PALEOLIMNOLOGY AS A QUANTITATIVE INDICATOR OF ECOSYSTEM VULNERABILITY

by

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ABSTRACT

External stressors to freshwater systems present challenges for management. Stress can exacerbate ecosystem vulnerability, which is a result of numerous components, making quantifying vulnerability logistically difficult. The purpose of this research was to understand the use of paleolimnology as an effective method of quantifying vulnerability in freshwater ecosystems to inform management decisions. A systematic map revealed that using paleolimnology to discuss the concept of vulnerability is an emerging field and can provide a clearer lens of changes over time. To demonstrate this, we examined two ponds on Sable Island National Park Reserve, where historic ecosystem changes were inferred based on changes in biological indicators preserved in lacustrine sediments. The ponds demonstrate inherent vulnerability to impacts from a large horse population, global environmental change, and shifting island morphology. Quantifying ecosystem vulnerability on Sable Island is essential for management decisions and promotes the application of a paleolimnological perspective in further vulnerability research.

LIST OF ABBREVIATIONS USED

^{14}C	Carbon-14
^{210}Pb	Lead-210
CE	Common era
DOC	Dissolved organic carbon
HC g-1 DW	Head capsules per gram of dry weight
KOH	Potassium hydroxide
LOI	Loss on ignition
SINPR	Sable Island National Park Reserve
TN	Total nitrogen
TP	Total phosphorus

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CHAPTER 1: INTRODUCTION

1.1 Introduction

The vulnerability of a freshwater ecosystem can exacerbate impacts of stress on ecological integrity. Numerous factors including risk, resilience, exposure, adaptive capacity, and sensitivity can all define an ecosystem's susceptibility to change as a result of pressure or disturbance and are all components of ecosystem vulnerability (Ford and Smit 2004; Aven 2010; Weißhuhn et al. 2018). However, vulnerability can be difficult to quantify and requires site-specific analysis to conceptualize the state of an ecosystem (De Lange et al. 2010). To gain an understanding of vulnerability, long-term historical data can demonstrate the ecosystem's history and natural responses, offering insight into its ecological integrity and potential effective management practices (Smol 1992). Yet, many ecosystems are missing long-term data and, therefore, missing historical context on how the ecosystem has functioned and experienced changes (Quinlan et al. 2008). Paleolimnology joins the study of lacustrine sediments with the historic and prehistoric ecological context (Smol 1992), offering quantitative data over a timescale that is otherwise difficult to collect (Walker 2001). This insight plays a key role in conceptualizing vulnerability and establishing reference conditions that help with implementing ecosystem management and restoration efforts.

Paleolimnological methods are often used to analyze disturbance (Burge et al. 2017) or environmental changes in variables such as temperature (e.g., Barley et al. 2006; Langdon et al. 2008; Korosi et al. 2013; McKeown and Potito 2016) or nutrient availability (e.g., Reavie et al. 2006; Logan et al. 2011) over time. Filling in these gaps can define pre-disturbance conditions and distinguish the difference between natural variability and changes that are forced by external factors (Norberg et al. 2008). Knowledge of the ecosystem's pre-disturbance state as well as its structure and functions are crucial for restoration and conservation methods to create desirable and achievable targets for recovery (Roberts et al. 2019). Enhanced understanding of the ecosystem and its specific vulnerabilities provided by the paleolimnological lens helps to develop productive management practices, which is pivotal for agencies mandated to protect vulnerable ecosystems.

Parks Canada holds administrative management and protection over the country's 48 national parks, which includes responsibility to protect and conserve the ecological health of these areas. Sable Island National Park Reserve (SINPR) located almost 300km southeast of Halifax, Nova Scotia, was established as a National Park in 2013 (Sable Island Institute 2018). SINPR is geographically distinct and sustains a high diversity of species whose survival is largely supported by the freshwater ponds (Beson 1998). These ponds have experienced historical shifts in availability and surface area (Howe 2019), and their vulnerability is unknown. The need to better define the vulnerability of these ecosystems and the changes that have occurred has been articulated by Parks Canada in their management plan to improve the protection of SINPR from future disturbances. Understanding the past can bring clarity to the challenges that SINPR may face in the future, which can help Parks Canada establish goals for conservation and maintaining the ecological integrity of the island.

There are two primary questions in this research: the effectiveness of paleolimnological analysis in understanding ecosystem vulnerability, and the long-term changes of the freshwater ecosystems of Sable Island National Park Reserve (SINPR). These will be explored through a systematic map of the value of paleolimnology in reconstructing and managing ecosystem vulnerability and an examination of sediment cores from SINPR aquatic ecosystems, respectively. These combined allow for the knowledge acquisition required for managing ecological integrity of SINPR. As such, the aim of this thesis is to add to the expanding field of paleolimnology for purposes of vulnerability assessment applied to the pond ecosystems of SINPR. Each of these research questions are evaluated in a separate chapter. Chapter 2 reviews of the ways paleolimnology has been and can continue to be used to assess vulnerability to enhance our interpretation of ecosystem functions; Chapter 3 applies the use of paleolimnology to investigate lacustrine sediment collected from SINPR and determine its ecosystem vulnerability; and finally, Chapter 4 concludes the thesis by considering the future of management on SINPR and paleolimnological research. These conclusions will allow for considerations of how paleolimnological research can play an integral role in management of national parks and unique ecosystems.

1.1.1 Overview of the problem to be addressed

Ecosystems can experience natural variability, but without knowledge of how the system inherently changes, it can be difficult to determine the difference between natural and forced change caused by disturbances (Battarbee and Bennion 2011). Disturbance can cause major stress on an ecosystem whether it is direct or indirect, impacting its natural processes and altering the system altogether (Bishop et al. 2018). Although there is a long-standing meteorological station on Sable Island with weather records dating back to the late 1800s, there is a lack of ecosystem monitoring for changes in conditions, which presents a gap in the knowledge with minimal historical context for environmental responses, and an unclear trajectory of change for SINPR's freshwater systems. In order to ensure that the most-informed management decisions are made to protect the park, it is necessary that these long-term changes are defined, and the extent of risk posed to the ecosystems is examined.

1.1.2 Primary data research purpose and objectives

The central objective of the present research is to understand and effectively apply paleolimnological methods to vulnerability assessment and ecosystem conservation. It is important that Parks Canada has a well-rounded understanding of the different factors that may be putting the current environment at risk. Parks Canada has developed the Sable Island National Park Reserve of Canada Management Plan (2019) comprising of three key strategies. These key strategies are; (1) protection in the context of past and future change, (2) inspiring connections that build support for conservation, and (3) sustainability, innovation, and efficient operations (Howe 2019). This research will help with the first key strategy as it will provide background for changes in environmental conditions by reconstructing the past and examining disturbance-driven changes to define ecosystem vulnerability, which will be done through evaluating sediment cores from the freshwater ponds on SINPR with paleolimnological chironomid-based analysis. An in-depth understanding of the trajectory of change is necessary for applying management and conservation principles to protected areas. Thus, we hypothesize that paleolimnological analysis is a useful metric for monitoring the trajectory of change in these ecological systems and can be used to assess the vulnerability of the freshwater ecosystems of Sable Island. We specifically address two primary predictions to support this hypothesis: 1) analysis of the sediment history of SINPR ponds will indicate a shift in biological indicators that are responsive to nutrient enrichment, 2) the ponds will represent different quantitative changes in indicators depending on the factors that impact them the most on an individual scale, one of which is the presence of horses.

The use of paleolimnology for management and conservation will depend on the successful demonstration of three objectives: (1) review of the use of paleolimnology in literature to understand how it can be utilized in research to determine vulnerability; (2) use of paleolimnology to evaluate trends in indicators and understand how Sable Island has undergone ecosystem changes in the past; and (3) use paleolimnological inferences to determine ecological integrity and vulnerability as well as inform context for management. Through investigation of the freshwater systems on SINPR, we infer change through the analysis of biological indicators (subfossil remains of the Family Chironomidae). The analysis will be based on surface samples from several ponds and sediment cores collected from two ponds on SINPR; (1) Pond PD67 core (8.4 cm diameter and 15.0 cm deep); and (2) Pond PD03 core (8.4 cm diameter and 25.0 cm deep). The current state of these ponds represents two different habitats on SINPR, and comparing them will offer a range of the type of ecosystem factors potentially contributing to conditions. The understanding of ecosystem vulnerability provided by the analysis will help Parks Canada with establishing the necessary goals for conservation to preserve the ecological integrity of Sable Island.

1.2 Literature Review

Globally, many ecosystems are at risk of being affected by the escalating impacts of climate change. Issues such as climate warming, increased weather severity and sea level changes are expected to vary from habitat to habitat as not all systems are impacted in the same way (NASA 2019). Some ecosystems are likely to be more vulnerable to climate change than others, meaning that the impacts are expected to be more severe in those locations. Numerous factors can contribute to varying ecosystem dynamics, making it necessary to make sure ecosystems are understood on an individual level.

Sable Island National Park Reserve is an ecosystem of interest due to its offshore location and unique landscape. It has a notable species composition and is often remembered for its population of iconic feral horses, as well as the world's largest grey seal breeding colony (Sable Island Institute 2018). However, the extent that the island is experiencing environmental change is currently understudied. Sable Island was established as a national park in 2013, which means that Parks Canada has assumed responsibility to fulfill its goal of maintaining the island's ecological integrity alongside all Canadian national parks (Parks Canada Agency 2019). It is important that Parks Canada has a comprehensive understanding of the different factors that may be putting the current ecosystem at risk. Using paleolimnological analysis can quantitatively define long-term change to the freshwater ecosystems, which will help determine the susceptibility to stress and primary stressors themselves, inherently quantifying ecosystem vulnerability. Defining these characteristics can provide valuable information and implications for park management.

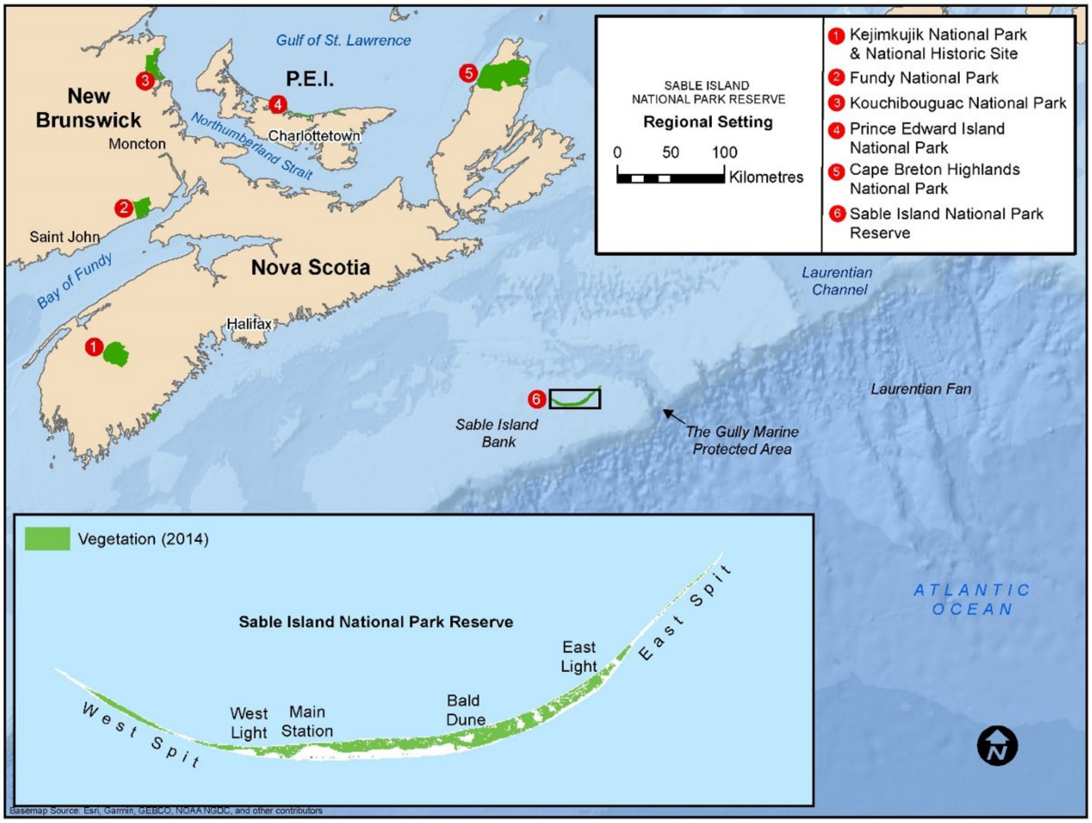
1.2.1 Sable Island National Park Reserve

About 290 km southeast from Halifax, Nova Scotia, Sable Island is an isle of sand on the edge of the continental shelf in the Atlantic Ocean that is about 49 km long and only 30 square km (Cameron 1965) (Figure 1.1). SINPR has milder climate that is tempered by the ocean but can frequently experience severe weather conditions and high winds (Parks Canada 2020). It has a mean annual temperature of 7 °C experiencing low 20s °C in summers and around 0 °C in winters (Government of Canada 2020). Formed during the retreat of the last glaciation, the crescent-shaped island is an emergent part of the Sable Island Bank in the Northwest Atlantic, making it the only exposed portion near the edge of the continental shelf (Beson 1998).

SINPR is commonly noted for its feral horse population. Numbers have fluctuated between 250 to over 400 for many decades (Plante et al. 2007), and currently sits at more than 500 as of August 2019. The population has naturalized from horses that were brought to the island by humans in the eighteenth century as an attempt to stock the island with various animals, and are now their own distinct species (Freedman 2016). SINPR also hosts the world's largest grey seal breeding colony on its beaches (Parks Canada Agency 2019). The island is rich in diversity; there are over 200 plant species, 350 bird species, and 600 invertebrate species – some of which are endemic to the national park such as the Sable Island sweat bee (*Lasioglossum sablense*) or considered a species at risk such as the Ipswich sparrow (*Passerculus sandwichensis princeps*) (Tissier et al. 2013; Sable Island Institute 2018). SINPR only has one stunted tree but has high coverage of grasses and shrubs. The low-growing vegetation is suited for the sandy environment, with minimal establishment of introduced plant species (Stalter and Lamont 2006). While there are stress-tolerant plant-communities dispersed across the island, inland plant communities are more protected from wind and waves and consist of shrub and heath vegetation in some parts (Tissier et al. 2013). The pattern of plant community distribution can be described as a response to repeated environmental disturbance as opposed to gradual soil development or competition (Tissier et al. 2013).

The freshwater ponds of Sable Island are replenished by precipitation and an underground aquifer, providing freshwater for the island (Beson 1998). However, due to high coliform bacteria levels caused by horse feces as well as saltwater intrusion, the pond water is non-potable (Beson 1998). The surface area of freshwater has decreased over time, which is concerning due to its role in maintaining life on the island (Howe 2019). Protection and better understanding of the freshwater within five years is one of Parks Canada's management goals for the island in order to prevent depletion and further contamination from outside sources (Howe 2019).

Although there has been continuous human presence on the island since the early 1800s, the island was a common site for shipwrecks for centuries prior (Beson 1998). Currently, there are frequent visitors to the island for tourism and research opportunities, in addition to permanent Parks Canada and Meteorological Services Canada staff (Sable Island Institute 2018). One of the greatest concerns for the current topography on Sable Island is erosion, mostly caused by roaming horses, staff or visitors, high winds and frequent storms (Beson 1998). Additionally, continuous sea level rise occurring since the early Holocene poses a threat, potentially resulting in submergence of the island in the future (Beson 1998). To improve management of Sable Island, it would be beneficial to know the state in which the ecosystem functions best. Past climate needs to be known as a point of reference to compare the current ecological state, so it can be understood how the ecosystem has changed. Long term data offers insight into effective management practices (Smol 1992), however there is currently limited data on Sable Island's past ecosystem conditions. SINPR was designated as Canada's 43rd national park in 2013, bringing it under administrative management and protection of Parks Canada (Sable Island Institute 2018). Because it has only been an established national park reserve for a short time, the first management plan was made public as recently as 2019 following a few years of drafts, public outreach and consultations with Indigenous rights-holders, resulting in the Sable Island National Park Reserve of Canada Management Plan (Parks Canada Agency 2019). This document serves as the framework for the island's determined ecological integrity, future goals and strategies that is integral for everyone involved in the process of managing the national park.



Basemap Source: Esri, Garmin, GEBCO, NOAA NGDC, and other contributors

Figure 1.1. Sable Island National Park Reserve resides 290km southeast of Halifax, Nova Scotia (Howe, 2019).

1.2.2 Paleolimnology

Long-term environmental data can be difficult to come by, so scientists have turned to reconstructing past conditions using alternative methods (Smol 1992). Observing climate-related variables such as temperature can help us create quantitative reconstructions to distinguish differences between natural climate variability and major forced changes (Sullivan and Charles 1994). However, regular monitoring of these variables usually does not occur over a long enough time period to provide reference (pre-disturbance) conditions (Norberg et al. 2008), meaning that an external method is often required to collect missing long-term monitoring data. Since this pre-disturbance data is often missing, paleolimnology can fill this knowledge gap (Walker et al. 1991).

Previous climate data can be remodelled from lake sediment archives in areas where there is a lack of documentation on former conditions (Flower 2017). Paleolimnology is a valuable science used for the past few decades that can help determine the former functions of an aquatic ecosystem (Frey 1988). It joins the study of lacustrine sediments with the historic and prehistoric ecological context (Smol 1992), offering method of quantitative data collection over a timescale that is otherwise difficult to access (Walker 2001). Paleolimnology uses physical, chemical, and biological information preserved in the sediment of a pond or lake that can be used to rebuild historic environmental conditions (Smol 1992). This information is maintained through the deposition of aquatic, terrestrial, and atmospheric materials in lakes that preserves the context of surrounding environment in accumulated sediments over time (Williamson et al. 2009).

Aquatic sediment is often less impacted by erosion and other disturbances than terrestrial sediment (Burge et al. 2017). Closed lake systems have defined boundaries that control the flow of inputs and outputs (Fergusson and Bangerter 2015) that allow lakes to preserve proxy records, making lake dynamics such as water level and chemistry highly responsive to climatic changes (Sullivan and Charles 1994; Walker 2001). The unique ability to collect and preserve surrounding ecological information makes lakes useful tools for preserving and studying the past as lakes can act as indices for climate variability (Saulnier-Talbot 2016). Using this recording of long-term trends preserved in lakes quantifies past ecosystem changes – a valuable insight for projecting future scenarios (Fordham et al. 2020).

Paleolimnology has inferred changes in climate using fossil indicators that can convey past states of hydrology and temperature (Sullivan and Charles 1994). Diatoms, Cladocera, and Chironomidae (or *chironomids*) are some of the most valuable organism remains due to the abundance, diversity and ability to indicate environmental conditions (Frey 1988). These organisms respond to numerous environmental variables because they are impacted by changes in limnology such as temperature, salinity, acidification, and nutrients (Walker 2001), which allows them to be utilized when understanding relationships between aquatic biota and changes in the environment (Medeiros and Quinlan 2011). Chironomids, also known as non-biting midges, are sensitive to temperature because they depend on it for reaching multiple life stages which makes them a good ecological indicator of temperature changes (Smol et al. 1991). Chironomids are the most abundant family in the order *Diptera* (flies). At different life stages, chironomids shed head capsules that get preserved as subfossils in the lake sediment (Walker et al. 2001). Sediment is deposited chronologically in lakes (Frey 1988), meaning the oldest sediment is the typically the lowest point of a depth profile with the most recent sediment on top. Collecting a sediment core and analyzing the different layers for chironomid species compositions can be used to understand long-term changes in ecosystems (Smol 1992), which also requires baseline knowledge of trends between biota and the environment (Medeiros and Quinlan 2011). Although considered a reliable indicator for climate, chironomids can also be impacted by other limnological trends and environmental variables including salinity, oxygen levels, or metals, which is important to consider in the site of interest (Barley et al. 2006). While the use of chironomids as an indicator has been practiced consistently for decades, many researchers are working on expanding the understanding of the chironomids to further define the family and their ecological role to continue to improve the practice (Frey 1988).

The use of chironomid subfossils has been applied to paleoecology for nearly a century but has become increasingly relevant in the past few decades (Walker 2001). Many aquatic ecosystems have demonstrated the adverse impacts of anthropogenic activity and climate change such as lowered oxygen levels, leading to increased environmental concern and ecosystem biomonitoring (Belle et al. 2017). Multiple studies in recent decades have explored the effectiveness of paleolimnological analysis in assessing environmental changes and conditions and its ability to compensate for missing long-term monitoring information. Paleolimnology has been useful for monitoring particularly sensitive ecosystems such as the Canadian Arctic and identifying limnological shifts caused by changes in environment (Rühland et al. 2003). These methods are particularly valuable for understanding the rates and extent of changes occurring in environments that are known to be highly impacted by rapid climatic changes. When studying the environmental factors that may limit chironomid distribution in ponds of the eastern Canadian Arctic, Medeiros and Quinlan (2011) found that temperature gradients as well as nutrient conditions correlated with species composition.

