Paleoecological Indicators and Carbon Dynamics in Lake Sediments in Western Canada, and Potential Implications for Protected Area Carbon Management in Canada

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Abstract

Lake sediment from 18 lakes across western Canada was studied in regards to carbon accumulation rate over the last 150 years. Carbon (C) accumulation rate was found to be 3.8 times greater on average in the modern time period (1980-2010) when compared to the historical time period (1830-1860). The largest C accumulation rate change was found in the Boreal Plains ecozone. Maximum lake depth, lake geometry ratio, and temperature related climate variables (e.g., number of ice free days) were significantly correlated to C accumulation rate. There was not a statistically significant difference between lake C accumulation rate between protected and non-protected lakes.

To better understand how climate controlled millennial forces of vegetation composition and fire related to carbon accumulation, paleo proxies of pollen and charcoal were investigated on two longer sediment cores in adjacent biogeoclimatic zones of the Kootenay Valley of British Columbia. Broad-scale climatic controls are interpreted as the major influence on high fire frequency and carbon accumulation rate in the dry and hot xerothermic period (11,500-8,000 cal. yrs BP). The Kootenay Valley is expected to return to xerothermic-like climate conditions within the next century.

The conversation pertaining to how protected areas would manage for carbon in the future began with a workshop exploring how to frame carbon management. Experts were then interviewed and ecological integrity measures were determined to be the best place for carbon to act as either a co-benefit or as a separate ecological integrity measure. A survey of protected area manager perspectives on the importance of each ecological integrity measure to carbon management was created. Vegetation-related ecological integrity measures were found to have the most importance to co-benefit carbon management. Active management in protected areas should use paleo proxies to find reference biogeoclimatic zones and restoration efforts should focus on retaining carbon on the landscape through maintenance of vegetation-related ecological integrity measures like prescribed burning.

Keywords: carbon, management, lake sediment, protected areas

For my wife Carlye and my son River.

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Table of Contents

List of Tables

List of Figures

Chapter 1. Introduction

Climate change represents an unprecedented challenge to protected areas (PAs) and their ability to achieve conservation mandates(s) (Scott et al., 2002; Melilio et al., 2016). A number of strategies within PAs can contribute to mitigation solutions to climate change such as using cleaner energy than fossil fuels (Owusu and Amsumadu-Sarkodie, 2016), greater efficiencies through technology (Worrell et al., 2008), carbon capture and storage (Wennersten et al., 2015), as well as "natural solutions" such as the protection, restoration, and creation of land and seascapes that naturally store and sequester carbon (Canadian Parks Council Climate Change Working Group, 2013; Nantel et. al., 2014; Environment and Climate Change Canada, 2016; Commission for Environmental Cooperation, 2016; Griscom et al., 2017; Canadian Parks Council, 2018). However, there has been a limited response to manage carbon by PA agencies, particularly at the institutional level here in Canada. To understand the dynamics of carbon and how they are influenced by climate change and disturbances within the natural systems that are protected by PA agencies, it is critical to understand carbon in the context of adaptation.

PAs must adapt to changing environmental conditions through time (Lee and Jetz, 2008), while simultaneously maintaining their cultural and social roles as an institution that manages long term conservation of nature. The core of PA institutional identity lies in the ability to support the long-term persistence of ecosystem services (Jax, 2010). Ecosystem services are processes such as climate regulation that humans freely gain from properly functioning natural systems. Carbon as an ecosystem service includes management that would regulate carbon by providing storage and promote sustainable use of carbon sinks to contribute to climate change mitigation (Raupach, 2013).

Incorporating ecosystem service information in PA management decision-making is typically done through reporting of indicators. In the case of Parks Canada, ecological integrity (EI) indicators provide information on the state of the environment and changes over time of key ecological services. Indicators can be used as early-warning tools and help diagnose the causes of environmental problems (Dale and Beyeler, 2001). Indicators may also help to predict future states of ecosystems and identify actions for mitigation of unwanted future conditions (Niemi and McDonald, 2004). For example, in a aquatic system when cyanobacteria increases it can be indicative of a state change to more eutrophic conditions (Paerl et al., 2003). Crucial to using indicators is establishment of a baseline or reference (Frost et al., 1992; Pellatt, 2002; Karr, 2004).

Central to Parks Canada EI indicators is the establishment of an ecological baseline. Ecological baselines refer to the baseline conditions of an ecosystem that against which changes in the ecosystem can be evaluated (Parks Canada and the Canadian Parks Council, 2008). Establishing ecological baselines requires knowledge of ecological and functional processes and services of the modern ecosystem and how the ecosystem has shifted overtime. Paleoecology provides data over sufficiently "long time periods" to allow for meaningful information to be related about changes in ecosystem structure, disturbance frequencies, rates, and trends in ecosystem shifts (Swetnam et al., 1999; Pellatt, 2002; Dearing et al., 2012). For PA agencies, defining the aforementioned "long time periods" depends on the processes involved and the history of the system. I argue that the century timescale is a minimum time period to observe major developments stemming from the modern social-ecological system interactions of PAs. While setting aside areas to protect their intrinsic values is not exclusively a century-scale human endeavor, modern institutional management systems only span the last century and a half on the North American continent. The establishment of Yellowstone National Park in the United States in 1872 is often cited as the beginning of the modern era of PAs (Chape et al., 2005). Information offered by century to millennium scale paleoecology can reveal a range of ecosystem processes at different spatial and temporal scales. Paleoecology can also offer insight into the extent to which modern vegetation has been altered by human activities (Pellatt, 2002).

The interactions between different spatial and temporal scales of ecological aspects can be conceptually challenging. The boundaries of a PA can span multiple scales. Each PA interacts directly with its immediate geospatial boundary, within which different temporal dynamics occur. At the PAs spatial scale, short-term processes, such as prescribed burns occur on a daily scale while long-term processes such as development of a climax forest vegetation composition can take centuries to millennia. Ecological time frames are often not compatible with the shorter term PA management goals (Pellatt, 2002; Gillson and Marchant, 2014) (Figure 1.1). However, time periods in the paleoecological record may provide analogs for how ecosystems may react in the near future under climate change (Pardi and Smith, 2012). For example, in the Pacific

Northwest, pollen, charcoal, and macrofossil records indicate that vegetation communities that contained *Alnus rubra, Pseudotsuga, and Pinus contorta* were most abundant during times of rapidly changing climate in the past, and these taxa will likely be equally successful in colonizing rapidly changing and disturbed environments in the future (Whitlock, 1992).

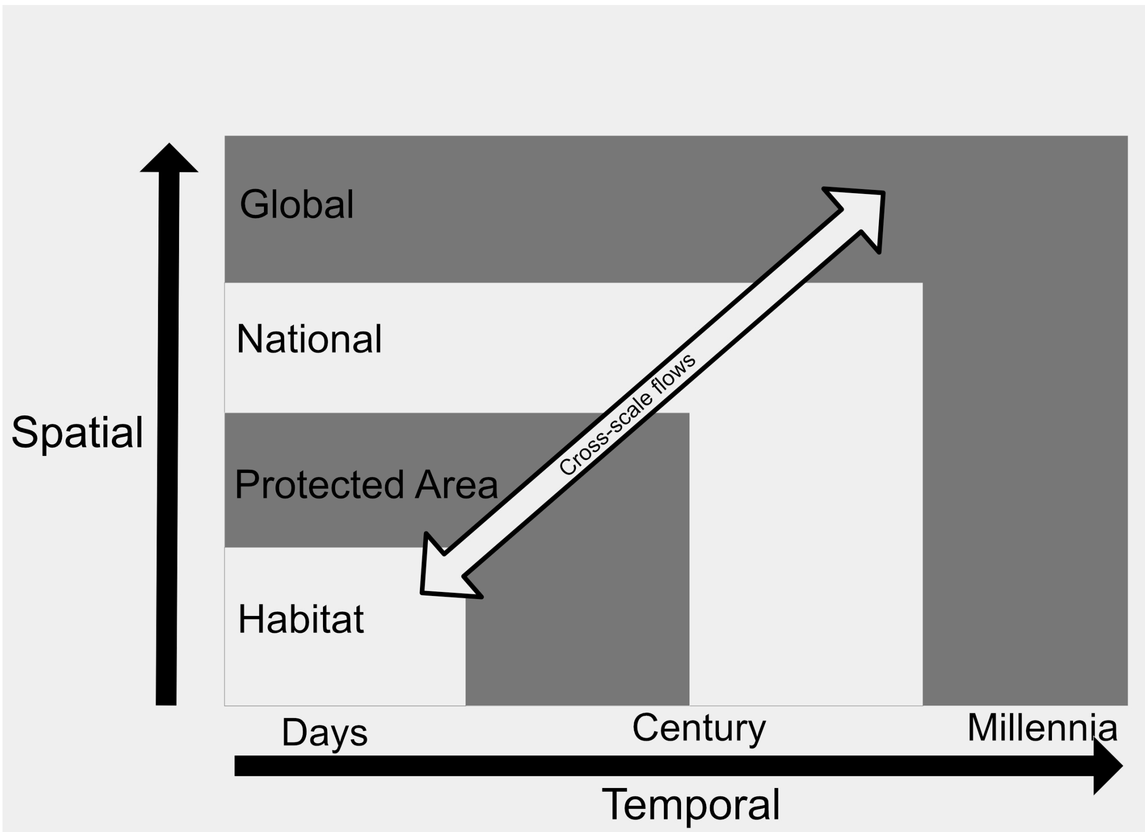

Figure 1.1. Ecological landscape perspective of protected areas. Note the nested spatial scales. Adapted after Cumming et al., 2015.

Lake sediments provide an archive of ecosystem conditions over annual to millennial timescales. Lake sediments contain concentrations of organic carbon and calcium carbonate, which are often inversely related (Dean, 1999). Carbon enters a lake system either via the atmosphere or through hydrologic and fluvial pathways that transport dissolved and particulate organic carbon (DOC and POC) through terrestrial sources (Benoy et al., 2007) (Figure 1.2). Several ecological factors influence the concentration and accumulation rate of organic matter in lake sediment including climate, local environment, and human activity. Understanding these dynamics and their importance to carbon in the past lake sediment archive provides an opportunity to consider how they are likely to change in the future.

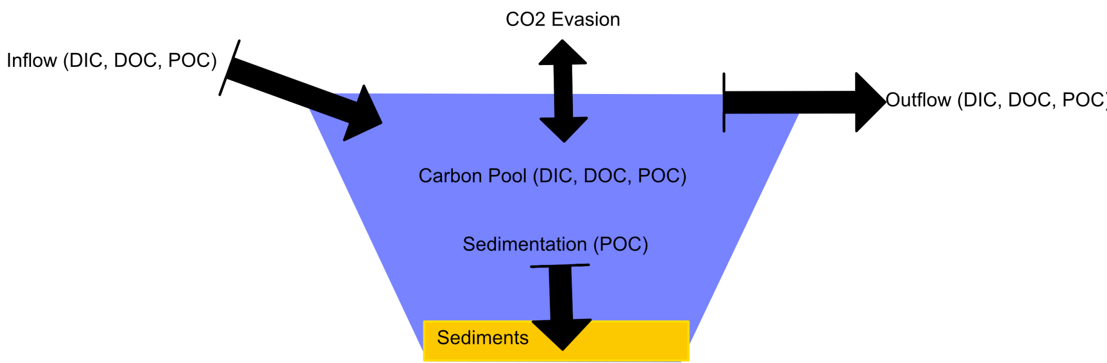

Figure 1.2. Overview of lake carbon cycling. Adapted after Benoy et al., 2007.

Lake sediment carbon accumulation rates are linked to climate-fire-vegetation interactions at the watershed scale. Known as the fire regime triangle (Whitlock, 2010) (Figure 1.3), climate influences both vegetation and wildfire, and vegetation and wildfire can interact to influence each other. Disturbances such as fire can permanently alter vegetation patterns and composition (White, 1979). Climate change can alter responses to disturbances such as fire and invoke a new ecosystem state (Pace et al., 2015). Ecosystem state changes may feedback to alter the disturbance regime and alter ecosystem function and vegetation composition. Paleoecology can provide insights on these dynamics through the proxies of charcoal and pollen (Appendix A).

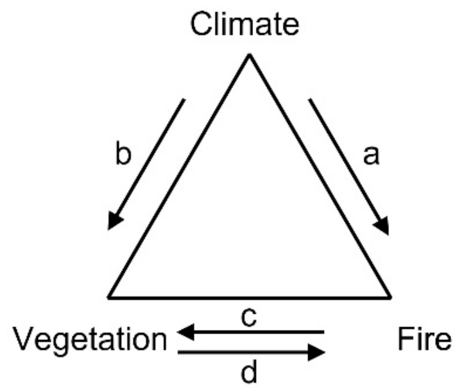

Figure 1.3. Fire regime triangle indicating the relationship between climate change, wildfire, and vegetation (Whitlock, 2010).

Studying the links between climate, fire, and vegetation through examination of paleoecological proxies is best done at the limits of ecological states where sensitivity to changes in climate can be observed. The subalpine forests have been used in the past because they are located at the boundary of elevation and climatic limits. In addition subalpine forest have the ability to support stand-replacing fires (e.g., Calder, 2019). In the Kootenay Valley of British Columbia, Canada, climate and fire regimes have been previously documented and changed substantially in recent millennia and shown to produce landscape-scale state shifts evidenced by vegetation composition (Hallett and Walker, 2000). In addition, PAs adjoin managed landscapes in the area, allowing differences in decadal and century-scale management to be investigated.

In the context of PAs, there is a need to connect and make sense of different ecological data to report on the protected area's condition that will inform future management decisions and a possibility to incorporate carbon dynamics management strategies (LaPaix et al., 2009). However, carbon management has yet to enter the decision making process of PA agencies. This is likely due to a mismatch between spatial and temporal scales required for integration of social science in decision analysis. Due to this mismatch, how carbon will be managed in PAs remains in the problem definition stage of decision analysis (Cash et al., 2006; Peterman and Peters, 1998).

Establishing a multi-disciplinary team early in the process of framing carbon management was deemed a priority for this study. Including social scientists at the beginning of a decision problem can be useful in the adaptive management context in dealing with uncertainty. Uncertainty is not just restricted to the ecological data, but also related to human values (Robinson et al. 2019). Targeting PA managers in framing the problem of carbon management we can construct a scale to elicit preferences for integration into existing decision making with PA managers and create a stated objective (Louviere et al., 2000). By asking PA managers to state preferences for hypothetical actions, we can elicit the strength of different carbon management alternatives. Currently the relay of ecosystem service information into PA management decision-making is typically done through reporting of indicators. We can incorporate stated preferences directly into the analysis of tradeoffs (Hunt et al., 2010). By gleaning preferences between carbon management alternatives, we can estimate how well PA managers will be able to deal with carbon in the future.

Both PAs and non-PAs are in a position of “managing” ecosystems. The climate is changing and ecosystems are responding to this change. This research places ecosystem change within a paleo and historical perspective, asking:

1) Over the past century, what are the dynamics of carbon accumulation?

2) Over the last 10,000 years, what are the dynamics of carbon accumulation?

3) Is carbon important to PA management?

4) How prepared are PA managers to deal with carbon management?

5) How have PA managers dealt with carbon in the last decade?

To address question 1, chapter 2 of this thesis provides an ~150 year record of lake sediment carbon dynamics in and out of PAs across four western Canadian Provinces. To address question 2, chapter 3 provides an ~10,000 year record of lake sediment carbon dynamics of a lake in a PA and a lake adjacent to a PA. Addressing questions 3, 4, and 5, chapter 4 explores PA manager perspectives of carbon management through a workshop, semi-structured interviews and a stated preference survey.

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Chapter 2. Changes in lake carbon accumulation rates in southwestern Canada since the mid-1800's

2.1. Abstract

Carbon (C) accumulation in lake sediments is recognized as an important reservoir of carbon on the landscape, but the variations in this accumulation are poorly understood. Here we have measured carbon accumulation rates between 1830 and 2010, in sediments collected from 18 lakes across four ecozones in southwestern Canada. Average C accumulation rates since 1830 range from 4.86 to 1500 g C/m^2/yr across the study region. C accumulation rates increase 3.81 times on average between 1830-1860 and 1980-2010. We explored reasons for these changes by examining temporal relationships between C accumulation rates and 36 variables that describe the characteristics of climate, lake morphology, and land use conditions surrounding each lake. While agricultural and logging influences cannot be ruled out, a spearman's ρ correlation analysis showed that climate related variables (i.e., growing degree days, mean temperature of the warmest month, number of frost-free days, frost-free period, average temperature of the summer, and mean annual temperature) had significant relationships with C accumulation rates in 69% of the lakes examined. Spatial variations in carbon accumulation rates showed significant relationships with the lake morphological variables, exhibiting positive correlations with lake geometry ratio (lake area$^{0.25}$/maximum depth) and negative correlations with maximum lake depth and catchment area. These results are consistent with several studies of other Northern Hemisphere lakes, which also show increases in lake C accumulation rates over the past 150 years.

Special note: The sediment focusing factor that was originally suggested by outside reviewers is incorporated into methods, the results tables, text in results, Appendix B5 and discussion. However, due to the revisions timeline of this thesis, the figures and appendices besides Appendix B5 do not incorporate the focusing factor.

2.2. Introduction

Recent estimates of lake carbon (C) accumulation rates and storage indicate that lake sediments contribute a significant portion to boreal forest C storage (e.g., Einola et al., 2011; Ferland et al., 2012; Hanson et al., 2014a). Boreal aquatic systems have been estimated to contain as much as 15% of the total terrestrial C storage in the boreal biome (Benoy et al., 2007), with Canadian boreal lakes possibly comprising >10% of global lake C burial (Tranvik et al., 2009). However, estimates of C accumulation in lake sediments vary widely by region and methodology (Hanson et al., 2014b).

Lake C accumulation rates may also be expected to change with time, but how these changes may occur is uncertain (Benoy et al., 2007; Gudasz et al., 2010; Kastowski et al., 2011; Hanson et al., 2014b). Lake C accumulation rates in boreal forest regions could be affected by a combination of processes, including climate, climate-related changes in lake inputs, and land surface changes (Mustaphi and Pisaric, 2014). In addition, both natural (e.g., wildfire) and human-induced disturbances (e.g., logging) could also contribute to changes in lake C accumulation (Anderson et al., 2013). Information on how these processes might affect C accumulation rates is of increasing importance to natural resource management agencies that attempt to understand the role these systems might play in the context of climate change mitigation (Theissen et al., 2012; Hobbs et al., 2014).

The period of change following the industrial revolution (1860-present) represents a time when many factors could affect lake C accumulation, including warming temperatures in the Northern Hemisphere (IPCC, 2018: Summary for Policymakers) and influences associated with increasing population density in the catchment areas surrounding lakes. Some studies suggest primary productivity may increase as temperatures warm (e.g. Lewis, 2011). However, C accumulation in lake sediments may also decrease in response to temperature-dependent increases in C mineralization (Gudasz et al 2010; 2012). Alternatively, some lakes may respond primarily to changes in terrestrial inputs of C from runoff (Dillon and Molot, 1997; Sobek et al., 2009; Finlay et al., 2010; Kortelainen et al., 2013). For example, allochthonous C inputs and therefore also C accumulation rates may decrease if regional precipitation rates decrease.

In addition to anthropogenic climate change, regional land-use changes also may have affected C dynamics in lake systems across western Canada as this area underwent colonization by Europeans in the mid-19th century. Eutrophication associated with agricultural land use changes could both increase C accumulation and decrease CO_2 outgassing in shallow lake systems, resulting in an increasingly important long-term role of anthropogenically impacted lakes in C sequestration (Heathcote and Downing, 2012; Anderson et al., 2014; Pacheco et al., 2014). Understanding the impact of natural processes and human activities on lake C accumulation in the period following the industrial revolution is paramount to making accurate estimates of C accumulation rates and storage in lacustrine environments.

The aim of this chapter is to quantify changes in C accumulation rates since the industrial revolution in 18 lakes spanning Canada's southern boreal and temperate forest region, from coastal British Columbia to Manitoba. In addition, this chapter seeks to explore the following hypotheses: (1) changes in C accumulation rate are related to climate; (2) changes in C accumulation rate are related to lake morphology; and (3) changes in C accumulation rate are related to surrounding land-use. Lake sites have been chosen across the southern boreal forest boundary to examine the potential impacts of climate-related shifts in ecosystem structure on C accumulation. In addition to quantifying changes in C accumulation rates over the past 150 years, we also examine multiple factors that could potentially affect C accumulation rates in western Canada, focusing on the roles of climate, lake morphology, and surrounding land-use.

2.3 Methods

2.3.1. Study area

We selected 18 lake sites located in the southern boreal and temperate forest regions of western Canada (48-55°N, 99-127°N; Table 2.1, Figure 2.1) in a transition zone between prairies and coastal climates. Nine of the lakes sampled have protection status while nine lakes have no protection status. The study area spans a range of climatological conditions and distinct ecozones (Atlas of Canada, 2009). Mean annual temperatures range between 3.5 °C in the Prairies ecozone and 10.4°C in the Pacific Maritime ecozone. Mean annual precipitation ranges from 283 mm in the Prairies ecozone to 5168 mm in the Pacific Maritime ecozone (Wang et al., 2012). The ecosystems along this southern boreal transition zone are expected to be highly sensitive to projected climate change (Scheffer et al., 2012), and as a result, C accumulation in associated lake systems might also be affected. I anticipate that the C accumulation rates vary among ecozones largely correlated with temperature. Recognizing the difficulty in accounting for both climate and land-use changes influence on C accumulation rates (Heathcote et al., 2015), I hope to constrain direct and indirect C accumulation rate alteration by human activities using a paired site selection strategy (Section 2.3.2).

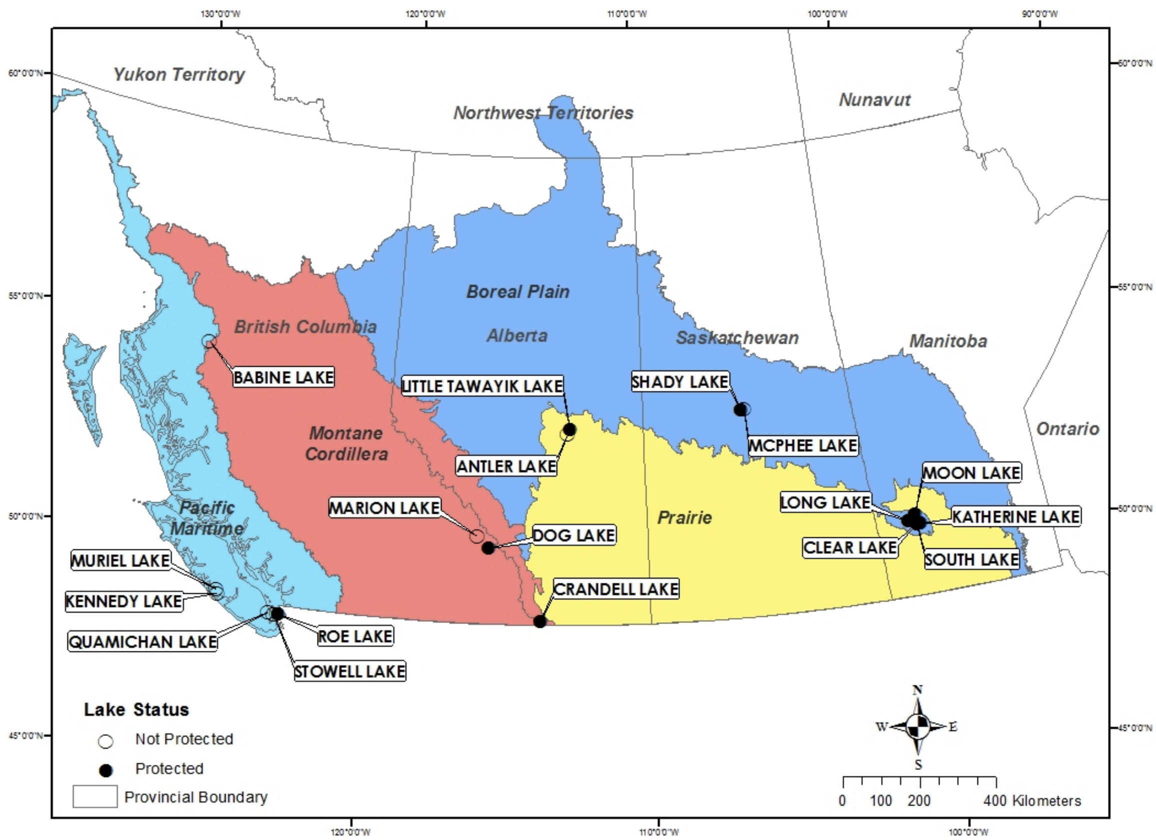


Figure 2.1 **Map of lake coring sites. Shaded area represents different ecozones (Atlas of Canada, 2009). Circles represent lake coring location and protection status. Solid circles represent cores from lakes that lie within a protected area (such as a national park) and hollow circles represent cores from lakes that lie outside any protected areas.**

Table 2.1 **Setting, description, average C accumulation rate, and sediment focusing factor for several time periods of the lakes included in this study.**

Site Name	Latitude (N)	Longitude (W)	Elev. (m)	Lake Area (ha)	Catch-ment Area (ha)	Max. Water Depth (m)	Eco-zone	1830-1860 mean C accumulation rate (g/m^2/yr)	1980-2010 mean C accumulation rate (g/m^2/yr)	1980-2010: 1830-1860 mean C accumulation rate (g/m^2/yr)	Sediment Focusing Factor
Babine	54 49'19.94	126 8'47.52	714	47900	NA	235	PM	1.27	4.14	1.12	0.334
Muriel	49 8'23.88	125 36'1.76	12	150	1650	45	PM	4.39	14.9	1.25	0.369
Kennedy	49 3'7.81	125 32'3.25	7	4268	29946	140	PM	0.0850	0.199	0.216	0.0941
Quami-chan	48 48'15.98	123 39'28.10	62	285	3465	8	PM	4.24	24.3	0.708	0.124
Stowell	48 46'54.87	123 26'36.32	97	5.65	911	7.5	PM	14.9	60.0	5.07	1.26
Roe	48 46'57.74	123 18'11.00	118	3.2	221	25	PM	12.6	37.2	2.09	0.686

Site Name	Latitude (N)	Longitude (W)	Elev. (m)	Lake Area (ha)	Catch-ment Area (ha)	Max. Water Depth (m)	Eco-zone	1830-1860 mean C accumulation rate ($g/m^2/yr$)	1980-2010 mean C accumulation rate ($g/m^2/yr$)	1980-2010: 1830-1860 mean C accumulation rate ($g/m^2/yr$)	Sediment Focusing Factor
Marion	51 2'49.47	116 21'28.79	1264	13.6	2519	13.7	MC	0.727	3.05	0.444	0.105
Dog	50 46'50.56	115 55'44.14	1185	15.1	1428	4.7	MC	41.0	242.19	17.9	2.99
Crandell	49 5’13.26	113 58’4.62	1534	6.4	98	15	MC	105	168	6.68	4.00
Antler	53 29’50.89	112 58’57.66	764	166	796	4.6	P	82.4	324	11.9	3.03
Little Tawayik	53 34'36.64	112 53'3.70	718	127	493	1.2	P	149	113	0.922	1.03

Site Name	Latitude (N)	Longitude (W)	Elev. (m)	Lake Area (ha)	Catch-ment Area (ha)	Max. Water Depth (m)	Eco-zone	1830-1860 mean C accumulation rate (g/m^2/yr)	1980-2010 mean C accumulation rate (g/m^2/yr)	1980-2010: 1830-1860 mean C accumulation rate (g/m^2/yr)	Sediment Focusing Factor
Shady	53 52'9.99	106 6'57.33	597	98	379	6.3	BP	24.2	60.5	3.25	1.28
Moon	50 52'46.23	100 3'0.36	580	178	1775	5	BP	21.6	120	4.81	0.855
Long	50 46'17.12	100 19'33.52	580	63	1543	7.3	BP	8.35	8.14	0.713	0.673
South	50 38'42.17	100 0'39.46	625	238	958	1.5	BP	33.7	67.2	2.96	1.48
Clear	50 41'1.32	100 0'13.97	616	2947	12069	23	BP	24.5	283	54.2	3.85

Site Name	Latitude (N)	Longitude (W)	Elev. (m)	Lake Area (ha)	Catch-ment Area (ha)	Max. Water Depth (m)	Eco-zone	1830-1860 mean C accumulation rate (g/m^2/yr)	1980-2010 mean C accumulation rate (g/m^2/yr)	1980-2010: 1830-1860 mean C accumulation rate (g/m^2/yr)	Sediment Focusing Factor
Kather-ine	50 39'25.38	99 53'37.04	642	25.2	106	10.5	BP	20.7	89.9	4.32	0.962
McPhee	53 52’31.36	105 57’48.20	522	206	1218	7.2	BP	28.3	35.0	1.47	1.17

2.3.2. Site selection and coring strategy

Initial lake selection was based on several criteria. First, single closed-lake systems (i.e., hydrologically closed with no significant aquatic inflow and outflow) with readily-defined catchment areas that have been minimally impacted by human activities (e.g. road construction) were preferred, to minimize complexity of C budgets associated with heterogeneities in inputs, outputs, and sedimentation regimes. Second, lakes with minimal influences from glacial inputs were chosen to minimize the impacts of glacially produced sediment loading as well as the buffering effect that cool glacial-water inputs will have on the lake as a recorder of regional climate changes. Babine Lake is the notable exception at a lake area of $4.7x10^4$ (ha). Babine Lake is an order of magnitude larger than the next largest lake in this study (Kennedy at $4.2x10^3$ (ha) (Table 2.1)). Despite spanning multiple catchment areas it was included in this study as an example of a large lake.

To investigate the potential effect of anthropogenic land-use influences on C accumulation rates, we paired lakes with a protected status (i.e., limited impacts of resource extraction or land modification such as logging, agriculture, and infrastructure development over past 100 years) to adjacent lakes with no protected status (which are more likely to be impacted by human activities). The four pairs of lakes included: (1) Dog (Kootenay National Park) and Marion (No Protection Status), (2) Roe (Gulf Islands National Park) and Stowell (No Protection Status), (3) Little Tawayik (Elk Island National Park) and Antler (No Protection Status), and (4) Shady (Prince Albert National Park) and McPhee (No Protection Status). When choosing lakes to couple, the lake morphology characteristics of surface area and depth as well as distance between lakes were considered (Table 2.1).

Sediment cores were obtained from the deepest point of each lake which was determined using a recreational-grade sonar fish finder. Due to limited time and resources only one sample was taken at each site. Sediments were extracted using a gravity corer (Glew et al., 2001) by either Dr. Marlow Pellatt from Parks Canada or the author (Table 2.2) and subsequently preserved at 4°C and transported to the Climate Oceans and Paleoenvironments (COPE) laboratory at Simon Fraser University in Burnaby, Canada.

Table 2.2 Who retrieved the core and in what year for each lake in this chapter.

Lake	Cored by
Babine	Dr. Marlow Pellatt in 2002
Muriel	Dr. Marlow Pellatt in 2002
Kennedy	Dr. Marlow Pellatt in 2002
Quamichan	Dr. Marlow Pellatt in 2003
Stowell	Dr. Marlow Pellatt in 2004
Roe	Dr. Marlow Pellatt in 2004
Marion	Thomas Rodengen in 2012
Dog	Dr. Marlow Pellatt and Thomas Rodengen in 2011
Crandell	Thomas Rodengen in 2013
Antler	Thomas Rodengen in 2013
Little Tawayik	Thomas Rodengen in 2013
Shady	Thomas Rodengen in 2013
Moon	Dr. Marlow Pellatt in 2010
Long	Dr. Marlow Pellatt in 2008
South	Dr. Marlow Pellatt in 2010
Clear	Dr. Marlow Pellatt in 2010
Katherine	Dr. Marlow Pellatt in 2010
McPhee	Thomas Rodengen in 2013

2.3.3. Carbon accumulation rates

Cores were sampled at one cm intervals to estimate the change in accumulation rates of total organic C in each lake versus time. Lake C accumulation rates (TOC MAR) were determined using the following equation:

$$\text{TOC MAR (g/m}^2\text{/yr)} = \text{TOC (\%)} * \text{MAR (g/m}^2\text{/yr)} \qquad (1)$$

Where TOC is the total organic C concentration, and MAR is the mass accumulation rate. TOC was estimated by calculating the difference between the percent total carbon (TC) and the percent total inorganic carbon (TIC) (Last and Smol, 2001). TC was measured using a Costech ECS 4010 elemental analyzer, and TIC was measured using a UIC CM5130 acidification module connected to a UIC CM5014 CO_2 coulometer (Appendix B7). Although more labor-intensive, this method of determining TOC has the advantage that it is a direct measure of sediment C content (Meyers and Teranes, 2001).

MAR was determined by the following equation:

$$\text{MAR (g/m}_2\text{/yr)} = \rho_{DBD} \text{ (g/m}^3\text{)} * LSR \text{ (m/yr)} \qquad (2)$$

Where ρ_{DBD} is the measured dry bulk density of the sediments, and *LSR* represents the linear sedimentation rate. Dry bulk densities (ρ_{DBD}) were measured directly on one cc of sediment sample material after 24 h in a drying oven set at 60°C. The linear sedimentation rate *LSR* was based on age models determined for each core. The chronologies were constructed using between five and 18 ^{210}Pb measurements per core, made by MyCore Scientific Inc and using a ^{210}Pb constant rate of supply model (Oldfield & Appleby, 1984) (Rowan et al., 1994). Average linear sediment rates per core ranged from 0.03 cm/yr (Stowell lake) to 2.00 cm/yr (Quamichan lake), based on these age models (Appendix B1).

A sediment focusing factor was estimated for all cores and applied to the C accumulation rate (TOC MAR) to account for sediment focusing on a lake-by-lake basis in Table 2.1. The representation of whole-lake C accumulation rates from a single-core has been shown to be inaccurate when compared with multi-core studies (Engstom and Rose, 2013). A multi-core study from a single lake concluded that sediment focusing accounted for 59% of the variance in sediment accumulation rate (Hilton et al., 1986). The focusing factor allows one to estimate the magnitude of uneven sediment deposition rates that occur as a result of horizontal transport of sediment. The focusing factor is calculated by dividing the observed ^{210}Pb flux (measured in sediments) by estimates of the atmospheric flux of ^{210}Pb and assuming a constant rate of supply of ^{210}Pb to the lake surface (Anderson et al., 2013; Anderson et al., 2014; Heathcote et al., 2015). We assumed average ^{210}Pb flux of 100 Bq kg^{-1} per year per 1,000 mm of precipitation in lieu of measured ^{210}Pb flux (Appleby, 2001). Mean annual precipitation (MAP) rates were acquired from ClimateWNA over the available record (1901-2009) (Wang et al., 2012). Focusing factor data necessary for calculation can be found in Appendix B5.

The focusing factor was calculated by the following equation:

$$\text{Focusing Factor} = \text{Average Flux of } ^{210}\text{Pb (Bq m}^{2}\text{ yr) (observed)} / \text{Expected Flux/yr (Bq kg}^{-1}\text{) (100 Bq kg}^{-1} / \text{(MAP / 1000 (mm))} \quad (3)$$

Estimates of the organic C/N (atomic) ratios were also calculated based on TOC and Total Nitrogen (TN) values from each sample processed using the Costech ECS 4010 elemental analyzer. C/N (atomic) values are used as a potential indicator of different sources of organic matter (e.g., Meyers, 1997). The C/N ratio can be used to classify the source of organic matter found accumulating in sediments as either autochthonous (i.e., formed in-lake), allochthonous (formed out-of-lake), or some mixture of these two sources. Previous investigators have found that the C/N ratios of allochthonous, terrestrial organic matter inputs are enriched in humic compounds with much higher C contents (C/N ratios of >20) than C/N ratios resulting from *in situ* production, which are typically less than 9 (Meyers and Ishiwatari, 1993; Dean and Gorham, 1998; Meyers and Lallier-Vergès, 1999). We used these C/N categories to classify organic matter as either aquatic (C/N of 3-9), terrestrial (C/N of >20), or a mix of the two sources (C/N between 10 and 20) (Appendix B6).

Inorganic carbon (%TIC) is found mainly in the form of calcium carbonate. Average TIC is only greater than 1% in Clear (2-6%), Dog (4-10%), Little Tawayik (1-2%), Long (0-5%), Marion (2-4%), and South (3-4%) Lakes (Appendix B7). Dog and Marion Lakes are in the Kootenay Valley of the Rocky Mountains that contain calcareous

(5-40% calcium carbonate) exposed bedrock (Achuff et al., 1984), which provides dissolved inorganic carbon to the water column and ultimately the lake sediment. Clear, Little Tawayik, Long, and South lakes are all shallow lakes with inflows from both surface water and shallow groundwater. Dissolved inorganic carbon in shallow groundwater and surface water can provide the foundation for autochthonous organic carbon through enhanced primary productivity (Wetzel, 2001).

2.3.4. Supporting climatological data and temporal analysis

With the goal of explaining any patterns in C accumulation rates, we assembled supporting information describing the regional climate variability around each lake. Climate can affect C cycling in lake systems leading to changes in C burial in lake sediments (e.g., Gudasz et al., 2010; Mustaphi and Pisaric, 2014; Campbell, 2015; Velthuis et al., 2018). We extracted climate data from the Parameter-elevation Relationships on Independent Slopes Model's (PRISM) downscaled version of monthly climate data for 30-year climate normals (e.g., 1980-2010) and over the entire record available (1901-2009) (Daly et al. 2002; 2008), using ClimateWNA (Wang et al., 2012). These data have been downscaled to a resolution of 2.5 x 2.5 arcmin to represent the average conditions at our study sites in western Canada. Seventeen ClimateWNA variables were considered (Appendix B2). Collectively, these variables provide information on (a) seasonal, annual, and extreme temperatures experienced within the watershed; (b) the numbers of growing-degree and frost-free days that could impact surrounding vegetation and lake productivity; and (c) seasonal to annual changes in precipitation, which could affect runoff into lake catchments.

