Investigating the impact of cryogenic landslides on lakes in the eastern Mackenzie Delta (NT, Canada) using a paleolimnological framework

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Abstract

The Canadian Northwest is warming at an accelerated rate compared to other Arctic regions, the rest of Canada, and the rest of the globe. Enhanced temperatures can influence the development of thermokarst features, including cryogenic landsliding, which can impact downstream limnological systems, physically, chemically and biologically. A total of 11 sediment cores were collected from three landslide-impacted lakes and one control lake at the eastern edge of the Mackenzie Delta (Northwest Territories, Canada) in the summer of 2023. These cores were sectioned into 0.5 cm intervals and then analyzed in the lab for total mercury (THg), nitrogen (N), and carbon (C) content. Grab samples taken directly from terrestrial sites close to the landslides had similar mercury concentrations as peaks in the sediment cores. Trends observed with organic carbon (OC) and C/N ratios were shared between cores in individual lakes but not between different lakes, highlighting the unique limnology of each lake. The peak mercury concentration recorded in two impacted lake cores fell just below the interim sediment quality guidelines for total mercury established by the Council for Canadian Ministers for the Environment, highlighting the potential for mercury loading to aquatic ecosystems caused by permafrost degradation. Further, landslide history was more discernable in sediment cores from the smallest lake where sediment deposition occurred rapidly. This research demonstrates the potential for cryogenic landslides to impact the physical and chemical conditions of receiving waterbodies in the eastern Mackenzie Delta. This is particularly important because permafrost thaw influences ground stability and impacts people, wildlife, and natural environmental processes. These paleoenvironmental data will enable researchers, ecosystem managers, and land users to make informed decisions regarding the trajectories of lake ecosystem change associated with terrestrial mass movement into lakes following permafrost thaw.

Dedication

Mom and Dad
Thank you so much for encouraging me to follow every dream and for always being a safe place for me to fall if they don't work out. Your unwavering support and guidance mean everything to me.

Shannon
I could not ask for a better little sister or best friend. You are so important to me, and I am so lucky to have you by my side. I love you.

To my grandparents
Nana and Papa Bagnell, thank you for the love and inspiration. Nana and Papa Carroll, we miss you every day!

Tenzin
Thank you for your endless encouragement and for your never-ending positivity.

Angela
Thank you for being there for everything. Your friendship means the world to me.

To my friends, my loved ones, and my family, your love and support mean more to me than I will ever be able to express. Thank you all for cheering me on through all parts of life.
I am so unbelievably grateful for you. I love you all so much.

Josh and Jenny thank you so much for introducing me to a world of opportunities that I could never have imagined! Joining your lab (and meeting all my incredible lab mates) has been a transformative experience. I am beyond grateful for the support, knowledge, inspiration, and fun you have continuously brought into my academic life. You are exceptional mentors and I am so excited for all that we have planned!

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Table of Contents:

List of Figures

Introduction

The Mackenzie River hydrologically connects much of Canada's western boreal and subarctic with the Arctic Ocean. Flowing northbound toward the Beaufort Sea, the Mackenzie River branches at Point Separation, forming the Mackenzie Delta, the second-largest Arctic Delta (Fig. 1). The Mackenzie Delta is hydrologically rich, home to tens of thousands of lakes across an area roughly twice the size of Prince Edward Island (Marsh, 1998). In tandem with rising temperatures and precipitation, permafrost thaw events in the Mackenzie Delta region can and are dramatically altering the physical environment across wide-reaching scales (Segal et al., 2016). These landscape changes impact the people and wildlife that rely on the delta and its resources and are occurring with increased prevalence as global temperatures rise and weather patterns shift in response to climate change. Ongoing climate change has caused observable geomorphological disturbances across Arctic, subarctic and northern landscapes, including

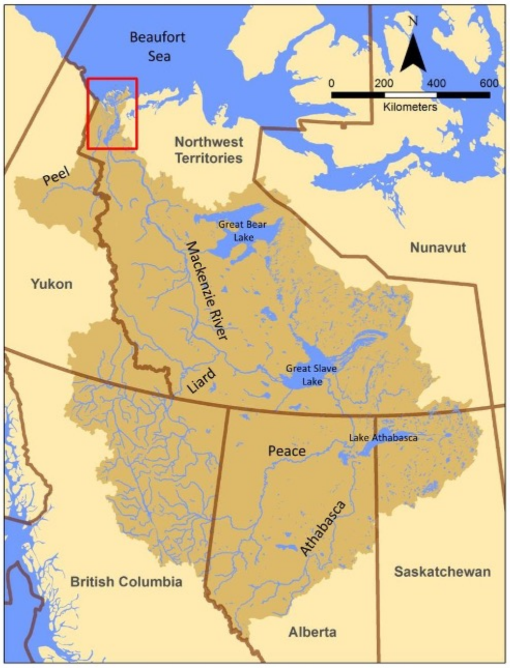


Figure 1: Map of Western Canada. Highlighting the Mackenzie River's drainage basin (dark beige) and the Mackenzie Delta (inside red box) (Gareis, 2018).

landform alteration and deformation in the form of thermokarst (Segal et al., 2016). Cryogenic landslides (Fig. 2), the focus of this research, are mass movement features driven by permafrost thaw that can alter northern systems biologically, chemically, and geomorphologically. This research examines how permafrost thaw events in the form of cryogenic landslides have the potential to translocate considerable amounts of hillslope terrestrial material, potentially triggering biological and chemical shifts in low-lying delta lakes (Leibman et al., 2014).

Figure 2: Scarring from recent cryogenic landslide on impacted study lake – Caribou 3. Image taken July 2023.

This research's study site was along the Mackenzie Delta's eastern edge, ~25 km NNW of Inuvik, NT, in the Northwest Territories on the traditional land of the Inuvialuit and Gwich'in peoples. The Mackenzie River and Delta are major hydrological features in Canada's northwest. The Mackenzie River, Canada's longest and North America's second-longest river, is more than 1700 kilometres long, with its headwaters originating at Great Slave Lake. The Mackenzie River at Point Separation (near the hamlet of Tsiigehtchic) separates to form the Mackenzie Delta, which ultimately terminates in the Beaufort Sea of the Arctic Ocean. The Mackenzie Delta is bounded east and west by the Caribou Hills and the Richardson Mountains, respectively. The

Caribou Hills contrast the low-lying Mackenzie Delta with the rapid elevation gain and the transition to thicker continuous permafrost from the discontinuous permafrost found in the Mackenzie Delta itself due to the ground-warming properties of numerous lakes and river channels (Burn & Kokelj, 2009).

Permafrost thaw can be initiated during periods of exceptional temperatures or rainfall, and where it occurs in areas of notable relief can result in landslides translocating terrestrial material, which can be deposited into downslope lakes. Near-surface permafrost is vulnerable to degradation, even in regions where the overall permafrost table is thick and continuous. The steep slopes of the Caribou Hills enhance degradation potential. In this area, cryogenic landslide features can be recognized as pronounced tree-less tracts extending downslope, often to the edge of the low-lying lakes at the foot of the Caribou Hills. Within some lakes, translocated slope material from years prior is still evident and very prominent, particularly within nearshore areas.

It is generally accepted that scientists can track recent climatic changes using direct monitoring; however, a lack of long-term data can make it challenging to know the extent of these changes when pre-impact monitoring data are not available. Lake sediments archive a record of changes in a lake and its catchment that can be used to infer ecosystem changes (Smol, 1992). This discipline is called paleolimnology, and by using this framework, researchers can identify changes over time through the analysis of physical, chemical, and/or biological information preserved in lake sediments. Lake sediments can allow scientists to infer reliable environmental timelines because they are the topographical low point in many ecosystems. Due to runoff, atmospheric deposition, and other transport mechanisms, lakes can collect a wide range of materials deposited over time. While a wide range of proxy variables are available to paleolimnologists to reconstruct lake histories, this research focused on chemical indicators, particularly total mercury (THg), total organic carbon (TOC), total carbon (TC), nitrogen (N), and elemental C/N ratios (C/N ratio). This research aimed to understand changes across impacted low-lying lake basins and patterns of accumulation of translocated material from upslope cryogenic landslides. To do this, a series of sediment cores were collected at three delta lakes, downslope of the Caribou Hills and one control lake. According to local land users, landslides within the study area occurred in the fall of 2017.

Sediment cores were collected in July 2023 at four lakes (all names unofficial) 20-30 km NNW of Inuvik. Cryogenic landslides impacted three lakes (Douglas, Caribou 2, and Caribou 3), and one lake (Caribou Control) across the East Channel served as the control location. In a boat, multiple sediment cores were collected across each basin using a UWITEC gravity core. Water quality data was collected using a multimeter probe, while lake depths were taken along a transect using an echosounder to provide rough bathymetry. In addition to core sampling, grab samples of shoreline sediment were collected from presumed terrestrial landslide material in the three impacted lakes.

Sediment cores were sectioned into 0.5 cm intervals and kept cool and dark until freeze-dried. A Milestone DMA-80 Direct Mercury Analyzer was used for THg analysis, and an Elementar UniCube Elemental Analyzer run in CN mode was used for TOC, TC, and TN measurements. Before the elemental analysis of TOC, samples were acidified for 72 hours using hydrochloric acid fumigation to remove carbonate content, after which samples were neutralized and re-dried. Grab samples underwent identical analyses. THg concentrations are expressed both per unit of dry weight (THg mg/kg DW or THg ng/g DW) and per unit of TOC (THg ng/g OC). All other variables will be presented as a percentage of DW, excluding C/N, which is expressed as a ratio.

THg concentrations were elevated in all landslide-impacted lake samples compared to the control location. The highest concentration recorded was 165 ng/g DW, close to the Interim Sediment Quality Guidelines of 170 ng/g DW established by the Canadian Council for Ministers of the Environment for Freshwater Lakes (Canadian Council of Ministers of the Environment, 1999). Concentrations higher than this could potentially result in toxicity in benthic organisms, and both cores collected from Caribou 2 (C2-1, C2-2) exhibited peak sediment mercury concentrations very close to this guideline. However, the values are below the probable effects level of 486 ng/g, DW; therefore, toxicity is unlikely under current conditions (Canadian Council of Ministers of the Environment, 1999).

In both Caribou 2 – Core 1 and Caribou 2 – Core 2, large pulses of THg (ng/g DW) were recorded, with peaks within the core having a thickness of 5 and 20 cm, respectively. These pulses were likely because of the recent (2017) landslide events, which caused material to be translocated to the lake from the upslope hills. Caribou 2 is the smallest lake and would be expected to record the most significant impacts from the landslide events. Translocated material from the nearby hills to the lake will not likely be evenly distributed across the basin. Instead, it is expected to be more concentrated along the shoreline where the landslide occurred, explaining the variability across different cores from a single lake occurring with the same landslide event. Similar increases in THg were recorded in Caribou 3 and Douglas. The peak concentration was smaller however, the thickness of sediment deposited also ranged from ~5 to 20 cm, indicating significant deposition to these lakes over the recent past, inferred to be from landslides in 2017.

The highest concentrations of THg (ng/g DW) and %TOC recorded in any of the impacted lake cores, were found in Caribou 2 – Core 2, which was visually the most impacted core while on site, which is corroborated with the lab results. These values were 164.1 ng/g and

5.25%, respectively. Excluding the control lake, %TN was also highest in Caribou 2 – Core 2, peaking at 0.35% at the estimated point of landslide occurrence. Carbon and nitrogen content in the sediment and the ratio of C/N will allow inferences about the source of organic matter source in lakes to be made (Meyers & Teranes, 2002). Terrestrial plants produce higher C/N ratios in sediment, upwards of 20, whereas algae-derived organic matter sources have C/N ratios between 4 and 10 (Meyers & Teranes, 2002). Using this ratio in the lake sediment, we can infer if elevated C/N ratios are due to a flux of terrestrial material during landsliding.

Significant landslides in the Caribou Hills were recorded in 2009 and 2017, and thus, understanding historical impacts on lakes is essential for characterizing the risk from future thaw-induced landslide events in the western Arctic region. More broadly, this research provides insights regarding the role of rapid mass movement due to permafrost thaw for downstream lake ecosystems. Permafrost degradation, under-projected warming, and altered weather patterns are expected to continue. Thus, research on this topic is imperative, with implications for aquatic ecosystem health in water-rich northern locations.

This research aims to:

1. Identify if and how cryogenic landslides display a paleolimnological record in the sediments of low-lying lakes in the Eastern Mackenzie Delta.
2. Quantify the potential for cryogenic landslides to introduce elemental loading into lake benthic systems, including the potential for contaminant loading and potential toxicity.
3. Predict if cryogenic landslides will continue to occur in this region and how this data will be stored in the sediment over time.

Literature Review

Reliable, consistent, and easy-to-obtain climate records from the last millennia and even the previous centuries are few and far between. Humans have not, until recently, had the means to track or predict climate patterns or trends as done today. Around 150 years ago, systematic temperature measurements became more prevalent across the globe. However, due to numerous issues, many records are inconsistent, and few have records lasting over a few decades, often with missing data during that timeframe. Even written histories of climate predating the last millennia are scarce and difficult to compare with historical measurements directly. The global climate is everchanging, and the Earth has experienced vast temperature shifts in response to ice ages, extreme volcanic activity and atmospheric shifts. Present-day climate change differs from previous climatic cycles because of the impact of anthropogenic activity. Incredible advancements in technology, agriculture, and transportation have led to wide-scale and measurable changes, whether in rapid landscape degradation, resource depletion or waste product introduction into global systems. Understanding climate warming is complex in that it is impossible to know with complete clarity the climate conditions of the past. Determining trends based on roughly a century of recorded climate data can tell us about trends within the industrialized period of human history but very little else, and these are only available for a handful of locations.

Accelerated warming is particularly intense in Canada's western Arctic compared to the rest of the globe (Lantz & Kokelj, 2008). Even within Canada, this region is experiencing an elevated rate of warming (Technical Guide: Infrastructure in Permafrost: A Guideline for Climate Change Adaptation, 2019). Over 100 years of temperature data recorded from the late

19th century to the end of the 20th-century record a 1.7°C increase in air temperature in the Mackenzie Valley, which is the highest of all Canadian regions over the same period (Dyke & Brooks, 2000). This accelerated warming is partially due to the phenomenon called Arctic Amplification. Additionally, the range of intensity of summer and winter conditions presented by 24-hour daylight during the summer and 24-hour polar night during the winter means that Arctic locations experience the greatest temperature extremes.

Inuvik (and nearby communities) have exhibited warming trends for the last century, particularly during the winter. Lantz et al. (2019) synthesized temperature data from Aklavik between 1926 to 1957 and Inuvik from 1957 to 2017 (Fig. 3). This air temperature record highlights a roughly 3-degree increase in the winter temperatures and a near 2-degree increase in the summer temperatures in this region of the Mackenzie Delta. Across this period, a roughly 2 degrees increase in permafrost temperatures has also been recorded (Lantz et al., 2019).

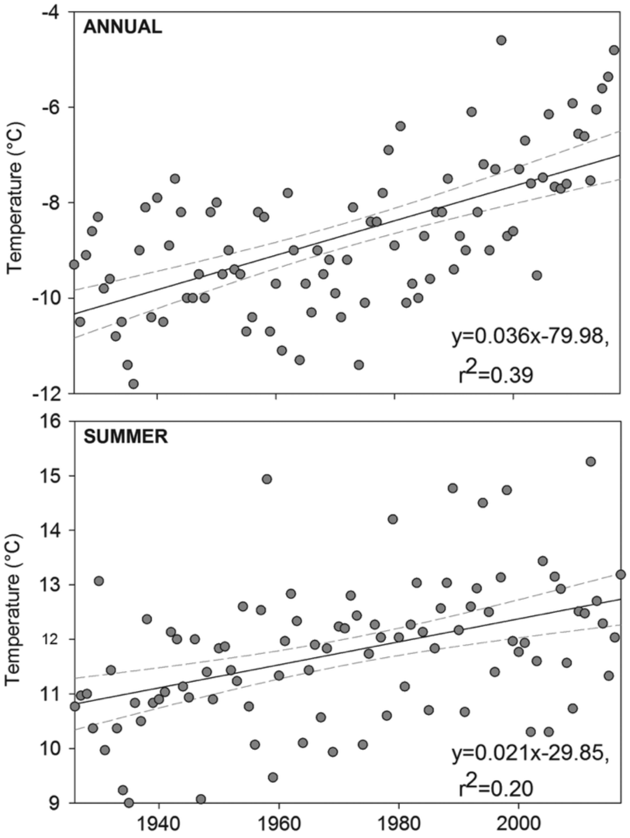
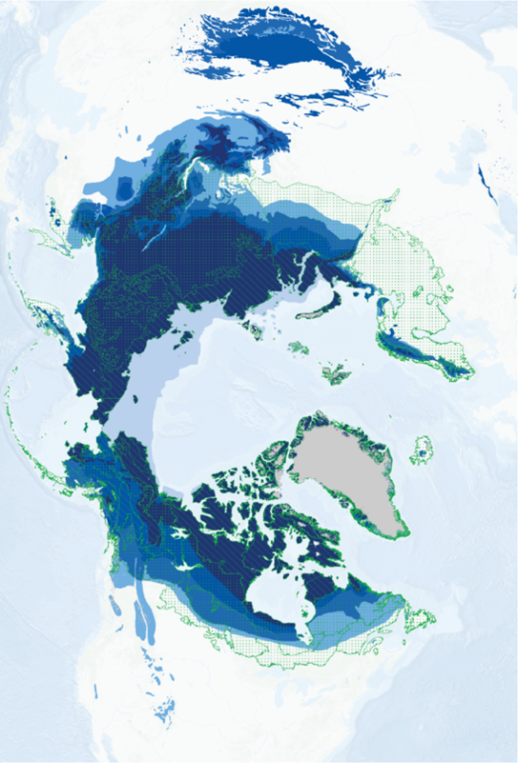


Figure 3: Warming mean annual temperatures across the last century in Aklavik (1926-1957) and Inuvik (1957-2017) (Lantz et al., 2019).

Permafrost is defined as any ground that remains at or below 0°C for two or more consecutive years (Woo, 2012; Technical Guide: Infrastructure in Permafrost: A Guideline for Climate Change Adaptation, 2019). Local climate is the most reliable predictor of permafrost presence (Technical Guide: Infrastructure in Permafrost: A Guideline for Climate Change Adaptation, 2019). Roughly



Permafrost Zone	
■	Glaciers/ice sheets
■	Continuous permafrost (90 – 100%)
■	Discontinuous permafrost (50 – 90%)
■	Sporadic permafrost (10 – 50%)
■	Isolated permafrost (0 – 10%)
■	Subsea permafrost

Figure 4: Northern Hemisphere permafrost presence displayed as durability category. The Mackenzie Delta is entirely encompassed within the continuous permafrost zone (Schuur & Mack, 2018).

one-quarter of all landmasses in the Northern Hemisphere are underlain by permafrost (In 'T Zandt et al., 2020). Factors influencing the persistence of permafrost are both physical (location, topography, local hydrology, geology) and climatic (precipitation, snow cover, vegetation, fire) (Woo, 2012). Many of these variables are in flux in Arctic systems in response to changing conditions. These factors additionally determine if permafrost coverage is continuous (> 90%), discontinuous (50-90%), sporadic (10-50%) or isolated (< 10%) (Schuur & Mack, 2018) (Fig. 4). When permafrost warms above freezing, thaw occurs. The thaw of permafrost impacts ground stability, weakening the landscape with warming (Technical Guide: Infrastructure in Permafrost: A Guideline for Climate Change Adaptation, 2019). This thaw is a concern in populated regions underlain by permafrost as the structural integrity of architecture and ground may be lost (Technical Guide: Infrastructure in Permafrost: A Guideline for Climate Change Adaptation, 2019).

Permafrost thickness varies by hundreds of metres across the Beaufort-Delta Region of Canada's western Arctic. A significant driver of this variation is historical glacial coverage (Burn & Kokelj, 2009). Some unglaciated regions have recorded permafrost thicknesses upwards of 500 meters. In contrast, those that deglaciated with the end of the Wisconsin Glaciation are found to be closer to 100 meters thick (Burn & Kokelj, 2009). The Mackenzie Delta, which the Laurentide Ice Sheet covered, is underlain by permafrost less than 100 meters thick due to thermal insulation of the ground, primarily by water bodies, as well as forest cover (Burn & Kokelj, 2009). More detailed studies of permafrost continuity across the Mackenzie Delta (with perforation), reported depths of 60 to 70 meters (Forbes et al., 2022). Permafrost thicker than 100 m is unlikely to exist within the Mackenzie Delta's boundaries, despite being observed in near delta locations like Inuvik, because of local warming caused by river and lake presence (Dyke & Geological Survey of Canada, 2000). The stability of permafrost in the delta is promoted by regional characteristics, including vegetation, soil type and drainage potential (Dyke & Brooks, 2000). External climate conditions like snow cover and air temperature can either sustain or hinder permafrost stability (Dyke & Geological Survey of Canada, 2000).

Thermokarst features are subsidence landforms that change ground stability and compositional makeup, particularly during the thawing of ice-rich permafrost or the melting of massive ground ice (Kokelj & Jorgenson, 2013; Staniszewska et al., 2022). Climate variables, primarily increased precipitation and temperatures, are first-order drivers of thermokarst development and growth (Schuur & Mack, 2018). Precipitation plays an enhanced role on slopes by influencing stability (Segal et al., 2016). Thermokarst features are as dynamic and varied as the landscapes they exist in; found across the world's cold regions, 22 thermokarst types have been identified in Alaska (Kokelj & Jorgenson, 2013).

Permafrost disturbance can be described as either thermal or physical (Beel et al., 2020). Thermal disturbance includes active layer depth expansion promoted by high summer temperatures (Beel et al., 2020). This change is often less evident from a physical standpoint; however, it does have measurable impacts on hydrological potential and solute transport within a region. Physical change, which this research has a greater focus on, is the mobilization, sometimes rapidly, of previously stable ground (Beel et al., 2020). This mass movement can be exemplified on sloped terrain, where enhanced relief can translocate thawed material and associated overburden, leading to further permafrost thaw. These forces are driven thermally by increased temperatures, natural events like wildfire or climate and weather events like increased rain (Heginbottom, 2000). These events have the potential to impact hydrological systems at a significant scale. Permafrost loss not only reintroduces historically stored water back into the system but also creates new hydrological pathways because of the increased permeability of the ground laterally and from above (Quinton et al., 2011). New and changed hydrological pathways can broadly impact terrestrial and aquatic systems.

Thermokarst formation is driven by many factors, including the geomorphology of an environment, permafrost makeup, regional climate and anthropogenic influence (Segal et al., 2016). This geomorphological variation between places means that thermokarst development is not consistent across cold regions and relies heavily on local disposition (Staniszewska et al., 2022). For example, those along coastal shores may exhibit enhanced development due to hydrologically driven erosion, such as waves or rushing water (Obu et al., 2016). For others, thaw can be driven thermally when frozen ground is exposed to a warmer body, such as a lake (Kokelj & Jorgenson, 2013) or in response to extreme precipitation events. Thermokarst development is enhanced by climate change, mainly due to changes in weather patterns, rapid warming, and landscape factors which are all major determining factor in slump presence and type (Segal et al., 2016). Thermokarst can additionally develop in response to rapid warming caused by wildfires or anthropogenic influences like warming features (Bouchard et al., 2017) such as residential or extractive development. Thermokarst landforms (e.g., active layer detachment slides, retrogressive thaw slumps or polygonal ground) vary in size from 1m^2 to thousands of hectares (Kokelj & Jorgenson, 2013) (Fig. 5). Accelerated warming in Canada's western Arctic results in thermokarst features occurring at an amplified rate (Lantz & Kokelj, 2008).

