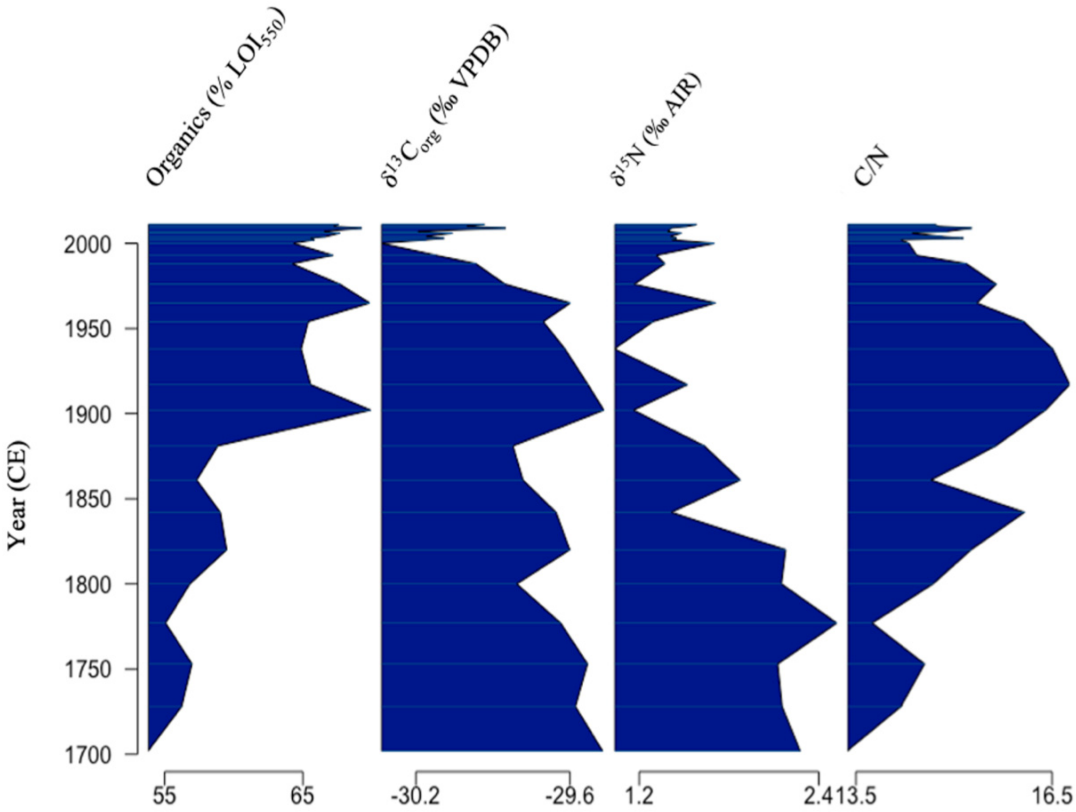

Figure 3.7 Lake PG3 elemental and isotopic geochemical stratigraphy plotted against estimated ^{210}Pb linear extrapolation age.

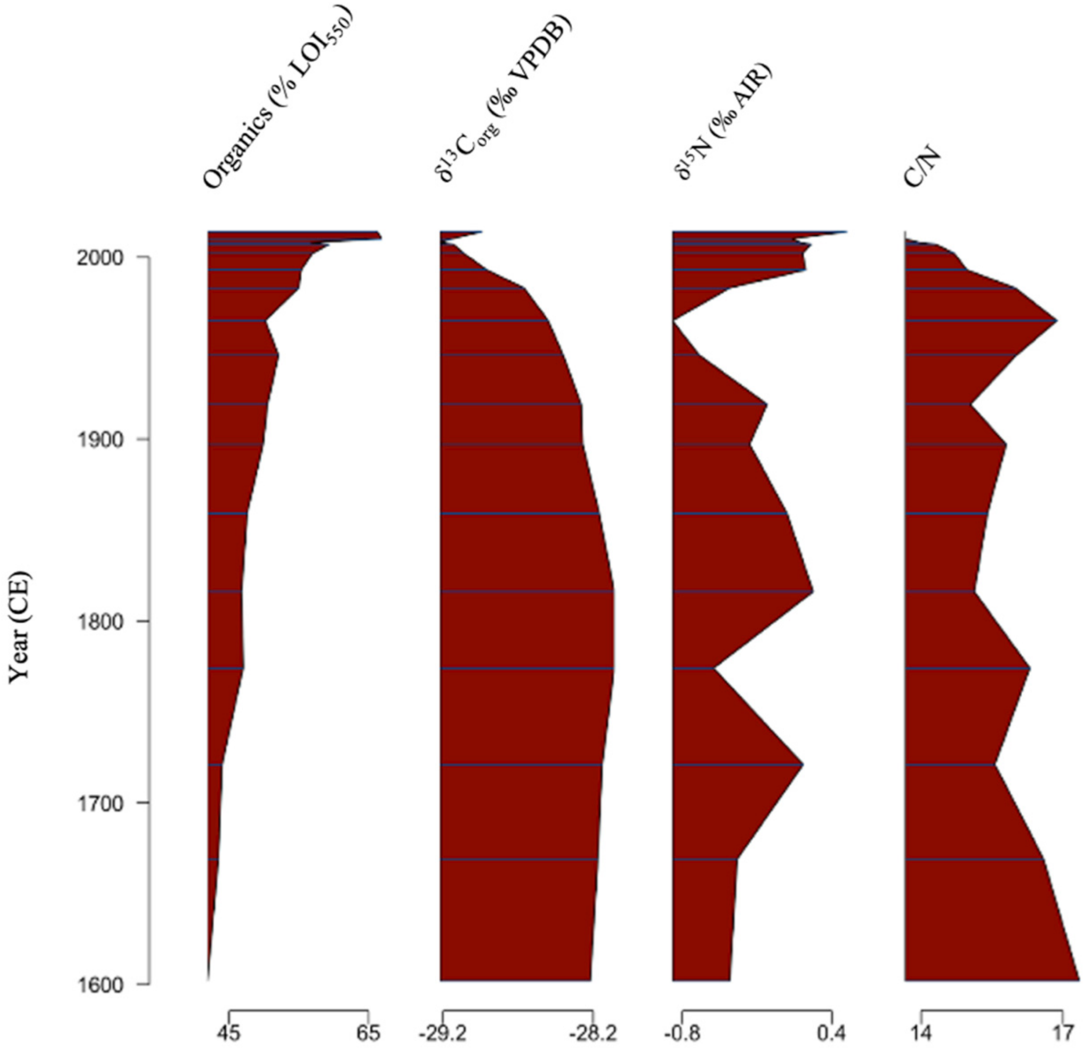

Figure 3.8 Lake PG9 Elemental and isotopic geochemical stratigraphy plotted against estimated ^{210}Pb linear extrapolation age.

3.6.4 The Influence of Terrestrial Connectivity on Productivity Through Time

Chironomid production follows differing trajectories for each record, where Lake PG3 production fluctuates with two small peaks (~1820 CE & ~1902 CE) until the 21st century when the trajectory largely increases, while Lake PG9 production gradually increases until ~1965 CE, after which production increases rapidly (Figure 3.9). Specifically, Lake PG3 demonstrates three peaks of >900.0 HC g^{-1} DW, occurring at ~1820 CE (906.18 HC

g^{-1} DW), ~1902 CE (1060.45 HC g^{-1} DW), and ~2007 CE (1114.74 HC g^{-1} DW). Prior to ~1993 CE the PG3 record indicates fluctuating production between a low of 364.61 HC g^{-1} DW and a peak of 1060.45 HC g^{-1} DW. At ~1993 CE the production of PG3 decreases to the lowest point of the record with 338.19 HC g^{-1} DW, which is followed by a steadily increasing trend until the peak of the record at ~2007 CE. Lake PG9, in contrast, shows a positive trajectory with the chironomid production largely increasing from the lowest point (169.18 HC g^{-1} DW) of the record at ~1669 CE to the ultimate peak (3979.81 HC g^{-1} DW) at ~2014 CE. The growth in production increases steadily in the period of ~1602-1816 CE, after which the majority of intervals were calculated to have >1000.00 HC g^{-1} DW. Production then increases again around ~1965 CE, where chironomid production increases by approximately 3000 HC g^{-1} DW to reach the peak of the PG9 record at ~2014 CE. Outliers of this trend include a significant decrease at ~2008 CE, where production falls by about 2000.00 HC g^{-1} DW from 2347.74 HC g^{-1} DW at ~2007 CE to 286.73 HC g^{-1} DW at ~2008 CE.

Organic content (LOI_{550}) largely reflects the chironomid production for each system, where Lake PG3 sees fluctuating values over time, while Lake PG9 exhibits an initially steady and then increasingly rapid increase of organic content (Figure 3.9). The period prior to ~1700 CE is only observed within the PG9 record, where the lowest LOI_{550} values of the record are observed (41.91% & 43.47%). LOI_{550} data from Zone 1 (~1702-1902 CE) of Lake PG3 indicates an overall increase by 16.10%, while Lake PG9 experienced a 6.51 % increase throughout a similar time period (~1721-1919 CE). Between ~1917-2006 CE Lake PG3 LOI_{550} data suggests an overall increasing trend with three peaks; at 12.5 cm (~1965 CE) the highest recorded LOI_{550} value occurs with 69.85

%; the second peak occurs shortly afterward with 67.17 % at 6.5 cm (~1993 CE); the last peak of the zone occurs in the final interval at 2.5 cm (~2006 CE) with 67.67 %. This general period is reflected by an increasing trend within the PG9 record, where the organic content begins with 50.52 % at 7.5 cm (~1919 CE) and ends with 59.37 % at 2.0 cm (~2007 CE). The final zone of Lake PG9 (~2008-2014 CE) is characterized by a 10 % overall increase in LOI_{550} values, while a similar time period within the PG3 record (~2009-2011 CE) indicates a slight decreasing trend from 69.28 to 67.61 %.

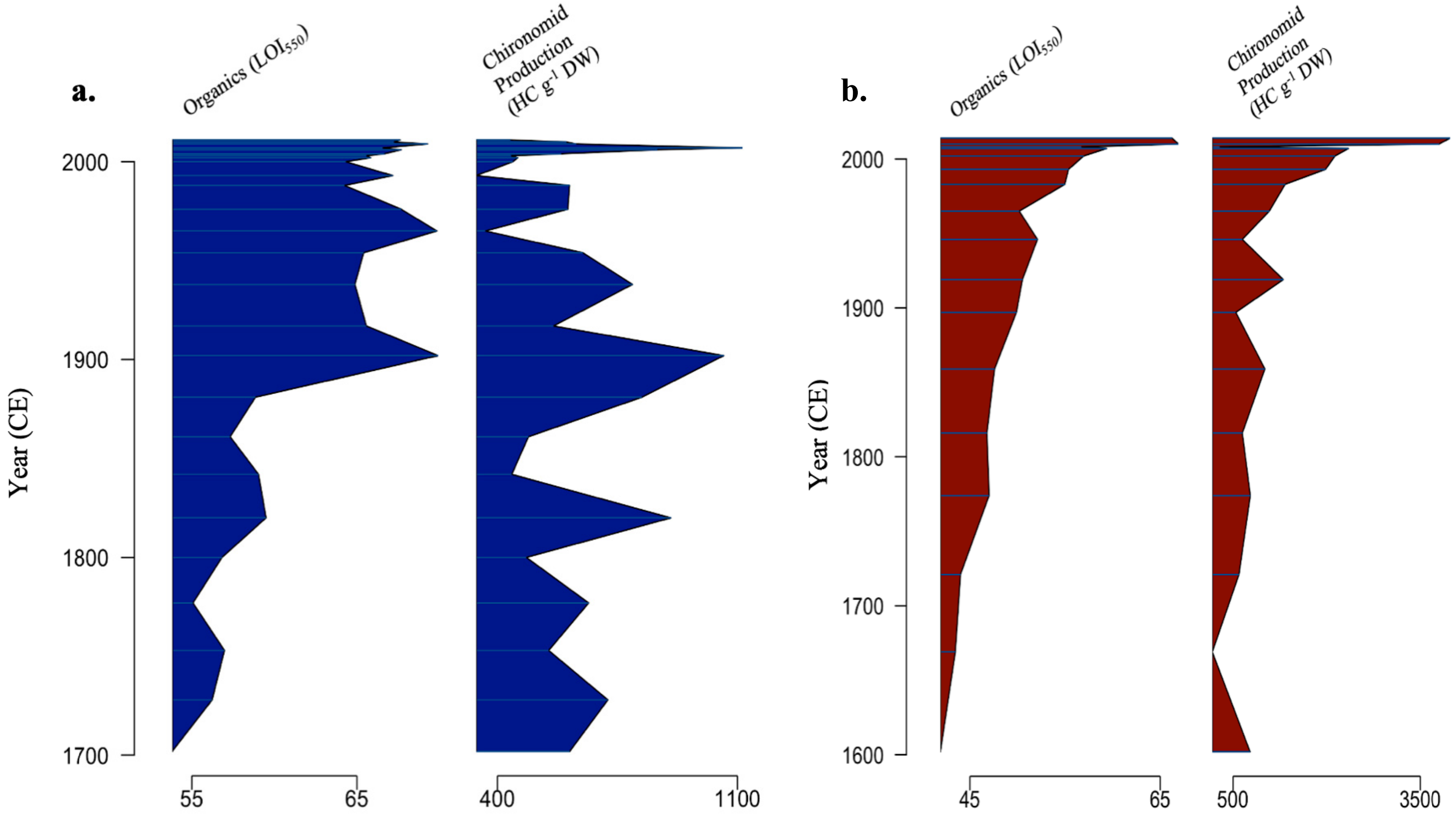

Figure 3.9 Chironomid production (HC g^{-1} DW) and organic matter (LOI_{550}) data plotted against ^{210}Pb linear extrapolation age (year CE) for Lake PG3 (a.) and Lake PG9 (b.).

Taxa-specific chironomid information enables the interpretation of productivity relationships present in each system over time. *Procladius* follows a decreasing trend up the PG3 record, where the highest abundance is observed in Zone 1 with a peak of 54.38 HC g^{-1} DW at ~1902 CE (Figure 3.6). However, the taxon experiences a high overall increase throughout the PG9 record with the majority of intervals (six out of seven) maintaining abundance >100.0 HC g^{-1} DW since ~1983 CE. Indeed, Zone 3 of Lake PG9 exhibits rapid abundance increases for *Procladius*, with a jump from 32.64 HC g^{-1} DW at ~2008 CE to the peak of the record at ~2013 CE (557.2 HC g^{-1} DW). A similar positive trend is observed for *Ablabesmyia* within the Lake PG9 biostratigraphy, where the abundance of the group steadily increases from 5.90 HC g^{-1} DW at ~1602 CE to an abrupt increase at ~2010 CE (306.62 HC g^{-1} DW). However, *Ablabesmyia* are not represented within the Lake PG3 biostratigraphy.

In the PG3 record *Heterotrissocladius grimshawi type* demonstrated an increasing trend in abundance from ~1702 CE (3.36 HC g^{-1} DW) until ~1820 CE (63.31 HC g^{-1} DW), which is followed by a second peak of 60.3 HC g^{-1} DW at the beginning of Zone 2 (~1938 CE), after which the abundance decreases to <20.0 HC g^{-1} DW for the remainder of the record (Figure 3.6). *Heterotrissocladius spp.* did not have great enough abundance to be included within the Lake PG9 biostratigraphy. *Cladopelma lateralis type* remained a dominant taxon throughout the entire PG3 record (range= 13.13-115.5 HC g^{-1} DW), while the taxon demonstrated relatively low abundance (<40.0 HC g^{-1} DW) throughout the PG9 record.

Cricotopus spp. also display divergent trajectories within the biostratigraphies of Lake PG3 and Lake PG9 (Figure 3.6). *Cricotopus intersectus type* demonstrates relatively large fluctuations throughout the PG3 record, ranging from 3.103 HC g^{-1} DW at ~1993 CE to 49.51 HC g^{-1} DW at ~2006 CE. In contrast, the *Cricotopus spp.* present in lake PG9 reflect large increases in abundance up the core and all peak at ~2010; *Cricotopus cylindraceus type* peaks at 25.55 HC g^{-1} DW, *Cricotopus intersectus type* peaks with 76.66 HC g^{-1} DW, and similarly *Cricotopus laricomalis type* also peaks with 76.66 HC g^{-1} DW.

Stictochironomus rosenschoeldi type has the greatest frequency and abundance within Zone 1 of Lake PG3, where the taxon is present at six of ten intervals and increases to the peak of 54.38 HC g^{-1} DW at ~1902 CE (Figure 3.6). Following the beginning of the 20th century, the taxon decreases in both abundance and frequency until disappearing from the PG3 record after Zone 3 (~2007 CE). *Micropsectra radialis type* follows a similar decreasing trajectory throughout PG3; the taxon is only present in Zones 1 and 2, with the highest abundance (36.12 HC g^{-1} DW) at ~1729 CE, ultimately disappearing after ~2001 CE. *Sergentia coracina type* also exhibits a decreasing trend up the Lake PG3 core, from a peak of 130.6 HC g^{-1} DW at ~1820 CE to a low of 5.9 HC g^{-1} DW at ~2004 CE. In contrast, *Sergentia coracina type* increases up the PG9 record, not appearing until ~1816 CE with 10.68 HC g^{-1} DW and then peaks at ~2010 CE with 204.4 HC g^{-1} DW.