To examine potential causes of changes in TOC MAR through time, we examined, temporal correlations between changes in, C/N ratios and the continuous climate variables were calculated, and their significance was quantified using the non-parametric Spearman's rank correlation coefficient (Spearman's ρ), using R (R Development Core Team, 2013). Spearman's ρ provides an estimate of the strength and direction of the relationship between explanatory variables and C accumulation rates over time. In trend analyses, we consider results significant at the $p \leq 0.05$ level. Typically, autocorrelation would be tested using the Durbin-Watson statistic. However, the data values are not equally spaced in time to use this formal testing technique. Additionally, most of the lakes contain less than 30 data paints making it very difficult to observe or detect any autocorrelation using any statistical test. Effects of autocorrelation were taken into consideration when reporting the any trends. Two lakes (South, Babine) contained less than 10 data points after 1901 and were not included in this part of the analysis (Appendix B8).

2.3.5. Supporting land-use and morphological data and spatial analysis

Lake morphology has been suggested to modulate the ability of lakes to retain carbon, with lower C accumulation rates per unit area generally found in larger lakes with greater dynamic ratios (e.g., Mulholland and Elwood, 1982; Downing et al. 2006; Dong et al., 2012; Ferland et al., 2012). We characterized lake morphology using the following variables: lake area, catchment area, catchment area: lake area ratio (CA:LA), lake geometry ratio (LGR) used by Dietz et al. (2015), and a modified version of the dynamic ratio previous used by Ferland et al. (2012). Lake and catchment area were calculated from either a watershed atlas or published sources (Appendix B3; Mitchell and Prepas, 1990; BC Ministry of Environment, 2005; Saskatchewan Watershed Authority, 2009; White, 2010; Earth Point, 2014). The lake geometry ratio is defined as the lake area$^{0.25}$ divided by the maximum depth (Dietz et al., 2015). Ferland et al. (2012) previously defined the dynamic ratio as the square root of lake area divided by mean lake depth. For this study, we use the maximum depth of the lake (which was determined during sediment core retrieval using a recreational sonar device) instead of mean lake depth as accurate bathymetric maps for most of our study lakes did not exist.

We characterized land use in each catchment area by estimating the percentage of each of 12 land cover types that were found in a lake's catchment area (Land Cover for Agricultural Regions of Canada, circa 2000, 2001). These land cover types include: water, exposed land, shrubland, wetland, grassland and native grass, agriculture, mixed forest, coniferous forest, deciduous forest, total developed and agriculture (Appendix B4). We combined the "annual cropland," "perennial cropland and pasture," "agriculture" categories into one "% agricultural use" category and combined the "Agricultural use" and "Development" categories to create a "total development and agricultural use" category.

To examine possible spatial relationships between C accumulation rates and regional variables, we compared our estimates of historical (1830-1860) and modern

(1980-2010) C accumulation rates with climate, morphological, and land-use variables determined for each lake, using a pairwise correlation and considering results significant at the $p \leq 0.05$ level. To understand if any of these variables influence the rate at which C accumulation rates change, we also compared these environmental variables with the ratio between modern and historical C accumulation rates.

Finally, our distribution of lakes allowed for the comparison of four pairs of lakes, with each consisting of a "protected" and "non-protected" lake. Lakes were classified as “protected” if the majority (>50%) of the lake area exists inside of a municipal, provincial, or national protected area (Appendix B3). The pairs of lakes included: Dog (protected) and Marion (not protected); and Roe (protected) and Stowell (not protected); Shady (protected) and McPhee (not protected); Little Tawayik (protected) and Antler (not protected). I anticipate that lakes without protected status would have experienced larger impacts from human activities and therefore would have larger changes in C accumulation rates than those lakes with protected status.

2.4. Results

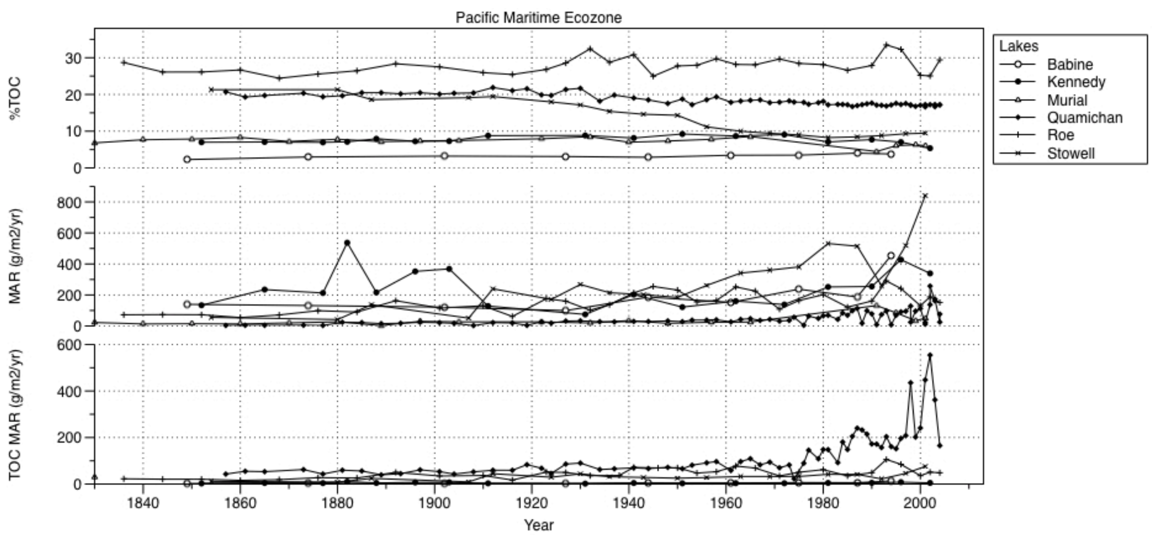
2.4.1. C accumulation rates, % total organic carbon, and mass accumulation rates since the mid 1800s

Average C accumulation rates since 1830 range from 0.457 ± 0.075 (Kennedy Lake) to 186 ± 144 (Quamichan Lake) $g/m^2/yr$ across the study region. Of the 16 lakes included in the trend analysis, 13 demonstrated significant C accumulation rate trends between 1860 and 2010 (Spearman rank correlation, p-value < .05; Appendix B8). Of these 13 lakes, 12 demonstrated increasing trends since 1860. Long Lake was the only site that demonstrated a significant decreasing trend in C accumulation rates since 1860. An additional three lakes (Little Tawayik, Kennedy, Marion) did not demonstrate significant trends in C accumulation rate since 1860.

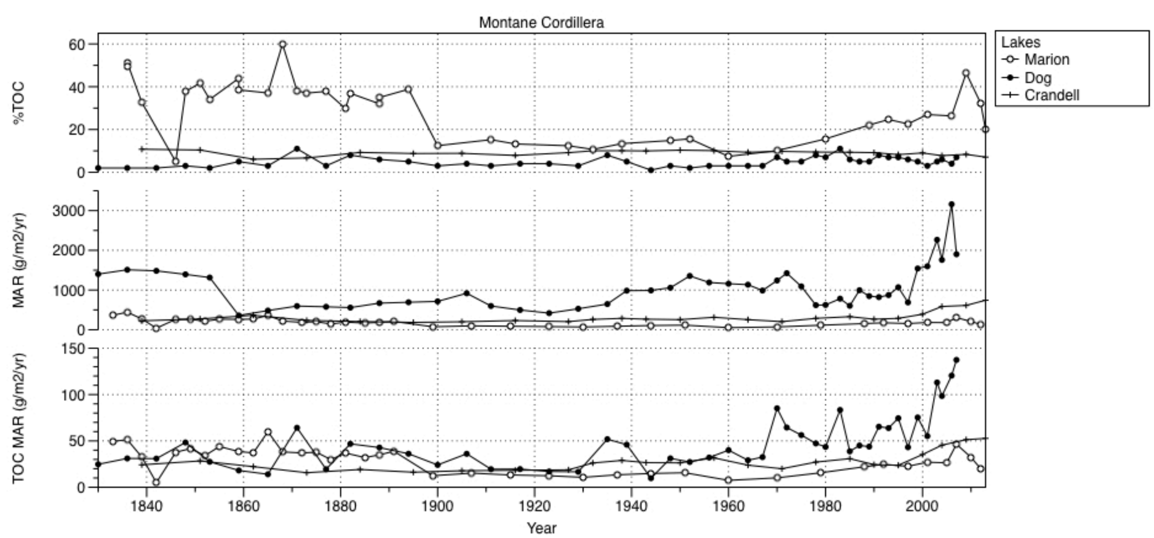
Between 1860 and 2010, 13 lakes demonstrated significant trends in MAR (Spearman rank correlation, p-value < .05; Appendix B8). Twelve of the 13 lakes are the same as those that demonstrated significant trends in C accumulation rate. The lakes that did not demonstrate significant MAR trends included Kennedy, Marion and Long lakes. Only Little Tawayik Lake had a negative MAR trend.

Unlike C accumulation rates and MAR, only eight of 16 lakes had significant trends in %TOC between 1860 and 2010 (Spearman rank correlation, p-value < .05; Appendix B8). Four of the eight lakes had positive trends (Little Tawayik, Dog, Clear, and Long Lakes) and four had negative trends (Kennedy, Muriel, Quamichan, and Moon) (Appendix B8).

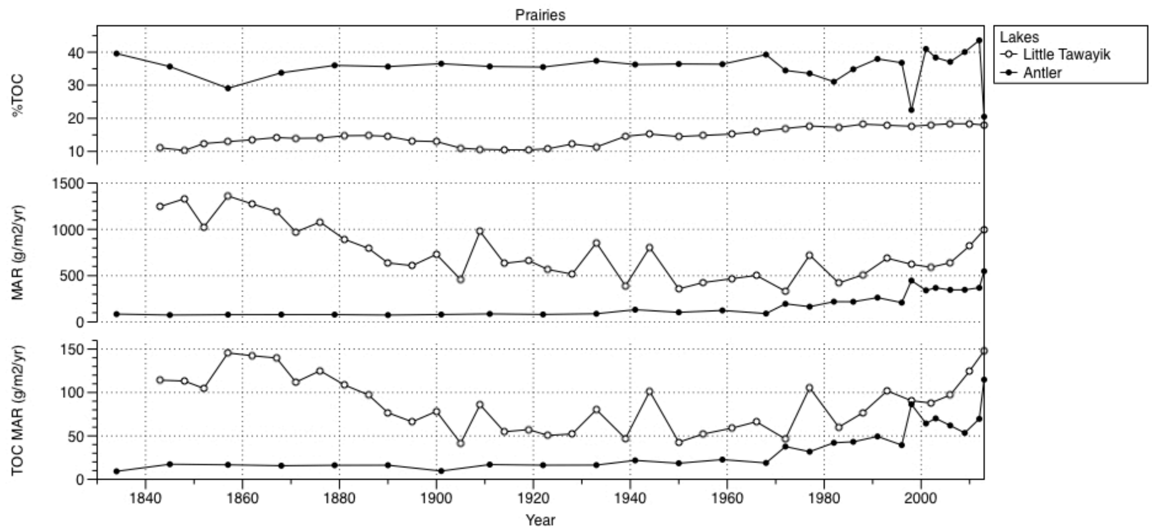
(a)



(b)



(c)



(d)

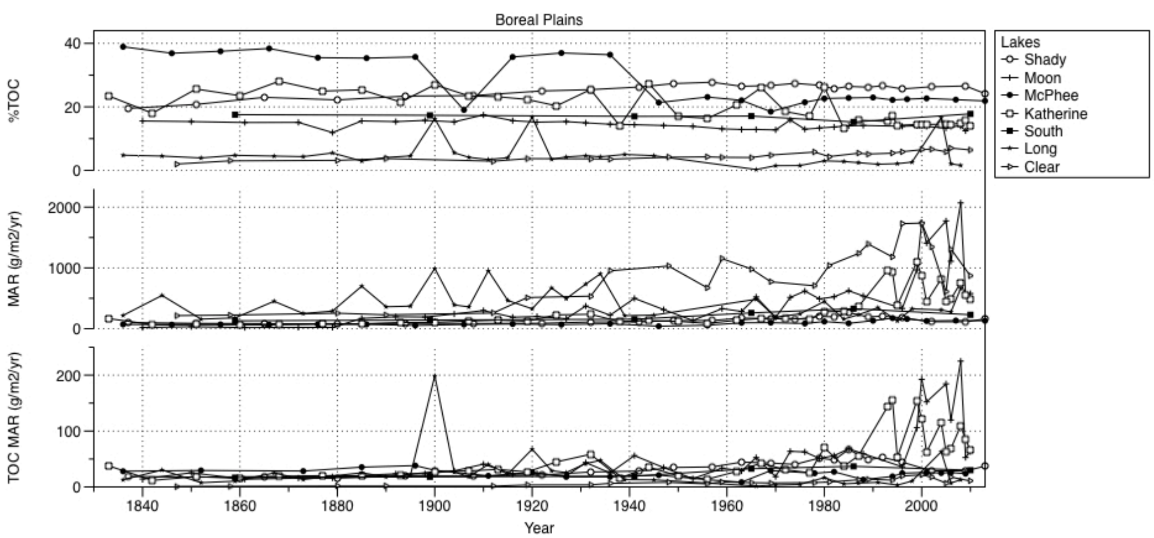
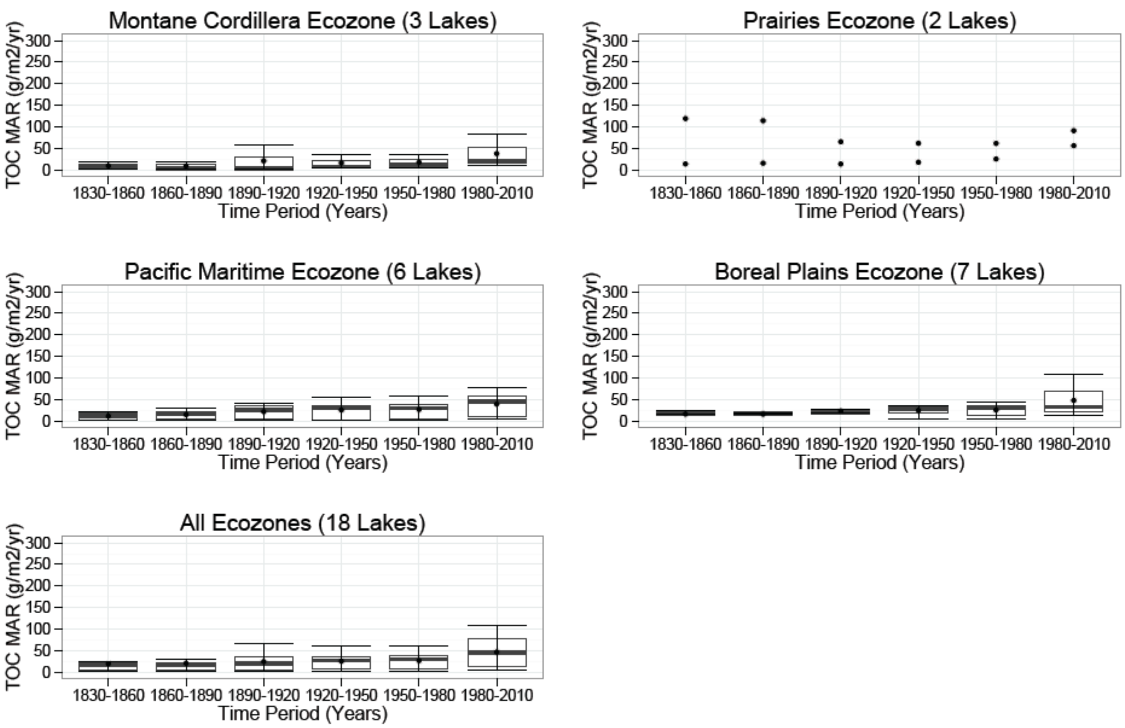


Figure 2.2 %TOC, MAR (g/m^2/yr), and TOC MAR (g/m^2/yr) between 1830-2010 for all lakes separated by ecozone. (a) Pacific Maritime. (b) Montane Cordillera. (c) Prairies. (d) Boreal Plains.

We calculated average C accumulation rates for a series of 30-year time periods for each lake sediment record (Figure 2.3) (Appendix B9). In general, estimates of TOC MAR increase from the earliest to the latest time periods for all ecozones (Figure 2.3). The largest average C accumulation rates are observed in the most recent time period

(1980-2010), and C accumulation rates are greater during the 1980-2010 compared with the 1830-1860 time periods for 16 out of the 18 lakes (Table 2.1). The exceptions to this pattern are observed in Little Tawayik (Prairies ecozone) which shows a ~20% decrease in C accumulation rates during 1980-2010 relative to 1830-1860, and Long Lake (Boreal Plains ecozone) which exhibits little or no change (Table 2.1; Figure 2.3).

(a)



(b)

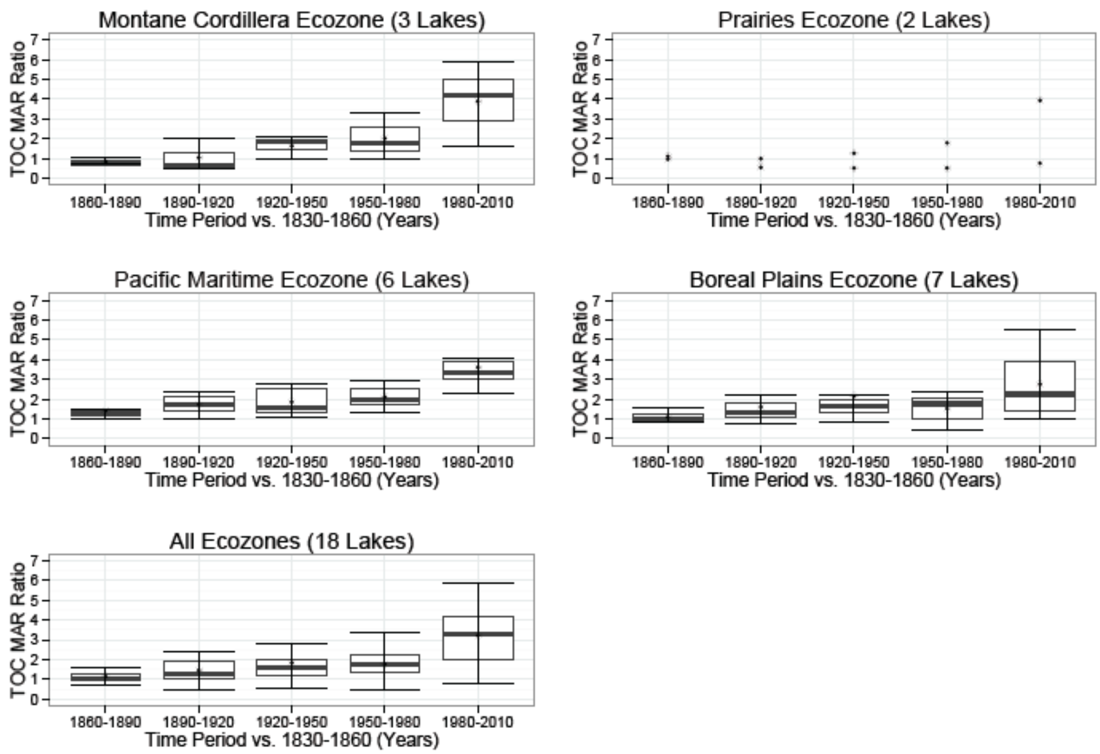


Figure 2.3 **(a) Average carbon accumulation rates for five time periods (1830-1860, 1860-1890, 1890-1920, 1920-1950, 1950-1980, 1980-2010) separated by ecozone. (b) C accumulation ratios (selected by time period relative to the 1830-1860 period) separated by ecozone. Boxes represent the inter-quartile range, midlines indicate median values, solid dots are the means, and whiskers denote 90% Confidence Intervals.**

On average, C accumulation rates are 3.8 times greater during the 1980-2010 time period when compared with the 1830-1860 time period. Of the 16 lakes that showed an increase, increases in C accumulation rates ranged from 1.2 times in McPhee Lake (Boreal Plains ecozone) to 14 times greater in Clear Lake (Boreal Plains ecozone) in 1980-2010 compared with 1830-1860. If we consider changes by ecozone, the six lakes in the Pacific Maritime ecozone have C accumulation rates that are 3.6 times greater in 1980-2010; C accumulation rates were 4.4 times greater for the seven lakes in the Boreal Plains ecozone; and 3.9 times greater for the three lakes in Montane Cordillera ecozone in 1980-2010 compared with 1830-1860 (Figure 2.3). Little Tawayik Lake of the Prairies ecozone had C accumulation rates decrease ~20% during between

1830-60 and 1980-2010, while Antler Lake of the Prairies ecozone had C accumulation rates that were 3.9 times greater during1980-2010 when compared to 1830-1860.

In most instances, changes in MAR mirror the observed C accumulation rate increases. Average MARs are 7.1 times greater during the 1980-2010 time period compared with the 1830-1860 time period, with differences ranging from no change in MARs in Dog Lake (Montane Cordillera ecozone) to MARs that are 40.2 times greater in 1980-2010 compared with 1830-1860 in Moon Lake (Boreal Plains ecozone). Only Marion Lake (Montane Cordillera ecozone) experienced a 37% decrease in MAR between the 1980-2010 and 1830-1860 time periods.

2.4.2. Temporal relationships between C accumulation rate, sedimentary variables, and climatological variables

Eleven of the 16 lakes showed significant relationships with one or more temperature-related variables (Appendix B8). Mean Annual Temperature (MAT) was positively correlated with C accumulation rates in five lakes. The number of frost-free days (NFFD), Growing Degree Days above 5°C (GDD5), Mean Warmest Month Temperature (MWMT), Summer Mean Temperature (Tave_sm), and Frost-free Period (FFP) all demonstrated significant positive relationships with C accumulation rates in four of the 16 lakes.

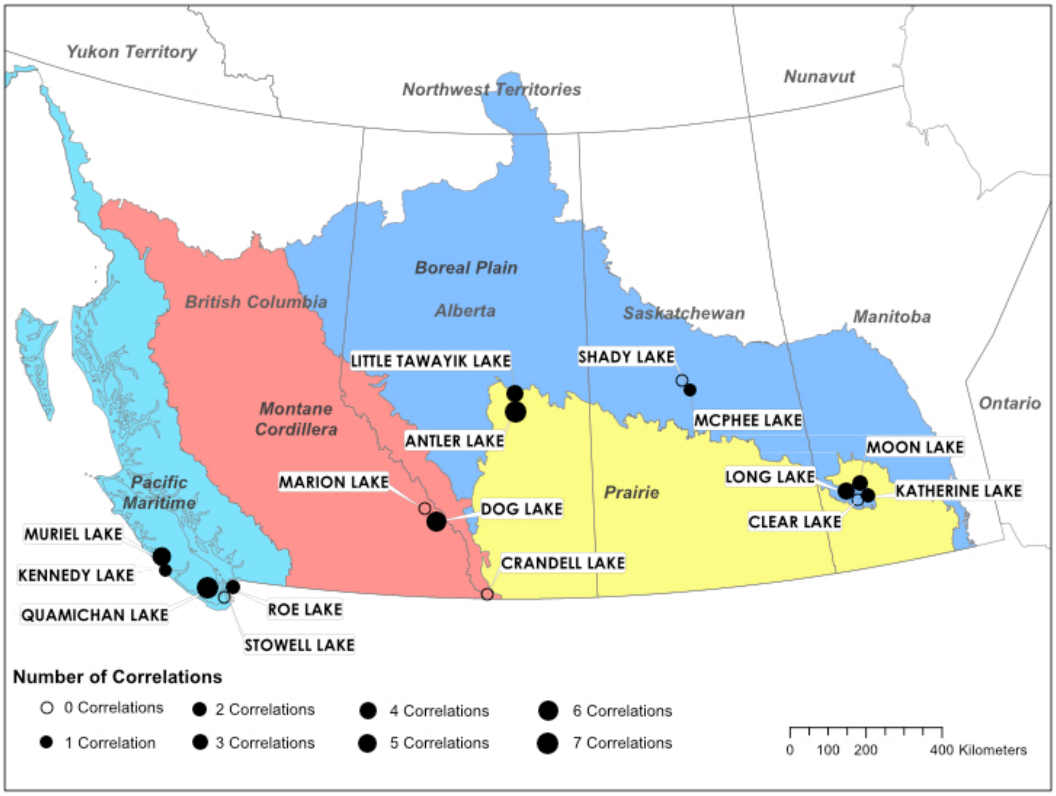


Figure 2.4 **Number of correlations between C accumulation rate and climate-related variables.**

The strongest correlations between increases in C accumulation rates and increases in climate-related variables were observed at Quamichan, Dog, Muriel, and Antler Lakes, each of which showed significant correlations with five or more climate-related variables (Appendix B8). Exceptions were where increases in C accumulation rate were correlated with decreases in the number of degree-days below 0°C (DDBO) at Dog, Katherine, Roe and Quamichan Lakes. Another exception is where increases in C accumulation rate were correlated with deceases in Autumn (September – November) Mean Temperature (Tave_at) at Dog Lake. A final temperature-related exception is where C accumulation rate were correlated with decreases in Mean Warmest Month Temperature (MWMT), Spring Precipitation (PPT_sp), Growing Degree-days above 5°C (GDD5), and Summer (June-August) Mean Temperature (Tave_sm) at Long Lake.

Only two lakes showed any significant correlation with precipitation variables (Appendix B8). Antler Lake showed increases in C accumulation rate towards present day were correlated with a decrease in Winter Precipitation (PPT_wt) and increases with Summer Precipitation (PPT_sm). Long Lake showed increases in C accumulation rate towards present day were correlated with a decrease in Spring Precipitation (PPT_sp).

Six lakes demonstrated significant relationships between C accumulation rate and C/N (Appendix B8). Antler and Muriel Lakes showed increases in C accumulation rate towards present day were correlated with a trend towards allochthonous sediment influx, while Little Tawayik, Marion, Kennedy, and Moon Lakes showed increases in C accumulation rate towards present day were correlated with a trend towards autochthonous sediment influx.

2.4.3. Spatial relationships between climatic, morphometric, and land-use variables and modern (1980-2010) and historical (1830-1860) C accumulation rates at all lakes

Our spatial comparison revealed no significant correlations between the lake C accumulation rates and the geographic, climatic, and land use variables, for either the modern (1980-2010) or historical (1830-1860) time intervals (Spearman's ρ correlation; $p < 0.05$; see Appendix B10).

However, we did find statistically significant relationships between lake C accumulation rates and several lake morphological explanatory variables, including a negative relationship with maximum depth and a positive relationship with the lake geometry ratio. This suggests that greater lake depths are associated with decreasing C accumulation rate. Also, increases in C accumulation rate are associated with how large a lake is in relation to its depth. Historical C accumulation rates also showed a significant negative relationship with catchment area (i.e. larger catchment areas were associated with lower historical C accumulation rates) (Appendix B10). Finally, lake C accumulation rates were positively related to %TOC, suggesting that lakes with higher organic carbon content also had higher C accumulation rates.

A matched paired t-test revealed no significant differences (0.05 significance level) between the either the average C accumulation rates between 1980 and 2010 (t(3)

=-1.92, p=0.15) or estimates of MAR between 1980 and 2010 (t(3)=-0.90, p=0.43) for the pairs of lakes assigned with “protected” and “not protected” status.

2.5. Discussion

2.5.1. Possible causes of temporal changes in C accumulation rates - Land use

Our study agrees with other studies that show increases in lake C accumulation rates since the mid-1800s. Similar increases have been seen across all eco-regions of China after 1900 (Zhang et al., 2017). A study of European lakes has shown that C accumulation rates at 20 cm core depth (~200 cal. yrs BP) are 2 times higher than the long-term average (5,000 to 2,000 years BP) (Kastowski et al., 2011). A Finnish lake has shown increases in C accumulation rates over the past 100 years (Rantala et al., 2016). Since 1850, C accumulation rates have increased 2.8 times in the Boreal and Plains ecozones in Minnesota (Anderson et al., 2013; Dietz et al., 2015), and 4.5 times in Iowa lakes (Heathcote and Downing, 2012). Although not the focus of their paper, lakes from north-central Alberta, Canada (Squires et al., 2006) also showed increases in C accumulation over the last 50 years. These studies suggest that increases in lake C accumulation rates over the past ca. 150 years have occurred in many regions of the Northern Hemisphere.

Several studies have suggested that land use changes explain increases in lake C accumulation rates. Many studies find that land use (specifically, agricultural activity) is a primary driver of increases in C accumulation rates (e.g., Kastowski et al., 2011; Heathcote and Downing, 2012; Anderson et al., 2013; Dietz et al., 2015). Zhang et al. (2017) attribute temporal changes in C accumulation rates to (a) changes in agricultural development, and (b) enhanced lake productivity from eutrophication in response to additional of chemical fertilizers after 1980. Thus, land-use change appears to be an important driver of the changes in carbon accumulation rates, particularly in lakes situated near agricultural activity.

Although our sampling strategy attempted to minimize the effects of land use, several of the lakes in this study may be affected by regional activities. Specifically, Quamichan, Stowell, and Roe are located on Vancouver and Gulf Islands on developed landscapes. These lakes have C accumulation rates that are 3.0-5.7 times greater in

1980-2010 compared to 1830-1860. In the Boreal Plain ecozone, McPhee, South, and Clear lakes have C accumulation rates that are 1.2-14-times greater in 1980-2010 when compared with 1830-1860. Surrounding agricultural activities may also impact these lakes. In the Prairie region, Antler Lake (3.9 times greater C accumulation rates in 1980-2010) is situated outside of Elk Island National Park in a region with agricultural activities.

Several lakes such as Babine, Muriel, and Kennedy may also have been affected by logging activities that influenced carbon accumulation. These lakes show 2.3-3.4 times higher C accumulation rates during 1980-2010 when compared to 1830-1860 (Table 2.1). Thus, this study does not rule out the role of agricultural and logging activity in driving changes in carbon accumulation.

Protected area status did not have any statistical significance in relation to C accumulation rate. Several reasons may have distorted this comparison. Our threshold of protected status (>50% of the area within a protected area) might be too low. Also, most protected areas have only been established within the last century and the effects of protection status may not be realized within the timeframe of this study.

In looking for drivers of C accumulation rate with surrounding land use variables future work will want to take a narrow approach (Hanson et al., 2014b). I ran into the drawback of too broad a scope in selecting possible explanatory variables and in turn could only provide first-order estimates on their contributing significance. If planning or land use decisions are to be made on this line of inquiry, then in-depth analysis on their explanatory variables implications. For example, if lake C accumulation rate were taken into consideration in the next wildfire plan of the region, then proxies of pollen for vegetative state and charcoal for fire interval should be considered alongside historical records of logging. My investigation found that McPhee Lake demonstrated a change in sediment sourcing after 1946 that was not found in its companion lake outside Prince Albert National Park (Shady Lake). This is most likely due to a series of nearby fires from 1933-1945 (Prince Albert National Park Fire History, 2009). It is this kind of lake-by-lake analysis that must be done when analyzing surrounding land use variables to explain the increasing trend in C accumulation.

2.5.2. Possible causes of temporal changes in C accumulation rates - Climate

Previous studies have attributed changes in lake C accumulation to climatic changes that affect the autochthonous inputs on C accumulation in surface sediments (Rantala et al. 2016). Other studies, which do not explicitly document lake C accumulation rates, have also inferred a role of climatic variables in increasing C accumulation rates, largely through changes in temperature-correlated autochthonous inputs (Dillion and Molot, 1997; Rosen et al., 2009).

In our study, 69% of lakes showed significant relationships with C accumulation rate and one or more temperature-related variables. These temperature-related climate variables are likely to affect lake productivity. For example, the number of ice-free days has been shown to affect dissolved organic C, phytoplankton growth, food-web dynamics, and other autochthonous inputs on C accumulation (Dillion and Molot, 1997; Rosen et al., 2009; Heathcoate et al., 2015; Rantala et al., 2016). The NFFD and FFP are positively correlated with C accumulation in five of our 16 lakes including both of the lakes in the Prairies ecozone (Antler and Little Tawayik). Antler and Little Tawayik lakes are both relatively shallow lakes where a lengthening of the ice-free period would manifest in increased aquatic primary productivity due to elevated UV transparency in the water column (Rantala et al., 2016). Warming temperatures have been associated with regime shifts in aquatic communities including those of the benthic zone (Smol et al., 2005; Lehnherr et al., 2018). Thus, although not likely an exclusive driver, these correlations between temperature-related variables and C accumulation rate in 11 out of 16 lakes suggest some overarching influence of climate on C accumulation rates.

2.5.3. Possible causes of temporal changes in C accumulation rates - Other and uncertainties

Previous studies have suggested that mineralization followed by evasion to the atmosphere can also affect overall C accumulation rates in lake sediments through its influence on burial efficiency of carbon (e.g., Cole et al., 2007). While not restricted to the uppermost sediment layer, mineralization includes benthic processes that respond to a host of factors, including lake temperature (Pace and Prairie, 2005). Gälman et al.

(2008), demonstrated that 20% of the C concentration in lake sediment was lost in the first five years after deposition and 23% after 27 years. An increase of temperature in various climate-warming scenarios predicted a 4-27% decrease in C accumulation in boreal lakes though increased mineralization (Gudasz, 2011). C accumulation rate's sensitivity to mineralization needs to be considered alongside a lakes individual organic carbon sourcing and resulting ecological stability. Benthic respiration, mineralization, and other in-lake processes like CO_2 efflux are areas of continuing research in organic carbon sedimentation and needed for future understanding of long-term C accumulation in these lakes (Ferland et al., 2014; Solomon et al., 2015; Hanson et al., 2014b). In this study removing the upper 10cm of sediment to account for mineralization between 1830 and 2010 reduced the number of available data points by 43%. Removal of the upper 10cm of sediment also reduced the average C accumulation rate from 1830 to present by 72% (Appendix B10). Removal of such a large component of the sediment record made this method of addressing mineralization unfeasible for this study.

Ferland et al. (2014) argue that while C accumulation may be functionally linked to mineralization, lake shape is the primary control on C accumulation rate due to sediment focusing, the concept that lake sediments do not accumulate uniformly over a lake's basin. Indeed, our data also show that the variables Maximum Lake Depth and Lake Geometry Ratio were significantly correlated with C accumulation rate in both the modern and historical accumulation rates. These correlations suggest that the deepest lakes tended to have lower C accumulation rates. These results are consistent with lake size scaling observed in other studies in western Canada (Molot and Dillion, 1996; Campbell et al., 2000; Squires et al., 2006; Finlay et al., 2010; Ferland et al., 2012), and are consistent with the idea that lake shape will influence how much sediment will accumulate.

Another potential source of uncertainty in calculating C accumulation rates in this study is use of the Linear Sedimentation Rate (LSR) (Appendix B1). LSR was applied downcore using the ^{210}Pb constant rate of supply (CRS) model. The CRS model is influenced by atmospheric flux and sediment transport from the catchment area and in the water column including sediment focusing. To account for atmospheric flux the CRS model includes validation of ^{210}Pb dates using ^{137}Cs and ^{241}Am peaks due to nuclear weapons fallout records (Appleby et al., 1991). Uncertainty with sediment transport is best-constrained using independently dated material (e.g., pollen, diatoms). The lakes in this chapter have not previously been dated and independent dating was outside of the financial constraints of this study. A correctional ^{210}Pb factor was not used to account for transport processes, as a “flattening” of the ^{210}Pb profile was not visible in any of the lakes. In cases where a corrected ^{210}Pb are used outside of this study a maximum error of less than 2 years for a mixing zone spanning 10 years suggests that transport in the CRS model is a negligible problem (Appleby, 1998).

A large source of uncertainty is the application of a sediment focusing factor. Seven of the 18 (39%) lakes had a focusing factor greater than one. Nine of 18 (50%) lakes had a focusing factor less than one. Two of 18 (11%) had a focusing factor within ±0.08 of one (Appendix B5). Half of the lakes focusing factors indicate that not all of the atmospheric deposition, which was deposited on the lake, made it into the sediments. This alludes to two possibilities. Either (1) I did not sample at the point in the lake where the full sediment record is realized, or, (2) there is a mechanistic process that is not being captured. Heathcote et al. (2015) suggests one such process might be the deposition of anthropogenic-derived nitrogen (N_r). N_r decreases mineralization through soil C sequestration increases and subsequent C input to the lake (Maaroufi et al., 2015). Future work will want to constrain the first uncertainty with multiple (more than five) cores (Engstrom and Rose, 2013). Applying the focusing factor to modern (1980-2010) C accumulation rates altered the rate by an average of 247% (Appendix B5). Given the variability in lake morphology and location across four ecozones in western Canada, I anticipated a change in focusing across lakes, but the spread in focusing factors above and below one needs further investigation.

Our data suggest that increases in C accumulation rate are highly correlated to increases in MAR, suggesting that changes in lake sedimentation rates are also a key factor in carbon burial in these lakes. These increases in MAR could be related to changes in the source (autothonous vs allocthonous) of materials reaching the lake sediments. The C/N ratios can provide an indication of carbon source material (Meyers and Teranes, 2001), and changes in the C/N over time could indicate changes in sediment and/or carbon sources that might influence both MAR and TOC MAR. Values less than 9 suggest autochthonous (in-lake) materials dominate; values greater than 20 suggest that most of the material is allochthonous, or coming from outside the lake. Values between 11 and 19 suggest a mix of sources (Meyers and Teranes, 2001).

In this study, the general absence of large changes in C/N ratios suggests that changes in sediment source are not a large driver of MAR changes at a regional scale (Appendix B6). However, land-use history of an individual lake might shed light on C accumulation rate controls and responses. For example, McPhee Lake experienced a change from in-lake, aquatic sources of carbon (average of 7 C/N) prior to 1946 to a mixture of terrestrial and aquatic carbon sources (average of 16 C/N) between 1946 and the present (Appendix B6). McPhee Lake is located just outside Prince Albert National Park, Saskatchewan, and may have been affected by a series of fires from 1933-1945 inside the park boundaries (Prince Albert National Park Fire History, 2009). Increase in fire occurrence on the landscape can translate into increased terrestrial sediment sourcing in a lake basin from soil erosion (Carcaillet et al., 2006) and charcoal (biomass) (Whitlock and Millspaugh, 1996), which might be the cause of the higher C/N ratios after 1946. Long Lake inside Riding Mountain National Park, Manitoba might be another example of where the C/N record points out a more localized C accumulation rate story. This coupled with three spikes in the %TOC record (Appendix B7) would be interesting to future investigation at a local level.