Slope failures in the Mackenzie Valley can be characterized as either rotational slides (thaw slumps) or active layer detachment slides (Dyke & Geological Survey of Canada, 2000) and both thermokarst features can result in substantial land deformation and are common around the Mackenzie Delta. Collectively, these can both be referred to as cryogenic landslides. Retrogressive thaw slumps are an incredibly dramatic visualization of thermokarst commonly found in ice-rich areas, such as the Western Canadian Arctic (Kokelj & Jorgenson, 2013). They are widespread along the banks of the Mackenzie River and are thoroughly documented (Dyke & Geological Survey of Canada, 2000). Erosion caused by fluvial systems can influence slide development and reoccurrence. Active layer detachment slides occur when the active layer, the portion of the ground that freezes and thaws on a seasonal basis, detaches from the permafrost and translocates down the slope (Kokelj & Jorgenson, 2013). These slides occur rapidly and often in the Mackenzie Valley and do not require a substantial angle of slope to occur (Dyke & Geological Survey of Canada, 2000); however, they often appear on steeper slopes. Characteristics of active layer detachment slides often include identifiable scarring where the lateral movement of breakaway occurred (Kokelj & Jorgenson, 2013). These landslides are most common in areas that are rich in permafrost, have fine-grained sediments and low hydraulic conductivity (Kokelj & Jorgenson, 2013). They are usually prompted by external circumstances (Dyke & Geological Survey of Canada, 2000), including weather events or rapid temperature changes. Further permafrost thaw can occur rapidly or over time. Deepening of the active layer is an example of a slower process, whereas landslides are more rapid (Christensen, 2024).

Figure 5: Thermokarst features in the Mackenzie Delta Region. Top left: Scarring from active layer detachment slide (Caribou Hills); top right: patterned ground; bottom (Mackenzie Uplands): retrogressive thaw slump (Mackenzie Uplands).

Magnified thermokarst activity, both in size and frequency, is observed in tandem with climate change, particularly increased temperatures and precipitation. Despite this, regional characteristics and their relation to thermokarst are yet to be entirely confirmed (Segal et al., 2016). This can concern researchers and local land users since cryogenic landslides are a significant source of geomorphological change in the Western Canadian Arctic, as the landscape is dominated by ice-rich permafrost (Segal et al., 2016). Structural landscape instability caused by permafrost thaw is not unique only to the present day, and has also occurred historically during the Holocene Climate Optimum, for example (Segal et al., 2016). Massive amounts of thawed sediment can travel downslope into lower elevation systems, including lakes, potentially altering existing geochemical processes. Beyond this, landslides can significantly alter the physical makeup of landscapes over extended timescales (Segal et al., 2016). Permafrost thaw initiates the transfer of many materials, including water, organic and inorganic matter and dissolved chemicals, to other locations (Bouchard et al., 2017). This is particularly obvious in the case of hillslope thermokarst, of which cryogenic landslides are a form.

Permafrost thaw and the melting of ground ice can substantially influence chemical properties in downstream receiving waterbodies (Kokelj & Jorgenson, 2013). In addition, translocated terrestrial landslide material deposited into lakes can result in many limnological, biological and contaminant responses (Bouchard et al., 2017). Limnological changes may include ion introductions, pH shifts, or changes in the lake's water colour, and chemical or biological impacts may influence shifts in biodiversity throughout the water column or in benthic organisms (Bouchard et al., 2017). Additional sediment flux may impact contaminant makeup through dilution or concentration (Bouchard et al., 2017). Thermokarst induces carbon and nitrogen release from deeper permafrost (In ’T Zandt et al., 2020). Thaw slumping impacts thousands of lakes along the Mackenzie Delta and the surrounding uplands by introducing ion-rich soils through direct deposition and surface runoff (Lantz & Kokelj, 2008). This trend is likely to continue in upcoming years with amplified precipitation and temperatures (Lantz & Kokelj, 2008; St. Pierre et al., 2018). This can be amplified in hillslope thermokarst, where thaw can introduce sediment solutes rapidly and in mass quantities onto downslope landscapes or into water bodies (Kokelj & Jorgenson, 2013). Accumulation in delta lakes can be complicated to quantify since sediment loads are greater during the ice-free season and during high flow but are suspended during lake freeze-over (Crann et al., 2015).

Lakes are dynamic in thermokarst regions in their features and abundance (Marsh, 1998). For example, size may change with lake drainage or the erosion of the shoreline, and abundance may fluctuate because of permafrost loss, causing lakes to merge (Marsh, 1998). Bathymetry in lakes can be a determining feature in lake ecology and ice dynamics and can also speak to a region's geomorphology. It can also be an essential consideration in lakes where extensive landsliding occurs since sediment loading may distribute unevenly across the lake basin. During substantial cryogenic landsliding, the lake's morphometry may be altered due to mass amounts of sediment flowing into the lake basin.

As direct limnological monitoring is absent for the vast majority of locations, inferences of change must be generated using proxy records. Proxy data is reliably stored information and can indirectly explain other variables. These methods allow scientists to reconstruct environmental histories where monitoring is absent. Paleolimnology is the scientific discipline that identifies the histories within lake ecosystems using proxy data in lake sediment archives. Paleolimnological records in thermokarst water bodies can be exceptionally detailed and often underexplored (Bouchard et al., 2017). This sediment archive can be used to create a reliable environmental change timeline across the lake's history (Bouchard et al., 2017). Since the degradation of permafrost in or around lakes impacts in-lake chemistry (Kokelj et al., 2009) landscape changes should be identifiable within sediment cores. This research will focus on selected elemental proxies that are expected to be affected by an influx of terrestrial material during landsliding: %TC, %TOC, %TN, C/N, and THg . Carbon (%TC & %TOC) is of interest in climate research for many reasons. This research will use carbon as a proxy to indicate landslide occurrence within the core since terrestrial sediment is likely to be more carbon-rich than lake sediment because the sources of organic matter, vascular plants and algae, produce different amounts and signatures in organic matter deposited to lakes (Meyers & Terranes, 2002). This would be evident in the stratigraphy as elevated carbon content compared to the background. This research also recognizes the vast potential for permafrost thaw to reintroduce stored carbon into the carbon cycle. The southern and central Mackenzie Delta is a large reservoir of organic carbon that is characterized by ice-bonded sediments (Forbes et al., 2022). During thaw, which can occur rapidly in ice-rich permafrost, this carbon can swiftly be remobilized into hydrological systems. Additionally, methane and carbon dioxide released into the atmosphere can be exacerbated by the introduction of organic carbon during sediment thaw with greater quantities of organic matter to decay (Schuur & Mack, 2018; Heginbottom, 2000). While this research does not explicitly analyze these variables, it is important to note that elevated organic carbon in the lake body that becomes bioavailable during thaw can have measurable implications for the carbon cycle. This concern is further elevated under warming conditions since lakes with taliks (unfrozen sediments below the water body) can maintain biological activity during the coldest months and the potential for methane production is elevated (Schuur & Mack, 2018). Nitrogen (%TN) is an important biological indicator of ecosystem health. Nitrogen and other nutrient loading caused by anthropogenic runoff and discharge can lead to eutrophication in many southern lakes. Northern lakes are much less likely to experience eutrophic conditions since they are generally more nutrient-poor in colder climates and unimpacted by sources of anthropogenic waste. In permafrost-rich soils, nitrogen can be the most notable limiting nutrient for plant growth due to either being kept in a frozen state (permafrost) or being less accessible to microorganisms at cold temperatures (Schuur & Mack, 2018). Some of this nitrogen is accessible to plants during the thaw season of the active layer (Schuur & Mack, 2018). Mass sediment loading can introduce nitrogen rapidly into lake ecosystems, providing thawed nitrogen. The C/N ratio (C/N) can illuminate the source of organic matter within the sediment. Ratios greater than 20 indicate terrestrial organic matter input since terrestrial plants generally contain higher carbon content than aquatic flora (i.e. algae, phytoplankton). C/N ratios in lakes that are less than 10 indicate predominantly algal organic matter sources. Values between 10 and 20 indicate mixed sediment organic material origin. Landslides in the Caribou Hills will contain grassy and herbaceous plants and sometimes even shrubs/trees, depending on the landslide scale. As a result, these landslides are expected to introduce peaks of TOC, raising the C/N ratio when they occur. Total mercury is of interest in lakes for two reasons: 1) as a tracer of terrigenous inputs from the landscape, and 2) as a potential environmental contaminant. The latter is of particular interest for lakes that support fishing due to the element's ability to bioaccumulate across the food chain. Mercury dynamics are also strongly linked to changes in organic carbon availability, with an influx of terrestrial material from erosion. A change in organic matter concentration with shifts in sediment makeup can drive mercury concentration onto a smaller organic pool of available TOC.

The Mackenzie Delta is a glacially produced feature that was formed during the Wisconsin Ice Age (Mackay & Dyke, 1990). Around 14,000 years ago, the Laurentide Ice Sheet retreated and exposed the Mackenzie River Delta during a warming period. This is supported by pollen, and macrofossil remains found in the Mackenzie Delta area (Ritchie, 1985). Glacial activity has driven the present-day form of the Mackenzie Valley. Erosion caused by the retreat of the Laurentide Ice Sheet – which formerly covered the entirety of the delta with thick layers of ice – determined much of the present-day geology and geologic features (Burn & Kokelj, 2009). The Laurentide Ice Sheet, which covered much of Canada, reached its furthest extent around 30,000 years ago, stretching across the plains and terminating northbound at the Mackenzie Mountain range (Duk-Rodkin & Lemmen, 2000). The Mackenzie River is estimated to be just over 12,000 years old, flowing meltwater through the now-present channel (Duk-Rodkin & Lemmen, 2000). The Mackenzie River and Delta hydrologically connect vast expanses of Canada's western boreal forest and subarctic with the Arctic Ocean. The Mackenzie River, Canada's longest river, flows from Great Slave Lake to the Beaufort Sea, a subsection of the Arctic Ocean (Bigras, 1990). Researching the Mackenzie Delta has historically been complicated due to its remoteness (Bigras, 1990). While few inhabit the delta itself, many live in surrounding towns. The most populated are Tuktoyaktuk (pop. 937), Aklavik (pop. 536), and Inuvik (pop. 3,137) as of 2021 (Census Profile, 2021 Census of Population, 2023). The river stems are used for travel in the warm and cold months.

The Mackenzie River basin’s catchment area is massive, draining almost 20% of the mainland Canadian landmass (Bigras, 1990). The Mackenzie River becomes the delta at Point Separation, where the Mackenzie River divides into three distinct stems: Richardson Channel, Middle Channel and East Channel. To the west of the Richardson Channel are the Richardson

Mountains, and to the east of the East Channel are the Caribou Hills. Freshwater lakes comprise nearly 50% of the Mackenzie Delta plain (Marsh & Hey, 1989). The delta is 12,995 km^2 in area, 210 kilometres long and an average of 62 kilometres across (Marsh, 1998). The delta has a varied makeup and is increasingly barren to the north (Bigras, 1990).

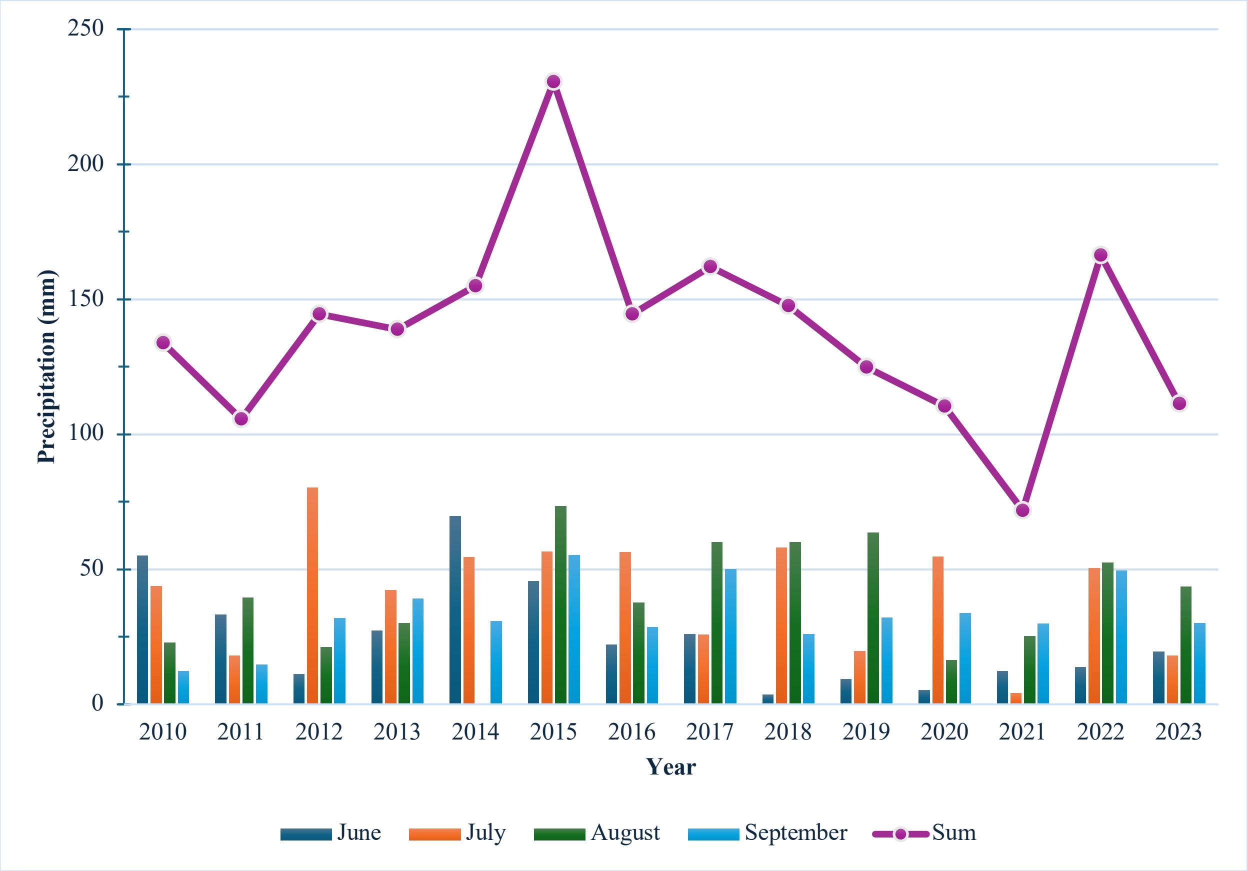


Figure 6: Summertime (June, July, August & September) Precipitation Trends 2010 to 2023 In Inuvik. (Inuvik Climate (Precipitation Data), 2024)

Being north of the Arctic Circle, the Mackenzie Delta, like other Arctic regions, experiences dramatic climatic shifts across seasons primarily driven by the solar radiation present at a given time of year (Dyke, 2000). With the coldest months getting little to no daylight and the warmest having full days of sunlight, the temperature gradient is exceptional. During the study year for this research, 2023, the temperature ranged between -42.3°C (February 5th) and 31.3°C (July 4th), a range of 73.6°C (Inuvik - A (Temperature Data), 2024). In the summer, the

Mackenzie Region, due to air circulation patterns and lengthy sunlight hours, is warmer than areas with the same latitude across Canada (Dyke, 2000). The delta is ice-covered for about eight months yearly (Marsh, 1998). Permafrost underlies most of the Mackenzie Delta, barring sections with substantial channels (e.g. East Channel) (Marsh, 1998) and is ice-rich in the near-surface (Kokelj et al., 2023). Precipitation in the Beaufort-Delta Region is heavily influenced by the nearby Cordillera across the valley to the west, with decreasing averages with increasing latitude (Dyke, 2000). Inuvik receives 250 mm of rain per year and heavy rainfall in the summer is rare, with most occurrences being less than 5 mm (Dyke, 2000); however, recent trends have suggested that larger precipitation events do occur (Fig. 6). Snowfall begins by November, with high volumes in the fall and a rapid decline over the most frigid months (Dyke, 2000).

In early May, the Mackenzie River water levels are driven up by snowmelt and ice jams in the southern basin and main channels (Marsh & Hey, 1989). These increased water levels result in more deltaic lake flooding (Marsh & Hey, 1989). The East Channel is a distributary channel of the Mackenzie River, transporting vast quantities of water north from Point Separation to the Beaufort Sea (Marsh & Hey, 1989). Beyond this, the East Channel is a significant factor that influences the water levels of lakes in the eastern delta (Marsh & Hey, 1989). Lakes, covering a massive portion of the delta and playing a role in the region's hydrology, are essential in regulating ecosystem productivity (Marsh & Hey, 1989). The hydrology of delta lakes can be substantially influenced by spring breakup and freshet; however, lake impact is less when ice cover remains during this period.

The Mackenzie Delta is exceptionally productive for such a northern region. The ground warming provided by lake and riverine features facilitates tree growth at higher latitudes than most other regions. And multiple species, including geese, moose, bears, and many others, call the area home (Marsh, 1998).

This research aims to show how cryogenic landslide records can be stored in lake sediments, whether they directly deposit into the lake or through another mechanism. Further, by understanding paleolimnological responses to historical landsliding, I hope to infer about future instances of thaw in similar systems. Through paleolimnological practices I aim to quantify landslide impacts in these lakes through proxy variables (mercury, carbon and nitrogen) and further analyze to see if these elements are exhibiting loading caused by landsliding. The paleoenvironmental context of this research is important because terrestrial mass movement events in arctic settings can have biogeochemical impacts on the hydrological systems they interact with and, as a result, the communities of people and habitats that rely on them.

Methods

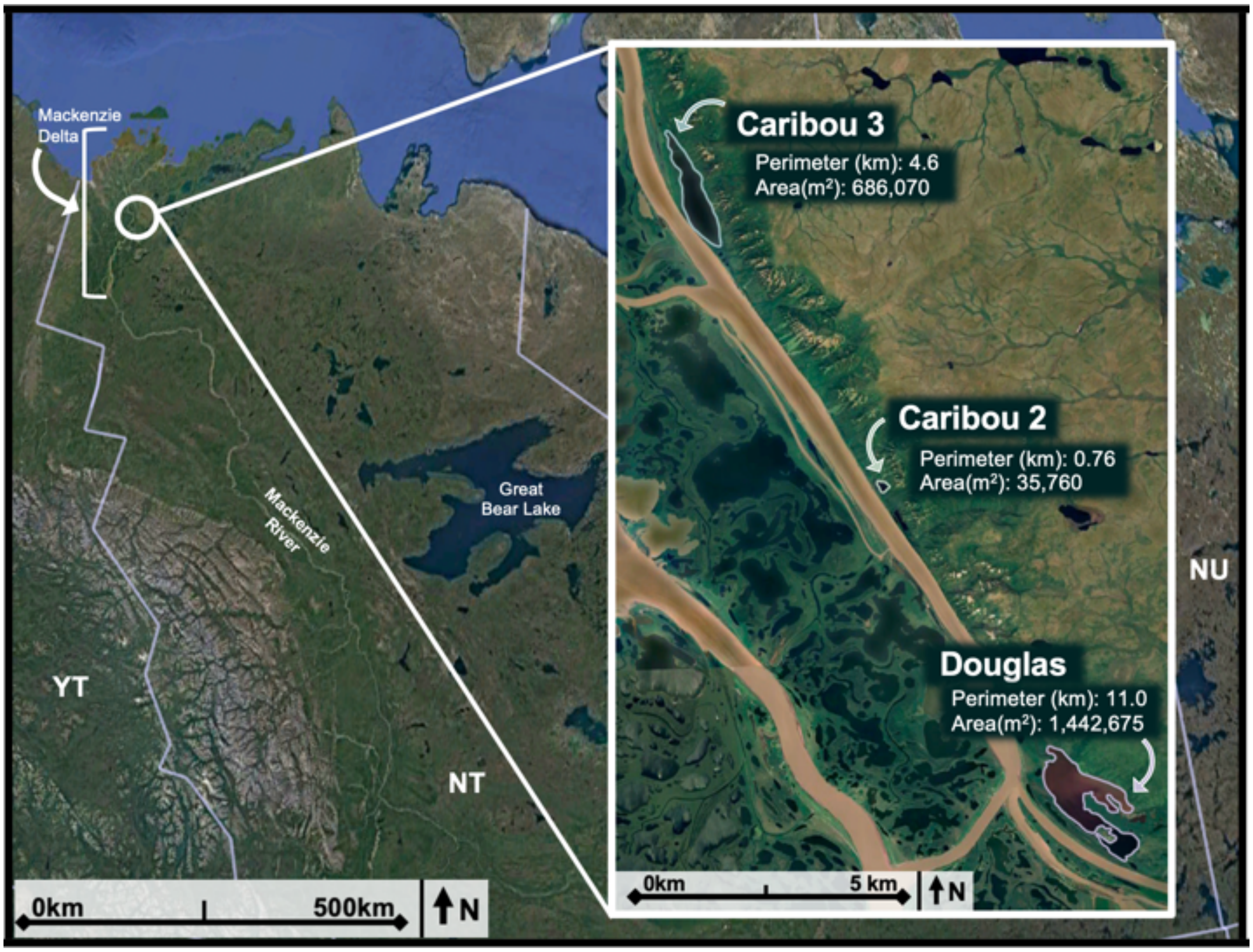


Figure 7: Four study lakes for this research are circled and labelled. The Caribou Hills fall directly to the east and the East Channel to the west. Images from Google Earth Pro.

This research took place in the Northwest Territories, NNW of Inuvik near Reindeer Station. This research will focus on four lakes: Douglas (D), Caribou 2 (C2), Caribou 3 (C3), and Caribou Control (CC) (Fig. 7). Three lakes were (and are) exposed to varying degrees of cryogenic land sliding occurring on the adjacent Caribou Hills and are all different sizes, depths, and shapes (Fig. 8; Fig 9). The fourth lake was selected as a control location, across East Channel.

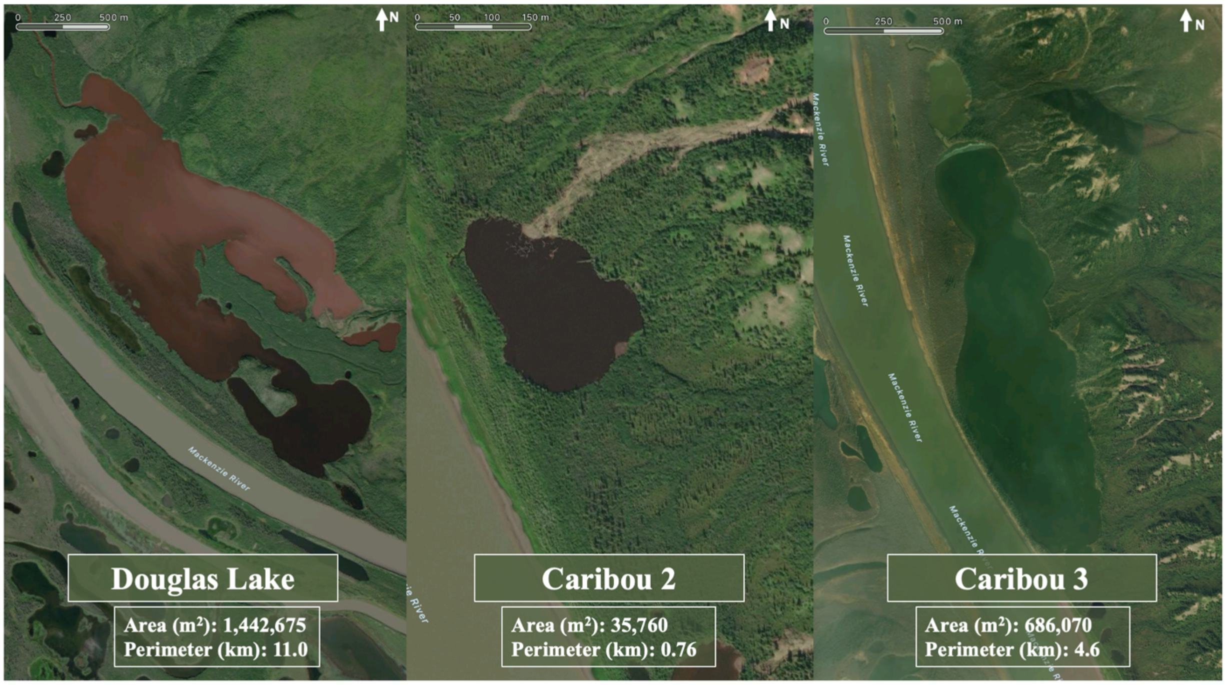


Figure 8: The three impacted study lakes in order from southernmost to northernmost: Douglas, Caribou 2 and Caribou 3. Images from Google Earth Pro.