Psectrocladius sordidellus type decreases (58.91-4.377 HC g^{-1} DW) during the period of ~1902-2011 CE in Lake PG3, while the abundance of the taxon in Lake PG9 largely increases in the period after ~1919 CE with six of the ten intervals being >100.0 HC g^{-1} DW (Figure 3.6). Similarly, after ~2007 CE *Paratanytarsus type* consistently increases (46.62-318.4 HC g^{-1} DW) until the end of the PG9 record (~2014 CE), while the reverse is true for Lake PG3 (54.82-8.754 HC g^{-1} DW). The trends of *Dicrotendipes nervosus type* in each record also differ. In Lake PG3 the taxon peaks at ~1902 CE with 45.32 HC g^{-1} DW and then decreases to the lowest abundance >0 HC g^{-1} DW (17.51 HC g^{-1} DW) at ~2011 CE. While in Lake PG9 the abundance generally increases from the earliest presence of *Dicrotendipes nervosus type* (4.880 HC g^{-1} DW at ~1669 CE) to the peak of 102.2 HC g^{-1} DW (~2010 CE).

The transition between Zones 2 and 3 of Lake PG9 (~2007-2008 CE) is marked by an increase to greater than half of the taxa present, and notably is the first occurrence of *Tanytarsus lugens type* within the record (Figure 3.6). Additionally, the *Tanytarsus lugens type* abundance of Lake PG9 follows the trend of %C_{org} closely; with intermediate to low values at ~2007-2008 CE (range= 38.17-13.99 HC g^{-1} DW & range= 30.19-31.12 %), while the highest abundance and second highest organic content of the entire record are observed at ~2010 CE (255.5 HC g^{-1} DW & 31.27 %). However, the taxon shows little relationship to organic content within the PG3 record, where *Tanytarsus lugens type* abundance decreases up the core from a peak of 72.23 HC g^{-1} DW at ~1729 CE to disappearing from the record following ~2006 CE, while %C_{org} data suggests an overall increase from the basal interval at ~1702 CE (31.51 %) to the peak at ~1917 CE (37.74 %), followed by moderate to high values (range= 35.09-37.30 %) for the period of ~1938-2011 CE.

Chironomus anthracinus type, Chironomus plumosus type, Limnophyes, and *Tanytarsus mendax type* follow similar trajectories throughout the Lake PG3 record, where the peaks of each taxa (118.3 HC g^{-1} DW, 100.5 HC g^{-1} DW, 219.3 HC g^{-1} DW, & 73.10 HC g^{-1} DW, respectively) occur during the period of ~2007-2010 CE (Figure 3.6).

The abundance of *Tanytarsus mendax type* within the Lake PG9 record demonstrates greater overall abundance and frequency throughout, when compared to Lake PG3, with >100 HC g^{-1} DW as early as ~1919 CE. Similarly, *Chironomus anthracinus type* and *Chironomus plumosus type* both have greater peaks in Lake PG9 with 199.0 HC g^{-1} DW, while *Limnophyes type* peaks with slightly less than observed in Lake PG3 (204.4 HC g^{-1} DW).

Cladotanytarsus mancus type were excluded from the Lake PG3 biostratigraphy for not having great enough abundance (>2%), while the taxon displays a clear increasing trend since ~1993 CE (range= 15.01-79.60 HC g^{-1} DW) within Lake PG9. *Tanytarsus pallidicornis type* is also only present in the Lake PG9 biostratigraphy and demonstrates a positive trend for the period of ~1602-2010 CE (range= 2.951-153.3 HC g^{-1} DW). Notably, *Tanytarsus pallidicornis* closely follows the %C$_{org}$ trajectory of the Lake PG9 core with large increases in taxon abundance (range= 12.65-153.3 HC g^{-1} DW) and organic content (range= 28.44-32.66 %) since ~1945 CE. *Zalutschia lingulata pauca type* is present in Lake PG3 but shows decreasing abundance (from 45.69 HC g^{-1} DW to 8.75 HC g^{-1} DW) after Zone 2 (~2007 CE), while the taxon demonstrates abundance increases (>100%) in the majority of Lake PG9 intervals since ~1983 CE.

3.6.5 Paleo-Temperature Reconstructions

Chironomid-inferred mean July air temperature reconstructions were completed for Lake PG3 and Lake PG9 using the Fortin model (Fortin et al. 2015). The Lake PG3 and Lake PG9 models exhibited different changes in the estimate July air temperature trends and magnitude. The July air temperature reconstruction attempt for Lake PG9 was not found to follow the primary temperature gradient (see supplemental), despite good agreement with analogues and the inference model (Supplemental Figures S7 & S9). The Lake PG3 WA-PLS July air temperature reconstruction reflects an overall increase of ~2.25 ^{o}C since ~1850 CE. An initial decline in temperature was observed at ~1850 CE (~9.5-9.0 ^{o}C), after which there is a clear and rapid warming trend (~9.0-11.75 ^{o}C) that continues until the end of the record ~2011 CE (Figure 3.10).

Paleo-temperature estimates for Lake PG3, based on The Fortin et al. (2015) model, range from ~ 9.25-12.25 ^{o}C (Figure 3.10). Diagnostic tests completed with the R statistical language (R Core Team 2019) and the package rioja v0.9-21 (Juggins 2017) include analogue distance analyses (squared-chord distance) and goodness of fit (squared residual distance) tests for each record. Lake PG3 squared residual distance shows good alignment between the subfossil samples and the inference model, with 21 of the total 26 observations fitting well (supplemental Figure S10). The Lake PG3 squared-chord distance demonstrates overall good agreement to the analogues, with 16 of the total 26 observations fitting well, 4 fitting fair, and 6 fitting poorly (supplemental Figure S8). While these diagnostic tests are less agreeable with the analogues than Lake PG9 data, the resulting reconstructions demonstrate confidence in the Lake PG3 result rather than the Lake PG9 due to comparisons with an independent record and measured meteorological data (Porter et al. 2014) (supplemental Figure S13).

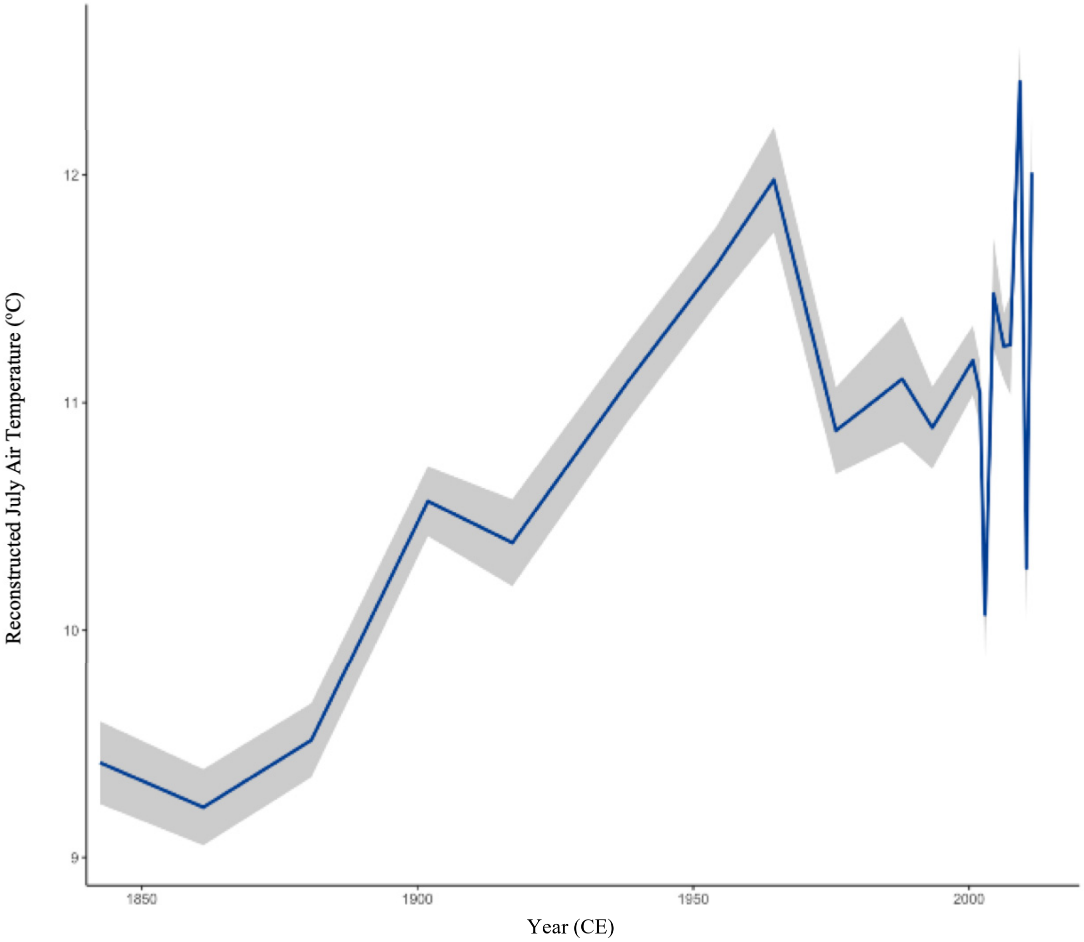

Figure 3.10 Chironomid-inferred mean July air temperature (°C) since ~1800 CE, reconstructed using data from Lake PG3 and the Fortin WA-PLS model (Fortin et al. 2015).

3.7 Discussion

Temperature is largely considered the primary controlling factor of chironomid larvae community assemblages, which are widely used as a proxy for paleo-temperature reconstruction (Walker 2001; Barley et al. 2006; Medeiros & Quinlan 2011; Upiter et al. 2014). Yet, recent research suggests this relationship may be confounded by secondary or co-linear variables in relation to landscape disturbance (Quinlan et al. 2005; Brodersen & Quinlan 2006; Medeiros et al. 2015). Accelerating permafrost degradation can result in increased terrestrial-aquatic connectivity, which may cause alterations to the status of Arctic aquatic systems (Kokelj et al. 2009b; Moquin et al. 2014; Koch et al. 2018). Smol et al. (2005) note warming temperatures may allow for thresholds to be crossed by chironomid species, that were once range-limited, to access northern environments. Indeed, these threshold changes are noted to result in increasing productivity within shallow Arctic lakes, while deeper lakes have been characterized by enhanced planktonic development (Smol et al. 2005). Increased connectivity in Alaska has been associated with increased fish species richness, suggesting landscape changes can also impact the distribution of vertebrates that are significant to ecosystem processes and Inuit subsistence (Watt-Cloutier 2015; Laske et al. 2016). Here, we compared two lakes with varying degrees of landscape connectivity (Lake PG3 and Lake PG9) to elucidate differences in the systems that reflect the influence of landscape rather than regional temperatures, allowing for a greater understanding of the relationship between lakes and landscape disturbance.

3.7.1 The Influence of Landscape Connectivity

Landscape disturbance is known to result in ecological succession (Kokelj & Burn 2005; Jorgenson et al. 2013), which highlights the significance of a greater understanding of the complex consequences of recent rapid increases to permafrost degradation. Moquin et al. (2014) note cascading Arctic aquatic foodweb alterations as a possibility for the Inuvik, N.W.T., area under future warming conditions, as suggested by current differences in macroinvertebrate abundance and diversity. Likewise, Mesquita et al. (2010) found lakes disturbed by retrogressive thaw slumps had greater submerged macrophyte communities than undisturbed lakes, suggesting nutrient enrichment from permafrost degradation can increase primary production and alter habitat structure. The impacts of landscape disturbance are, therefore, shown to result in foodweb and habitat structural changes, suggesting the records of Lake PG3 and Lake PG9 may display divergent trends if, as hypothesized, landscape alterations (e.g., patterned ground) rather than regional temperature is primarily impacting the chironomid community assemblage of Lake PG9.

The influence of microtopography within the permafrost regions of the Arctic is a significant factor that has cascading influence from controlling overland hydrology to nutrient content of isolated aquatic systems (Koch et al. 2018). This is especially relevant within the Mackenzie River Delta uplands region, where recent permafrost degradation has the capacity to increase connectivity of the terrestrial-aquatic interface (Lantz & Kokelj 2008; Steedman et al. 2017). Aerial photography of Lake PG3 and Lake PG9 provide indications of diverging microtopographies, where Lake PG3 shows little modern evidence of permafrost degradation induced topographic changes while Lake PG9 demonstrates extensive and increasing development of patterned ground in the surrounding catchment since at least 1950 CE (Figures 3.2 & 3.3). Medeiros et al. (2015) examined Canadian Arctic lake surface samples for chironomids and found the majority of sites not significantly associated with temperature were located in ecotonal areas. The location of Lake PG9 within a transitional permafrost gradient (Figure 3.1) suggests landscape disturbance in the surrounding area, as evidenced by aerial photography (Figure 3.2), would support a large influence from the terrestrial environment.

The C:N ratio has been described as indicative of the source of organic matter within an aquatic system, where an increased ratio suggests increasing allochthonous inputs. Values of >10 for the C:N ratio are accepted as possibly indicating terrestrial origin while <10 suggests algal sources (Meyers 1994; Kaushal & Binford 1999; Meyers 2003; Stivrins et al. 2019). Kaushal & Binford (1999) investigated the applicability of C:N ratios in determining the source of nutrients and material from lacustrine sediment cores; they demonstrated this to be an effective method as it was able to detect historic deforestation surrounding Lake Pleasant, Massachusetts, USA. Consequently, the C:N ratio for both records reflect some amount of terrestrial influence as values <10 are not observed in either lake; however, an examination of the fluctuations over time with additional lines of evidence may elucidate changes to sources of nutrients within the sediment.

Isotopic $\delta^{13}C$ content is known to show differences in source material between lakes when considered with C:N ratio data; $\delta^{13}C$ values of -25 to -30 ‰ can indicate both lacustrine algae and C_3 terrestrial vegetation while the C:N ratio can help differentiate sources as here a ratio >15 is associated with terrestrial material (Meyers 2003; Torres et al. 2012). The combination of $\delta^{13}C$ and C:N data for Lake PG9 suggest the basin predominantly received terrestrial material for the period of ~1602-1983 CE and then transitioned to algal sources until the end of the record. In particular, the Lake PG9 C:N ratio rapid increase during the period of ~1900-1960 CE supports an increase in allochthonous material entering the basin, relative to the preceding years (Itkonen et al. 1999). These data agree well with the results of Koch et al. (2014) that suggest a growing consequence of channelization caused by ice-wedge troughs, is the result of nutrient-rich additions to Arctic lakes and ponds. Lake PG3 $\delta^{13}C$ content and C:N ratio reflect terrestrially sourced of material entering the basin for the period of approximately 1843-

1975 CE, while data suggests autochthonous material as the primary source from ~1702-1820 CE and ~1988-2011 CE. These data reflect greater terrestrial influence throughout the history of Lake PG9, when compared to Lake PG3, and support the conclusion of sustained allochthonous influence for the period of ~1602-1983 CE.

Following ~1960 CE Lake PG9 sharply transitions to high LOI_{550} and low C:N ratio conditions, suggesting a transition to higher aquatic (algal) production than previously observed. The evidence of allochthonous additions to Lake PG9 between ~1900-1960 CE reflects possible nutrient loading, which would support increasing primary production resulting in reduced C:N and increased organic content. The C:N ratio inferred increase in primary production for Lake PG9 is also supported by high %N content since ~1960 CE, which suggests the very low $\delta^{15}N$ values observed within the record may be due to the ability of algae to discriminate against $\delta^{15}N$ (Torres et al. 2012). This apparent nutrient loading will be examined in relation to *in situ* productivity in section 3.7.2.

3.7.2 The Influence of Terrestrial Connectivity on Productivity Through Time

Chironomid production, taxonomic abundance, and the geochemical data of Lake PG3 and Lake PG9 exemplify different lake histories. Lake PG9 is characterized by taxa associated with greater productivity than those seen in Lake PG3. The overall decrease in the abundance of nutrient-sensitive taxa coupled with increases to nutrient-tolerant taxa within the PG9 record, particularly since ~1983 CE, support nutrient enrichment that could contribute to greater productivity. Greater secondary production is also observed within Lake PG9, where chironomid production values (HC g^{-1} DW) are much higher than those within the PG3 record. These differing taxonomic assemblages and trends support greater evidence of increasing productivity within Lake PG9 than is seen throughout the Lake PG3 record, which is supported by the organic carbon and nitrogen elemental and isotopic geochemical data discussed in section 3.6.1.

Alterations to $\delta^{13}C$ and organic carbon content can suggest productivity and source changes within the aquatic system, due to differing demands of the algal community (Hodell & Schelske 1998; Meyers 2003; Torres et al. 2012). This relationship is observed within the PG9 record where increasing allochthonous material is suggested by the relatively high $\delta^{13}C$ values, which is followed by a decrease to isotopic carbon within the sediment following ~1960 CE Increasing productivity over time is observed within the PG9 record where $\delta^{13}C$ values decrease following ~1960 CE, suggesting increased aquatic productivity, until ~2008 CE after which there is an increasing trend until ~2014 CE that supports greater primary production due to the increased algal nutrient demand. Concurrently, the $\%C_{org}$ content remains on a steady positive trajectory increasing by ~10% from ~1602-2011 CE.