However, this study also suggests that responses to climate may be indicated by specific taxa regardless of trophic status, which can be useful for assessing Arctic ecosystems as they are further infiltrated by species whose ranges are expanding (Medeiros and Quinlan 2011). Continuing to expand this field of research will allow for more holistic understandings of changing environments. With a growing interest in the field, the application of paleolimnological methods can expand in research and be further utilized in science and policy decisions.

Anthropogenic activity is known as one of the most impactful ecosystem stressors. Paleolimnology can provide representation of stressors in a system, but it has been questioned if anthropogenic activity influences the resolution of the data. This was addressed in a study by Langdon et al. (2012) where successful records of early Holocene temperature data were inferred using chironomid samples found in a Northern England lake. It is proposed that Holocene data can be effectively remodelled through chironomid analysis in environments that have minimal impact from anthropogenic activity (Langdon et al. 2012), which was reiterated by a study that analyzed the reliability of chironomid-inferred temperature models on two lakes in western Ireland, with one lake being impacted by human activity and the other impacted significantly less (McKeown and Potito 2016). McKeown and Potito (2016) found that chironomid models were more effective at reflecting air temperatures, including acceleration of anthropogenic-induced warming, for the lake that was less impacted directly by human activity. The other lake demonstrated confounding environmental variables such as eutrophication from nearby human activity, compromising the integrity of the chironomid-based signal (McKeown and Potito 2016).

While reliability of paleolimnological analysis can be compromised by ecosystem changes directly influenced by anthropogenic activity, it has proven to be successful at recognizing shifts caused by anthropogenic activity. This is done by determining differences between natural climate variability and forced change caused by anthropogenic activity (Sullivan and Charles 1994). Landscape changes such as land cultivation can be indicative of the impact that human activity has on sediment records, showing a diversion from natural variability in sediment (Flower 2017). Sable Island's dynamic landscape has experienced changes influenced by winds, waves, ocean currents and storms (Muise 2012). The island is not dominated by anthropogenic landscape changes, but it is possible that distant anthropogenic activity or anthropogenic-induced warming will be evident in the sediment records. The direct human impact to the freshwater on Sable Island National Park Reserve is extremely limited, however, it is expected that there is direct stress caused by the free-roaming horses. Therefore, it is unknown if this will present challenges in accuracy of the chironomid-inference models for reflecting real environmental changes.

1.2.3 Ecological vulnerability

"Vulnerability" is a term many people are likely familiar with, but there is hardly a single understanding of it. The term can be used in variety of contexts but is typically defined as a potential for loss (Adger 2006) and is a result of multiple complex factors that are each difficult to quantify in their own way (Aven 2010). These factors generally include a combination of risk, resilience, exposure, sensitivity, and the capacity to adapt to change (Aven 2010; Ford et al. 2007; IPCC 2014). The capacity to adapt implies a system's ability to maintain its own balance and trajectory, referring to the integrity of the system

(Karr 1996). In the ecological context, adaptive capacity allows an ecosystem to cope with stress and adapt to change or disturbance (Luers 2005; Smit and Wandel 2006). Therefore, if an ecosystem's integrity is being compromised as a result of some form of stress, it may experience increased ecosystem vulnerability caused by reduced adaptive capacity.

Despite general agreement on the multiple factors involved in defining ecosystem vulnerability, there are still ambiguities in vulnerability as a concept. Füssel and Klein (2006) raise the questions of whether vulnerability is a starting point or outcome, whether it should be defined in relation to a stressor or outcome, whether it is a property or response, and whether it is static or dynamic (Füssel and Klein 2006). The IPCC defines vulnerability in the context of climate change as "degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes" and describes it as a function of the system (IPCC 2001). Using consistent qualifying terms can lead to a better conceptualization of vulnerability in an effort to minimize confusions and misunderstanding of the term in the context of interest (Füssel and Klein 2006).

Vulnerability is often looked at through the social dimension, attempting to understand how nearby communities are impacted by environmental changes (Ford and Smit 2014). Plummer et al. (2012) discuss the importance of a holistic approach when assessing freshwater vulnerability to include both biophysical and social dimensions. Estimating future vulnerability with biophysical dimensions can involve the use of ecological indicators and understanding the consequences that changing climate has and may continue to have on those metrics (Lemieux et al. 2014). Assessing vulnerability aims to understand ecosystem weaknesses and identify the threats and their extents and would need to be followed by proper management (Weißhuhn et al. 2018). For a site-specific ecological risk assessment, characterization of biological and ecological properties of a system are necessary for more precise risk-quantification (De Lange et al. 2010). The level of detail and understanding requires spatially-explicit baseline information (Lee et al. 2017).

There is a lack of understanding regarding environmental change on Sable Island although research has been taking place there for decades. Since Sable Island is a recently established national park, there has not yet been an aquatic biomonitoring program implemented. Therefore, there is no way to understand how the current state of the aquatic ecosystems compares to conditions prior to recent decades. This research addresses a gap in the knowledge by reconstructing past environmental conditions on Sable Island and aiding in the conception of a biomonitoring program. Although assessing vulnerability is not a linear process (Lemieux et al. 2014), paleolimnological methods can provide a base for building upon knowledge and informing future decisions.

1.3 Research Sites

1.3.1 Sable Island National Park Reserve

The 32 km^2 of land that forms Sable Island National Park Reserve is one of Canada's furthest offshore islands being 161 km southeast from the nearest point of mainland Nova Scotia and 290 km from the city of Halifax (Howe 2019). The north-facing crescent-shaped island is composed of unconsolidated sediment extending nearly 1km below sea level (Byrne and McCann 1993; Berger et al. 1965) and is physically characterized by low rolling sand dunes, sand-loving vegetation, and freshwater ponds (Beson 1998; Howe 2019). Sable Island is an emergent part of the Sable Island Bank in the Northwest Atlantic, making it the only exposed portion near the edge of the continental shelf (Beson 1998). Its dynamic form influenced by winds, waves, ocean currents and storms has experienced ongoing land erosion from the western end and accumulation of sand at the eastern tip (Muise 2012).

1.3.2 Landscape

SINPR's vegetation is highly influenced by its moderate climate, including the cooler growing season temperatures and infrequent frosts (Catling et al. 1984). The vegetation communities are characterized by Nova Scotia's coastal dune habitats that experience high winds and often salt spray from the ocean (Porter et al. 2020). Communities with the highest surface areas include Sparse Grasslands, Heath, and Marram-Forb (Catling et al. 1984). Some of the typically described species on the island include shrubs such as Black Crowberry (*Empetrum nigrum*), Virginia Rose (*Rose virginiana*), and low growing Northern Bayberry (*Morella pensylvanica*), as well as grasses such as Marram Grass (*Ammophila brevigulata*) (Porter et al. 2020). Several ponds are found scattered across the terrain that are vital to supporting the biodiversity on the island. A bioassessment of the freshwater ecosystems using aquatic macroinvertebrates recorded 27 taxa with highest abundances of Coroxidae, Amphipoda, Oligochaeta, and chironomid species *Polypedilum bicrenatum* (Jacks et al. 2021). Over time, the ponds have experienced shifts in availability and seasonal fluctuations in surface area (Howe 2019). Although the sand dunes have acted as barriers between the ocean and the fragile habitats on the island's inland (Beson 1998), saltwater intrusion and sediment transport are still two known threats to the freshwater ponds (Howe 2019). There is also a collection of macrophytes in the freshwater ponds and pond-edge herbaceous communities. In deeper ponds of up to 1.5 m there are commonly species of pondweed or watermilfoils, where cranberry heath and other low growing species can often be found bordering gradually sloped pools; various pondweeds and grasses can also be found in brackish ponds (Catling et al. 1984). The lens of fresh water is dependent on replenishment of precipitation and sustainable extraction by well to fulfill needs of personnel on the island. However, the stability of the ponds remains uncertain due to the questionable longevity of processes on the island (Bell and Ure 2015).

1.3.3 Naturalized horses

A population of genetically distinct feral horses resides on SINPR, assumed to descend from a collection from French settlers in 1755 that were relocated to the island (Christie 1995). With a population that fluctuates from 250 to over 400, the horses were given legal protection in 1961 and have since been protected from human interaction (Plante et al. 2007). In their free roam of the island, the horses are known to have impacts on the vegetation through stomping and grazing, with the greatest impact on Marram grassland communities (Freedman et al. 2011). Areas around ponds are referred to as "horse lawns" and are mostly comprised of stunted prostrate graminoids, retained flat by frequent trampling and grazing by horses (Freedman et al. 2011). The ponds themselves also experience impacts from high horse activity, such as higher pond productivity and an influx of nutrients as indicated in biomonitoring macroinvertebrates (Jacks et al. 2021), increased coliform bacteria from defecation (Beson 1998), and feeding on macrophytes in summer seasons (Freedman et al. 2011). While these impacts are documented today, the long-term impacts of the horses on the freshwater ecosystems are not well-defined.

1.3.3 Pond PD67

Pond PD67 (43.932481 N, -59.900146 W), commonly named “Gallinule”, is the largest standing pond on Sable Island with an area of approximately 3500 m^2. It also has the greatest volume, reaching a maximum depth of 1.3 m during our period of data collection, and the largest catchment that is mostly made of sand. Its inland location makes it more isolated than most other ponds. According to a bioassessment of the SINPR ponds using aquatic macroinvertebrates, PD67 experiences extreme abundances and low diversity of macroinvertebrates with dominance of amphipods and an Average Shannon Index of 0.498 across 3 sampling periods in May, July and August 2019 (Jacks et al. 2021). This dominance could be credited to lack of predation (Peterson 1979). PD67 also does not experience drastic water volume fluctuations, which might allow dominance of few taxa and low vulnerability (Jacks et al. 2021). Water quality parameters are compared to the ecosystem thresholds established by the water quality analysis performed by Parks Canada Agency. According to the water quality measurements from 2015-2020, the pH for PD67 usually stays within the established threshold of 9.5-6.5, teetering towards the higher end in recent years. Turbidity is low, nitrogen is usually below threshold of 1.9 mg/L except for a spike of >3.0 mg/L in 2016, however phosphorus has fluctuated above and below the threshold of 0.384 mg/L, reaching near 1.0 mg/L in 2016.

1.3.4 Pond PD03

Pond PD03 (43.932364 N, -60.026706 W), commonly named “Mummichug 1”, has a surface area of approximately 1200 m^2. It reaches a maximum depth of 1.7 m but is shallow through much of the pond, and has a catchment that is predominantly sand. The pond has low numbers of fish and an Average Shannon Index of 1.073 across 3 sampling periods in May, July and August 2019 (Jacks et al. 2021). According to the water quality measurements from 2015-2020 and the established ecosystem thresholds, the pH for PD03 is often above the established threshold of 9.5-6.5, having values between 9.5-10. Turbidity is consistently above the threshold of 23.1 NTU reaching a maximum of 70 NTU in 2016, apart from 2019 where it was within threshold. Nitrogen levels are also consistently above the threshold of 1.9 mg/L, reaching >5.0 mg/L from 2015-2017. Phosphorus has been above the threshold of 0.384 mg/L at concentration >1.0 mg/L in 2015 but has been declining until 2020 where it was just below the threshold.

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CHAPTER 2: THE VALUE OF PALEOLIMNOLOGY IN RECONSTRUCTING AND MANAGING ECOSYSTEM VULNERABILITY: A SYSTEMATIC MAP

2.1 Statement of Student Contributions

Review design by Victoria Watson and Andrew Medeiros, chapter writing by Victoria Watson with editorial contributions from Andrew Medeiros, subject editor Irene Gregory-Eaves, and anonymous reviewers for the journal *Facets*.

2.2 Abstract

Vulnerability can measure an ecosystem's susceptibility to change as a result of pressure or disturbance, but can be difficult to quantify. Reconstructions of past climate using paleolimnological methods can create a baseline to calibrate future projections of vulnerability, which can improve ecosystem management and conservation plans. Here, we conduct a systematic map to analyze the range and extent that paleolimnological published studies incorporated the concept of vulnerability. Additional themes of monitoring, management, conservation, restoration, or ecological integrity were also included. A total of 52 relevant unique articles were found, a majority of which were conducted in Europe or North America since 2011. Common themes identified included management and adaptation, with the latter heavily focussed on climate change or disturbance. From this, we can infer that the use of paleolimnology to discuss the concept of vulnerability is an emerging field. We argue that paleolimnology plays a valid role in the reconstruction of ecosystem vulnerability due to its capacity to broaden the scope of

long-term monitoring, as well as its potential to help establish management and restoration plans. The use of paleolimnology in vulnerability analysis will provide a clearer lens of changes over time; therefore, should be frequently implemented as a tool for vulnerability assessment.

2.3 Introduction

Examining climate variability and ecosystem responses of the past can help describe an ecosystem's capacity for change. Decisions about conservation, restoration, and often remediation, cannot be effective unless a clear understanding of the cause of the issue exists (Vos et al. 2000). Environmental monitoring aims to measure certain variables over time and space, and can be recognized as a tool for early warning and control (Vos et al. 2000). As such, monitoring informs policy makers with the necessary information for designing and implementing effective environmental policy (Lovett et al. 2007), as well as for managing vulnerability and the conditions that cause it (Luers 2005). Here lies an inherent problem, understanding the context of vulnerability and elucidating the factors that make a system susceptible, is essential for a decision-makers ability to prepare and adapt to change (Ford and Smit 2004). However, "vulnerability" is not easily quantifiable, and is used in a variety of contexts, such as describing conditions in social, economic, or environmental settings.

Vulnerability can be discussed on multiple scales, for example, the fragility of urban water infrastructures facing the impacts of climate change addresses social (those that rely on the infrastructures), economic (potential costs due to damages), and environmental (detrimental impacts to the resource) vulnerabilities (Dong et al. 2020).

Thus, vulnerability as a measure can only be considered as a result of a complex set of factors, each requiring multiple parameters to define and quantify (Aven 2010). As a core concept, vulnerability has been defined as the potential for loss (Adger 2006), but the determination of vulnerability in a system contains components of risk and resilience (Aven 2010) as well as exposure, sensitivity, and the capacity to adapt to changes (Ford et al. 2007). While these descriptions are applied to general discussion of vulnerability, they are especially relevant in the context of ecosystems (Weißhuhn et al. 2018).

Defining the state of an ecosystem can partly be done through the lens of monitoring ecological integrity, which evaluates the extent that an ecosystem has comparable diversity and function of other similar local natural ecosystems, and an ability to maintain and support these ecological processes (Karr and Dudley 1981). Ecological integrity demonstrates self-organization of an ecosystem and can include elements of biotic structures and changes in energy, hydrological, and chemical budgets (Müller et al. 2009). The concept of integrity inherently implies an adaptive capacity to support and maintain the balance and trajectory of the system (Karr 1996), and understanding factors that contribute to ecological integrity, such as responses and resilience to change, can help determine the system's ability to adapt to change or to disturbance (Luers 2005). In an ecological context, adaptation refers to a process or action that allows the ecosystem to adjust or cope with stress (Smit and Wandel 2006), and adaptive capacity is considered the extent of an ecosystem's functional ability to be able to respond and reduce risk (Ford and Smit 2004). Being capable of adapting can greatly affect resilience to external pressures, such as anthropogenic stressors that could lead to collapse (Perga et al. 2015), making this an important factor in determining ecosystem vulnerability.

Vulnerability assessments help to identify the ecosystem components facing the biggest threat and the extent of that exposure (Luers 2005) and are generally not a one-size-fits-all approach. Though vulnerability assessments are historically most applied to a social context, ecological vulnerability assessments, which categorize risk, have gained more traction in recent decades (De Lange et al. 2010). The determination of risk can vary based on the scope of assessments for ecological vulnerability. For example, in the case of chemical contamination, data on the toxicity of chemicals released to the environment can provide a 'yes' or 'no' answer to whether risk exists for a general non-site-specific assessment; whereas a site-specific assessment requires characterization of a system's specific biological and ecological properties (such as structure or sensitivity) for more precise quantification of risk (De Lange et al. 2010). However, these assessments are rarely spatially explicit (Lee et al. 2018) and often require more baseline information for an in-depth understanding of site-specific vulnerability. To improve understanding of specific ecosystems, long-term historical data can offer a well-rounded representation of the environment and demonstrate its natural history, providing target conditions and offering insight into potential effective management practices (Smol 1992). However, many ecosystems are missing long-term data; therefore, they are missing historical context on how the ecosystem has functioned and experienced changes (Smol 1992).

Regular monitoring usually does not occur over a long enough time period to provide reference (pre-disturbance) conditions (Norberg et al. 2008), meaning that an external method is often required to collect missing long-term monitoring data. When pre-disturbance data are missing (which is often the case), paleolimnology can fill this gap (Walker et al. 1991). Paleolimnology is a science that joins the study of lacustrine sediments with the historic and prehistoric ecological context (Smol 1992), offering a range of quantitative data over a calibrated timescale that is otherwise difficult to collect (Walker 2001). The collection of aquatic, terrestrial, and atmospheric deposition in lakes preserves the context of surrounding environment in deposited sediments over time (Williamson et al. 2009), meaning lakes can act as indices for climate variability (Saulnier-Talbot 2016). This is particularly true for closed lakes, which have defined boundaries that control the flow of inputs and outputs (Fergusson and Bangerter 2015). These boundaries allow lakes to preserve proxy records, making lake dynamics such as water level and chemistry highly responsive to climatic changes (Sullivan and Charles 1994; Walker 2001). Lakes are also especially vulnerable to climate change because of the limited capacity for species to relocate due to habitat fragmentation, water density dependence on ambient temperature, and high exposure to human activity (Woodward et al. 2010) making them good sites for analyzing impacts. Using this recording of long-term trends preserved in lakes quantifies past ecosystem changes – a valuable insight for projecting future scenarios (Fordham et al. 2020).

To gain a comprehensive understanding of the value of paleolimnological practices in assessing vulnerability in ecosystems, it is prudent to understand the extent and reach of current research. Here, we conduct a literature search using a systematic mapping approach to analyze the extent of peer-reviewed articles where paleolimnology has been applied in relation to vulnerability, as well as review the value of paleolimnological practices in vulnerability assessment. This will help to highlight how paleolimnology can be used to reconstruct ecosystem vulnerability and inform decision-makers. By identifying examples of the use of paleolimnology in monitoring, management, and restoration in the literature, we argue that paleolimnological practice has a rightful place in analyzing vulnerability and ecological integrity. Paleolimnology provides an important comprehensive perspective on ecosystem change and what work needs to be done, so that management needs can be fulfilled.

2.4 Methods

To understand the extent of paleolimnological methods used in vulnerability assessments, a systematic map protocol was used to identify, select, and synthesize articles using replicable methods (Supplementary Figure S1). Using the ROSES format (Haddaway et al. 2017), the trends in the extent and range of published literature was mapped in broad topic areas to identify gaps in research and clarify the types of approaches that paleolimnological methods are using within a larger context of vulnerability and ecological integrity. Our review included three steps, (*i*) identifying the broad research realm of paleolimnology and vulnerability assessment through a key word search, (*ii*) systematically identifying and selecting key research articles that captured the themes identified, and (*iii*) extracting and summarizing the results to identify key knowledge gaps. For this study, the aim was to include as many relevant articles as possible in our initial key word search to be able to gather a broad scope of studies in the field of paleolimnology including content related to the desired topics.

2.4.1 Search strategy

Based on our areas of interest and main topics, a search was chosen as follows (Boolean logic shown in Table 2.1); *pal*eolimnolog*, vulnerability, monitor*, manag*, conserve*, restor*, and ecological integrity* (* to allow for variations of spelling and use of the root words). Since the use of three databases improves the comprehensiveness of the search, we examined the Boolean logic criteria in combination with each other to search three different online databases; Web of Science, Scopus, and PubMed (the terms *paleolimnolog* OR palaeolimnolog** were used for PubMed). Web of Science and Scopus were set to search for these terms in the titles, key words, and abstracts of the articles to avoid results that only mention the words in references or briefly throughout the paper. PubMed does not provide this option, as such all fields were searched and more thoroughly examined for relevant content. The initial search was conducted on 11 July 2020 and updated on 1 August 2020. The searches were restricted to articles published in the present and previous century (1 January 1900, to the date the search took place).