The control lake, Caribou Control, is small and thin and located on the opposite side of the river channel as the impacted lakes. The area of the lake is comparable to Caribou 2, and the shape to Caribou 3. Caribou Control is a productive lake with grasses along much of the shallow lake basin. Caribou Control was selected during aerial observations taken by helicopter because it was directly across from Caribou 2 Lake and was accessible by boat and short hike. Caribou Control was visited on two separate occasions, first by boat and then by helicopter. The smallest of the study lakes, Caribou 2 (~0.035 km^2), is located between Douglas and Caribou 3. Caribou 2 is round and impacted by one large landslide, the most prominent of all on-lake landslides, proportional to lake size. There was a potential second thaw feature opposite the substantial landslide; however, it was less well-defined. The landslide material remained evident in the lake from the 2017 landslide during the 2023 field sampling. Between the lake and channel, there are numerous shrubs and wetland features. Caribou 3 is the second largest lake in this study (~0.68 km^2) and is furthest from Inuvik, roughly 30 km NNW. This lake was long and thin, parallel with the East Channel, and was impacted by cryogenic landslides along its northeastern bank. Caribou 3 is the closest to the East Channel, with a tall and steep, roughly 5 m wide bank between the two features. Douglas Lake is the largest of the study lakes (~1.44 km^2). It is also the closest to the town of Inuvik. The lake's shape is unique, with two arms oriented north to south connecting at the northern end. As of July 2023, Douglas Lake showed no visible landsliding directly on the lake’s shore. Instead, a small creek flowing into the lake's southeasternmost point flowing from the uplands was responsible for the delivery of some sediment into Douglas Lake. Multiple active retrogressive landslides were occurring upstream, along Douglas Creek. Douglas Lake is connected to the East Channel through a distributary on its north end making this lake accessible directly by boat.

Figure 9: Primary landsliding features affecting the impacted lakes. Caribou 2 - single active layer detachment slide (a), Caribou 3 - active layer detachment slides at the northern end of (b) Douglas - retrogressive landslides up creek (c)

Figure 10: Photos of all study lakes. 1st row: Caribou Control; 2nd row: Caribou 2; 3rd row: Caribou 3; 4th row: Douglas

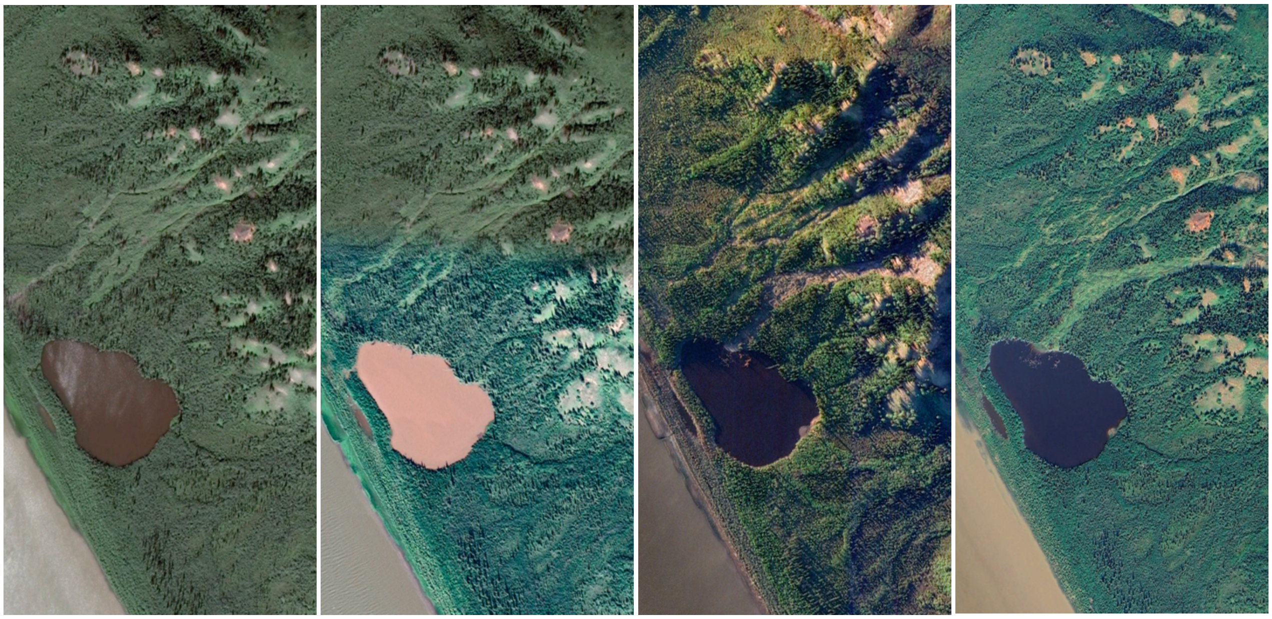


Figure 11: Caribou 2 Lake Landslide progression. July 2012, August 2017, June 2019, July 2022 Images from Google Earth Pro

The three impacted lakes were chosen due to their proximity to active cryogenic landslides and the East Channel. While all study lakes (Fig. 10) are close to each other and experience the same climate, weather, and general external pressures, the landslide features affecting each of the impacted study lakes are different. Caribou 2 was impacted by one landslide (Fig. 11), Caribou 3 by six landslides, and while Douglas is unimpacted directly by hillslope landslides on its shoreline, there were over 12 landslide features within 6 km up creek of it that drain into the lake.

At all sites, sediment cores were taken using a UWITEC gravity core with an added hammer action (Fig. 12). A total of 11 cores were collected from the 4 study lakes (Caribou Control (1), Caribou 2 (2), Caribou 3 (3), Douglas (5)). The number of cores taken at each lake were determined based on lake size. All cores varied in length from 11 cm to 30 cm. At each impacted lake, terrestrial grab samples were taken to contextualize the elemental make up of the landslide material ending up in the lake during these thaw events.

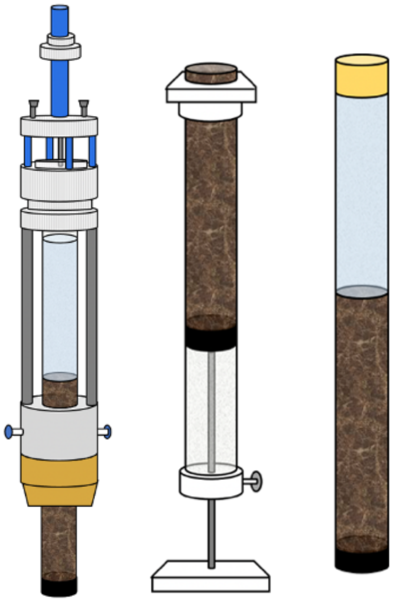


Figure 13: UWITEC Gravity Corer with added brass weight for hammering into sediment (a), sediment extruder (b) and PVC tube with sediment core encased and sediment/water interface maintained (c).

Figure 12: Caribou 2 – Core 1 & Caribou 3 – Core 2 Pre-sectioning. In lab, Inuvik, NT.

All sediment cores were kept cold and dark and sectioned within 24 hours of collection (Fig. 13). Lake depth data was recorded using a HumminBird Echosounder. Preliminary cores taken in the spring of 2021 were sent for lead-210 radioisotope dating. The results of these cores came back with low isotopic values and no apparent exponential decline, making them unsuitable for sediment dating and suggested rapid deposition. Recognizing this would likely be the case again, no cores from the summer 2023 field season were dated. Upon returning to the lab, 200 samples (193 sectioned from lake cores and seven terrestrial grab samples) were freeze-dried. Mercury analysis was completed using a Direct Mercury Analyzer (DMA-80). Regular blanks and soil standards were used to calibrate the machine, ensure quality control, and triplicate samples were run daily across all cores. Elemental analysis (carbon and nitrogen) was completed using an Elementar Unicube elemental analyzer set to CN mode. Blank, elemental (sulfanilamide) and soil standards were also measured throughout sample runs. Samples that were tested for OC concentration were acid fumigated using HCl for at least 48 hours to remove carbonate content (Korosi et al., 2018). C/N ratios determined from the CN analyzer are mass ratio, and thus atomic ratio was calculated by multiplying results by 1.167 (Meyers and Terranes 2001). Stratigraphies were created using RStudio software. All proxy data was compiled post-lab analysis and displayed along depth units for each corresponding core.

Results

The study lakes were visited in the summer of 2023, and sediment cores were taken, ranging in size from 11 to 30 cm long (Fig. 14). An additional Control Lake was also cored. In the winter of 2021, a single sediment core was taken from each impacted study lake (Caribou 2 (Fig. 15), Caribou 3 (Fig. 16) and Douglas (Fig. 17)) for preliminary research. Recent (2017) landslide history was expected to be maintained in all cores since sediment deposition, excluding landsliding and extreme weather events, in northern regions occurs at slower rates (Crann et al., 2015).

Stratigraphies will be displayed independently in this results section, and further context will be provided regarding within-lake variation. Water quality data will be presented directly after the preliminary core results (Table 1). A comparison of elemental proxies within individual lake cores will be displayed following the represented lake, and a synthesis of multi-lake comparisons will be at the end of the results. While the sediment cores collected in 2023 were not dated, isotopic lead (^{210}Pb) dating was completed on the preliminary cores from the three impacted lakes collected in February 2021. The results found that the top 20 cm of each core had consistent and low isotopic activity, indicating the material was likely deposited quite rapidly.

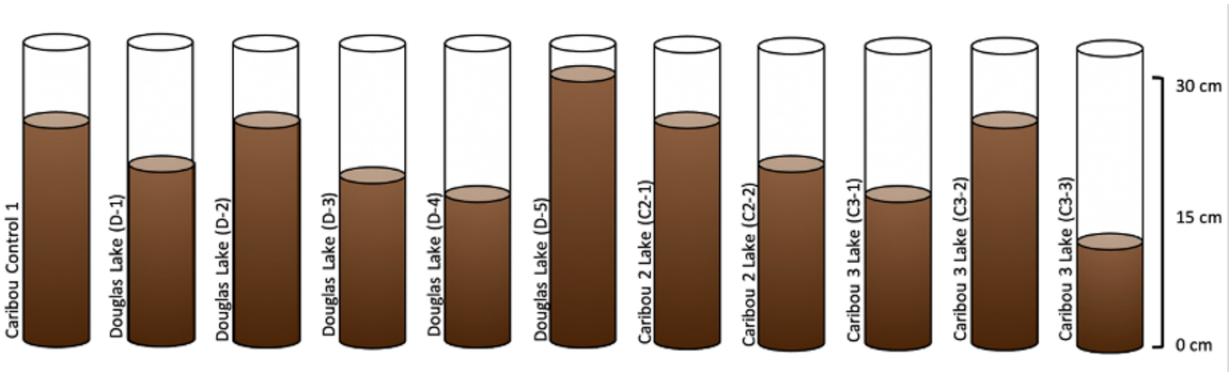


Figure 14: Lengths of all 2023 sediment cores collected.

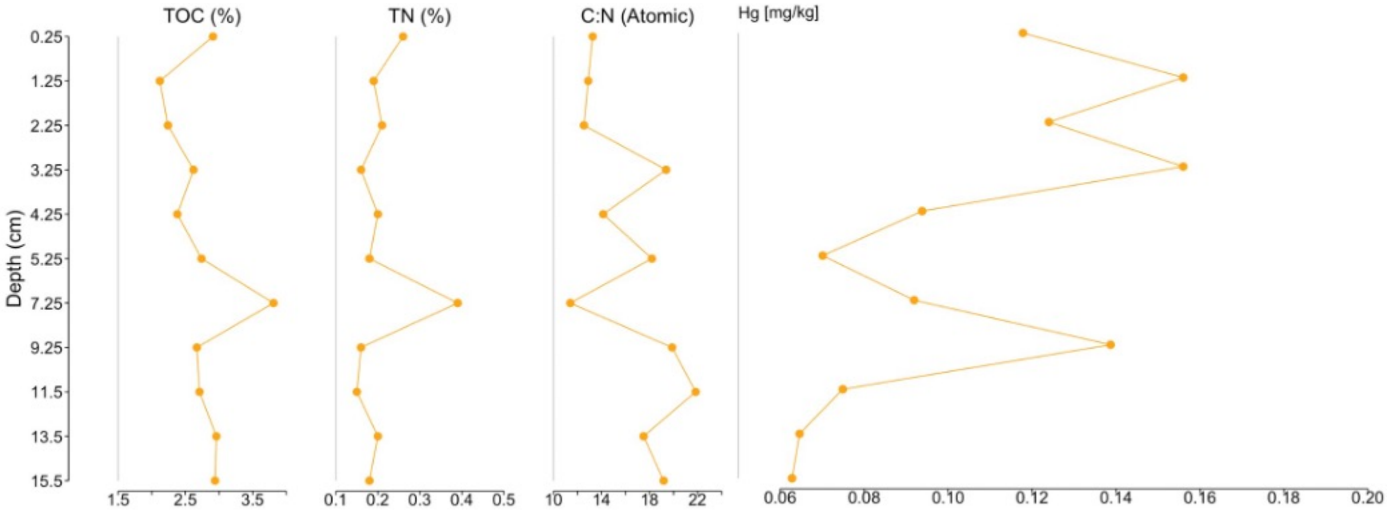


Figure 15: Preliminary Caribou 2 core stratigraphy for elemental analysis and total mercury. Collected in spring 2021.

In the preliminary core from Caribou 2TOC values were stable, ranging between 2.5% and 3% (Fig. 15). A minor peak in TOC occurred at 7 cm. At the same depth, TN also peaked, doubling from roughly 0.2% to 0.4%. Aside from this peak, TN values were very stable at around 0.2%. The C/N ratio varied throughout the core, with a general decline toward the surface sediment. Overall, the C/N ratio suggested a mixed organic carbon source with increasing autochthonous production in the surface intervals. THg (mg/kg DW) displayed substantial variation, with the concentration rising toward the surface of the sediment core. The highest THg (mg/kg DW) values in this core fell just below 0.16 mg/kg DW, more than double the concentration of the deepest sediment intervals.

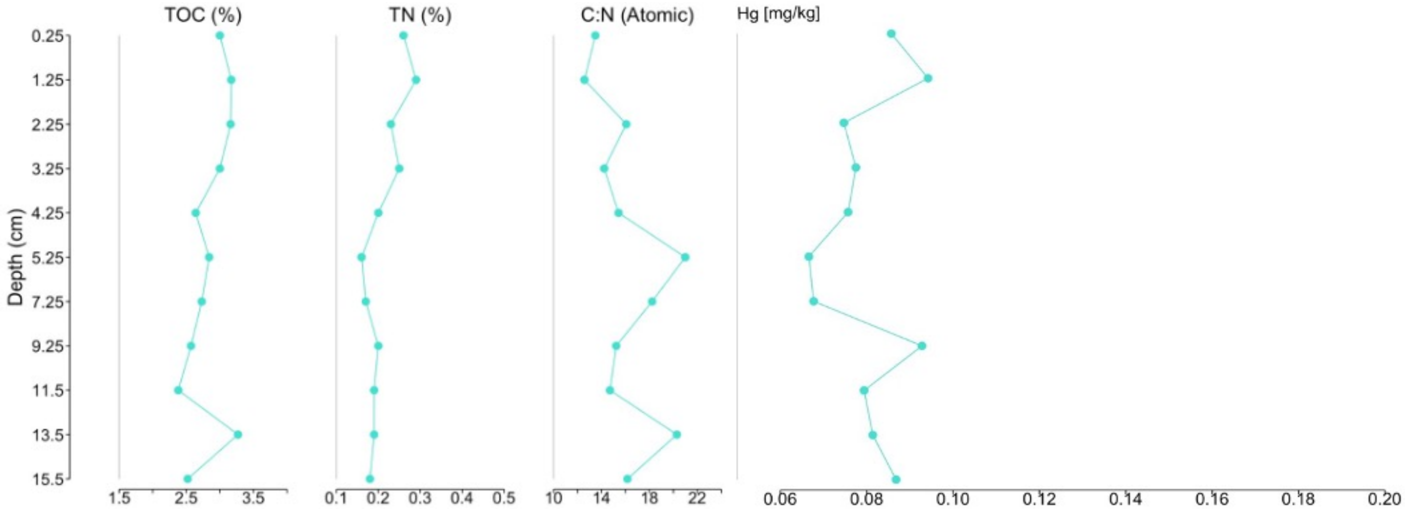


Figure 16: Preliminary Caribou 3 core stratigraphy for elemental analysis and total mercury. Collected in spring 2021.

TOC was very stable in Caribou 3's preliminary core, around 2.5%, with a ~1% increase to 3.5% near the core's base (13.5 cm). TN remained relatively stable along the core's depth between 0.2% and 0.3%. Similar to Caribou 2, there was a steady decrease in the C/N ratio of the shallower sediment, suggesting less influence from terrestrial organic carbon sources and more in-lake production influence. The THg in Caribou 3's preliminary core had no apparent trend. While it displayed occasional peaks and troughs in the concentration along its stratigraphy, they were minor and remained around 0.08 mg/kg DW.

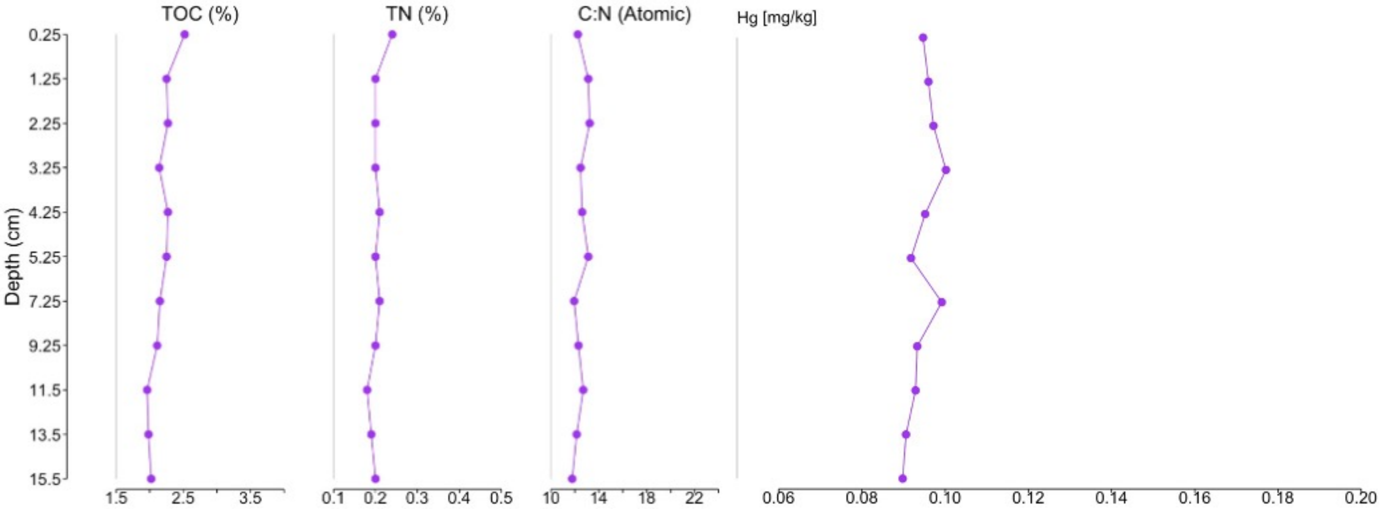


Figure 17: Preliminary Douglas core stratigraphy for elemental analysis and total mercury. Collected in spring 2021.

Values of all proxies were stable in Douglas Lake's preliminary 2021 core. TOC displayed a steady concentration around 2% - 2.5%. TN showed a similar, stable trend of approximately 0.2% to 0.25%. In both TOC and TN, the surface values had the highest concentration along the core’s length. The C/N ratio was steady with depth, maintaining a ratio of roughly 12, suggesting that the primary source of lake carbon was produced autochthonously. THg was also steady with a slightly elevated background values compared to the other impacted lakes around 0.09 mg/kg DW.

YSI Water Quality Collection								
Date	Lake	Depth (m)	Temperature (°C)	Specific Conductivity (uS/cm)	pH	Turbidity (NTU)	O_2 Concentration (mg/L)	O_2 Saturation (%)
July 7, 2023	**Caribou Control**	Surface	21.4	42	7.50	4.7	10.08	114
July 6, 2023	**Caribou 2** - Core 1	Surface	20.4	250	7.44	3	9.52	105.5
	Caribou 2 - Core 2	Surface	20.4	240	7.44	2.6	10.11	112
July 6, 2023	**Caribou 3** - Core 1	Surface	20.74	235	7.46	5.9	9.67	108
	Caribou 3 - Core 2	Surface	20.72	252	7.45	5.5	9.8	109.5
	Caribou 3 - Core 3	Surface	20.87	253	7.44	5.3	n/a	112
June 30, 2023	**Douglas** Creek	Surface	20.87	583	7.43	n/a	9.2	117
	Douglas (Central)	Surface	22.3	163	7.45	n/a	9.7	112
		2 m	22.0	167	7.46	n/a	9.8	n/a
		3 m	16.8	147	7.40	n/a	9.8	100
		4 m	13.6	132	7.45	n/a	10.8	105
	Douglas - Core 1	Surface	22.3	163	7.45	n/a	9.7	112
	Douglas - Core 2	Surface	20.5	160	7.44	n/a	9.5	106
	Douglas - Core 3	Surface	22.7	170	7.45	n/a	9.8	113
	Douglas - Core 4	Surface	21.6	162	7.45	n/a	9.8	111
	Douglas - Core 5	Surface	19.77	180	7.44	n/a	9.36	103

Table 1: YSI water quality data from all study lakes.

Elemental Analysis of Carbon, Nitrogen, and Mercury

Caribou Control Lake

Figure 18: Control Lake sampling site. Image from Google Earth Pro.