While subfossil chironomid assemblages are known to be effective indicators of lake productivity, co-linear and secondary variables (e.g., temperature, depth, nutrients availability, and habitat condition) can complicate this relationship (Brodersen & Quinlan 2006; Balasubramaniam et al. 2017). Landscape connectivity of thaw polygons in the catchment of Lake PG9, as demonstrated by the geochemical data explored in section 3.6.1, likely strongly contributed to changes in chironomid production. The peak chironomid production of PG3 (1114.74 HC g^{-1} DW) was considerably less than the observed peak within the PG9 record (3979.81 HC g^{-1} DW). Likewise, the abundance of chironomid indicators observed in Lake PG9 increased throughout the record, with the largest growth observed after ~1983 CE, which was accompanied by increases to both %C_{org} and %N in the same period, indicating conditions conducive to rapid aquatic production. *Ablabesmyia* and *Procladius* are known to be carnivorous and the observed drastic increase within Lake PG9 since ~1983 CE may be caused in part by the increasing overall chironomid production within the record, suggesting increased prey availability (Walker et al. 2001). Production in Lake PG3 increased at a more gradual rate through time, where growth was typically characterized by <500 HC g^{-1} DW, which was then reversed as the chironomid production decreased following ~2007 CE. Subsequently, chironomid production within Lake PG3 was consistently less than that observed within Lake PG9.

Increased primary productivity would also be expected under increased terrestrial contribution conditions due to a greater amount of bioavailable nutrients, as evidenced by rapid increases to the $\delta^{15}N$ and %N content of Lake PG9 following ~1965 CE suggesting nitrogen enrichment. In contrast the nitrogen content of Lake PG3 sees a much more muted increase. These data are supported by reduced *Cladopelma lateralis type* abundance within Lake PG9 as compared to Lake PG3, suggesting greater production and nutrient availability within Lake PG9 as the taxon is not tolerant of high nutrient conditions (Brooks et al. 2007; Taylor et al. 2017). Brodersen & Quinlan (2006) observed extinction of *Heterotrissocladius spp.* from lake records after periods of nutrient loading, suggesting an inability of the taxon to adapt to enhanced nutrient levels. *Heterotrissocladius spp.* did not have >2 % abundance and are therefore not represented within the Lake PG9 biostratigraphy, suggesting possible influence of the nutrient levels observed in the record.

These trends are also demonstrated through the *Cricotopus spp.* data from each record. *Cricotopus intersectus* remained steady throughout the PG3 record, while *Cricotopus spp.* increased in the PG9 record over time. The largest peaks were found in Zone 3 of Lake PG9, where *Cricotopus spp.* experienced the highest abundance at ~2010 CE. These data suggest relatively stable or moderate productivity throughout the PG3 record, yet Lake PG9 may reflect increased production as *Cricotopus spp.* surges within shallow lakes are associated with greater lake productivity (Brodersen & Quinlan 2006). Indeed, increasing productivity within Lake PG9 over time may be linked to permafrost disturbance caused nutrient loading, which is initiated and sustained through a positive feedback system with warming temperatures.

The organic content (LOI_{550}) of lacustrine sediment cores is also associated with productivity, temperature, and depth, and is considered a significant factor that can control chironomid distributions (Walker et al. 1991; Larocque et al. 2001; Brodersen & Quinlan 2006; Luoto et al. 2016). In particular, increasing organic content has been descriptive of higher aquatic productivity (Upiter et al. 2014). Gajewski et al. (2005) investigated chironomid distribution in 50 lakes located in the Canadian Arctic Archipelago, also finding a relationship between high LOI values and *Sergentia type* abundance. This association between the taxon and high organic content supports the observed abundance increases to *Sergentia coracina type* since ~1965 CE within the PG9 record, while, in contrast, *Sergentia coracina type* abundance within Lake PG3 does not reflect the LOI_{550} values as closely as Lake PG9.

The LOI_{550} values at ~1881-1902 CE (58.85 - 69.92 %) do suggest an increase in aquatic productivity in Lake PG3 at the beginning of the 20th century. However, following a ~1902 CE peak, LOI_{550} values generally stabilizes with organic content ranging from 64.32 - 69.85 % for the remainder of the record. *Sergentia coracina type* and *Stictochironomus rosenschoeldi type* have been described as indicators of mesotrophic conditions by Meriläinen et al. (2000), who note increases to the taxa's abundance from Lake Lappajärvi following 1950 CE and a decline of *Micropsectra spp*. The Lake PG3 biostratigraphy reflects this succession to moderate levels of productivity, with increasing mesotrophic indicator taxa between ~1881-1902 CE (Figure 3.6). The Lake PG3 C:N ratio for ~1881-1902 CE demonstrates an increasing trend towards a peak at ~1917 CE, also suggesting the increasing abundance of mesotrophic taxa may be due to increasing terrestrial material entering the lake and subsequently leading to greater productivity as a result of additional available nutrients. The combination of taxonomic and geochemical changes observed in Lake PG3 at the end of the 19th century and beginning of the 20th century support increased productivity relative to the time before (~1881 CE) and the period following (~1917-2014 CE).

Increased chironomid abundance since ~1983 CE (Zones 2 & 3) is observed within the PG9 record, where the majority of taxa reach peak abundance levels. However, chironomid taxa abundance of Lake PG3 demonstrates varied changes. The peaks in abundance for *Dicrotendipes nervosus type,* within both Lake PG3 and Lake PG9, coincide with intervals containing high organic content. This agrees well with results from the analyses of 31 lakes in the subarctic region of Finnish Lapland by Luoto et al. (2016), whom demonstrated a strong association between *Dicrotendipes nervosus type* and highly organic sediments, while noting *Paratanytarsus type* and *Psectrocladius spp.* distribution was also selective for organic material-rich sediments. The PG3 record showed increased organic content coincided with increases to *Psectrocladius sordidellus type* abundance; yet, the taxon was also observed to have higher abundance in intervals of moderate organic content, suggesting nutrient availability may not be the primary controlling factor. Lake PG9 *Paratanytarsus type* and *Psectrocladius spp.* abundance more closely followed the peaks and overall trend of the sediment organic content especially following ~2002 CE, where the LOI_{550} values increase steeply. These trends in chironomid assemblage change in relation to organic content can also be influenced by the depth of each lake, as the quantity of organic material precipitating to the profundal of deep lakes is lower compared to shallower lakes (Brodersen & Quinlan 2006), suggesting depth may have skewed the relationship within the shallow basin of Lake PG9.

Tanytarsus lugens type has been suggested as positively associated with organic carbon (Gajewski et al. 2005), which is observed within the PG9 record where the only intervals with the taxon present coincide with the peak LOI_{550} values (56.7-66.9 %) and relatively high $\%C_{org}$ (~30-31 %). The lack of a relationship between *Tanytarsus lugens type* and $\%C_{org}$ in Lake PG3 suggests temperature may act as the primary factor influencing the taxon, yet the strength of the relationship in Lake PG9 supports the hypothesis of an influence of secondary variables.

Increased nutrient availability would be expected to allow for greater primary production, which may be observed as an increase to aquatic macrophytes (Brodersen & Quinlan 2011). Increases in the abundance of *Tanytarsus mendax type, Limnophyes,* and *Chironomus spp.* in the PG3 record after ~1993 CE, with a peak at ~2007 CE ~2010 CE, suggests a transition to a more macrophyte-rich environment than previously observed (Smith et al. 1998; Medeiros et al. 2015; Taylor et al. 2017). However, the abundance of *Tanytarsus mendax type* within the PG9 record exceeds that observed within the PG3 record, and also begins increasing much earlier (~1919 CE compared to ~2007 CE).

Cladotanytarsus mancus type and *Tanytarsus pallidicornis type* have also been descriptive of productive littoral environments (Hall et al. 1999; Potito et al. 2014; Chique et al. 2018). The evident abundance increases within the PG9 record to *Tanytarsus mendax type, Cladotanytarsus mancus type,* and *Tanytarsus pallidicornis type* suggest a transition to a more nutrient-rich system since the end of Zone 1 (~1983 CE) (Brooks et al. 2007; Potito et al. 2014; Chique et al. 2018). This is also supported by clear abundance increases for *Zalutschia lingulata pauca type* from those observed within the period prior to ~1993 CE. The association of *Zalutschia spp.* with macrophytes (Brooks et al. 2007; Medeiros & Quinlan 2011) may help explain the increase of *Zalutschia lingulata pauca type* observed in the PG9 record over time, as LOI_{550} and C:N ratio data supports the system increasing in aquatic primary productivity.

3.7.3 Paleo-Temperature Reconstructions

Temperature is known to be a primary variable that governs the distribution of chironomid assemblages in northern environments, which has led to many investigations using chironomids as proxies of climate and environmental change (Larocque et al. 2001; Walker et al. 2001; Gajewski et al. 2005; Barley et al. 2006; Walker & Cwynar 2006; Medeiros & Quinlan 2011; Potito et al. 2014; Medeiros et al. 2015; Luoto et al. 2016). Porter et al. (2014) note recent climate warming in the Mackenzie Delta region through

δ^{18}O analysis of tree-rings, finding their reconstruction of increasing spring-summer temperatures since 1780 CE agreed well with local measured temperature increases since 1871 CE. The reconstructed chironomid-inferred July air temperature of Lake PG3 indicated an increase in temperature since ~1850 CE (Figure 3.10). This agrees well with the δ^{18}O reconstruction of Porter et al. (2014) and the observed meteorological record (supplemental Figure S13). It is not surprising that a chironomid-based temperature reconstruction in Lake PG3 was in agreement with the noted trends for region; however, an attempt to use the same calibration-in-time model (Fortin et al. 2015) for Lake PG9 found a starkly opposite trend (supplemental Figure S18). The chironomid taxa that changed in abundance and diversity through time for the PG9 record were primarily those reflective of changes in nutrient availability and habitat conditions. Indeed, examinations of specific taxa within each record reveals divergent trends.

Walker et al. (1991) associated *Stictochironomus spp.* with cold conditions, which is supported by the findings of Brooks et al. (2007) and Taylor et al. (2017). Additionally, Meriläinen et al. (2000) found *Stictochironomus rosenschoeldi type* were more abundant under oligotrophic conditions and decreased with greater eutrophication. This association of *Stictochironomus spp.* with cold-water and oligotrophic conditions is reflected within the PG3 record where the taxon has the greatest abundance prior to ~1917 CE, which is the timing of steep increases to temperature minima in both the Porter et al. (2014) reconstruction and the local meteorological record (supplemental Figure S13). A similar trend is observed within the PG3 record for the cold and ultra-oligotrophic indicator *Micropsectra radialis type* (Meriläinen et al. 2000; Barley et al. 2006; Brodersen & Quinlan 2006), where the taxon declines in abundance until ultimately disappearing after

~2001 CE. The modelled gradual increase in temperature from Lake PG3 data is supported by the opposite trend observed in *Micropsectra radialis type* abundance.

Within the PG3 record, the chironomid community assemblage follows the expected trajectory of influence from temperature, as based on known warming for the period of ~1958-2019 CE. *Sergentia* have typically been interpreted as cold temperature optima taxa (Barley et al. 2006; Medeiros & Quinlan 2011; Upiter et al. 2014). The chironomid-temperature relationship is exemplified within the PG3 record where *Sergentia coracina type,* along with other cold-water and/or oligotrophic taxa (e.g., *Psectrocladius sordidellus type, Stempellinella-Zavrelia type,* and *Tanytarsus lugens type*), exhibit a decreasing trend up the core, which supports the warming $\delta^{18}O$ reconstruction by Porter et al. (2014) and matches well with the meteorological data recorded in Inuvik since 1958 CE (Brooks et al. 2007; Potito et al. 2014; Taylor et al. 2017; Chique et al. 2018). In contrast, *Sergentia coracina type* and *Tanytarsus lugens* show the opposite trajectory within the PG9 record, where the abundance increases up the core to peaks at ~2010 CE for both taxa. The typical association of *Sergentia coracina type* and *Tanytarsus lugens type* with cold conditions suggests the increase in abundance observed within the PG9 record is the result of secondary variables rather than temperature.

Warm-water associated taxa can also highlight the differences within the Lake PG3 and Lake PG9 records. The warm-water indicator *Pseudochironomus type* was not present within the Lake PG3 biostratigraphy, yet it was represented as a dominant taxon within Lake PG9 throughout Zones 1 & 2 (~1993-2014 CE). However, rapid fluctuation of *Pseudochironomus type* within the PG9 record, coupled with the known lack of correlation of the taxon with depth (Barley et al. 2006), suggest factors other than temperature and depth may have contributed to the growth in abundance of that taxon. Taxonomic data from Lake Várddoaijávri, northern Finland, along with weighted average temperature optima described by the combined Finnish training set, define *Tanytarsus mendax* as having an optimum July temperature >14^{o}C (Luoto et al. 2014). This association of *Tanytarsus mendax type* with a relatively warm temperature suggests the abundance increases observed within the PG3 record since ~2007 CE reflect increasing temperatures.

Comparisons of the chironomid-inferred July air temperature reconstruction for Lake PG3 with an independent temperature reconstruction covering the period since 1780 CE (Porter et al. 2014) and recorded meteorological data since 1958 CE (supplemental Figure S13) support a strong relationship between temperature and the chironomid community assemblage. As such, temperature seems to be the primary controlling factor of the Lake PG3 chironomid community assemblage over time, where the decrease of cold-water taxa and the subsequent increase of warm-water taxa demonstrate expected relatively rapid warming for the region since ~1850 CE. In contrast, the Lake PG9 chironomid assemblage does not appear to be associated with temperature as a primary factor directing chironomids assemblages as the changes in abundance were not able to produce an accurate temperature reconstruction that aligned with analogue climatic changes. Rather, secondary variables seem to be driving the observed trends in chironomid abundance for Lake PG9, as the majority of increasing taxa are associated with heightened productivity.

3.8 Conclusion

The uplands region of the Mackenzie River Delta, N.W.T. is characterized by a gradient of permafrost, which controls connectivity of the terrestrial-aquatic interface. Changes in connectivity have been linked to alterations within polar aquatic systems, including cascading foodweb and habitat alterations (Burn & Kokelj 2009; Mesquita et al. 2010; Grosse et al. 2011; Moquin et al. 2014; Medeiros et al. 2015; Koch et al. 2018). Chironomids are noted as an excellent proxy indicator due to their rapid response to variables such as temperature, nutrients, and habitat changes, and they have provided a method to understand the lake histories of a highly connected system (Lake PG9) and a less connected system (Lake PG3). Consequently, the abundance changes of temperature-associated taxa throughout the PG3 record and nutrient-associated taxa in Lake PG9 revealed three key insights: (1) the chironomid community of Lake PG3 successfully reconstructed July air temperature since ~1702 CE, reflecting rapid climate warming since ~1850 CE; (2) the chironomid community of Lake PG9 reflects the influence of secondary or co-linear variables (e.g., nutrients availability), which is likely due to observed increasing connectivity with the terrestrial environment through permafrost degradation; and (3) Lake PG9 has experienced rapidly growing aquatic productivity since ~1965 CE, which is indicated to be the result of increasing terrestrially sourced material entering the basin.

While the PG3 and PG9 lake systems may seem isolated and small within the context of the global climate crisis, they provide important evidence of a concerning trend within the western North American Arctic, where the landscape is changing at an alarmingly rapid rate (Lantz & Kokelj 2008; Kokelj et al. 2009a; Breton et al. 2009;

Liljedahl et al. 2016). This acceleration of landscape disturbance and the resulting in Lake changes are significant to our understanding of the Arctic environment, as the terrestrial-aquatic interface relationship can lead to ecological repercussions (e.g., species threshold changes and habitat alteration). These results build upon the conclusions of Moquin et al. (2014), whom suggested retrogressive thaw slumps can greatly disturb the macroinvertebrate community structure of impacted lakes. In particular, our research suggests cascading structural changes can also occur in lakes that experience more indirect landscape disturbance (e.g., increased channelization from thaw polygon formation) rather than the catastrophic effects of retrogressive thaw slumps. These results are significant and suggest the cascading *in situ* impacts of permafrost degradation may be more widespread than previously observed. Thus, we highlight growing concern of the reliability of chironomid-inferred July air temperature reconstructions from transitional regions that may be susceptible to landscape disturbance impacts; suggesting future studies should take great care when interpreting chironomid data from such regions.

3.9 References

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CHAPTER 4 CONCLUSION

4.1 Statement of Student Contribution

Chapter design by Alannah Niemeyer, chapter writing by Alannah Niemeyer with editorial contributions from Andrew Medeiros.

4.2 Introduction

The influence of landscape disturbance, whether environmentally or anthropogenically caused, strongly controls the structure and functioning of aquatic systems (Moquin et al. 2014; Chique et al. 2018; Lacelle et al. 2019). Here, the long-term influence of human settlement in western Scotland in relation to landscape-use change was reviewed, while primary data from two lakes (Lake PG3 & Lake PG9) in the western Canadian Arctic investigated the impacts of warming-induced permafrost degradation and the resulting topography and hydrological changes on aquatic systems. This research supports the conclusions of previous studies (Brodersen & Quinlan 2006; Mesquita et al. 2010; Battarbee et al. 2012; Moquin et al. 2014; Mederios et al. 2015; Luoto et al. 2016; Balasubramaniam et al. 2017), identifying the importance of caution and multiple lines of evidence when employing proxy reconstruction methods to areas with historical or current landscape disturbance.