2.4.2 Inclusion criteria

Inclusion criteria were developed to validate the relevance of the search results. Articles were considered relevant if they were studies using methods in paleolimnology. Studies that discussed similar terms such as paleoclimatology, paleoecology, or paleoenvironmental reconstructions were considered applicable as these terms are often used in similar or applicable contexts. It was important for studies to pertain to vulnerability or ecological integrity in some way by including monitoring, management, conservation, or restoration with a paleolimnological context. Articles that reviewed paleolimnology were noted but not included, and articles that mentioned paleolimnology but did not include it as part of a study were not included. Only articles published in English were included.

2.4.3 Article selection process

To select relevant articles, the titles and abstracts of each article from the results were screened for key words and overall inclusion of paleolimnology and vulnerability/ecological integrity, deciphering if it captured the identified themes as outlined (Table 2.1). If the inclusion of paleolimnology or vulnerability/ecological integrity was not clear from the title or abstract, then the full article was screened for key terms of interest to determine the context that the search terms were included. Articles that were found to fit the inclusion criteria and contained content relevant to paleolimnology and vulnerability/ecological integrity were included in the data as existing literature on the topics. The initial search and data extraction was done by VW and the consistency of decisions was checked by AM. One paper by one of the authors of this paper was found, but it was excluded as it was not relevant to vulnerability.

2.4.4 Analysis

Our analysis focussed on understanding the ways that paleolimnology has been applied to analyzing different aspects of environmental vulnerability as well as mapping the range of published literature and identifying gaps in the research regarding these areas. After articles were narrowed down to those containing relevant information for this research based on the inclusion criteria and selection process, we also examined the inclusion of capacity and adaptation in the literature. While the terms are often used together for the concept of “adaptive capacity”, they are also often seen separately in the literature. Searching them separately allowed us to analyze the different contexts they were used (eg. resilience capacity vs. carrying capacity), which were relevant to the concept of vulnerability. The inclusion of these terms allowed for an understanding of the extent that capacity and adaptation are discussed in papers regarding paleolimnology and vulnerability, and the proportion in comparison to the total of papers from initial results.

Metadata were extracted from each publication, which included the year of publication, region of the study, key words that each publication identified (if they identified keywords), and thematic topics. The papers were read through and organized based on the search terms they were found under – the inclusion of vulnerability, monitoring, management, conservation, or restoration in reference to applying paleolimnology. Some papers were relevant in more than one topic and were placed in multiple categories with appropriate notes. Organizing articles based on content helped determine the amount of literature that is available on these topics. Although this is not a fully complete collection of papers that discuss these areas of research, it can help determine the reach of each thematic area in the literature. The articles were organized based on the systematic search process, as well as additional relevant background, and they are discussed based on the role of paleolimnology in vulnerability assessment, as well as four subtopics (ecological integrity, reference conditions and ecosystem monitoring, establishing management goals, and creating targets for ecosystem restoration) that contribute to the discussion of paleolimnological application.

2.5 Results

A total of 52 unique peer-reviewed primary research articles were found (Table 2.1). Among all search criteria, 25 articles were selected from Web of Science (4 unique), 28 from Scopus (7 unique), and 21 from PubMed (20 unique). One article overlapped all three databases, and 20 articles overlapped Web of Science and Scopus. Some articles also resulted in more than one combination of key words and were identified in more than one Boolean search process (e.g., counted as results for *Pal*eolimnolog AND vulnerability AND monitor** as well as *Pal*eolimnolog* AND vulnerability AND manag**) but were only counted once in the total of unique papers. The 5 most popular key words used throughout the 52 articles were "paleolimnology", "lakes", "diatoms", "climate change", and "Holocene" (Figure 2.1). Fourty-four of the 52 articles, just over 84%, were published in the last decade (between 2011 and 2020).

Table 2.1. Search results for selected key words and different databases for published articles about paleolimnology and environmental vulnerability. A total of 52 unique articles are included in this table.

Words (*"Paleolimnolog* OR Palaeolimnolog*"* used in PubMed searches)	**Web of Science**	**Scopus**	**PubMed**
*Pal*eolimnolog* AND vulnerability*	16	19	15
*Pal*eolimnolog* AND vulnerability AND monitor**	3	5	2
*Pal*eolimnolog* AND vulnerability AND manag**	6	8	5
*Pal*eolimnolog* AND vulnerability AND conserv**	0	1	4
*Pal*eolimnolog* AND vulnerability AND restor**	3	2	1
*Pal*eolimnolog* AND ecological integrity*	9	9	6
*Pal*eolimnolog* AND ecological integrity AND manag**	2	3	2

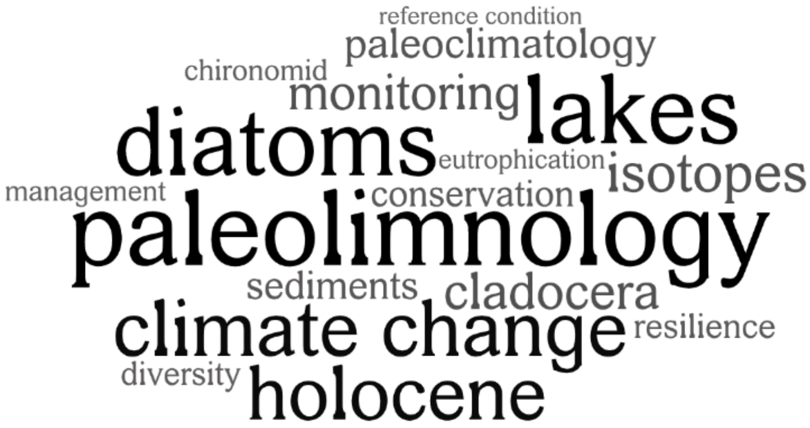


Figure 2.1. Most commonly used keywords utilized out of the 52 selected articles. The size of the word is proportional to how frequent the word was listed as a keyword in the articles, "paleolimnology" being the most frequent at 20 uses and "reference condition" at 2 uses.

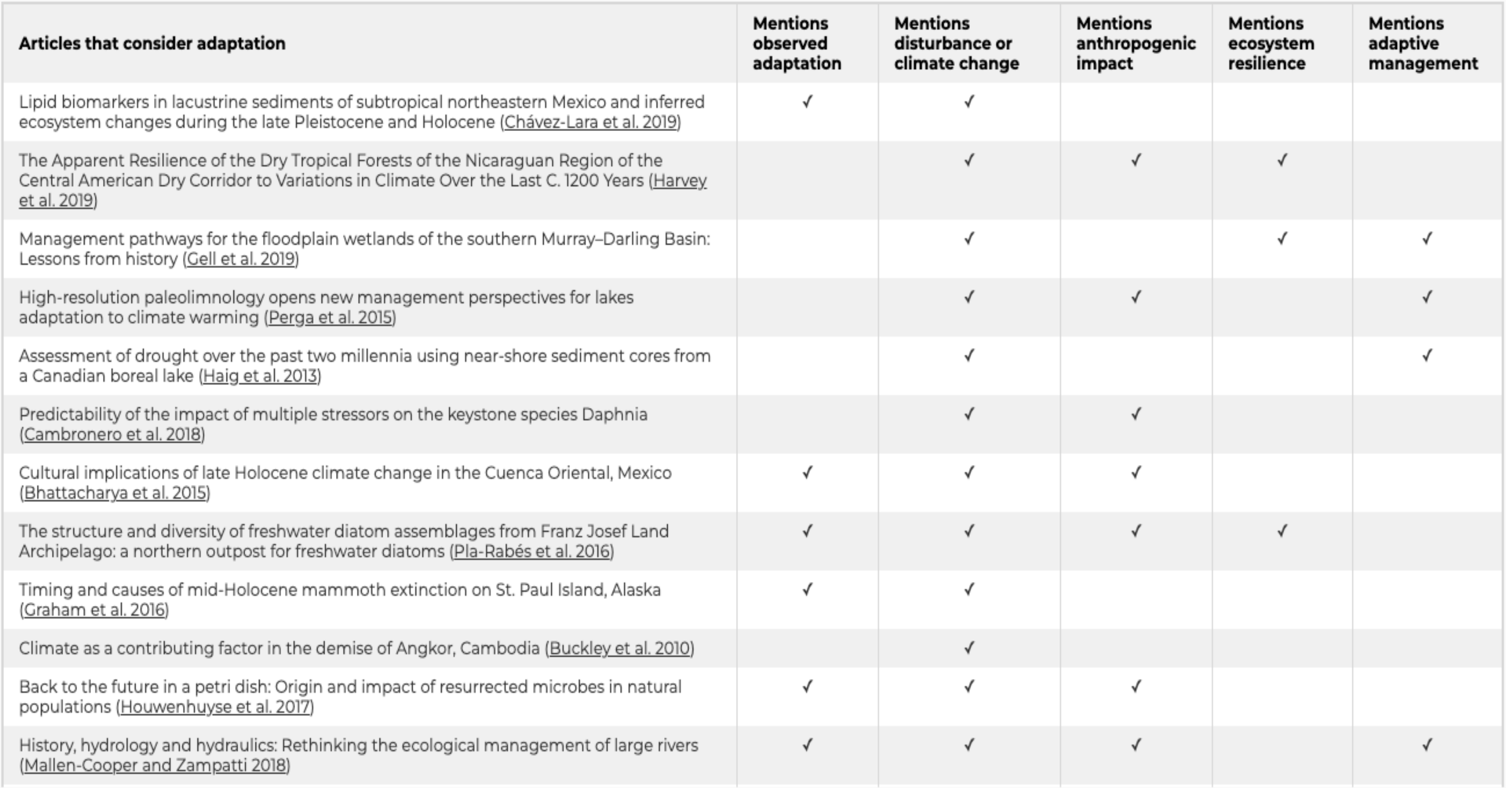
2.5.1 To what extent is capacity covered in the paleolimnology and vulnerability literature?

Out of the 52 unique articles that meet our inclusion criteria, only three articles utilized the term "capacity" within the context of vulnerability; the articles were found to specifically discuss an ecosystem's capacity for change (Buckley et al. 2010; Mallen-Cooper and Zampatti 2018), and (or) capacity for disturbance (Buckley et al. 2010; Harvey et al. 2019), which are all elements of ecosystem sensitivity and vulnerability. These three papers also include the key word "management" (Figure 2.1).

2.5.2 To what extent is adaptation covered in the paleolimnology and vulnerability literature?

Out of the 52 articles, 15 were found that consider adaptation in a vulnerability context, all of which also discuss disturbance or climate change (Table 2.2). Out of these 15, just over 73%, were published in 2015 or later (Figure 2.2A). Sixteen of the 52 studies took place in North America (approx. 31%), and five of these consider adaptation. Eighteen of the 52 studies took place in Europe (approx. 35%), and four of these consider adaptation. There are no visible trends between the studies that consider adaptation and the location of the study (Figure 2.2B).

Table 2.2. A summary of articles in the paleolimnology + vulnerability search that consider adaptation, and whether it is mentioned in the context of adaptation observed in the study, disturbance or climate change, anthropogenic impact, ecosystem resilience, or adaptive management.



Articles that consider adaptation	Mentions observed adaptation	Mentions disturbance or climate change	Mentions anthropogenic impact	Mentions ecosystem resilience	Mentions adaptive management
Lipid biomarkers in lacustrine sediments of subtropical northeastern Mexico and inferred ecosystem changes during the late Pleistocene and Holocene (Chávez-Lara et al. 2019)	✓	✓			
The Apparent Resilience of the Dry Tropical Forests of the Nicaraguan Region of the Central American Dry Corridor to Variations in Climate Over the Last C. 1200 Years (Harvey et al. 2019)		✓	✓	✓	
Management pathways for the floodplain wetlands of the southern Murray–Darling Basin: Lessons from history (Gell et al. 2019)		✓		✓	✓
High-resolution paleolimnology opens new management perspectives for lakes adaptation to climate warming (Perga et al. 2015)		✓	✓		✓
Assessment of drought over the past two millennia using near-shore sediment cores from a Canadian boreal lake (Haig et al. 2013)		✓			✓
Predictability of the impact of multiple stressors on the keystone species Daphnia (Cambronero et al. 2018)		✓	✓		
Cultural implications of late Holocene climate change in the Cuenca Oriental, Mexico (Bhattacharya et al. 2015)	✓	✓	✓		
The structure and diversity of freshwater diatom assemblages from Franz Josef Land Archipelago: a northern outpost for freshwater diatoms (Pla-Rabés et al. 2016)	✓	✓	✓	✓	
Timing and causes of mid-Holocene mammoth extinction on St. Paul Island, Alaska (Graham et al. 2016)	✓	✓			
Climate as a contributing factor in the demise of Angkor, Cambodia (Buckley et al. 2010)		✓			
Back to the future in a petri dish: Origin and impact of resurrected microbes in natural populations (Houwenhuyse et al. 2017)	✓	✓	✓		
History, hydrology and hydraulics: Rethinking the ecological management of large rivers (Mallen-Cooper and Zampatti 2018)	✓	✓	✓		✓

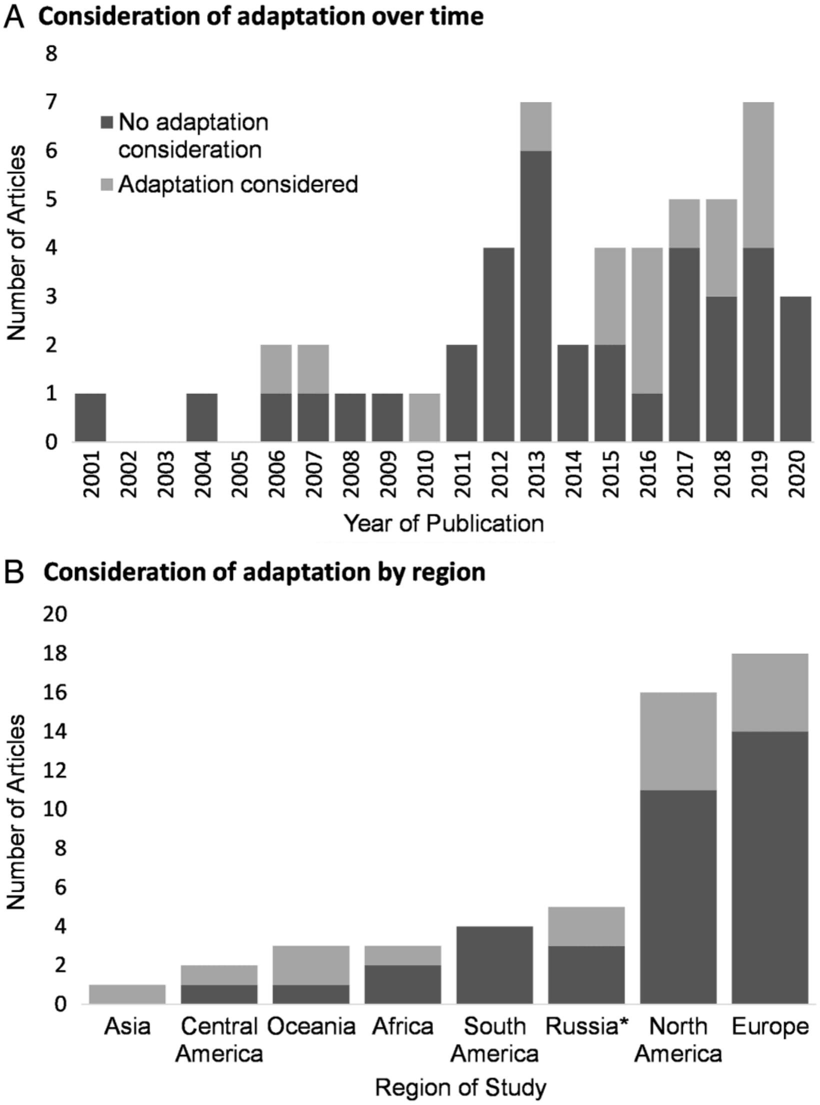


Figure 2.2. Consideration of adaptation in articles by (A) time; and (B) region, within the selection of paleolimnology + vulnerability articles that meet the criteria.
*Russia is considered a part of both Europe and Asia.

2.6 Discussion

The terms adaptation and capacity are both discussed when defining the concept of vulnerability, and are often used to describe its magnitude in interchangeable ways (Adger 2006; Plummer et al. 2012). Capacity can define the ability of an ecosystem to cope with or adapt to circumstances that make it vulnerable (Füssel and Klein 2006), and absence of the capacity to adapt in an ecosystem can also lead to vulnerability, making adaptation vital to achieve ecosystem recovery whether that is natural or managed (Adger 2006). In our systematic mapping process, adaptation was found to be used much more frequently than capacity. All of the articles identified in our search that contained a discussion of the concept of adaptation referenced it in the context of disturbance(s) or climate change (Table 2.2). This is intuitive as methods in paleolimnology are often used to analyze environmental change and (or) environmental disturbance (Burge et al. 2017). Only 18 articles considered either adaptation or capacity in a vulnerability context. Although the low number of papers published that consider these could be due to a variation in key words, it is more likely that these contexts are only recently being investigated with approaches that use paleolimnology. There is a significant increase in papers that use the terms "paleolimnology" and "vulnerability" after 2010, and the majority of the studies took place in either North America or Europe. We can infer that the use of paleolimnology in the context of discussions of vulnerability is an emerging field, with over 30% of articles in this search having been published in the last 3 years (2018 to July 2020). The terms used for this literature search offered insight into some of the different ways paleolimnology can be applied to assess vulnerability. Here, we discuss the role of paleolimnology in vulnerability assessment as well as four subtopics (ecological integrity, reference conditions and ecosystem monitoring, establishing management goals, and creating targets for ecosystem restoration) that display the validity of paleolimnological application. To keep discussion concise and to avoid repetition, only select articles from the review are integrated.

2.6.1 The role of paleolimnology in vulnerability assessment

The concept of vulnerability is a highly important factor to consider in regards to ecosystem health. Environmental vulnerability specifically analyzes the susceptibility to harm, or the adaptive capacity of, an ecosystem (Adger 2006) and the threshold for change (Luers 2005). Climate change represents a multi-scalar environmental threat, and escalating impacts are heterogeneous across different biomes (NASA 2019). Therefore, ecosystems cannot always be generalized with the use of large-scale assessments and often need to be understood on an individual level. This makes site-specific vulnerability assessments crucial to understanding ecosystem responses and vulnerability on a case-by-case basis. For example, lakes can be treated for the causes of eutrophication (e.g., nutrients), but some eutrophic lakes experience more severe impacts than others (Perga et al. 2015) and must be treated accordingly. Understanding site-specific vulnerability will address the particular needs of the ecosystem such as nutrient control or hydrological regulation, which can lead to defining the best management practices to implement.

Paleolimnology can unlock details of prior ecosystem state and function (Walker et al. 1991) as well as the stressor itself (Korosi et al. 2013) by establishing baseline and trends that can date back hundreds or thousands of years (Smol 1992). As such, paleolimnology can expand the available timeframe and establish the basis for monitoring whereby the scope of current conditions can be compared with historic patterns (Reavie et al. 2006). Sedimentary profiles can provide water quality data as well as harbour physical, chemical, and biological indicators preserved in the sediment that allow for the interpretation of environmental changes (Walker et al. 1991). Some of these include subfossil remains of dipteran aquatic larvae (e.g., chironomids) and siliceous algae (diatoms), as these remains can signify climatic factors that drove their abundance in their specific timeframe (Smol 1992). Observing changes in these compositions across a lake sediment profile can delineate environmental changes such as temperature (e.g. Barley et al. 2006; Korosi et al. 2013; Langdon et al. 2008; McKeown and Potito 2016), nutrient availability (e.g. Logan et al. 2011; Reavie et al. 2006), and disturbances (e.g. Brenner et al. 1993; Quinlan et al. 2008) over time. The analysis of these variables can generate quantitative reconstructions of past climate patterns, define reference conditions of the natural state prior to a disturbance (Norberg et al. 2008), and distinguish the differences between natural variability in the ecosystem's trajectory from forced changes influenced by external factors (Sullivan and Charles 1994). Policy development concerning the impacts of climate change could greatly benefit from ecosystem vulnerability assessments that include paleolimnology (Füssel and Klein 2006). Indeed, implementing effective management protocols for monitoring can be based on a baseline assessment using paleolimnological methods (Figure 2.3). Paleolimnology's ability to conceptualize the historical impacts of environmental change on independent proxies of an ecosystem as well as project patterns of future change helps create an understanding of an ecosystem's susceptibility and ability to withstand change and, as a result, its vulnerability. This also means that the concepts that contribute to and help understand vulnerability are fundamentally connected to the concepts that play a role in lake health (Figure 2.4).