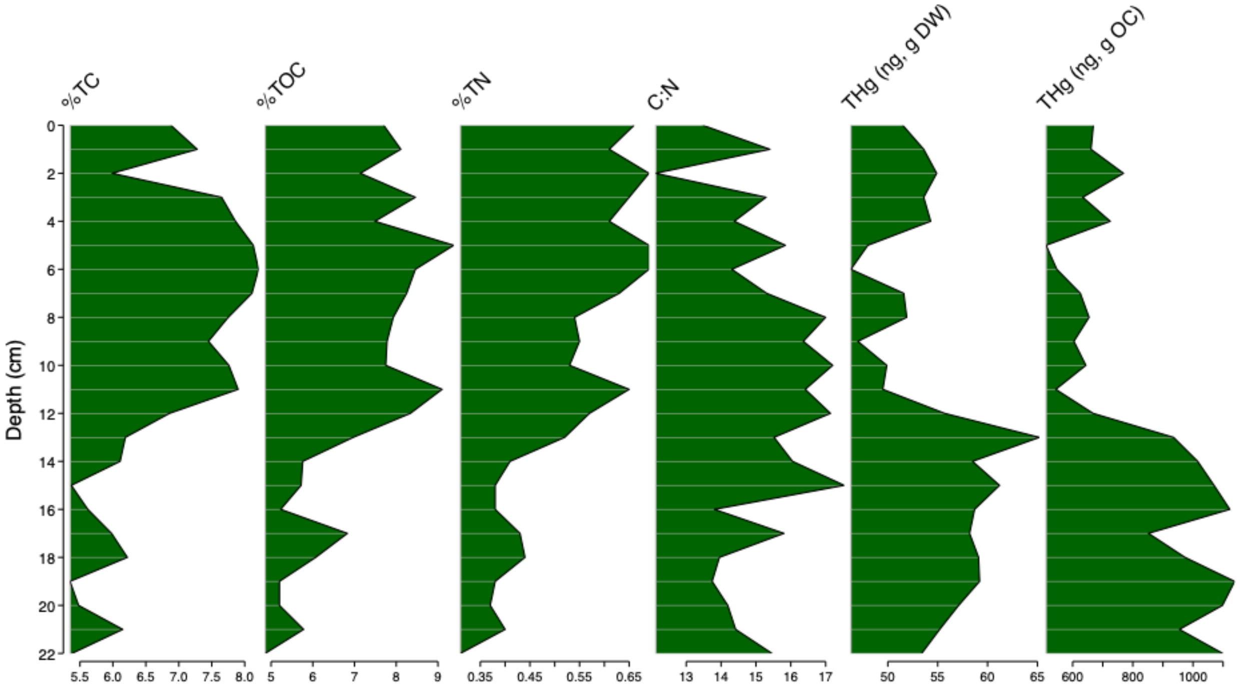


Figure 19: Control Lake core stratigraphy for elemental analysis and total mercury. Core taken July 7, 2023.

Caribou Control (Fig. 18; Fig. 19) displayed a shift to higher TC and TOC content in the core's top 13 cm compared with the bottom 9 cm, rising from roughly 6% to 8% (Figure 19). TN followed a very similar trend to TC and TOC values. TN background values were near 0.40% and rose to around 0.65% above 13 cm. The C/N ratio was stable, exhibiting values indicating a mixed organic carbon source. THg (ng/g DW) values were stable, ranging between 46.3 to 65.2 ng/g DW. A dip in THg (ng/g DW), mirrored the trend displayed in both carbon proxies with a stable, slightly lower THg (ng/g DW) makeup in the upper half of the sediment core than the bottom half. The THg (ng/g OC) also dropped to almost 50% of the core bottom values, from around 1100 (ng/g OC) to around 600 (ng/g OC). This is in response to the steady THg (ng/g DW) concentrations and elevated carbon concentrations in the top half of the core.

Caribou 2 Lake

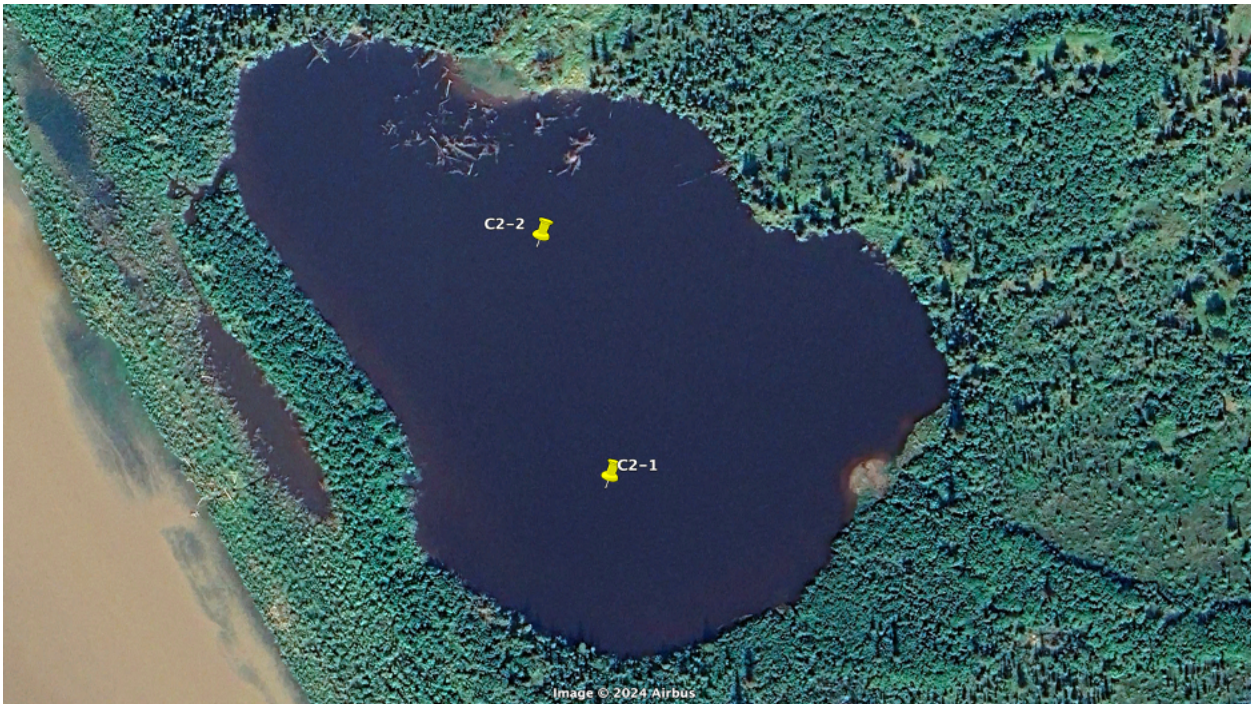


Figure 20: Caribou 2 Lake sampling site. Images from Google Earth Pro.

Caribou 2 – Core 1 (C2 – 1)

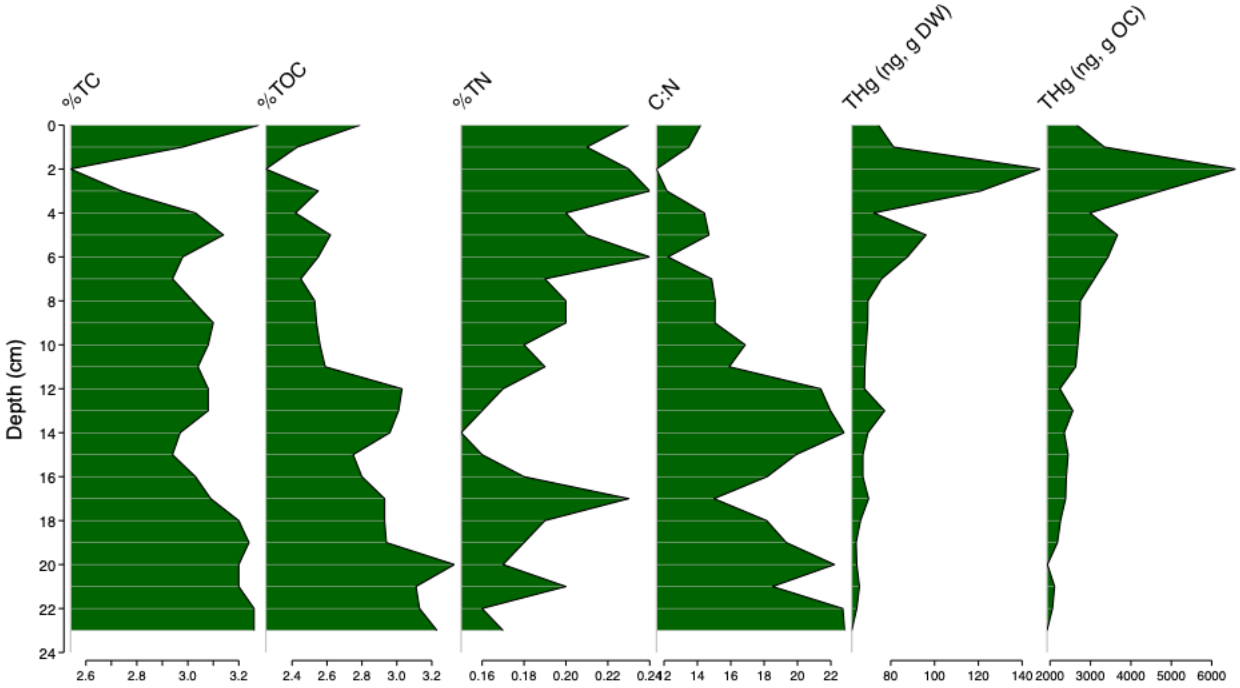


Figure 21: Caribou 2 Lake – Core 1 stratigraphy for elemental analysis and total mercury. Core taken July 6, 2023.

The TOC of Caribou 2 – Core 1 (Fig. 20; Fig. 21) was stable between 4 and 23 cm around 3.10% and then sharply dropped to 2.54% at 2 cm, returning to background values in the surface sediment. Similarly to TC, TOC also dipped to 2.25% at 2 cm. The trend of TOC indicates a steady decrease toward the surface sediment; however, similarly to TC, most surface sediment also rebounded to background values. The TN increased up core. The C/N ratio of this core steadily decreased from the bottom to the top of the core, from 22.9 to 14.2, displaying some variation throughout the stratigraphy. THg (ng/g DW) values sharply increased to 148.3 ng/g DW, roughly two times the core's average of 76.6 ng/g DW values, at 2 cm depth. The surface sediment returned to background values. THg (ng/g OC) displayed a sharp peak to 6591.1 ng/g OC at 2 cm from the background levels around 2500 ng/g OC. These values return to the background level in the surface sediment.

Caribou 2 – Core 2 (C2 – 2)

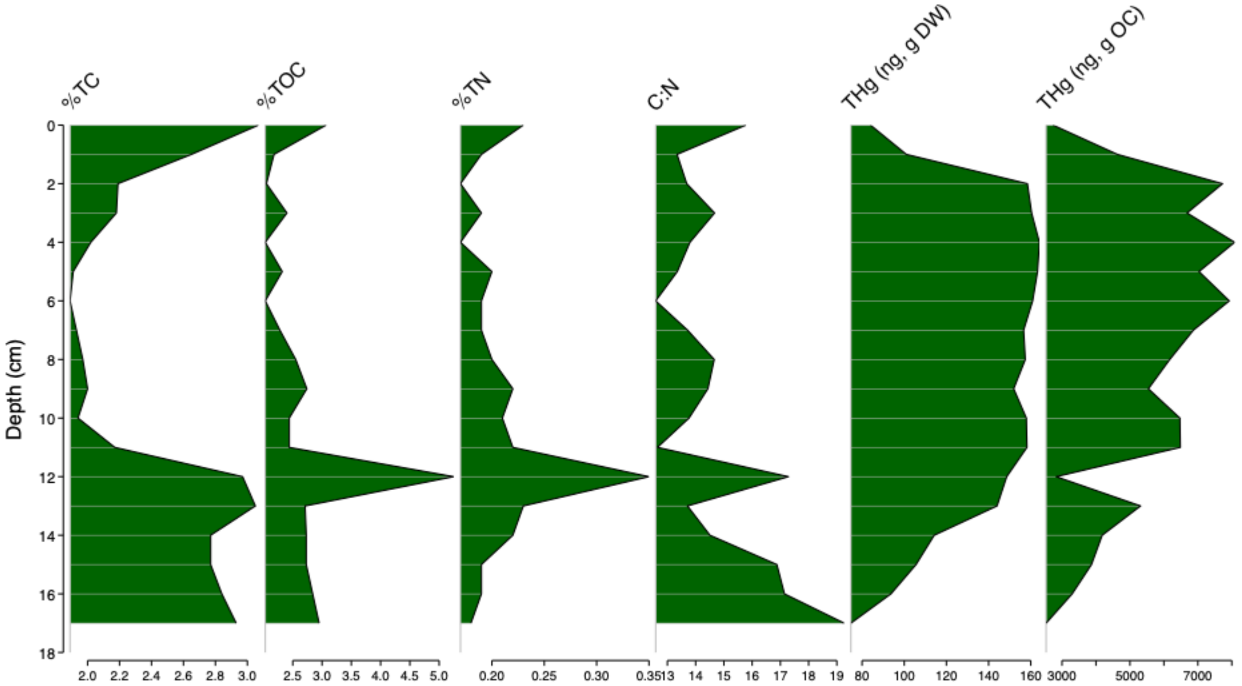


Figure 22: Caribou 2 Lake – Core 2 stratigraphy for elemental analysis and total mercury. Core taken July 6, 2023.

Caribou 2 – Core 2 (Fig. 20; Fig. 22) TC values averaged around 2.90% in the bottom 6 cm of the core. This was followed by an abrupt dip between 2 and 11 cm, to an average of 2.02%. A return to background TC was apparent in the surface sediment. TOC followed a similar trend as TC, with an average background of 2.79% between 13 and 17 cm and then a dip to 2.33% between 2 and 11 cm. A significant peak in TOC was recorded at 12 cm, just before the rapid decrease. As with TOC, TN also displayed a peak to 0.35% at 12 cm. Excluding this peak, TN in the rest of the core was stable, averaging 0.20%. The C/N ratio was stable between 2-11 cm, averaging 13.7. A spike in C/N at 12 cm matches the peaks observed in TC, TOC and TN. As with Caribou 2 – Core 1, this core's peak THg (DW) value roughly doubled compared to the lowest recorded concentration. This core lacks a steady background reference point because the core was too short; however, the lowest value of 74.7 ng/g DW at the base is supported by the background values in Caribou 2 – Core 1's average background of 76.6 ng/g DW. Across the core's depth, the THg (OC) values increased, more than doubling in the near-surface sediment, from around 3000 ng/g OC to 8083.7 ng/g OC. The THg ng/g OC at the base of the core suggested a more than three-fold increase in concentration makeup in the lake's sediments. Caribou 2 – Core 1's background THg (OC) values around 2500 ng/g OC again match this lake's lowest of 2532.2 ng/g OC.

Caribou 2 Lake – Trends

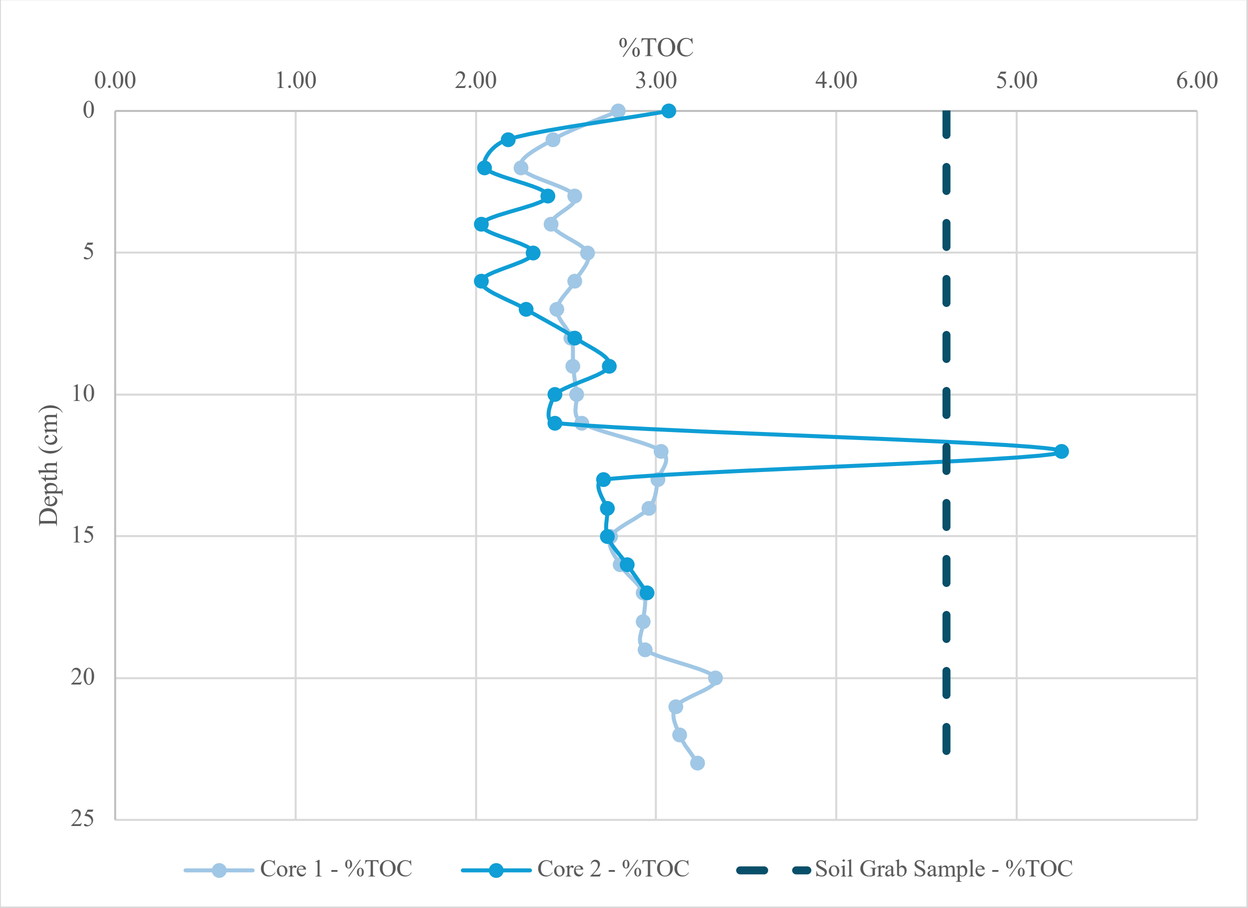


Figure 23: %TOC of Caribou 2 - Cores 1 & 2 compared to terrestrial grab sample %TOC. Core and grab sample taken July 6, 2023.

In both cores from Caribou 2, there was a decreasing trend of TOC toward the top of the sediment core. The exception to this trend was the pulse in Core 2 at 12 cm. Caribou 2's terrestrial grab sample comprised 4.61% total organic carbon. (Olo. 23)

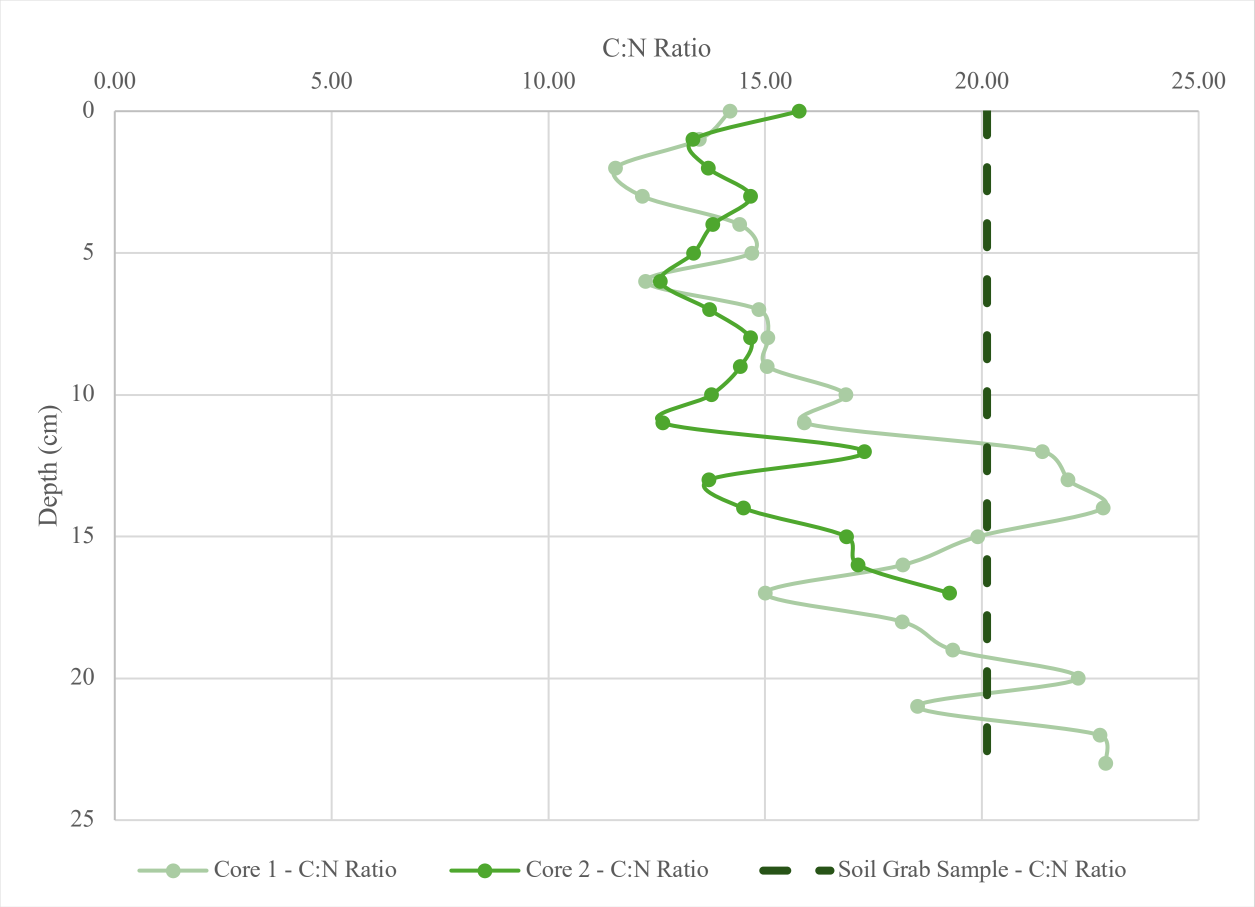


Figure 24: C/N of Caribou 2 - Cores 1 & 2 compared to terrestrial grab sample C/N. Core and grab sample taken July 6, 2023.