4.3 Landscape Disturbance and Aquatic Systems in Western Scotland: Key Insights

The review of existing literature, paleolimnological reconstructions, and archaeological evidence from western Scotland revealed the entangled nature of long-term human settlement and environmental controls. This review resulted in three key insights:

1. The impacts of landscape disturbance from anthropogenic activity can confound paleoenvironmental attempts to reconstruct past conditions.

Within the context of long-term human occupation, paleolimnological research has been forced to contend with co-linear variables (Barber et al. 2013; Taylor et al. 2017; Bishop et al. 2018; Chique et al. 2018; Edwards et al. 2019). This review revealed site and proxy selections to be significant to the ability to overcome confounding co-linear variables; the most successful studies of historic environmental change and human influence carefully interpreted information from several sources of proxy data, including a mixtures of chironomid inferred air temperature, pollen and plant macrofossil inferred vegetational changes, charcoal inferred human activity/presence, and diatom inferred water quality changes (Jones et al. 1989; Bishop et al. 2018; Chique et al. 2018).

2. Increasing connectivity with the terrestrial environment (e.g., forestry & agriculture) can provide flow pathways and subsequent additions of sediment that alter the state of an aquatic system.

Long-term human occupation of western Scotland has disturbed the natural landscape, with human-induced environmental change estimated to have begun during the Neolithic period (c. 3800-3600 BCE) due to the introduction of agriculture resulting in deforestation; with possible degradation of woodlands over time due to a possible prolonged lag effect (Tipping et al. 2012; Bishop et al. 2018). Similarly, Robinson (1983) note Mesolithic pollen evidence suggests a transition from woodlands to open habitat on the Inner Hebridean Island of Arran. These landscape disturbance examples demonstrate the relatively early and drastic changes to the environment of western Scotland.

Moreover, this evidence of prolonged anthropogenic influence is apparent within aquatic records where human occupation has been linked to greater terrestrial inputs (e.g., agricultural runoff) (Bennion et al. 2004). This nutrient loading results in alterations to the biotic and abiotic conditions of an aquatic system, effectively shifting the state of the system and typically resulting in eutrophication (Chique et al. 2018).

3. The integrity of paleoclimate results within areas of known disturbance may be upheld by careful site and proxy selection, as demonstrated within the context of co-linear variables affecting Scottish records.

Within the context of research within western Scotland, which has a high density of prehistoric human settlement (Figure 2.1) (Saville & Wickham-Jones 2012), remote high elevation sites are of particular interest as those locations have historically been inaccessible to human settlement. Consequently, the lack of settlement at remote high elevation sites suggests a lack of direct anthropogenic landscape disturbance (e.g., forestry & farming), indicating western Scotland as an important region where the influences of co-linear variables can be detangled through comparisons between disturbed and undisturbed aquatic systems. The advocacy of western Scotland as a unique site for paleolimnological research of co-linear variables is supported by a previous study from Tipping et al. (2012), whom called for increased research in light of the scarcity of Scottish paleoclimate records.

The combination of proxies utilized for reconstruction is shown to increase confidence in results. For example, Walker et al. (2003) demonstrated the use of multiple proxies (e.g., pollen, plant macrofossil, coleopteran, geochemical & isotopes) to reconstruct Lateglacial environmental change in the southwestern UK; these results agreed well with Scottish records (Brooks et al. 2012b; Saville & Wickham-Jones 2012) and exemplify the strength added to conclusions through multiple lines of reconstruction evidence. Additionally, emerging proxies of climatic and anthropogenic change have emerged in recent years (e.g., faecol sterols & sedimentary DNA) and may provide increased confidence in results for future studies (Haile et al. 2007; Sjögren et al. 2016; Argiriadis et al. 2018; Harrault et al. 2019).

4.4 Landscape Disturbance and Aquatic Systems of the Western Canadian Arctic: Key Conclusions

The investigation of the influence of connectivity on productivity along the terrestrial-aquatic interfaces utilized subfossilized chironomids and geochemical data to better understand lake histories of systems located within the transitional permafrost zone near Inuvik, N.W.T. The specific research question of this thesis concerning the primary data from Lake PG3 and Lake PG9 asks:

How does the observed productivity in lakes surrounding Inuvik N.W.T., Canada relate to: a) lake productivity in the southern discontinuous permafrost zone; and b) reconstructions of productivity from lacustrine sediment cores of the study lakes?

In order to address this research question three research objectives were investigated;

Research Objective # 1: Outline surface and/or near surface flow.

The Chapter 1 of this thesis effectively outlined surface and near surface flow within the context of the Arctic ecosystem. The literature review of this thesis summarized the hydrological cycle of the Arctic and the critical role of overland flow due to the inability of sub-surface transport to occur in the presence of permafrost (Lemieux et al. 2008; Andresen & Lougheed 2015; Abolt et al. 2018; Bond & Carr, 2018). This review established the context of the western Canadian Arctic environment to allow for a better understanding of the parameters in which Lake PG3 and Lake PG9 exist and function.

Research Objective # 2: Contrast productivity in highly connected lakes to productivity of lakes with lower connectivity.

This objective was investigated through a combination of literature review and primary data analysis. Within the literature it is established that the hydrological cycle of the Arctic is in part controlled by overland flow due to the presence of permafrost (Bond & Carr, 2018). Warming induced permafrost degradation has been associated with increasing connectivity, and subsequent greater movement of water and sediments, largely due to the release of long-frozen substrate from retrogressive thaw slumps and increased channelization from the formation of thaw polygons (Anderson et al. 2007; Andresen & Lougheed 2015; Medeiros et al., 2015; Schuur et al. 2015). This release of substrate from retrogressive thaw slumps has been shown to alter aquatic systems drastically (e.g., biota and productivity changes) due to the addition of nutrients and ions that are typically only available at low levels (Kokelj et al. 2009a; Moquin et al. 2014; Frey et al., 2016).

The results of this thesis allowed for the comparison of productivity changes over time within a highly connected system (Lake PG9) and a less connected system (Lake PG3), where the connectivity of each lake to the surrounding environment was apparent from aerial photographic evidence of permafrost degradation (Figures 3.2 & 3.3) and the position of Lake PG3 in a location with greater permafrost depth than Lake PG9 (Figure 3.1). The productivity differed greatly between Lake PG3 and Lake PG9; chironomid assemblages of each record displayed divergent trends of productivity associated taxa. For example, *Cricotopus spp.* are noted as indicators of productivity (Brodersen & Quinlan 2006), and while the taxa fluctuate throughout the PG3 record there are clear increases observed within the PG9 record following ~1983 CE (Figure 3.6).

Research Objective # 3: Identify contemporary productivity relationships and compare observations with reconstructions of historic productivity from lacustrine sediment cores.

The contemporary productivity observed within Lake PG3 suggests moderate levels, while in contrast Lake PG9 data suggests relatively high levels. Chironomid abundance and geochemical data results from Lake PG3 support productivity increasing around the beginning of the 20th century (~1881-1917 CE). Specifically, the combination of increased organic content, mesotrophic chironomid taxa (e.g., *Sergentia coracina* & *Stictochironomus rosenschoeldi*), and C:N ratio indicate possible nutrient loading from terrestrial inputs and subsequent increased productivity (Meriläinen et al. 2000). While the ~1881-1917 CE period suggests increased productivity than observed prior to ~1881 CE, the remainder of the PG3 record is characterized by stabilization of productivity levels and instead indicated abundance changes to temperature associated taxa. Conversely, the results from Lake PG9 reflect clear increases in productivity over time, with the greatest levels observed within the contemporary sediments. Chironomid production in particular reflects the greatest productivity of Lake PG9 occurred since ~1983 CE (Figure 3.9). This conclusion of increased productivity following ~1983 CE is supported by the increases in abundance of nutrient-tolerant taxa (e.g., *Tanytarsus mendax type, Cladotanytarsus mancus type,* & *Tanytarsus pallidicornis type*) (Brooks et al. 2007; Potito et al. 2014; Chique et al. 2018), as well as the reduction in the abundance of the nutrient intolerant taxon *Cladopelma lateralis type* (Brooks et al. 2007; Taylor et al. 2017). Thus, the productivity trend of the lakes over time are divergent; where Lake PG3 reflects an early increase to moderate levels that were sustained into the modern time, while Lake PG9 contemporary evidence supports relatively high productivity compared to the earlier intervals of the record.

4.5 Final Thoughts and Future Directions

While geographically distant, the examinations of western Scotland and the western Canadian Arctic have allowed for considerations of terrestrial-aquatic connectivity within two unique regions, where similar ecological and methodological challenges are being faced. Both regions have encountered changes throughout history due to landscape disturbance (e.g., glaciation, human occupation & permafrost degradation) and recent climate warming is expected to exacerbate these impacts (Jones et al. 1989; Edwards & Mithen 1995; Bennion et al. 2004; Gregory et al. 2005; Quinlan et al. 2005; Smol et al. 2005; Kokelj et al. 2009b; Post et al. 2009; Mesquita et al. 2010; Brooks et al. 2012;

Saville & Wickham-Jones 2012; Moquin et al. 2014; Medeiros et al. 2015; Bishop et al. 2018; Edwards et al. 2019). This thesis highlights the importance of transitional landscapes (e.g., the Western Isles of Scotland & the uplands region of the Mackenzie Delta, N.W.T.) as areas of concern due to their vulnerability to the impacts of increasing terrestrial-aquatic connectivity and supports future research within such regions.

Methods of combating the issue of secondary or co-linear variables impacting paleoclimate reconstructions have recently emerged. Sedimentary DNA analysis has recently been utilized to create high-resolution vegetation and land-use history through utilizing trace amounts of ancient DNA (Willerslev et al. 2003; Haile et al. 2007; Smith et al. 2015; Sjögren et al. 2016). Similarly, recent advancements in the analyses of faecal sterols and bile acids have allowed for fine-grain resolution reconstructions of species historically present (Harrault et al. 2019). The application of this method in conjunction with traditional proxies (e.g., chironomids & pollen) may enable direct linkages between landscape change and human occupation, essentially discerning the influence of anthropogenic activity from natural/climatic induced changes (Argiriadis et al. 2018). The statistical technique of additive modelling (AM) examines the relationship between controlling factors and the observed proxy response, serving as a potential method to address confounding co-linear variables within records (Simpson & Anderson 2009). While these methods are not perfect, as no proxy is, they suggest new ways of understanding past conditions in relation to confounding variables. Thus, emerging lines of paleoenvironmental analyses may allow for greater confidence in proxy results and should be applied to vulnerable transitional regions where they may be effective in detangling the influence of secondary or co-linear variables.

Finally, greater understandings of environmental change in relation to aquatic systems could provide insights for past human behaviour to change and may inform adaptive paths forward within a rapidly warming world. In particular, aquatic systems are an important part of Inuit life, providing subsistence and cultural functions (Weatherhead et al. 2010; Medeiros & Niemeyer 2020). Sheila Watt-Cloutier has been an advocate and voice for Inuit rights within the global political sphere, describing the intrinsic relationship between the Arctic environment and Inuit while shining a light on the present and unrelenting implications of environmental degradation (e.g., loss of ice, difficulties with hunting and fishing, and problems of passing on traditional knowledge to the next generation) (Watt-Cloutier 2015). The results from Lake PG3 and Lake PG9 support these issues and suggest changes in patterns of species distribution and richness within Arctic aquatic systems have altered within recent history and will continue to change under warming conditions. Understanding these changes, and subsequent vulnerabilities, could support methods of adaptation for impacted groups. Therefore, future research at sites of transition across the Arctic is recommended to enable a better understanding of the clearly changing terrestrial-aquatic relationship that will most likely have biological (e.g., species crossing thresholds) and anthropogenic (e.g., subsistence and knowledge sharing) consequences in the near future.

4.6 References

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APPENDIX: SUPPLEMENTARY MATERIALS FOR UNDERSTANDING THE INFLUENCE THAW POLYGONS ON PRODUCTIVITY OF ARCTIC LAKES

S.1 Statement of Student Contributions

Study design by Alannah Niemeyer and Andrew Medeiros, site information compiled by Anthony Todd, loss on ignition completed by Anthony Todd, chironomid data analysis completed by Alannah Niemeyer and Andrew Medeiros, supplemental material writing by Alannah Niemeyer with editorial contributions from Andrew Medeiros.

S.2 Introduction

The paleolimnological methods of chironomid subfossil, elemental and isotopic geochemical analyses were applied to two lacustrine sediment cores from the Mackenzie River Delta uplands region, near Inuvik, N.W.T. One lake (Lake PG9) had known permafrost degradation in the surrounding catchment, while the second (Lake PG3) exemplified a less impacted system and was therefore designated as the reference lake. Here, additional information of physical lake characteristics, diagnostic tests, and chironomid diversity through time are presented.

S.3 Site Information

Table S1 Location of both PG3 and PG9, shown with accompanying physical and chemical characteristics observed/taken July of 2013 (Todd 2014).

Site	Latitude	Longitude	Area (ha)	Temp (°C)	DO (mg/L)	SPC (µs /m)	pH	Depth (m)
PG3 (Reference lake)	68.839722	-134.279444	13.9	17	9.71	32.8	6.88	>2.0

PG9 (Thaw Polygon lake)	68.813500	-134.031700	0.2	16.2	8.65	24	6.39	2.0

S.4 Methods

S.4.1 Chironomid Analysis

Lake core sediment samples from both PG9 and PG3 were sorted into 0.5 cm intervals and bagged accordingly. Both cores had a diameter of 8.4 cm, while PG3 was 38.5 cm deep, and PG9 was 14.5 cm in depth. Sample processing was then undertaken for PG9 between November 2018 and February 2020, while PG3 samples were processed between May 2019 and March 2020. Samples were initially sifted using 106 µm and 212 µm nested sieves and washed with 95% ethanol, then the two grain sizes (labelled 100 and 200) for each interval were stored in 20 mL scintillation vials. These samples were then treated with a potassium hydroxide (KOH) hot bath at 75^{o}C for 30 min, with periodic stirring, in order to deflocculate the sediment and allow for chironomid heads to more easily be identified. Both the 100 and 200 samples from each interval were processed using a dissecting microscope and chironomid head capsule subfossils were picked out using fine forceps. The sediment was processed at least 3 times to ensure a 95% capture rate of all chironomid head capsules within each sample. The extracted specimens were then mounted on glass cover slips and attached to microscope slides permanently using entellen®. Following Walker (2001), a minimum of 50 head capsules were recovered from each interval sample, however the many of counts from the samples were greater than 100. Chironomid subfossilized head capsules were identified primarily using Brooks et al. (2007) and Medeiros & Quinlan (2011).

S.4.2 Loss on Ignition

Organic and carbonate content of sediment intervals from each site were estimated using weight loss on ignition (LOI), following methods defined by Heiri et al. (2001). Lacustrine sediment samples weighing 1.0 g were dried in a drying oven at 90 °C for 24 hours and then placed in a desiccator for an additional 24 hours. The samples were then weighed, and the dried sediment weight (DW_{90}) along with the original wet sediment weight (WW) were used to calculate the percent water content with the equation:

$$LOI_{90} = ((WW - DW_{90}) / WW) * 100$$

Organic matter within each sample was then combusted to carbon dioxide (CO_2) and ash by burning at 550 °C for two hours within a muffle furnace. Burned samples were placed in a desiccator for 24 hours and then weighed. The dried weights after combustion at 550 °C (DW_{550}) were used to calculate percent organic matter with the equation:

$$LOI_{550} = ((DW_{90} - DW_{550}) / DW_{90}) * 100$$

Finally, samples were again burned in the muffle furnace for two hours, yet at 950 °C, to evolve CO_2 from carbonate. The carbonate content of the sediment was calculated using the dry weight of the sample after combustion at 950 °C (DW_{950}) in the equation:

$$LOI_{950} = ((DW_{550} - DW_{950}) / DW_{90}) * 100$$

S.4.3 Chironomid Production

Chironomid production was calculated as head capsules per gram of dry weight (HC g^{-1} DW), which was calculated for each interval of Lake PG3 and Lake PG9. First the water content (WC) of each interval was calculated using the %water (W%), with the equation:

$$WC = W\%/100$$

The grams of dry weight (g^{-1} DW) for each sample were then calculated from the total weight of the sample (TW) and WC using the equation:

$$g^{-1}\ DW = TW * (1 - WC)$$

The HC/ g^{-1} DW for each sample was calculated from the total head capsules (HC) and g^{-1} DW.

S.5 Diagnostic Tests

S.5.1 Broken Stick Model

A broken stick model was run with R statistical language v.3.6.2 (R Core Team 2019) and the package rioja v0.9-21 (Juggins 2017) for the relative abundance and raw abundance of each lake. Analysis of PG9 raw abundance data using the broken stick model (bstick) found three significant zones, while the relative abundance analysis identified between five and six shifts (Figures S1 & S2). The PG3 raw abundance broken stick model suggests between seven and eight significant zones, while the relative abundance model identified eleven zones of significant change (Figures S3 & S4).