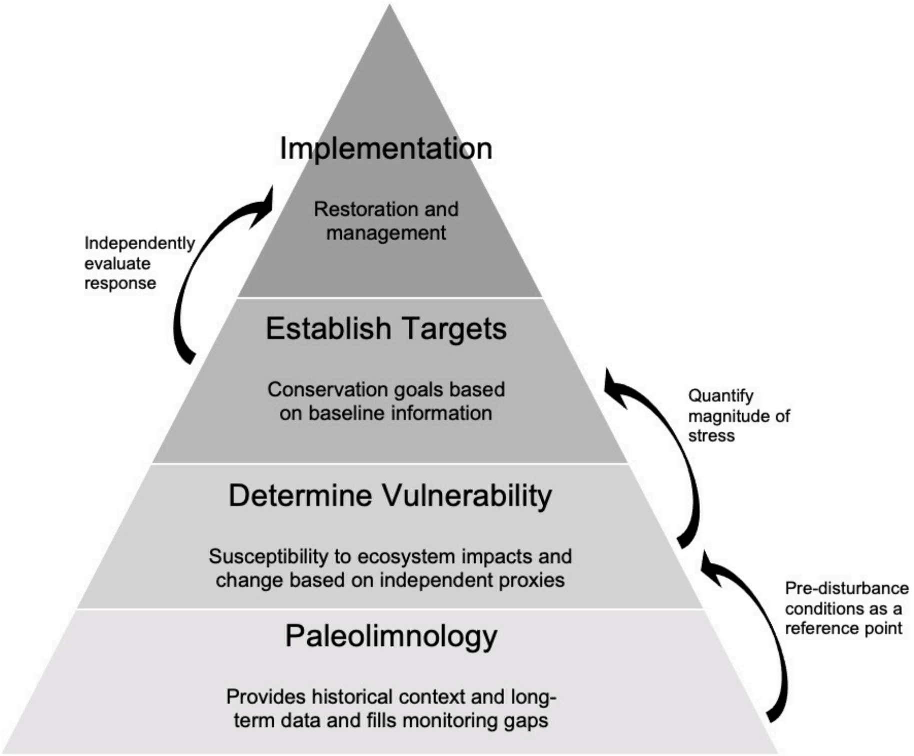


Figure 2.3. Paleolimnological data act as a base for understanding long-term ecosystem change and quantify the magnitude of stressors by evaluating the response using either independent proxy or record. This makes it an important first step in the process of implementing goals and plans to achieve desirable ecosystem conditions.

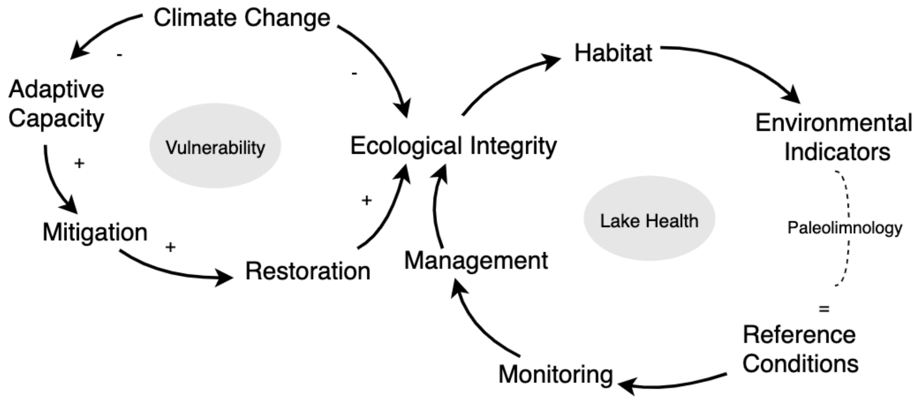


Figure 2.4. A Causal Loop diagram connecting the concepts discussed in this review paper. “+” indicates a positive effect, ″-″ indicates a negative effect.

2.6.2 Ecological integrity

The components of an ecosystem that are impacted by vulnerability include adaptive capacity, the ability to maintain ecological function, and diversity (Smit and Wandel 2006), which are all elements that make up the concept of ecological integrity (Karr and Dudley 1981). Paleolimnology has historically been used to offer insights into the trajectory of an ecosystem (Smol 1992), helping outline historical changes in community and maintenance of ecosystem function (Gregory-Eaves and Beisner 2011), integral to determining ecological integrity. Although integrity is considered a subjective concept (Wicklum and Davies 1995), it is helpful for determining susceptibility to environmental change (Luers 2005). Eggermont and Verschuren (2007) used an approach that considered ecological integrity to reconstruct changes in productivity due to glacial retreat. They concluded that paleolimnology could be useful for evaluating changes in ecological integrity and anthropogenic climate change (Eggermont and Verschuren 2007). Mallen-Cooper and Zampatti (2018) evaluated the ecological integrity of the Murray River in Australia using paleolimnological evidence to understand changes in hydrology on the site. Knowledge of historical conditions reconstructed through paleolimnological evidence was combined with models that incorporated spatial, temporal, and hydrodynamic information to project future changes and improve management plans for the site (Mallen-Cooper and Zampatti 2018) outlining the value of defining ecological integrity.

Ecological vulnerability assessment can help better understand the various factors that impact ecological integrity, and therefore understanding vulnerability can help decision-makers make informed choices regarding environmental management (He et al. 2018). Identifying areas of vulnerability and disturbance can point towards the stressors themselves, which can impact lake management decisions and goals to mitigate problems effectually (Brenner et al. 1993). For example, excess phosphorus in an aquatic ecosystem acts as the disturbance agent and agricultural runoff can act as the source, resulting in decisions to reduce runoff. The detailed reconstructions offered through monitoring and supplementary paleolimnological data can clearly define ecosystem vulnerability (Smol 1992), providing the stepping stone towards establishing environmental management goals (Luers 2005). A broad scope of natural variability over time is the best way to understand the natural trajectory of change and state at which the ecosystem functions best, which will undoubtedly determine the improvements needed and enhance ecological integrity. This can help avoid uninformed, short-sighted decisions that can result in irreversible mistakes with unintended consequences (Frissell and Bayles 1996).

2.6.3 Reference conditions and ecosystem monitoring

Monitoring often precedes decisions about conservation, restoration, remediation, or other management implementation because it can lead to a clear understanding of change over time (Vos et al. 2000). Regular monitoring does not usually occur over a long enough time period to provide reference (pre-disturbance) conditions so paleolimnological practices are utilized to supplement gaps in long-term monitoring data (Norberg et al. 2008). Logan et al. (2011) used paleolimnology to assess nutrient statuses of rivers in Australia to compensate for the lack of long-term data. This study analyzed diatoms and stable isotopes from cores and was able to show fluctuations in normally-oligotrophic estuaries that are now becoming increasingly eutrophic likely as a result of changing climate. Lami et al. (2010) compared paleolimnological data with monitoring data available from annual limnological surveys. The paleolimnological data were able to demonstrate ecosystem responses to changing climate over time through varying algal assemblages and productivity over the last 3500 years, as well as complement the known variations in the Himalayas from the available long-term data. Paleolimnological data can also help differentiate driving forces in aquatic ecosystem changes, such as where Summers et al. (2016) determined if the observed changes in lake productivity were climate change driven or industry driven in lakes near the Athabasca oil sands region. The study found that these specific changes were driven by climate warming, showing that paleolimnology can be used to differentiate impacts from simultaneous disturbances and fill gaps in monitoring information. These studies validate the efficacy of paleolimnological-based data as supplemental monitoring.

Human activity plays a unique role in ecosystem function, driving changes outside the natural range of variability (Battarbee and Bennion 2011) which can cause distortion and vulnerability in an ecosystem (McKeown and Potito 2016; Norberg et al. 2008). While paleolimnological records can often detect these changes to ecosystems, it is not always easy to distinguish anthropogenic-driven disturbances from natural or random variability (Bennion et al. 2011). Langdon et al. (2004) found that chironomid-based paleolimnology has proven useful for detecting land-use changes and other anthropogenic-driven ecosystem alterations that can affect sediments and chemistry of the aquatic system. Humans were found to have interacted with the site through land-use disturbances, such as deforestation, inducing vulnerability. Langdon et al. (2004) also found that Holocene-era temperatures can be reconstructed in the absence of anthropogenic disturbance interfering with the record.

An important part of quantifying vulnerability is having reliable variables to measure and compare conditions. Change over time could not be detected as easily without dependable indicators (Gorham et al. 2001), making indicators key for reliable monitoring. Paleoecological indicators include preserved physical, chemical, and biological information in aquatic sediment such as pollen (e.g., Langdon et al. 2004), diatoms (e.g., Chraïbi and Fritz 2020; Pienitz et al. 1999; Quinlan et al. 2008), *Daphnia* (e.g., Azan and Arnott 2017), and *Chironomidae* (e.g., Langdon et al. 2008; Massaferro and Corley 1998; McKeown and Potito 2016), that have all been used as reliable monitoring proxies (Gorham et al. 2001). For example, food web structural variations can be indicated by diatoms, since their different environmental tolerances allow them to be responsive to change (Sculley et al. 2017). Diatom assemblages have also proven useful in Pienitz et al. (1999) as quantitative indicators of environmental change in northern treeline lakes. Pienitz et al. (1999) determined that the historic limnologic changes do correlate with the regional treeline advancement and retreat, as well as add further evidence that climate warming impacts are exacerbated in high latitude aquatic ecosystems. This was also stressed by Smol (2005), as the lack of monitoring data available as well as the intensified climate change impacts in the Arctic further stress the need for reference conditions and importance of paleolimnological studies in these regions. While we know that anthropogenic stressors exist and are placing high stress on ecosystems, it is impossible to understand the extent and urgency for action without a full scope of the historical changes and the time scale on which they occur (Quinlan et al. 2008). With an expanded timeframe available to create climate reconstructions, paleolimnology can project future changes and determine ecosystem vulnerability, setting up for successful management planning.

2.6.4 Establishing management goals

Land management strategies can be necessary to avoid ecosystem destruction or loss, and thorough understanding of the ecosystem and the components facing the biggest risk are needed to inform these decisions (Lee et al. 2018). Natural resources have irreplaceable value and management of these resources can help maintain their health. In addition to environmental significance, reduced quality of resources such as freshwater can have many economic and social consequences, for example pressure on fisheries could impact the economy and the communities that rely on it as well as the general balance of the ecosystem itself (Korosi et al. 2013), providing more incentive for management strategies to be implemented. Frissell and Bayles (1996) emphasized that every person would benefit from resource management and conservation, and that it is not an ecosystem problem that we are facing, but a management problem. Paleolimnology is one tool that can help improve the establishment of management needs and eventual implementation and practice.

Perga et al. (2015) concluded that vulnerability to climate warming varied among different lakes, and these impacts may be minimized with local management strategies to address the lake's specific needs such as nutrient input, fishery management, or hydrological regulations, that will help promote ecosystem services at each site. Smeltzer and Swain (1985) determined that paleolimnology provided valuable help developing management plans for two Vermont lakes, determining the phytoplankton dominance to be anthropogenically induced, therefore needing restoration. Additionally, filling gaps in the knowledge of long-term data can prevent making assumptions that lake conditions are caused by human interference. Reavie et al. (2006) studied cultural eutrophication in three Southern Ontario lakes using paleolimnology to understand the extent of degradation that has occurred, and they found that one of the lakes was historically more eutrophic and demonstrated naturally higher nutrients and hypolimnetic anoxic conditions prior to human impact. Therefore, the current state of the lake is not a big concern because the conditions are not very different from its natural past, removing the need for management of these conditions. Vermaire et al. (2013) emphasized the necessity of proper management to protect northern communities and the ecosystems they rely on from storm activity increasing due to climate change.

Paleolimnology can also offer information regarding species and biodiversity changes, offering unique perspectives of drivers of change over time leading to management propositions (Gregory-Eaves and Beisner 2011). Recovering historical data can answer questions about species ranges and habitats, such as in the case of the yellow perch (*Perca flavescens*) by Stager et al. (2015). Although it was believed to have been an invasive species in lakes of northern New York state, DNA preserved in paleolimnological record showed that the yellow perch is actually a native species, appearing in the sedimentary record of the region for over the past two millennia which changed the conservation strategies for these lakes. Similarly, nitrogen isotopes were used as indicators by Finney et al. (2000), to represent changes in sockeye salmon abundance over the last 300 years, showing that changes in climate have impacted salmon returns and therefore lake productivity from salmon carcass nutrient input. This highlights the importance for salmon stock management for this multi-value species. Thus, productive management practices can be put in place with the help of the enhanced understanding of ecosystem needs provided by paleolimnological methods and quantified vulnerability.

2.6.5 Creating targets for ecosystem restoration

The current linkages between paleo-based science and conservation are weak in both literature and practice (Birks 2012). Restoration ecology aims to return the ecosystem to the state in which it operates best, which is often considered "predisturbance" or as the state prior to cultural interference (Bennion et al. 2011). To restore to a previous state, the structure and function of the predisturbance state must be understood to make sure the targets are both desirable and achievable in the context of an ecosystem's natural trajectory (Roberts et al. 2019). When long-term data are missing, paleolimnological data can help define the predisturbance reference conditions that can act as targets for restoration attempts (Brenner et al. 1993), which can help lead to successful aquatic ecosystem management and restoration (Roberts et al. 2019). Reference conditions provide the standard of the ecosystem state without human-driven changes, as well as offer knowledge of past ecosystem functions. This helps create evidence-based goals for restoration as well as an idea of potential responses to management (Roberts et al. 2019), making paleolimnology a valuable asset for restoration plans.

Paleolimnology can be utilized for establishing restoration targets that revolve around the concept of aiming for desirable, pre-disturbance conditions. Brenner et al. (1993) used paleolimnological methods to define predisturbance conditions for lakes in Florida to set restoration targets for nutrient and Chl *a* levels, and apply these targets towards successful restoration of the sites. Norberg et al. (2008) required the use of paleolimnological monitoring data to explain the cause and extent of lake acidification, and whether it is natural or human-induced, as monitoring data are needed to implement appropriate liming restoration efforts. This supplemented missing long-term monitoring data and provided evidence of pre-acidic conditions that acted as targets for restoring the lakes (Norberg et al. 2008). Gell et al. (2019) also used paleolimnology to determine how resilient a floodplain was prior to human disturbance for restoration goals the Murray-Darling Basin (Southeastern Australia). However, many factors were found that also contributed to the initial degradation of the ecosystem, including natural changes. This highlights the importance of not only establishing restoration goals, but understanding the multi-faceted mechanism of change through inferences of multiple responsive parameters.

One of the major obstacles with restoration is some environmental changes are difficult to reverse. Bennion et al. (2011) concluded that when defining restoration targets through reference conditions, it is important to consider the other ecosystem changes that may have occurred between the time of the desired ecosystem state and the current state. Therefore, reference conditions defined by paleolimnology should be considered a "benchmark" rather than a target to leave room for improved conclusion of ecosystem structure (Bennion et al. 2011). Yasuhara et al. (2012) completed a meta-analysis to demonstrate that few sites return to the pre-degraded state from the degraded state, and even fewer experience full recovery. Yasuhara et al. (2012) also noted the challenge that the pre-disturbance or pre-industrial trajectories have higher diversity, making returning to the pre-disturbance state more difficult. For the cases that do experience recovery, it always occurs after initiation of restoration efforts and environmental regulations, proving the value of implementing these actions (Yasuhara et al. 2012). Though full ecosystem restoration is difficult to achieve, paleolimnology can still help work towards ecosystem recovery and reduce overall vulnerability.

2.7 Conclusion

Paleolimnological methods can be a useful tool for reconstructing environmental vulnerability. Our systematic mapping process established that 84 % of articles included were published in the last decade, and just over 30 % of articles in this search were published in the last 3 years at the time of our search. This seems to indicate that including paleolimnology in the discussion of vulnerability is an emerging topic, and it is proven in the literature to have a valid role in the reconstruction of ecosystem vulnerability because of its capacity to broaden the scope of long-term monitoring, as well as its potential for helping establish management and restoration goals.

The multi-faceted science is an integral priming step for establishing reference conditions so that decision-makers can move forward with management plans and conservation goals. However, Gillson and Marchant (2014) showed that paleolimnological tools and data lack a transparency and are not always applicable or user-friendly for stakeholders or policy-makers, preventing it from being used more commonly in conservation sciences. Even when considering conservation or restoration practices, it is not stable or realistic to plan to prevent disturbance from occurring in a dynamic system. Therefore, full understanding of a system requires integrating available facets of information in a multiscalar perspective such as historical ecology, long-term monitoring, etc., in combination with paleolimnology (Gillson and Marchant 2014). Steps to manage vulnerability need to be well informed, and paleolimnology should be applied often in studies due to the range of perspective it can offer. Full knowledge of the ecosystem gained through paleolimnology can be a key factor in establishing management, but it can only be effective if it is implemented successfully and maintained over time (Frissell and Bayles 1996).

Ecosystem monitoring can also be improved by conceptualizing environmental change that has occurred over time as well as creating benchmarks that help with implementing ecosystem management and restoration efforts. Paleolimnology can define susceptibility and thresholds for change and, as a result, its vulnerability. Understanding the insight that paleolimnology can provide for ecosystem vulnerability can promote its value and place in ecosystem decision-making. Based on our research and the literature we have reviewed, we believe that paleolimnological practice has a rightful place in analyzing vulnerability and ecological integrity.

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CHAPTER 3: A PALEOLIMNOLOGICAL PERSPECTIVE OF ECOLOGICAL VULNERABILITY AND MANAGEMENT OF FRESHWATER ECOSYSTEMS OF SABLE ISLAND NATIONAL PARK RESERVE, CANADA

3.1 Statement of Student Contribution

Study design by Victoria Watson and Andrew Medeiros, limnological data collection by Victoria Watson, Andrew Medeiros, Frederica Jacks, Michael Bakaic, and Kathleen Hipwell, chapter writing by Victoria Watson with editorial contributions by Andrew Medeiros and Dan Kehler.

3.2 Abstract

Protected areas require long-term monitoring data to understand the influence and extent of ecosystem stress to inform management and conservation decisions. As long-term data are not always available, paleolimnological methods offer a way of extending our knowledge of past environmental conditions necessary to use as context for remediation. Here, we examine two ponds located on Sable Island National Park Reserve Canada (SINPR), where long-term ecological changes and vulnerability to disturbance are not well defined. We demonstrate a paleolimnological approach to assessing environmental vulnerability through the use of biological indicators (Insecta: Diptera: Chironomidae), where shifts in the chironomid communities over time are linked to changes in the terrestrial catchment. Analysis of surface sediments from 12 other ponds showed four

distinct clusters; these were characterized by presence of *Glyptotendipes, Chironomus, Microtendipes*, and *Dicrotendipes;* each primarily reflecting four different habitat types. Biostratigraphic analysis of sediment cores show the effects of nutrient loading, erosion, and changes to terrestrial vegetation based on indicator taxa where the biological assemblages of each pond experienced a shift in taxa dominance, reflecting changes in the habitat. Ecological stress caused by a large, unmanaged, feral horse population as well as natural and forced morphological change are likely primary causes. Our findings established a baseline of historical change in SINPR, broadening the scope of long-term monitoring, which is essential for defining goals for management and conservation of the ecological integrity of Sable Island.

3.3 Introduction

A common challenge for effective ecosystem management is sufficient long-term historical data to establish context and understand natural variability over time. Vulnerability can be defined as a function of risk, resilience, exposure, sensitivity, and adaptive capacity of a system (Ford et al. 2007; Aven 2010), but is difficult to quantify. Quantifying stress, or vulnerability, may be necessary for management planning and avoiding irreversible destruction to an ecosystem (Lee et al. 2018), but requires indicators of long-term change to understand these responses. Paleolimnology is a science that uses proxies preserved in lacustrine sediments to study the historic and prehistoric context of an ecosystem (Smol 1992). This expands the scope of monitoring and quantifies susceptibility to change in freshwater ecosystems, inherently reconstructing ecosystem vulnerability and contextualizing needs for management and conservation (Watson and

Medeiros 2021). Establishing these pre-disturbance or reference conditions of an ecosystem can create evidence-based goals that may help inform restoration (Roberts et al. 2019), a step towards rebuilding ecological integrity (Karr and Dudley 1981).

Closed freshwater systems are valuable sentinels for change due to their unique ability to collect and chronologically preserve surrounding ecological information (Williamson et al. 2009; Saulnier-Talbot 2016). The impacts of stress can often have cascading effects on aquatic biota, especially in responsive groups, such as Chironomidae (chironomids). Chironomids are sensitive to changes in environmental conditions (Walker and Cwynar 2006; Quinlan et al. 2008), and their assemblages are driven by environmental factors such as temperature, productivity, and landscape changes (Walker 2001; Barley et al. 2006; Medeiros and Quinlan 2011). Therefore, they are useful biological indicators of the environmental conditions that influence their abundance during their aquatic lifecycle (Smol 1992). Reconstructing past conditions can distinguish differences between an ecosystem's natural variability (unforced) and major climate-driven changes (forced) (Sullivan and Charles 1994); this leads to an understanding of the parameters impacting ecological integrity, which describes the extent that an ecosystem's diversity and function is comparable to similar local natural ecosystems as well as its ability to support its own ecological processes (Karr and Dudley 1981). Furthermore, targets for ecosystem restoration can be created based on insight provided by defining long-term changes and natural ecosystem trajectory (Brenner et al. 1993), having major implications for making informed management decisions (He et al. 2018; Watson and Medeiros 2021).