The overall trend exhibited by both cores from Caribou 2 decreases toward the shallower sediment from roughly 20 to 13. A variation in this trend occurs in Caribou 2 – Core 1 between 12 and 15 cm, where the C/N ratio peaked at 22.8. Caribou 2’s terrestrial grab sample had a C/N ratio of 21.12. (Fig. 24)

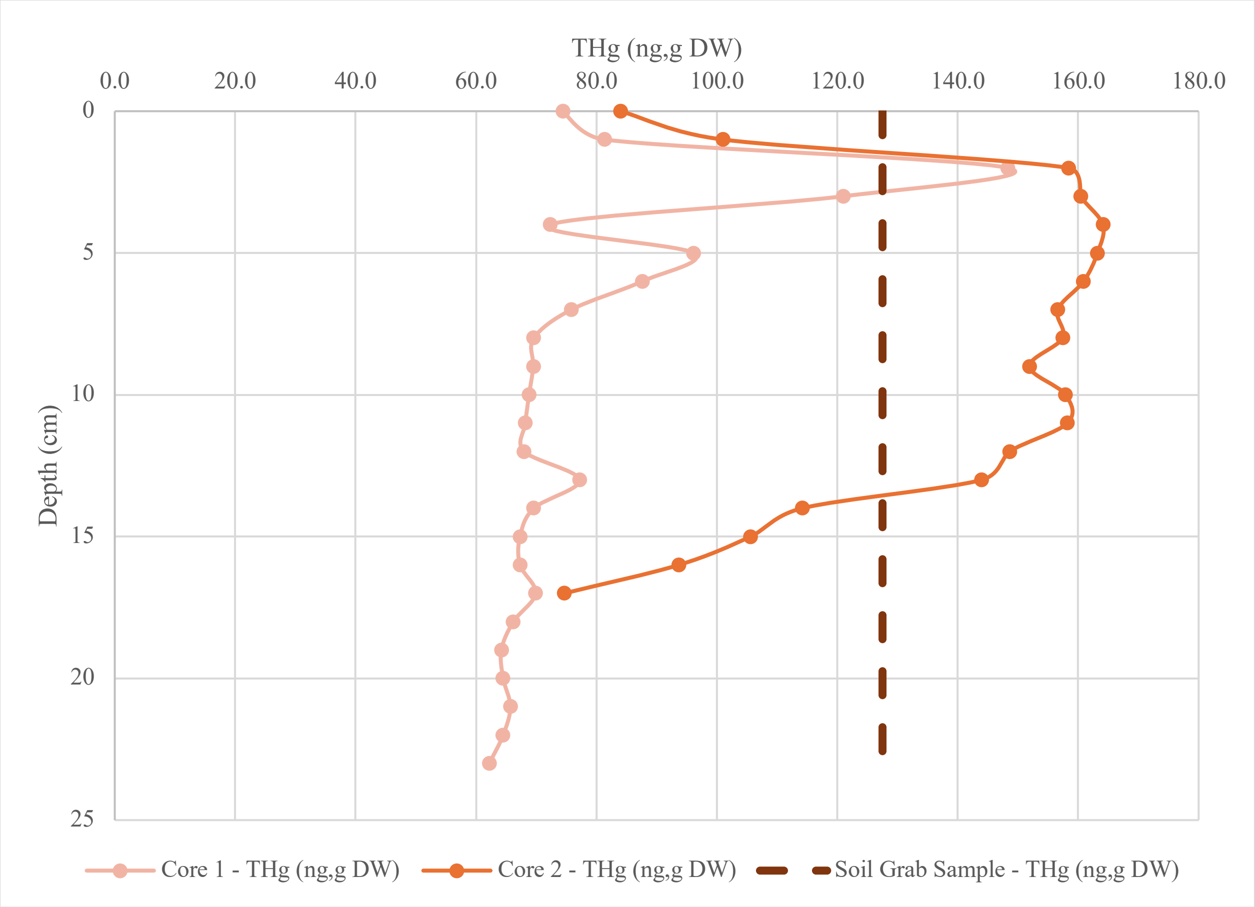


Figure 25: THg (ng/g DW) of Caribou 2 - Cores 1 & 2 compared to terrestrial grab sample THg (ng/g DW). Core and grab sample taken July 6, 2023.

The core's THg (ng/g DW) climbed substantially in both Caribou 2 cores; however, the peak was much more extended in Caribou 2 – Core 2 (Fig. 25). Caribou 2 – Core 1 indicated a steadily increasing concentration toward the surface sediment. Caribou 2's terrestrial grab sample concentration was 127.5 ng/g THg DW.

Caribou 3 Lake

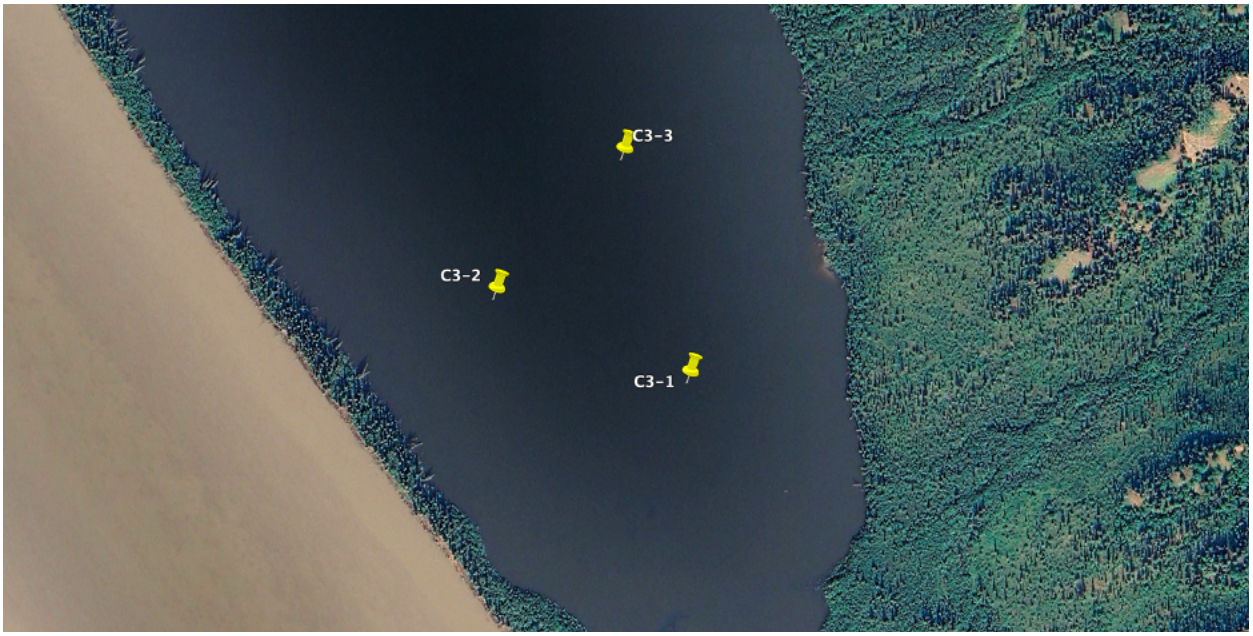


Figure 26: Caribou 3 Lake sampling site. Images from Google Earth Pro.

Caribou 3 – Core 1 (C3 – 1)

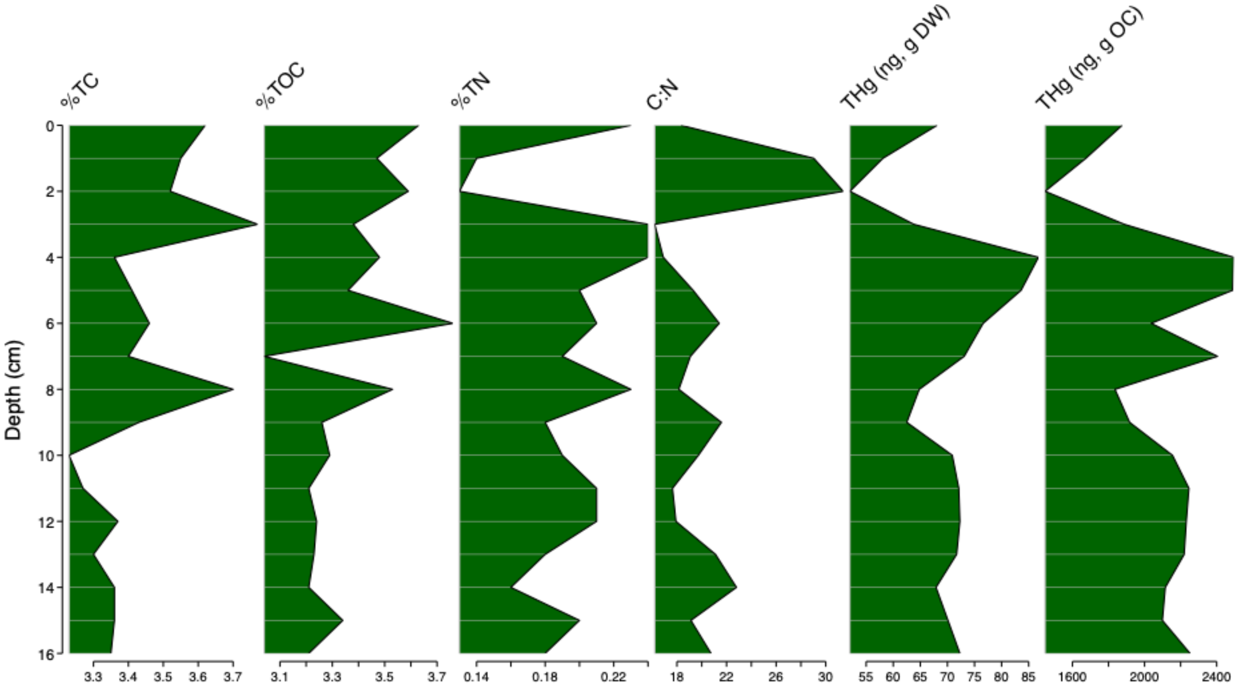


Figure 27: Caribou 3 Lake – Core 1 stratigraphy for elemental analysis and total mercury. Core taken July 6, 2023.

The TC increased slightly up the Caribou 3 – Core 1 (Fig. 26; Fig. 27) core from around 3.3% to 3.6%. There were two minor pulses at 3 and 8 cm to 3.77% and 3.70%, respectively. As with total carbon, TOC also steadily increased from around 3.2% at the core's base to 3.6% at the surface. The highest peak was 3.76% at 6 cm depth. TN was stable, with an average of 0.20%, between 3 and 16 cm deep. There was a drop from 0.24% at 3 cm depth to 0.14% and 0.13% at 1 and 2 cm, respectively. Between 3 and 16 cm, the C/N ratio was stable, averaging 19.41. At 2 cm, there was a sharp rise to 31.40; it remained high at 1 cm with a ratio of 29.03, then dropped in the surface material to 18.33. Caribou 3 – Core 1's THg (ng/g DW) range was small compared to Caribou 2; however, it still displayed a peak to 86.8 ng/g DW at 4 cm, followed by a dip to 52.0 ng/g at 2 cm and a return to background levels in the surface level. From 8 cm to the base of the core, the values were stable, averaging 69.4 ng/g DW. THg (ng/g OC) exhibited its highest values of 2494.3 and 2488.1 ng/g OC at 4 and 5 cm and was followed immediately by the core's lowest concentration at 2 cm of 1448.5 ng/g OC.

Caribou 3 – Core 2 (C3 – 2)

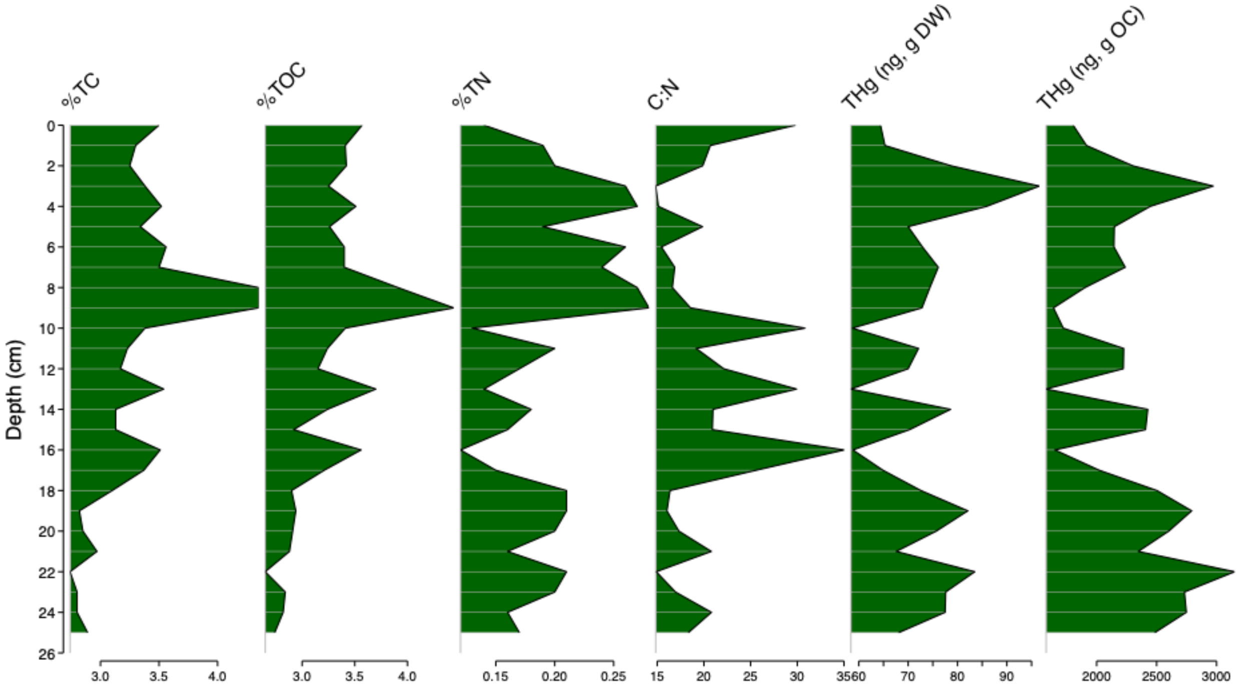


Figure 28: Caribou 3 Lake – Core 2 stratigraphy for elemental analysis and total mercury. Core taken July 6, 2023.

The average TC in Caribou 3 – Core 2 (Fig. 26; Fig. 28), excluding 8 and 9 cm depth intervals, was 3.20%. The pulse of 4.35% at both 8 and 9 cm was an evident peak along the core, as the values above and below on the core were all stable with a primary trend of gradually increasing. The TOC values mimicked TC in trends and peaks. The highest pulse of TOC was to 4.44% at 9 cm depth. Similarly to the carbon values, there were peaks in TN at 8 and 9 cm depth to 0.27% and 0.28%. A TN peak was exhibited between 3 and 9 cm with an average of 0.25%, higher than the rest of the core, which averaged 0.17%. The C/N ratio values were variable across the core's depth; however, four notable peaks above the background values fell between 15 and 21. Samples from the surface, 10, 13, and 16 cm, reached C: N ratios of 29.8, 30.8, 29.9, and 35.0, respectively. THg (ng/g DW) concentrations across Caribou 3 – Core 2 were minimally variable. Between 5 and 25 cm, the average was 71.6 ng/g DW. A 96.6 ng/g DW peak occurred at 3 cm and rapidly fell to background levels in the surface sediments. THg (ng/g OC) was variable around 2000 across the core's depth with two peaks at 3 and 22 cm to 2972.3 and 3150.94 ng/g OC.

Caribou 3 – Core 2 (C3 – 3)

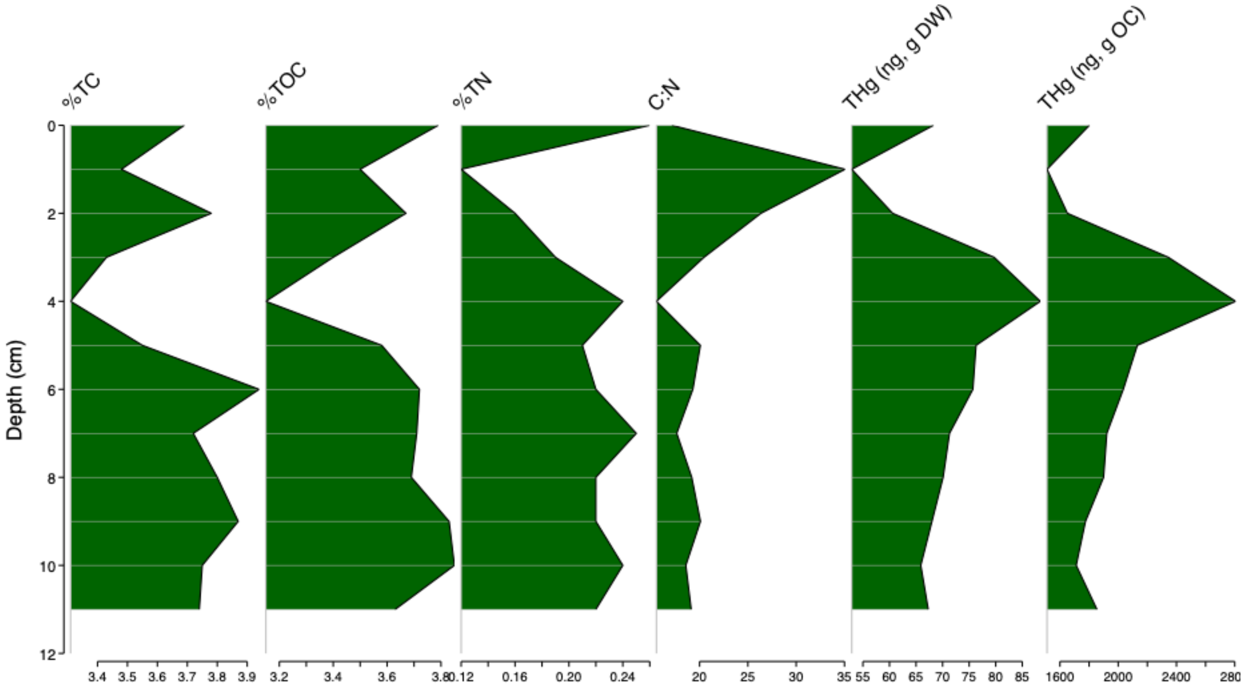


Figure 29: Caribou 3 Lake – Core 3 stratigraphy for elemental analysis and total mercury. Core taken July 6, 2023.

TC and TOC were stable along Caribou 3 – Core 3 (Fig. 26; Fig. 29) depths, with both their lowest points at 4 cm of 3.31% and 3.15%, which was about a half percent lower than background values for both. TN decreased from its background values (stable around 0.23%) to the lowest recorded point, 0.12%, at 1 cm. The surface sample returned to background levels. The C/N ratio closely mirrored TN changes, suggesting that TN concentration changes drove this trend. At 4 cm, levels of C/N displayed a distinct increase to 35.1 from steady background values between 3 to 11 cm, averaging 18.9. From 5 cm to the base of the core, the THg (ng/g DW) values were stable, averaging at 70.7 ng/g DW. A minor peak of 88.8 ng/g DW at 4 cm was followed immediately by a dip to 52.9 ng/g DW at 1 cm. The surface sediment returned to 68.3 ng/g DW in the surface sediment, close to the background. THg (ng/g OC) concentrations averaged 1904.1 ng/g OC between 5 cm and the base of the core and peaked at 2806.3 ng/g OC at 4 cm. In the more surface sediments, the values dropped below background levels to 1511.4 and 1651.2 at 1 and 2 cm deep and returned to background at the surface. Caribou 3 – Core 3 exhibited similar patterns to Caribou 3 – Core 1.

Caribou 3 Lake – Trends

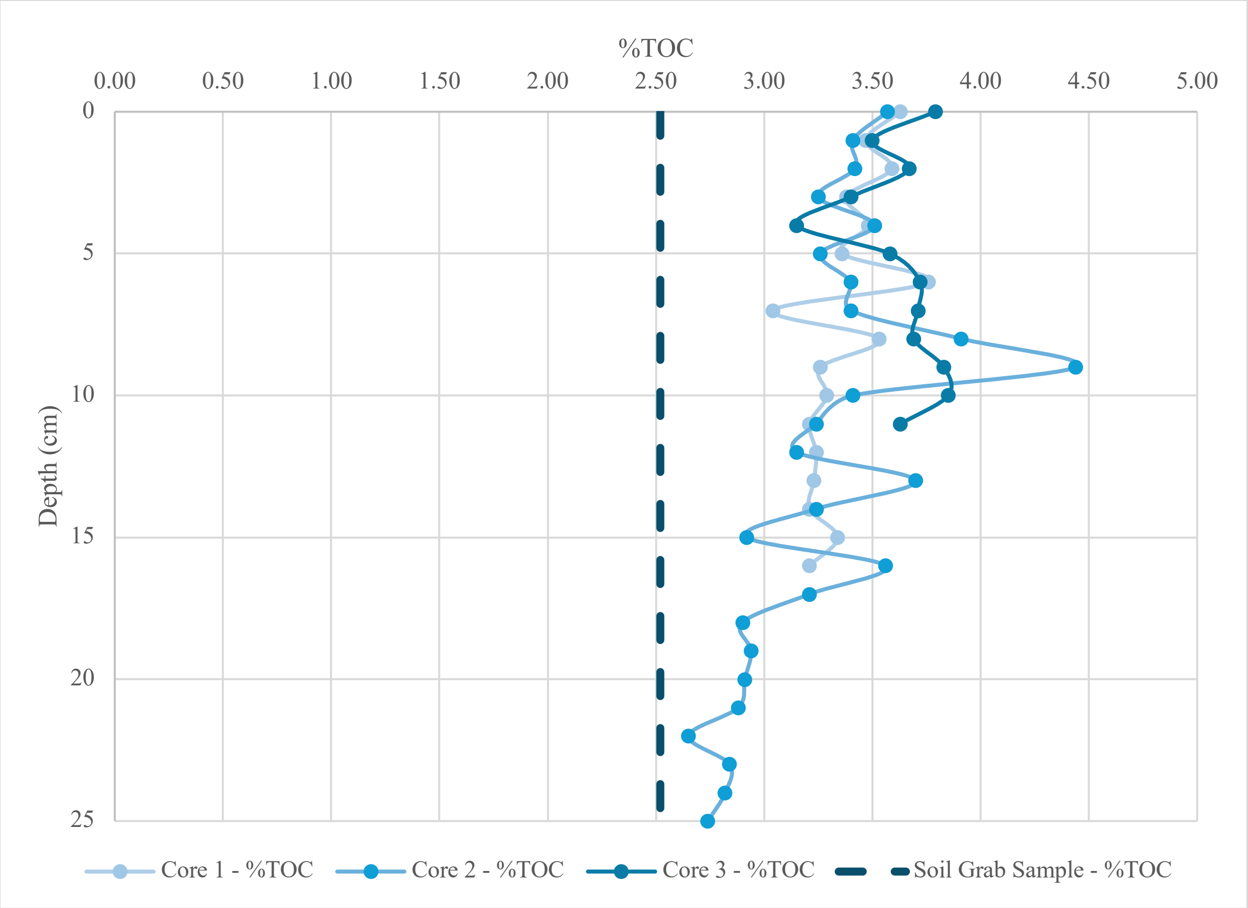


Figure 30: %TOC of Caribou 3 - Cores 1, 2 & 3 compared to terrestrial grab sample %TOC. Core and grab sample taken July 6, 2023.

In all three Caribou 3 cores, the TOC content increased away from the grab sample's organic carbon makeup (Fig. 30). The deepest sediment collected from this lake aligned closely to the terrestrial concentration. Within the overall trend of increased TOC, there was also some minor variation with pulses across the depth. Caribou 3's terrestrial grab sample contained 2.52% total organic carbon.