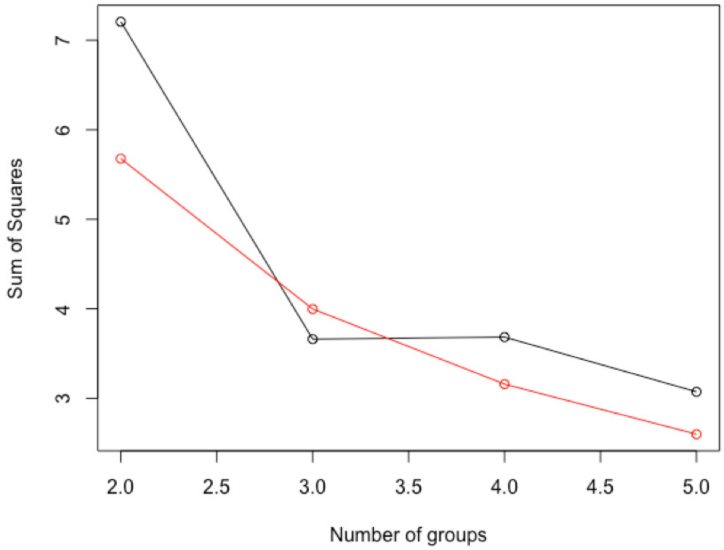

Figure S1 Broken stick model of raw abundance for Lake PG9.

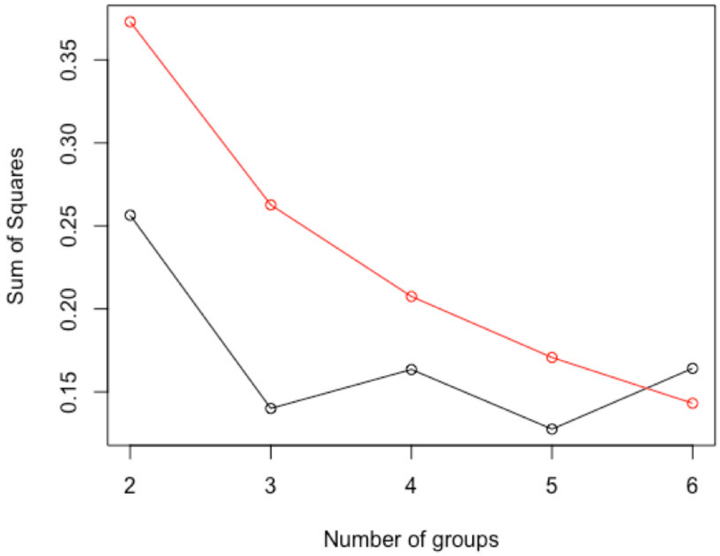

Figure S2 Broken stick model of relative abundance for Lake PG9.

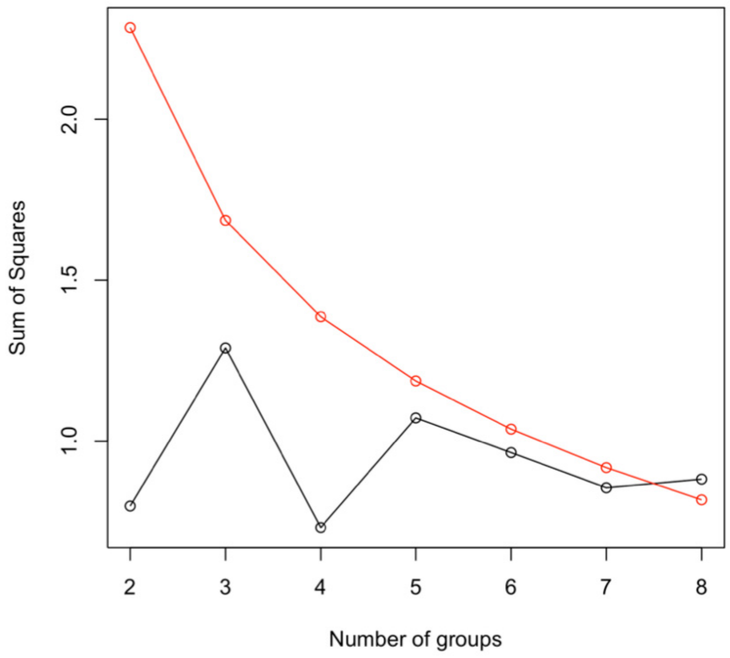

Figure S3 Broken stick model for the raw abundance of Lake PG3.

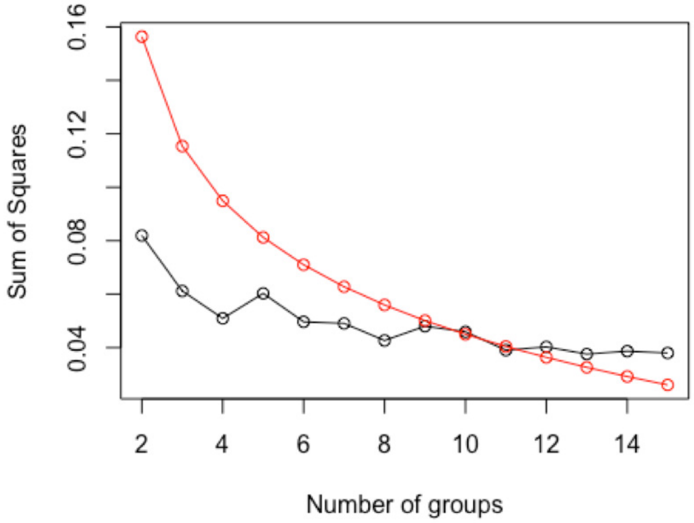

Figure S4 Broken stick model for the relative abundance of Lake PG3.

S.5.2 Detrended Correspondence Analysis and Principal Component Analysis

Detrended correspondence analysis (DCA) and principal component analysis (PCA) Euclidean distances were calculated using the software R and are shown for both Lake PG9 and Lake PG3 (Figures S5 & S6).

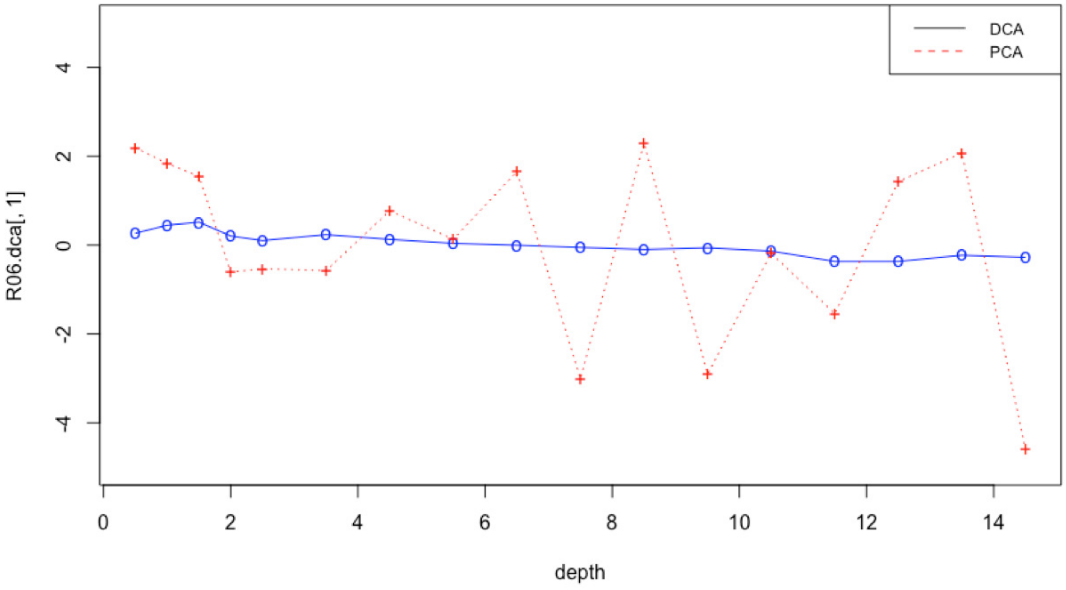

Figure S5 DCA and PCA distances for Lake PG9.

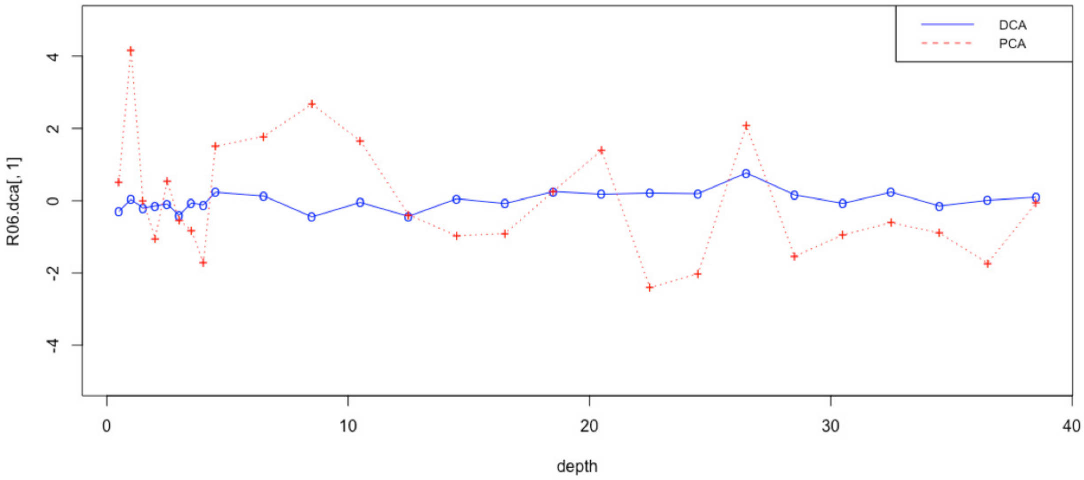

Figure S6 DCA and PCA distances for Lake PG3.

S.5.3 Goodness of Fit

Goodness of fit tests were carried out on Lake PG9 and Lake PG3 data, which determined if down core subfossil assemblages had analogues with the modern Fortin et al. (2015) calibration dataset. Squared-chord distance for Lake PG9 showed good analogues for the entire record (Figure S7), while analysis of Lake PG3 data showed the majority of samples had good analogues with some fair and a few poor (Figure S8). Squared residual distance tests revealed similar results with all Lake PG9 data being a good fit for temperature, while Lake PG3 had some data fit poor and others good.

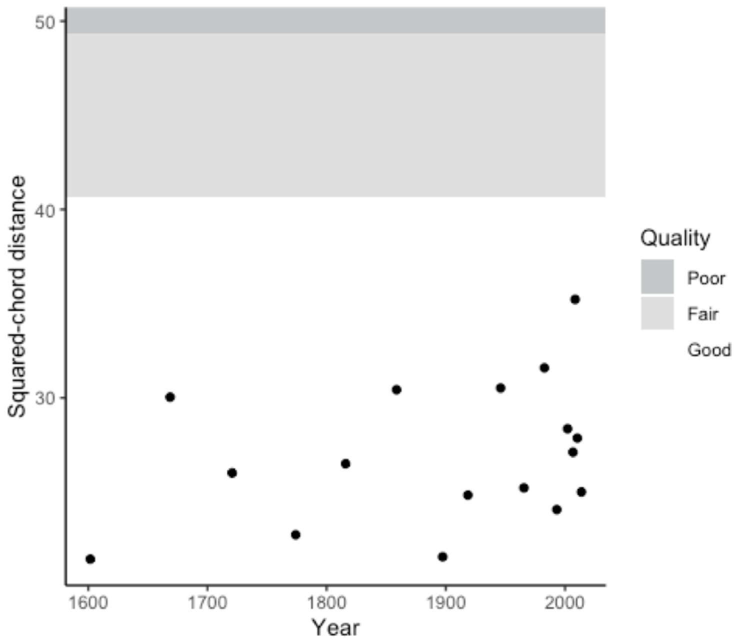

Figure S7 Squared-chord distance for Lake PG9, as compared to the Fortin calibration set (Fortin et al. 2015).

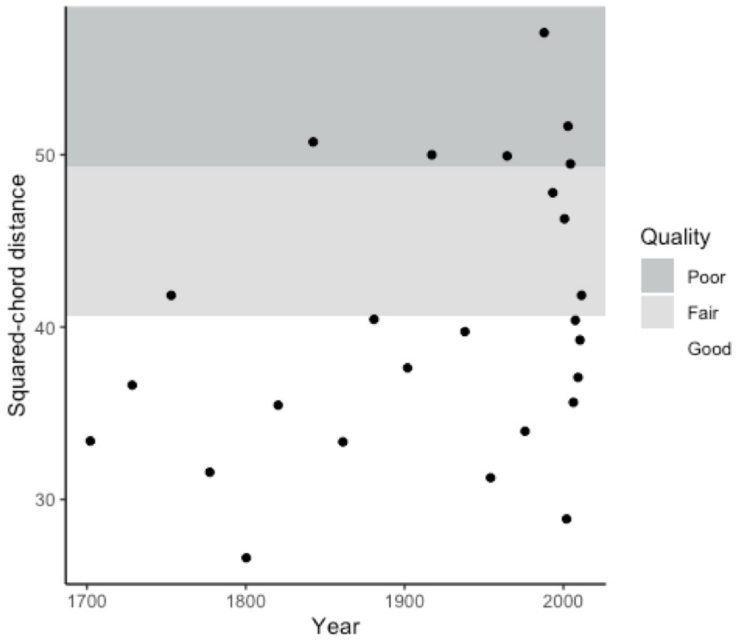

Figure S8 Squared-chord distance for Lake PG3, as compared to the Fortin calibration set (Fortin et al. 2015).

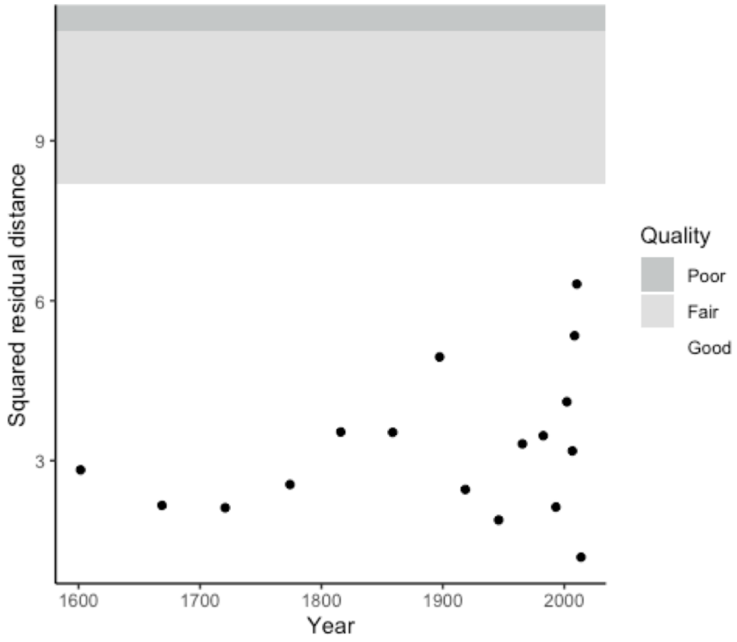

Figure S9 Squared residual lengths for Lake PG9, as compared to the Fortin calibration set (Fortin et al. 2015).

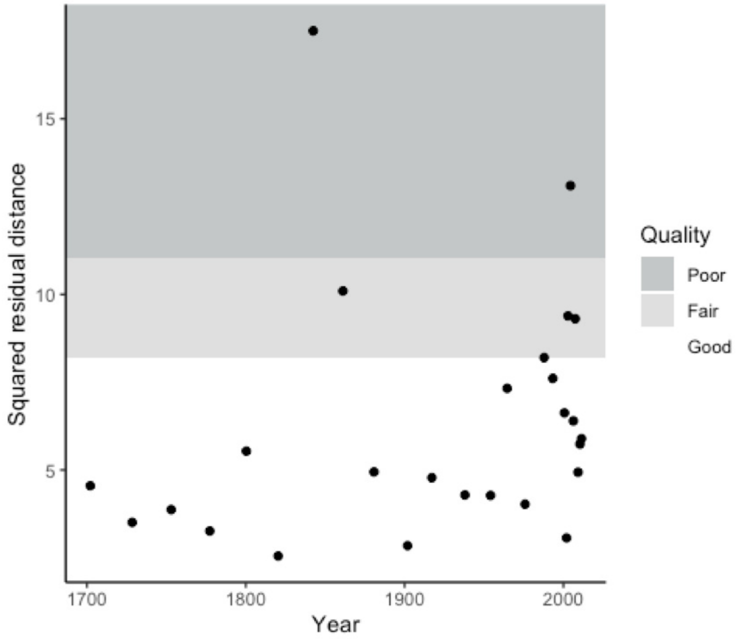

Figure S10 Lake PG3 squared residual distance, as compared to the Fortin calibration set (Fortin et al. 2015).

S.6 Ordination

A PCA biplot was constructed for both Lake PG9 and PG3 using Hellinger transformed chironomid taxonomic data, excluding rare taxa present at <2 %, in the software R. Taxonomic data was plotted passively through time, showing the changes of each lake.