Informed management is essential for protected areas, which are established with the intent of long-term conservation of the services, values, and state of the system (IUCN

2008). Sable Island National Park Reserve (SINPR) is a 30 km^2 emergent sandbar 49 km long and a maximum of 1.5 km wide in the Atlantic Ocean (Freedman 2016), and is mandated as a National Park of Canada to maintain the ecological integrity of the island's ecosystem (Howe 2019). Vital for supporting the unique species composition, several freshwater ponds are stressed due to bacterial contamination from feral horse defecation, saltwater intrusion, windblown sand, and fluctuating water volume (Beson 1998; Howe 2019; Eamer et al. 2021). Additionally, the continuity of the fresh groundwater lens that replenishes the ponds is unknown and faces threats of flooding or sea level rise that could move seawater into the source (Cantelon et al. 2019). A bioassessment using aquatic macroinvertebrates recorded 27 taxa in the ponds of SINPR, with the largest diversity of aquatic macroinvertebrates reflected by chironomids (Jacks et al. 2021). As chironomids are well known to offer insights for the environmental conditions in which they operate (Walker 2001), a paleolimnological assessment of changes in their diversity and abundance over time allows for both the establishment of a pre-disturbance context, as well as inferences of responses over time.

Here, we examine pond systems from SINPR to understand the implications of centuries of environmental stress on the island's freshwater ecosystems. Through assessment of subfossil biological indicators from the surface sediments of 14 freshwater systems on SINPR as well as sediment cores from 2 of the 14 ponds, we examine historic ecological trends of the SINPR ponds in order to: (1) identify trends in chironomid indicators over time; (2) infer causes of ecosystem stress; and (3) reconstruct environmental vulnerability to inform management and conservation. We aim to demonstrate paleolimnological assessment of long-term environmental change in freshwater systems to be used to reconstruct vulnerability and responses to stress.

Establishing baseline conditions and the pre-disturbance context of these systems will be integral to helping Parks Canada determine the extent of risk facing the freshwater ecosystems on SINPR, and help define necessary goals for management and preservation of the ecological integrity of the island.

3.4 Study site

Sable Island is 161 km southeast from the nearest point of mainland Nova Scotia (Howe 2019) (Figure 3.1). The north-facing crescent-shaped island is characterized by low rolling sand dunes, sand-loving vegetation, and freshwater ponds (Beson 1998; Howe 2019). Sable Island is the only emergent land near the edge of the continental shelf (Beson 1998), with a highly dynamic form influenced by winds, waves, ocean currents and storms (Muise 2012). Several freshwater ponds across the island are vital to supporting its biodiversity. Many ponds contain macrophyte communities that include pondweed or watermilfoils, and herbaceous communities such as cranberry heath and other low growing species on pond edges (Catling et al. 1984). The vegetation of SINPR is influenced by a moderate climate of cooler growing season temperatures with infrequent frosts (Catling et al. 1984), high winds and sea spray (Porter et al. 2020). Terrestrial vegetation is characterized by sparse grasslands, heath, and marram grass (Catling et al. 1984), with a variety of low growing shrubs such as Black Crowberry (Porter et al. 2020).

A population of genetically distinct feral horses resides on SINPR, descending from settlement and agriculture attempts in the mid-eighteenth century (Christie 1995). With a population that had fluctuated from 250 to over 400, the horses were given legal protection from human interaction in 1960, and have since reached over 500 members (Plante et al. 2007; McCloughlin 2012). In their free roam of the island, the horses are known to degrade the vegetation through stomping and grazing, with the greatest impact on marram grassland communities and causing recession and stunted growth of herbaceous communities (Freedman et al. 2011). Horse influence on the ponds is reflected in increased coliform bacteria (Beson 1998) and macroinvertebrate-indicated high productivity and nutrient influx (Jacks et al. 2021).

We examined 14 ponds on SINPR that are part of an aquatic monitoring program conducted by Parks Canada (Jacks et al. 2021). For each of the 14 ponds (Figure 3.1), we collected a surface sediment sample for analysis. Sediment cores were collected from 2 of the 14 ponds; PD67 and PD03. Commonly named “Gallinule”, PD67 (43.932481 N, -59.900146 W), is the largest standing pond on Sable Island with an area of approximately 3500 m^2. It also has the greatest volume, reaching maximum depth of 1.3 m, and has the largest catchment. Commonly named “Mummichug 1”, Pond PD03 (43.932364 N, -60.026706 W) has an area of approximately 1200 m^2, reaching a maximum depth of 1.7 m but is shallow through much of the pond. Both ponds are characterized by a sandy littoral zone.

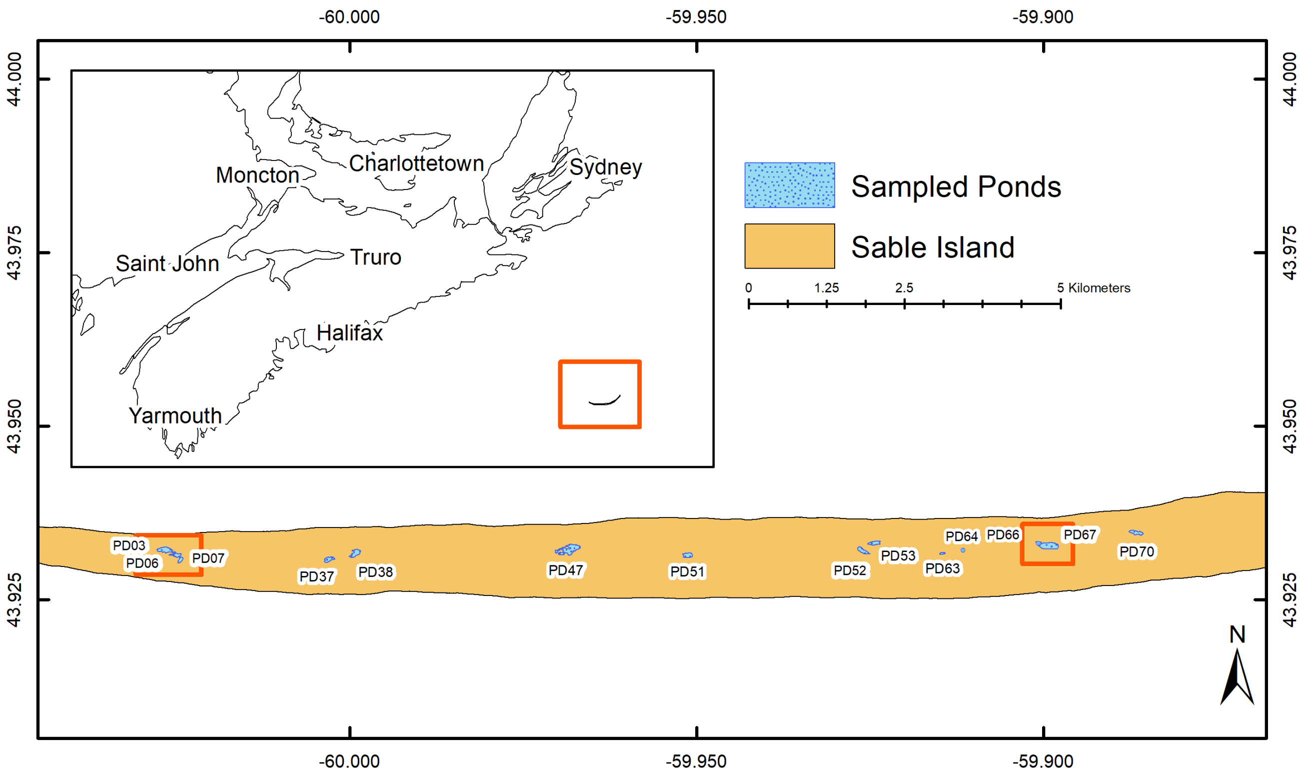

Figure 3.1. Map of Sable Island National Park Reserve and the freshwater ponds used for sampling. Cores were extracted from PD03 and PD67, indicated by the red boxes, and surface samples were collected from all ponds indicated.

3.5 Methods

3.5.1 Field sampling

Water quality parameters were collected between May and October of the years 2015–2020 by Parks Canada Agency. Temperature, dissolved oxygen, conductivity, pH, salinity, and turbidity were measured on site. Pond water samples were tested for major ions, nutrients and metals at the Environment and Climate Change Canada (ECCC) laboratory in Moncton, New Brunswick. An analysis of water quality can be found in the supplemental materials.

During August 2019, an Uwitec gravity coring device (8.4 cm tube diameter) was used to collect two sediment cores from the mid-basin of each lake from an inflatable boat. The PD67 core totalled 15 cm in length, and the PD03 core totalled 26 cm in length. Cores were divided into 0.5 cm intervals in the field, placed in labelled Whirl-Pak® bags, transported in a cooler, and stored at 4 °C for processing. Surface samples were collected from 14 ponds (Supplementary Table S1) by scooping surface sediment from the pond into a labelled Whirl-Pak® bag, then transported in a cooler, and stored at 4 °C for processing.

3.5.2 Laboratory analysis

Chronologies of the PD67 and PD03 cores were established using alpha ^{210}Pb and ^{14}C dating techniques completed at the University of Ottawa. ^{210}Pb spectrometry was completed with the Constant Rate of Supply (CRS) model (Appleby 2001) completed by Chronos Scientific Ltd (formally myCore). ^{14}C radiocarbon calibration was performed using OxCal v4.4 (Bronk Ramsey, 2009) and the IntCal20 calibration curve (Reimer et al, 2020) completed by the University of Ottawa Radiocarbon Laboratory. To determine percent organics and percent carbonates content throughout each core, loss-on-ignition (LOI) analysis (Heiri et al. 2001) was carried out for each 0.5 cm interval.

Sediment samples were processed for subfossil chironomids following standard methods (Walker 2001). The PD67 sediment core was analyzed at every 1.0 cm from the basal sample (15.0 cm), in addition to 1.5, 7.5, and 11.5 cm intervals of the core. The PD03 core was analyzed at 0.5 cm intervals from 0.5 to 6.0 cm, then 1 cm resolution between 7.0 cm and 10.0 cm, then 5 cm resolution between 15.0 cm and 25.0 cm, with additional analysis of 12.0, 17.0, and 22.0 cm. Each sample was treated with potassium hydroxide (KOH) at 75 °C for 30 minutes, with intermittent stirring, to deflocculate the sediment. The residual was then poured through nested sieves of 212 and 106 µm and rinsed with 95 % ethanol.

Subfossil chironomids were sifted and counted for each sample with the use of a dissecting microscope and fine forceps, with at least three rounds of sifting per sample to ensure a 95 % capture rate of all head capsules within the sample. A minimum of 50 head capsules from each interval were collected as per recommended methods (Quinlan and Smol 2001), with the exception of the intervals between 6.5 - 9.5 cm for Pond PD03 due to extremely low abundances. For the other intervals, if less than 50 head capsules were found then more sediment was subsampled until total identifiable remains were greater than 50. The collected specimens were then permanently mounted on glass slides using Entellen® then identified using a Stereo microscope to the lowest possible taxonomic resolution with the use of Oliver and Roussel (1983) and Brooks et al. (2007).

3.5.3 Statistical and numerical methods

Data analysis were completed using R statistical software v.3.6.0 (R Core Team 2019). The abundance of chironomids was calculated as head capsules per gram of dry weight (HC g^{-1} DW) for each interval of PD67 and PD03. Relative abundances were also calculated as the percentage of identifiable chironomids in each sample. Rare taxa, those with total of < 2 % in less than 2 ponds, were removed from analysis. Taxa were represented by their relative abundance, and plotted stratigraphically over depth and time. A hierarchical cluster analysis of the surface samples was completed, where the Ward's D2 method grouped ponds based on minimum variance and squared dissimilarities into clusters as determined by a Mantel-optimal number (Borcard et al. 2018). Significant chironomid indicators that represented each cluster were determined through their indicator value (IndVal; Dufrene and Legendre 1997) using the R package '*labdsv'*. A Principal Component Analysis (PCA) was then used to outline the trends in the chironomid communities of each core over time plotted passively across the chironomid assemblages identified from the surface samples using the function *timetrack* in the R package 'analogue' (Simpson 2007).

3.6 Results

3.6.1 Chronology

The chronology for PD67 (Figure 3.2a) was established based on 22 ^{210}Pb measurements and one ^{14}C bulk sediment sample at the base of the core (15 cm). One additional ^{14}C measurement of a 'modern' result at 10.0cm was discarded. The level of unsupported ^{210}Pb activity decreased from 1.202 to 0.0075 Bq/g between 1.0–12.0 cm; the lowermost three samples were below background. A CRS model was used to estimate the age of each interval from 1 – 11 cm, and linear interpolation, based on the ^{14}C calibrated date of 1772 CE at 15 cm, was used for the intervals from 11.5 – 14 cm.

The chronology for PD03 (Figure 3.2b) was established based on 8 ^{210}Pb measurements. The level of unsupported ^{210}Pb activity decreased from 0.650 Bq/g at 1.0 cm to 0.563 Bq/g at 5.0 cm. An influx of sand content between 5.0 and 10.0 cm caused an unconformity in the unsupported ^{210}Pb activity below 5.0 cm. Two ^{14}C measurements at 20 and 25 cm returned with 'modern' values and were discarded. As such, we used a linear interpolation based on the CRS model for each interval from 10.0 – 25.0 cm, subtracting the sand-interval from the chronology. Each interval from 5.0 – 10.0 cm was assigned a date of 1960, followed by the linear interpolation of dates to the basal section of the core.

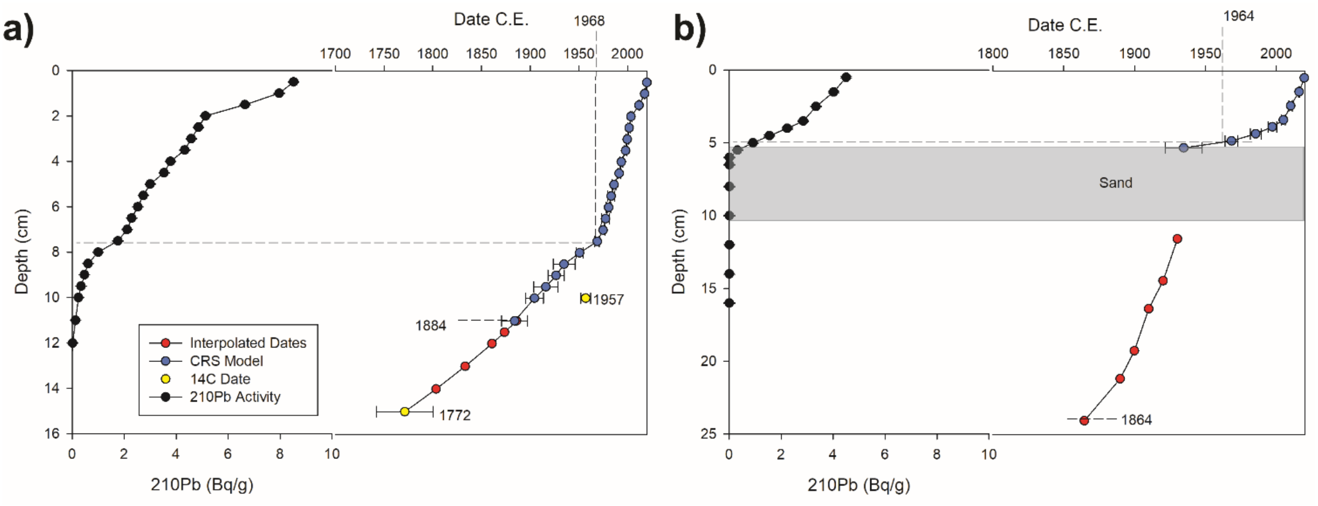

Figure 3.2. Age-depth model for (a) PD67 and (b) PD03 based on ^{210}Pb and ^{14}C-inferred dates and the linear interpolation.

3.6.2 Chironomid assemblages

A total of 1326 chironomid head capsules were enumerated from the lacustrine sediment core of PD67. There were 17 different taxa found in the 18 sampled intervals (head capsules per interval: average = 73.75; and range = 52 – 129.5). PD67 had an average abundance of 43.5 chironomid head capsules per gram of dry weight (HC g^{-1} DW), with a range of 12.3 to 59.3 HC g^{-1} DW throughout the core, and a peak of 150.2 HC g^{-1} DW in 2012 CE. For PD03, a total of 1369 head capsules were enumerated with 26 different taxa found in the 25 sampled intervals (head capsules per interval: average = 59.52; and range = 7 – 106). PD03 had an average abundance of 201.2 HC g^{-1} DW, with a range of < 5 to 502.5 HC g^{-1} DW. Abundances of < 20 HC g^{-1} DW occur between 6 and 10 cm during the sand layer where < 50 head capsules were collected due to extreme low abundance. Prior to the sand intervals (1864 – 1960 CE), maximum productivity was 157.5 HC g^{-1} DW. After the sand intervals, productivity ranged from 148.4 to 502.5 HC g^{-1} DW.

Changes in the ecosystem over time are inferred based on known environmental tolerances of chironomid indicators. The dominant taxa in the sediment record of PD67 are *Microtendipes pedellus*-type*, Glyptotendipes*, *Cricotopus*, and *Paratanytarsus* (Figure 3.3a). *Microtendipes pedellus*-type peaked at 64 % in 1803 CE (14.0 cm), then decreased to < 23 % in 2019 CE (0.5 cm). *Microtendipes pedellus*-type is a wood miner often associated to treeline, and indicates the dominance of shrubs in the terrestrial environment (Walker et al. 1995; Moller Pillor 2009). *Glyptotendipes*, which indicates grazed grasslands, sedimentation, and eutrophication (Campbell et al. 2009; Brodersen et al. 2001), increased from 23 to 52 % between 1772 and 1886 CE (11.0 –15.0 cm), then decreased to 3 % in 2019 CE (0.5 cm). *Paratanytarsus*, which is associated with aquatic vegetation (Buskens 1987; Brodersen et al. 2001; Brooks et al. 2007), increased from 2 to 20 % between 1772 and 2019 CE (0.5 – 15.0 cm), reaching maximum abundance of 34 % in 2012 CE (1.5 cm). *Cricotopus* remained < 7 % between 1772 and 1951 CE (8.0 – 15.0 cm), then increased over time to 40 % by 2019 (0.5 cm). The genus *Cricotopus* is comprised of many taxa; however, they are not easily distinguishable from each other as subfossils. Taxa of the genus *Cricotopus* can indicate several different environmental conditions; for example, *Cricotopus (Isocladius) sylvestris* are found in degraded waters with algae (Oliver and Roussel 1983; Brodersen et al. 2001), *Cricotopus (Cricotopus) cylindraceus* have been associated with agricultural activities (McKeown and Potito 2016), small eutrophic lakes (Janecek 1995), and macrophytes (Tarkowska-Kukuryk and Toporowska 2021), and *Cricotopus (Cricotopus) elegans* are associated with aquatic *Potamogeton* (Berg 1950; Boesel 1983). Based on our morphological identifications, we feel these three taxa are likely those found within the sediment record, but we cannot distinguish between them reliably as subfossils in the samples from Sable Island as many of the head capsules for this genus appear worn and are similar in their morphological characteristics.

The dominant taxa in PD03 are *Cricotopus*, *Glyptotendipes*, *Chironomus*, and *Microtendipes pedellus*-type (Figure 3.3b). Abundances of *Cricotopus* increased from 18 to 41 % between the base of the core and the sand interval (25 – 10 cm), and then increased to its maximum abundance of 57 % ~1964 CE (5.0 cm). *Glyptotendipes* and *Microtendipes pedellus*-type reached maximum abundances of 28 % in 1900 CE (20.0 cm) and 20 % in 1920 CE (15.0 cm), respectively. Between 1930 and 2019 CE (0.5–12.0 cm), *Glyptotendipes* ranges from 5 to 15 % and *Microtendipes pedellus*-type remained < 6 %. Abundances of *Chironomus*, which is often associated with productive conditions (Brooks et al. 2007), decreased from 15 to 3 % between 1772 and 2019 CE (0.5–25 cm). We note that *Chironomus anthracinus*-type decreased from 4 % from the base of the record to 1920 CE to < 1 % for the remainder of the record. Abundances of *Chironomus plumosus*-type, an indicator of eutrophication (Quinlan and Smol 2001), also decreased from 10 % at 15 cm (1920 CE) to sporadically present at 0 - 5 % for the remainder of the record. In contrast, *Dicrotendipes*, which is associated with littoral areas and mesotrophic conditions (Brodin 1986; Brodersen et al. 2001), were abundant only in the basal interval (31 % in 1864 CE at 25.0 cm), then remained < 8 % for the remainder of the record.