2.6. Conclusion

We present C accumulation rates from 18 lakes in western Canada that show a 3.8 times increase from 1830-1860 to 1980-2010. We explored land-use, climatic, morphological and other variables to explain this increasing trend. Our results are consistent with other studies that show changes in climate and differences in lake morphology. We show that these changes in C accumulation rates are most strongly correlated with temperature-related variables that affect lake productivity and differences in lake morphology related to depth. Increases in MAR would be consistent with the influence of land-use changes since the mid-1800s as has been suggested by several previous authors.

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Chapter 3. Holocene environmental change in southeast British Columbia, Canada

3.1. Abstract

Paleoecological investigation of two montane lakes in the Kootenay region of southeast British Columbia, Canada reveal Holocene changes in vegetation and carbon burial in response to climate and fire change over the Holocene (~12,000 cal. yrs. B.P.). Pollen, charcoal, and lake sediment carbon accumulation rate analyses reveal seven distinct vegetation zones at Marion Lake presently in the subalpine Engelmann Spruce-Subalpine Fir (ESSF) biogeoclimatic (BEC) zone of Kootenay Valley, British Columbia. Comparison of these records to nearby Dog Lake of Kootenay National Park in the Montane Spruce (MS) BEC zone of Kootenay Valley, British Columbia reveals (1) that by the onset of the neoglacial (~4,500 years to present), the MS BEC zone transitioned from an open to a closed forested landscape, while the ESSF BEC zone remained an open landscape with the establishment of subalpine meadows. (2) Inferred wetter conditions in the neoglacial resulted in a closed forested landscape in the MS BEC zone, which led to biomass buildup that caused increased carbon accumulation. Future climate warming will likely result in the MS transitioning into an Interior Douglas Fir (IDF) dominated landscape, while the ESSF may become more forested, similar to the modern MS, or develop into a grassland-like landscape dependent on fire frequency.

3.2. Introduction

National Parks and other protected areas are commonly established to conserve biodiversity and ecological integrity (Parks Canada Agency, 2000; Parks Canada and the Canadian Parks Council, 2008). Even though these parks are protected from most forms of resource extraction, climate change impacts are expected to affect the structure and function of ecosystems at a rate that exceeds natural ranges of variability (Canadian Parks Council Climate Change Working Group, 2013). Land managers are faced with the challenge in understanding how park ecosystems will respond to future change. Paleoecological proxies offer information on long-term climate, vegetation, and disturbances (e.g., fire) and their anticipated relationship with ecological states that can be observed at present.

Previous Holocene paleoecological research in southeastern British Columbia has focused on vegetation dynamics and paleolimnological responses to climate changes occurring at the treeline at alpine sites in the Canadian Rockies (Beaudoin, 1986; Luckman and Kearney, 1986), the northern Cascade Mountains (Pellatt et al., 1998; Smith et al., 1998; Pellatt et al., 2000; Heinrichs et al., 2002) and forest cover changes at mid and lower elevations (Mack et al., 1983; Hebda, 1995; Hallett and Walker, 2000). All of these studies propose an approximation of the following climate history. The early Holocene (~11,400 to 10,500 cal. yr B.P.) is warm and dry. The xerothermic (~10,500 to 8,000 cal. yr B.P.) is hot and dry. The mesothermic (~8,000 to 4,500 cal.yr B.P.) is warm and wet except on the Pacific Coast where near modern (cool and wet) conditions existed. The neoglacial (~4,500 cal. yr B.P. to present) is cool and wet (Hansen, 1955; Mathewes, 1973; Mathewes and Rouse, 1975; Mathewes, 1985; Hebda, 1982; Hebda, 1995; Walker and Pellatt, 2008). More recent work has taken a site-specific look at vegetation dynamics and disturbance regimes in the Columbia Mountains and found that fire is the most important disturbance over the Holocene along with other more localized disturbances like insect outbreaks and windthrow (Mustaphi and Pisaric, 2014; Mustaphi and Pisaric, 2017).

In this study, we examine the vegetation, fire, climate, and lake sediment carbon accumulation rate of a catchment area within Kootenay National Park of Canada and in an adjacent non-protected catchment area, both in the Kootenay Region of southeast British Columbia (Figure 3.1). This work differs from previous studies by comparing similar catchment areas in and outside a protected area providing insight into the causal mechanisms of ecosystem responses to disturbance. By analyzing the paleoecological proxies of pollen, carbon, and charcoal over the Holocene we can characterize ecosystem response to disturbance and begin to explain the causal mechanisms. These anticipated relationships between proxies and disturbances, can be understood through resiliency theory by way of a response model. A response model is an explicit statement of the anticipated relationships among proxies, disturbances and resilience properties (Davies et al., 2018). When faced with a disturbance, resilience is the ability of an ecosystem to retain its current state rather than rearranging into an alternative, functionally and structurally different state (Gunderson and Holling, 2002). A crucial need for assessing resilience in an ecosystem is detecting thresholds and changes that provide early warning signs of impending regime shifts (Kéfi et al., 2014). For the purposes of this study a regime shift would be a change in BEC zone. The goal of this study is to provide ecologists and/or land managers a paleoecological data driven response model of two adjacent catchment areas currently representing two adjacent BEC zones within the Kootenay Valley of British Columbia.

3.3. Methods

3.3.1. Study area

Marion and Dog Lakes are situated in the northwest-southeast trending Kootenay Valley (Figure 3.1) just west of the Continental Divide in the Rocky Mountains of southeastern British Columbia. Kootenay Valley is the drainage basin of the upper Kootenay River and part of the Columbia River watershed. Marion Lake sits near the headwaters of the Kootenay River in a sub-region of the Kootenay Valley known as the Beaverfoot Valley. Dog Lake sits near the Kootenay River downstream of Marion Lake in the Kootenay Valley inside Kootenay National Park.

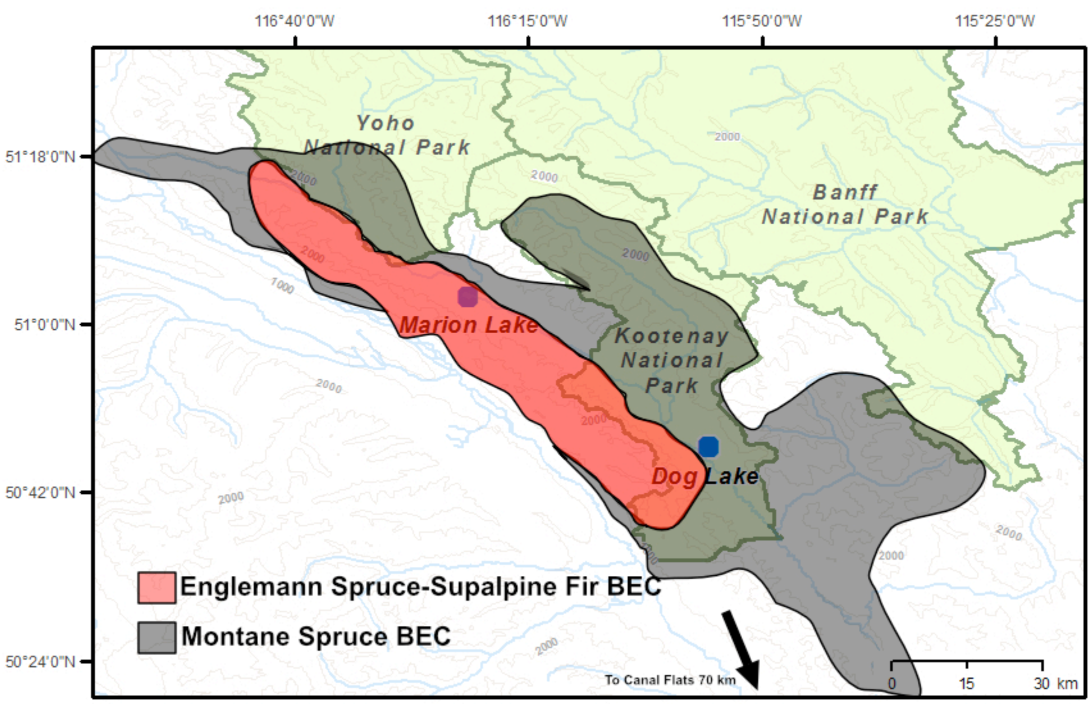


Figure 3.1 Study area of Marion and Dog Lake.

Marion Lake was chosen as a companion lake to Dog Lake on the basis of proximity outside the national park boundaries, surrounding catchment characteristics, lake morphology, and biogeoclimatic properties (Table 3.1). A biogeoclimatic zone (BEC) is a geographic area that has a broadly homogenous macroclimate and similar vegetation (Ministry of Forests and Range, 2008). Dog and Marion Lakes both possess small outlets that are active during spring snowmelt. Both lakes have a flat rectangular bathymetric basin with steep sides and a broad littoral zone.

Table 3.1 Dog and Marion Lakes characteristics summary.

	Dog	**Marion**
Latitude	50° 46’50.56” N	51° 2’49.47” N
Longitude	115° 55’44.14” W	116° 21’28.70” W
Lake Area	15.1 ha	15.4 ha
Catchment Area	1428 ha	2519 ha
Lake Depth	4.7 m	13.7 m
Elevation	1183 m	1263 m
BEC Zone	Montane Spruce	Engelmann Spruce-Subalpine Fir
Protection Status	Protected since 1920	Not Protected

Marion Lake is in the Engelmann Spruce-Subalpine (ESSF) zone. Mean annual temperature is -2°C - 2°C. Mean monthly temperatures are below 0°C for five to seven months, and above 10°C for zero to two months (Meidinger and Pojar, 1991). The ESSF zone is observable at elevations higher than Dog Lake with closed stands of *Picea* and *Abies cf. lasiocarpa*. At elevations below Marion Lake the MS zone is observable (<500m) with mixed stands of *Pinus*, *Pseudotsuga* and *Betula*. Dog Lake is in the Montane Spruce (MS) biogeoclimatic (BEC) zone and Marion is in the Engelmann Spruce-Subalpine Fir (ESSF) zone. Relatively, both MS and ESSF have cold winters. However, ESSF is characterized as having short cool summers while MS is characterized as having short warm summers. At Dog Lake, mean annual temperature is 0.5°C - 4.7°C. The average temperature is below 0°C for five months of the year and above 10°C for two to four months. The wide range of temperatures is due in sizeable geographical area this zone covers across central BC.

Surrounding the Kootenay Valley and the drier Columbia Valley to the west of Kootenay Valley is an Interior Douglas Fir (IDF) zone. The Columbia and Kootenay Valleys converge to the south near Canal Flats. Canal Flats is the headwaters of the Columbia River and relatively low in elevation (~850 m). Xerophytic taxa (e.g., *Pinus ponderosa*) from this IDF area can extend into the Kootenay Valley and upslope, driven by warmer and drier climate and frequent forest fires. Conversely, during cooler and moister climate periods with less frequent forest fires, the ESSF taxa may extend downslope and create forests with both ESSF and MS taxa (Hallett and Hills, 2006).

3.3.2. Field methods and chronology

A 216 cm sediment core was retrieved from the deepest part of Marion Lake (13.7 m) using a Glew corer (upper 54 cm) (Glew et al., 2001) and a modified Livingstone corer (Wright, 1967) in July, 2012. A 420 cm sediment core was retrieved from the deepest part of Dog Lake (4.7 m) using a Glew corer (upper 41 cm) (Glew et al., 2001) and a modified Livingstone corer (Wright, 1967) in June of 2011. Cores taken using the Livingstone corer were matched using a Bartington MS2 Magnetic Susceptibility reader. Sediment cores were subsampled at 1 cm intervals and placed in Whirlpak® bags and transported to the Climate Oceans and Paleoenvironments (COPE) laboratory at Simon Fraser University in Burnaby, Canada where it subsequently was preserved at 4°C.

The chronologies were developed using radiocarbon dating on pollen samples from the lower Livingstone sections and using ^{210}Pb dating of bulk sediment from the upper, Glew section of the cores from both Marion and Dog Lakes. Accelerator mass-spectrometry (AMS) ^{14}C ages from pollen from the lower Livingstone sections of the Marion and Dog Lake cores were processed at the Center for Accelerator Mass Spectrometry at the Lawrence Livermore National Laboratory. The ^{210}Pb ages were determined from bulk sediment samples in the upper Glew section of both the Marion and Dog Lake cores. MyCore Scientific Inc. processed all the ^{210}Pb samples for Marion Lake and Core Scientific International processed all the ^{210}Pb samples for Dog Lake (Appendix C1). ^{210}Pb and ^{14}C ages were then used to create an age-vs.-depth model for Marion and Dog lakes (Figure 3.2a and Figure 3.2b) using the Bayesian age-depth model Bacon (v2.3.7) (Blaauw and Christen, 2011). ^{14}C ages in the Bacon model were calibrated using IntCal13 (Reimer et al., 2013). Data generated from the model can be found in Appendix C1.

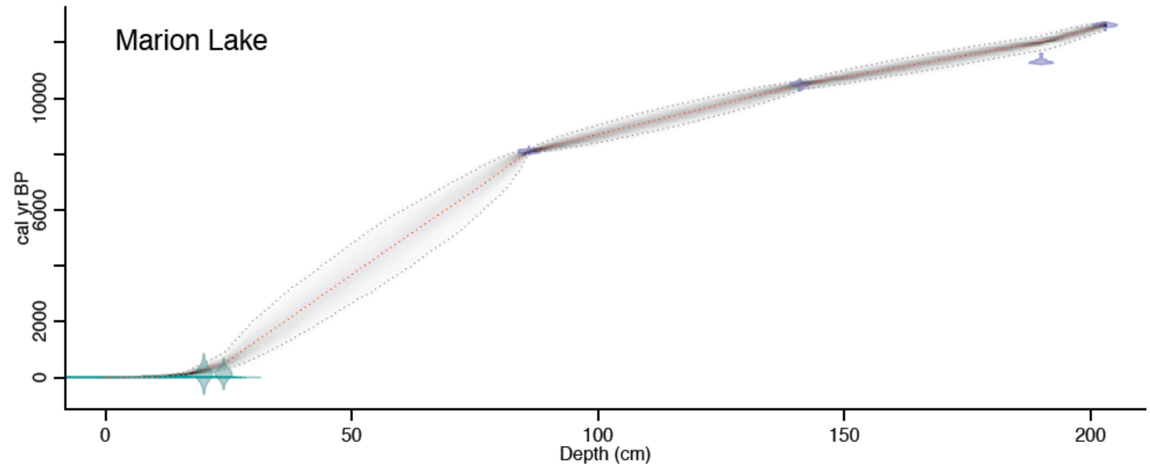


Figure 3.2a Marion Lake age-vs.-depth relationship. The likelihood the model runs through a sample (points with errors) in greyscale, where the darker the grey, the more likely the model runs through that sample.

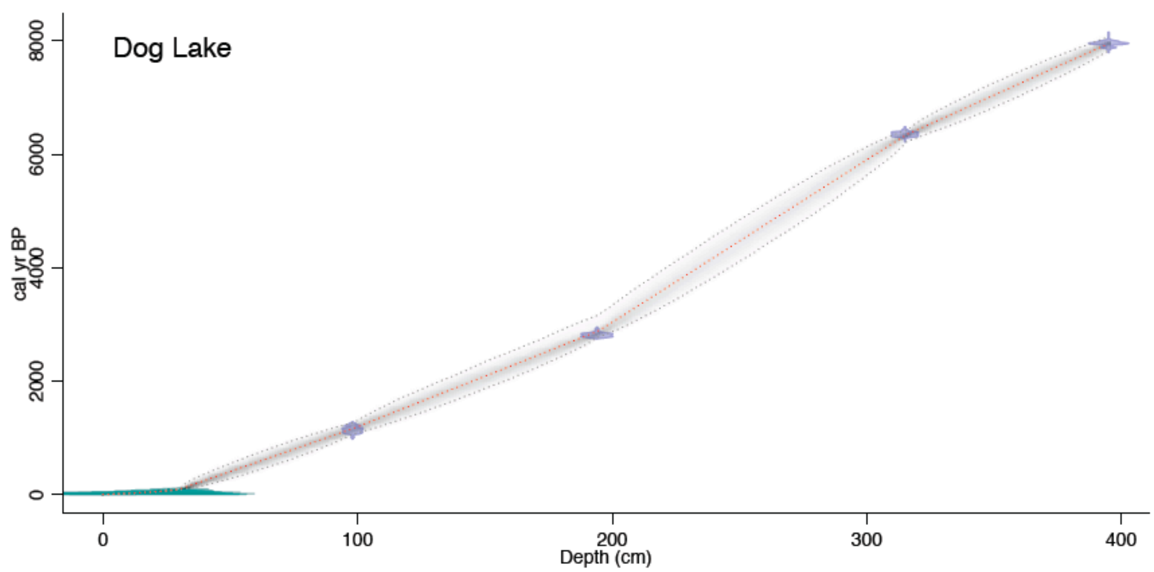


Figure 3.2b Dog Lake age-vs.-depth relationship. The likelihood the model runs through a sample (points with errors) in greyscale, where the darker the grey, the more likely the model runs through that sample.

3.3.3. Pollen analysis

We collected 50 (1 cm^3) plugs taken at 1 cm intervals throughout the Marion Lake core. Pollen preparation followed the standard acetolysis technique outlined in Fægri and Iverson (1989) at the Parks Canada Vancouver Ecology Laboratory and the Geological Survey of Canada Vancouver Laboratory. Exotic (10,679 *Lycopodium*) tablets were added to calculate pollen accumulation rates. Pollen and spores were identified at 400x magnification and difficult identifications were made at 1000x under oil immersion. Pollen and spores were identified using in-house reference keys at the Parks Canada Vancouver Ecology Laboratory and the Mathewes Laboratory at Simon Fraser University. A minimum of 500 pollen grains were counted per sample. A percentage diagram based on the terrestrial pollen sum was produced using TILIA v1.7.16 (Grimm, 1993). Pollen assemblage zones were established using the application of CONISS in the TILIA program using squareroot transformed percent data (Appendix C2). A pollen influx diagram using linear interpolation of calendar dates was also prepared using TILIA. Dr. Hallett conducted pollen analysis using the same methods for Dog Lake (Hallett and Hills, 2006).

3.3.4. Charcoal laboratory, fire peak, and frequency analysis

Reconstructing western North American fire histories on century-to-millennial scales is often done through analysis of macroscopic charcoal (Long et al., 1998; Higuera et al., 2011). Macroscopic charcoal analysis can be used to differentiate between background and peak fire events. Peak events in the charcoal history are an indications of fire episodes localized near the lake basin. Because charcoal can enter a catchment area and ultimately the lake basin in a number of ways (e.g., wind (Whitlock and Millspaugh, 1996), landslides, or anthropogenic fires), interpretation of charcoal peaks as a fire episode needs to be done cautiously. Records in lake sediments often can be distinguished between fires burning within the catchment area and those at a distance. However, characterization of charcoal transport is still difficult due to low empirical data, changes in source particle size/morphology, and understanding of the transportation processes (Clark and Patterson, 1997; Crawford and Belcher, 2014). Despite this concern, macroscopic charcoal remains the best tool for reconstructing fire history and can be paired with other independent paleoecological proxies.

One cm^3 samples were taken at contiguous, one cm intervals in both the Glew (upper) and Livingstone (lower) Marion Lake cores for charcoal analysis. Samples were soaked in 10% KOH and placed in a hot water bath for 15 minutes. After shaking, centrifuging, and decanting, 6% H_2O_2 was added to the remaining sample and soaked at 50°C for 24 hours. Samples were washed on a 125 μm mesh sieve and the residue was transferred into gridded petri dishes and counted. Only charcoal particles > 125 μm in minimum diameter were counted as previous studies indicate that large particles are not transported far from the source and thereby indicate local fire activity (Whitlock and Larsen, 2001).

Charcoal analysis for the Marion Lake core followed methods outlined in Higuera et al. (2010) using the program CharAnalysis (Higuera et al., 2010). Peak fires represent inferred "fire episodes", or, one or more fires occurring in the duration of a peak (Long et al., 1998). Fire frequency is the sum of the total number of fires within a 1,000 year period. Mean fire return interval (mFRI) is the average number of years between fire episodes. Sensitivity analysis showed that the signal-to-noise ratio (i.e., the measure of the separation between peak and non-peak values) was maximized at 500 years. Charcoal analysis of Dog Lake was done by Hallett and Walker (2000) following the methods of Long et al. (1998).

3.3.5. Carbon and nitrogen, accumulation rate analysis

Samples were taken at contiguous one cm intervals in both the Glew (upper) and Livingstone (lower) Marion and Dog Lake cores for carbon and nitrogen analysis. Samples were dried at 60°C for 24 hours and crushed. A dried subsample was used to measure the percent total carbon (TC) and nitrogen using a Costech ECS 4010 elemental analyzer. Another dried subsample was used to measure total inorganic carbon (TIC) using a UIC CM5130 acidification module connected to a UIC CM5014 CO_2 coulometer. The weight percentage of total organic carbon (TOC) was then estimated by taking the difference between TC and TIC (Meyers and Teranes, 2001). Estimates of the organic C/N (atomic) ratios were also calculated based on TOC and nitrogen weight percentage from each sample.

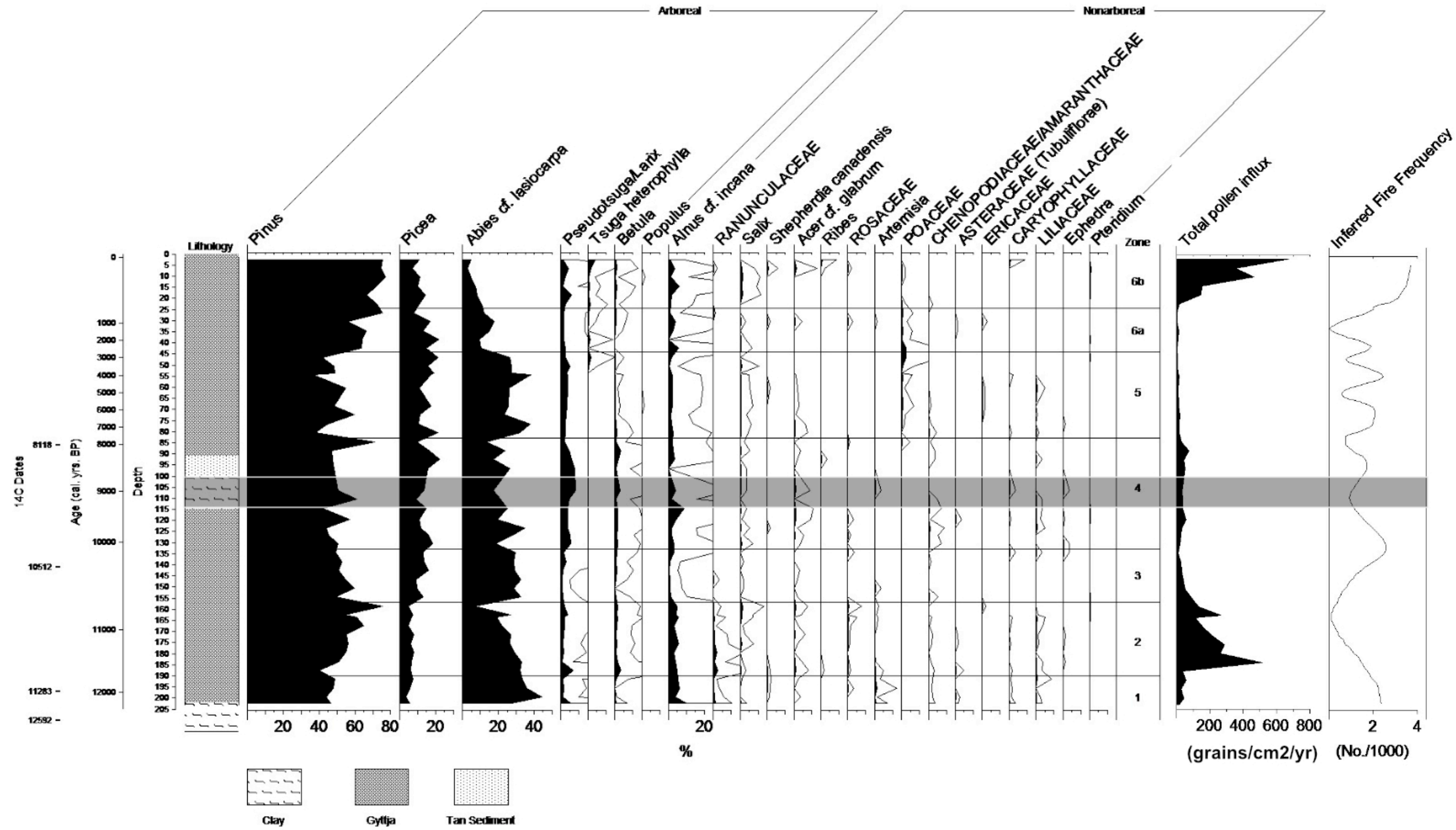
Mass accumulation rate (MAR) was determined by the following equation:

$$\text{MAR (g/m}^2\text{/yr)} = \rho_{DBD}\ \text{(g/m}^3\text{)} * LSR\ \text{(m/yr)} \qquad (1)$$

Where ρ_{DBD} is the measured dry bulk density of a one-cm^3 volume of sample one-cm^3 , and *LSR* represents the linear sedimentation rate. Dry bulk densities ρ_{DBD} were measured after 24 h in a drying oven set at 60°C. The linear sedimentation rate (*LSR*) was based on the age-depth model determined for each core. Total organic carbon accumulation rate (TOC MAR) was then determined using the following equation:

$$\text{TOC MAR } (g/m^2/yr) = \text{TOC (wt \%)} * \text{MAR } (g/m^2/yr) \qquad (2)$$

3.4. Results



Arboreal
Nonarboreal
Lithology
Pinus
Picea
Abies cf. lasiocarpa
Pseudotsuga/Larix
Tsuga heterophylla
Betula
Populus
Alnus cf. incana
RANUNCULACEAE
Salix
Shepherdia canadensis
Acer cf. glabrum
Ribes
ROSACEAE
Artemisia
POACEAE
CHENOPODIACEAE/AMARANTHACEAE
ASTERACEAE (Tubuliflorae)
ERICACEAE
CARYOPHYLLACEAE
LILIACEAE
Ephedra
Pteridium
Zone
Total pollen influx
Inferred Fire Frequency
14C Dates
Age (cal. yrs. BP)
Depth
%
(grains/cm2/yr)
(No./1000)
Clay
Gyttja
Tan Sediment

Figure 3.3 **Simplified pollen diagram of Marion Lake (see Appendix B2 for detailed pollen diagram of Marion Lake). Grey box highlights the clay lithological layer.**

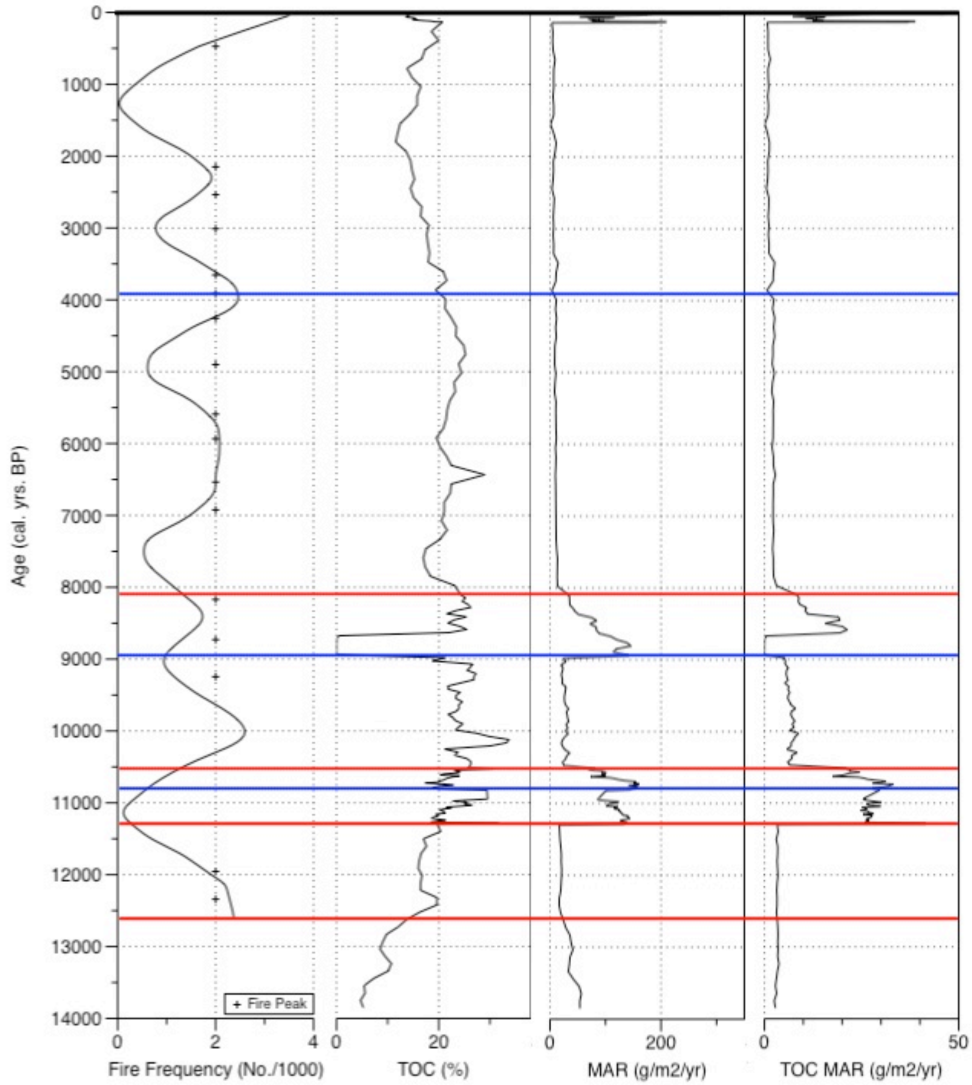


Figure 3.4a **TOC MAR, MAR, TOC, inferred fire frequency, and fire peaks of Marion Lake. Blue lines represent core breaks. Red lines represent tie points (Appendix C1).**

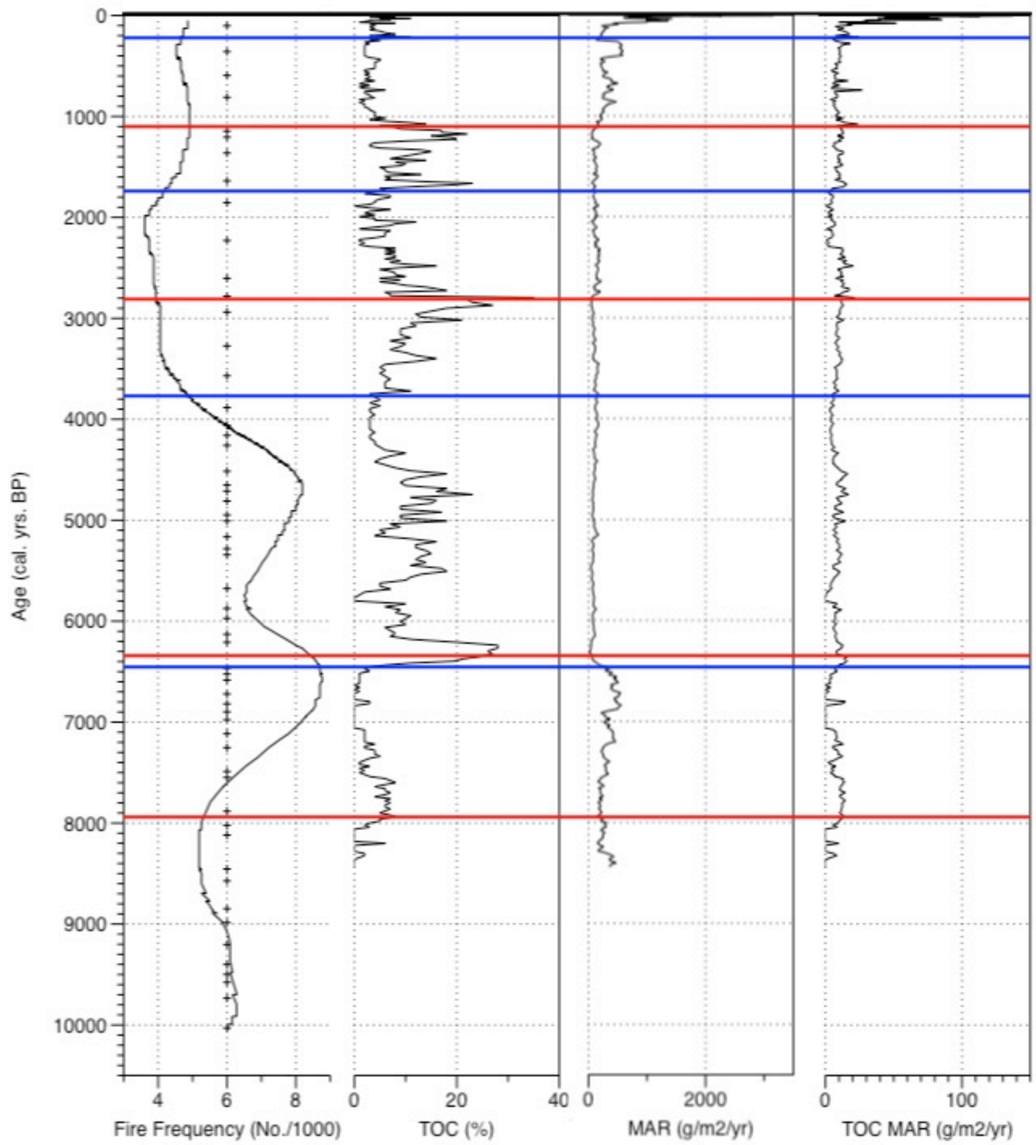


Figure 3.4b TOC MAR, MAR, TOC, inferred fire frequency, and fire peaks of Dog Lake. Blue lines represent core breaks. Red lines represent tie points (Appendix C1). Dog Lake charcoal data is interpolated from Hallett and Walker (2000).

Six vegetation zones and one sub-zone were delineated by the unconstrained cluster analysis program CONISS for Marion Lake (Appendix C2). Each zone (Figure 3.3) will have its results for Marion Lake reported and then both Marion and Dog Lake using the zones from Marion Lake in discussion.

Zone ML-1 (202.5-190.5 cm) *Abies-Picea-Artemisia,* 12,580-12,060 cal. yr B.P.

Abies has its highest pollen percentage (44%) at 12,438 cal. yr B.P. and steadily decreases throughout the zone. This decrease is accompanied by a corresponding increase in *Pinus* that continues into zone ML-2. *Picea* has its lowest value (3.5%). *Artemesia* has its highest percentage (1.4%) at 12,244 cal. yr B.P.

Fire frequency in this zone is high with 2.1-2.4 (average 2.3) fire events per 1,000 years. The mFRI is 301 years (n=2).

Carbon accumulation rate in this zone is low with 3.1-3.4 (average 3.0) $g/m^2/yr$.

Zone ML-2 (190.5-158.5 cm) *Pinus-Abies*-Ranunculaceae*,* 12,060-11,010 cal. yr B.P.

Pinus spikes to its second highest value (75%) while *Abies* steadily drops to one of its lowest values (7%). Ranunculace*a*e pollen has its highest percentage in this zone (2.5%).

Fire frequency in this zone is low with 0.1-2.0 (average 0.9) fire events per 1,000 years. The mFRI is 774 years (n=2).

Carbon accumulation in this zone is at its highest rate with 3.3-41 (average 26) $g/m^2/yr$.

Zone ML-3 (158.5-134.5cm) *Picea*, 11,010-10,180 cal. yr B.P.

Alnus cf. incana, *Betula,* and *Pseudotsuga/Larix* have their lowest values (3%, 0%, and 3% respectively). *Picea* increases and *Pinus* decreases.

Fire frequency in this zone is low with 0.2-2.4 (average 1.1) fire events per 1,000 years. The mFRI is 473 years (n=1).

Carbon accumulation rate in this zone is high with 5.7-33 (average 21) $g/m^2/yr$.

Zone ML-4 (134.5-80.5 cm) *Pseudotsuga/Larix-Alnus cf. incana -Picea*, 10,180-7,342 cal. yr B.P.

Abies and *Pinus* have similar values to ML-1. *Pseudotsuga/Larix* and *Alnus cf. incana* have high percentages. *Betula* has similar values to ML-1. *Picea* has its highest percentage (22%). Poaceae appears at the end of this zone.

Fire frequency in this zone is moderate with 0.58-2.5 (average 1.4) fire events per 1,000 years. The mFRI is 502 years (n=6).

Carbon accumulation is moderate with 0.052-21 (average 7.2) g/m^2/yr with high fluctuation (20 g/m^2/yr) towards zone ML-4.

Zone ML-4 contains a tan sediment layer between 92.5 and 98.5 cm above the clay layer between 98.5 and 114.5 cm. There is core break between D1 and D2 at 105.5 cm. in the clay layer.

Zone ML-5 (80.5-42.5 cm) *Tsuga*-Poaceae, 7,342-2,685 cal. yr B.P

Tsuga heterophylla appears at the end of this zone. Poaceae increases and possess its maximum value (2.5%) at the end of this zone. *Abies* has relatively high values. *Alnus cf. incana* and *Betula* have relatively low percentages in this zone.

Fire frequency in this zone is low with 0.6-2.5 (average 1.5) fire events per 1,000 years. The mFRI is 439 years (n=10).

Carbon accumulation is low throughout this zone with 0.7 to 2.7 (average 2.0) g/m^2/yr.

Zone ML-6a (42.5-24.5 cm) *Pinus*-Poaceae-*Psedudotsuga/Larix*, 2,685-400 cal. yr B.P.

Pinus is increasing throughout the zone. Poaceae starts at its second highest value (2.4%) and then decreases. *Pseudotsuga/Larix* is low throughout the zone.