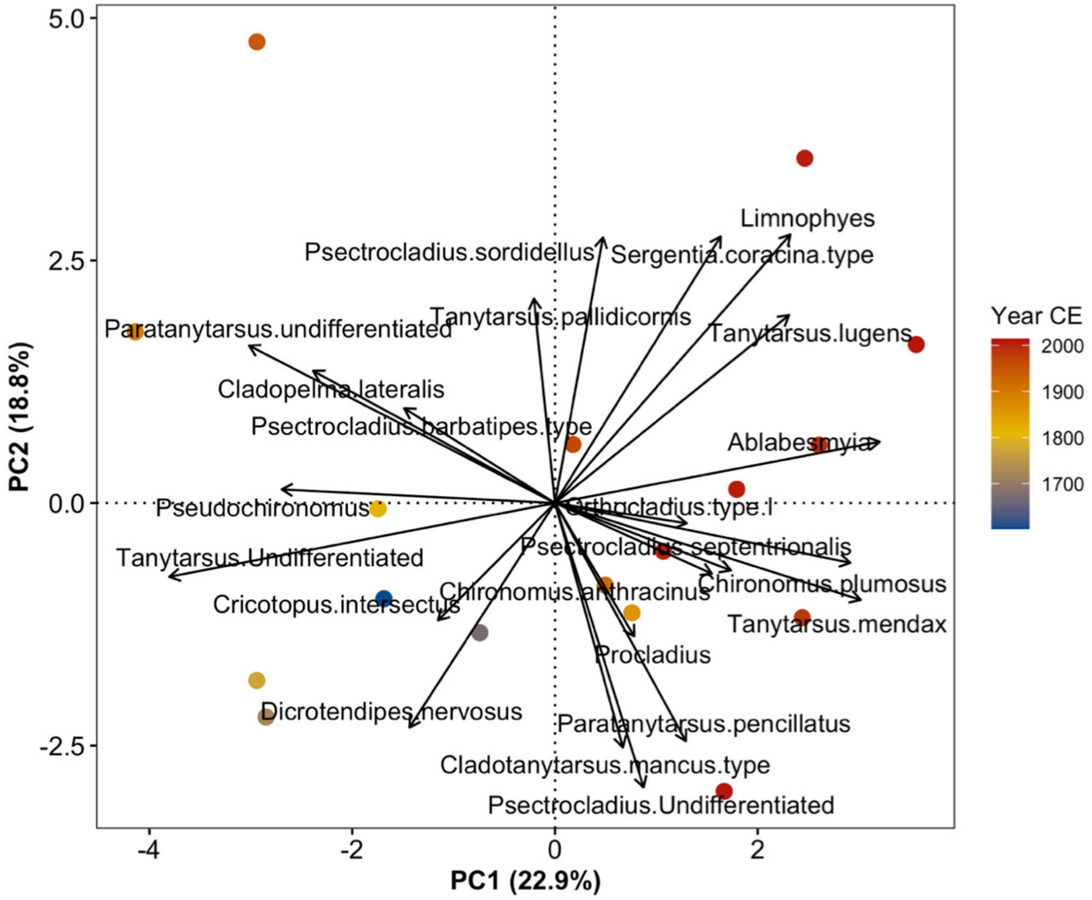

Figure S11 PCA biplot for PG9 chironomid taxonomic data highlighting changes in community assemblages through time.

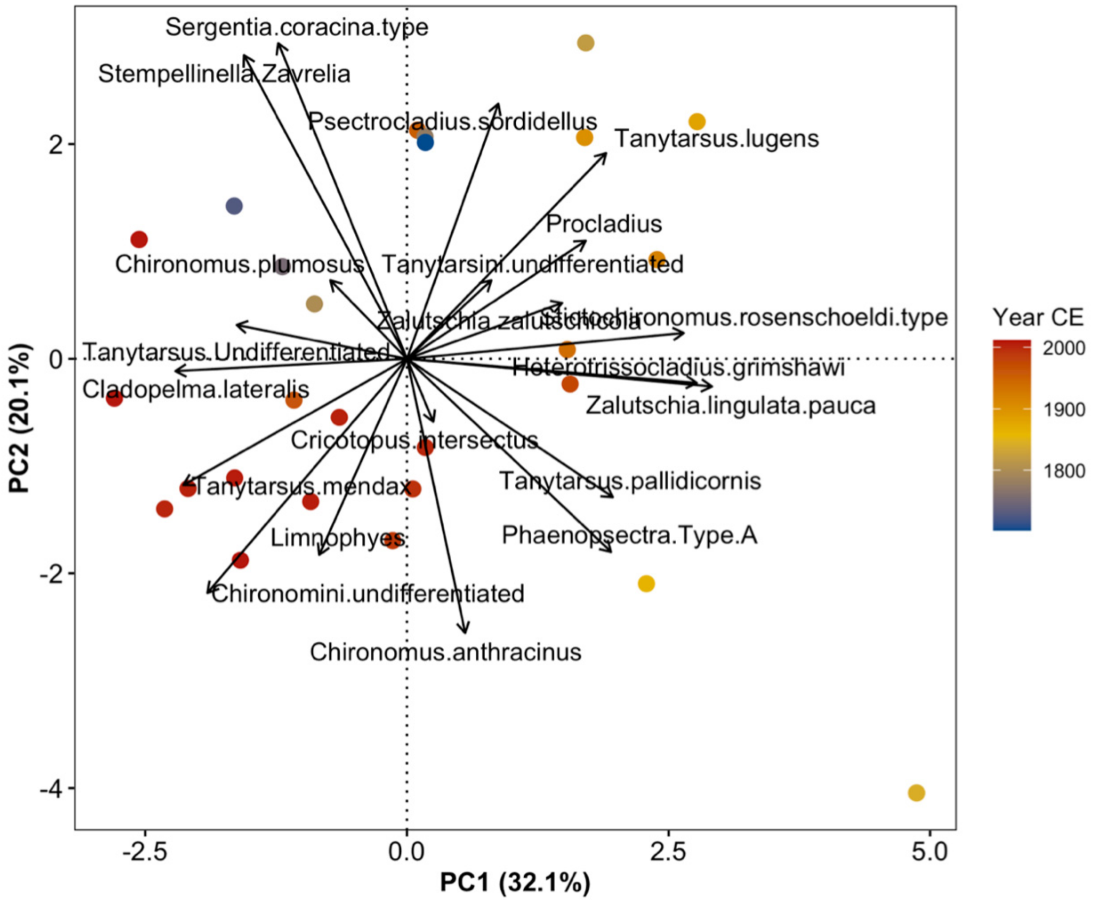

Figure S12 PCA biplot for PG3 chironomid taxonomic data highlighting changes in community assemblages through time.

S.7 Climate

S.7.1 Mackenzie Climate

Climate data gathered by Environment Canada suggests air temperatures have been increasing since 1958 CE (Figure S13). These data correspond well to the chironomid-inferred reconstructed July air temperature, GAM, and temperature effect for Lake PG3, which predicted an overall increasing mean temperature since ~1700 CE (Figures S14, S16, & S19). However, the chironomid-inferred July air temperatures from Lake PG9 data illustrate an overall cooling trend since 1600 CE (Figures S15, S17, S18, S20), indicating secondary variables may be driving chironomid community changes. Overall changes in modelled chironomid-inferred July Air temperature for Lake PG9 suggest a cooling effect of approximately 1.0 ºC since ~1600 CE (Figure S20), while the Lake PG3 modelled change is an increase of approximately 0.5 ºC since ~1700 CE, with a warming effect of approximately 1.0 ºC since the modelled cold period ~1850 CE (Figure S19). PCA comparisons of Lake PG9 and Lake PG3 data to the Fortin calibration dataset (Fortin et al. 2015) demonstrate the differing passive trajectories of the lakes through time (Figures S21 & S22).

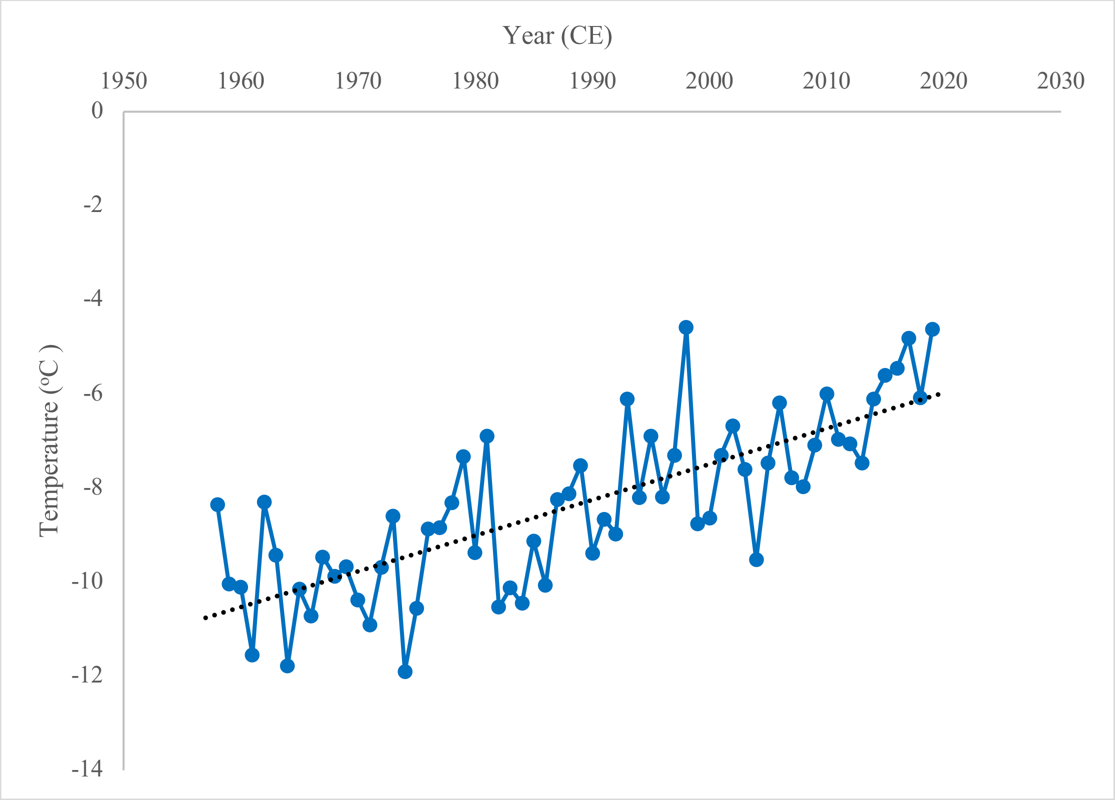

Figure S13 Inuvik, N.W.T, mean annual temperature (ºC) with linear trendline for the period of 1958-2019 CE (Environment Canada, http://www.climate.weather.gc.ca)

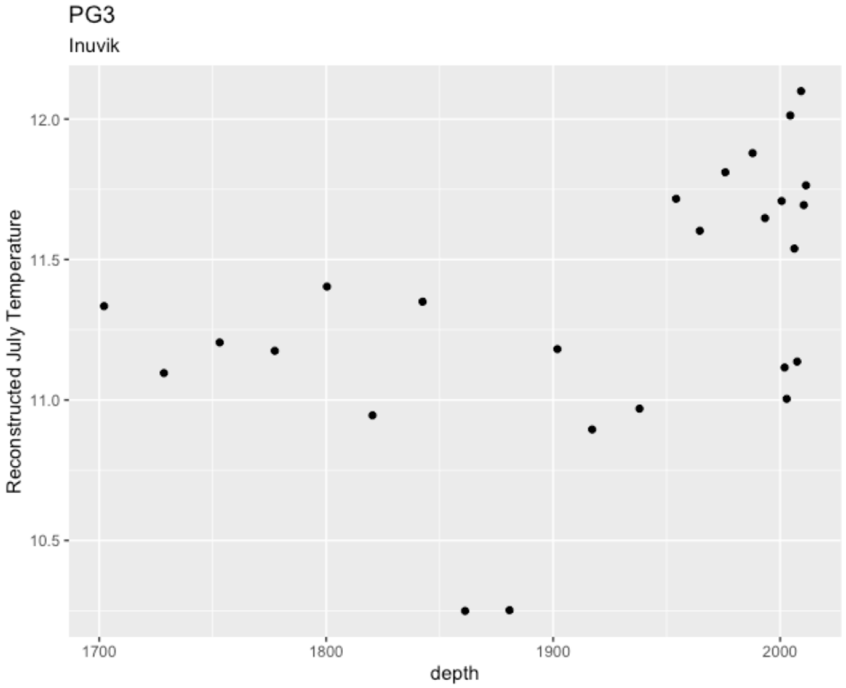

Figure S14 Reconstructed July air temperature (ºC) for Lake PG3 using the Fortin et al. (2015) model.

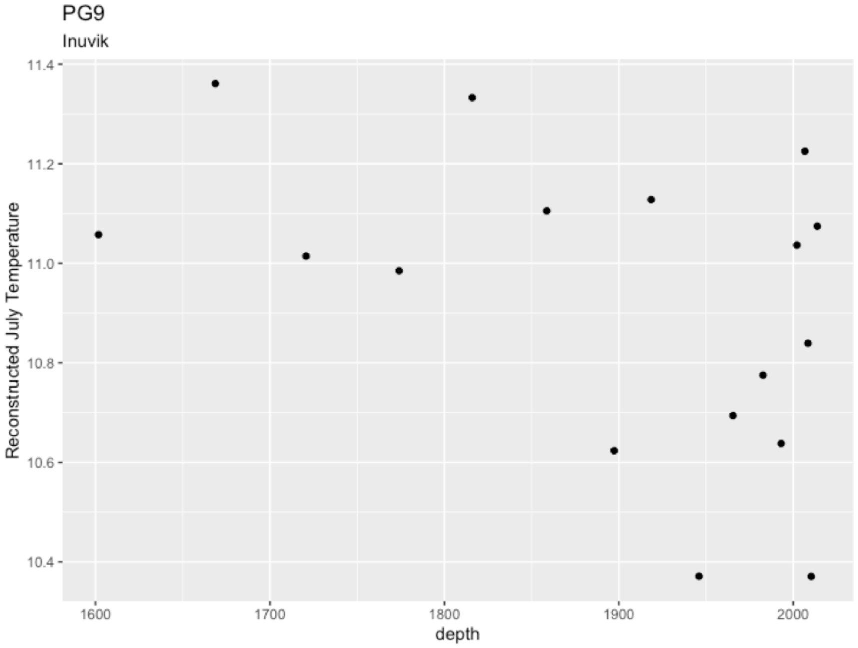

Figure S15 Reconstructed July air temperature (ºC) for Lake PG9 using the Fortin et al. (2015) model.

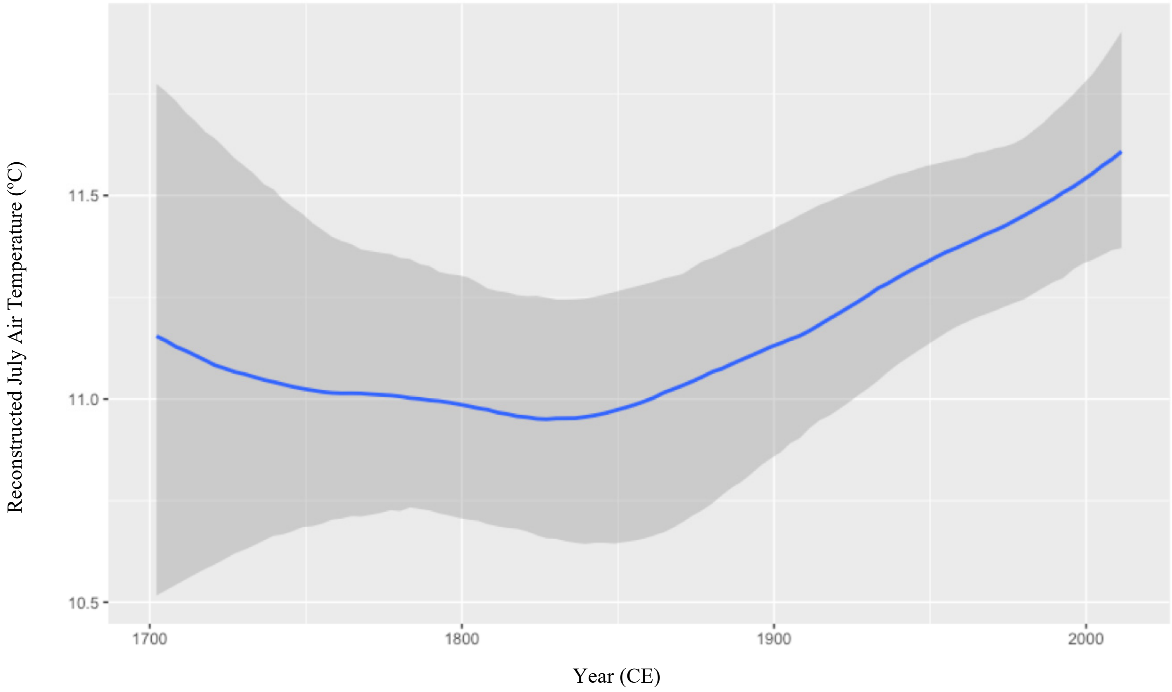

Figure S16 Chironomid-inferred mean July air temperature (ºC) since ~1700 CE, reconstructed using data from Lake PG3 and the Fortin general additive model (GAM) (Fortin et al. 2015).