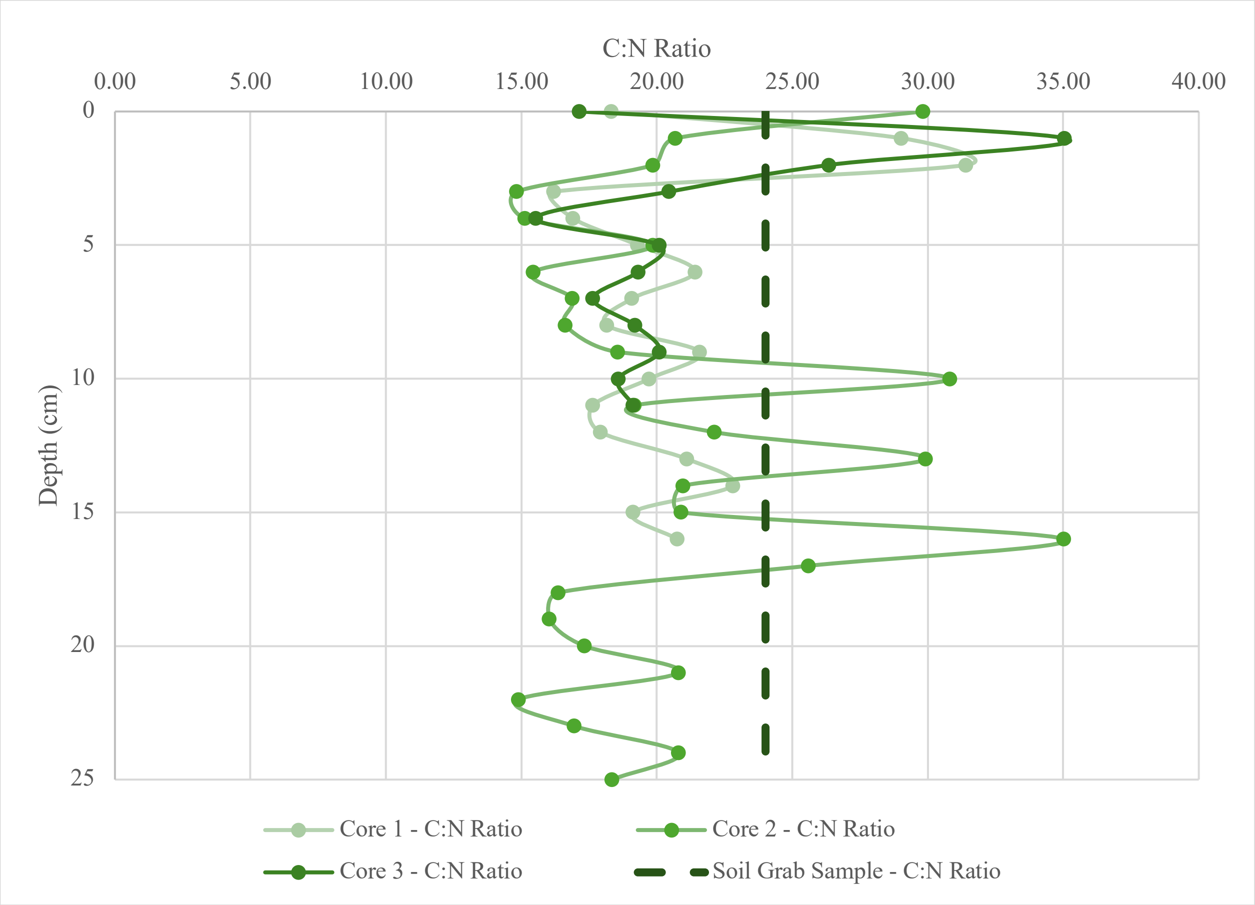


Figure 31: C/N of Caribou 3 - Cores 1, 2 & 3 compared to terrestrial grab sample C/N. Core and grab sample taken July 6, 2023.

At multiple points across the Caribou 3 cores, the C/N ratio exceeded the concentration in the terrestrial material (Fig. 31). Core 2, nearest to the river, displays peaks throughout the core, particularly in the middle. All cores, however, showed elevated C/N ratios in the near-surface sediment between 30 and 35. Caribou 3's terrestrial grab sample had a C/N ratio of 24.01.

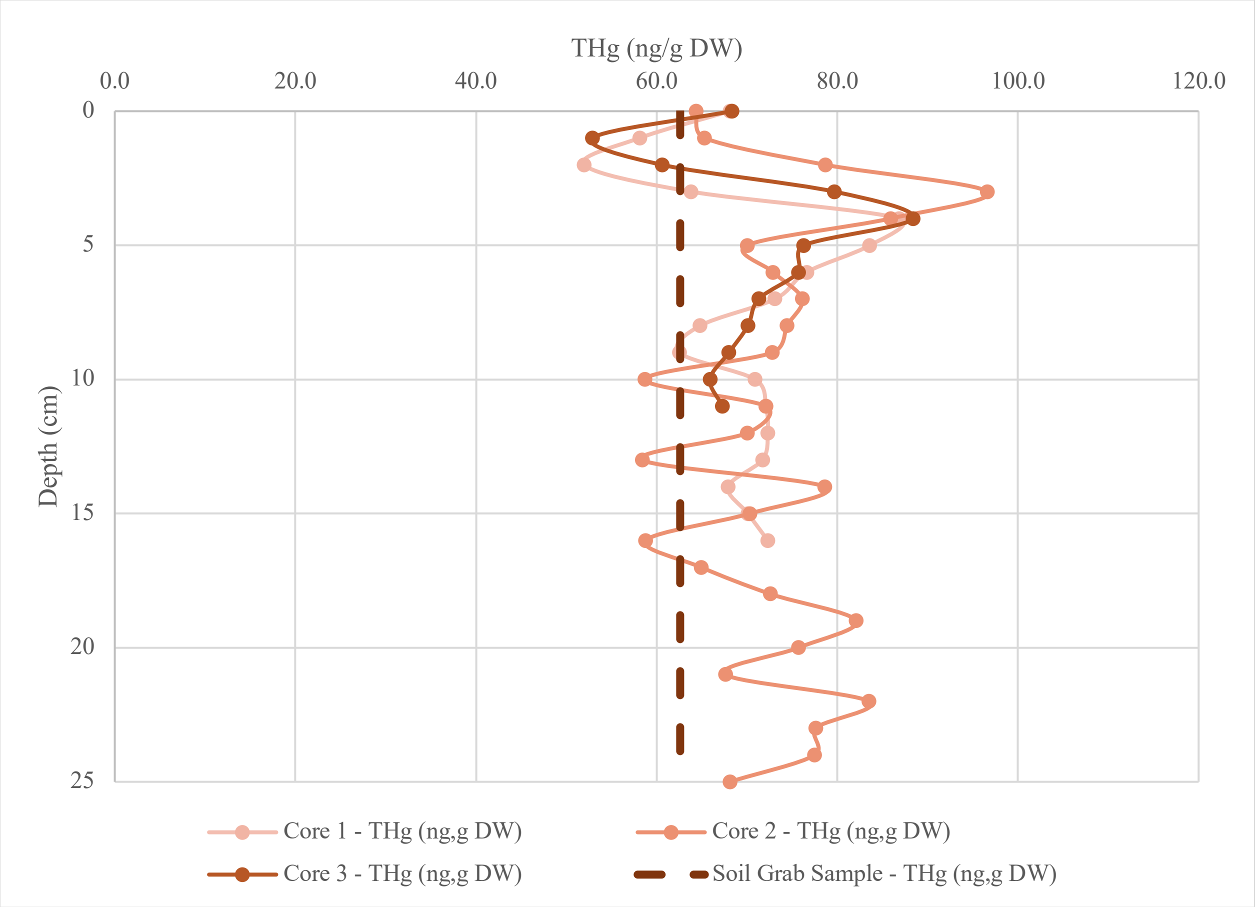


Figure 32: THg (ng/g DW) of Caribou 3 - Cores 1, 2 & 3 compared to terrestrial grab sample THg (ng/g DW). Core and grab sample taken July 6, 2023.

THg (DW) values remained stable with some in-core variation across all Caribou 3 cores (Fig. 32). In the near-surface sediment, all three cores exhibited the same trend of a peak pulse around 3 to 5 cm, a dip in the top 2 cm and then a return to the background in the surface layer. Caribou 3's terrestrial grab sample had 62.2 ng/g THg DW.

Douglas Lake

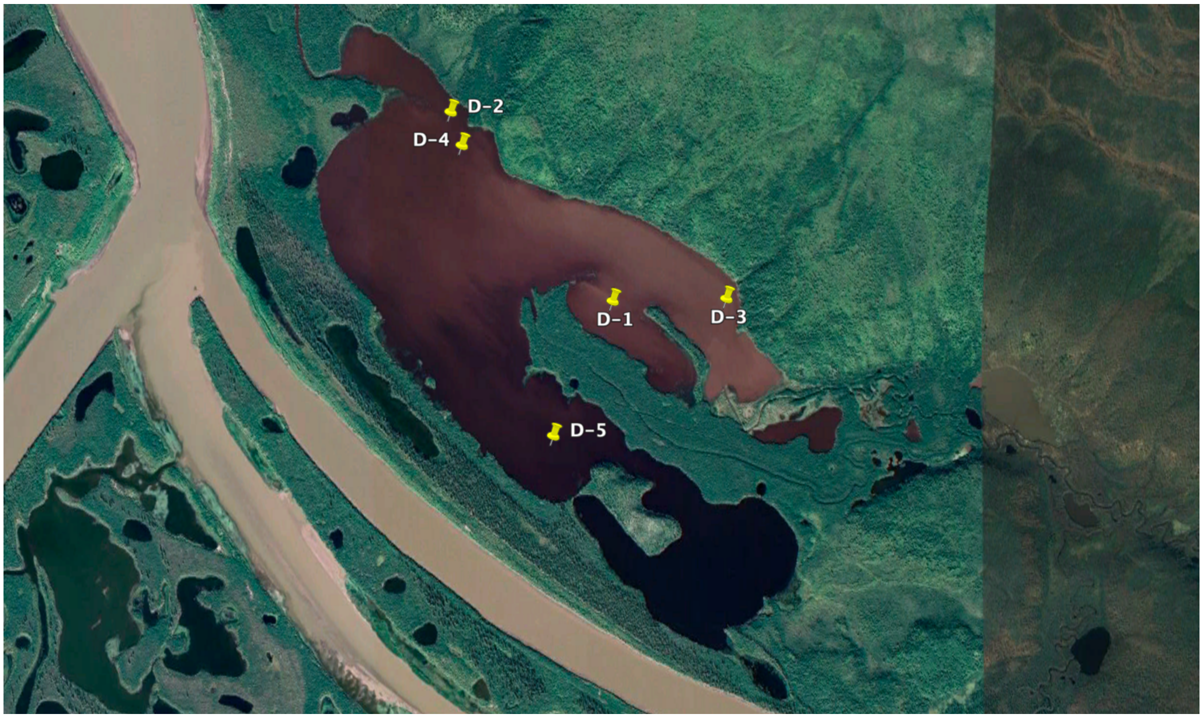


Figure 33: Douglas Lake sampling site. Images from Google Earth Pro.

Douglas Lake – Core 1 (D – 1)

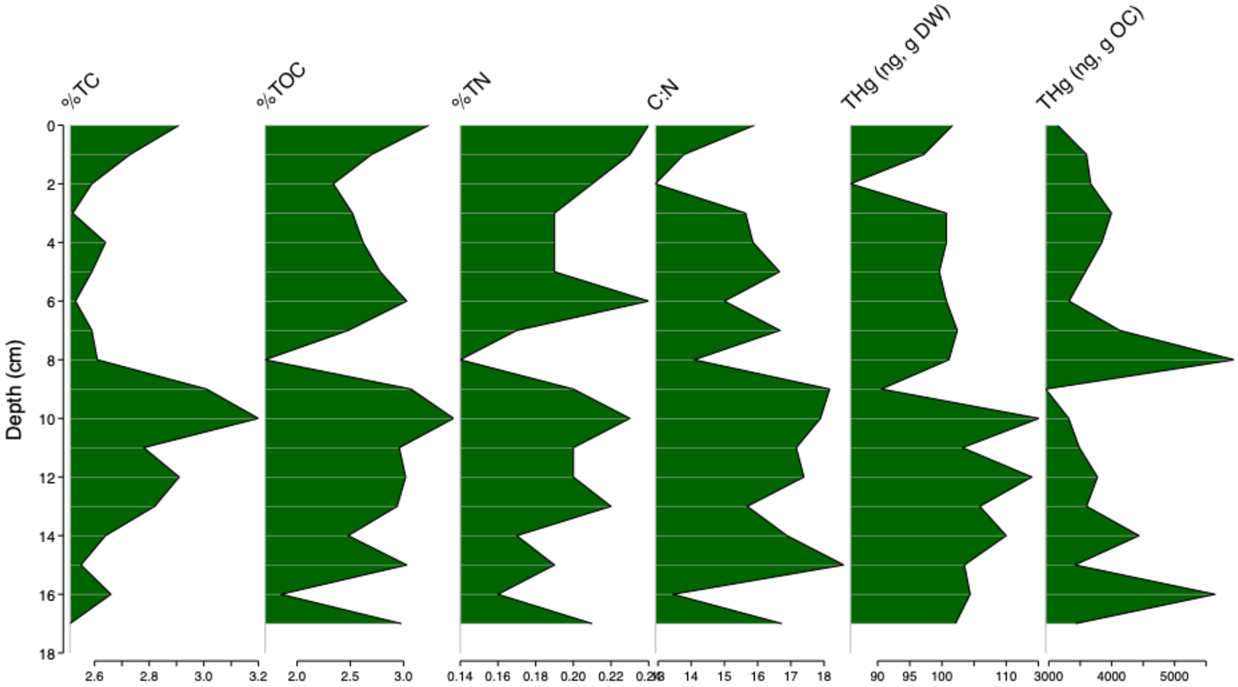


Figure 34: Douglas Lake – Core 1 stratigraphy for elemental analysis and total mercury. Core taken June 30, 2023.

Douglas – Core 1's (Fig. 33; Fig. 34) TC was steady across depth, with a peak to 3.20% at 10 cm. TOC displayed two dips below 2% at 8 and 16 cm; however, the remainder of the core was stable. TN followed a very similar trend to TOC. For much of the core, the TN values oscillated around the 0.20% average; however, at 8 cm, dropped to the lowest point at 0.14%. The C/N ratio has no evident trends and remains well within the range of mixed organic sources. THg (ng/g DW) displayed a steady and gradual decline toward the more surficial sediment. This core contained higher THg content across its stratigraphy than all of the others, averaging 102.2 ng/g DW. THg (OC) was stable across this core yet displayed pulses at the same depths as the other recorded proxies. For most of this core, THg (OC) values were close to the core's average of 3848.9 ng/g OC; however, at 8 and 16 cm, they pulsed to 5947.1 and 5643.2 ng/g OC.

Douglas Lake – Core 2 (D – 2)

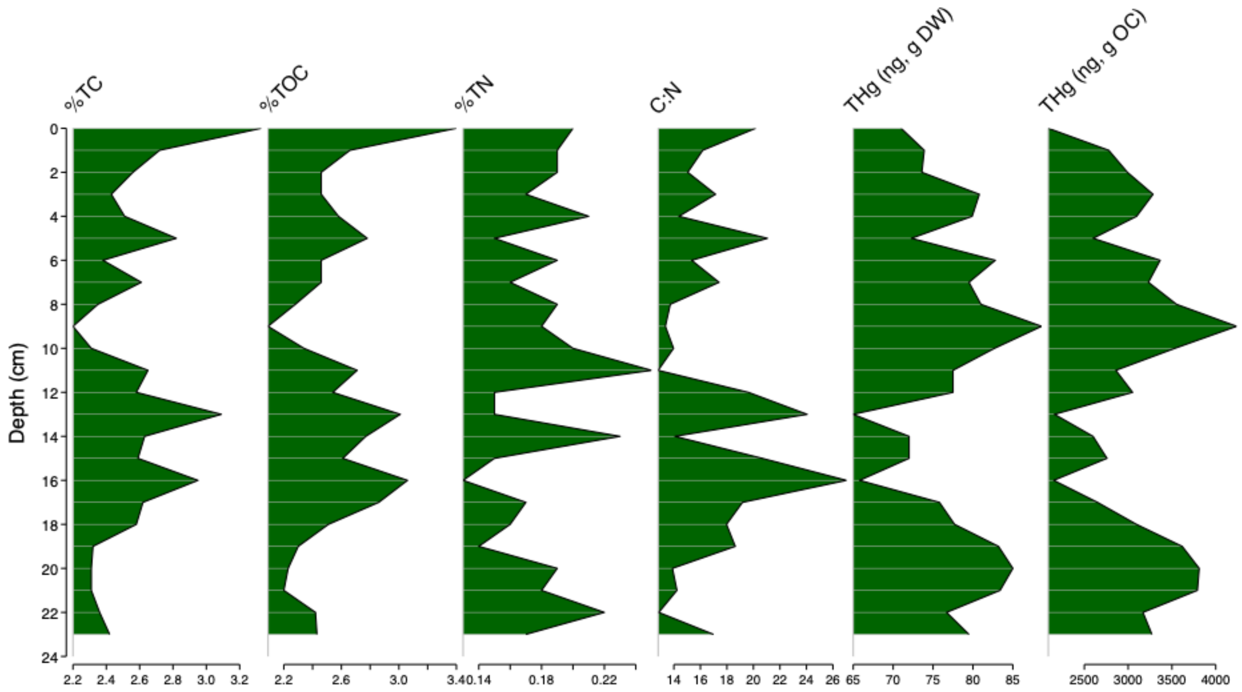


Figure 35: Douglas Lake – Core 2 stratigraphy for elemental analysis and total mercury. Core taken June 30, 2023.

TC and TOC showed very similar trends across the Douglas Core 2 (Fig 33; Fig. 35) depths, with most values around 2.5%. TOC was highest in the surface sample at 3.4%. TN had no observable trends, with a core average of 0.18%. The C/N ratios across this core generally suggested mixed terrestrial and lacustrine sediment makeup with values between 13 and 21. Two C/N pulses were recorded at 13 and 16 cm to 24.1 and 27.0. As with Douglas – Core 1's THg (ng/g DW), this core was steady; however, it displayed less concentrated levels, averaging 77.4 ng/g DW across the core's depth. THg (ng/g OC) also displayed no clear tendency other than very closely mimicking the THg (ng/g DW) trend, suggesting that changes in mercury content drove this ratio more than the carbon fluctuation.

Douglas Lake – Core 3 (D – 3)

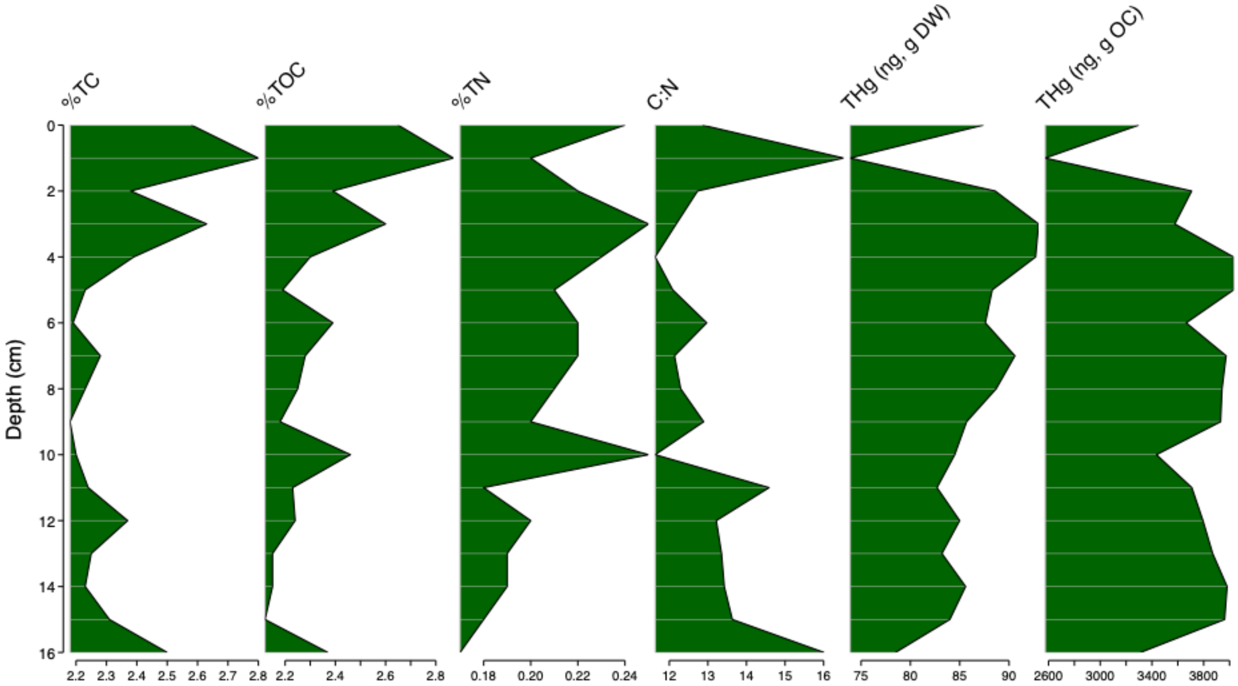


Figure 36: Douglas Lake – Core 3 stratigraphy for elemental analysis and total mercury. Core taken June 30, 2023.

TC and TOC were stable in Douglas – Core 3 (Fig. 33; Fig. 36), with a slight but rapid concentration rise in the surface sediment. Between 4 and 16 cm, TC and TOC had averages of 2.7% and 2.5% respectively and both had their highest value at 1 cm deep of 2.80% and 2.87%. TN exhibited a gentle overall increase toward the surface sediment. C/N values were most elevated in the surface sediment but still represented organic matter from mixed sources ranging between 11 and 17. THg (ng/g DW) values were steady, with a minor dip at 1cm to 73.9 ng/g DW, slightly lower than the entire core's average of 85.9 ng/g DW. THg (ng/g OC) values were also steady, with a low point of 2574.9 ng/g OC at 1cm.

Douglas Lake – Core 4 (D – 4)

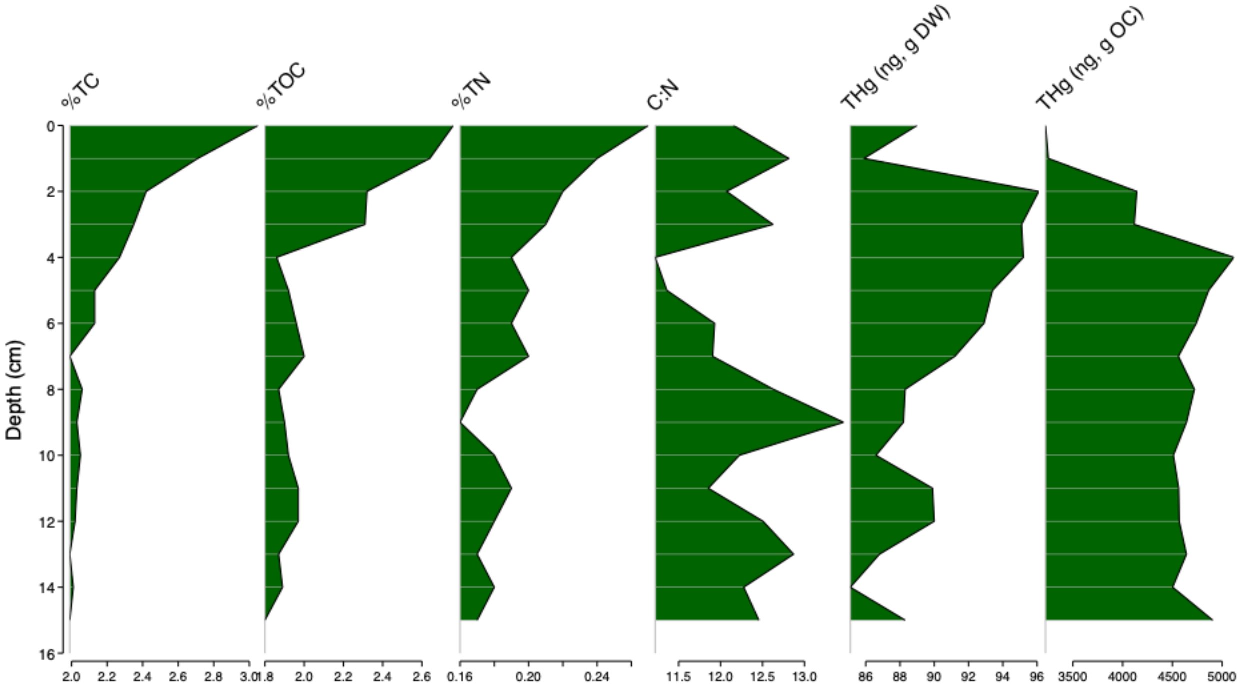


Figure 37: Douglas Lake – Core 4 stratigraphy for elemental analysis and total mercury. Core taken June 30, 2023.