Fire frequency in this zone is low with 0.043-1.9 (average 1.0) fire events per 1,000 years. The mFRI is 846 years (n=3).

Carbon accumulation is low in this zone with 0.1 to 37 (average 2.7) g/m^2/yr.

Zone ML-6b (24.5-0 cm) *Abies-Picea-Pinus-Tsuga*-Poaceae, 400-0 cal. yr B.P.

This transitional zone shows abrupt changes in pollen ratios. This zone has lower *Abies* values. *Abies* and *Picea* are both decreasing. The largest percentages of *Pinus* (undiff.) (77%) and *Tsuga* (4%) pollen occurs in the last 100 cal. yr B.P. Poaceae is present, but is decreasing.

Fire frequency in this zone is high with 2.0-3.5 (average 2.8) fire events per 1,000 years.

Carbon accumulation is high in this zone with 7.42 to 46 (average 21) g/m^2/yr.

3.5. Discussion

Zone ML-1 (202.5-191.5 cm) *Abies-Picea-Artemisia,* 12,580-12,060 cal. yr B.P.

The peak abundance of *Artemisia* in Marion Lake occurs during the Younger Dryas period (~12,800 – 11,500 cal. yr B.P.). The high abundance of *Artemisia* during the Younger Dryas period has also been noted in Waits Lake, northeastern Washington in the nearby Columbia River basin (Mack et al., 1978; Walker and Pellatt, 2008). The Younger Dryas was a period of rapid cooling approximately 12,800 to 11, 500 cal. yr B.P. that was first considered to be restricted to Europe. However, it has since been corroborated in coastal British Columbia (Mathewes, 1993; Mathewes et al., 1993), the American Rockies (Reasoner and Jodry, 2000), the Canadian Rockies (Reasoner et al., 1994), and the Canadian Maritimes (Levesque et al., 1993). The geographic extent of the Younger Dryas suggests that it was caused by a reduction in Atlantic meridional overturning circulation (McManus et al., 2004). While still an area of ongoing research, it is inferred that freshwater discharge from the melting Laurentide Ice Sheet to the North Atlantic slowed Atlantic meridional overturning circulation shifting the intertropical convergence zone southward. The shifting of the intertropical convergence zone resulted in an oscillation of the thermohaline circulation that when modeled demonstrated a warming in the Southern Hemisphere and cooling in the Northern Hemisphere (e.g., Fawcett et al., 1997).

At Dog Lake, early Holocene pollen assemblages and inferred vegetation indicates a *Pinus*-*Juniperus* parkland typical of lower elevation sites in the Kootenay Valley and Columbia Valley (Hallett and Hills, 2006). At Marion Lake, the abundance of *Artemisia*, *Alnus cf. incana*, Cyperaceae, Asteraceae, and Ranunculaceae indicate a subalpine landscape occurred during the late glacial. High percentages of nitrogen-fixing shrubs such as *Alnus cf. incana* and *Shepherdia canadensis* indicate a pioneering vegetation assemblage. It is estimated that most taxa arrived in the Kootenay Valley by 10,000 cal. yr B.P., (Hallett and Hills, 2006). At high enough elevation, the pioneering tree species, *Picea* and *Abies* likely grew as krummholz, or stunted trees, as the relatively high percentages of these taxa resemble those of modern subalpine assemblages. The absence of *Juniperus*/Cupressaceae pollen indicates that Marion Lake did not have a pollen assemblage like those of dry, alpine sites. The *Abies* and *Picea* pollen around the lower elevation Dog Lake might have been derived from subalpine sites akin to Marion Lake. The relatively low *Pinus* (undiff.) pollen around Marion Lake is likely transported from distant stands (Pellatt et al., 1998, 2000; Heinrichs et al., 2002).

The high pollen influx rate (Ritchie and Lichti-Fedorovich, 1967) and absence of Poaceae indicate a closed forest landscape. The peaks in *Alnus cf. incana* indicate that disturbance was part of the landscape (Hallett and Hills, 2006). Fire, wind, temperature, and avalanches are usual causes of disturbance, yet with the low fire frequency and lack of soil it would not be a main force around Marion Lake. Dog Lake also has low fire frequency for this period (Hallett and Hills, 2006).

Zone ML-2 (191.5-158.5 cm) *Pinus-Abies-Ranunculaceae,* 12,060-11,010 cal. yr B.P.

The end of the Younger Dryas (~11,500 cal. yr B.P.) was marked by sudden warming. Following the Younger Dryas period, the remainder of the Holocene climate history of the southern interior of BC is described as having three periods: (1) a xerothermic period that is relatively dry and hot from 11,500-8,000 cal. yr B.P., (2) followed by warm and moist mesothermic interval from 8,000-4,500 cal. yr B.P., (3) and a cool and moist neoglacial period from 4,500 cal. yr B.P. to present. Fossil midge paleotemperature reconstructions for south central interior BC, also support a warmer temperature (~2-3°C) during the xerothermic period (Pellatt et al., 2000; Palmer et al., 2002; Walker and Pellatt, 2003). It should be noted that midges are accepted as good indicators of summer temperatures, but offer little information on winter temperatures as midges spend winter in larval stages beneath lake ice (Walker and Pellatt, 2008).

The high C accumulation rate (Figure 3.4 and Appendix C2) in Marion Lake in this zone could be caused by (1) high runoff and input of allochthonous matter from the surrounding catchment area, (2) increased in-lake productivity of autochthonous matter, (3) dating artifacts, or (4) a combination thereof. C/N ratios during this time indicate that the organic material is derived from mixed allochthonous and autochthonous sources (Appendix C3). Increasing levels of %N (Appendix C3) indicate that a complex shrub layer of nitrogen-fixing taxa was established (*Alnus cf. incana*, *Shepherdia*, and Rosaceae) in the catchment area and/or in-lake productivity of nitrogen-fixing taxa increased (e.g., cyanobacteria). The tie points 10,512 and 11, 283 cal. yrs. B.P. in Marion Lake (Figure 3.4a) (Appendix C1) appear to bound this period of high C accumulation. Every effort was made by the authors to constrain the potential for dating artifacts through the use of core imagery and magnetic susceptibility to assemble the sediment core sections (see Methods section 3.3.2) and choosing material to date not near (<5 cm) a visual lithology change (Figure 3.3).

Zone ML-3 (158.5-134.5cm) *Alnus cf. incana, Betula, Pseudotsuga/Larix*, 11,014-10,180 cal. yr B.P.

With years of soil accumulation in the Kootenay valley, tree species began to transition into new areas. The lower *Betula and Alnus cf. incana* percentages suggest that these pioneering species were being outcompeted by species like *Picea,* adapted to lower levels of disturbance.

N (%) is at its highest level in this zone and the C/N ratio indicates a shift to exclusively autochthonous deposition (Appendix C3). This is supported by the near absence of nitrogen-fixating taxa (*Alnus cf. incana*, *Shepherdia*, and Rosaceae) and presence of a variety of aquatic pollen taxa. In sum, at the elevation of Marion Lake, in-lake productivity was the main contributor to the moderate C accumulation rate noted in this zone.

Zone ML-4 (134.5-80.5 cm) *Pseudotsuga/Larix-Alnus cf. incana -Picea*, 10,180-7,342 cal. yr B.P.

This zone had the highest summer air temperatures, +3°C higher than today, as indicated by fossil chironomid head capsule records in southern British Columbia. Warm-adapted stenotherms (e.g., *Dicrotendipes and Cladopelma*) began to increase rapidly after 9,500 cal. yr B.P. and cold-stenotherms begin to disappear in the southern interior of British Columbia (Palmer et al., 2002). Inferred climate records from other southern BC studies concur that this was the beginning of the early Holocene warm and dry xerothermic interval (Hebda, 1995; Heinrichs, 1999; Heinrichs et al., 2001; Pellatt et al., 1998; Smith et al., 1998)

Around Dog Lake, *Pseudotsuga/Larix* appears in the core at 9,500 cal. yr B.P. likely migrating from lower elevations (Hazell, 1979; Hebda, 1995; Hallett and Hills, 2006). By 8,800 cal. yr B.P. in Jasper National Park, isotopic determinations from logs indicate temperatures became warmer at higher elevations in the region (Luckman and Kearney, 1986). The composite midge paleotemperature reconstruction for southern British Columbia confirms that the period between 9,000 and 6,600 cal. yr B.P. was warmer for southern British Columbia (Rosenberg et al., 2004). Based on regional climate reconstructions of maximum warmth this zone lies in the xerothermic climate interval (Mathewes, 1985; Hebda, 1995; Pellatt et al., 2000). The xerothermic period appears earlier (11,500 – 8,000 cal. yr. B.P.) on the Pacific Coast and west of the continental divide than the Hypsithermal period (9,000 – 6,000 cal. yr. B.P) referred to east of the continental divide (Anderson et al., 1989; Hallett et al., 1997). The Hypsithermal was marked by increased *Artemisia*, Chenopdiaceae/Amaranthaceae, Poaceae, and *Juniperus* pollen in southwestern Alberta (Macdonald, 1989) and a decrease in *Picea engelmannii* in Glacier National Park (US) (Hansen, 1948). Marion Lake had increases in *Artemisia*, Chenopodiaceae/Amaranthaceae, and Poaceae and Dog Lake has increases in Chenopodiaceae/Amaranthaceae and Poaceae pre-9,000 cal. yr. B.P. (Hallett and Hills, 2006). Both Dog and Marion lake's records show decreased *Picea* abundance pre-9,000 cal. yr. B.P (Hallett and Hills, 2006). For these reasons, in terms of vegetation composition, the Kootenay Valley falls within the definition of the xerothermic and not the Hypsithermal.

A sharp increase in fire frequency starting at 8,000 cal. yr B.P. peaks at ~6,700 cal. yr B.P. around Dog Lake (Hallett and Hills, 2006). Marion Lake follows a similar fire frequency path, but peaks at 9,800 cal. yr. *Alnus* and *Betula* can grow in response to fire, and the high percentages of both around Marion Lake suggest high fire activity in the catchment area during this zone. It should be noted that *Alnus* might also grow in response to other disturbances such as landslides and avalanches. However, a similar pattern of high fire frequency is seen during this zone in the subalpine conifer forests in the northern United States Rocky Mountains (Huerta et al., 2009). This increase in fire activity coincides with the interval of high summer insolation and stronger-than-present subtropical high pressure (Brunelle and Whitlock, 2003). This climate would manifest itself as the wet winters akin to the western United States at this time (Bartlein et al., 1998; Kutzbach et al., 1998). The increase in *Alnus* pollen in this zone is likely from *Alnus virdis*, a shrub that favours moist conditions and suggests heavy winter snowpack (Kershaw et al., 1998; Thilenius, 1990). Broad-scale climatic controls are interpreted as the major influence on fire frequency in the nearby Engelmann Spruce-Subalpine Fir (ESSF) zone as indicated by charcoal sediment records in the Columbia Mountains (Gavin et al., 2006; Mustaphi and Pisaric, 2014; Mustaphi and Pisaric, 2017) and American Rockies (Morris et al., 2013).

At Dog Lake recovery in charophyte accumulation with high percentages of aquatic pollen or spores or other microremains and *Abies* pollen indicate a moist climate (Hallett and Hills, 2006). The increase of *Picea* throughout this zone signals a closing forest around Marion Lake.

In Marion Lake the second largest peak in C accumulation rate (> 20 $g/m^2/yr$) rate occurred between 8,535 and 8,622 cal. yr B.P. In addition, 8,500 cal. yr B.P. is when the C/N ratio switches from mixed sourcing (~8 (C/N (atomic))) to terrestrial sourcing levels (~13 (C/N (atomic))) that carries on into zone ML-6b (Appendix C3).

Zone ML-4 contains a clay layer from 9,331 to 8,631 cal. yr B.P. that is coupled with a sharp reduction in organic carbon, inorganic carbon, and nitrogen (Figure 3.4 and Appendix B2). It is important to note that this clay layer creates a large break that may not be representative of actual carbon deposition because of an abrupt sediment deposition. This large sediment deposition could have been caused by a number of natural disturbances. Given the current geomorphology of the area this abrupt change was likely due to the Kootenay River changing course in the Beaverfoot Valley. Further work would need to be conducted to conclude that a river shift would manifest itself in this way in the sediment.

Zone ML-5 (80.5-42.5 cm) *Tsuga*-Poaceae-*Equisetum*, 7,342-2,685 cal. yr B.P

Midge-inferred summer temperature reconstructions for southern British Columbia reveal an abrupt end to the xerothermic period at approximately 6,700 cal. yr

B.P. (Rosenberg et al., 2004). In the northern United States Rockies, the end of the seasonal cycle of insolation led to *Pseudotsuga* being replaced by *Pinus* and *Abies* indicating a return to cooler and more moist conditions (Brunelle and Whitlock, 2003). At Marion Lake, replacement of *Psedotsuga* by *Abies* indicates that a similar cool and moist state was established. Corresponding increases in *Abies* and *Picea* indicate similar events in subalpine forests of southern BC (Pellatt et al., 1998; Pellatt et al., 2000; Henrichs et al., 2001; Heinrichs et al., 2002). Around Dog Lake, the *Picea* pollen increases represent a lowering of the ESSF into the surrounding MS zone (Hallett and Hills, 2006). Around Marion Lake, the presence of *Juniperus/*Cupressaceae pollen, which grows today in alpine sites of southern British Columbia (Heinrichs et al., 2002), indicates the lowering of the Alpine Tundra (AT) zone. In addition, subalpine meadows may have been established in the ESSF at Marion Lake. The presence of Poaceae indicates an open landscape and the low total pollen accumulation rate (Ritchie and Lichti-Fedorovich, 1967) corroborates the suggestion of a more open landscape.

At Dog Lake, charophyte (freshwater algae) values rise consistently after 5,400 cal. yr B.P. suggesting higher lake levels (Hallett et al., 2003). This is concurrent with global recirculation and glacial advance (Mayewski et al., 2004). Cool and wet winters likely supply Dog and Marion lakes with a cool water supply from snowpacks melting long into the summer. Wetter summers account for the low fire frequency and low carbon accumulation rate. In Dog Lake, wetter summers increase OC content by 10-20% in this zone. This increase is spurred by in-lake activity (Hallett and Hills, 2006). Marion Lake derives its OC content from terrestrial sources during this zone and wetter summers provide only a small foray into mixed sourcing (Appendix C3).

Tsuga heterophylla pollen arrives and continually increases at 3,100 cal. yr B.P. to present. This arrival is in agreement with other fossil pollen studies from southern British Columbia (Rosenberg et al., 2003b) and indicates the continuation of a wet moisture regime and less seasonably extreme winter climate (Thomson et al., 1993; Bartlein et al., 1998; Walker and Pellatt, 2003; Hallett and Hills, 2006).

Zone ML-6a (42.5-24.5 cm) *Pinus*-Poaceae-*Psedotsuga/Larix*, 2,685-400 cal. yr B.P.

Modern forest types were being established at this time in southern BC as the climate continued in the cool and moist state that first began in the mid-Holocene

(Kearney and Luckman, 1983; Mathewes 1985, Luckman and Kearney, 1986; Hebda, 1995; Pellatt et al., 1998; Pellatt et al., 2000; Heinrichs et al., 2002; Hallett and Hills, 2006). The continued decrease in *Picea* and the presence of fire-adapted taxa such as *Pinus*, *Pseudotsuga/Larix*, *Alnus cf. incana,* and *Pteridium* indicate that forests around the lake were being disturbed and moving towards a more open landscape. Finally, increased pollen accumulation rates in this zone from shrubs and herbs support the idea that subalpine meadows established in ML-5 were maturing. The mix of meadows and forest composition points towards establishment of the modern ESSF forest as early as 2,500 cal. yr B.P.

Zone ML-6b (24.5-0 cm) *Abies cf. lasiocarpa-Picea-Pinus-Tsuga*-Poaceae, 400-0 cal. yr B.P.

Of specific note, *Abies cf. lasiocarpa* pollen is especially low (3-8%) in the last 100 cal. yr B.P. This is likely an artifact of large counts of *Pinus* (undiff.), which produces abundant pollen. *Pinus* abundance is likely a result of extensive logging or increased fire frequency in the immediate area.

At Marion Lake, the high disturbance at the end of this zone, a product of increased fire frequency, coincides with an increased C accumulation rate (Figure 3.4) and a spike in terrestrial sourcing material (Appendix C3). The general trend towards a more mixed sourcing material (Appendix C3) is likely explained by the establishment of the current littoral zone, today supporting a fringe of *Equisetum* and Cyperaceae and increase in autochthonous productivity as marked by increased *Pediastrum* counts. This coincides at Dog Lake with high charophyte growth during this zone.

3.5.1. Marion and Dog Lake comparison

The beginning of the cool and moist neoglacial is around 4,700 - 4,500 cal. yr B.P. at Dog Lake (Walker and Pellatt, 2008). However, Marion Lake exhibits this climate in zone ML-5 as early as 7,300 cal. yr B.P. This earlier climate signal is likely due to the 80m higher exposure found at Marion Lake in the ESSF. Marion Lake's warming climate signal only begins in the last 700 cal. yr B.P., while Dog Lake begins to warm as early as 1,000 cal. yr B.P. This is likely the same elevation effect working in reverse. Higher elevation lakes are more exposed to cooler climate conditions, while lower elevation lakes are more exposed to warmer climate conditions. Interpreting beyond the climatic controls on the landscape is challenging because of the difficulty in separating climatic effects from plant species responses to those effects (Schoonmaker and Foster, 1991). For example, Ephedra pollen is present at the Marion Lake site, but likely originated in the Midwest through long range carriage (Maher, 1964). To assume that the peaks of Ephedra represent a particularly windy climatic effect for those periods would be beyond the interpretative ability of a single vegetation genus or species.

In the xerothermic period (11,500 – 8,000 cal. yr B.P.), Marion Lake switches from a dry to a wet landscape while Dog Lake stays dry until the onset of the neoglacial (4,500 cal. yr B.P.). This is most likely the influence of the melt of accumulated snow at higher elevations where clumps of trees accumulate snow and supply growing season moisture (BC Ministry of Forests, 1991).

In the wetter neoglacial (4,500 cal. yr B.P. to present), Dog Lake switches from an open to a closed landscape while Marion Lake has a continued open landscape to present day. This is likely because when neoglacial conditions took effect, Marion Lake had already established subalpine meadows. The vegetation shift around Dog Lake corresponds to an increase in biomass, which is reflected in C accumulation. Marion Lake's shift towards a more open landscape is reflected in a decrease in C accumulation (Appendix C2).

In the last 700 cal. yr BP of zone ML-6a, pollen ratios of *Pseudotsuga-Larix* + Poaceae divided by *Picea* + *Abies* at Dog Lake decrease, suggesting a return to the wet-closed conditions of the MS zone at the onset of the neoglacial (Hallett and Hills, 2006). This change is synchronous with the Little Ice Age glacial advances in British Columbia (Luckman, 1995). Fire Frequency is low to moderate at both Dog and Marion Lakes. This late Holocene low to moderate fire frequency in the Kootenay Valley indicates that more complex local controls play more of an influence on fire activity than in the early and middle Holocene climate-driven high fire frequency (Gavin et al., 2006; Mustaphi et al., 2015).

Local controls on recent fire regimes appear different between Marion and Dog Lakes. The recent mFRI of Dog Lake indicates a stand replacing fire regime akin to wetter areas (Hallett and Hills, 2006). A longer fire-free interval would allow the recent development of a closed forest and create better available fuel to continue this stand replacing fire regime. An ecological succession model (Keane et al., 1990) demonstrates that with a longer mFRI, *Pinus* and *Pseudostuga/Larix* can be better established. At present a closed MS forest exists around Dog Lake and an open ESSF forest around Marion Lake. Looking to the local site factors we can also see influences on carbon accumulation.

In both Marion and Dog Lakes carbon accumulation is visually synchronous with inferred fire frequency (IFF) (Figure 3.4) (Hallett and Hills, 2006). The Columbia Valley and southern United States Rockies have a similar early Holocene vegetation with composition of *Pinus* and *Alnus* cf. *incana* (likely near the lakeshore) dominating, but have are replaced by the late Holocene with *Picea, Abies,* and *Pseudotsuga/Larix* (Gavin et al., 2006; Morris et al., 2013; Mustaphi and Pisaric, 2014). *Pseudotsuga/Larix* and *Alnus* cf. *incana* have their peaks in the mid-Holocene. This mid Holocene difference between the Kootenay Valley and the Columbia Valleys and Southern United States Rockies is highlighted by the IFF maximum exhibited by the Kootenay Valley and IFF minima of the Columbia Valley and Southern United States Rockies. With the exception of modern times, C accumulation is high during this unique vegetation period and high IFF of the mid Holocene. Local site factors of fire regime and vegetation composition seem to control carbon accumulation in the Kootenay Valley, however, additional factors need to be considered.

Additional local site factors in the MS and ESSF zones that can control fire-vegetation-carbon accumulation dynamics may include humans (Johnson and Larsen, 1991), aspect and erosion (Mustaphi and Pisaric, 2017), and disturbance (e.g., bark beetle outbreaks and lightning).

3.5.2. Management implications

Fire and vegetation management decisions are based on the assessment of current vegetation, fire activity and their long-term range of natural variability (Hallett and Walker, 2000). Climate predictions for the Kootenay Valley expect a +4°C mean annual temperature by 2085 (Wang et al., 2016). This would be analogous to the xerothermic period. If climate were to return to xerothermic conditions, vegetation and fire regimes may look similar to what we have interpreted here for the xerothermic. This would suggest Dog Lake would move from the warm, wet –closed modern MS landscape to a warm, dry-open landscape typified by the current Interior Douglas Fir (IDF) zone (Hallett and Hills, 2006). The response around Marion Lake would likely be moving from the cool, wet-open landscape of the ESSF today to a warmer wet landscape that might resemble the modern MS landscape with vanishing meadows determinate on if *Abies* cf. *lasiocarpa* continues its most recent increase and establishes closed stands around these meadows. Using Dog Lake as the representative MS site (Table 3.1), the new MS ecological zone distribution is predicated to shift northward, reaching Marion Lake as early as 2025 and an elevation shift reaching Marion Lake as early as 2085 (Hamann and Wang, 2006). If fire frequency were to increase and drier conditions prevail, a dry meadow-laden and later ESSF forest might give way to grasslands (Heinrichs et al., 2001) or a landscape typified by the current IDF. Dog Lake's probable return to a dry-open IDF forest type is within the natural climatic, vegetation, and fire conditions of the Kootenay Valley. The ESSF landscape in the Kootenay Valley around Marion Lake has only been established since the neoglacial (last 4,500 cal. yr B.P.) and markedly subject to future fire regime variability.

Understanding a local disturbance regime within an Ecosystem-based Management (EBM) framework has become a more holistic approach to ecological management within conservation agencies like Parks Canada (Parks Canada and the Canadian Parks Council, 2008). EBM is place-based and employs ecological processes and their respective investigative tools to inform planning decisions (Caldwell, 1970; Grumbine, 1994; Slocombe, 1998). Applying the response model might be the best way to use paleoecological data to influence future management decisions in an EBM framework. Looking at the ESSF in a response model would place emphasis on vegetation, fire, and climate drivers that might push past a threshold of the modern climax ESSF forest. Starting with vegetation, Engelmann spruce and subalpine fir are the dominant climax tree species in the ESSF (BC Ministry of Forests, 1991). Both of these tree species live a relatively long time. Subalpine fir pollen percentages have steadily decreased towards the present. This is indicative of a drier climate within the ESSF around Marion Lake, with a moderate fire regime at play over this time period. Land managers should treat this vegetation signal as a potential seral shift. If drier conditions persist and the climate continues to warm then a complete BEC regime change around Marion Lake change might occur as MS expands into the area. Thinking about an area's ecological trajectory alongside a management strategy, a manager can use paleoecological data to influence decisions in regards to more locally controlled human-controlled disturbances (e.g., fire) and any potential restoration efforts.

Ecological restoration has the goal of adjusting an ecosystem toward what is characteristic of a protected area's ecological baseline. This might or might not include efforts to accelerate this adaptation (Parks Canada and the Canadian Parks Council, 2008). Using our paleoecological data as guideposts for future biogeoclimatic shifts in the Kootenay Valley, managers can make informed efforts using modern ecological restoration techniques in line with EBM strategy.

Management priorities in Kootenay National Park seek to improve the condition of native biodiversity through active management programs and increase understanding of the impact of climate change and develop adaptation strategies (Parks Canada, 2010). In the Kootenay Valley, the emerging IDF will most likely be expanding BEC zone. The ecological trajectory around Dog Lake will likely fit this pattern moving from the MS to the IDF zone as the climate continues to become drier (Wang et al., 2016) and if forest fires become more prevalent. Characteristic of the IDF is *Pseudotsuga*. *Pseudotsuga* has been identified as a tree that may become maladapted if climate changes too rapidly (St. Clair and Howe, 2007). One ecological restoration adaption strategy that addresses this problem is assisted migration. Assisted migration involves planting seedlings adapted to future climates either through genetic breeding or transfer from one perceived climatic setting to another (O'Neill et al., 2008).

Ecological restoration will need to focus at species level to adapt to the multi-faceted threat of climate change. *Pinus albicaulis* is a keystone species whose loss is radically changing sub-alpine ecosystems in the Kootenay Valley. *Pinus albicaulis* was designated as a Species at Risk in 2012 and identified in the 2015 Kootenay National Park Management Plan Implementation Report as needing to be restored (Parks Canada, 2015). At present, *Pinus albicaulis* grows in the ESSF surrounding Marion Lake. One large threat to *Pinus albicaulis* is the mountain pine beetle. Excessive fire suppression has created large, even age stands of *Pinus* around the current ESSF that spread into *Pinus albicaulis* stands (Parks Canada, 2017). Restorative efforts might also use fire as the solution. Using our paleo data of fire around Marion Lake we can infer that using a shorter mFRI and prescribing fire when necessary can help *Pinus albicaulis* from being overtaken by other conifers and restore a vegetation mosaic akin to that found in zone 6a. The main threat to *Pinus albicaulis* is blister rust. The blister rust infection cuts off nutrients needed to make cones. A small percentage of *Pinus albicaulis* is rust resistant. Parks Canada and BC Parks have collected cones in nearby British Columbia and Alberta as part of a research project to screen seedlings planted at old burn sites for resistance to blister rust (BC Parks, 2019).

3.5.3. Limitations

Making natural resource decisions based on the response model using BEC zones has its limitations. Most notably, the spatial scale of the BEC system reduces complexity to a level that ignores a host of species-level responses to drivers that are often the focus of restorative efforts. This loss of site complexity may mis-align with is important for making resiliency-focused decisions.

This study focused on two sites within the Kootenay Valley. However, when considering implications for management, spatial complexity among sites, the focus needs to be on the site level. In the example of fire history reconstruction our two sites show significant asynchrony. Asynchrony between sites close in proximity has been documented on the coast of British Columbia coast (Murphy et al., 2019). This asynchrony between sites that are in close proximity highlights the need to create site-specific fire-related management decisions around the natural range of variability produced by fire reconstructions (Whitlock et al., 2003).

3.6. Conclusion

Marion and Dog lake broadly follow the climate history for southern interior BC previously put forth. Both Marion and Dog Lakes' carbon accumulation records are synchronous with inferred fire frequency peaking in the xerothermic period. Carbon accumulation rate in Marion and Dog Lake is high during the xerothermic. High runoff due to fire-related activities, or increased in-lake production, or both could cause this. In the mesothermic, vegetation patterns show a lowering of the BEC zones and establishment of subalpine meadows in the ESSF and a more open landscape in the MS. Wetter summers are likely the driver for decreased fire frequency and low C accumulation rate.

Modern forest and fire frequency is established in the Kootenay Valley by the neoglacial. Marion Lake's climatic signal appears earlier in comparison to Dog Lake and the rest of the region. This earlier signal is likely due to higher exposure and maintains a modern landscape due to early establishment of subalpine meadows. Dog lake switches to a more open closed landscape in the neoglacial likely due to wetter neoglacial conditions. As a result, Dog Lake has an increase in C accumulation due to increased biomass on the landscape.

Future climate predictions for the Kootenay Valley are expected to be dry and hot analogous to the xerothermic period. This would move the MS landscape around Dog Lake to a dry-open landscape typified by the current Interior Douglas Fir (IDF) zone. Around Marion Lake, the ESSF would likely transition to a MS-like landscape if a sufficient moisture regime (i.e., winter snowpack at higher elevations) is sufficient. If fire frequencies were to increase and drier grasslands were to prevail, then an IDF-like landscape may occur.

As representatives for the Kootenay Valley, Marion and Dog Lake provide paleo insight into the future for two adjacent BEC zones. When considering management implications, spatial complexity between Marion and Dog Lakes needs to be highlighted. Identifying key ecosystem characteristics should be assessed in terms of their ecological thresholds and addressed alongside any larger management directives.

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Chapter 4. Protected area carbon management in Canada

4.1. Abstract

To orient to the problem of how carbon should be managed in Canada's protected areas we initiated discussion in a workshop with protected area managers and other experts on current carbon management knowledge and knowledge gaps, and what role carbon management might play in protected area decision-making. A follow-up set of semi-structured phone interviews with Parks Canada managers indicated that carbon management would best be integrated in park planning alongside ecological integrity measures as a co-benefit. To assess which ecological integrity measures would be the most important on which to focus we conducted an online survey of Parks Canada and BC Parks employees in which we proposed carbon management as a separate measure or as a co-benefit beside eleven different ecological indicators used by Parks Canada. The ecological indicators with a vegetation component received the highest ratings of importance in comparison with the hypothetical new carbon measure. These results suggest that the indicators with a vegetation component would be the most important on which to focus in carbon management. Available tools to provide data on carbon for these measures include the Carbon Budget Model of the Canadian Forest Service, paleo proxies, and citizen science. If done collaboratively across the issue network, the integration of carbon data with vegetative ecological integrity measures could help to build trust in the institutions that manage protected areas and address the problem of how to manage carbon in protected areas. To update our discussion of carbon management as a co-benefit in protected areas, we discuss Canadian initiatives that have taken place since the original workshop in 2011 and current non-government recommendations.

4.2. Introduction

The average global temperature is likely to reach 1.5°C above pre-industrial levels between 2030 and 2052 (IPCC, 2018: Summary for Policymakers). To achieve net emissions by mid-century along pathways that are consistent with an increase of 1.5°C or less will require minimizing greenhouse gas emissions along with mitigative actions (de Coninck et al., 2018). Protected areas (PAs) have the potential to play an important part in the mitigation of climate change through maintenance and enhancement of natural carbon (C) storage in the land and seascapes. Globally, PAs are estimated to currently sequester 0.5 Pg of C annually, although accelerated climate and land-use change threaten to reduce this to 0.3 Pg C annually (Melillo et al., 2016). In Canada, exactly how much carbon is stored in the country's PAs is still under investigation as researchers investigate various ecosystem components not previously analyzed for their storage potential (e.g., Blue Carbon stored in eelgrass and salt marshes (Postlethwaite et al., 2018)). However, one study estimated that Canada's national parks alone store 4.43 billion tonnes of carbon (Kulschreshtha and Johnston,, 2000).

Environment and Climate Change Canada has identified the uptake and storage of carbon as the ecosystem service in PAs that is most relevant to climate change mitigation in Canada (Environment and Climate Change Canada, 2019). However, insufficient attention has been paid to how to manage this carbon in PAs (National Advisory Panel, 2018). The primary participants in PA management in Canada are usually government agency staff working in bureaucratic institutions at the local, regional, and national scale. Indigenous people are also involved in the development and management or co-management of PAs, and some non-government organizations (NGOs) manage areas that are designated for conservation. Other participants in PA management may include affected or interested individuals or groups in what is known as an issue network (Bland and Abaidoo-Asiedu, 2016).

To investigate the views of Canadian PA managers about carbon management in PAs, we initiated discussions with PA managers and other experts at a workshop on carbon management that we organized as part of the 2011 British Columbia Protected Area Research Forum (BCPARF). BCPARF is a biennial academic conference attended by employees of Canadian and provincial parks agencies and by researchers interested in PAs. We used the results of this workshop to inform a set of interviews that we conducted in March and April of 2013 with Parks Canada managers about their views concerning various strategies to integrate carbon management in their decision-making. Then, at the 2013 BCPARF, we conducted an online survey in which we asked PA managers about their agency's role in carbon management and the possibility of using carbon management as an indicator of ecological integrity (EI) in parks, or as a potential “co-benefit” of other existing indicators used to assess EI. All of this research on the views of PA managers was conducted more than five years ago. In this paper we discuss the results in light of the evolving climate change context and the carbon management initiatives that have taken place in Canadian parks since our research was conducted.

We frame the issue of carbon management in protected areas as a policy problem: “a substantial discrepancy between what is and what should be” (Dery 1984). The policy sciences literature identifies five “intellectual tasks” that policy analysts should undertake in order to understand policy problems and develop effective strategies to address them: clarify policy goals; describe trends in relationship to the goals; analyze the conditions or factors that are causing or contributing to trends; project (i.e., predict) future developments if conditions do not change; and invent, evaluate and select alternative strategies to address the problem (Lasswell, 1971; Clark and Brewer, 2000; Clark, 2002). Table 4.1 sets out the key questions associated with each of these five tasks of problem orientation and identifies the components of our research (workshop, interviews, and survey) that covered each task.

Table 4.1. The five intellectual tasks of problem orientation and the components of our research that dealt with each (adapted from Lasswell, 1971; Clark and Brewer, 2000; Clark, 2002).

Task	Title	Questions	Method
1	Clarifying goals	What are the goals or ends?	Workshop at BCPARF 2011
2	Describing trends	What are the historical and current ecological and socio-political trends? How do these trends compare with the goals? Where are the knowledge gaps?	Workshop at BCPARF 2011 and semi-structured interviews
3	Analyzing conditions	What relationships, factors and conditions are causing or contributing to the trends? For example, what factors are affecting decision-making?	Workshop at BCPARF 2011 and semi-structured interviews
4	Projecting developments	What is likely to happen in the future if there is no intervention to change conditions? How do future scenarios align with the goals?	Workshop at BCPARF 2011 and semi-structured interviews
5	Inventing, evaluating, and selecting alternatives	What interventions or alternative strategies could be implemented to achieve the goals? How do these alternatives compare and which are most likely to achieve the goals?	Semi-structured interviews and survey launched at BCPARF 2013

4.3. Methods

To address the problem of how to manage carbon as a climate change mitigation strategy in protected areas, we designed an iterative course of investigation around two research forums on protected areas in British Columbia, Canada (Table 4.2).

Table 4.2 The three-phase methodological approach used in this study.

Phase	Title	Research Question(s) or Goal	Method	Who is Involved
1	Problem structure	What is the role of PAs in climate change mitigation? What are the opportunities, knowledge gaps, and constraints for carbon management in PAs?	Workshop including a panel discussion and forum	Participants in the 2011 British Columbia Protected Area Research Forum
2	Assess alternatives	Assemble carbon management alternatives	Semi-structured telephone interviews	PA managers
3	Evaluate and compare alternatives	What are the PA practitioner's preferences among carbon management alternatives?	Online survey	Participants in the 2013 British Columbia Protected Area Research Forum

British Columbia Protected Area Research Forum (BCPARF)

The BCPARF is a biennial event that is held at different universities across British Columbia. Members of BC Parks, Parks Canada, and BC universities govern the conference with the goal of facilitating research and its application to PA management. The conferences are attended by 150-200 individuals and are open to anyone interested in PA research and management. The conference format includes plenary sessions, presentations, posters, workshops, and displays (UNBC, 2019). Past BCPARF meetings have been a place where leaders and managers of PAs gather, learn, and share ideas. For these reasons the BCPARF was chosen as a reasonable venue at which to explore the problem of carbon management as a potential means of mitigating climate change in protected areas.

A workshop was conducted at the 2011 BCPARF held at the University of British Columbia, focusing on clarifying goals and roles of carbon management in PAs. At the 2013 BCPARF held at the University of Northern British Columbia, a survey was administered to determine preferences of park managers and administrators when presented with alternative methods of carbon management within parks and protected areas (Table 4.2).

Phase One: 2011 BCPARF Workshop: Framing of Carbon Management

Attendees of the 2011 BCPARF were invited to our two-hour workshop entitled, “Starting the Conversation: Climate Change Mitigation in Canada’s Protected Areas.“ The abstract in the promotional material for the workshop stated:

> With this session we would like to initiate a discussion about the role(s) of protected areas in climate change mitigation, which is an important solution within a larger portfolio of climate change solutions. The session will begin with short background presentations on the current understanding of climate change mitigation from the perspective of the panelists. The subsequent discussion goals are to define climate change mitigation as it relates to protected areas, identify where protected area agencies fit into larger climate change strategies, frame objectives of climate change mitigation in protected areas, and, if time permits, prioritizing climate change management options.

(see Appendix D1 for a full copy of the abstract).

Approximately 35 people participated in the workshop with varying backgrounds in the private sector, industry, academia, and PA institutions (BC Parks and Parks Canada). The expert panel that led the workshop included the following individuals: Thomas Rodengen (Simon Fraser University), Wolfgang Haider (Simon Fraser University), Marlow Pellatt (Simon Fraser University and Parks Canada), Eva Riccus (BC Parks), and Tory Stevens (BC Ministry of the Environment).

Phase Two: Semi-structured Interviews: Framing of Carbon Management in Parks Canada State of the Park Reporting

Both Parks Canada and BC Parks promote EI as a primary management goal within their agencies (Parks Canada, 1994; Parks Canada Agency, 2000; BC Parks, 2012). BC Parks utilizes EI to guide vision, plans, and operational policies, typically in the form of recommendations in annual reporting across the province. EI in Parks Canada is integrated into the review process for each PA management plan through State of the Park Reports (SOPRs). SOPRs inform individual Park Management Plans on a legislated five-year cycle (Parks Canada, 1998). SOPRs are fact-based documents that describe the current conditions of a PA using an indicator framework. The SOPR assesses the PA’s performance in meeting the indicators using measures to describe the current conditions. Across the eight publicly available SOPRs we were able to access at the time of our research, EI as an indicator had a variety of measures. For our research, we decided to use 11 EI common measures from these SOPRs (Table 4.3). Since these or similar EI measures are already used by Parks Canada and BC Parks managers to assess conditions in their PAs, they offer a means through which carbon assessment and management could be introduced into existing park planning processes.