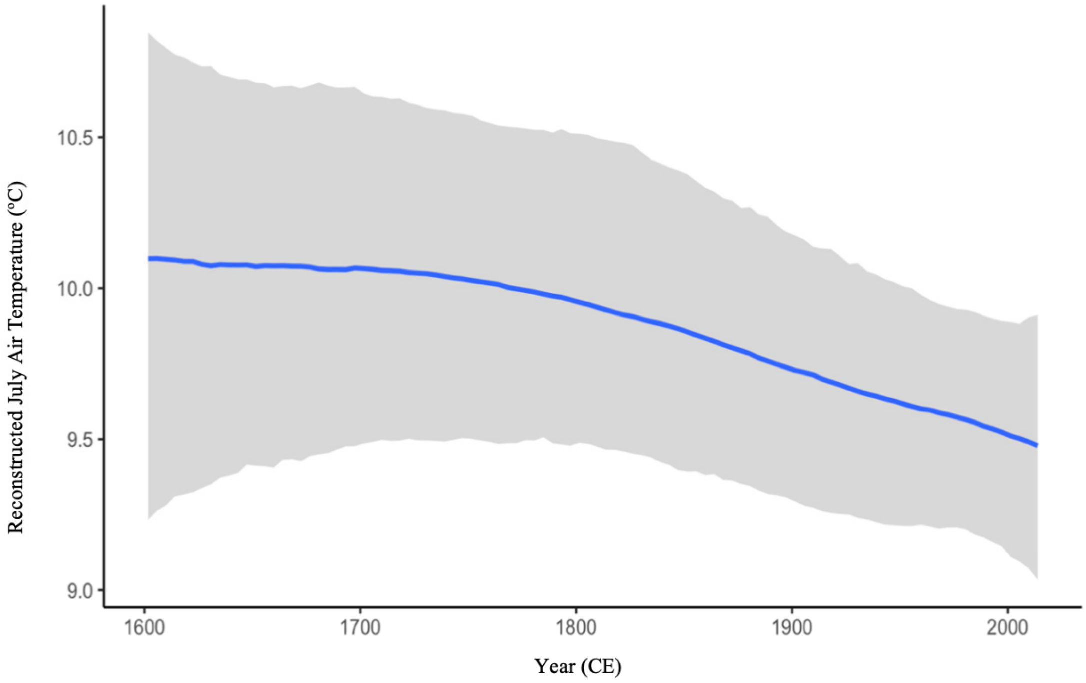

Figure S17 Chironomid-inferred July air temperature since ~1600 CE, reconstructed using Lake PG9 data and Fortin GAM (Fortin et al. 2015).

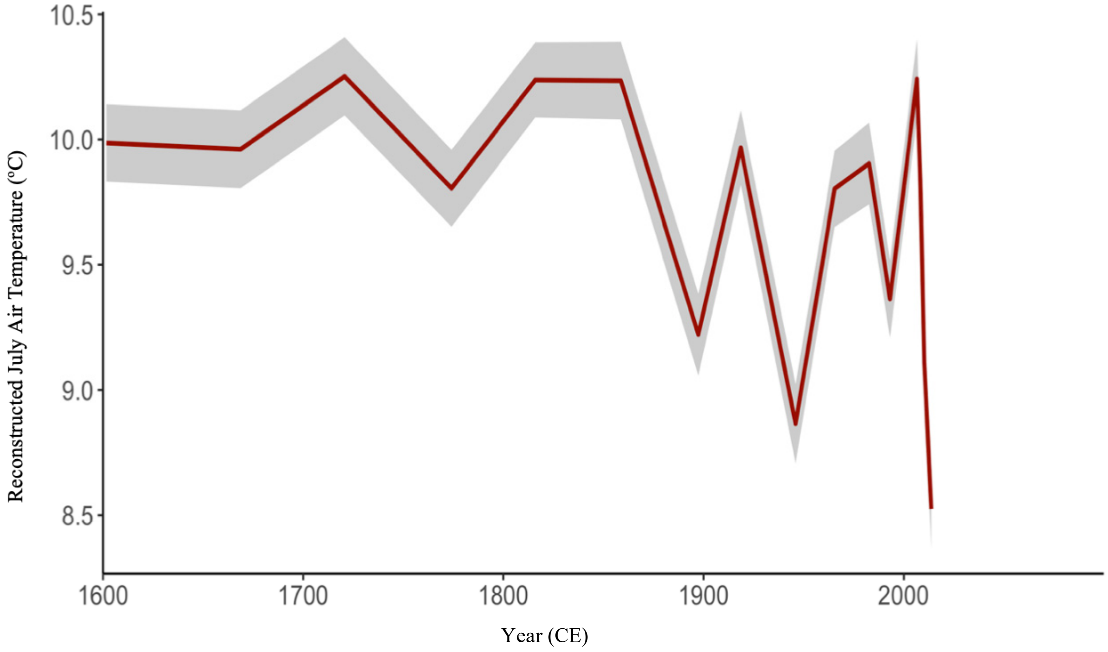

Figure S18 Chironomid-inferred July air temperature since ~1600 CE, reconstructed using Lake PG9 data and Fortin weighted averaging-partial least squares (WA-PLS) (Fortin et al. 2015).

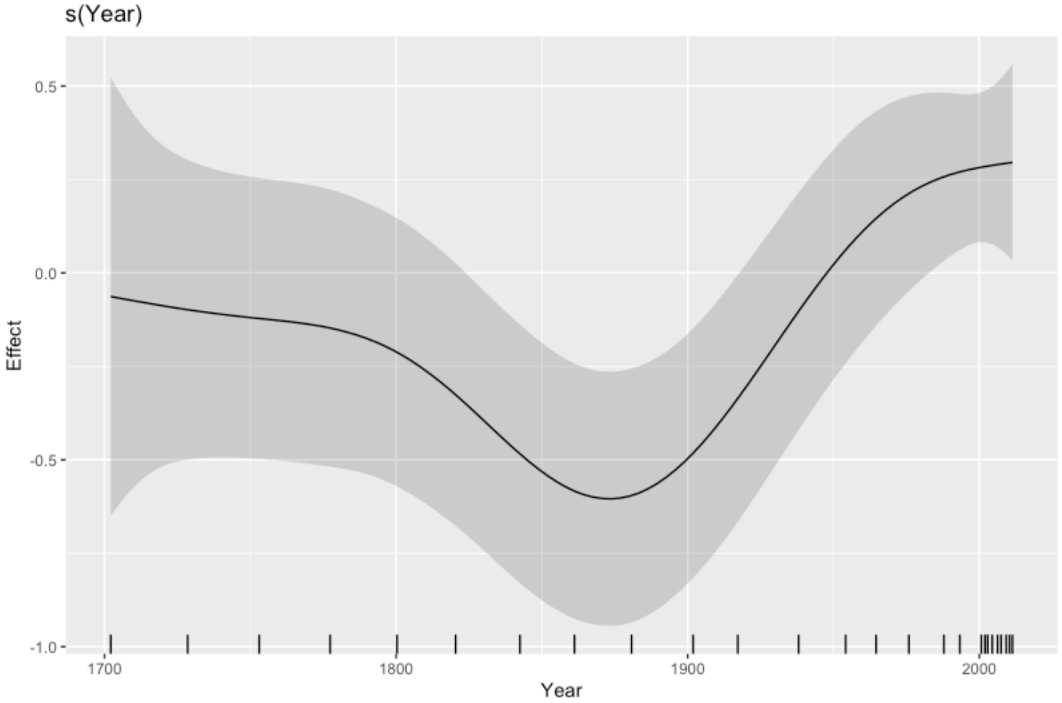

Figure S19 Lake PG3 chironomid-inferred reconstructed July air temperature change (^{o}C) for the period of ~1700-2011CE.

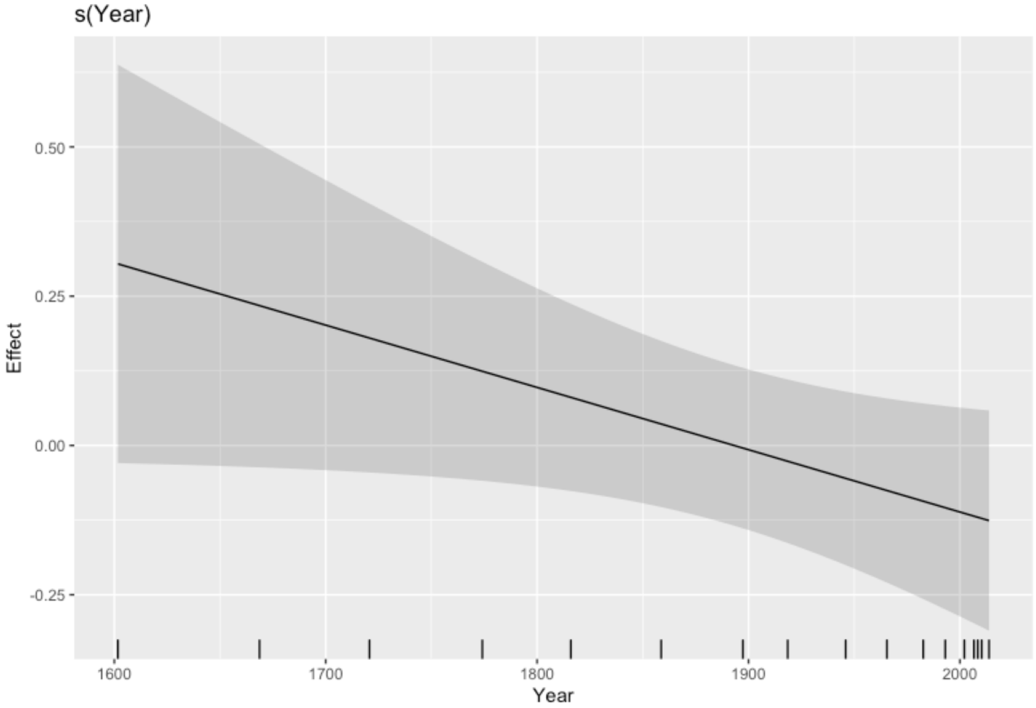

Figure S20 Lake PG9 chironomid-inferred reconstructed July air temperature change (°C) for the period of ~1600-2014 CE.

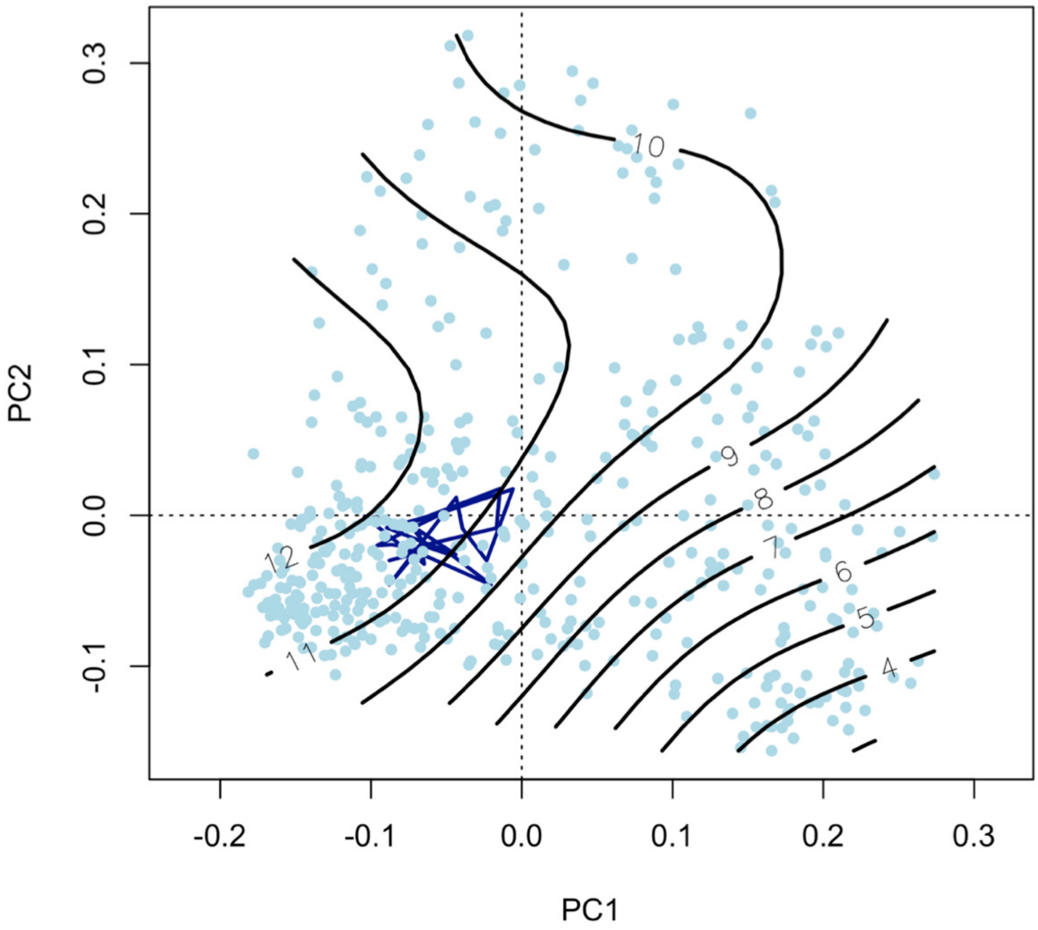

Figure S21 Principal component analysis (PCA) biplot for chironomid-inferred temperature of Lake PG3, as compared to the Fortin calibration dataset (Fortin et al. 2015), showing the passive trajectory of the core intervals throughout the period of ~1702-2011 CE.

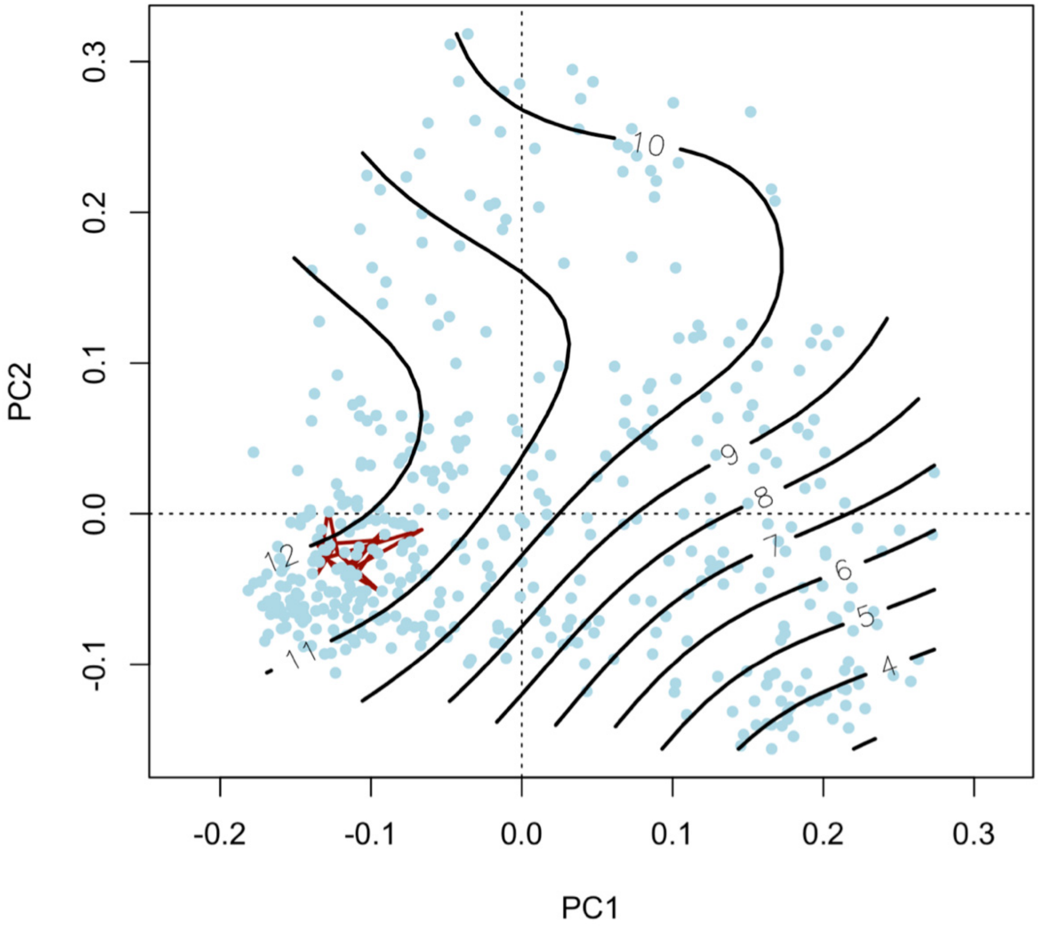

Figure S22 Principal component analysis (PCA) biplot for chironomid-inferred temperature of Lake PG9, as compared to the Fortin calibration dataset (Fortin et al. 2015), showing the passive trajectory of the core intervals throughout the period of ~1602-2014 CE.

S.8 Diversity Results

Diversity analyses of chironomid subfossil data were completed for Lake PG3 and Lake PG9 (Figures S23 & S24). Recent sediments of Lake PG9 indicate fluctuating but increasing chironomid community diversity since ~1945 CE, while Lake PG3 data suggests relatively linear diversity for the entire record. Thereby indicating Lake PG9 may have experience changes (e.g., increasing temperature and nutrients) transitioning it to a less severe system over the last ~400 years.