TC rose quickly from a background average of 2.05% between 4 and 15 cm to a peak of 3.05% in the surface sediment in Douglas – Core 4 (Fig. 33; Fig. 37). This was mirrored in the

TOC trend at slightly lower concentrations and peaked at 2.76%. Following the same trend as both carbon markers, TN exhibited increasing makeup with a maximum peak in the surface sediment of 0.27%. C/N values were stable, ranging between 11 and 13.5. THg (ng/g DW) concentrations were stable across the core, averaging 90.1 ng/g DW. THg (ng/g OC) maintained a linear trend between 2 and 15 cm with an average of 4614.2 ng/g OC that was disrupted in the top two intervals, plummeting to 3224.6 and 3252.8 ng/g OC. This was because of the stable mercury and rising organic carbon values at the near-surface.

Douglas Lake – Core 5 (D – 5)

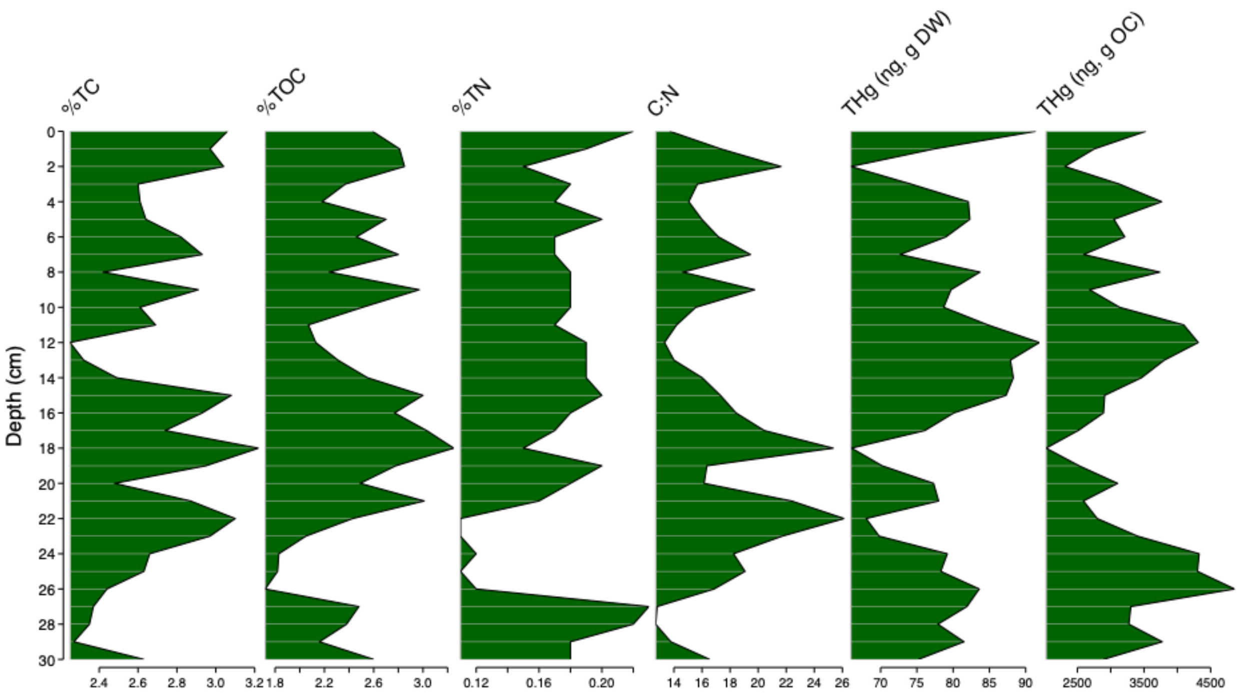


Figure 38: Douglas Lake – Core 5 stratigraphy for elemental analysis and total mercury. Core taken June 30, 2023.

TC fluctuated across Douglas – Core 5 (Fig. 33; Fig. 38) but remained around 2.7%. TOC exhibited the same trend as TC, varying around 2.4%. TN was steady at around 0.17%. C/N exhibited two primary pulses at both 18 and 22 cm, to 25.34 and 26.13, indicating terrestrial input; however, the remainder of the core exhibits mixed organic carbon sources. THg (DW) across this core was variably steady, averaging 79.0 ng/g DW, with no apparent trend. THg (OC) also showed no clear trend, averaging 3260.7 ng/g OC for the entire core.

Douglas Lake – Trends

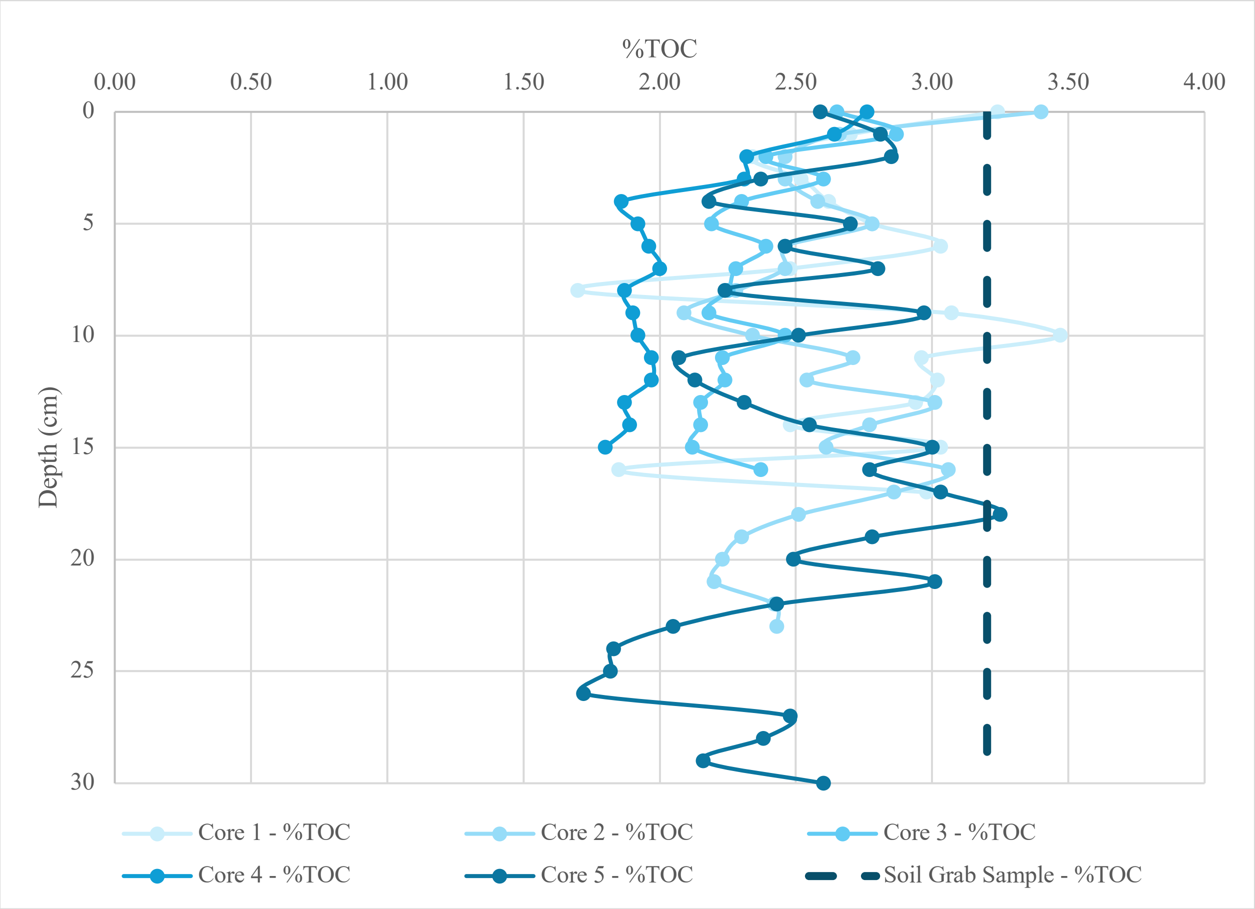


Figure 39: %TOC of Douglas - Cores 1, 2, 3, 4 & 5 compared to terrestrial grab sample %TOC. Core and grab sample taken June 30, 2023.

Douglas's in-lake TOC content was less than that of the terrestrial grab samples (Fig. 39). There was variation throughout all cores collected from Douglas. Douglas's lake carbon content reached values at or greater than that of the terrestrial sample at four points between all cores. Caribou 2's terrestrial grab sample was 3.20% total organic carbon.

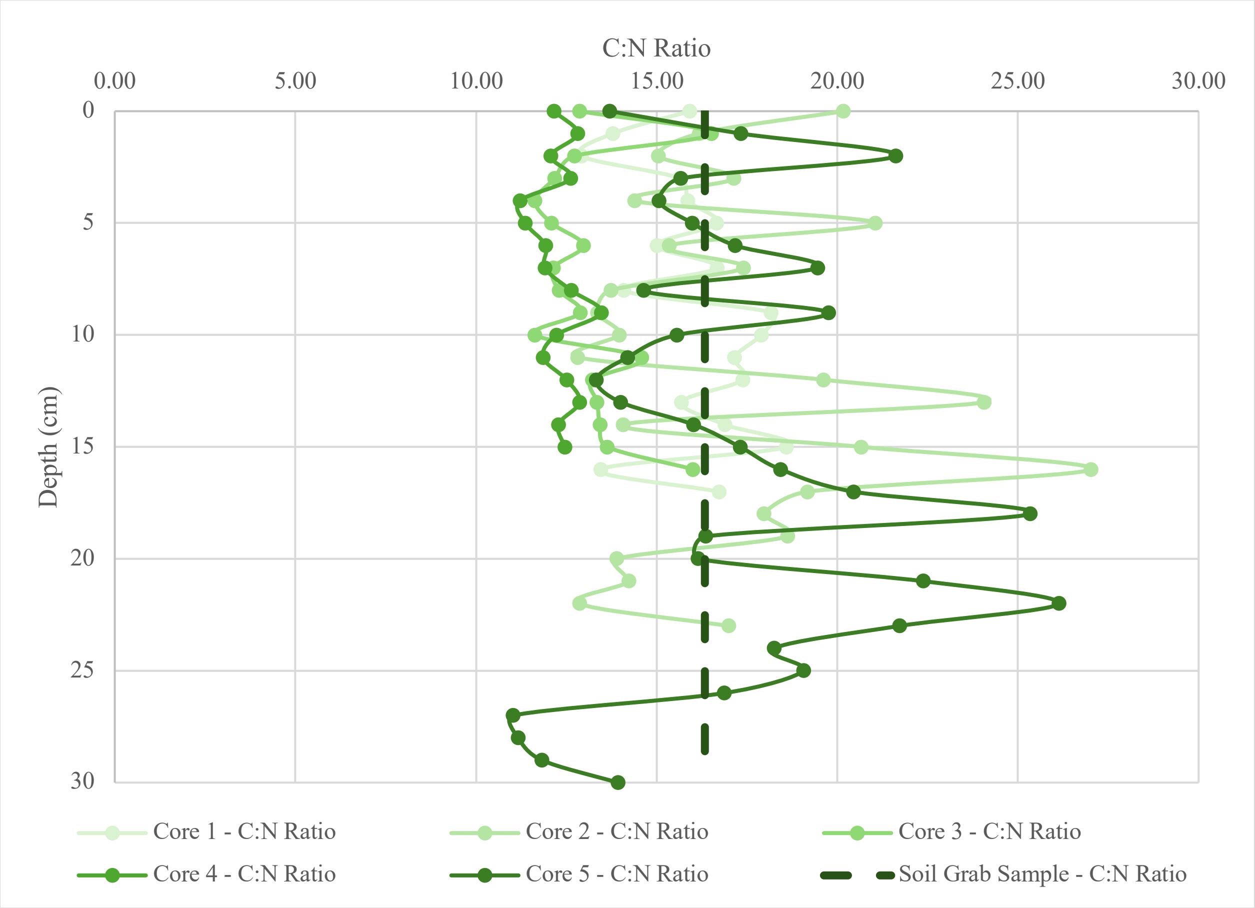


Figure 40: C/N of Douglas - Cores 1, 2, 3, 4 & 5 compared to terrestrial grab sample C/N. Core and grab sample taken June 30, 2023.

The C/N ratio in the lake compared with terrestrial grab samples behaved differently in Douglas than in other lakes (Fig. 40). Caribou 2's terrestrial grab sample had a C/N ratio of 16.33.

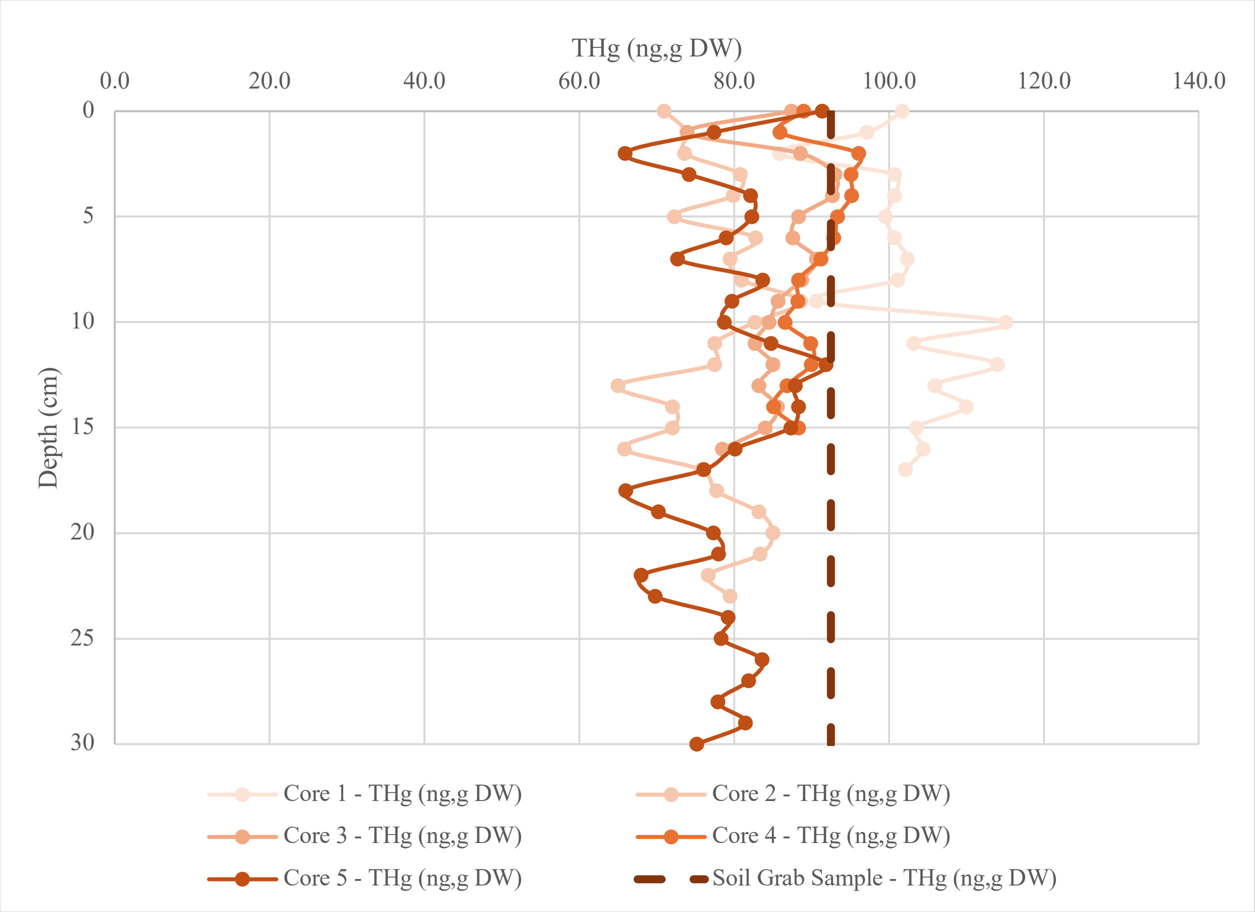


Figure 41: THg (ng/g DW) of Douglas - Cores 1, 2, 3, 4 & 5 compared to terrestrial grab sample THg (ng/g DW). Core and grab sample taken June 30, 2023.

THg (ng/g DW) measurements in all Douglas cores trended toward the landslide values in the more surficial sediment (Fig. 41). This was true for cores that had THg (DW) values below (Cores 2, 3, 4 & 5) and above (Core 1) the landslide values. Douglas's terrestrial grab sample had 92.5 ng/g THg DW.

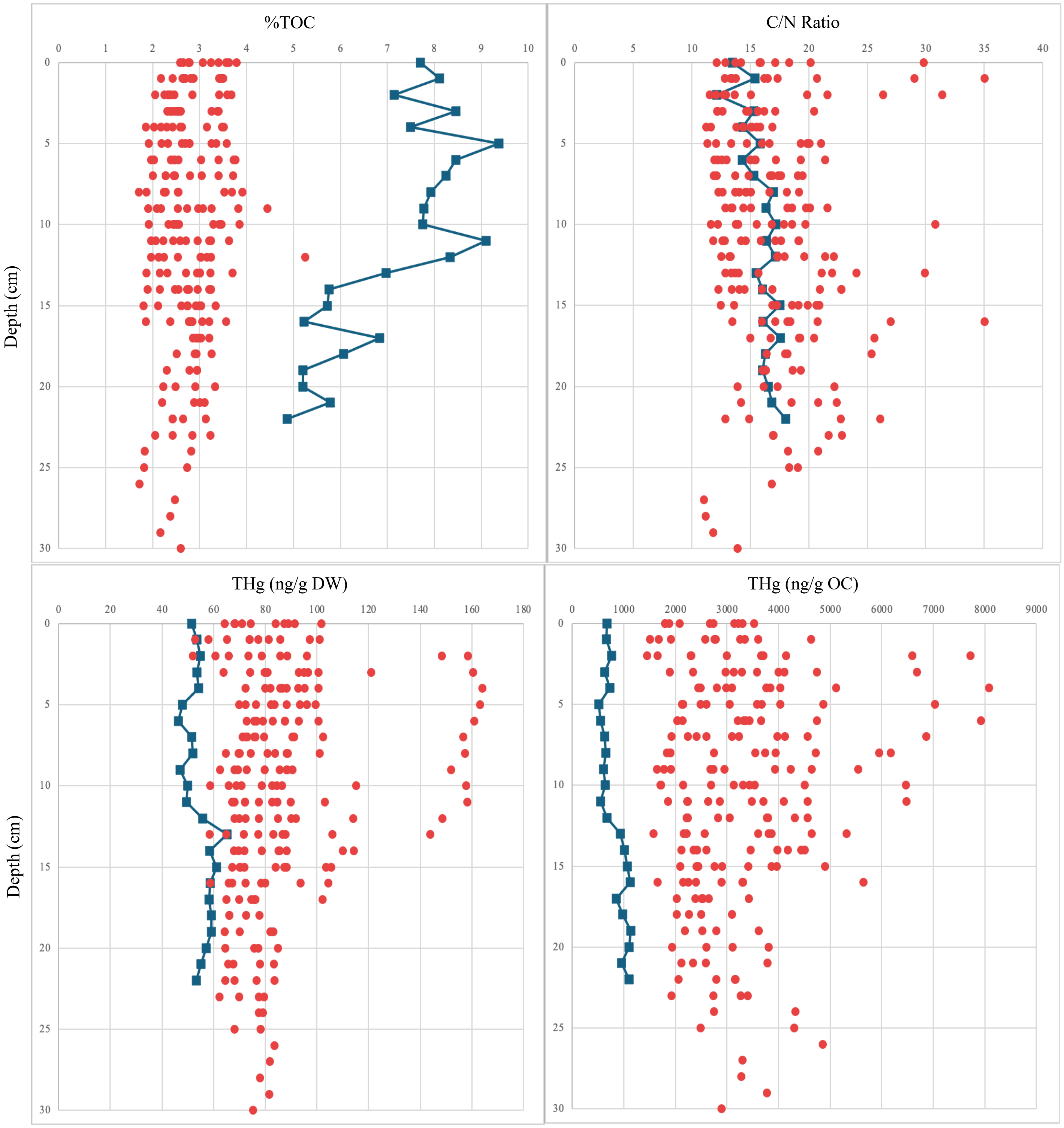


Figure 42: All: %TOC (a) C/N Ratio (b), THg (ng/g DW) (c), & THg (ng/g OC) stratigraphies. Impacted lake points (all intervals from cores taken in lakes Caribou 2, Caribou 3, and Douglas Lake) displayed with red circles and Caribou Control displayed with blue squares connected by a line.

Across all proxies we see variation between the control lake and the impacted lakes (Fig. 42). TOC values were much lower in all impacted lakes than in the control lake. They were additionally more stable, generally between 2 and 4% TOC. The control lake organic carbon was between 4 and 5% in the bottom half of the core and around 8% in the top half; the increase in this percentage makeup occurred around 13 cm depth. While most C/N ratio data points fell within the 10-20 range across all cores several higher values were recorded in the impacted lake cores near the surface intervals. THg (ng/g DW) concentration is higher across all impacted lakes than the control lake. The control lake's THg (ng/g DW) concentration was consistent across the depth, ranging from around 45 to 60 ng/g DW. Both cores from Caribou 2 represented the highest mercury values. THg (ng/g OC) carbon concentrations were stable in the control lake compared to the much greater variation and elevated values in all the impacted lakes. Some THg (ng/g OC) values were roughly 10x the control core values, which suggests the immense potential for mercury loading in these lake’s benthic systems. Additionally, there is a trend of increasing values toward the surface sediments in the impacted lakes.

Discussion

Comparing Impacted Lakes with the Control Location

The paleolimnological results presented in this research strongly indicate the potential for changes in the lake basin when terrestrial sediment is introduced during cryogenic landsliding. This observation is particularly obvious when comparing individual proxies between the control lake and impacted lakes. Proxy variation between the impacted and control lakes was generally expected because slope processes will always influence local limnology, and this is further exacerbated by cryogenic landsliding introducing pulses of terrestrial material. This variation will be evident in lakes like Douglas, which are indirectly impacted by cryogenic landsliding and are broadly impacted by slope processes. Other than the C/N ratio, which was expected to fall in the middle range indicating mixed sediment origin, all measured proxies differed between the control and impacted lakes (Fig. 42). The C/N ratio remaining consistent across the control lake core's depth is to be expected since, other than standard seasonal variations, there was no primary physical driver of sediment accumulation in the lake as opposed to the impacted lakes, which experienced this as either runoff or on a grander scale during landslides. When considering all sediment proxies analyzed in this thesis, the control lake was far more stable in its trends than those affected by nearby hillslope dynamics (Figure 42). THg (ng/g DW) and THg (ng/g OC) showed higher values at all impacted lakes, though to varying extents. In contrast, TOC values on impacted lakes fell below the control location. Mercury occurring naturally within the sediment is likely to be the primary source of the element since atmospheric deposition will occur at a lower magnitude due to its remoteness from major industrial areas. Weathering and erosion, which occur on these thawing hillslopes, can instigate the release of mercury and may help explain these elevated values. The presence of increased mercury also elevates the potential for toxification. Under anaerobic conditions, inorganic mercury can undergo methylation and become methylmercury, which is organic and bioavailable. Organic carbon can bind with this mercury and carry it through the food chain.