Table 4.3 EI measures, their ecosystem, and their definition used in this study.

Measure (ecosystem)	**Definition**
Vegetation Condition (Terrestrial)	measured by forest community composition, structure, diversity, and primary productivity
Disturbance by Forest Insects and Disease (Terrestrial)	measured by insect and disease outbreak, frequency, extent, host species, and age class
Connectivity of Rivers and Streams (Aquatic)	measured by the capacity (full or partial barrier) for fish and terrestrial wildlife passage
Water Quality (Aquatic)	measured by trophic status
Disturbance by Prescribed Fire (Terrestrial)	measured by area burnt versus total area targeted for burning
Invasive Species (Terrestrial)	measured by non-native flora and fauna presence, distribution, relative abundance, and rates of expansion
Invasive Species (Aquatic)	measured by non-native flora and fauna presence, distribution, relative abundance, and rates of expansion
Disturbance by Wildfire (Terrestrial)	measured by area disturbed by fire, condition of remaining forest after a fire, and the fire cycle
Fish and Wildlife Population (Aquatic)	measured by benthic invertebrate diversity abundance, creel census, tagging, and fish counts
Wildlife Population (Terrestrial)	measured by abundance, birth rate, mortality, species richness, range, and condition

Measure (ecosystem)	**Definition**
Vegetation Condition (Aquatic)	measured by vegetation response to wildlife, primary productivity, vegetation productivity, macrophyte monitoring, and algal monitoring

Six semi-structured phone interviews were conducted with Parks Canada managers in which they were asked about how carbon was managed in their agency and their PA, and how it could be better managed in the future (Appendix D2). Semi-structured interviews were considered the most appropriate methodology for this phase by allowing an open format, while ensuring key themes and ideas could be addressed (Babbie and Benaquisto, 2002).

Phase Three: 2013 BCPARF Survey: Analyzing Preferences of Carbon Management Alternatives

To investigate the preferences of PA managers for carbon management alternatives, an online survey was developed and launched at BCPARF 2013. The introduction to the survey advised participants that "The primary goal of this survey is to investigate how managers and researchers working in protected areas perceive the role of carbon management." The survey had 18 questions in total. Four questions were aimed at collecting the participant's demographic information. Three questions were created as a training set aimed at preparing participants for a choice experiment (Louviere et al., 2000). An example of a training set question is found in Table 4.4. Each of the ensuing 11 choice experiment questions contained five possible EI measures and asked the respondent to treat carbon management as a co-benefit to these measures in a terrestrial-based PA within their agency's jurisdiction. A copy of the survey can be found in Appendix D3. An example of a choice experiment question is found in Table 4.5.

Table 4.4 Example of a training set question in the survey.

Imagine that your agency has adopted a new EI measure for carbon. The new carbon measure describes any process, activity or mechanism that can store carbon and reduce greenhouse gas emissions. Compared to the new carbon measure, how important is each of these aquatic measures listed below? Please check the response that best describes your opinion						
Measure	*Unimportant*	*Of Little importance*	*Moderately Important*	*Important*	*Very Important*	*Don't Know*
Water Quality			✔			
Vegetation Condition					✔	
Connectivity of Rivers and Streams		✔				
Invasive Species				✔		
Fish and Wildlife Population				✔		

Table 4.5 Example of a choice experiment question from the survey.

Imagine you are making a management decision at a terrestrial-based protected area within your agency's jurisdiction. Please check which measure you would find implementation of carbon management to be the easiest and which measure you would find implementation the most difficult.		
Measure (Ecosystem)	*Easiest*	*Most difficult*
Disturbance by Forest Insects and Disease (Terrestrial)		
Vegetation Condition (Terrestrial)	✔	
Wildlife Population (Terrestrial)		
Invasive Species (Aquatic)		✔
Disturbance by Wildfire (Terrestrial)		

Descriptive analysis was conducted on the survey responses to ascertain the distribution, detect any errors, and explore associations among the data. Descriptive analysis and chart visualization was carried out in Microsoft Excel (Microsoft Corporation, 2010). To provide insight on the factors of our survey question a principal component analysis (PCA) was used. The PCA was carried out in JMP (SAS Institute Inc., 2014).

4.4. Results

4.4.1. Phase one: 2011 BCPARF workshop

In the first stage of the workshop, five panel members described the current setting and background for climate change mitigation in PA, in a panel discussion format covering the following:

- a definition of climate mitigation and the differences between mitigation and adaptation;
- an acknowledgement from the BC Parks panel member of the carbon storage potential in BC PAs;
- an acknowledgement from the Parks Canada panel member of the potential role of National Parks in climate change mitigation;
- uncertainty about the amount of carbon in PAs and the projected difference in carbon dynamics in PAs versus adjacent areas with different primary uses;
- the lack of information communicated to the general public in regards to the role of Canada's PAs in climate change mitigation.

The second stage grouped participants (~5 people) and each group was asked to answer the following questions with answers recorded on a flipchart.

1. What are the opportunities for climate change mitigation in PAs?
2. What are the knowledge gaps for climate change mitigation in PAs?
3. What are the constraints or concerns for climate change mitigation in PAs?

The following summaries were reported to the workshop in stage three of the workshop. Each summary point reflects multiple groups reporting.

Question 1:

-PAs have an opportunity to tailor existing practices to include climate change mitigation especially in relation to forest practices.

-PAs have an opportunity to be a showcase for research and inspire green behaviour. This would be best to highlight at the operational level (e.g., bus transportation).

Question 2:

-It is unknown how much carbon is in PAs.

-How do different ecosystems respond to climate change and how does that response affect carbon budgets and dynamics?

Question 3:

-Concern for how newly created PAs versus existing ones will incorporate carbon storage. Also, could new PAs be created with the primary goal of storing carbon?
-Concern for lack of information in relation to how effective PAs are at climate change mitigation versus surrounding areas.
-Concern for potential conflict between goals of PAs when trying to incorporate climate change mitigation.

The fourth stage of the workshop was an open-ended discussion during which the panel and participants interacted. A question from the participants to the panel asked, “What percentage of effort is put toward adaptation versus mitigation at your PA?” The panel representatives from Parks Canada and BC Parks both said that the majority of institutional focus is on adaptation. The BC Parks panel member said that mitigation is something that carries a lot of caveats, especially if mitigation in PAs enters into some sort of market mechanism (e.g., carbon trading). A question from the panel to the participants asked, “If you are a PA manager, could you choose between potential mitigation strategies for your region now?” All four of the responding participants said that climate change mitigation is “on our radar screen”, and that choosing between different strategies would depend on how the choice is framed. Two of the responding participants suggested that the choice be framed in the PA’s management plan review process

The 2011 BCPARF workshop provided significant progress towards defining the problem of climate change mitigation in PAs and inventing, evaluating, and selecting alternatives. In reviewing the responses of participants in stages three and four of the workshop, it became clear that participants considered carbon and carbon management to be key when discussing climate change mitigation in PAs. Participants also made evident the knowledge gaps about the quantity of carbon existing in PAs and which ecosystems might be directly affected by changing conditions arising from climate change. Despite the poor understanding of trends related to carbon, participants were able to identify a complex interplay of factors that might affect carbon management. The responses of stage four of the workshop revealed the conditioning factors that PA managers identify that might explain trends in planning for carbon systems in PAs.

4.4.2. Phase two: Semi-structured interviews

In the semi-structured interviews, park managers from Parks Canada were asked questions about carbon management in their PAs. Some managers responded by identifying measures for carbon management that they considered to be the easiest to implement. Other managers responded by identifying measures for carbon management that they considered to be the most effective. This contrast in emphasis between what is easiest and most effective underpins an important divergence in thinking among PA managers. To elaborate on this point, four of the six managers specifically referenced fire management programs in their PA as activities that contribute to carbon management. These same four managers said that a more advanced understanding is needed to realize how fire as a process influences carbon management and stressed potential confounding effects and goals. So, while disturbance by prescribed fire or wildfire might be carbon management measures that are easy to implement, their effectiveness for carbon management might need further investigation. One of the four interviewees asked how measuring/quantifying carbon at all could improve the EI system.

The managers who were interviewed were from PAs that contained a wide range of ecosystems from across the Parks Canada system. Furthermore, the preferences of these managers for specific carbon management alternatives varied with the PA with which each manager was associated Five of the six managers cited the ecological uniqueness of their own PA as a major challenge in the absence of an agency wide directive or set of guidelines to help incorporate carbon management into decision-making. All managers expressed a need to share knowledge generated about carbon across parks. One interviewee summed up this sentiment as:

> *Understanding how our individual ecosystems contribute, or do not contribute, to carbon management is the biggest challenge. We should have a system of knowledge sharing between similar parks.*
>
> *(RMNP representative, interview, March, 2013)*

Responses from phase two were discussed among the authors and we developed an online survey incorporating a choice experiment for phase three.

4.4.3. Phase three: 2013 BCPARF survey

Nineteen participants took the survey. Eleven of the 19 participants took the survey on-site at the 2013 BCPARF. The remaining eight participants took the survey online via email invitation. Four of the 19 respondents did not complete the survey in its entirety and were not included in further analysis. Of the remaining 15 respondents, 53% worked for the Parks Canada agency and 47% for BC Parks, 7% of respondents had only terrestrial ecosystems represented in their unit's/office's jurisdiction, 40% of respondents had terrestrial ecosystems and freshwater aquatic ecosystems represented, 7% of respondents had terrestrial ecosystems and coastal/marine ecosystems represented, and 46% of respondents had all three ecosystems represented in their jurisdiction.

When asked if their agency has a role in carbon management, 80% of respondents said yes, 7% said no and 13% indicated that they did not know or were unsure. When asked if carbon management should be a separate EI measure, 7% strongly agreed, 33% agreed, 13% were neutral, 20% disagreed, and 27% strongly disagreed. When asked if carbon management should be a co-benefit of other activities, processes or mechanisms that further other measures 40% strongly agreed, 40% agreed, 13% were neutral, 7% disagreed, and 0% strongly disagreed. When asked if carbon should be its own ecological integrity measure, Parks Canada employees averaged a response of 2.9 while BC Parks employees averaged 2.6 on a 5 point likert scale, with 1 being strongly agree and 5 being strongly disagree. When asked if carbon should be treated as a co-benefit, Parks Canada employees averaged a response of 2.0, while BC Parks employees averaged a 1.9 on a 5 point likert scale with 1 being strongly agree and 5 being strongly disagree.

The three training set questions revealed that respondents rated EI measures related to vegetation as most important to carbon management in comparison to a hypothetical new carbon measure (Figure 4.1). A principal component analysis of these responses (Table 4.6) revealed three main factors, each consisting of a group of EI measures. We labeled these factors to reflect the EI measures included in each: 1. Water and Wildlife; 2. Vegetation; and 3. Invasive Species. The Vegetation factor (Factor 2) included five of the EI measures related to vegetation.

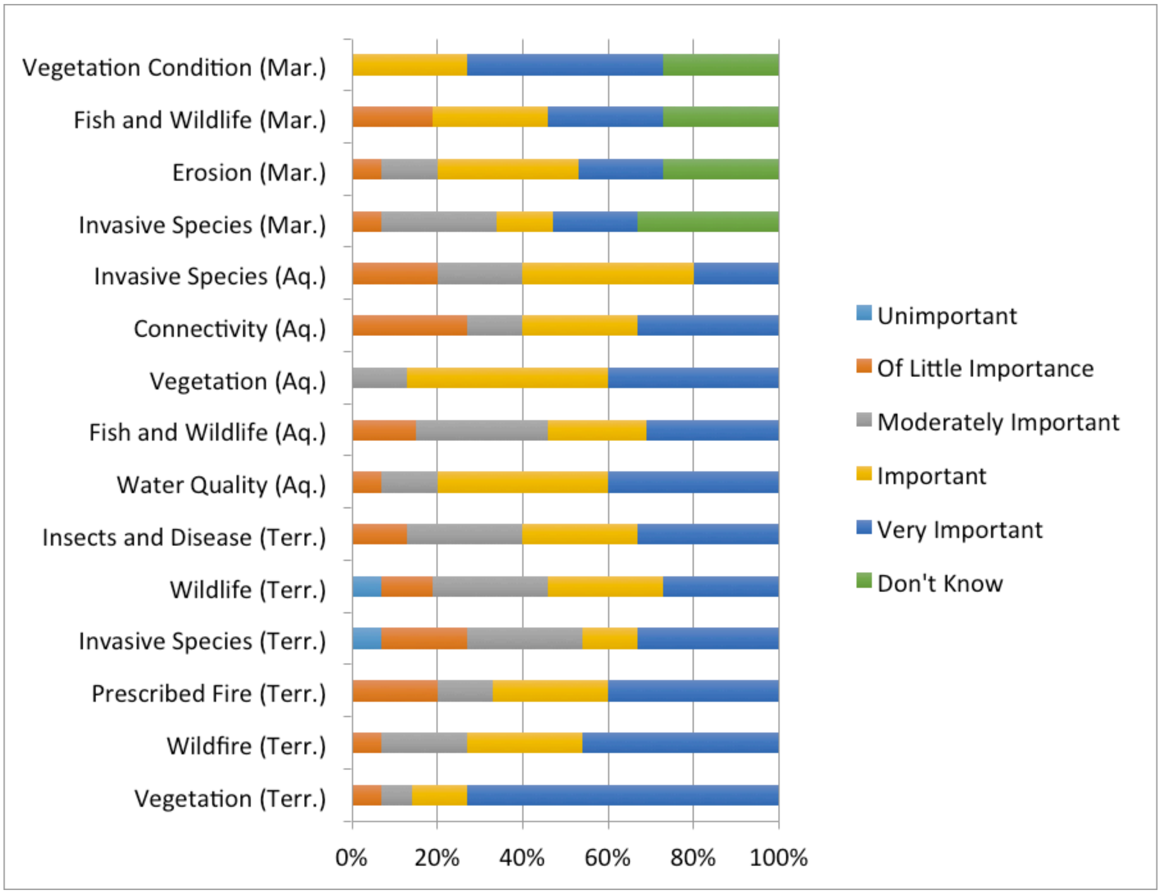

Figure 4.1 Bar plot of respondents' Likert-scale ratings of the importance of EI measures when asked to compare them to a hypothetical new carbon management measure. (Terr.) = Terrestrial; (Aq.) = Freshwater Aquatic; (Mar.) = Marine/Coastal.

Table 4.6 Three factor grouping principal component analysis of the training set questions of the survey. (T) = Terrestrial (A) = Freshwater Aquatic.

Factor 1 – "Water and Wildlife"	Factor 2 – "Vegetation"	Factor 3 –"Invasive Species"
Wildlife Population (T)	Vegetation Condition (T)	Invasive Species (T)
Fish and Wildlife Population (A)	Vegetation Condition (A)	Invasive Species (A)
Connectivity of Rivers and Streams (A)	Disturbance by Forest Insects and Disease (T)	
Water Quality (A)	Disturbance by Wildfire (T)	
	Disturbance by Prescribed Fire (T)	

Due to the small number of responses to the survey, the choice set questions could not be analyzed using any advanced statistical modeling methods (e.g., logit model, latent class analysis).

4.5. Discussion

80% of PA managers surveyed agreed that their agency has a role to play in carbon management, but only 40% of PA managers surveyed agreed that carbon management should be incorporated as a separate EI measure. 80% of PA managers surveyed agreed that carbon management should be assessed as a co-benefit to existing indicators used to assess EI. For carbon to be framed and managed as a co-benefit, our results highlight two large challenges related to the outlined intellectual tasks (Table 4.1) that need to be addressed in the larger context of carbon management in PAs as a policy problem.

First, in the initial workshop and in our interviews PA managers expressed concern over issues related to "top-down" policy implementation. Notably, in discussions about the possibility of carbon management becoming a policy within Canadian park agencies, PA managers said that such a policy would need to align with the formal structure of PAs and the existing incentives in planning and management, and also be readily downscaled. For agencies like Parks Canada and BC Parks, successful implementation of innovative policies such as carbon management will depend to a large extent on the individual PA-level where the perspectives of local managers and other stakeholders are important in the policy process (BC Parks, 2016; Parks Canada, 2018). This is highlighted by the responses in the phase one workshop and phase two interviews where participants identified that carbon management practices that are easy to implement and carbon management practices that are the most effective may not be the same.

A second challenge is that managers conveyed a poor understanding of the trends and conditions relating to carbon in their PAs. The participants at the 2011 BCPARF workshop and semi-structured interviews of PA managers emphasized this lack of information. Without these intellectual tasks sufficiently attended to in a form that is useful for PA managers, these managers are not making an informed selection between carbon management alternatives.

Strategies for Implementation of Carbon Management in Parks Canada

In the phase one workshop, the initial intellectual task of clarifying goals led to conceptualizing the preferred objective of maintaining or storing more carbon in PAs and away from the atmosphere. Phase two of the study clarified that incorporating measures for carbon assessment and management as co-benefits to existing ecological integrity indicators could pursue this goal. This strategy involves efficiently leveraging existing PA resources and policies.

In the broader institutional context of Canadian park agencies, the strategy of linking carbon management to existing indicators of EI is a policy innovation (see Steelman, 2010). Innovation begins when new ideas are placed on the policy agenda. The probability of an innovation being implemented increases when top-down and bottom-up factors are aligned and are mutually supportive for the innovation (Steelman, 2010). The conceptual framing of an innovation is a critical factor that affects individual's perceptions of the proposed change and whether they will collectively work towards an improvement. Bottom-up implementation theory indicates that individuals in an organization are more likely to support an innovation if it aligns with existing organizational culture and accepted practices, and it is perceived as preserving institutional harmony. Top-down implementation theory suggests that an innovation is more likely to be implemented when there is clear administrative support and high-level organizational commitment to the innovation. Since implementation is a social process, basic qualities of trust and communication are important factors in both top-down and bottom-up approaches, Trust can be built through recognition of differences in individual perspectives and open communication. When trust is integrated into the social process of PA governance it opens the pathway to adapting an innovation though improvement in social relations (Moulaert et al., 2013). These factors are explored in the following discussion of policies related to carbon management by Parks Canada and BC Parks since the time of our research.

The Canadian Parks Council and National Advisory Panel have made several recommendations for carbon management in recent years. A report of the National Advisory Panel (2019) included recommendations (#34, #35, and #36), that state that landscape-level planning should include consideration of how to maximize the protection, maintenance, and enhancement of carbon-rich ecosystems and that Canada should develop a carbon inventory based on the best available science and monitoring (National Advisory Panel, 2019). The recommendations cite the need for an enhanced inventory system that builds on the Carbon Budget Model of the Canadian Forest Sector version 3 CBM-CFS3 (National Advisory Panel, 2019). Parks Canada's SOPR system already requires data and monitoring for each EI measure and could incorporate data and monitoring on how carbon dynamics change as a potential co-benefit associated with each EI measure. This would begin carbon monitoring in National Parks in association with the terrestrial, freshwater aquatic, and coastal/marine vegetated systems identified as potentially important by PA managers (Figure 4.1, Table 4.6).

Using inventory tools such as the CBM-CFS3, Parks Canada could include CBM-CFS3 generated data in the vegetation grouping of EI measures (Table 4.6) in the next SOPR cycle. In our survey of PA managers, the terrestrial vegetation EI measure was considered the most important (Figure 4.1). Terrestrial vegetation condition is defined by the growing dynamics of a landscape (e.g., structure). The CBM-CFS3 provides a yearly estimate of the volume of carbon (in tonnes) on the basis of these dynamics, making it an excellent tool to quantify carbon (Kull et al., 2019; National Advisory Panel, 2019). The CBM-CFS3 was used by the Pacific Carbon Trust to quantify emission offsets before the trust was transferred to the Climate Action Secretariat within the Environment Ministry by BC government (Greig and Bull, 2009). The CBM-CFS3 is still used in Intergovernmental Panel on Climate Change (IPCC) compliant reporting for forests, however it is no longer used to validate carbon offset projects as it was under the Pacific Carbon Trust.

Quantifying the volume of carbon in vegetation condition can be achieved through the creation of carbon maps: spatial representations of where the carbon is on the landscape. A carbon map of a PA could use various colours to represent differing amounts of stored carbon within the PA boundaries (Parks Canada, 2019a). The CBM-CFS3 can also determine the amount of carbon on the landscape before and after disturbances such as wildfires or insect or disease outbreaks (e.g., Sharma et al., 2013). Both natural and human disturbances are defined by the user in the CBM-CFS3 so future management scenarios can be described. Disturbances are user-defined in the CBM-CFS3 model. To add predictive capabilities in the model, the National Forest Carbon Monitoring, Accounting, and Reporting System projects a suite of CBM-CFS3 scenarios based on likely future disturbance rates and management actions in the next two to three decades. The Parks Canada Climate Change Team has started a Carbon Atlas for all the National Parks of Canada designed to estimate and spatially map baseline carbon stocks using the CBM-CFS3 in a geospatial database called the Carbon Atlas. The Carbon Atlas is expected to be completed in March, 2021 (Sharma, 2019).

To address some of the uncertainty in the predictive modeling of the CBM-CFS3, past disturbance rates can be obtained by paleo proxies. For example, charcoal analysis from a lake sediment core can yield a mean fire return interval that can be used to inform future fire disturbance rate. The majority of managers interviewed in phase two identified fire management in their park as a likely area for carbon management. All managers who identified fire management in their PA emphasized that carbon management would need to be tailored to their unique fire management program (e.g., prescribed burns versus wildfire containment). Furthermore, they pointed to the complexity of carbon's relationship to fire on an ecosystem-by-ecosystem basis within their PA. Indeed, there are highly varying spatial and temporal scales to consider with fire regimes. For example, sites as close together as 120 km in the same biogeoclimatic zone can vary dramatically in fire frequency over the past 5,000 years due to changing climate, human, and local site factors (e.g., Murphy et al., 2019).

Another effort to quantify carbon in PAs has been the Blue Carbon Project (Commission for Environmental Cooperation, 2018; Parks Canada, 2019b). With collaboration from the Commission for Environmental Cooperation, Parks Canada, and academia, the project seeks to quantify how much carbon is stored in the shallow-water ecosystems of Canada's coasts. Postlethwaite et al. (2018) found that eelgrass in coastal shallow-water sites can store more carbon than non-vegetated reference sites. However, the storage they measured in their studies of Clayoquot Sound (BC) is at a lower rate than more tropical seagrass areas. Projects like Blue Carbon provide data that form the base of the SOPRs and provide needed information related to EI measures like marine/coastal vegetation condition to make more informed decisions.

All of the EI measures in the vegetation grouping (Table 4.6) include EI measures deemed important or very important by PA managers (Figure 4.1). However, the EI measure of Vegetation Condition in freshwater aquatic ecosystems (Table 4.3) is not something that can be inventoried by the CBM-CFS3. This does not preclude it from being included in the carbon budget. One way to estimate its carbon budget would be to monitor the freshwater aquatic trophic state and size and calculate annual carbon storage based on primary productivity (e.g., using algal monitoring data). While this might seem like a complicated way to manage carbon, Parks Canada managers and operations staff do not need to do this work in isolation. As pointed out in the semi-structured interviews, sharing of information between similar PAs would help to understand how individual ecosystems contribute to carbon management. Information generation and sharing could come from anywhere in the relevant policy universe including academia, non-government organizations, citizens, or BC Parks.

As an example of bottom-up efforts to pursue carbon management within protected areas, BC Parks has collaborated with a non-government organization (NGO) to permanently store carbon on Denman Island in the Strait of Georgia of the BC coast. In the project, the NGO ERA Ecosystem Services based in Oregon spearheaded the contracting, finance, and development to ensure that 493 hectares targeted by BC Parks avoided conversion to agricultural and real estate development. The Climate, Community and Biodiversity Alliance (CCBA) predicted that this avoided conversion (forest cover) will sequester 430,000 tCO2e over the next 100 years (ERA, 2014a). This unique approach to the carbon management problem has won the Award for Innovation and Excellence by the Premier of BC (ERA, 2014a). The Great Bear Forest Carbon Project in north and Central-Mid Coast and Haida Gwaii, BC, is currently attempting a similar approach involving avoided forest conversion in cooperation with NGOs, First Nations, and individuals (ERA, 2014b). Both of these projects work with the vegetation grouping of factors in areas that have more than one ecosystem represented.

Individual's perspectives, which drive their participation and positions in institutional decision making about PAs, are something the authors sought to investigate in the 2013 BCPARF survey (Appendix D3). This was attempted in a choice experiment architecture directed at PA managers questioning what EI measures are important to carbon management as a co-benefit. Indeed, the difference between the co-benefit qualities of being easy and effective to implement were pointed out in the phase two semi-structured interviews. Exploring these attributes of carbon management co-benefits will help policymakers to frame how PA managers choose between alternative EI measures. Getting towards a more complete problem definition and strategy for carbon management, and extending the discussion beyond PA managers, will become necessary as the scope of carbon and its management in PAs widens. Interest groups, NGOs, academics, and anyone else in the policy universe could be presented with a similar choice architecture as in our survey. This diversity of input could help to clarify the problem and ensure that all the important issues are addressed in structuring future management decisions and their implementation for carbon management in PAs.

4.6. Conclusion

PA managers in Canada recognize the potential of carbon management as a co-benefit to EI measures. Specifically, PA managers place "vegetation" EI measures as having the most importance when compared with a hypothetical separate measure for carbon management. However, PA managers indicated that they required more information on trends and conditions in carbon to be able to implement any form of carbon management as a climate change mitigation strategy within parks and protected areas.

The CBM-CFS3 complemented by paleo proxies can quantify carbon to inform future management decisions. Engaging individuals across the issue network could contribute to carbon data generation and build trust in the institutions that manage PAs in Canada. Gaining perspectives on what would be the easiest and most effective “vegetation” EI measures to implement across the issue network can both aid in selecting where to put effort and build broader support for carbon management implementation.

4.7. References

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Chapter 5. Conclusions

This thesis addresses the potential of carbon management in protected areas by investigating carbon and paleoecological indicators in lake sediment and protected area managers' perspectives on carbon management. Connection between data like carbon in lake sediment and its utility in management of protected areas relies on broader understanding of the data itself, and creation of an opportunity for integration in current protected area management. This thesis focuses on how to frame the problem of carbon management by targeting the following research questions:

1) Over the past century, what are the dynamics of carbon accumulation?

2) Over the last 10,000 years, what are the dynamics of carbon accumulation?

3) Is carbon important to PA management?

4) How prepared are PA managers to deal with carbon management?

5) How have PA managers dealt with carbon in the last decade?

The following summarizes the key findings of chapters two-four of this thesis, which address the three research questions.

In Chapter 2, we investigated carbon (C) accumulation rates in lake sediment across southwestern Canada since the mid 19^{th} century. Previous studies vary in estimates of C accumulation rates since the industrial revolution due to a combination of different processes. Ascertaining how these processes might affect C accumulation rates can aid in understanding the role and importance lake sediment and the surrounding landscape might play in resource management. Carbon stored in lake sediments enters the lake system in one of two pathways. The first pathway occurs when CO_2 concentrations in the atmosphere is greater than in the water column. This atmospheric pathway can follow periods of high primary production in nutrient-poor lakes (Hanson et al., 2004). The second pathway of carbon inflow is from hydrologic and fluvial processes that include the dissolved inorganic carbon complex of carbon dioxide, bicarbonate, carbonate, and calcium carbonate and the organic carbon pool. For carbon pools and fluxes in Canadian boreal lakes, the most important component is organic carbon (Benoy et al., 2007). However, processes such as mineralization that facilitate the transfer of carbon between inorganic and carbon pools should not be overlooked. To better understand how the processes of climate, lake morphology, and modern land-use might explain patterns in C accumulation rate we directly ascertained paleo C accumulation data and statistically compared any patterns to ecozone, climate model data, lake area, maximum lake depth, catchment area, lake area ratio, lake geometry ratio, modified dynamic ratio, land cover data, sourcing of organic matter data and protection status. We found that for our lakes average C accumulation rates are an average of 3.8 times greater in the modern time period (1980-2010) when compared to the historical time period (1830-1860). The largest C accumulation rate change between modern and historical periods is found in the Boreal Plains ecozone. 69% of lakes showed significant relationships with C accumulation and one or more temperature-related variables. Temperature related variables (e.g., number of ice-free days) are likely to affect lake productivity. Maximum lake depth and lake geometry ratio were significantly correlated with C accumulation rate in both modern and historical periods. Surrounding land-use had confounding results and would likely need to be further investigated on a lake-by-lake basis. This chapter suggests that lake sediment C accumulation rates in southwestern Canada since the industrial revolution are influenced by temperature-related climate and lake morphological variables. Chapter 2 suggests no significant difference in C accumulation rates between protected areas and non-protected areas in southwestern Canada on the centennial scale. By using a multi-site approach, chapter 2 underscores the notion that an individual lake's carbon accumulation rate is reflective of its morphometry and response to climate.

Chapter 3 explored two Holocene (past ~10,000 cal. yr B.P.) records of lake sediment in the Kootenay Valley of British Columbia, Canada for pollen, charcoal, and carbon as indicators for vegetation assemblage, fire, and carbon accumulation rate. The two lakes are in different biogeoclimatic (BEC) zones. Dog Lake is in the Montane Spruce (MS) BEC and Marion Lake is in the Engelmann Spruce-Subalpine Fir (ESSF) BEC. Through the Holocene, both lakes progress through three climatic periods following the Younger Dryas (~11,500 cal. yr B.P.): (1) a xerothermic period that is relatively dry and hot from 11,500-8,000 cal. yr B.P., (2) followed by a warm and moist mesothermic interval from 8,000-4,500 cal. yr B.P., (3) and a cool and moist neoglacial period from 4,500 cal. yr B.P. to present. The xerothermic period had high fire activity in the Kootenay Valley evidenced by charcoal and pollen records. Broad-scale climatic controls are interpreted as the major influence on fire frequency. C accumulation rate in the Kootenay Valley was high during the xerothermic period. This could be caused by high runoff due to fires or increased in-lake production. In the mesothermic period, vegetation patterns show a lowering of the BEC zones and establishment of subalpine meadows in the ESSF and a more open landscape in the MS. Wetter summers are likely the driver for decreased fire frequency and low carbon accumulation rate. Modern forest and fire frequency was established in the Kootenay Valley by the neoglacial period. Marion Lake switches to modern vegetation composition earlier in the paleo record likely due to higher exposure and maintains a modern landscape due to early establishment of subalpine meadows. Dog lake switches to a more open closed landscape by the neoglacial period likely due to wetter neoglacial conditions. As a result, Dog Lake has an increase in C accumulation due to increased biomass on the landscape. Future climate predictions for the Kootenay Valley are expected to be dry and hot analogous to the xerothermic period. This would move the MS landscape around Dog Lake to a dry-open landscape typified by the current Interior Douglas Fir (IDF) BEC zone. Around Marion Lake, the ESSF would likely transition to a MS-like landscape if a sufficient moisture regime (i.e., winter snowpack at elevation) continues. If fire frequencies were to increase and drier grasslands were to prevail, then an IDF-like landscape may occur. Both Dog and Marion Lakes have a C accumulation rate that is synchronous with inferred fire frequency (Table 5.1).

Table 5.1. Relative importance of climate, vegetation, and fire controls on carbon accumulation visualized by the fire-regime triangle (Whitlock et al., 2010). Bolded apex of the triangle represents the most influential component of the fire-regime triangle for the given time period.

	Early Holocene >11.5k cal. yrs BP	**Xerothermic** 11.5-8k cal. yrs BP	**Mesothermic** 8k -4.5k cal. yrs BP	**Neoglacial** 4.5k cal. yrs BP - present	**Future** Present to 1k cal. yrs
Kootenay Valley Climate	Warm and Wet	Hot and Dry	Wet and Warm	Wet and Cool	Hot and Dry
Marion Lake (Not Protected)	Vegetation	Climate	Vegetation	Vegetation	Climate
Marion BEC	Alpine Tundra	ESSF (Parkland)	ESSF	ESSF	MS or IDF or ESSF (Parkland)
Dog Lake (Protected)	Vegetation	Climate	Fire	Vegetation	Climate
Dog BEC	ESSF (Parkland)	IDF	MS	MS	IDF

In the forests of southern BC, fire is the most important disturbance (Dorner, 2001; Wong et al., 2004; Gavin et al., 2006; Mustaphi and Pisaric, 2014) (Figure 5.1). The current fire regime around Dog Lake extends back about 1,500 years with only small changes in the last millennium (Hallett and Walker, 2000). Only in the last ~700 years has the current fire regime been established around Marion Lake (ESSF). Millennial-scale fire regimes can be influenced by forest structure, biomass, and fuel connectivity (Morris et al., 2013). In review of the highest fire frequencies around Dog Lake (8,200 to 4,000 cal. yrs ago), the mFRI was ~150 years. This higher rate of burning during the dry and hot xerothermic drove changes in vegetation composition that pushed past the ecological threshold of the BEC MS class into IDF. As long as the region remained warm, the high rates of burning persisted with likely large-scale wildfires. When the climate changed to one with a higher moisture regime in the mesothermic, the rate and likely spatial extent of wildfires permitted a return to the MS BEC. Potentially, vegetation composition could have given way to a discontinuous mix of IDF-like ecosystems, but the return across an ecological threshold is an important note of the influence of fire on vegetation composition. Integrating fire with vegetation composition around our study sites helps to explain the natural variability of past ecosystem dynamics.

Adding to the complexity of fire across temporal and spatial scales is parsing natural and anthropogenic fire dynamics. The Ktunaxa (Kootenay) are an indigenous people who occupied territories including the Kootenay Valley. The Ktunaxa used fire throughout southern BC to enhance productivity of important resource plants and animals (Turner, 1999). Biomass combustion increase can be seen in the paleo record as early as 5,550 cal. yrs. BP in the Pacific Northwest (Walsh et al., 2015). Most of the fire research to date has been conducted in viewing indigenous people influence on fire within a “wilderness” paradigm, that is to say minimal. Given the variability in our fire records between sites within the same valley, burning and other forms of cultivation should not be ignored. With the important role of fire in shaping landscapes, understanding the local disturbance regime and management controls on that regime should be a priority to management agencies (Gavin et al., 2007).

Chapter 4 positioned the problem of how carbon would be managed in front of protected area managers in Canada. We started the conversation with in a workshop at the 2011 British Columbia Protected Area Research Forum (BCPARF) by working through a definition of carbon management and in small and large group discussion moving towards where carbon might exist in or alongside current management. We learned that carbon management would be best framed along with ecological integrity (EI) measures. We then conducted semi-structured interviews with Parks Canada managers. The interviews highlighted the need to structure a choice architecture to elicit responses that separated EI measures where carbon management would be easy to implement and where carbon management would be effective to implement. Following the semi-structured interviews, we created a survey asking if carbon management should be a co-benefit or separate EI measure and what the importance of each EI measure was to carbon management along with choice sets of EI measures that geared towards effectiveness and easiness of carbon management implementation. We launched the survey at the following BCPARF conference. Due to a low response rate, the choice component of the survey could not be statistically analyzed. However, the 15 protected area (PA) respondents recognized the potential of carbon management as a co-benefit to EI measures. More specifically, vegetation-related EI measures have the most importance to co-benefit carbon management.

Since the 2013 BCPARF conference where the survey was launched only a minimal amount of action related to carbon management in protected areas across Canada has occurred. Parks Canada has spearheaded two carbon management projects. One project is the Blue Carbon Project that seeks to quantify carbon stored in the shallow-water ecosystems of Canada's coasts. The other project is the Carbon Atlas that is attempting to spatially map baseline carbon stocks using the Carbon Budget Model of the Canadian Forest Service. As presented from a problem orientation, the major impediments surrounding implementation of carbon management is its context as a larger social dilemma and lack of information about carbon conditions.

Protected areas provide a mitigation "natural" solution to climate change by safeguarding vital ecosystem services like carbon. Most protected areas were only established within the last century making it difficult to determine if protected areas play a differential role in carbon accumulation rates on the landscape (Research Q2) from a paleo perspective. Nevertheless, chapter 4 found that vegetation-related EI measures were the most important to manage carbon in PAs. These measures include disturbance by wildfire and prescribed fire. Active management policies of PA agencies like Parks Canada (Parks Canada, 1994) recognize that in protected ecosystems the disturbance process of fire has been altered and this of affecting the structure and function of ecosystems. Fire management programs can thereby actively restore fire in ecosystems within the guidelines of ecological integrity. The ecosystems investigated in Chapter 3 suggest that fire regimes and forest cover has changed along with climate in the last millennium and will continue to change in the future. Climate change is driving a general increase in wildfire occurrence, size, and severity projected by the end of the century (Flannigan et al., 2005; Flannigan et al., 2009). In the Kootenay Valley this would manifest itself into conditions akin to the xerothermic (Table 5.1). Kootenay National Park is currently classified as having a mixed-severity fire regime (Kubian, 2013) and would be pushed into a high-severity fire regime. Given the predicted rate of future climate change (centuries) and the future range of variability for high-severity fire events of 60-130 years (Kubian, 2013) this would likely reduce any forest legacy stands (e.g., mature Douglas-fir) to beyond structural recognition. If xerothermic climatic conditions continue on the decadal and centuries rate they are likely to overwhelm the known ecological succession for the area (Table 5.1). With a no-analogue scenario both the ESSF and MS in the Kootenay Valley will likely slip into grassland-like areas that have relatively little terrestrial biomass. Without terrestrial biomass, the “active pipe” of C transfer dries up and regardless of fire frequency lake sediment carbon accumulation rate dwindles. Active management in protected areas should include restoration efforts under this future high-severity fire regime scenario. Restoration efforts may include fire as a pre-treatment to establish individual legacy tree species that might persist beyond century scale climate change. Restoration efforts that include other threats to longevity of known forest structure should be considered including pathogenic organisms.

In managing for carbon on protected area landscapes social implications of management should also be considered. Restoration efforts such as burning in protected areas to manage for carbon might not be socially acceptable. Involving First Nations and other stakeholders early on in the process of restoration can benefit larger carbon management directives. Ultimately, I envision climate change will induce a future transitory ecosystem that will not have a successional analogue. Futuring management around an ecological condition that does not yet exist goes beyond our historical and paleo perspective and into basic human attitudes and perspectives around PAs. If the goal is to safeguard carbon on the landscape in an unknown future, then a paradigm shift in our PAs is needed being seen for what they do not permit to be destroyed, instead of what they provide, needs to be built.