S.8.1 Diversity Lake PG3

Lake PG3 features 4 significant zones; zone 1 from approximately 38.5-28.5 cm (~1700-1830 CE); zone 2 from approximately 26.5-12.5 cm (~1830-1970 CE); zone 3 from approximately 10.5-4.5 cm (~1970-2000 CE); and zone 4 from approximately 4.0-0.5 cm (~2000-2011 CE) (Figure S23).

S.8.1.1 Zone 1 (38.5-28.5 cm)

Zone 1 of Lake PG3 is dominated (~10-20 %) by; *Chironomus spp., Cladopelma spp., LImnophyes/ Paralimnophyes, Psectrocladius spp., Sergentia spp., Stempellinella zavrelia spp., Tanytarsina,* and *Zalutschia spp.* The majority of dominant taxa remain relatively stable throughout Zone 1, excluding *Sergentia spp.* which exhibit a large increase at ~1820 CE. *Glyptotendipes spp., Procladius,* and *Hetertrissocladius spp.* all increase at ~1820 CE to diversity greater than previously observed in Zone 1. Conversely, *Micropsectra spp.* demonstrate an abrupt absence for the remainder of Zone 1 after ~1729 CE. Taxa groups that also exhibited low (<5 %) and sparse relative abundance throughout Zone 1 include; *Dicrotendipes spp., Ladiodimesa, Microtendipes spp., Phaenopsectra spp., Polypedilum spp.,* and *Stictochironomus spp.* The only group absent from Zone 1 is *Endochironomus spp.* Both the δ^{13}C and δ^{15}N content of Zone 1 remain relatively stable, with ranges of -29.81 to -29.47 ‰ and 2.13-2.57 ‰, respectively (Figure S23). Diversity of Zone 1 also remains fairly stable, ranging from ~25-30 %, with an exception at ~1753 CE where the diversity increases to ~35 %. %C_{org} content steadily increased throughout Zone 1, from 31.51 % at ~1702 CE to 34.19 % at ~1820 CE. While in contrast, %N content fluctuates throughout Zone 1 in the range of 2.16-2.49 %. The C:N ratio for this period generally increases from 13.37 at ~1702 CE, with a moderate peak of 14.55 at ~1753 followed by a decrease to 13.75 at ~1777 CE, which then increased until the zone peak of 15.26 at ~1820 CE.

S.8.1.2 Zone 2 (26.5-12.5 cm)

Zone 2 encompasses the first half of the 20th century (~1902-1965 CE) and is characterized by the continued dominance of the majority of leading taxa observed in Zone 1, as well as large increases to previously reduced groups (Figure S23). Isotopic content varied greatly throughout Zone 2, where $\delta^{13}C$ maintained relative stability ranging from -29.82 to -29.47 ‰, while $\delta^{15}N$ values generally decreased sharply from a high of 1.88 ‰ (~1861 CE) to a low of 1.29 ‰ (~1954 CE), which was then followed by a steep jump to 1.71 ‰ at ~1965 CE. The organic matter content trended positively compared to Zone 1, increasing from 59.04-69.85 % over the entire period, with the peak LOI_{550} occurring at ~1902 (69.92 %). The $\%C_{org}$ content maintained a relative stability, ranging from 2.20-2.38 %. Many groups exhibit sharp increases ranging from 5-20 % in the middle of Zone 2 (~1902 CE), including; *Chironomud spp., Cladopelma spp., Dicrotendipes spp., Procladius, Psectrocladius spp., Sergentia spp., Stempellinella zavrelia spp., Stictochironomus spp., Tanytarsina,* and *Zalutschia lingulata pauca.* Only three taxa groups demonstrated decreases at ~1902 CE compared to the previous interval; *Limnophyes/Paralimnophyes, Micropsectra spp.,* and *Microtendipes spp.* This interval of great taxonomic change also coincides with; a $\delta^{13}C$ increase (-29.82 to -29.47 ‰), a

%C_{org} increase (35.20-36.75 %), a relatively large $\delta^{15}N$ decrease (1.64-1.16 ‰), fairly stable %N content (2.25-2.24 %), and a large increase of organic matter (LOI_{550}) (58.85-69.92 %). The C:N ratio of Zone 2 peaks in the middle of the period at ~1917 CE with 16.77, while the surrounding intervals fluctuate between 14.65-16.40. Overall, many groups are characterized by the greatest relative abundance in the middle of Zone 2 (~1881-1938 CE), which is followed by a decreasing trend until the end of Zone 2 for; *Chironomus spp., Cladopelma spp., Cricotopus Orthocladius spp., Dicrotendipes spp., Procladius, Psectrocladius spp., Sergentia spp., Stempellinella zavrelia spp., Stictochironomus spp., Tanytarsina ,* and *Zalutschia lingulata pauca.* In contrast, some groups maintained a relatively stable trend throughout Zone 2, including; *Corynoneura Thienemanniella spp., Cricotopus Orthocladius spp.,* and *Limnophyes/ Paralimnophyes.* Diversity in Zone 2 remains relatively stable between ~30-35 % until ~1965 CE where the diversity sharply decreases to ~25 %.

S.8.1.3 Zone 3 (10.5-4.5 cm)

Zone 3 of Lake PG3 covers the late 19th century (~1976-2001 CE) and is marked by relative stability with some decreases to taxa relative abundance (Figure. S23). However, the geochemical and isotopic content of the intervals varies greatly (Figure S23). The relative abundance of many taxa groups demonstrates decreased levels compared to previous periods, including; *Corynoneura Thienemanniella spp., Cricotopus / Orthocladius spp., Heterotrissocladius spp., Limnophyes/ Paralimnophyes. Micropsectra spp., Procladius, Psectrocladius spp., Sergentia spp., Stempellinella zavrelia spp., Stictochironomus spp., Tanytarsina,* and *Zalutschia lingulata pauca.* In particular, *Corynoneura Thienemanniella spp., Micropsectra spp.,* and *Stempellinella zavrelia* *spp.*are all only present with low relative abundance (<5 %) at ~2001 CE. The organic matter of Zone 3 is less than observed in previous zones, decreasing from 67.68 % (~1976 CE) to 64.32 % (~2001 CE). The %C_{org} content decreases throughout Zone 3 (36.39-35.09 %). The %N content maintains relatively stable values ranging from 2.33 % (~1976 CE) to 2.48 % (~1993 CE). The C:N ratio decreases throughout Zone 3 (15.65-14.31). Isotopic carbon content decreases throughout the period, with -29.85 ‰ at ~1976 CE to -30.33 ‰ at ~2001 CE. In contrast, $\delta^{15}N$ content generally increases for the period, ranging from a low of 1.17 ‰ (~1976 CE) to 1.70 ‰ (~2001 CE). The overall diversity of Zone 3 decreases to ~20-25 % at approximately 1988 CE, followed by a recovery to 25-30 % for the remainder of the zone.

S.8.1.4 Zone 4 (4.5-0.5 cm)

Zone 4 of Lake PG3 generally sees increases to taxa relative abundance when compared to Zone 3 (Figure S23). However, the last zone of PG3 is characterized by lower taxa relative abundance than was observed in Zones 1 and 2. Zone 4 is dominated by; *Chironomus spp., Cladopelma spp., Limnophyes/ Paralimnophyes,* and *Tanytarsina.* The majority of the dominant groups experience the greatest peak of Zone 4 at ~2007 CE, with the exception of *Cladopelma spp.* which peaks at ~2010 CE. The interval corresponding to ~2007 CE also demonstrates, the lowest $\delta^{13}C$ of Zone 4 (-30.19 ‰), the lowest $\delta^{15}N$ (1.39 ‰), the lowest LOI_{550} (66.55 %), along with moderate values for the C:N ratio (14.90) and %N (2.47 %), while the %C_{org} content of the interval is relatively high (36.86 %). The zone is also marked by an overall decreasing trend in relative abundance for the majority of taxa groups, with the exceptions being; *Lasiodiamesa, Polypedilum spp.,* and *Sergentia spp.* The general trend of organic matter content for

Zone 4 is increasing until the peak of 69.28 % at ~2009 CE, which is followed by a slight decrease to 67.61 % at ~2011 CE. Similarly, the δ^{15}N peak occurs at the beginning of Zone 4 (1.70 ‰) and is followed by a sharp decrease, after which the values then gradually increase once more. The C:N ratio of Zone 4 shows relative stability ranging from 14.31 to 15.27. A slightly positive trend is observed for the δ^{13}C content of Zone 4, with fluctuations ranging from -30.33 ‰ (~2001 CE) to a peak of -29.93 ‰ (~2011 CE). The diversity trend for Zone 4 recovers from the decrease at the end of Zone 3 and maintains stability between 25-30 %.

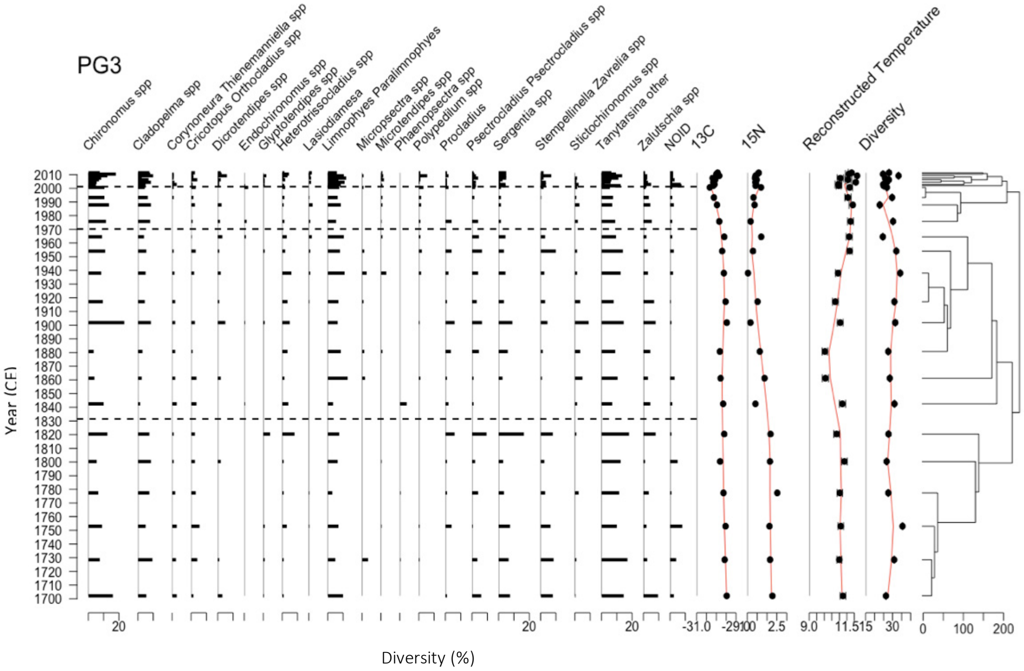

Figure S23 Biostratigraphy for chironomid diversity with taxa presented as percent relative abundance, isotopic carbon and nitrogen, reconstructed temperature, and diversity for Lake PG3.

S.8.2 Diversity Lake PG9

Lake PG9 has 2 significant zones; Zone 1 is the bottom of the core 14.5 cm (~1600 CE); Zone 2 begins at 13.5 cm and continues until the top of the core (~1669-2011 CE) (Figure S24).

S.8.2.1 Zone 1 (14.5 cm)

Constrained cluster analysis identified ~1602-1660 CE as a significantly different zone than the following years (Figure S24). Zone 1 is dominated (≥20 %) by *Paratanytarsus undifferentiated, Procladius, Psectrocladius sordidellus,* and *Tanytarsus mendax.* Moderate diversity (~5-15 %) was exemplified by *Cricotopus cylindraceus, Cricotopus intersectus, Dicrotendipes nervosus, Psectrocladius barbatipes, Psectrocladius undifferentiated, Pseudochironomus,* and *Zalutschia lingulata pauca.* Several taxa are absent from Zone 1 including; *Chironomus plumosus, Orthocladius type I, Paratanytarsus austriacus, Sergentia coracina,* and *Tanytarsus lugens.* The remainding majority of taxa demonstrated low diversity (≤5 %). Overall diversity for Zone 1 is the lowest observed within the PG9 record (~20 %) (Figure S24). Zone 1 is characterized by relatively high $\delta^{13}C$ (-28.22 ‰), low $\delta^{15}N$ (-0.42 ‰), the lowest $\%C_{org}$ of the record (23.29 %), low %N (1.44 %), the greatest C:N ration of the core (17.34), and the lowest organic content (LOI_{550}) (41.91 %).

S.8.2.2 Zone 2 (13.5-0.5 cm)

Zone 2 encompasses the remaining intervals of the PG9 record ~1669-2014 CE. Increases in diversity of *Ablabesmyia, Chironomus plumosus, Limnophyes, Orthocladius type I, Paratanytarsus pencillatus, Sergentia coracina, Tanytarsus lugens,* and *Tanytarsus pallidicornis* mark the period since ~1900 CE. In contrast, the latter half of Zone 2 is characterized by declining diversity for the majority of taxa after ~1910 CE, which includes; *Chironomus anthracinus, Cladopelma lateralis, Cladotanytarsus mancus type, Corynoneura arctica, Cricotopus cylindraceus, Cricotopus intersectus, Dicrotendipes nervosus, Hydrobaenus conformis, Paratanytarsus undifferentiated, Procladius, Psectrocladius barbatipes, Psectrocladius septentrionalis, Psectrocladius sordidellus, Psectrocladius undifferentiated, Pseudochironomus, Tanytarsus mendax,* and *Zalutschia lingulata pauca.* Overall diversity for Zone 2 indicates greater values than observed in Zone 1, with peaks of diversity (≥24 %) occurring at ~1669, ~1919, ~1965, ~1983, and ~2010 CE (Figure S24). Elemental and isotopic nitrogen trends generally increase throughout Zone 2, with $\delta^{15}N$ increasing from -0.36 ‰ at ~1669 CE to the core peak of 0.52 ‰ at ~2014 CE, while %N begins the zone with 1.50 % and similarly increases to the peak of the record with 2.39 % at ~2014 CE. In contrast, the elemental and isotopic carbon content of Zone 2 follows differing trajectories. $\delta^{13}C$ decreases from -28.17 ‰ at ~1669 CE to -28.94 ‰ at ~2014 CE, with the lowest values recorded at ~2008 CE (-29.22 ‰). The %C_{org} content increases from the beginning of Zone 2 with 24.16 % to the peak of the entire record at ~2014 CE with 32.66 %. The organic content of the sediment (LOI_{550}) increases throughout Zone 2, with the peak occurring at ~2010 CE with 66.91 %.

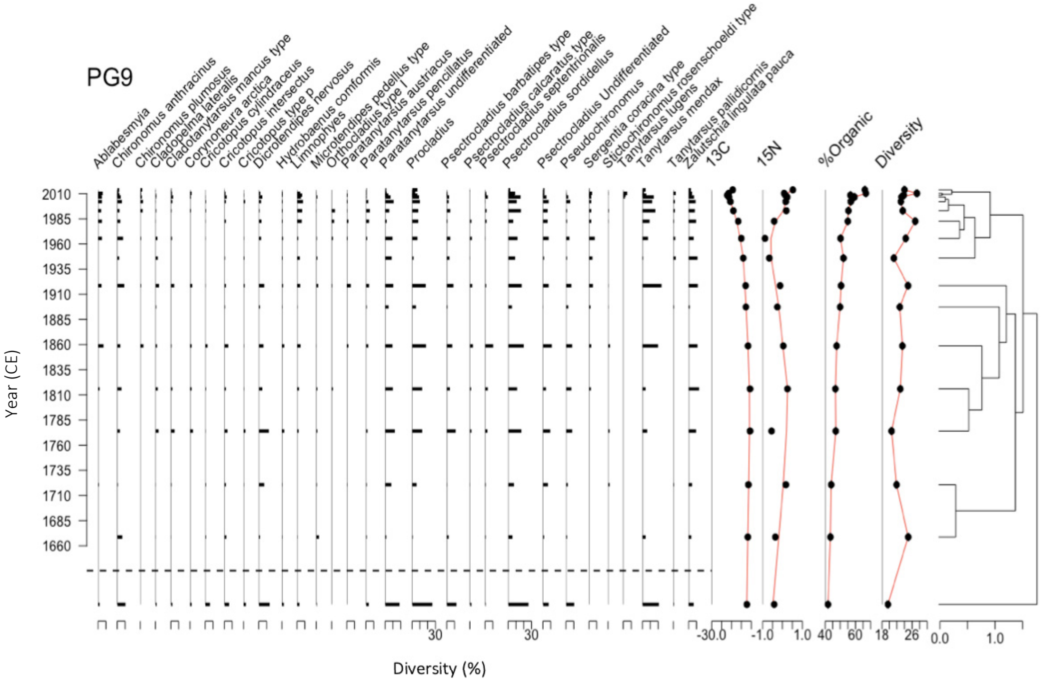

Figure S24 Biostratigraphy for Lake PG9 including; chironomid diversity with taxa presented as % relative abundance, isotopic carbon and nitrogen content, % organic content (LOI$_{550}$), and diversity.

S.9 References

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