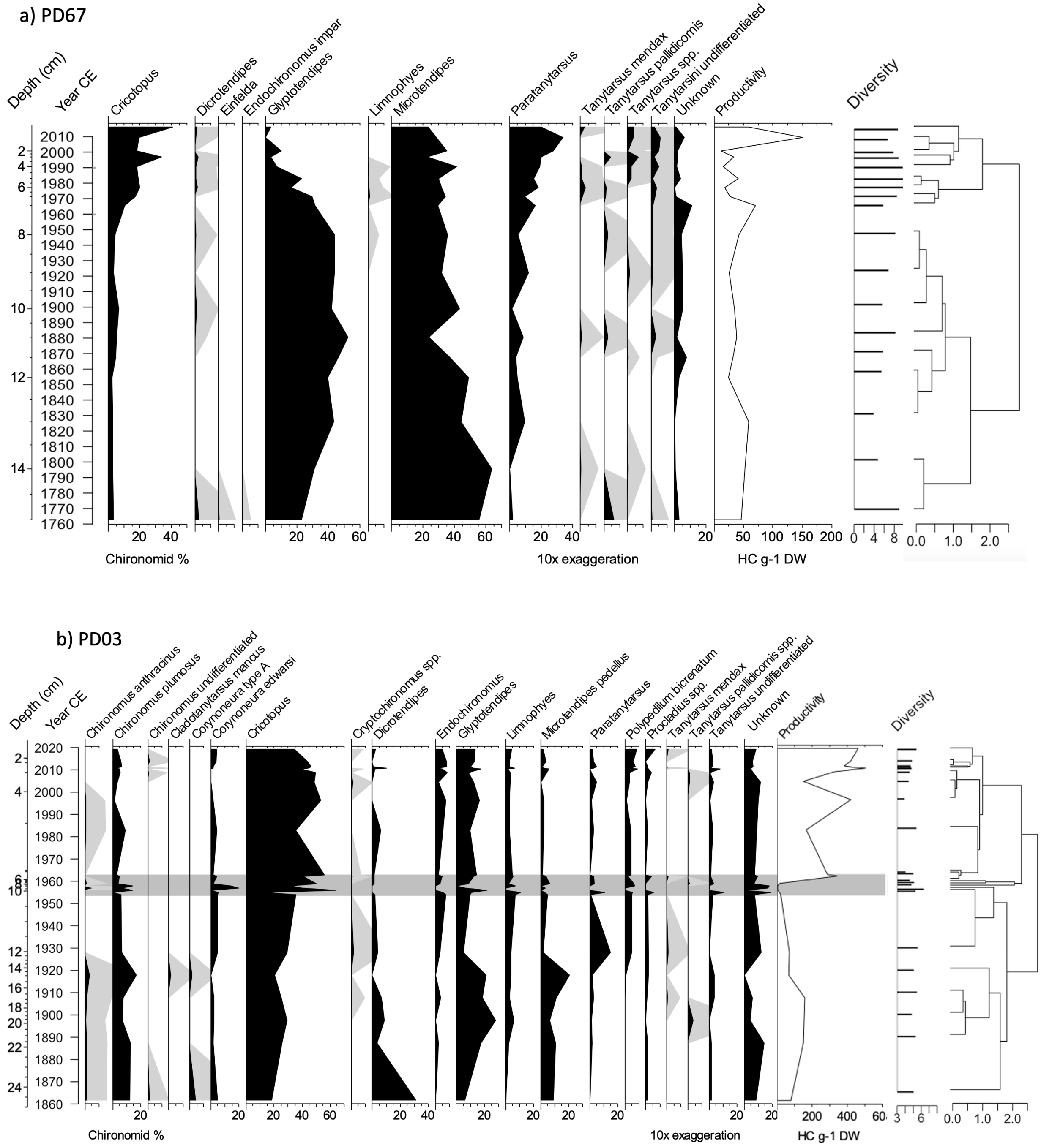

Figure 3.3. Biostratigraphy of chironomid relative abundance (%) in cores (a) Pond PD67 and (b) PD03 plotted over depth and time. The light grey represents a 10x exaggeration of low abundances for increased visibility. Sand intervals in PD03 are indicated by horizontal grey bar. CONISS zonation represented by the clustering on the right.

More than 1200 subfossil head capsules were extracted from the 14 surface samples, with an average of 91 head capsules (range = 54.5 - 143.5). The most abundant taxa were *Microtendipes pedellus* (17.85 %), *Paratanytarsus* (16.8 %), *Tanytarsus* (13.86 %), *Cricotopus* (11.28 %), *Dicrotendipes* (10.34 %), *Glyptotendipes* (8.73 %), and *Chironomus* (7.83 %). A hierarchical cluster analysis of the 14 ponds showed four distinct clusters based on the Mantel-optimal number, and four distinct habitat types based on chironomid indicator taxa (Figure 3.4). The taxa that were statistically significant ($p < 0.05$) for each cluster were: *Glyptotendipes* ($p < 0.01$) for Cluster 1 (PD03, PD66 and PD67); *Chironomus* ($p < 0.05$) for Cluster 2 (PD06, PD07, PD63, PD64, and PD70); *Microtendipes* ($\mathrm{p} < 0.05$) for Cluster 3 (PD37, PD47, PD51, and PD53); *Dicrotendipes* ($\mathrm{p} < 0.01$) for Cluster 4 (PD38 and PD52). *Paratanytarsus* had a p-value > 0.05, but was considered to have strong importance in Cluster 2.

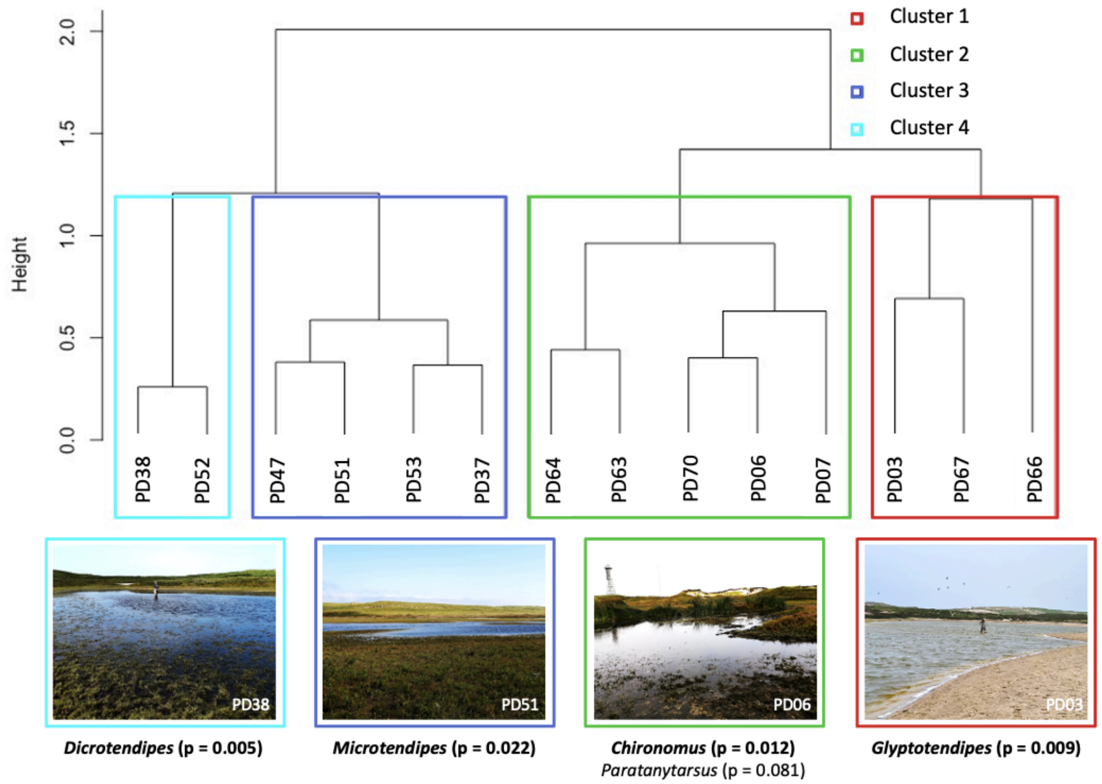

Figure 3.4. A hierarchical cluster analysis of all SINPR ponds using Ward's minimum variance method and the Mantel-optimal number of clusters. The significant indicator taxa and a photo of a pond from each cluster is included beneath. The p-value for *Paratanytarsus* is >0.05, but is still noted for strong influence. Photos taken by Victoria Watson and Kathleen Hipwell.

A PCA demonstrated the trends in chironomid assemblages of each core interval aligned passively across the assemblages of the surface samples from the 14 sampled ponds (Figure 3.5). Variance throughout each core shows changes in chironomid assemblages over time, where assemblages of the core intervals have become more or less alike that of the other ponds. The surface interval of both PD67 and PD03 show similarities, reflected by higher abundances of *Cricotopus*. High abundances of *Microtendipes* downcore (prior to 1994 CE) distinguished PD67 from other ponds, and as the abundance decreased it became more similar to the assemblages of present-day ponds with higher proportions of *Microtendipes* and a vegetated catchment primarily comprised of heath. The higher abundances of *Dicrotendipes* downcore in the PD03 record (1864 CE) were more similar to the present-day chironomid assemblages of PD38 and PD52. An increase in *Cricotopus* abundance since 1890 CE makes PD03 dissimilar to most other ponds.

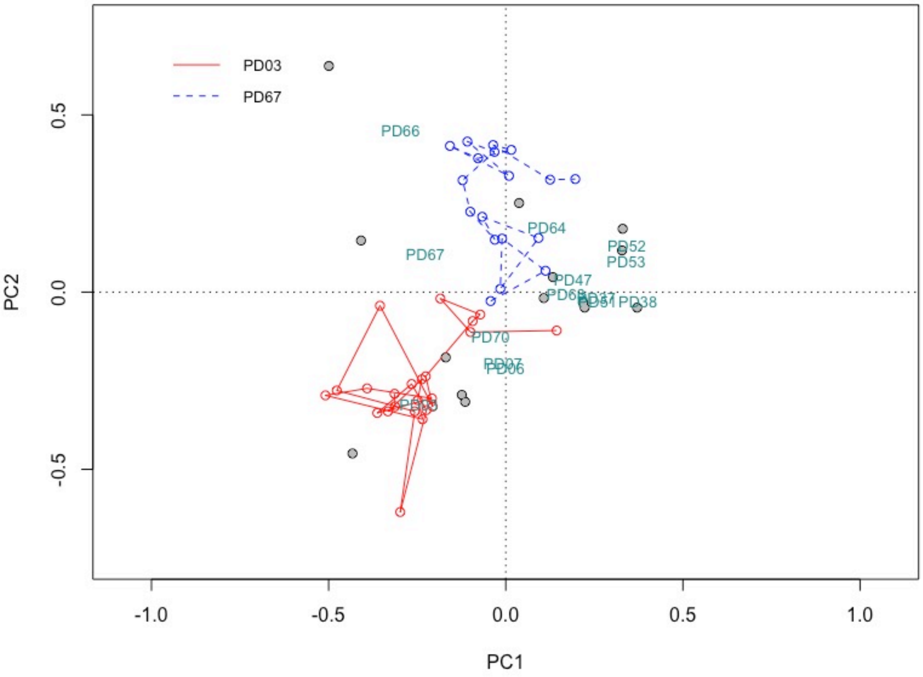

Figure 3.5. PCA biplot of chironomid communities in the pond surface samples and the PD67 and PD03 core intervals.

3.6.3 Water quality

Water quality measurements from 2015–2020 (Jacks et al. 2021) were compared for all the ponds included in this study. The values for chloride, dissolved organic carbon (DOC), nitrogen (TN), pH, phosphorus (TP), and turbidity were grouped and averaged per cluster (Table 3.1). The most notable difference between the clusters is that Clusters 1 and 3 have higher average concentrations of TP and TN. Cluster 1–4 have TN concentrations of 2.4, 1.9, 2.3, and 1.1 mg/L TN, respectively. Cluster 1–4 have TP concentrations of 0.46, 0.28, 0.41, and 0.11 mg/L, respectively.

Table 3.1. Significant and strongly correlated indicator taxa and the average water chemistry per cluster based on Ward's minimum variance method of all sampled SINPR ponds.
* Water quality data is missing.

Cluster	Ponds	Significant Indicator Taxa (P-Value)	Average Water Chemistry
1	PD03 PD66* PD67	*Glyptotendipes* (p = 0.009)	Chloride = 75.8 mg/L Dissolved Organic Carbon = 9.6 mg/L Nitrogen = 2.4 mg/L pH = 8.2 Phosphorus = 0.46 mg/L Turbidity = 14.6 NTU
2	PD06 PD07 PD63 PD64* PD70	*Chironomus* (p = 0.012) *Paratanytarsus* (p = 0.081)	Chloride = 73.6 mg/L Dissolved Organic Carbon = 12.4 mg/L Nitrogen = 1.9 mg/L pH = 7.6 Phosphorus = 0.28 mg/L Turbidity = 15.1 NTU
3	PD37 PD47 PD51 PD53	*Microtendipes* (p = 0.022)	Chloride = 63.3 mg/L Dissolved Organic Carbon = 12.2 mg/L Nitrogen = 2.3 mg/L pH = 7.2 Phosphorus = 0.41 mg/L Turbidity = 19.1 NTU
4	PD38 PD52	*Dicrotendipes* (p = 0.005)	Chloride = 66.0 mg/L Dissolved Organic Carbon = 8.0 mg/L Nitrogen = 1.1 mg/L pH = 7.7 Phosphorus = 0.11 mg/L Turbidity = 8.0 NTU

3.7 Discussion

Little is known about the baseline conditions of the freshwater systems of SINPR as regular water quality monitoring began in 2013. Maps of Sable Island date back as far as 1766 (Cameron 1965). While PD67 is distinguishable on the 1766 hand drawn map, most of the other ponds are not shown and those areas are instead covered by a large saltwater lagoon. SINPR has long had a history of shifting sands from coastal erosion processes whereby sediment erodes from the western tip and accumulates at the eastern tip, resulting in gradual migration of the island (Cameron 1965; Gray 2016). Additionally, shoreline retreat, overwash processes, and windblown sand have resulted in burial of vegetation and loss of some freshwater ponds (Eamer et al. 2021). Harsh coastal weather and intense storms are also known to cause infiltration of ponds with sand as well as alter pond chemistry (Freedman 2016). Most freshwater chironomids are intolerant to saltwater; however, we found no evidence of saltwater intrusion events from the water quality monitoring performed by Parks Canada, albeit records only exist from the establishment of the park in 2013. Here lies the opportunity for paleolimnological methods to fill this knowledge gap. In order understand the extent of stress and ecological change for optimal park management, we focus on inferences of changes in the productivity of chironomid indicators through time to contextualize environmental vulnerability and inform management and conservation. Although there are limited comparable freshwater ecosystems located on sandbar islands in the Atlantic Ocean, we are still able to describe changes in ecological condition through shifts in chironomid assemblages in a paleolimnological approach. Our analysis provides the baseline context for ecosystem management of SINPR, and helps quantify the vulnerability of these freshwater systems to ongoing environmental stress.

3.7.1 Ecosystem changes

The chironomid assemblages surveyed from recent conditions of the 14 freshwater ponds of Sable Island provides perspective of other habitats and communities that exist on the island today. Presently, both PD67 and PD03 have sandy catchments and littoral zones with nearby grassland, as opposed to many of the other ponds that have surrounding heath communities and are more densely vegetated. In our cluster analysis of the ponds, Cluster 1 (PD03, PD66, and PD67) is defined by grazed grassland and eutrophic conditions as indicated by significant indicator *Glyptotendipes*. The primary habitat types for clusters 2–4 as indicated by indicator taxa are associated with productivity (*Chironomus*), heath vegetation (*Microtendipes*), and mesotrophic conditions (*Dicrotendipes*), respectively. Although PD67 and PD03 have similar communities today, they had divergent communities in the past. Shifts in the chironomid taxa abundances throughout the lacustrine sediment cores allow for indication of habitat change over time, as shifts in the communities indicate change in ecosystem conditions.

The chironomid assemblages of PD67 experienced a shift from higher abundances of *Microtendipes* and *Glyptotendipes* to *Cricotopus* and *Paratanytarsus*, indicating a habitat shift has taken place over time. The decrease in *Microtendipes* suggests the retreat of previously well-established heath in the terrestrial catchment. The emergence of *Cricotopus* and *Paratanytarsus* in the core since 1969 CE reflects the grazed grasslands and prominence of submerged macrophytes consistent with present-day conditions. While PD03 had a similar present-day chironomid community as PD67, the assemblage was different prior to 1964 CE where a large inflow of sand occurred between 6.0 and 10.0 cm depth in the sediment record. The abundance of chironomids was low during this period. Prior to the sand interval, higher abundances of *Microtendipes pedellus*-type suggest that a denser heath community existed around the pond prior to the shift to the sandy pond margin with receded grass cover seen today. Increased %Organic of sediments after the sand intervals alludes to increased productivity following 1964 CE (Supplementary Figure S2), which is also reflected by increased abundances of *Cricotopus* and *Glyptotendipes;* both known to be found in nutrient-rich, grazed grasslands (Campbell et al. 2009). The water quality measurements from 2015 – 2020 also show that TN and TP concentrations are much higher in PD03 than the 12-pond average (Supplementary Figure

S3). However, *Cricotopus* and *Glyptotendipes* are also present prior to the sand intervals, as well as a high abundance of *Chironomus*, suggesting that PD03 has always been relatively productive. High abundances of *C. plumosus*-type suggest eutrophic conditions have long existed in PD03.

3.7.2 Causes of ecosystem stress

With intensifying global environmental change, climate variability is expected to accelerate and increase the frequency and severity of storms (Collins et al. 2019; IPCC 2019). These threats could increase likelihood of storm-induced habitat shifts, or even a change from a freshwater to brackish ecosystem as seen in some ponds in the past (Freedman 2016; Eamer et al. 2021). In addition to sea level rise, these projections of climate variability threaten isolated, oceanic islands whose stability is of concern with these increased risks (Leatherman et al. 2000). SINPR is located on the storm track for low-pressure systems, and is known as the windiest place in Nova Scotia (Stalter and Lamont 2006); its offshore location and exposure to harsh weather causes increased vulnerability to environmental changes and further habitat shifts.

The sand intervals observed in the PD03 record below 5.0 cm (1968 CE) seem to have been caused by a severe weather event. Based on historical aerial imagery of the island dating back to 1959, it appears PD03 was a more open system in the past (JBR Eamer, personal communication, June 25, 2021). The land west of PD03 experienced dune breaching prior to 1971, and storm overwash entered the system from the south beach; active terrain management eventually closed off the system and prevented inflow in 1991 (Byrne et al. 2014). The extreme low abundance of chironomids in the sand intervals are likely a direct result of a significant source of material entering the lake basin at a single point in time. The intrusion of sand in the catchment of PD03 is predicted to have caused the shift to the habitat seen today.

Both ponds exhibit impacts enhanced productivity, with the clearer increase in nutrient enrichment occurring in PD67. The unmanaged, naturalized horse population likely provides the largest impact on freshwater ecosystems of SINPR. Although the pond shorelines make up less than 1 % of the island's area, they experience disproportionately frequent grazing and trampling which alters the surrounding vegetation and catchment (Freedman et al. 2011). The horse population remained at a historical average around approximately 100 to 300 prior to legal protection in 1961, and has since been undergoing an increase to numbers between 500 and 600 in recent years (McCloughlin 2012). The high abundance of horses increases erosion and pond sediment accumulation, and also results in nutrient enrichment from higher rates of defecation in and surrounding the ponds (Peel 2009; Pärn et al. 2012; Fritz and Anderson 2013). In a study on the effects of agricultural land-use on chironomid communities, Campbell et al. (2009) found that cattle grazing had a particularly strong impact on water quality by disturbing pond margins and increasing turbidity and nutrient concentrations. We found similar contexts for both PD67 and PD03, where habitat-driven changes are associated with elevated nutrients, mostly occurring after 1950 CE. Nutrient enrichment in the ponds can also be attributed to input from nearby seal and horse carcasses, as well as roosting by seabirds such as gulls and terns. Nutrient enrichment impacts are largely evident in the habitat shifts in PD67, where increases in *Cricotopus* and *Paratanytarsus* abundance suggests a synchronous response to elevated productivity from the expanding horse population. Additionally, the water quality of PD03 also reflects eutrophic conditions defined by high nutrients and turbidity, which can be attributed to its shallow catchment, making it highly susceptible to trampling, grazing, and nutrient pollution. Likewise, recession of surrounding vegetation in both ponds can be caused by over-grazing and trampling of surrounding areas.