Paleo-based sciences remain underutilized in conservation management (Saulnier-Talbot, 2015). A major obstacle to paleo-data application in management is identifation of where in future policy paleo-dato needs might be best incorporated and how best to steer research goals around existing concerns of current managers. The research presented in this thesis was developed around the need to identify, where, if anywhere, carbon as a conservation need would best advance conservation goals in the future. This was done in conjunction with academics and the managers representing the conservation agencies themselves. Both the insights of current conservation manager's perspectives around carbon and the paleo-data around carbon itself have already been made available and presented by conversation managers. Including paleo-data into "real-world" problems from the start of this research was a challenge that I think moved the interpretation of pale-data out of the realm of just academics and helped move the real goal of "usable science" forward.

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Appendix A. Supplementary Material for Chapter 1.

Table A1. List of proxies found in lake sediment and what they may indicate.

Data	Description	Indicates
Pollen	Male part of a flower or cone in a microscopic grain	Vegetation composition
Charcoal	Carbon called char and ash residue from pyrolysis (fire)	Fire Frequency and Severity
Chironomid	Non-biting midge aka lake fly, look like mosquitos	Temperature
Charaphyte	Green Algae anchored to the lake bottom in shallow water by rhizoids	Lake Level
Phytolith	Silica plant remains. Plants take up silica from the soil.	Vegetation Composition
Diatom	A type of phytoplankton or algae (self-feeding aka does photosynthesis) with a shell	Nutrient Availability, Lake Level, Ice Cover
Ostracods	A Crustacea known as seed shrimp. A zooplankton. High sensitivity to pesticides, herbicides, heavy metal pollution and oil	Water quality (salinity, temp, pH, DO), sedimentation rate
Ash	Layers of Ash from nearby volcanic eruptions	Dating
Magnetic Resonance	Changes in Lithology	Boundaries
Macrophyte	Plant Macrophyte is a fossil remain large enough to be seen by the naked eye	Plant assemblage, Water Quality, Nutrient Cycling, Microhabitat, used to create SMI (indices) scores
Smear Slides	Lithology	Lithology
Bulk Sediment	Dry Bulk Density	Mass Accumulation Rate

Data	Description	Indicates
TC, TOC, TIC, LOI	Total Carbon, Total Organic Carbon, Total Inorganic Carbon. TOC-TIC relationship is usually associated, if not, than CaCO3 formation might not be linked to biological production, check increased $\delta^{13}C$	Sediment Carbon Content (%)
$\delta^{13}C$	Can be found in organic matter (algae, aquatic macrophytes, terrestrial plants) as ^{13}C to ^{12}C isotope ratios. Increase in primary productivity rise in the ratio of ^{13}C compared with ^{12}C. When organic C is buried (or locked in plants) more ^{12}C is locked out of the system.	C burial changes linked to changes in primary productivity (vegetation)
$\delta^{18}O$	Can be found in carbonates.	Changes in lake temp, Source of precipitation, lake level
$\delta^{15}N$	Can be found in organic matter from aquatic plants and algae (phytoplankton and macrophyte) and terrestrial plants as 14N and ^{15}N ratios. Increase in primary productivity rise in the ratio of ^{15}N to ^{14}N. When organic production proceeded ^{14}N is preferentially incorporated into primary producers cell material, which leads to ^{15}N enrichment in the remaining system.	Sources of nitrogen, rate of primary productivity and respiration, type of dentrification, lake level.
C/N	Measured as an atomic ratio, Values between 3-9 means organic matter produced in-lake, values between 11-19 are a mix between in and out of lake sourcing, and values of 20+ means organic matter produced terrestrially	Sourcing of sediments

Appendix B. Supplementary Material for Chapter 2.

B1. Age-depth models by lake

Chronologies for all 18 cores were derived from ^{210}Pb analysis. The ^{210}Pb chronologies are based on the Constant Rate of Supply (CRS) model (Appleby and Oldfield, 1978), which assumes a constant rate of supply of ^{210}Pb isotope to the sediment. The CRS model has the advantage over other models in assuming that changes in the rate of sedimentation through time will result in changes in the initial unsupported ^{210}Pb concentrations.

Samples including one cubic centimeter (cc) of sediment were prepared and sent to MyCore Scientific Inc. for ^{210}Pb analysis. The depth, age, measured ^{210}Pb, precision, the associated standard deviation in age, and linear sedimentation rate for each sample are presented by lake in both table and plot.

Table B1.1. Antler Lake

Depth (cm)	Pb-210 (Bq/g)	Precision 1 STD (%)	Pb-210xs (Bq/m2)	Age (years AD)	STD in Date (years)	LSR (cm/yr)
1	0.29	6.4	4459	2012	0	0.33
4	0.16	6.9	22988	2003	1	0.43
7	0.29	5.0	17715	1996	2	0.21
10	0.19	6.4	23049	1982	4	0.21
13	0.17	7.0	14658	1968	6	0.11
17	0.09	8.3	20090	1933	18	0.09
20	0.06	11.4	4967	1901	48	0.09

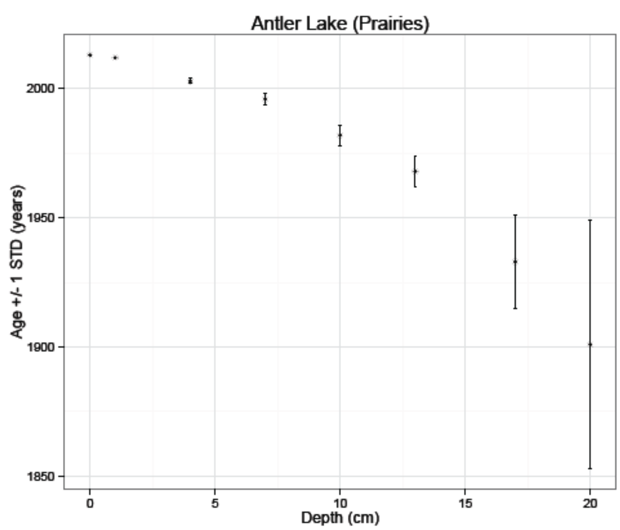


Table B1.2. Babine Lake

Depth (cm)	Pb-210 (Bq/g)	Precision 1 STD (%)	Pb-210xs (Bq/m2)	Age (years AD)	STD in Date (years)	LSR (cm/yr)
0	0.31	4.4	4188	2003	0	0.13
2	0.25	5.8	3964	1987	1	0.08
4	0.17	3.8	3304	1961	3	0.06
6	0.08	6.6	1344	1927	11	0.04
8	0.04	8.6	299	1874	57	0.04

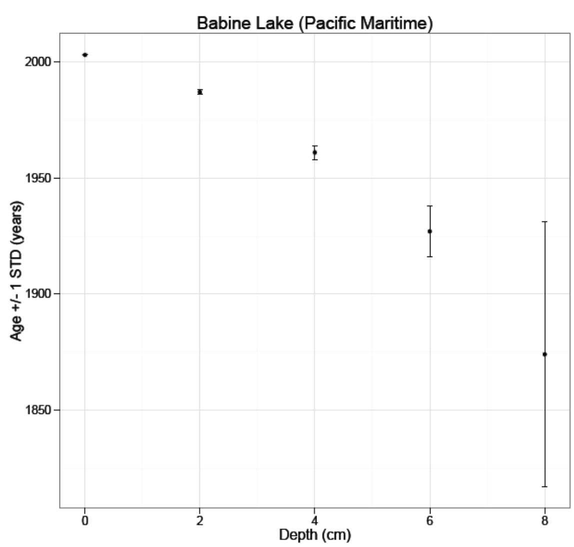


Table B1.3. Clear Lake

Depth (cm)	Pb-210 (Bq/g)	Precision 1 STD (%)	Pb-210xs (Bq/ms)	Age (years AD)	STD in Date (years)	LSR (cm/yr)
0	0.60	3.6	37293	2010	0	0.38
3	0.51	3.2	29883	2006	0	0.50
9	0.38	3.6	32113	1994	1	0.43
12	0.34	2.7	34088	1987	1	0.33
15	0.28	3.0	42853	1978	2	0.23
18	0.19	4.5	19689	1965	5	0.33
21	0.17	3.0	14788	1956	6	0.25
27	0.14	3.3	10732	1932	11	0.15
30	0.12	4.2	9870	1912	19	0.09
33	0.09	5.0	4110	1880	42	0.09

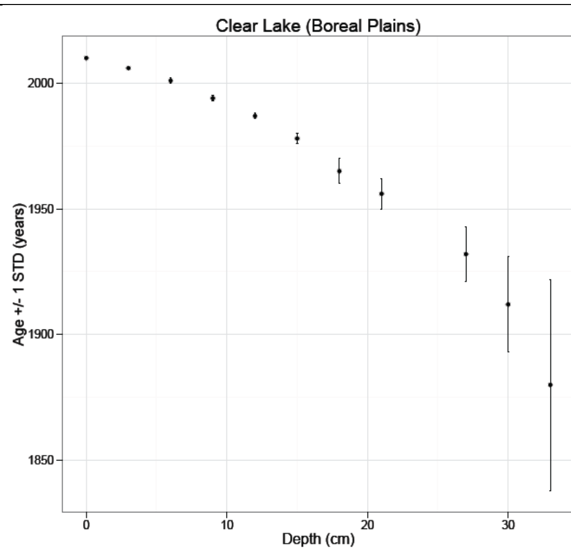


Table B1.4. Crandell Lake

Depth (cm)	Pb-210 (Bq/g)	Precision 1 STD (%)	Pb-210xs (Bq/m2)	Age (years AD)	STD in Date (years)	LSR (cm/yr)
0	0.60	7.1	37293	2013	0	0.25
1	0.48	3.0	63732	2009	1	0.22
3	0.60	2.9	29883	2000	4	0.20
6	0.44	5.2	42427	1985	11	0.14
9	0.31	3.3	32123	1964	30	0.14
12	0.18	5.4	34088	1943	108	0.19
15	0.15	4.9	42853	1927	208	0.09
18	0.15	5.2	19689	1895	255	0.09

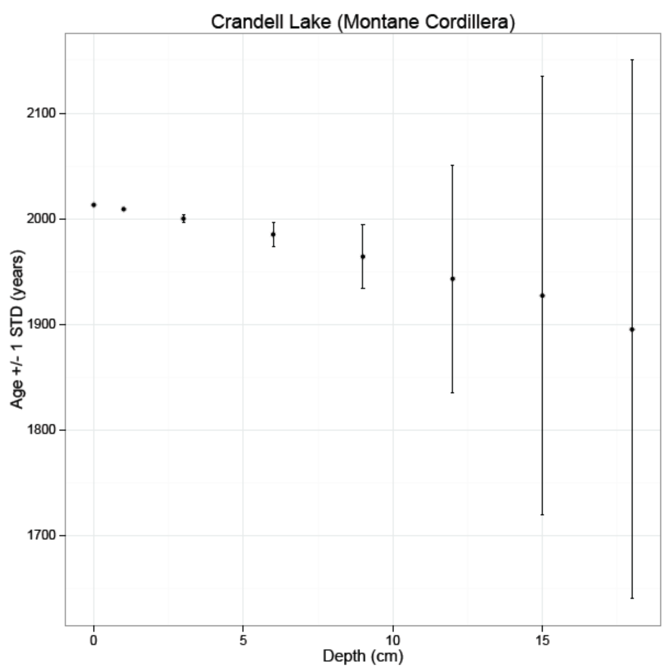


Table B1.5. Dog Lake

Depth (cm)	Pb-210 (Bq/g)	Precision 1 STD (%)	Pb-210xs (Bq/m2)	Age (years AD)	STD in Date (years)	LSR (cm/yr)
0	0.21	4.1	21050	2011	1	0.71
3	0.20	4.1	21400	2006	1	0.52
6	0.19	4.2	26010	1999	1	0.52
9	0.16	4.5	26640	1994	2	0.47
12	0.14	4.7	28350	1988	2	0.43
15	0.13	5.0	29010	1983	2	0.37
18	0.12	5.1	29550	1976	2	0.32
21	0.10	5.4	29970	1966	3	0.25
24	0.09	5.6	31200	1953	4	0.22
27	0.07	6.2	32340	1937	5	0.17
30	0.06	6.7	32880	1919	7	0.01
33	0.05	7.4	33600	1894	10	0.01

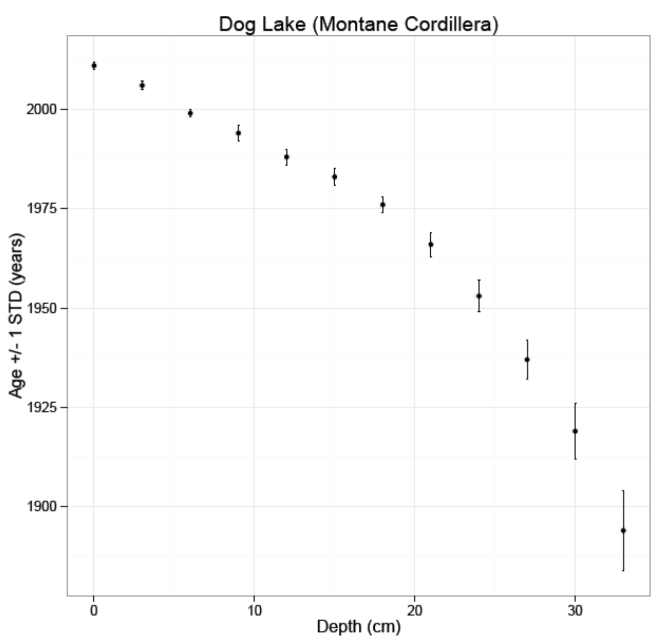


Table B1.6.   Katherine Lake

Depth (cm)	Pb-210 (Bq/g)	Precision 1 STD (%)	Pb-210xs (Bq/m2)	Age (years AD)	STD in Dates (years)	LSR (cm/yr)
0	0.90	3.4	7036	2010	0	1.00
3	0.95	2.9	13124	2006	0	1.00
6	0.72	2.8	13951	2001	0	1.00
9	0.75	2.8	9956	1995	1	1.00
12	0.71	2.8	14502	1987	1	0.30
15	0.73	3.3	12350	1977	2	0.20
18	0.71	3.4	9060	1962	3	0.17
21	0.40	3.3	10428	1944	4	0.16
24	0.25	4.8	8344	1925	8	0.17
27	0.20	5.2	4664	1907	11	0.14
30	0.15	6.9	3661	1885	20	0.12
33	0.09	6.0	3085	1860	37	0.11
36	0.09	6.0	1367	1833	47	0.11

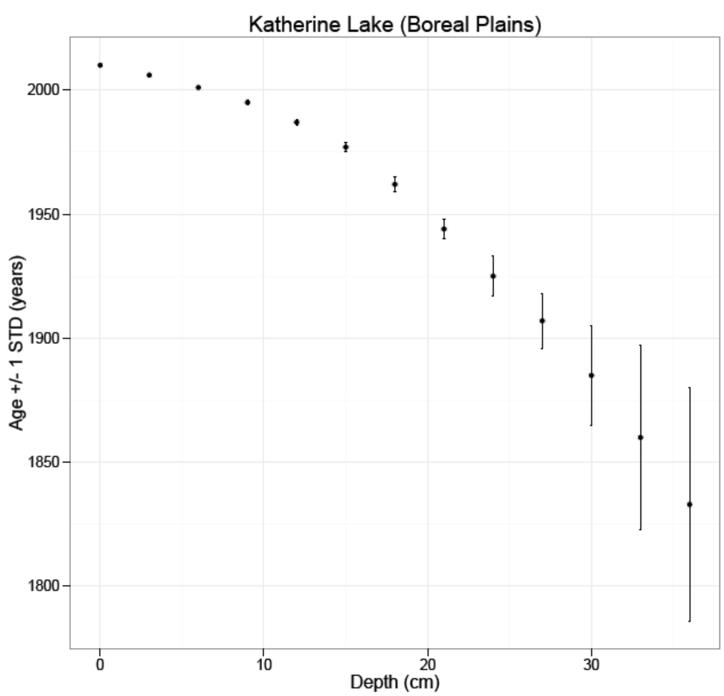


Table B1.7. Kennedy

Depth (cm)	Pb-210 (Bq/g)	Precision 1 STD (%)	Pb-210xs (Bq/m2)	Age (years AD)	STD in dates (years)	LSR (cm/yr)
0	1.57	3.6	14518	2002	0	0.17
2	1.10	3.4	14007	1990	1	0.11
4	0.82	3.0	9239	1972	1	0.10
6	0.47	3.5	4794	1951	3	0.10
8	0.31	1.9	3328	1931	3	0.05
10	0.17	5.4	7830	1911	9	0.13
12	0.05	3.5	196	1888	30	0.18
14	0.06	8.8	423	1877	33	0.08
17	0.05	9.4	358	1852	52	0.04
18	0.10	5.5	167	1829	120	0.04

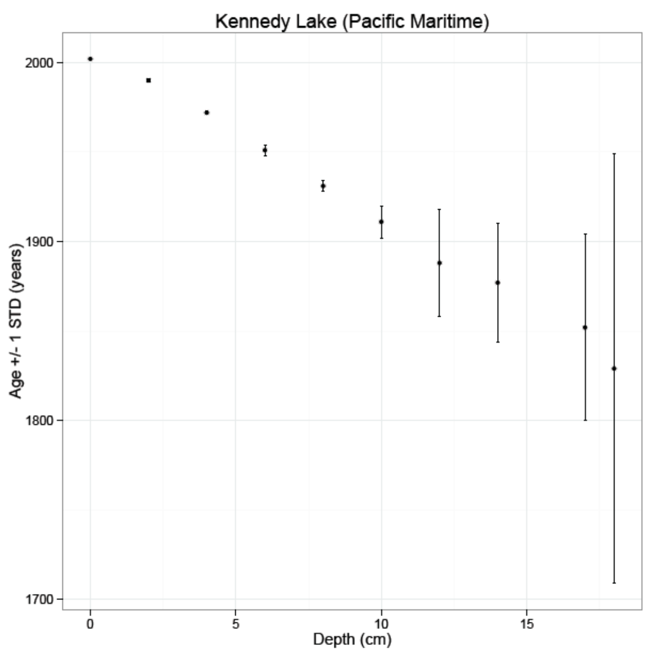


Table B1.8. Little Tawayik

Depth (cm)	Pb-210 (Bq/g)	Precision 1 STD (%)	Pb-210xs (Bq/m2)	Age (years AD)	STD in Dates (years)	LSR (cm/yr)
1	0.13	3.6	7862	2013	0	0.33
2	0.14	3.3	8115	2010	0	0.25
3	0.14	3.4	8770	2006	0	0.25
5	0.11	3.3	8538	1998	1	0.20
8	0.10	4.0	6108	1983	2	0.18
11	0.06	6.0	2948	1966	7	0.19
14	0.05	6.2	2255	1950	12	0.18
17	0.03	6.8	852	1933	35	0.21
20	0.03	7.2	1052	1919	42	0.21
21	0.03	8.5	1574	1911	42	0.21

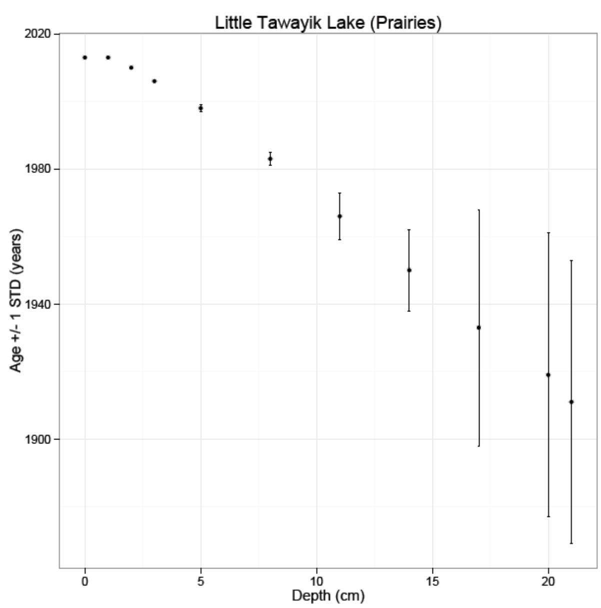


Table B1.9. Long Lake

Depth (cm)	Pb-210 (Bq/g)	Precision 1 STD (%)	Pb-210xs (Bq/m2)	Age (years AD)	STD in Dates (years)	LSR (cm/yr)
0	0.75	2.2	11628	2008	0	0.50
3	0.61	2.2	11144	2002	0	0.27
6	0.57	2.3	11600	1991	1	0.27
9	0.26	9.7	8125	1980	1	0.21
12	0.17	12.3	5683	1966	7	0.19
15	0.07	5.2	4193	1950	12	0.19
18	0.06	4.7	1534	1934	12	0.30
21	0.04	5.4	1778	1924	14	0.23
24	0.04	7.9	725	1911	34	0.27
27	0.03	9.2	618	1900	51	0.20
30	0.03	9.3	652	1885	59	0.17
33	0.03	8.8	306	1867	107	0.13
36	0.02	5.6	500	1844	108	0.13

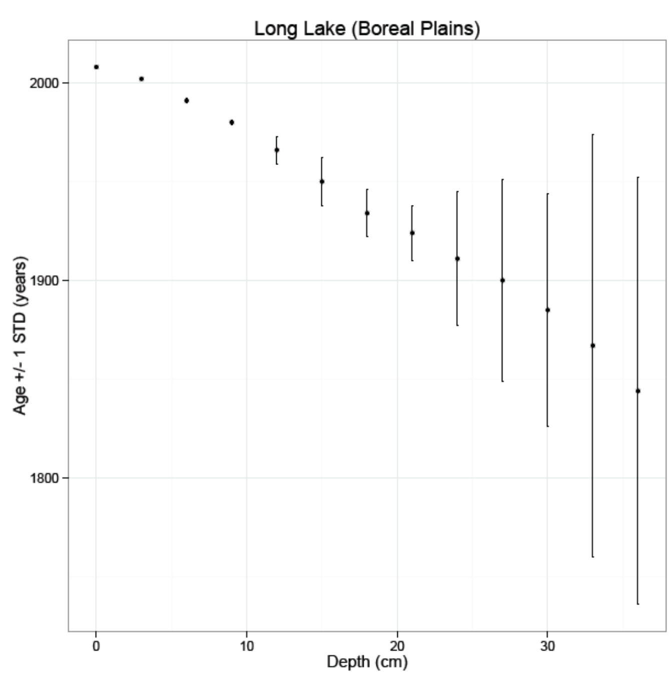


Table B1.10. Marion Lake

Depth (cm)	Pb-210 (Bq/g)	Precision 1 STD (%)	Pb-210xs (Bq/m2)	Age (years AD)	STD in Dates (years)	LSR (cm/yr)
1	0.59	4.9	2223	2012	0	0.43
4	0.49	3.1	3336	2005	0	0.24
8	0.21	4.3	5310	1988	2	0.11
12	0.10	5.0	663	1951	9	0.14
16	0.06	5.8	576	1923	25	0.13
20	0.03	7.6	43	1891	206	0.31
24	0.04	7.5	899	1878	159	0.01

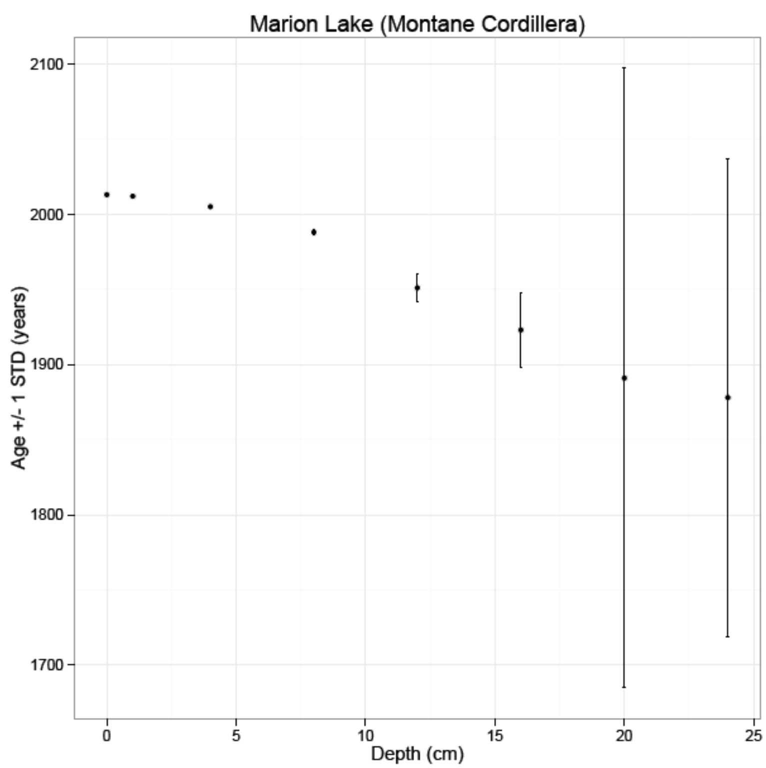


Table B1.11. McPhee Lake

Depth (cm)	Pb-210 (Bq/g)	Precision 1 STD (%)	Pb-210xs (Bq/m2)	Age (years AD)	STD in Dates (years)	LSR (cm/yr)
0	0.48	3.8	10040	2013	0	0.17
1	0.32	4.3	7539	2007	1	0.17
2	0.22	3.9	3821	2001	2	0.27
5	0.24	4.0	4424	1990	3	0.21
8	0.17	4.6	2267	1976	9	0.15
11	0.19	7.4	2590	1959	14	0.10
14	0.14	5.2	1489	1926	36	0.10

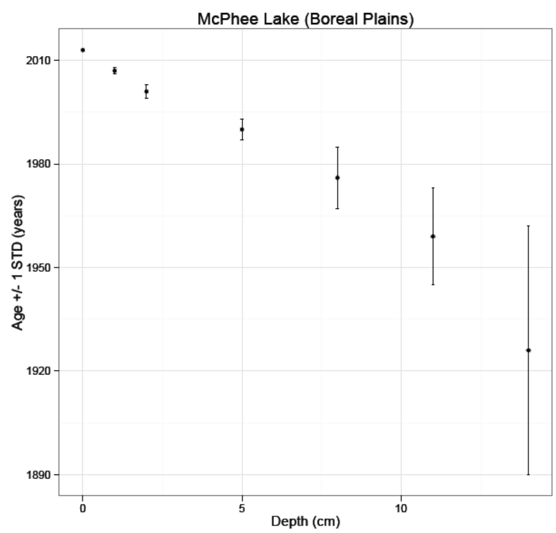


Table B1.12. Moon Lake

Depth (cm)	Pb-210 (Bq/g)	Precision 1 STD (%)	Pb-210xs (Bq/m2)	Age (years AD)	STD in Dates (years)	LSR (cm/yr)
0	0.67	2.8	12737	2011	0	1.00
3	0.56	3.1	15690	2006	0	1.00
6	0.46	4.2	9888	2001	1	1.00
9	0.44	4.5	12148	1996	1	0.00
12	0.43	5.1	13078	1988	2	0.33
15	0.34	3.8	10316	1979	2	0.33
18	0.27	5.4	7592	1970	4	0.27
21	0.30	5.6	11078	1959	5	0.17
24	0.15	5.4	4080	1941	9	0.21
27	0.14	4.8	3417	1927	10	0.18
30	0.11	3.9	2228	1910	14	0.17
33	0.09	4.1	1427	1892	25	0.15
36	0.07	4.5	907	1872	38	0.09
39	0.06	4.2	665	1840	65	0.09

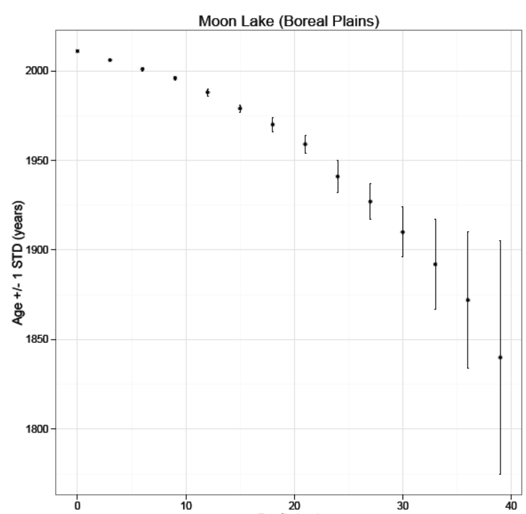


Table B1.13. Muriel Lake

Depth (cm)	Pb-210 (Bq/g)	Precision 1 STD (%)	Pb-210xs (Bq/m2)	Age (years AD)	STD in Dates (years)	LSR (g/cm3)
1	2.03	2.2	10290	2001	2	0.50
2	1.54	2.4	10978	1999	2	0.25
4	0.37	1.6	84882	1991	2	0.23
8	0.37	1.9	9593	1978	2	0.15
10	0.77	2.0	11607	1965	2	0.12
14	0.30	2.4	3842	1922	2	0.12
20	0.07	5.9	627	1870	6	0.10
25	0.03	7.6	150	1820	8	0.10

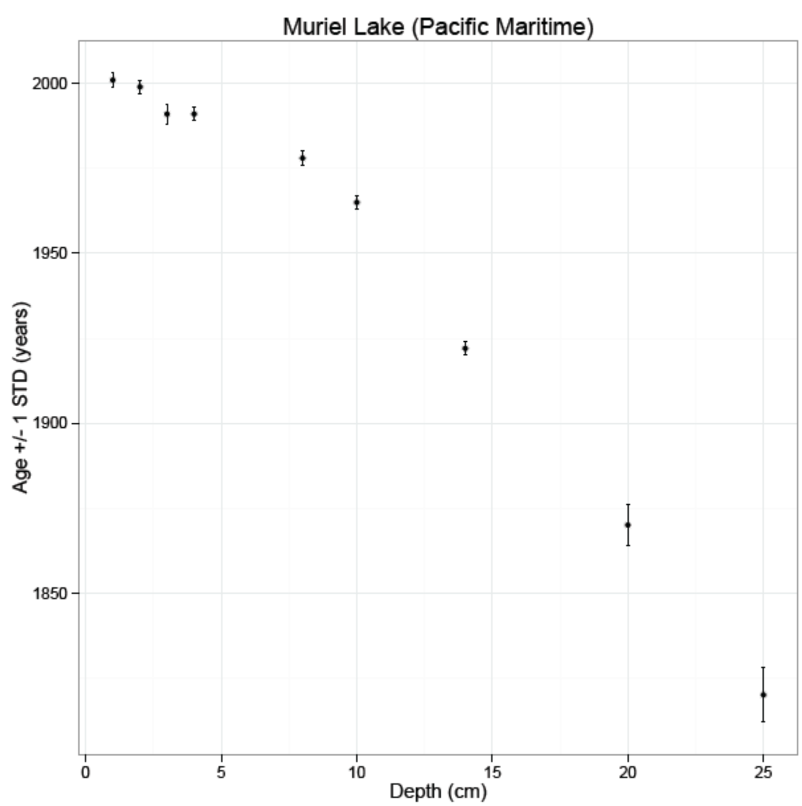


Table B1.14. Quamichan Lake

Depth (cm)	Pb-210 (Bq/g)	Precision 1 STD (%)	Pb-210xs (Bq/m2)	Age (years AD)	STD in Dates (years)	LSR (cm/yr)
0	0.59	4.7	524	2004	0	2.00
4	0.77	4.6	1634	2002	0	2.00
8	0.36	3.4	847	2000	0	1.00
12	0.49	3.3	1221	1997	1	1.00
20	0.33	6.1	879	1989	2	1.00
28	0.21	8.7	576	1980	3	0.71
40	0.13	6.9	387	1951	6	0.36
52	0.04	12.5	NA	1916	18	0.26

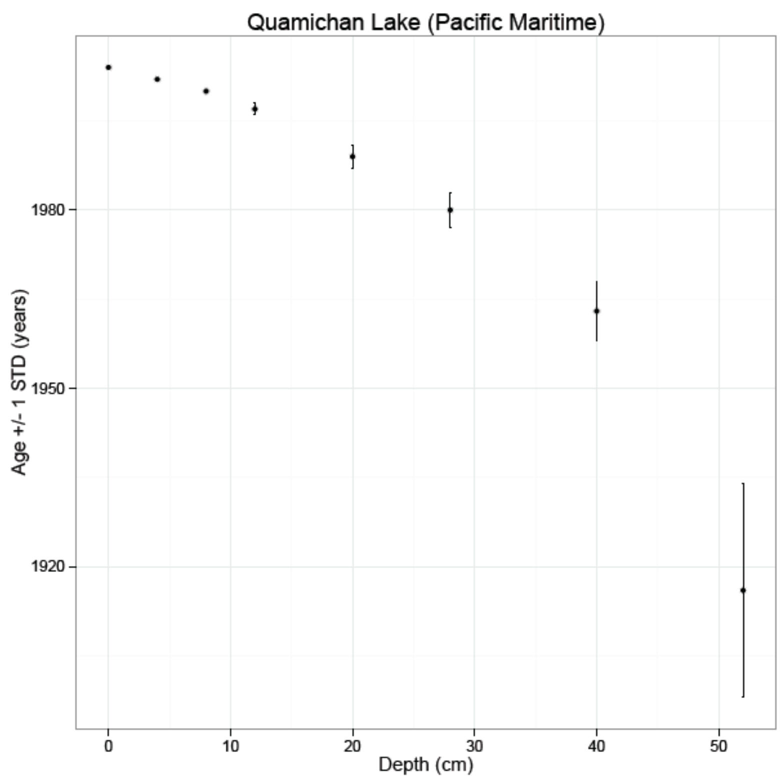


Table B1.15.   Roe Lake

Depth (cm)	Pb-210 (Bq/g)	Precision 1 STD (%)	Pb-210xs (Bq/m2)	Age (years AD)	STD in Dates (years)	LSR (cm/yr)
0	0.58	4.7	2415	2004	0	0.50
1	0.77	4.6	11276	2002	0	0.50
2	0.36	3.4	5481	2000	0	0.25
3	0.49	3.3	15897	1996	0	0.33
4	0.33	6.1	4190	1993	1	0.33
5	0.21	8.7	19093	1990	1	0.20
6	0.13	6.9	5341	1985	1	0.21
10	0.04	12.5	2713	1966	3	0.25
14	0.01	15.0	1376	1950	7	0.22
20	0.01	19.3	1193	1923	9	0.15
22	0.01	11.4	8570	1910	16	0.11
24.5	0.01	11.3	7700	1892	16	0.13
26	0.01	7.0	360	1876	23	0.13

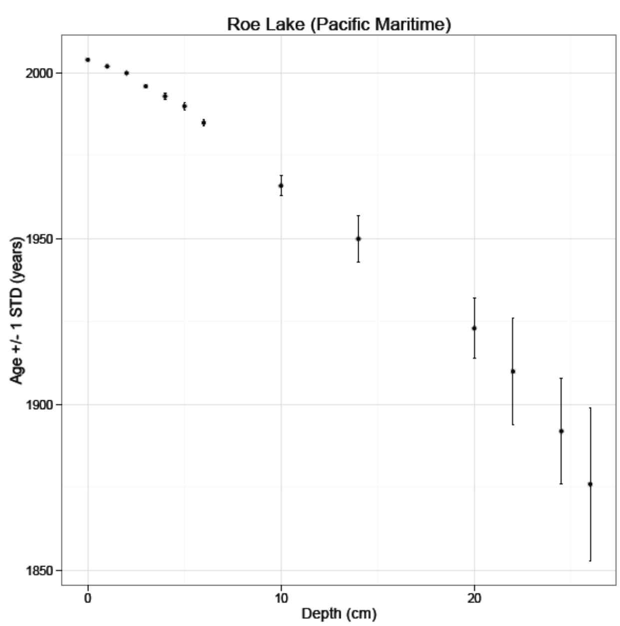


Table B1.16. South Lake

Depth (cm)	Pb-210 (Bq/g)	Precision 1 STD (%)	Pb-210xs (Bq/m2)	Age (year AD)	STD in Dates (years)	LSR (cm/yr)
0	0.32	3.1	18875	2010	0	0.08
2	0.087	4.3	10806	1986	2	0.10
4	0.069	4.8	5783	1965	5	0.08
6	0.052	5.9	4340	1941	10	0.05
8	0.022	7.4	1496	1899	41	0.05

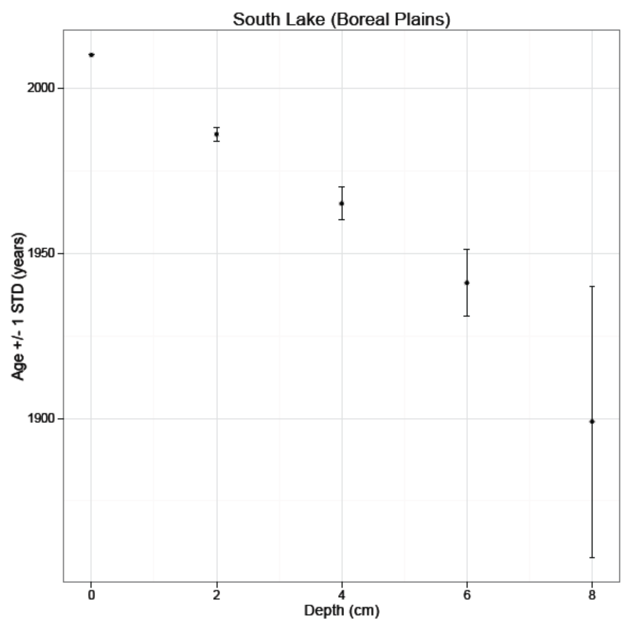


Table B1.17 Shady Lake

Depth (cm)	Pb-210 (Bq/g)	Precision 1 STD (%)	Pb-210xs (Bq/m2)	Age (year AD)	STD in Dates (years)	LSR (cm/yr)
0	0.52	2.5	12804	2013	0	0.25
1	0.44	2.4	19370	2009	0	0.14
2	0.37	2.4	11540	2002	1	0.17
3	0.26	2.8	7817	1996	1	0.25
4	0.20	3.9	5357	1992	2	0.29
6	0.18	3.3	5208	1985	3	0.33
8	0.14	4.1	5213	1978	6	0.29
10	0.13	3.6	4521	1969	8	0.17
12	0.11	5.2	3322	1957	13	0.13
14	0.10	4.6	2962	1942	20	0.10
16	0.08	4.0	2270	1922	36	0.07
18	0.06	4.8	1039	1894	107	0.07

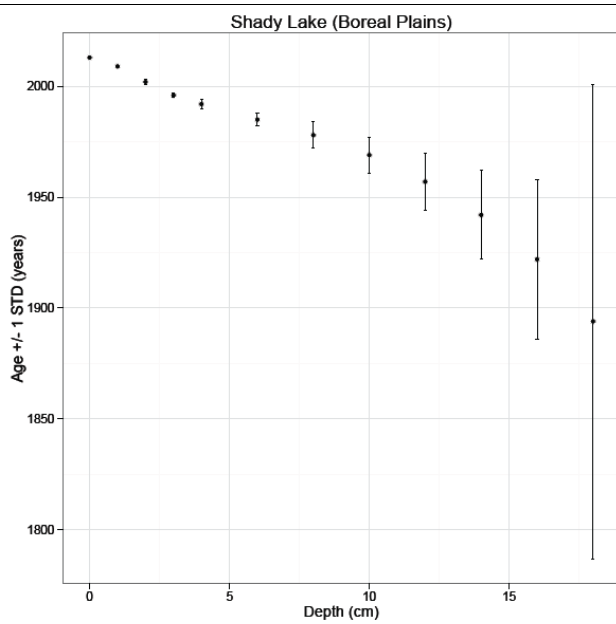
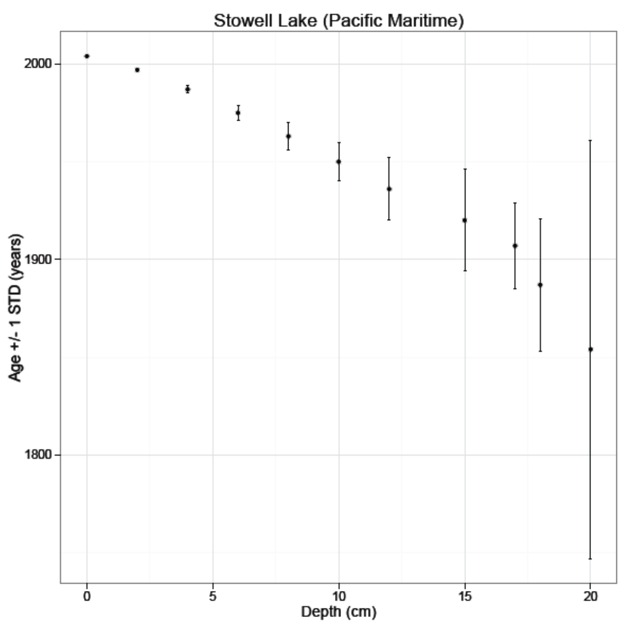


Table B1.18. Stowell Lake

Depth (cm)	Pb-210 (Bq/g)	Precision 1 STD (%)	Pb-210xs (Bq/m2)	Age (years AD)	STD in Dates (years)	LSR (cm/yr)
0	0.16	7.1	36568	2004	0	0.29
2	0.11	5.9	35542	1997	1	0.20
4	0.07	5.6	26214	1987	2	0.17
6	0.05	6.9	19354	1975	4	0.17
8	0.05	8.7	13277	1963	7	0.15
10	0.04	9.2	9036	1950	10	0.14
12	0.03	11.4	6032	1936	16	0.17
15	0.03	7.2	3887	1920	26	0.17
17	0.03	8.2	2417	1907	22	0.06
18	0.02	11.5	1405	1887	34	0.14
20	0.01	13.6	776	1854	107	0.04



References

Appleby, P. and Oldfield, F. 1978. The calculation of lead-210 dates assuming a constant rate of supply of unsupported 201Pb to the sediment. CATENA 5, 1-8.