The potential for mercury loading during the initiation of landsliding was made evident in these study lakes, particularly Caribou 2 (Fig. 22). While this research used mercury as a proxy for change in environmental conditions through a paleolimnological lens, the potential for toxicity through mercury introduction must also be considered. In the Caribou 2 results, there were instances where mercury per unit of organic carbon in the surface sediments were four times that of the background values and ten times that of the control lake. As noted throughout this thesis, Caribou 2 is an exceptional example of cryogenic landsliding at a magnified scale, so while mercury loading may not be as intense in other low-lying lakes exposed to landsliding, this lake represents a potential extreme case for mercury inputs from permafrost thaw. THg (ng/g DW) values found in these cores are well below the probable effects level of 486 ng/g DW so it is unlikely that organisms in Caribou 2 would be experiencing toxicity because of these landslides (Canadian Council of Ministers of the Environment, 1999). However, this does highlight the importance of understanding historical elemental sediment trends to see how they are impacted under these changing conditions, and it should be noted there are no guidelines for sedimentary mercury as a function of organic carbon concentrations.

I predict that future landsliding will influence sediment THg content in lakes downslope of the Caribou Hills in ways reminiscent of the trends observed in Caribou 2 stratigraphies (Fig. 21; Fig. 22). Mercury, under typical conditions, exhibits little to no post-depositional mobility in the sediment profile therefore, cryogenic landsliding is likely the primary driver of shifts observed in sediment concentrations in these cores. This is further supported by the profiles observed, where sediment concentrations return to background values in the surface sediment (Fig. 21; Fig. 22; Fig. 27; Fig. 29). Further, without direct deposition into the environment through industrial activity due to the remoteness of these lakes, the primary mercury introduction into lakes are cryogenic landslides.

TOC represents the portion of the carbon in the sediment cores that after sedimentation, did not break down into inorganic forms (Meyers & Teranes, 2002). For a variety of reasons, including method of carbon delivery, local biology and sediment makeup, it is common for TOC to vary across a lake basin (Meyers & Teranes, 2002). Further, since TOC is represented as a percentage of all sediment, its concentration is impacted broadly by the remaining makeup of the sediment, which can be variable (Meyers & Teranes, 2002). TOC is valuable in paleolimnological studies because its pulses can be quantified to suggest changes in organic sources. TOC was higher throughout the control lake's sediment core than across all impacted lakes (Fig. 42). This was not a surprise since the control lake was shallower than the impacted lakes and had notable rooted macrophytes at the time of sampling. The control lake displayed higher levels of TOC than all other lakes by nearly 2-3 times, and all lakes indicated a shift to higher TOC content in the near-surface sediment. This roughly 1-1.5% higher carbon concentration in the near-surface sediment than in the background of impacted lakes may be due to increasing carbon from landslides but also may be due to carbon presence naturally occurring in the lake basin from organic matter. Most TOC values measured in the impacted cores fell within the range of 2 to 4%. The analysis of all impacted points suggested a moderate increase in TOC content in the more surface material.

C/N ratios illuminate organic matter sources within sediments. Typically, vascular plants on land produce organic matter with a C/N ratio of over 20, whereas algae produce ratios between 4 and 10 (Meyers & Teranes, 2002). Since terrestrial C/N ratios are much higher than lake C/N ratios during a landsliding event, it would be unsurprising to see a rise in sediment C/N values. The C/N ratio was the only proxy that did not show apparent variation between the control and impacted lakes. The C/N ratio explains sediment origin, and low-lying lakes in the delta would have various carbon sediment influences introduced primarily through runoff, lake dynamics, and flooding from the nearby Mackenzie River during freshet. The C/N ratio across the control core was consistently around 15, which is defined as a mixed carbon origin. The impacted lakes ratios had values generally between 10 and 20, suggesting mixed organic carbon sources; however, some data points reached as high as 35, indicating an increase in the influence of terrestrial carbon in the system. Since higher C/N ratios are typically associated with allochthonous production sources, this pulse can be related to terrestrial material ending up in lakes, presumably during landsliding.

Lake Sediment Cores as Archives of Cryogenic Landslide Impacts

The results of this thesis show that landslide impacts on low-lying lakes in the Mackenzie Delta can be tracked through elemental proxies stored in the sediment. The variation between the stratigraphies of impacted lakes highlights the abilities of various limnological conditions to alter/modify landslide impacts and their histories in sediment records from each site. For the purposes of this research, Caribou 2 is an example of “ideal” conditions for paleolimnological record storage of cryogenic landslides. In contrast, Caribou 3 and Douglas Lake, because of their larger size and Douglas Creek, show variations in response. Caribou 2 is a small lake that experienced a proportionally large landslide in 2017. In comparison, Douglas Lake is a relatively large lake that experienced landsliding indirectly for an extended timeframe in its catchment but not directly on its shoreline. The stratigraphies produced by cores from these two (very different) lakes show that paleolimnological inferences of landsliding occur within the context of the unique limnological characteristics of the associated lake environments. The small, equant morphology and direct upslope influence of cryogenic landsliding make Caribou 2 the ideal type of ecosystem from which to infer the impacts of catchment disturbances. Douglas Lake highlights the muted changes observed when sediment loading is mediated through upstream transport processes. This, however, does not mean the proxies are less valuable in more complicated limnological settings; the trends or pulses may just be less noticeable.

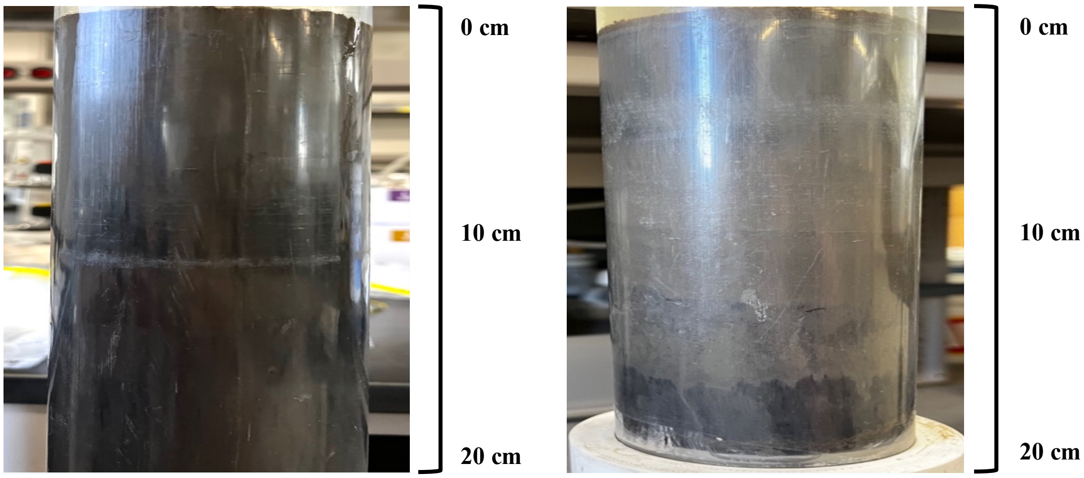


Figure 43: Visual examples of landslide material in Caribou 2 – Core 1 (a) and Caribou 2 – Core 2 (b) sediment cores. Images taken immediately before core sectioning.

Prior to sectioning, some cores had visual cues highlighting depositional change (Fig. 43). This was particularly evident in Caribou 2's cores, where substantial deposition of terrestrial material likely occurred rapidly in response to the 2017 landslide events. In the lab results, this terrestrial material was represented by 4 cm (C2 – 1) and 12 cm (C2 – 2) of inferred to be rapid terrestrial material deposition (Fig. 43). Similar observable sediment compositional changes were not noticeable in the other lakes, further highlighting the role of site selection for understanding significant impacts upslope, vs those more muted due to limnological characteristics of the chosen study site.

Identifying potential thermokarst activity on hillslopes is more complicated than on flat terrain because rather than the patterned/polygonal ground commonly observed across the Mackenzie Uplands, natural hillslope movement such as erosion can infill spaces left unoccupied by ground thaw (Burn et al., 2021). The steep natural topography (Fig. 44) of the Caribou Hills and the adjacent low-lying Mackenzie Delta is a prime environment for cryogenic landsliding during thermal shifts in permafrost, particularly in the case of exceptional temperatures and precipitation. This could be further amplified by warmer summers and a continued deepening of the active layer, both of which are predicted for the near future.

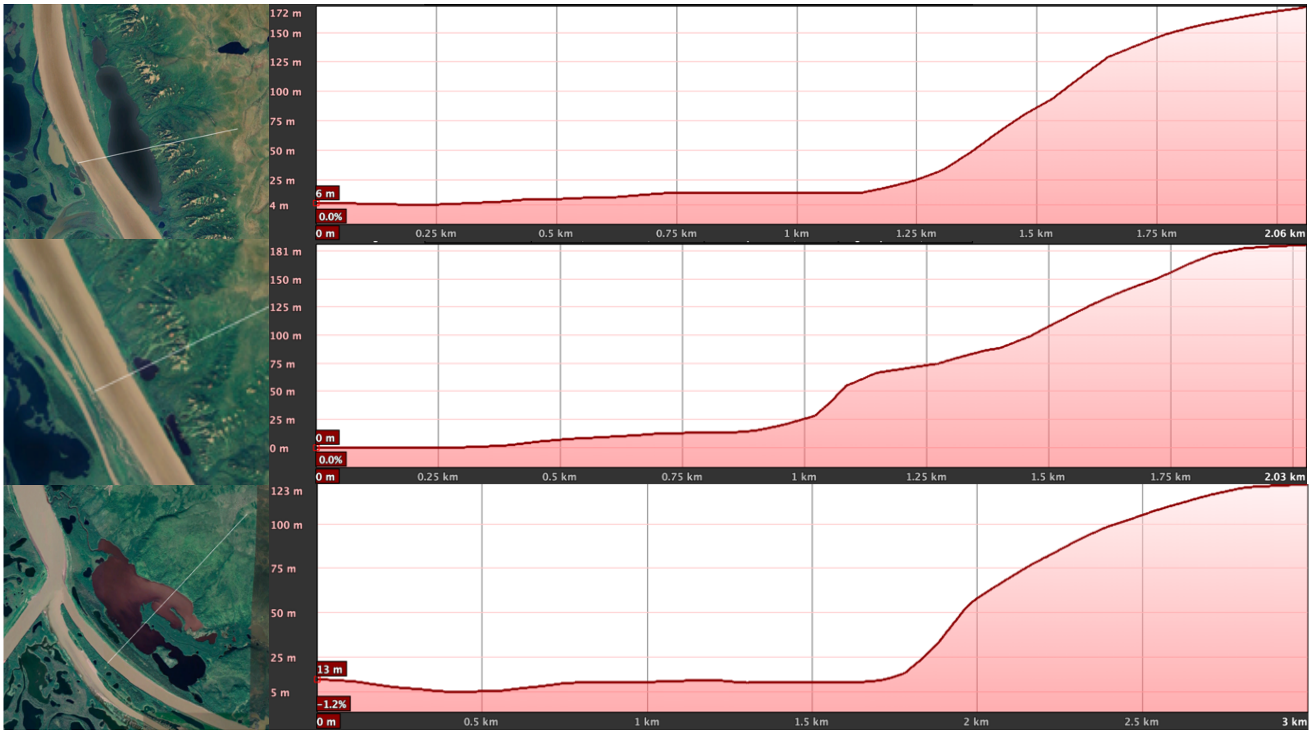


Figure 44: Elevation profiles of the impacted lakes. The highest elevation points are at the top of the Caribou Hills, and the lowest are the lakes and the East Channel.

At the time of fieldwork, Douglas Creek was impacted by more than 12 permafrost thaw features (primarily retrogressive thaw slumps) within 6 kilometres upstream of Douglas Lake (Fig. 9). While there is no visual evidence of cryogenic landslides directly depositing into Douglas Lake, sediment loading from up creek was very likely. Aerial imagery highlighted this, displaying varying turbidity across the lake with more turbid waters at the creek base and increasing clarity with increased distance from it (Fig. 9; Fig. 33). Caribou 2 was impacted by one landslide in the northeastern portion of the lake (Fig. 9; Fig. 20). Caribou 3 had six cryogenic landslides impacting the lake, three in the northern half and three in the southern half (Fig. 9; Fig. 26). The level of impact already observed indicates that the conditions for ground thaw were actively present, only to be elevated with climate change. Therefore, I anticipate the continued development of thermokarst and the resulting cryogenic landslides originating in the Caribou Hills of the Mackenzie Delta.

Reindeer Station, a few kilometres north of the study lakes, while no longer used for its initial purpose (reindeer harvest), is an example of infrastructure that is highly vulnerable to experiencing thaw-induced damage. This is because this station exists at the foothills of the Caribou Hills, and cryogenic landslides are occurring in identical terrain locally. Reindeer Station is not inhabited year-round, though it serves as a meeting place for local land users and a safe harbour during periods of poor weather on the Mackenzie River / Delta. Traditional land use activities may also be impacted/impeded when cryogenic landslides occur, decreasing land access, terrain predictability and safety in regions that have been used since time immemorial for practices such as hunting and trapping, including the east Mackenzie Delta area. Plenty of northern infrastructure relies on the persistence of permafrost. Both new developments and maintenance projects must consider changing conditions to permafrost at a local and regional scale. Developers and researchers alike must be aware of the increased strength presented by frozen water to the soil that helps bind sediment and what happens when that frozen water melts since this loss of strength can be detrimental to Northern and Arctic infrastructure (Technical Guide: Infrastructure in Permafrost: A Guideline for Climate Change Adaptation, 2019).

In addition to warming air temperatures, climatic variables can also influence permafrost disturbance. Precipitation trends across Canada are changing over time geographically and seasonally. In the Mackenzie Delta, yearly precipitation trends are changing, primarily during the winter. Warmer permafrost temperatures are also related to prolonged active-layer freeze back (Kokelj et al., 2017). Canadian permafrost thaw models have displayed the potential for supra-permafrost talik development under warming conditions, drastically impacting Arctic hydrogeomorphology and introducing unforeseen infrastructure challenges (Holloway & Lewkowicz, 2020).

Aside from local warming, other variables also prompt increased thaw in permafrost-underlain environments. Ice loss in sediment is geomorphologically dependent on environmental conditions, ground ice content and landscape but is particularly impactful in ground with higher ice content, promoting more significant subsidence. The decreased ground volume accompanying ice melt can manifest as landslides in sloped regions or ponds in flat terrain (Technical Guide: Infrastructure in Permafrost: A Guideline for Climate Change Adaptation, 2019) and infrastructure on land undergoing thaw can be seriously damaged. Added slide risk is also associated with increased active layer thickness caused by rising air temperatures. Under warming conditions, permafrost carbon feedback is also amplified, which is a climate concern since massive carbon stores exist in frozen ground. More than twice as much carbon exists in permafrost than in the atmosphere (Schuur & Mack, 2018), suggesting that thaw risk is substantial for carbon dioxide and methane release. Fires present further risk to permafrost environments and can occur in the north with increasing prevalence alongside climate warming (Heginbottom, 2000). Fire presence in Canada's far north is limited due to lower temperatures, less substantial vegetation and exceptional lake presence. Despite this, risk and potential impact should be evaluated due to the risks it poses to permafrost-rich regions under enhanced temperatures. For example, the catastrophic fire season in the Northwest Territories in 2023 included a large fire in the upland terrain northeast of Inuvik that prompted evacuation watches. As these events become more common, the linkage between fire and slope disturbance driving cryogenic landslides will likely increase downstream impacts.

According to the Canadian Standards Association classifications, permafrost warmer than -2°C is not resilient (Technical Guide: Infrastructure in Permafrost: A Guideline for Climate Change Adaptation, 2019). Between 2014 and 2015, Inuvik's mean annual ground temperature was -2.2°C at 10 m depth (Technical Guide: Infrastructure in Permafrost: A Guideline for Climate Change Adaptation, 2019). Physical landscape features such as vegetation presence/type, organic content, snow cover, and limnology can strongly influence ground temperatures, and local variation can be up to 4° C (Technical Guide: Infrastructure in Permafrost: A Guideline for Climate Change Adaptation, 2019) from the local average, suggesting that despite the -2.2° C yearly average, some areas may be far less resilient to permafrost thaw than others. Generally, snow, vegetation, and local limnology will promote ground warming due to the insulating properties and thermal exchange; however, organic presence will generally promote permafrost persistence.

Modelling permafrost presence, thickness, and richness are challenging for many reasons, including considering the extensive list of variables that influence its persistence. A consolidation of models estimating degradation predicted that the permafrost area lost by 2100 ranged from 15.9 to 93% (Schaefer et al., 2014). This range was so vast because of the substantial uncertainties presented by climate variables such as snow coverage and resulting soil temperature, as well as the regional coverage of each model (Schaefer et al., 2014). While models cannot predict exact permafrost degradation under future conditions with certainty, all systems did predict permafrost degradation. Improvements to the quality of aerial imagery and its accessibility are exceptionally beneficial to thermokarst research.

Permafrost regions contain almost twice as much mercury in the ground as in the rest of the pedosphere, atmosphere and ocean (Schuster et al., 2018). Mercury can be from industrial sources deposited atmospherically or naturally occurring in the ground (Schaefer et al., 2020), and local sedimentation histories will determine local concentrations. This mercury can be stored for very long periods in frozen ground, and its release during this thaw concerns northern systems (St. Pierre et al., 2018). Roughly 5% of mercury stored in permafrost soils has the potential to be released during the development of thermokarst features (St. Pierre et al., 2018). Permafrost thaw and thermokarst drive mercury introduction into cold region's hydrology (Staniszewska et al., 2022). Mercury release is further amplified by elevated precipitation, which can drive these substantial thaw events (St. Pierre et al., 2018). In addition to permafrost, mercury stored in the active layer is also considerable and is estimated to be the largest mercury reservoir on the planet (Schuster et al., 2018). And as this research presented, active layer detachment slides can be substantial driving features of mercury into lakes and other downslope systems.

Researchers looking at mercury concentrations in watersheds in the Peel Plateau found that concentrations were up to two orders of magnitude greater downstream of retrogressive landsliding than upstream (St. Pierre et al., 2018). Despite the variation in reservoir type, this research presents the potential for cryogenic landsliding to load mercury into the nearby hydrological systems. Mercury and methylmercury have been found to be closely related to organic carbon concentrations and inversely related to sedimentation rates due to the dilution that high sedimentation provides (Deison et al., 2012). This research did not support this dilution since high sedimentation drove increasing mercury concentrations into some lakes; however, this may be explained by the variation in landslide type and local geology between studies.

The processes driving mercury and carbon cycles are closely connected. For example, frozen mercury release was generally found to be the greatest in areas already experiencing thaw and with substantial frozen carbon (Schaefer et al., 2020). Significant mercury loss is expected in ice-rich, carbon-rich permafrost like that in the Upper Mackenzie River Basin (Schaefer et al., 2020; Schuster et al., 2018). This elevated mercury and carbon content can be of concern for methylmercury production. However, carbon-rich soils may slow the progression of mercury release due to the insolation properties provided by these soil types (Schaefer et al., 2020).

While not a major focus of this research, methylmercury, a bioavailable form of mercury produced in lakes during anaerobic conditions, can be of major concern in aquatic ecosystems and to those who use them for resources or recreation (Staniszewska et al., 2022). Elevated mercury and carbon introduced during cryogenic landsliding can promote conditions for methylation by providing a greater source of mercury to be consumed by microorganisms (Staniszewska et al., 2022). This accumulation through the food chain of mercury in its bioavailable form is of especially high concern due to the traditional diets consumed by many Northerners living on the delta.

While paleolimnology, with some accuracy, can allow for the extrapolation of data to make estimates of thaw feature initiation, satellite imagery and direct observations in the field can provide accuracy to much finer scales of novel changes (Kokelj & Jorgenson, 2013). Projects like the Northwest Territories Thermokarst Mapping Collective are creating comprehensive databases for permafrost thaw across extensive landscapes using academic and Indigenous knowledge (Kokelj et al., 2023). Complete and large databases like the NT-TMC are incredibly beneficial for permafrost research as they add up-to-date and detailed information regarding wide-ranging thermokarst features in northern regions. Data on the impacts of receiving waterbodies from thermokarst disturbance, such as those provided by this thesis, can complement these broad-scale mapping initiatives to contribute to a more complete understanding of the impacts of permafrost thaw and potential near-term changes under future warming scenarios.

Conclusions

This thesis examined the impacts of cryogenic landslides on three lakes. Still, the effect of permafrost thaw in and around the delta was visually astounding in a way that the graphs can only partially describe. Inuvik locals who provided fieldwork support spoke of how these massive hillslope features were blatantly apparent changes to the geography of the Caribou Hills to anyone who travelled the area regularly. From above, we saw extensive evidence of retrogressive thaw slumping across the Mackenzie Uplands and could hear the ice breaking while standing in some of them. While flying over the delta, we saw active layer detachment slides across the length of the Caribou Hills. This permafrost thaw is predicted to continue alongside rising temperatures and changes to precipitation trends; thus, understanding the geomorphological and chemical risks is paramount. During our research trip on July 4, 2023, the air temperature reached 33°C (31.3°C – recorded by ENR), the highest temperature recorded in Inuvik, and the last four Julys have had at least one about 30°C day (Inuvik - A (Temperature Data), 2024) highlighting the trajectory of frozen ground in this Arctic Delta region.

This research's paleolimnological focus highlighted that lakes can maintain exceptional records of cryogenic landsliding. My research shows that the most responsive sediment records require rapid deposition, such as during distinct and intense weather events or high temperatures, and in cases where cryogenic landsliding in the catchments is proportionately large to lake size. This research emphasizes the elemental loading potential of cryogenic landslides and that mercury loading during landsliding was significant. Paleolimnological studies that retrieved longer sediment cores with different coring techniques might provide longer inferences and context of cryogenic landsliding in the region to better contextualize recent changes in records spanning multiple decades.

Permafrost thaw is already broadly impacting the north, and increasing average temperatures have been recorded in the Inuvik region over the last forty years (Burn & Kokelj, 2009). Warming in the Arctic is occurring at an estimated 2.5 times faster than the rest of the globe, according to the IPCC IN 2013 (Schuur & Mack, 2018), and ground stability concerns are widespread and most prominent in areas with communities, infrastructure, or habitats relying on its sustenance. Slope stability is already fragile in many northern regions, and continued warming will only promote an already existing trend (Aylsworth et al., 2000). Understanding permafrost makeup is also vital for identifying climate and health risks associated with ground thaw and ice melt. This is primarily relevant in areas where contents may remobilize or new hydrological pathways are created.

For the purposes of this thesis, landslide magnitude, lake size, distance from the landslide, and many other factors that influence the reliability of sediment to maintain clear landscape histories were found to be important factors in lake response, but their roles were not explicitly tested. These factors are important for understanding the development of thermokarst features, how they manifest in the landscape and how they impact receiving waterbodies. They should be considered in future research on this topic.

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