3.7.2 Vulnerability and implications for management

The concept of vulnerability is defined by a complex set of factors, some of which include risk, exposure and ecosystem sensitivity (Ford et al. 2007; Aven 2010). Based on the chironomid-inferred habitat shifts over time, we can see that both PD67 and PD03 have experienced long-term changes outside their natural variability. Shifts in the chironomid assemblages of both systems indicate changes in habitat conditions that represent exposure and sensitivity to stress, indicating inherent ecosystem vulnerability. Furthermore, the changes that have occurred in PD67 and PD03 have caused convergence towards analogous habitats in recent decades as a result of the combination of horse activity and morphological changes, making these ecosystems more ecologically similar now than in the past.

Paleolimnology can fill long-term monitoring gaps and expand the available timeframe of the system, establishing the bases for monitoring, whereby the current conditions can be compared with historic patterns (Reavie et al. 2006). The monitoring of current conditions is necessary to quantify short-term, present-day changes, and the long-term outlook offered by paleolimnology puts these changes into perspective. The paleo record shows that the high use of ponds by the increasing feral horse population has caused a cascading effect whereby terrestrial vegetation has decreased, erosional processes have increased, and water quality has diminished. Benthic community compositions and water quality should continue to be monitored for analyzing the present conditions and trajectory of future changes. Investigation into the efficacy of physical ecosystem enclosures is currently in the beginning stages by Parks Canada and the Sable Island Institute, which may help to minimize and understand the direct and indirect influence of horses on different ecosystems, including the freshwater ponds (Parks Canada 2021). The short-term nature of pond enclosures combined with the long-term paleolimnological perspective will provide a complementary quantification of changes and better-defined previous conditions, which will continue to improve understanding of the impacts the horses have on the ponds, and enable conservation of ecological integrity. Furthermore, previous attempts of terrain management have included dune restoration next to the PD03, PD06, and PD07 system which has successfully created protection from storm surge, although this technique has not been successful at all locations (Byrne et al. 2014). While it is evident in the core and water quality data that PD03 has returned to a freshwater system after a storm-related event, the habitat conditions that were present prior to the dune breaching have not been restored, as indicated by the altered chironomid community.

The paleolimnological perspective is essential for defining these changes, as the current conditions of PD67 and PD03 do not reflect the past. PD67 likely has more horse activity now than in the past, and PD03 was not always as sandy as it is now. Quantifying past conditions and change over time informs management that these ecosystems were different, which is an important implication to consider when developing management objectives. It is important to note that management of natural ecosystems can be based on unpredictable circumstances through time. Paleolimnology can establish reference conditions and evidence-based goals for restoration (Roberts et al. 2019); yet, the ecosystem may never be able to return to the previous state because the parameters to support those conditions may no longer exist. The existence of horses on the island goes back to the eighteenth century, further than our paleo record was able to collect; the horse impacts reflected in the chironomid assemblages are likely caused by the expansion and persistence of the population, which is meaningful for quantifying their impact, but the pre-disturbance conditions remain unknown. If the horse population itself was to be managed, the changes done to the landscape may be difficult to reverse, such as return of the formerly well-established heath around PD67 and PD03. Even if extreme measures were taken such as the complete removal of the horses, the reference conditions for ecosystem recovery do not currently exist.

Additionally, the dynamic nature of Sable Island makes it impossible to rule-out other factors contributing to ecosystem change, and the continuous shifting morphology makes it more unlikely that returning to previous conditions is a possibility. Sable Island is known to be migrating eastward due to sediment erosion from the western tip (Cameron 1965; Gray 2016), and ongoing sea-level rise threatens the island's subaerial sediments with possibility of eventual submergence (Eamer et al. 2021). With the island's longevity in question, management plans must consider accelerated morphological change. Therefore, reference conditions established for PD67 and PD03 should be considered "benchmarks" rather than targets to work towards ecosystem recovery where complete restoration is difficult to obtain (Bennion et al. 2011). When multiple stressors are heavily impacting an ecosystem, it is difficult to isolate and manage overlapping factors (North et al. 2013). The combined stressors impacting the changing Sable Island pond ecosystems results in increased complexity for management, which needs to be considered in decision-making processes. Although SINPR's pond systems have been significantly impacted, informed management of stressors could reduce continued ecological change and result in stabilization over time.

3.8 Conclusion

The variability and changes in chironomid assemblages are representative of the ecosystem's responses to stress and overall ecological vulnerability. Based on the chironomid-inferred ecosystem changes observed in the sediment records of two ponds of SINPR, we can deduce that the horse population, morphological changes, and global environmental change are some of the most prominent stressors on the ponds. Both PD67 and PD03 exhibit changes in chironomid community assemblages that convey shifts in habitat; the decrease in *Microtendipes* and increase in *Cricotopus* in both ponds indicates loss of previously well-established heath and increase in productivity from nutrient enrichment. PD67 also exhibits impacts of erosion and increased submerged vegetation, while PD03 exhibits a shift after prominent inflow of sand from storm surge. The list of stressors is not definitive, yet these are key impacts to consider for management based on long-term ecosystem change seen in the paleo record.

As a national park, management decisions are called to prioritize maintaining and restoring the ecological integrity of SINPR. Historical data provided by the paleo-record provides context for management and conservation decisions as well as the means to create reference benchmarks. These findings show that while paleolimnological analysis is predominantly utilized to analyze changes in lakes, it is also effective for determining long-term changes in small, dynamic ponds and thus has potential for application in other similar ecosystems. For continued understanding of the vulnerability of SINPR, future work should include further analysis of chironomids in the adult stage to increase taxonomic resolution, as well as further assessment of ecological indicators such as diatoms to broaden the scope of defined ecosystem conditions. Continued monitoring of the ponds is essential for tracking ecosystem changes, and pond protection from disturbances such as horses should be experimented with to monitor change in the absence of their direct impact.

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CHAPTER 4: CONCLUSION

4.1 Statement of Student Contribution

Chapter design and chapter writing by Victoria Watson with editorial contributions by Andrew Medeiros.

4.2 Introduction

Interest in paleolimnology as a means to study ecosystem vulnerability has expanded in the last few decades. Vulnerability defines an ecosystem's susceptibility to change as a result of pressure or disturbance (Ford and Smit 2004; Aven 2010; Weißhuhn et al. 2018). Paleolimnology can broaden access to historic ecological data, which is useful for quantifying vulnerability. This concept is explored in this thesis, where two studies analyze the effectiveness of paleolimnological analysis in understanding ecosystem vulnerability, and the long-term changes of the freshwater ecosystems of Sable Island National Park Reserve (SINPR). These combined allow for the knowledge acquisition required for managing ecological integrity of SINPR and demonstrate the place for paleolimnology in vulnerability analysis.

4.3 The value of paleolimnology in reconstructing and managing ecosystem vulnerability: Key insights

Vulnerability assessments help to identify the ecosystem components facing the biggest threat and the extent of that exposure (Luers 2005) and are generally not a one-size-fits-all approach. To improve understanding of specific ecosystems, long-term historical data can offer a well-rounded representation of the environment and demonstrate its natural history, and offer insight into potential effective management practices (Smol 1992). The long-term history recorded in lakes quantifies past ecosystem changes (Fordham et al. 2020), and paleolimnology can retrieve this data.

A systematic review sought to understand the range and extent that paleolimnological studies discuss the concept of vulnerability and other overarching themes such as conservation, management, and ecological integrity. The 52 articles that met the inclusion criteria revealed an increase in relevance regarding these topics with majority of articles published since 2010. The literature demonstrates the application of paleolimnology for establishing long-term monitoring, management goals, and restoration targets. Based on the findings, we outline the four-step process in which paleolimnology can act as a base to help reach effective site-specific vulnerability management: 1) achieving historical context of the system provided by paleolimnological analysis, 2) proxy-based determination of ecosystem vulnerability and susceptibility to stress, 3) establishing conservation goals based on reference points and vulnerability assessment, and 4) implementation of the best management practices for the ecosystem's specific needs. Therefore, paleolimnological analysis is valuable for reconstructing and managing ecosystem vulnerability, and can help maintain ecological integrity of an ecosystem.

4.4 A paleolimnological perspective of ecological vulnerability of lakes in Sable Island National Park Reserve, Canada: Key insights

Making informed management decisions can be difficult without full context of the ecosystem at hand. Sable Island has been researched for many years, yet the historic conditions of the freshwater ecosystems is not well established. Paleolimnological sediment analysis of 14 ponds, two of which were cored, was completed to establish an understanding of the SINPR pond habitats using chironomid assemblages. The two cored ponds, PD67 and PD03, demonstrate long-term changes in habitat based on shifts in chironomid community. PD67 experienced a recession of a previously well-established heath community, and increased nutrient enrichment. This is likely a result of expansion of the large naturalized horse population that alter the pond ecosystems through excess nutrient pollution, and stomping and grazing, driving erosional processes and changing the terrestrial vegetation. While PD03 also demonstrates heath recession and nutrient enrichment from horse activity, a major disruption in the timeline caused an influx of sand into the ecosystem in the 1960s, likely a result of a major storm event. The habitat change that followed represents a combination of morphological changes and horse activity as primary stressors in this ecosystem. Additionally, the chironomid assemblages of both cores became increasingly similar over time, showing a disturbance-driven shift to comparable habitat conditions that were once more distinct.

The inherent vulnerability to stress exhibited by the long-term changes seen in PD67 and PD03 have numerous implications for management. Regardless of the management decisions that are implemented, it is important to note that restoration of the ponds may not be realistic due to their trajectory. Additionally, SINPR is known to have a continuously shifting morphology (Cameron 1965; Eamer et al. 2021) that will make it increasingly difficult to return to previous conditions that may no longer be supported. However, quantification of vulnerability of the ponds makes the requirement for management and monitoring of stress much more evident, and will help with understanding the conservation needs and maintenance of ecological integrity of SINPR.

4.5 Final thoughts and future directions

Ecosystem dynamics are complex and vary from system to system. Many lakes and ponds often experience impacts from multiple stressors, making it difficult to isolate the effects of each one to develop effective management (North et al. 2013). Paleolimnology is useful for quantifying stress from different sources, however, paleolimnological tools and data lack transparency and are often not user-friendly for stakeholders and policy-makers; this ultimately prevents it from being commonly applied in conservation sciences (Gillson and Marchant 2014). Paleolimnology effectively establishes pre-disturbance conditions, yet the rapid rate of environmental change in addition to complex ecosystem dynamics still presents a challenge for management planning. While paleolimnological assessment is an effective tool for assessing ecosystem vulnerability, applying it in combination with various perspectives such as bioassessment of the current ecosystem, traditional ecological knowledge, socioeconomic factors, and long-term monitoring (if available) will provide a holistic understanding of the current ecosystem (Wolfe et al. 2007; Gillson and Marchant 2014). Therefore, future vulnerability assessments should not only utilize paleolimnological analysis, but complement the historical ecological knowledge with interdisciplinary perspectives of the current ecosystem and other external components for informed conservation-oriented management.

The freshwater ponds of Sable Island are examples of dynamic systems experiencing impacts from multiple stressors. The paleolimnological analysis was able to determine that the horse population, morphological changes, and global environmental change are likely some of the most prominent stressors on the ponds. However, further work needs to be done to continue establishing and monitoring the ecosystem vulnerability. With the enclosure experiment underway, the direct and indirect impact of the horses and the extent of short-term recovery of the ecosystem will continue to be analyzed. Additionally, benthic community compositions and water quality should continue to be monitored for analyzing the trajectory of future changes. The dynamic nature of the ponds and the seasonal variability they experience is reflected in the water quality data for both PD67 and PD03 (Supplementary Figure S3). Additional fluctuations in water volume and biota emergence require a combination of regular and random monitoring measurements to observe trends and variation (Jacks et al. 2021). These measures will continue to establish the ponds' responses to stress.

A large saltwater lagoon occupied a large proportion of SINPR's surface area in the past and retreated over time. A series of hand drawn maps of the island from 1766 to 1964 show the migration of the island and the retreating perimeter of the lagoon (Cameron 1965). The PD67 core dates back to 1772 at the basal interval (15.0 cm), and saline conditions are not reflected in the chironomid assemblage due to the presence of saltwater-intolerant taxa. The PD03 chronology reflects the age of 1864 at the basal interval (25.0 cm), and also includes saltwater-intolerant taxa. Deeper cores of these ponds may provide context for the retreat of the lagoon and exhibit the emergence of the freshwater ecosystem. Considering the threats of saltwater intrusion to the ponds today, demonstration of recovery from a saline ecosystem in the past could provide hope for ecosystem recovery in the future should intrusion occur.

The value of paleolimnology in reconstructing and managing vulnerability was reviewed and demonstrated in this thesis. Application of paleolimnological analysis to Sable Island fills the gap in long-term monitoring and provides context for management and conservation of the ponds. These findings will act as a point of reference going forward where ecosystems continue to be monitored and managed for stress to maintain and restore the ecological integrity of SINPR. A demonstration of the efficacy of paleolimnology in a small, unique, and dynamic ecosystem is presented, and thus promotes the application of a paleolimnological perspective in further vulnerability research.

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APPENDIX: SUPPLEMENTARY MATERIALS FOR UNDERSTANDING THE PALEOLIMNOLOGICAL ANALYSIS OF SABLE ISLAND PONDS

S.1 Statement of Student Contributions

Study design by Victoria Watson and Andrew Medeiros, grain size analysis completed by Matthew Peros, supplemental material writing by Victoria Watson.

S.2 Introduction

A systematic map was completed to review the published paleolimnological literature for incorporation of the concept of vulnerability. This data was compiled and analyzed for understanding the use of paleolimnological analysis to interpret ecosystem vulnerability. These findings were then demonstrated in a study on Sable Island National Park Reserve to understand the long-term change of pond ecosystems using paleolimnology. The analysis of chironomid subfossils and geochemical data were applied to two lacustrine sediment cores from Sable Island. Here, additional information of the systematic map process, physical pond characteristics, diagnostic tests, and chironomid assemblages are presented.

S.3 Systematic Map of the Literature

The ROSES (RepOrting standards for Systematic Evidence Syntheses) systematic map protocol was used for reporting the findings in the review of the literature to analyze the range and extent that paleolimnological published studies incorporated the concept of vulnerability. The search terms (Table 2.1) were used in three databases; Web of Science, Scopus, and PubMed. After the screening process to remove duplicates and papers that were not considered relevant to the combined topics of paleolimnology and vulnerability, 52 studies were included.

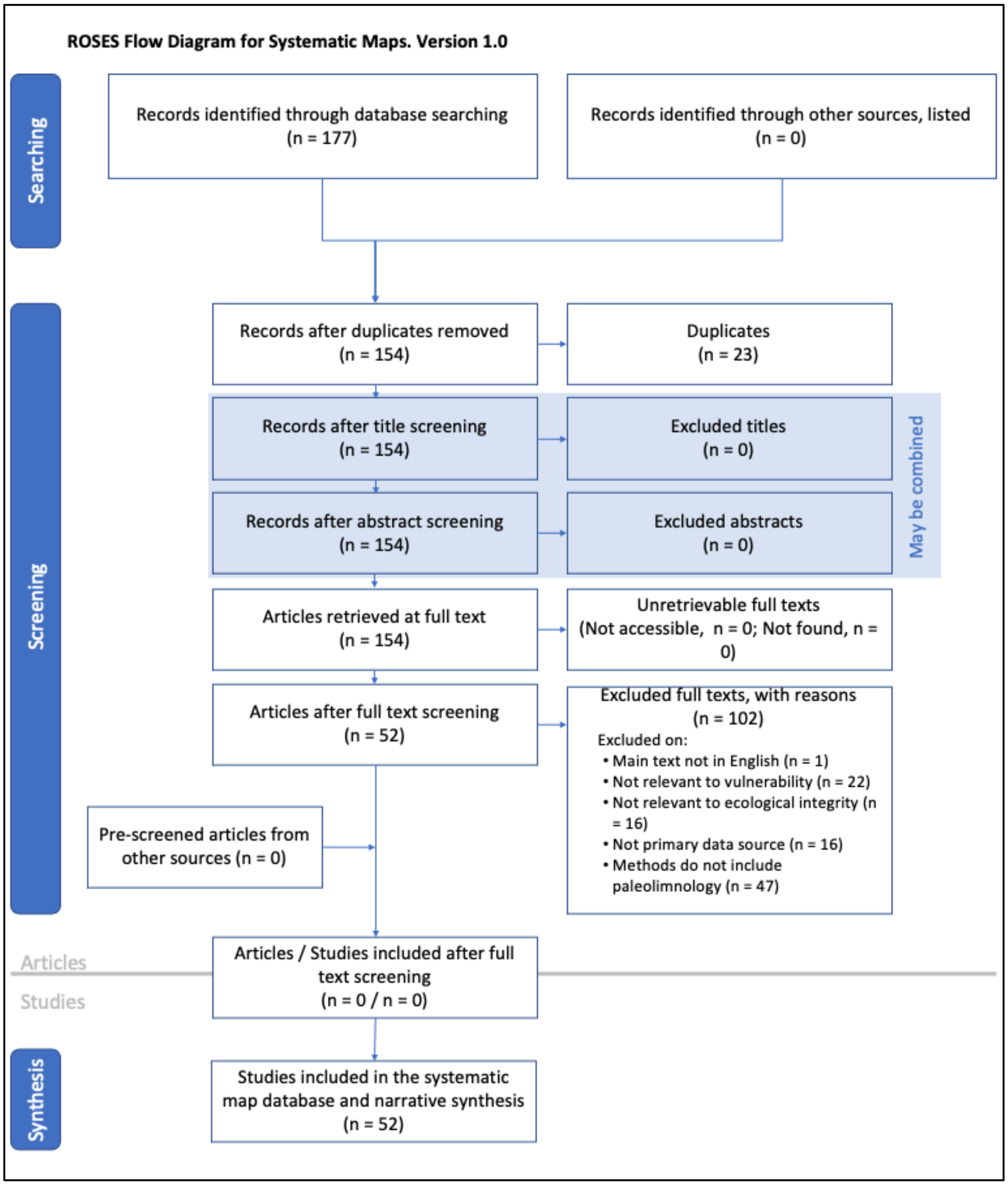


Figure S1. A ROSES flow diagram for systematic map (version 1.0) to record the selection process of articles based on the variations of search terms seen in Table 2.1. (Haddaway et al. 2017).

S.4 Site Information

Surface samples from the sediments of 14 freshwater systems on SINPR as well as sediment cores from 2 of the 14 ponds were collected in August 2019.

Table S1. Sable Island pond names and coordinates where sediment samples were taken. Compiled with data from Jacks et al. 2021. *Indicates ponds that were also cored.