B2. List of ClimateWNA variables and their description

Table B2.1 ClimateWNA variables list and description.

Variable	Description
MAT	Mean Annual Temperature (ºC)
MWMT	Mean Warmest Month Temperature (ºC)
MCMT	Mean Coldest Month Temperature (ºC)
MAP	Mean Annual Precipitation (mm)
SH:M	Summer Heat:Moisture index (MWMT)/(MSP/1000)
DDB0	Degree-days below 0ºC
GDD5	Growing Degree-days above 5ºC
NFFD	Number of frost-free days
FFP	Frost-free period
Tave_wt	Winter (December - February) Mean Temperature (ºC)
Tave_sp	Spring (March – May) Mean Temperature (ºC)
Tave_sm	Summer (June – August) Mean Temperature (ºC)
Tave_at	Autumn (September – November) Mean Temperature (ºC)
PPT_wt	Winter Precipitation (mm)
PPT_sp	Spring Precipitation (mm)
PPT_sm	Summer Precipitation (mm)
PPT_at	Autumn Precipitation (mm)

Table B2.2. Land use classifications and definitions

Classification	Definition
Water	Water bodies (lakes, reservoirs, rivers, streams, etc.).
Exposed Land	Non-vegetated and non-developed land. Includes: exposed lands, bare soil, snow, glacier, rock, sediments, burned areas, rubble, mines, other naturally occurring non-vegetated surfaces.
Developed	Land predominately built-up; including vegetation associated with these cover conditions. This may include road surfaces, railway surfaces, buildings and paved surfaces, urban areas, parks, industrial sites, farmsteads, golf courses, and ski hills.
Shrubland	Woody vegetation of relatively low height (<2m).
Wetland	Land with a water table near/at/above soil surface for enough time to promote wetland or aquatic processes.
Grassland	Native grasses and other herbaceous vegetation may include some shrubland cover.
Cultivated Agricultural Land	Annually cultivated cropland and wood perennial crops.
Annual Cropland	Fall seeded crops such as winter wheat may be erroneously identified in this class.
Perennial Cropland and Pasture	Periodically cultivated cropland (e.g., alfalfa and clover).
Mixed Forest	Mixed coniferous and deciduous treed areas.
Coniferous Forest	Predominately coniferous treed areas.
Deciduous Forest	Predominately deciduous treed areas.

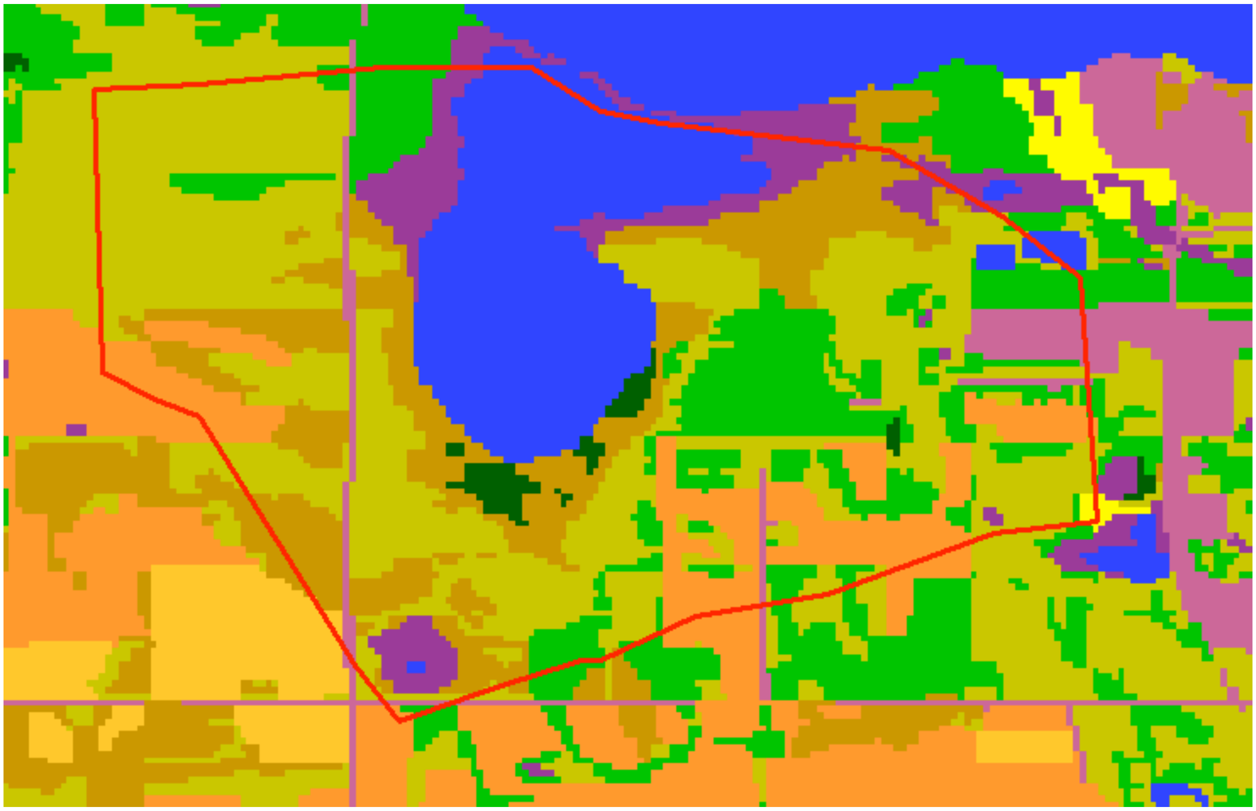


Figure B2.1. The South lake CA polygon (outlined in red) on top of the 30m landsat satellite pixilated land cover classification cells (pixels) from the Land Cover for Agricultural Regions of Canada, circa 2000.

Table B2.3: Percent Catchment Area Coverage of Exposed Land, Water, Vegetation, and Anthropogenic Land Use for each lake.

Lake	Water	Exposed Land	Shrub-land	Wet-land	Grass-land, Native Grass	Coniferous	Deciduous	Mixed Forest	Agriculture*	Total Developed and Agriculture**
South	17	0	0	5	35	1	13	15	9	12
Shady	11	0	7	12	0	19	10	39	0	2
Dog	2	0	0	2	0	91	5	0	0	0
Katherine	5	0	0	5	6	2	60	22	0	0
Kennedy	9	8	8	6	3	6	9	19	26	33
Little Tawayik	23	0	2	1	5	1	58	0	10	10
Long	6	0	0	17	0	13	15	48	0	1
Marion	6	3	5	6	0	74	0	6	0	0
Moon	7	0	0	8	0	22	1	63	0	0
Murial	16	0	14	1	0	68	0	0	0	0
Quamichan	7	1	1	4	0	48	7	0	13	32
Rodgers	10	16	6	1	0	65	1	0	0	0
Roe	7	4	2	0	0	75	3	0	2	8
Clear	27	0	0	6	3	4	6	51	1	2
Stowell	2	3	4	0	0	77	11	0	1	3
Antler	32	0	1	2	3	2	24	0	32	35
McPhee	15	0	4	17	0	29	11	24	0	0
Babine	30	1	6	1	0	43	13	7	0	0
Crandell	7	1	0	0	0	71	0	20	0	0

* Agriculture combines the categories of agriculture, perennial crops and pasture, and annual cropland categories

** Total development and Agriculture combines all agriculture with the development category

*** Note that "no data" and "unclassified" categories, which account for approximately 5% of catchment area for Kennedy lake, were excluded from these calculations.

References

Land Cover for Agricultural Regional of Canada, circa 2000. 2001. Agriculture and Agri-Food Canada.

B3. Sources used to determine lake and catchment area boundaries

Table B3.1. **Data sources used to determine lake and catchment area boundaries**

Lake	Source
Antler	Mitchell and Prepas, 1990
Babine	BC Ministry of Environment, 2005
Clear	White, 2010
Crandell	Mitchell and Prepas, 1990
Dog	BC Ministry of Environment, 2005
Katherine	White, 2010
Kennedy	BC Ministry of Environment, 2005
Little Tawayik	Mitchell and Prepas, 1990
Long	White, 2010
Marion	BC Ministry of Environment, 2005
McPhee	Saskatchewan Watershed Authority, 2009
Moon	White, 2010
Muriel	BC Ministry of Environment, 2005
Quamichan	BC Ministry of Environment, 2005
Rodgers	BC Ministry of Environment, 2005
Roe	BC Ministry of Environment, 2005
South	White, 2010
Shady	Saskatchewan Watershed Authority, 2009
Stowell	BC Ministry of Environment, 2005

References

BC Ministry of Environment. 2005. 1:50,000 BC Watershed Atlas. GIS Applications Unit, Information Services Branch, BC Fisheries.

Mitchell, P., and E. Prepas. 1990. Atlas of Alberta lakes. The University of Alberta Press, Edmonton.

Saskatchewan Watershed Authority. 2009. Watershed Map of Saskatchewan. Saskatchewan Watershed Authority, Geomatics Unit.

White, C. 2010. Sedimentary diatoms as indicators of water quality and ecosystem change in lakes of Riding Mountain National Park of Canada. Masters Thesis. Univ. of BC (Okanagan).

B4. Land Cover

Land cover in catchment areas is categorized into 10 cover types (Table B4.1) (Land Cover for Agricultural Regions of Canada, circa 2000, 2001). To determine the percentage of each land cover type represented in each catchment area, the .kml catchment area boundary data points were georeferenced onto a valued raster classification scheme derived from Landsat satellite imagery circa 2000 (e.g., South Lake, Figure B4.1). The land cover cells are counted and used to estimate relative percentage (Table B4.2).

Table B4.1. Land use classifications and definitions

Classification	Definition
Water	Water bodies (lakes, reservoirs, rivers, streams, etc.).
Exposed Land	Non-vegetated and non-developed land. Includes: exposed lands, bare soil, snow, glacier, rock, sediments, burned areas, rubble, mines, other naturally occurring non-vegetated surfaces.
Shrubland	Woody vegetation of relatively low height (<2m).
Wetland	Land with a water table near/at/above soil surface for enough time to promote wetland or aquatic processes.
Grassland and Native Grass	Native grasses and other herbaceous vegetation may include some shrubland cover.
Agriculture	Combines the categories of agriculture land, perennial cropland (periodically cultivated cropland (e.g., alfalfa and clover)), annual cropland (annually cultivated cropland (e.g., corn), and pasture
Mixed Forest	Mixed coniferous and deciduous treed areas.
Coniferous Forest	Predominately coniferous treed areas.
Deciduous Forest	Predominately deciduous treed areas.
Total Developed and Agriculture	Developed land is predominately built-up; including vegetation associated with these cover conditions. This may include road surfaces, railway surfaces, buildings and paved surfaces, urban areas, parks, industrial sites, farmsteads, golf courses, and ski hills. Developed land is combined with the category of agriculture to form this category.

Figure B4.1. The South lake CA polygon (outlined in red) on top of the 30m Landsat satellite pixilated land cover classification cells (pixels) from the Land Cover for Agricultural Regions of Canada, circa 2000.

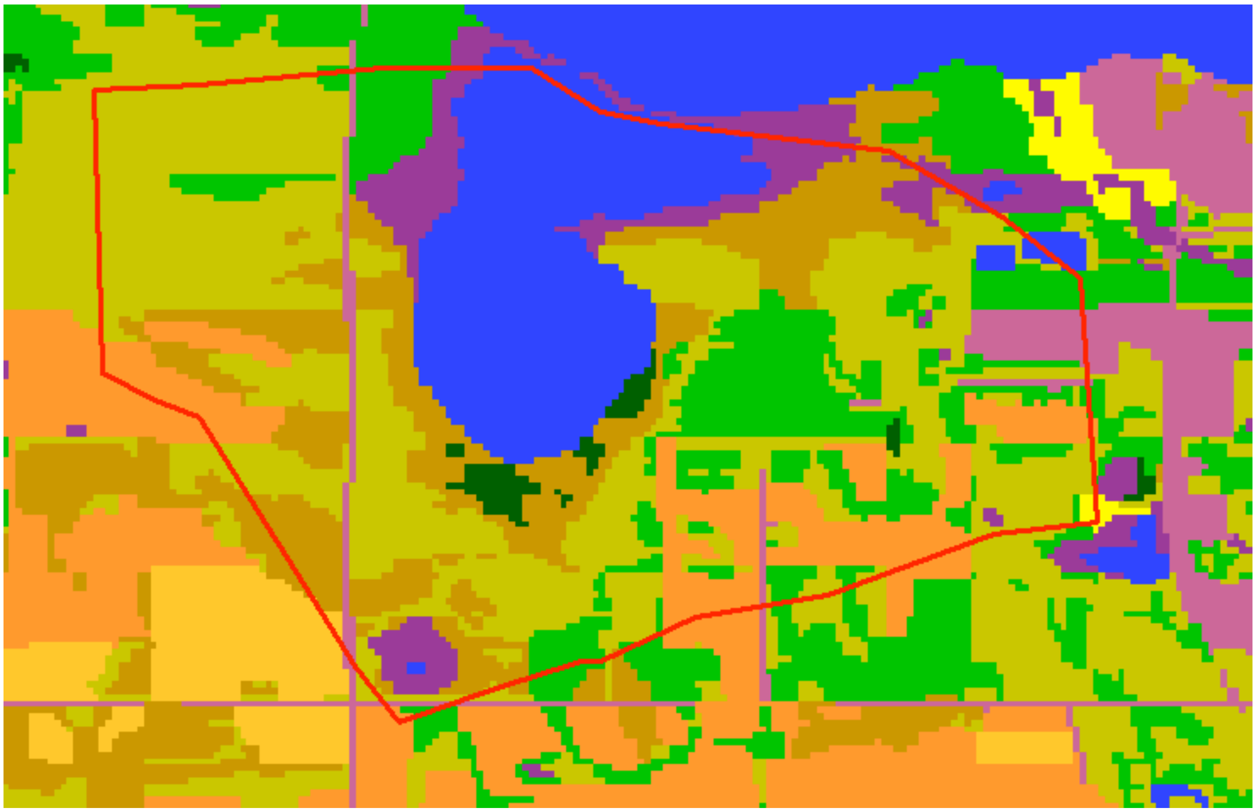


Table B4.2. Percent Catchment Area Coverage of the 10 Land Use Categories for each Lake.

Lake	Water	Exposed Land	Shrub-land	Wetland	Grass-land, Native Grass	Coniferous	Deciduous	Mixed	Agriculture*	Total Developed and Agriculture**
South	17	0	0	5	35	1	13	15	9	12
Shady	11	0	7	12	0	19	10	39	0	2
Dog	2	0	0	2	0	91	5	0	0	0
Katherine	5	0	0	5	6	2	60	22	0	0
Kennedy	9	8	8	6	3	6	9	19	26	33
Little Tawayik	23	0	2	1	5	1	58	0	10	10
Long	6	0	0	17	0	13	15	48	0	1
Marion	6	3	5	6	0	74	0	6	0	0
Moon	7	0	0	8	0	22	1	63	0	0
Murial	16	0	14	1	0	68	0	0	0	0
Quamichan	7	1	1	4	0	48	7	0	13	32
Roe	7	4	2	0	0	75	3	0	2	8
Clear	27	0	0	6	3	4	6	51	1	2
Stowell	2	3	4	0	0	77	11	0	1	3
Antler	32	0	1	2	3	2	24	0	32	35
McPhee	15	0	4	17	0	29	11	24	0	0
Babine	30	1	6	1	0	43	13	7	0	0
Crandell	7	1	0	0	0	71	0	20	0	0

* Agriculture combines the categories of agriculture, perennial crops and pasture, and annual cropland categories

** Total development and Agriculture combines all agriculture with the development category

*** Note that "no data" and "unclassified" categories, which account for approximately 5% of catchment area for Kennedy lake, were excluded from these calculations.

References

Land Cover for Agricultural Regions of Canada, circa 2000. 2001. Agriculture and Agri-Food Canada.

B5. Sediment Focusing Factor

Table 5.1. Sediment Focusing Factor by Lake. The average flux of Pb-210 was calculated by the average Pb-210xs (Bq/m2) (available in Appendix B1) divided by the number of calendar years of non-interpolated samples available (available in Appendix B1). The focusing factor was calculated using equation 3 in Section 2.3.3.

Lake	Ecozone	MAP (mm) (1901-2009)	flux/yr Bq kg-1 (100 Bq kg-1/1000mm MAP) (expected)	Average Flux of 210-Pb (Bq m2 yr1) (observed)	Focusing Factor
Antler	Prairies	459	45.9	139	3.03
Babine	Pacific Maritime	608	60.8	20.3	0.334
Clear	Boreal Plains	505	50.5	194	3.85
Crandell	Montane Cordillera	784	78.4	313	4.00
Dog	Montane Cordillera	815	81.5	244	2.99
Katherine	Boreal Plains	504	50.4	48.5	0.962
Kennedy	Pacific Maritime	3886	389	36.6	0.0941
Little Tai	Prairies	435	43.5	44.6	1.03
Long	Boreal Plains	509	50.9	34.3	0.673
Marion	Montane Cordillera	1203	120	12.6	0.104
McPhee	Boreal Plains	453	45.3	52.8	1.17
Moon	Boreal Plains	514	51.4	44.0	0.855
Muriel	Pacific Maritime	4242	424	156	0.369
Quam	Pacific Maritime	877	87.7	10.8	0.124
Roe	Pacific Maritime	750	75.0	51.5	0.686
Shady	Boreal Plains	444	44.4	57.0	1.28
South	Boreal Plains	503	50.3	74.4	1.48
Stowell	Pacific Maritime	741	74.1	93.6	1.26

Table 5.2. Sediment Focusing Factor by Lake and resulting TOC MAR ($g/m^2/yr$)

Lake	Focusing Factor	Modern TOC MAR	Focusing Factor Modern TOC MAR (g/m2/yr)	Historical TOC MAR (g/m2/yr)	Focusing Factor TOC MAR (g/m2/yr)
Antler	3.03	107.13	35.36	27.23	8.99
Babine	0.33	12.41	37.16	3.81	11.41
Clear	3.85	73.57	19.11	5.26	1.37
Crandell	4.00	42.17	10.54	26.29	6.57
Dog	2.99	80.95	27.07	13.74	4.59
Katherine	0.96	93.46	97.15	21.48	22.33
Kennedy	0.09	2.14	22.76	0.93	9.93
Little Tai	1.03	110.42	107.20	144.49	140.28
Long	0.67	12.05	17.91	12.41	18.44
Marion	0.10	29.02	279.02	37.14	357.09
McPhee	1.17	29.94	25.59	25.76	22.02
Moon	0.86	140.36	164.16	25.31	29.61
Muriel	0.37	40.41	109.51	11.89	32.21
Quam	0.12	196.27	1582.79	34.22	275.95
Roe	0.69	54.24	79.06	18.33	26.72
Shady	1.28	47.29	36.95	18.89	14.75
South	1.48	45.43	30.70	22.75	15.37
Stowell	1.26	47.62	37.80	11.79	9.36

B6. C/N Ratio

C/N ratios are classified as autochthonous (C/N of 3-9), allochthonous (C/N of >20), or a mix of the two (C/N between 10 and 20) (Meyers and Lallier- Vergès, 1999). Table S5.1 Summarizes the C/N ratio results by lake. Figure S5.1 illustrates the lakes in the allocthonous and mixed classifications and Figure S5.2 illustrates the lakes in the autochthonous classification.

B6.1. C/N ratio results by lake

Lake	1980-2010 (Modern) C/N Ratio	1830-1860 (Historic) C/N Ratio	Change b/w Historical and Modern	Lowest C/N Ratio	Highest C/N Ratio	Range of C/N Ratios	Classification	Did Classification Change?
Dog	36	57	-37%	23	62	39	Allocthonous	
Katherine	7	9	-18%	7	9	2	Autochthonous	
Long	3	9	-69%	3	3	0	Autochthonous	
Clear	6	4	60%	3	8	5	Autochthonous	
Quamichan	8	9	-5%	8	9	1	Autochthonous	
Antler	7	7	-11%	6	9	3	Mixed	
Babine	9	9	7%	9	11	2	Mixed	Yes
Crandell	12	16	-23%	14	17	3	Mixed	

Lake	1980-2010 (Modern) C/N Ratio	1830-1860 (Historic) C/N Ratio	Change b/w Historical and Modern	Lowest C/N Ratio	Highest C/N Ratio	Range of C/N Ratios	Classification	Did Classification Change?
Kennedy	16	19	-14%	13	20	7	Mixed	
Little Tawayik	10	13	-22%	9	13	4	Mixed	Yes
Marion	9	13	-29%	8	15	7	Mixed	Yes
McPhee	17	7	155%	6	17	11	Mixed	Yes
Moon	9	12	-21%	7	12	5	Mixed	Yes
Muriel	15	9	58%	8	23	15	Mixed	Yes
Roe	12	11	5%	10	14	4	Mixed	
Shady	14	15	-6%	13	17	4	Mixed	

Lake	1980-2010 (Modern) C/N Ratio	1830-1860 (Historic) C/N Ratio	Change b/w Historical and Modern	Lowest C/N Ratio	Highest C/N Ratio	Range of C/N Ratios	Classification	Did Classification Change?
South	16	18	-13%	14	18	4	Mixed	
Stowell	13	12	10%	12	13	1	Mixed	

Figure B6.1. C/N ratios of lakes in the allocthonous and mixed classifications

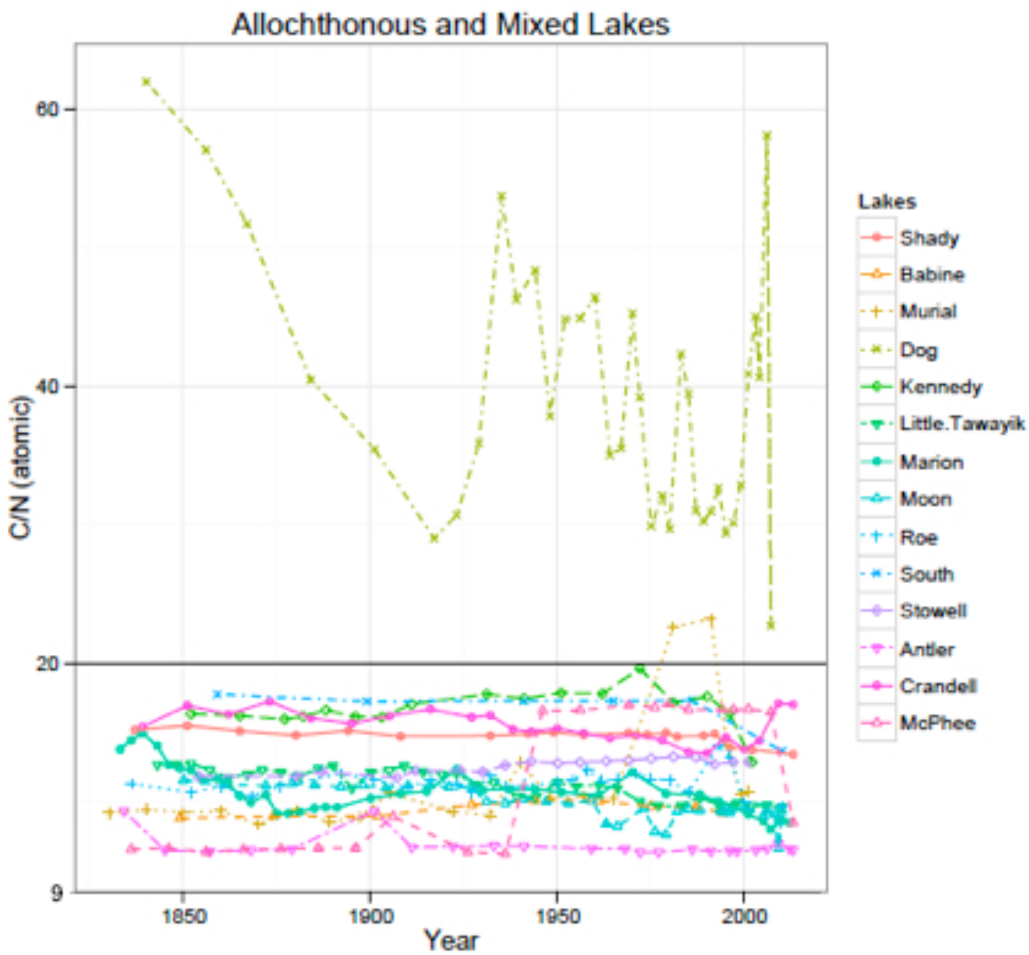
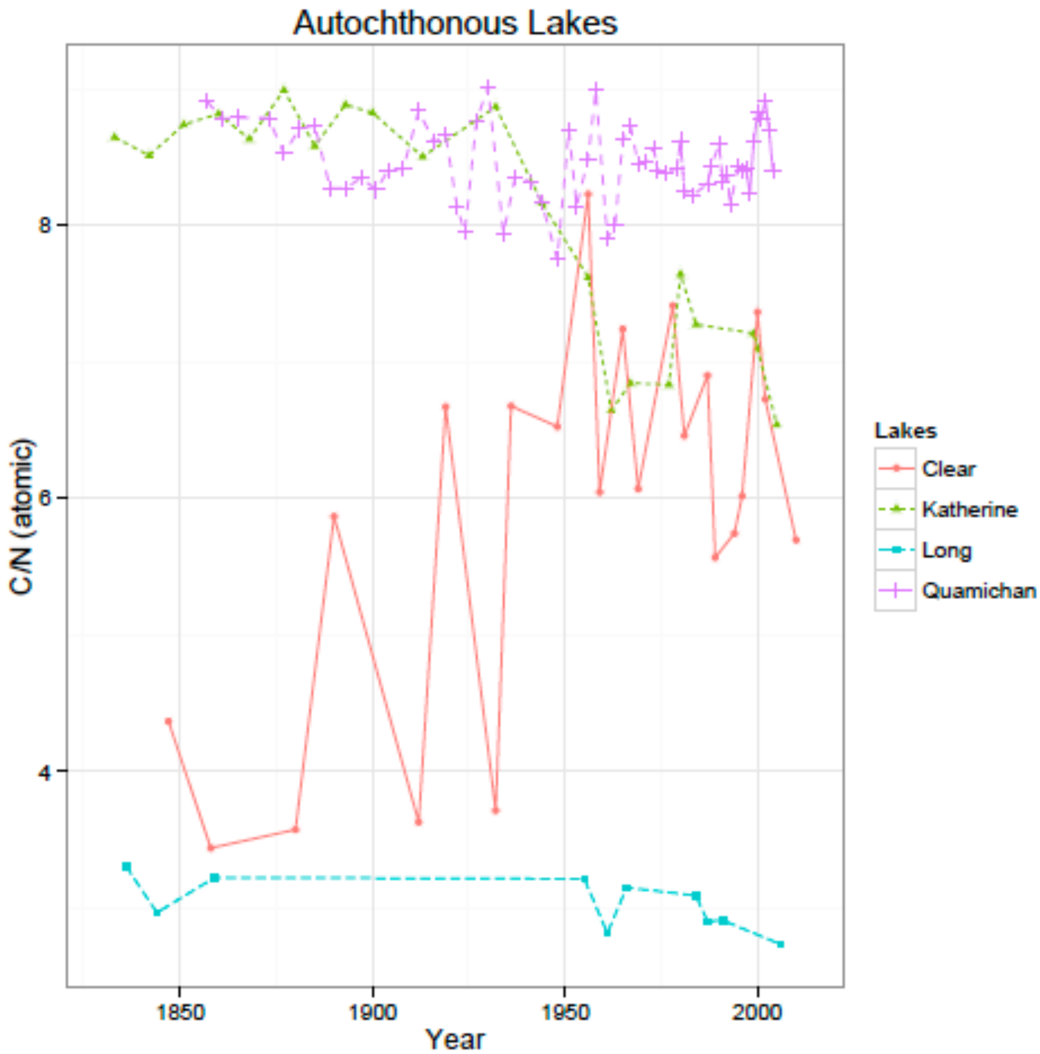


Figure B6.2. C/N ratios of lakes in the autochthonous classification



B7. Raw data supporting C accumulation rate calculation

Table B7.1. Antler Lake

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR ($g/m^2/yr$)	TOC MAR ($g/m^2/yr$)
1	2012	39.61	0.01	39.59	0.11	369.00	131.53
2	2009	35.65	0.00	35.65	0.11	347.16	100.95
3	2006	29.08	0.01	29.08	0.11	346.83	117.11
4	2003	33.78	0.01	33.77	0.09	368.14	132.56
5	2001	36.02	0.01	36.01	0.08	340.99	121.53
6	1998	35.65	0.01	35.64	0.10	446.77	163.21
7	1996	36.54	0.00	36.53	0.10	208.71	74.47
8	1991	35.69	0.01	35.68	0.13	262.71	93.27
9	1986	35.51	0.00	35.50	0.10	218.19	81.59
10	1982	37.40	0.02	37.39	0.10	219.21	79.52
11	1977	36.29	0.00	36.27	0.08	164.85	60.07
12	1972	36.44	0.01	36.44	0.09	195.93	71.26
13	1968	36.37	0.00	36.37	0.08	90.74	35.62
14	1959	39.26	0.00	39.26	0.11	124.41	42.89
15	1950	34.48	0.00	34.48	0.09	104.06	34.93
16	1941	33.57	0.00	33.57	0.12	132.44	41.13
17	1933	31.06	0.00	31.06	0.09	88.88	30.96
18	1922	34.84	0.00	34.84	0.09	81.00	30.76
19	1911	37.97	0.01	37.97	0.10	87.12	32.06
20	1901	36.81	0.03	36.80	0.09	80.19	18.06
21	1890	22.55	0.00	22.52	0.08	74.88	30.68
22	1879	40.97	0.00	40.97	0.09	79.56	30.53
23	1868	38.38	0.00	38.38	0.09	79.83	29.59

Table B7.2. Babine Lake

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR ($g/m^2/yr$)	TOC MAR ($g/m^2/yr$)
1	1994	3.82	0.02	3.80	0.35	455.26	17.32
2	1987	4.03	0.02	4.02	0.24	186.85	7.51
3	1975	3.48	0.00	3.48	0.30	237.20	8.25
4	1961	3.45	0.00	3.45	0.26	152.06	5.24
5	1944	2.90	0.01	2.88	0.31	186.18	5.37
6	1927	3.10	0.01	3.09	0.26	99.25	3.07
7	1902	3.22	0.00	3.22	0.30	121.28	3.90
8	1874	2.98	0.01	2.97	0.33	131.80	3.91

Table B7.3. Clear Lake

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR ($g/m^2/yr$)	TOC MAR ($g/m^2/yr$)
0	2010	6.43	4.96	6.42	0.23	867.75	55.75
2	2006	7.01	5.04	7.01	0.26	1310.50	91.88
5	2002	6.72	5.64	6.72	0.27	1348.50	90.60
6	2000	6.51	5.62	6.50	0.35	1737.50	113.02
8	1996	5.87	5.58	5.87	0.35	1728.50	101.43
9	1994	5.41	5.42	5.41	0.28	1179.00	63.83
11	1989	5.15	5.76	5.15	0.32	1393.63	71.71
12	1987	5.40	5.44	5.40	0.37	1237.00	66.76
14	1981	4.34	5.95	4.34	0.32	1042.47	45.29
15	1978	5.76	2.57	5.76	0.31	705.46	40.62
17	1969	4.83	2.71	4.83	0.34	771.42	37.27
18	1965	4.05	2.59	4.05	0.29	983.00	39.84
20	1959	4.11	2.84	4.11	0.35	1152.03	47.32
21	1956	4.25	2.47	4.25	0.27	671.00	28.52
23	1948	4.13	2.57	4.13	0.41	1031.50	42.60
26	1936	3.53	3.03	3.53	0.38	952.50	33.61
27	1932	3.63	2.96	3.63	0.36	534.75	19.43
29	1919	3.69	2.78	3.69	0.34	512.40	18.93
30	1912	2.90	2.76	2.90	0.27	256.88	7.44
32	1890	3.71	2.59	3.71	0.25	227.97	8.45
33	1880	3.15	2.77	3.15	0.28	254.52	8.01

Table B7.4.	Crandell Lake

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR ($g/m^2/yr$)	TOC MAR ($g/m^2/yr$)
0	2013	7.99	0.90	7.09	0.30	743.25	52.71
1	2009	9.30	0.93	8.37	0.28	613.11	51.32
2	2004	8.57	0.81	7.76	0.27	585.64	45.42
3	2000	9.48	0.45	9.03	0.20	391.00	35.29
4	1995	9.70	1.44	8.26	0.14	287.00	23.71
5	1990	9.33	0.15	9.18	0.13	265.80	24.40
6	1985	9.52	0.17	9.35	0.23	329.71	30.83
7	1978	9.65	0.19	9.46	0.20	286.86	27.13
8	1971	9.93	0.17	9.76	0.15	204.54	19.96
9	1964	9.53	0.17	9.36	0.18	254.43	23.82
10	1957	10.25	0.15	10.10	0.22	313.74	31.68
11	1950	10.50	0.17	10.33	0.18	254.66	26.31
12	1943	10.11	0.15	9.96	0.14	266.63	26.55
13	1938	10.24	0.16	10.08	0.15	287.09	28.95
14	1932	10.21	0.16	10.04	0.14	260.49	26.17
15	1927	9.35	0.16	9.18	0.22	204.56	18.78
16	1916	9.27	1.39	7.88	0.26	231.66	18.26
17	1905	9.00	0.15	8.85	0.22	201.06	17.78
18	1895	8.92	0.16	8.77	0.21	184.77	16.20
19	1884	9.43	0.15	9.27	0.23	206.73	19.16
20	1873	6.84	0.15	6.69	0.26	234.36	15.68
21	1862	6.24	0.16	6.08	0.41	365.94	22.24