Pond Name, Common Name	Latitude	Longitude
PD03, Mummichug 1*	43.932364	-60.026706
PD06, Mummichug 2	43.931552	-60.025251
PD07, Acadian	43.930788	-60.024268
PD37, Pine West	43.930712	-60.003118
PD38, Pine East	43.931990	-59.998964
PD47, Gull East	43.932291	-59.967460
PD51, No2 East	43.931243	-59.951624
PD52, Calopogon	43.931999	-59.926073
PD53, Sparrow	43.933170	-59.924648
PD63, Sverdrup West	43.931682	-59.914546
PD64, Sverdrup East	43.932140	-59.911680
PD66	43.933090	-59.900810
PD67, Gallinule*	43.932481	-59.900146
PD70, Iris	43.934460	-59.899844

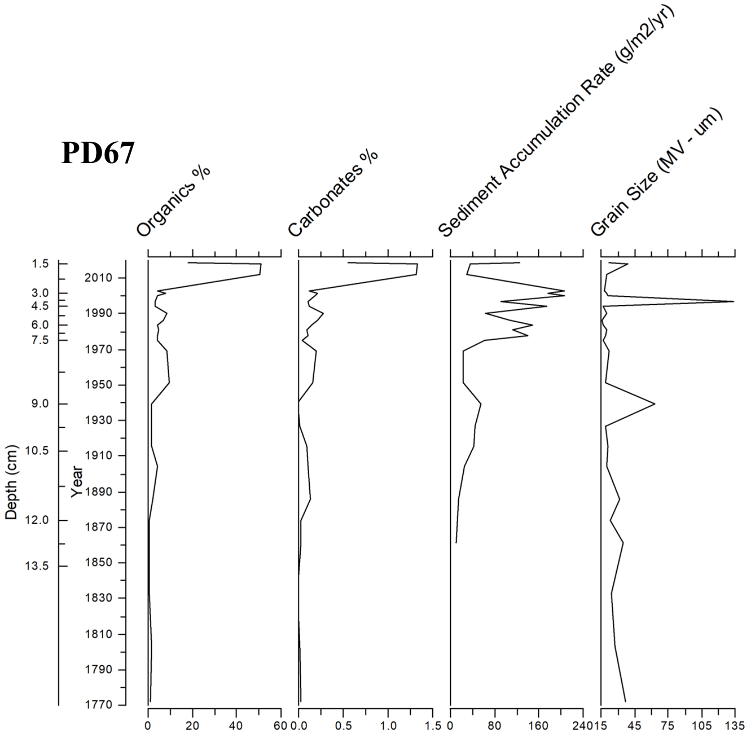
S.5 Pond Characteristics

Sedimentary stratigraphy

PD67 sediment accumulation rate ranged from 11 to 206 g/m^2/yr throughout the core, while the rate decreased from 52 to 9 g/m^2/yr from 0.5–5.0 cm for PD03 (Figure S2). The sediment accumulation rate below 5.0 cm for PD03 was disrupted by the sand influx in the following intervals. Using loss on ignition (LOI) data, %Organics and %Carbonates in PD67 fluctuate synchronously throughout the core (Figure S2). The %Organics ranged from 0.53 to 9.57 between 2.0 – 15.0 cm, reached 50.45 at 1.5 cm, and decreased to 17.95 at 0.5 cm. The %Carbonates ranged from 0 to 0.27 between 2.0–15.0 cm, peaked at 1.31

at 1.5 cm, and decreased to 0.55 in at 0.5 cm. In PD03, %Organics remained < 11 between 6.0 – 25.0 cm, then ranged from 53.75 to 64.45 between 0.5 – 5.5 cm (Figure 3). The %Carbonates remained <1 throughout the entire core, except for a peak of 7.45 at 0.5 cm. Grain size analysis of the cores determined that sediment grain size in each interval. Average grain size in PD67 ranged from 16.3 – 63.6 um throughout the core with a peak of 133.5 um at 3.5 cm. Average grain size in PD03 ranged from 11.9 – 604.6 um throughout the core, with a peak of 1404.0 um reached at 5.5 cm.

PD67



PD03

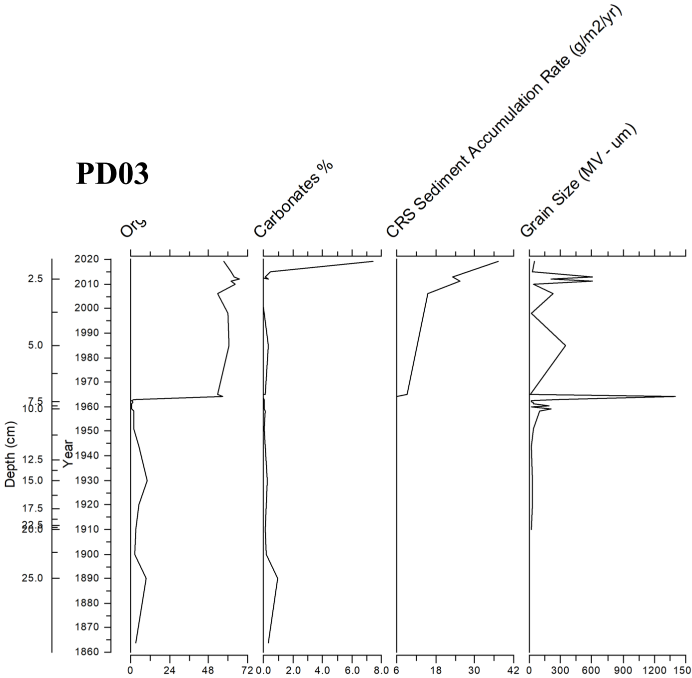


Figure S2. Loss on ignition data as % organics and % carbonates, and sediment accumulation rate, and sediment grain size for (a) PD67 (1.0 – 15.0 cm) and (b) PD03 (0.5 – 26.0 cm), plotted against age (year) and depth (cm) downcore.

Pond water quality

Water quality parameters were collected between May and October of the years 2015–2020 by Parks Canada. The parameters collected include total nitrogen, total phosphorus, turbidity, chloride, dissolved organic carbon, and pH. These parameters help establish the current conditions of the ponds, and contextualize their habitats and how they compare with one another.

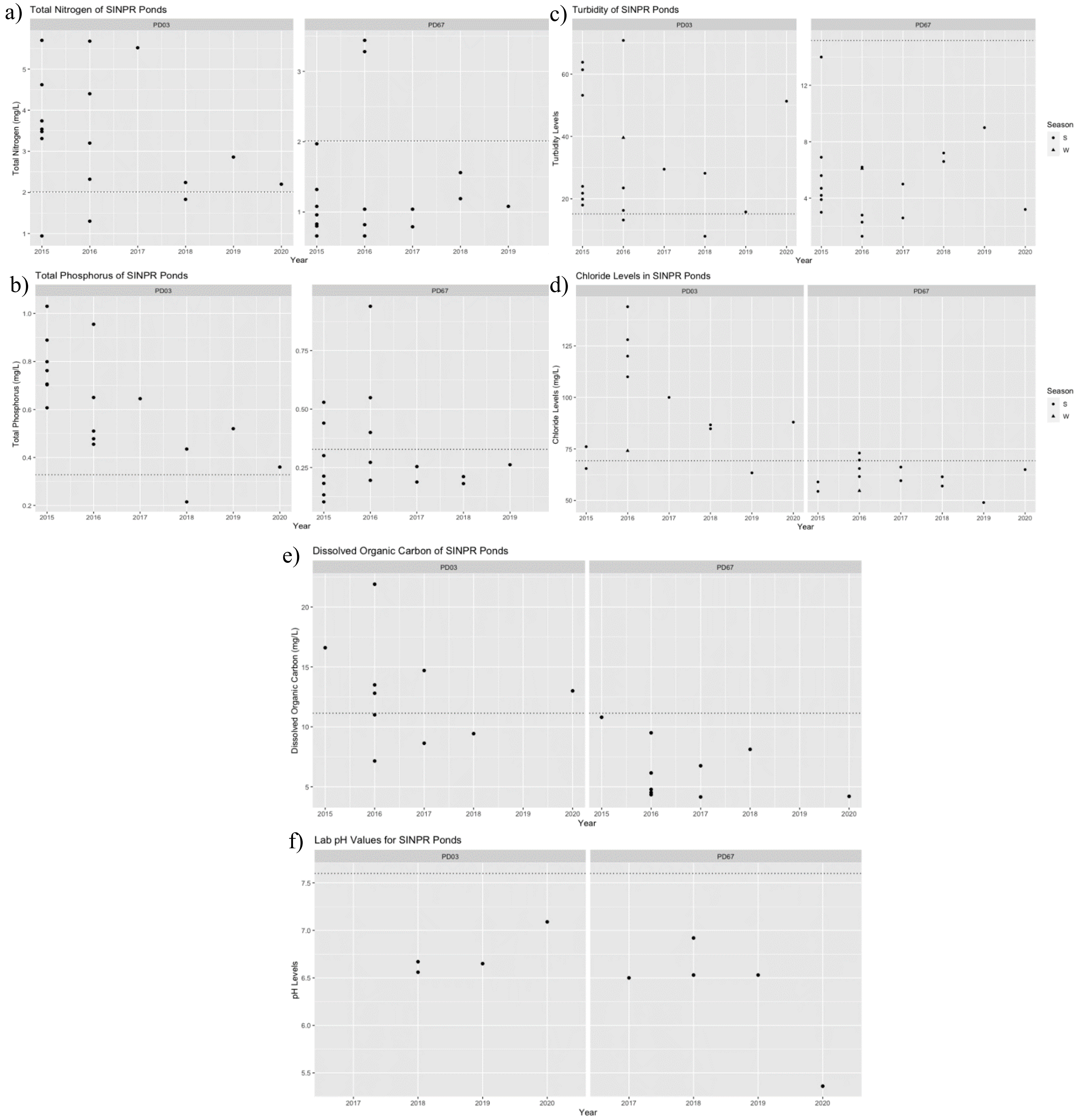


Figure S3. Water quality measurements for the years 2015–2020 for PD67 and PD03 shown with the combined average value for the SINPR ponds represented by the dotted lines on the associated plots; (a) total nitrogen; (b) total phosphorus; (c) turbidity; (d) chloride; (e) dissolved organic carbon; (f) pH.

S.6 Chironomid Assemblages

A hierarchical cluster analysis of the surface samples was completed (Figure S4), where the Ward's D2 method grouped ponds based on minimum variance and squared dissimilarities into clusters as determined by a Mantel-optimal number (Borcard et al. 2018). Significant chironomid indicators that represented each cluster were determined through their indicator value (IndVal; Dufrene and Legendre 1997) using the R package 'labdsv'. A hierarchical cluster analysis of the surface samples and core intervals was also completed (Figure S5). The intervals for each core were clustered with the surface samples to compare chironomid assemblages over time with the recent communities of the surface samples.

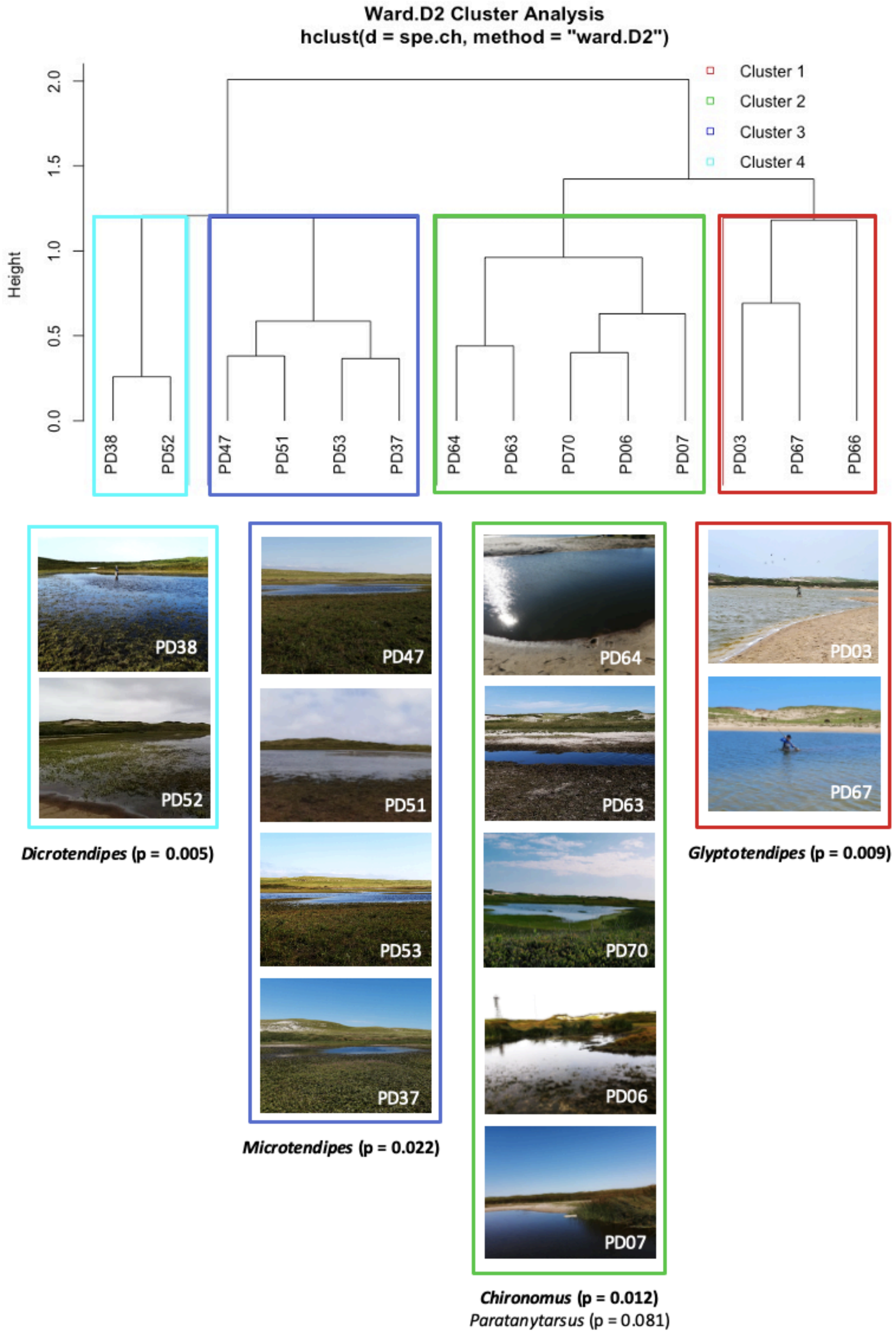


Figure S4. A hierarchical cluster analysis of all SINPR ponds using Ward's minimum variance method and the Mantel-optimal number of clusters. The significant indicator taxa and a photo of all* ponds from each cluster is included beneath. The p-value for *Paratanytarsus* is >0.05, but is still noted for strong influence. Photos taken by Victoria Watson and Kathleen Hipwell.

*No photo taken of PD66.

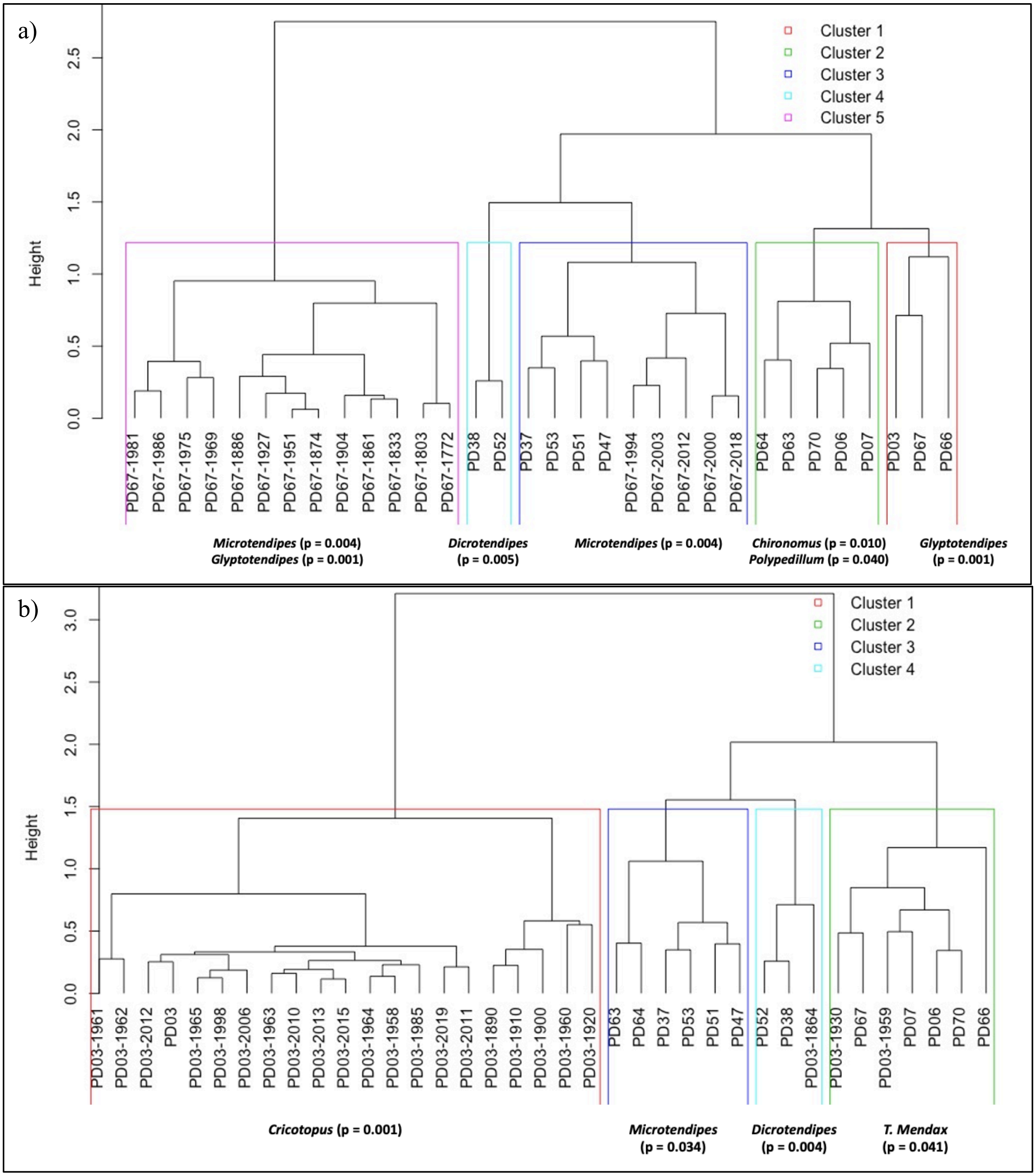


Figure S5. Cluster analysis of surface sample ponds and (a) PD67 core intervals and (b) PD03 core intervals, with significant indicator taxa.

S.7 Aerial Imagery

The sand intervals in PD03 were followed by a shift in the chironomid community. Based on aerial imagery of Sable Island from 1963, a more open system with susceptibility to storm surge is shown, where the inflow into PD03 is visible (Figure S6) (JBR Eamer, personal communication, June 25, 2021). The storm surge that likely flowed into PD03 from the south shore likely forced sand into the system that caused a shift in the habitat.

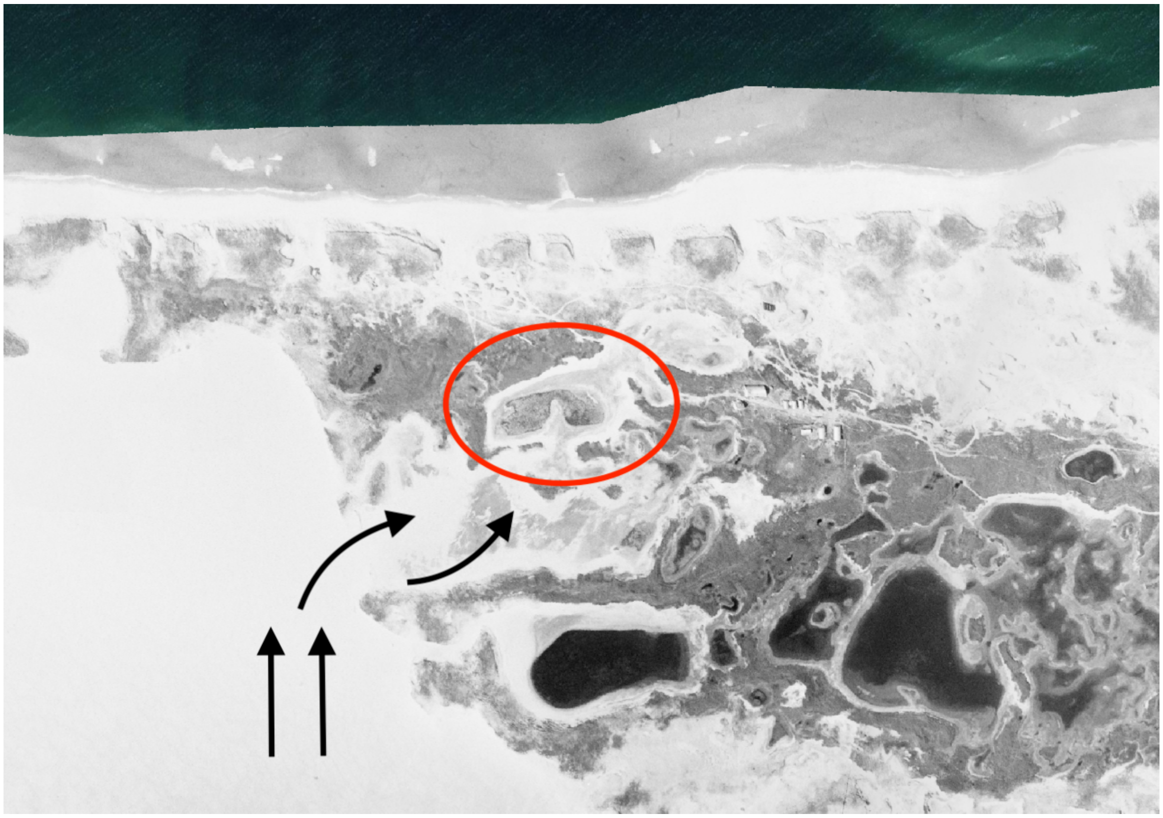


Figure S6. Aerial imagery of the PD03 pond system in 1963, after dune breaching as a result of storm surge. The black arrows indicate the likely direction of the storm surge that would have entered the system from south beach and forced sand into the pond, and the red circle indicates the area that represents PD03 (Parks Canada Agency 2021).

S.8 References

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