Table B7.5. Dog Lake

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR ($g/m^2/yr$)	TOC MAR ($g/m^2/yr$)
0	2007	12.17	4.94	7.23	0.27	1901.42	137.38
1	2006	8.69	4.88	3.81	0.45	3160.21	120.45
2	2004	11.87	6.28	5.60	0.25	1759.38	98.45
3	2003	10.73	5.74	4.99	0.44	2265.00	113.01
4	2001	9.50	6.04	3.45	0.31	1597.44	55.18
5	1999	13.34	8.46	4.88	0.30	1541.80	75.29
6	1997	14.49	8.22	6.27	0.13	688.45	43.13
7	1995	15.66	8.70	6.96	0.21	1070.16	74.48
8	1993	16.33	9.01	7.31	0.17	873.08	63.85
9	1991	15.59	7.65	7.95	0.18	822.19	65.33
10	1989	12.76	7.58	5.18	0.18	846.94	43.84
11	1987	11.17	6.64	4.52	0.21	995.46	45.03
12	1985	11.56	5.14	6.42	0.14	603.43	38.75
13	1983	15.45	4.80	10.65	0.18	782.60	83.37
14	1980	12.28	5.31	6.97	0.15	624.36	43.53
15	1978	13.19	5.56	7.63	0.17	619.26	47.26
16	1975	9.36	4.21	5.15	0.30	1091.87	56.28
17	1972	9.08	4.55	4.52	0.39	1424.50	64.44
18	1970	12.57	5.71	6.87	0.39	1240.42	85.18
19	1967	10.29	7.00	3.29	0.31	987.20	32.49
20	1964	9.39	6.83	2.56	0.35	1134.72	29.10
21	1960	7.94	4.49	3.45	0.47	1159.09	40.00
22	1956	7.23	4.54	2.69	0.48	1190.00	32.04
23	1952	5.93	3.92	2.01	0.54	1355.25	27.25
24	1948	6.85	3.90	2.95	0.48	1057.28	31.14
25	1944	7.84	6.86	0.98	0.45	990.44	9.74
26	1939	11.55	6.89	4.66	0.45	984.28	45.89
27	1935	15.55	7.54	8.01	0.38	647.07	51.86
28	1929	11.54	8.39	3.15	0.31	528.61	16.63
29	1923	13.09	9.04	4.06	0.24	418.61	16.98
30	1917	12.51	8.57	3.94	0.29	497.23	19.59
31	1901	7.32	4.07	3.25	0.35	225.76	7.35
32	1884	8.85	4.93	3.93	0.53	346.64	13.61
33	1867	8.30	4.93	3.37	0.41	269.48	9.08

Table B7.6. Katherine Lake

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR ($g/m^2/yr$)	TOC MAR ($g/m^2/yr$)
0	2010	17.72	3.65	14.07	0.06	481.50	67.73
1	2009	17.47	1.71	15.77	0.06	557.00	87.82
2	2008	17.40	2.50	14.90	0.08	755.00	112.46
3	2006	17.08	2.60	14.48	0.08	489.60	70.89
4	2005	17.06	2.49	14.57	0.04	446.00	65.00
5	2004	16.99	2.48	14.51	0.08	818.00	118.70
6	2001	17.03	2.53	14.50	0.09	443.00	64.25
7	2000	16.92	2.46	14.46	0.09	869.00	125.62
8	1999	16.91	2.47	14.44	0.11	1097.00	158.43
9	1995	16.66	2.49	14.17	0.08	384.50	54.48
10	1994	19.56	2.28	17.27	0.09	928.00	160.30
11	1993	17.46	2.04	15.42	0.10	961.00	148.15
12	1987	17.73	1.92	15.82	0.12	362.70	57.37
13	1984	14.97	1.76	13.21	0.10	289.80	38.28
14	1980	27.61	1.40	26.21	0.09	276.00	72.35
15	1977	18.40	1.32	17.07	0.08	153.40	26.19
16	1972	19.21	0.68	18.53	0.09	170.80	31.64
17	1967	26.29	0.25	26.04	0.08	168.20	43.79
18	1962	21.06	0.43	20.63	0.08	138.17	28.51
19	1956	16.92	0.56	16.37	0.05	87.72	14.36
20	1950	17.59	0.63	16.96	0.07	119.85	20.33
21	1944	27.69	0.40	27.30	0.08	133.58	36.46
22	1938	14.19	0.16	14.03	0.07	116.00	16.27
23	1932	25.66	0.21	25.45	0.15	236.64	60.22
24	1925	20.49	0.17	20.32	0.14	227.33	46.19
25	1919	22.53	0.19	22.34	0.07	123.93	27.68
26	1913	23.44	0.26	23.17	0.08	139.91	32.42
27	1907	23.64	0.19	23.45	0.09	126.27	29.62
28	1900	27.23	0.27	26.96	0.07	104.44	28.16
29	1893	21.75	0.24	21.52	0.07	100.66	21.66
30	1885	25.58	0.21	25.37	0.07	80.76	20.49
31	1877	25.20	0.23	24.97	0.07	83.04	20.74
32	1868	28.28	0.22	28.06	0.06	70.32	19.73
33	1860	23.81	0.29	23.52	0.06	66.78	15.70

Table B7.7. Kennedy Lake

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR ($g/m^2/yr$)	TOC MAR ($g/m^2/yr$)
0	2002	6.06	0.70	5.36	0.20	339.17	1.82
1	1996	7.47	0.45	7.02	0.25	427.55	3.00
2	1990	8.04	0.33	7.71	0.23	254.78	1.97
3	1981	7.89	0.82	7.07	0.23	251.79	1.78
4	1972	9.65	0.58	9.07	0.15	138.10	1.25
5	1962	9.34	0.65	8.68	0.16	160.20	1.39
6	1951	9.56	0.33	9.23	0.12	121.80	1.12
7	1941	8.86	0.71	8.14	0.20	202.70	1.65
8	1931	9.05	0.21	8.84	0.15	74.55	0.66
9	1911	8.78	0.00	8.78	0.10	128.48	1.13
10	1903	7.98	0.68	7.30	0.28	368.16	2.69
11	1896	8.10	0.85	7.25	0.27	352.04	2.55
12	1888	8.44	0.51	7.93	0.12	216.36	1.72
13	1882	7.84	0.73	7.11	0.30	536.94	3.82
14	1877	7.33	0.37	6.96	0.27	212.80	1.48
15	1865	7.48	0.42	7.06	0.29	234.72	1.66

Table B7.8. Little Tawayik

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR ($g/m^2/yr$)	TOC MAR ($g/m^2/yr$)
1	2013	19.25	1.28	17.97	0.30	996.00	179.02
2	2010	19.72	1.37	18.35	0.33	822.00	150.85
3	2006	19.60	1.23	18.36	0.26	639.75	117.48
4	2002	19.16	1.15	18.01	0.24	590.50	106.33
5	1998	18.88	1.29	17.59	0.31	622.40	109.50
6	1993	19.12	1.21	17.91	0.34	688.40	123.29
7	1988	19.48	1.26	18.23	0.25	509.20	92.81
8	1983	18.54	1.28	17.27	0.24	420.88	72.67
9	1977	18.89	1.22	17.67	0.40	721.80	127.57
10	1972	18.16	1.24	16.92	0.18	332.10	56.20
11	1966	17.10	1.15	15.95	0.27	502.69	80.20
12	1961	16.48	1.24	15.24	0.25	468.16	71.36
13	1955	16.10	1.28	14.82	0.22	425.41	63.04
14	1950	15.79	1.32	14.48	0.20	357.18	51.70
15	1944	16.47	1.21	15.25	0.45	803.70	122.60
16	1939	15.96	1.39	14.57	0.22	390.06	56.83
17	1933	12.60	1.26	11.34	0.40	855.21	97.00
18	1928	13.53	1.29	12.23	0.25	516.18	63.15
19	1923	12.16	1.36	10.80	0.27	566.58	61.17
20	1919	11.80	1.36	10.44	0.32	663.39	69.26
21	1914	12.00	1.53	10.47	0.30	633.15	66.27
22	1909	12.15	1.53	10.62	0.47	978.18	103.90
23	1905	12.45	1.46	10.99	0.22	457.80	50.31
24	1900	14.60	1.63	12.97	0.35	729.96	94.68
25	1895	14.78	1.61	13.16	0.29	608.37	80.08
26	1890	16.34	1.79	14.55	0.30	637.56	92.76
27	1886	16.54	1.74	14.80	0.38	794.01	117.53
28	1881	16.47	1.74	14.73	0.43	893.13	131.58
29	1876	15.67	1.64	14.02	0.51	1078.77	151.28
30	1871	15.47	1.53	13.94	0.46	971.46	135.40
31	1867	15.42	1.24	14.18	0.57	1191.54	169.02
32	1862	14.90	1.38	13.52	0.61	1274.07	172.27

Table B7.9. Long Lake

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR ($g/m^2/yr$)	TOC MAR ($g/m^2/yr$)
0	2008	4.69	3.11	1.58	0.13	661.50	10.44
1	2006	5.40	3.33	2.07	0.06	275.00	5.68
2	2004	19.63	3.10	16.53	0.06	308.50	50.99
4	1998	5.56	2.96	2.60	0.12	327.24	8.52
5	1995	5.19	3.07	2.12	0.05	127.44	2.70
6	1991	4.80	2.87	1.93	0.13	345.82	6.67
7	1987	5.13	2.70	2.43	0.08	228.96	5.57
8	1984	5.43	2.63	2.80	0.06	157.95	4.43
9	1980	5.73	2.73	3.00	0.21	448.50	13.45
10	1975	4.33	2.81	1.52	0.12	243.39	3.70
11	1970	5.17	3.69	1.48	0.09	189.84	2.81
12	1966	4.33	4.06	0.27	0.26	483.75	1.29
13	1961	3.87	4.47	0.00	0.11	211.85	0.00
14	1955	4.33	4.51	0.00	0.12	219.83	0.00
15	1950	4.84	5.41	0.00	0.30	565.13	0.00
16	1945	5.25	0.00	5.25	0.12	222.87	10.31
17	1939	5.41	0.00	5.41	0.11	213.18	10.71
18	1934	4.68	0.00	4.68	0.30	902.70	38.52
19	1931	5.01	0.00	5.01	0.24	732.90	33.89
20	1927	4.62	0.00	4.62	0.16	493.20	20.85
21	1924	4.08	0.00	4.08	0.29	669.92	23.46
22	1920	17.03	0.00	17.03	0.14	326.60	54.70
23	1915	4.33	0.00	4.33	0.20	464.37	18.53
24	1911	3.78	0.00	3.78	0.35	952.09	32.58
25	1907	4.47	0.00	4.47	0.13	358.29	14.75
26	1904	5.80	0.00	5.80	0.14	390.96	21.65
27	1900	16.78	0.00	16.78	0.50	990.40	161.01
28	1895	5.03	0.00	5.03	0.19	370.60	16.87
29	1890	4.43	0.00	4.43	0.18	360.60	14.62
30	1885	3.14	0.00	3.14	0.42	699.00	20.53
31	1879	5.67	0.00	5.67	0.17	289.17	15.86
32	1873	4.65	0.00	4.65	0.15	249.22	10.78
33	1867	4.71	0.00	4.71	0.35	451.04	20.23
34	1859	4.91	0.00	4.91	0.14	177.32	8.39

Table B7.10. Marion Lake

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR ($g/m^2/yr$)	TOC MAR ($g/m^2/yr$)
1	2012	17.96	3.21	14.75	0.03	135.43	19.97
2	2010	18.53	2.88	15.65	0.05	206.14	32.26
3	2007	18.41	3.27	15.14	0.07	306.43	46.39
4	2005	18.02	3.40	14.61	0.08	180.24	26.34
5	2001	18.13	3.41	14.73	0.08	183.29	26.99
6	1997	17.74	3.19	14.55	0.07	155.53	22.63
7	1993	17.27	3.17	14.10	0.07	174.82	24.65
8	1988	17.39	3.11	14.27	0.14	154.92	22.11
9	1979	16.95	3.11	13.84	0.10	112.65	15.59
10	1970	17.33	3.14	14.19	0.07	71.35	10.12
11	1961	17.14	3.23	13.91	0.05	53.30	7.42
12	1951	16.93	3.39	13.54	0.08	115.43	15.63
13	1944	17.05	3.10	13.95	0.07	106.43	14.85
14	1937	18.03	3.02	15.02	0.06	89.29	13.41
15	1930	18.32	2.94	15.37	0.05	69.43	10.67
16	1923	18.53	2.98	15.54	0.06	79.75	12.40
17	1915	18.16	3.27	14.89	0.07	88.88	13.24
18	1908	18.50	2.92	15.58	0.08	97.75	15.23
19	1900	19.31	2.73	16.59	0.06	75.00	12.44
20	1891	21.40	2.84	18.55	0.07	209.23	38.82
21	1888	21.70	3.02	18.68	0.06	187.08	34.95
22	1885	22.02	3.04	18.98	0.05	168.62	32.01
23	1881	21.61	2.38	19.23	0.06	192.00	36.92
24	1878	22.33	1.61	20.72	0.05	3.63	0.75

Table B7.11. McPhee Lake

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR (g/m^2/yr)	TOC MAR (g/m^2/yr)
0	2013	22.17	0.30	21.87	0.08	129.67	28.36
1	2007	22.61	0.35	22.26	0.08	133.83	29.79
2	2001	23.05	0.38	22.67	0.05	126.55	28.69
3	1997	22.83	0.42	22.42	0.06	159.57	35.77
4	1994	22.51	0.33	22.18	0.06	173.88	38.57
5	1990	23.31	0.35	22.95	0.06	131.14	30.10
6	1985	23.11	0.29	22.82	0.04	88.20	20.13
7	1980	22.98	0.35	22.63	0.06	117.18	26.52
8	1976	21.89	0.44	21.45	0.06	84.90	18.21
9	1969	18.79	0.29	18.49	0.07	99.00	18.31
10	1963	22.38	0.33	22.05	0.06	96.90	21.36
11	1956	23.40	0.31	23.09	0.06	56.30	13.00
12	1946	21.71	0.36	21.35	0.04	40.40	8.63
13	1936	36.88	0.47	36.42	0.08	81.20	29.57
14	1926	37.29	0.32	36.97	0.07	66.90	24.73
15	1916	36.01	0.30	35.71	0.08	76.60	27.36
16	1906	19.29	0.25	19.04	0.07	68.90	13.12
17	1896	35.99	0.27	35.72	0.05	53.30	19.04
18	1886	35.48	0.13	35.35	0.07	70.30	24.85
19	1876	35.69	0.20	35.49	0.07	73.90	26.22
20	1866	38.61	0.23	38.38	0.07	65.50	25.14

Table B7.12. Moon Lake

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR ($g/m^2/yr$)	TOC MAR ($g/m^2/yr$)
0	2010	14.52	0.49	14.02	0.08	578.25	81.07
1	2009	13.06	0.62	12.45	0.05	542.00	67.46
2	2008	14.56	0.64	13.92	0.21	2070.00	288.14
3	2006	14.47	0.65	13.82	0.22	1109.50	153.30
4	2005	13.91	0.60	13.31	0.18	1774.00	236.12
6	2001	14.41	0.58	13.84	0.20	1408.40	194.87
7	2000	14.76	0.66	14.09	0.17	1747.00	246.23
8	1999	14.73	0.67	14.05	0.10	967.00	135.89
9	1996	14.55	0.67	13.88	0.09	332.25	46.13
12	1988	14.79	0.64	14.15	0.16	538.33	76.17
13	1985	14.68	0.68	14.00	0.19	623.37	87.30
14	1982	14.26	0.60	13.65	0.16	524.37	71.60
15	1979	13.98	0.65	13.33	0.15	489.67	65.28
16	1976	13.61	0.65	12.96	0.19	618.75	80.22
17	1973	16.57	0.71	15.87	0.16	514.14	81.57
18	1970	13.48	0.74	12.74	0.07	184.91	23.56
19	1966	13.57	0.70	12.88	0.19	522.18	67.25
20	1963	13.66	0.80	12.87	0.11	284.04	36.55
21	1959	13.83	0.75	13.09	0.20	329.33	43.10
22	1953	14.71	0.82	13.89	0.08	134.98	18.75
23	1947	14.86	0.74	14.12	0.18	313.82	44.32
24	1941	15.11	0.73	14.37	0.23	499.29	71.77
25	1936	15.32	0.79	14.53	0.11	221.13	32.14
26	1931	15.78	0.82	14.96	0.18	372.54	55.73
27	1927	16.22	0.85	15.37	0.09	163.94	25.19
28	1921	15.98	0.79	15.19	0.11	200.16	30.40
29	1916	16.47	0.82	15.66	0.10	188.46	29.51
30	1910	18.28	0.81	17.47	0.18	298.33	52.12
31	1904	16.03	0.76	15.27	0.14	241.40	36.87
32	1898	16.56	0.82	15.74	0.11	191.42	30.13
33	1892	16.15	0.79	15.36	0.13	195.45	30.01
34	1885	16.34	0.76	15.57	0.11	169.65	26.42
35	1879	12.77	0.86	11.91	0.11	172.05	20.48
36	1872	15.90	0.79	15.11	0.14	134.72	20.36
37	1861	15.89	0.82	15.07	0.13	116.73	17.59
38	1850	16.08	0.72	15.37	0.23	211.23	32.46
39	1840	16.44	0.89	15.55	0.13	116.82	18.17

Table B7.13.   Muriel Lake

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR ($g/m^2/yr$)	TOC MAR ($g/m^2/yr$)
1	2001	6.08	0.00	6.08	0.10	494.50	30.04
2	1999	6.30	0.01	6.29	0.14	346.50	21.81
3	1995	6.06	0.01	6.06	0.34	840.75	50.93
5	1991	4.47	0.00	4.47	0.57	1317.69	58.85
10	1965	8.55	0.01	8.54	0.22	255.58	21.83
11	1957	7.81	0.01	7.80	0.20	243.36	18.98
12	1948	7.33	0.01	7.32	0.14	169.68	12.42
13	1940	7.04	0.04	7.00	0.29	348.36	24.38
14	1932	8.52	0.01	8.51	0.16	194.88	16.58
15	1922	7.96	0.02	7.94	0.23	263.19	20.89
16	1905	7.49	0.03	7.47	0.22	266.40	19.89
17	1897	7.36	0.03	7.33	0.25	298.08	21.86
18	1889	7.19	0.02	7.16	0.17	208.20	14.92
19	1880	7.82	0.02	7.81	0.22	269.40	21.03
20	1870	7.21	0.01	7.20	0.20	197.60	14.22
21	1860	8.30	0.00	8.30	0.13	130.10	10.79

Table B7.14. Quamichan Lake

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR ($g/m^2/yr$)	TOC MAR ($g/m^2/yr$)
1	2004	17.11	0.00	17.11	0.13	2500.00	427.85
2	2003	16.68	0.00	16.68	0.08	1618.00	279.26
4	2002	17.23	0.00	17.23	0.11	2106.00	350.08
6	2001	16.62	0.00	16.62	0.11	1130.00	192.84
8	2000	17.07	0.00	17.07	0.10	2044.00	348.39
9	1999	16.78	0.00	16.78	0.06	1286.00	220.99
10	1998	17.04	0.00	17.04	0.10	951.00	166.77
12	1997	17.55	0.02	17.54	0.07	691.00	121.53
13	1996	17.52	0.25	17.27	0.07	705.00	120.88
14	1995	17.76	0.17	17.59	0.10	967.00	162.95
15	1994	17.32	0.18	17.15	0.07	736.00	125.49
16	1993	16.92	0.07	16.85	0.08	803.00	137.35
17	1992	17.25	0.20	17.05	0.08	781.00	137.93
18	1991	17.27	0.16	17.10	0.10	984.00	171.82
19	1990	17.79	0.13	17.66	0.11	1079.00	185.88
20	1989	17.70	0.24	17.46	0.11	1133.00	192.24
21	1988	17.41	0.18	17.23	0.10	982.00	164.12
22	1987	16.97	0.00	16.97	0.09	691.20	118.83
23	1986	16.95	0.24	16.71	0.10	836.80	144.63
24	1985	17.39	0.20	17.19	0.05	425.60	73.67
25	1984	17.52	0.24	17.28	0.09	688.80	118.37
26	1983	17.37	0.06	17.31	0.09	655.00	118.75
27	1981	17.31	0.13	17.19	0.07	489.19	86.93
28	1980	18.18	0.05	18.13	0.09	634.74	110.06
29	1979	17.87	0.10	17.77	0.06	400.44	71.48
30	1977	17.51	0.17	17.34	0.08	562.32	100.82
31	1976	17.90	0.05	17.85	0.07	356.50	65.06
32	1974	17.93	0.00	17.93	0.06	312.50	55.90
33	1973	18.25	0.00	18.25	0.08	423.00	75.21
34	1971	17.89	0.00	17.89	0.07	357.00	66.12
35	1969	17.90	0.12	17.78	0.09	473.50	87.16
36	1967	18.64	0.11	18.52	0.10	423.75	77.11
37	1965	18.43	0.03	18.41	0.06	261.24	46.66
38	1963	18.26	0.07	18.20	0.10	399.00	77.17
39	1961	17.86	0.00	17.86	0.09	378.84	70.30
40	1958	17.25	0.00	17.25	0.09	376.74	64.85
41	1956	17.11	0.00	17.11	0.10	277.43	52.06

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR ($g/m^2/yr$)	TOC MAR ($g/m^2/yr$)
42	1953	16.68	0.00	16.68	0.11	326.83	57.36
43	1951	17.26	0.00	17.26	0.10	287.39	53.23
44	1948	17.23	0.00	17.23	0.10	292.61	55.71
45	1944	17.21	0.00	17.21	0.09	263.90	52.34
46	1941	16.62	0.00	16.62	0.09	274.63	49.93
47	1937	17.25	0.00	17.25	0.09	332.86	72.15
48	1934	17.07	0.00	17.07	0.09	318.96	68.06
49	1930	16.78	0.00	16.78	0.05	183.60	36.24
50	1927	17.04	0.00	17.04	0.08	272.88	54.26
51	1924	17.18	0.00	17.18	0.09	309.24	66.68
52	1922	17.55	0.02	17.54	0.07	193.42	40.73
53	1919	17.52	0.25	17.27	0.08	217.10	47.52
54	1916	17.76	0.17	17.59	0.08	205.14	41.91
55	1912	17.32	0.18	17.15	0.06	168.48	34.25
56	1908	16.92	0.07	16.85	0.08	212.42	42.68
57	1904	17.25	0.20	17.05	0.10	238.25	48.79
58	1901	17.27	0.16	17.10	0.07	176.50	35.60
59	1897	17.79	0.13	17.66	0.06	153.75	31.50
60	1893	17.70	0.24	17.46	0.09	219.50	44.96
61	1889	17.41	0.18	17.23	0.10	239.50	47.07
62	1885	16.97	0.00	16.97	0.07	177.50	34.38
63	1881	16.95	0.24	16.71	0.10	244.75	49.81
64	1877	17.39	0.20	17.19	0.09	213.25	42.06
65	1873	17.52	0.24	17.28	0.09	223.25	43.09
66	1865	17.37	0.06	17.31	0.13	2500.00	427.85
67	1861	17.31	0.13	17.19	0.08	1618.00	279.26

Table B7.15. Roe Lake

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR (g/m^2/yr)	TOC MAR (g/m^2/yr)
0	2004	29.47	0.05	29.42	0.03	151.50	44.57
1	2002	25.24	0.19	25.05	0.04	187.75	47.03
2	2000	25.27	0.03	25.24	0.05	130.75	33.00
3	1996	32.28	0.00	32.28	0.07	241.50	77.96
4	1993	33.57	0.09	33.48	0.09	290.33	97.21
5	1990	27.89	0.00	27.89	0.08	161.00	44.91
6	1985	26.70	0.10	26.60	0.06	121.68	32.36
7	1980	28.19	0.04	28.15	0.10	202.02	56.86
8	1975	28.50	0.04	28.46	0.08	164.01	46.68
9	1971	29.72	0.07	29.65	0.05	108.57	32.19
10	1966	28.20	0.11	28.09	0.09	225.25	63.28
11	1962	28.34	0.16	28.18	0.10	252.13	71.04
12	1958	29.76	0.05	29.71	0.07	163.88	48.70
13	1954	28.13	0.16	27.96	0.06	155.13	43.38
14	1950	27.87	0.10	27.77	0.10	231.44	64.26
15	1945	25.03	0.06	24.98	0.12	254.98	63.69
16	1941	30.84	0.03	30.81	0.10	213.73	65.85
17	1936	28.80	0.04	28.76	0.06	137.28	39.48
18	1932	32.58	0.15	32.42	0.05	101.86	33.03
19	1927	28.60	0.04	28.56	0.07	160.16	45.74
20	1923	26.91	0.09	26.82	0.11	175.92	47.18
21	1916	25.54	0.11	25.44	0.04	61.50	15.64
22	1910	26.03	0.09	25.94	0.12	130.33	33.81
23	1901	27.56	0.06	27.50	0.11	115.61	31.80
24	1892	28.48	0.12	28.36	0.13	163.06	46.25
25	1884	26.46	0.00	26.46	0.07	89.94	23.79
26	1876	26.04	0.47	25.57	0.08	98.63	25.22
27	1868	24.78	0.37	24.41	0.06	71.06	17.35
28	1860	26.89	0.22	26.67	0.04	54.38	14.50

Table B7.16. Shady Lake

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR ($g/m^2/yr$)	TOC MAR ($g/m^2/yr$)
0	2013	24.43	0.25	24.18	0.06	160.25	38.75
1	2009	26.87	0.30	26.57	0.08	112.14	29.79
2	2002	26.53	0.21	26.32	0.07	113.50	29.87
3	1996	25.89	0.24	25.65	0.07	180.00	46.17
4	1992	26.89	0.22	26.67	0.07	206.29	55.02
5	1989	26.37	0.19	26.18	0.07	192.85	50.48
6	1985	26.65	0.19	26.45	0.08	263.67	69.75
7	1982	25.83	0.13	25.70	0.06	194.37	49.95
8	1979	26.95	0.15	26.80	0.10	200.80	53.81
9	1974	27.53	0.12	27.41	0.08	153.20	41.99
10	1969	27.11	0.40	26.71	0.10	166.33	44.43
11	1963	26.78	0.31	26.47	0.10	174.42	46.16
12	1957	28.15	0.41	27.75	0.10	134.27	37.26
13	1949	27.54	0.20	27.33	0.10	132.60	36.24
14	1942	26.67	0.43	26.24	0.11	112.30	29.47
15	1932	25.64	0.22	25.42	0.11	109.50	27.84
16	1922	25.26	0.25	25.02	0.12	88.71	22.19
17	1908	23.75	0.20	23.55	0.12	85.47	20.13
18	1894	23.63	0.24	23.39	0.12	87.29	20.42
19	1880	22.43	0.24	22.19	0.11	74.34	16.49
20	1865	23.23	0.22	23.00	0.12	83.79	19.27

Table B7.17. South Lake

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR ($g/m^2/yr$)	TOC MAR ($g/m^2/yr$)
0	2010	17.80	3.26	14.54	0.00	228.96	33.28
2	1986	15.24	3.52	11.72	0.24	328.80	38.55
4	1965	17.10	3.67	13.43	0.31	259.68	34.89
6	1941	17.00	3.53	13.47	0.26	155.30	20.92
8	1899	17.33	3.44	13.89	0.30	141.15	19.61
10	1860	17.54	3.28	14.26	0.28	129.70	18.50

Table B7.18. Stowell Lake

Depth (cm)	Year	%TC	%TIC	%TOC	DBD (g/cm^3)	MAR ($g/m^2/yr$)	TOC MAR ($g/m^2/yr$)
1	2001	9.51	0.05	9.46	0.29	840.71	79.53
2	1997	9.33	0.03	9.30	0.26	518.80	48.25
3	1992	8.83	0.03	8.80	0.13	260.80	22.94
4	1987	8.49	0.03	8.46	0.31	514.42	43.51
5	1981	8.27	0.02	8.25	0.31	531.76	43.89
6	1975	9.03	0.05	8.98	0.23	381.00	34.23
7	1969	9.46	0.03	9.43	0.21	359.98	33.95
8	1963	10.02	0.03	9.98	0.22	341.31	34.07
9	1956	11.21	0.02	11.18	0.17	261.45	29.23
10	1950	14.34	0.02	14.32	0.13	184.29	26.39
11	1943	14.64	0.03	14.61	0.14	201.88	29.50
12	1936	15.43	0.03	15.40	0.12	214.48	33.03
13	1930	17.18	0.04	17.14	0.16	267.75	45.90
14	1924	18.00	0.03	17.97	0.10	171.28	30.78
16	1912	19.45	0.03	19.42	0.14	239.53	46.51
17	1907	19.13	0.02	19.11	0.10	50.63	9.68
18	1887	18.61	0.02	18.59	0.10	137.43	25.55
19	1880	21.33	0.01	21.32	0.11	41.42	8.83

B8. Spearman's rho

Table B8.1. Results of TOC MAR Spearman's rho and Pearson's r non-parametric test

Lake	df	Spearman's rho	p-value*	Pearson's r	Pearson's p-value*
Kennedy	14	0.047	0.862	-0.128	0.640
Marion	21	0.082	0.709	0.015	0.940
Roe	27	0.515	**0.004**	0.576	**0.001**
Stowell	16	0.531	**0.025**	0.589	**0.010**
Muriel	14	0.649	**0.007**	0.634	**0.010**
Quamichan	33	0.734	**0.000**	0.706	**0.000**
Shady	19	0.690	**0.001**	0.706	**0.000**
Katherine	32	0.788	**0.000**	0.666	**0.000**
South	3	NA	NA	NA	NA
Moon	33	0.655	**0.000**	0.655	**0.000**
Dog	32	0.821	**0.000**	0.755	**0.000**
Clear	20	0.825	**0.000**	0.805	**0.000**
Babine	6	NA	NA	NA	NA
Crandell	20	0.790	**0.000**	0.736	**0.000**
Antler	22	0.958	**0.000**	0.786	**0.000**
McPhee	17	0.544	**0.018**	0.433	0.064
Long	27	-0.487	**0.008**	-0.289	0.128
Little Tawayik	30	-0.075	0.682	-0.085	0.640

* Significant results (p<0.05) in bold

Table B8.2. Results of %TOC Spearman's rho and Pearson's r

Lake	df	Spearman's rho	p-value*	Pearson's r	Pearson's p-value*
Long	27	-0.5223	**0.004**	-0.138	0.476
Little Tawayik	30	0.749	**0.000**	0.717	**0.000**
Kennedy	14	0.056	0.839	-0.018	0.946
Marion	21	-0.558	**0.006**	-0.722	**0.000**
Roe	27	0.101	0.311	0.365	0.051
Stowell	16	-0.920	**0.000**	-0.952	**0.000**
Muriel	14	-0.485	0.059	-0.584	**0.018**
Quamichan	33	-0.651	**0.000**	-0.597	**0.000**
Shady	19	0.401	0.073	0.680	**0.001**
Katherine	32	-0.728	**0.000**	-0.764	**0.000**
South	3	NA	NA	NA	NA
Moon	33	-0.532	**0.000**	-0.506	**0.002**
Dog	32	0.275	0.086	0.140	0.389
Clear	20	0.941	**0.000**	0.886	**0.000**
Babine	6	NA	NA	NA	NA
Crandell	20	0.007	0.976	0.210	0.348
Antler	22	-0.194	0.362	-0.000	1.000
McPhee	17	-0.358	0.133	-0.668	**0.002**

* Significant results ($p<0.05$) in bold

Table B8.3. Results of MAR Spearman's rho and Pearson's r

Lake	df	Spearman's rho	p-value*	Pearson's r	Pearson's p-value*
Long	27	-0.325	0.086	-0.268	0.160
Little Tawayik	30	-0.391	**0.028**	-0.460	**0.008**
Kennedy	14	0.009	0.978	-0.071	0.794
Marion	21	0.190	0.384	0.253	0.245
Roe	27	0.535	**0.003**	0.575	**0.001**
Stowell	16	0.870	**0.000**	0.817	**0.000**
Muriel	14	0.591	**0.018**	0.592	**0.016**
Quamichan	33	0.795	**0.000**	0.776	**0.000**
Shady	19	0.687	**0.001**	0.690	**0.000**
Katherine	32	0.884	**0.000**	0.710	**0.000**
South	3	NA	NA	NA	NA
Moon	33	0.866	**0.000**	0.670	**0.000**
Dog	32	0.665	**0.000**	0.587	**0.000**
Clear	20	0.695	**0.000**	0.755	**0.000**
Babine	6	NA	NA	NA	NA
Crandell	20	0.654	**0.000**	0.597	**0.000**
Antler	22	0.965	**0.000**	0.815	**0.000**
McPhee	17	0.846	**0.000**	0.768	**0.000**

* Significant results ($p<0.05$) in bold

Table B8.4. Results of Spearman's rho correlation with continuous variables for lakes in the Prairies ecozone. See Appendix B2 for climate definitions.

	Antler		Little Tawayik	
	Spearman's rho	p value*	Spearman's rho	p value*
%TOC	-0.05	0.8541	0.5597	**0.0083**
MAR	0.9912	**<.0001**	0.7519	**<.0001**
CN	-0.5176	**0.04**	-0.5455	**0.0105**
GDD5	0.6255	**0.0096**	0.1701	0.4609
MAP	0.3382	0.2001	0.3163	0.1624
MAT	0.4772	0.0616	0.3918	**0.079**
MCMT	0.4471	0.0825	0.2727	0.2317
MWMT	0.5283	**0.0354**	-0.1674	0.4682
SHM	-0.134	0.6207	-0.3857	0.0842
DDB0	-0.2559	0.3388	-0.2753	0.2271
NFFD	0.5615	**0.0236**	0.4868	**0.0252**
FFP	0.5386	**0.0313**	0.5484	**0.01**
Tave_wt	0.4606	0.0726	0.4424	**0.0446**
Tave_sp	0.1516	0.5752	0.3941	0.0771
Tave_sm	0.5855	**0.0172**	-0.0488	0.8335
Tave_at	-0.3294	0.2128	0.08	0.7303
PPT_wt	-0.5147	**0.0413**	-0.0312	0.8931
PPT_sp	-0.2253	0.4014	0.2709	0.235
PPT_sm	0.5162	**0.0406**	0.3354	0.1372
PPT_at	0.2063	0.4433	-0.11	0.6352

* Significant results ($p<0.05$) in bold

Table B8.5. Results of Spearman's rho correlation with continuous variables for lakes in the Montane Cordillera ecozone. See Appendix B2 for climate definitions

	Crandell		Dog		Marion	
	Spearman's rho	p value	Spearman's rho	p value	Spearman's rho	p value
%TOC	0.1006	0.701	0.6408	**<.0001**	0.0265	0.9225
MAR	0.9265	**<0.001**	0.5949	**0.0003**	0.9824	**<.0001**
CN	-0.2868	0.2644	0.0627	0.7332	-0.8029	**0.0002**
GDD5	0.2034	0.4336	0.281	0.1192	-0.2618	0.3274
MAP	-0.4485	0.0709	0.215	0.2372	0.0676	0.8034
MAT	0.1978	0.4467	0.3771	**0.0334**	0.1888	0.4838
MCMT	0.0405	0.8773	0.1509	0.4096	0.0898	0.7409
MWMT	0.2074	0.4245	0.3883	**0.0281**	-0.3378	0.2007
SHM	0.0589	0.8225	0.0647	0.725	-0.1853	0.4921
DDB0	-0.2132	0.4112	-0.3807	**0.0316**	-0.3735	0.1541
NFFD	0.102	0.6968	0.2787	0.1224	0.2193	0.4145
FFP	0.385	0.127	-0.1424	0.4369	0.2	0.4577
Tave_wt	0.2701	0.2944	0.3162	0.0779	0.0574	0.8328
Tave_sp	0.2479	0.3375	0.3843	**0.0299**	0.1326	0.6243
Tave_sm	0.1613	0.5362	0.405	**0.0215**	-0.3873	0.1383
Tave_at	0.1452	0.5781	-0.4379	**0.0122**	0.2502	0.35
PPT_wt	-0.3151	0.2179	0.0964	0.5996	0.0235	0.9311
PPT_sp	-0.1667	0.5226	-0.2586	0.153	0.1458	0.59
PPT_sm	-0.281	0.2746	0.1496	0.4138	0.0957	0.7245
PPT_at	-0.3213	0.2086	0.2544	0.16	-0.2104	0.434

* Significant results (p<0.05) in bold

Table B8.6. Results of Spearman's rho correlation with continuous variables for lakes in the Pacific Maritime ecozone. See Appendix B2 for climate definitions.

	Kennedy		Muriel		Quam		Roe	
	Spearman's rho	p value	Spearman's rho	p value	Spearman's rho	p value	Spearman's rho	p value
%TOC	-0.8545	**0.0008**	-0.6727	**0.0233**	-0.8151	**<.0001**	0.3226	0.1242
MAR	0.9909	**<.0001**	0.9364	**<.0001**	0.9946	**<.0001**	0.9678	**<.0001**
CN	-0.6545	**0.0289**	0.7727	**0.0053**	0.1787	0.2095	0.2104	0.36
GDD5	0.3455	0.2981	0.6545	**0.0289**	0.3839	**0.0027**	0.3235	0.1231
MAP	0.4556	0.1591	0.1364	0.6893	-0.0635	0.633	0.0144	0.9469
MAT	0.328	0.3247	0.7091	**0.0146**	0.4516	**0.0003**	0.4397	**0.0316**
MCMT	0.0636	0.8525	0.7426	**0.0088**	0.2822	**0.0303**	0.2664	0.2083
MWMT	0.3524	0.2878	0.6515	**0.0299**	0.2016	0.1257	-0.0052	0.9807
SHM	-0.0455	0.8944	0.1321	0.6986	0.0115	0.9308	-0.1165	0.5877
DDB0	-0.1636	0.6307	-0.5818	0.0604	-0.3467	**0.0071**	-0.4941	**0.0141**
NFFD	0.3182	0.3403	0.7608	**0.0065**	0.5435	**<.0001**	0.3513	0.0924
FFP	0.3508	0.2902	0.6909	**0.0186**	0.5245	**<.0001**	0.4322	**0.0349**
Tave_wt	0.2237	0.5084	0.7818	**0.0045**	0.4516	**0.0003**	0.3503	0.0934
Tave_sp	0.1058	0.757	0.5421	0.0849	0.3376	**0.0089**	0.2606	0.2188
Tave_sm	0.615	**0.044**	0.3418	0.3035	0.2941	**0.0238**	0.155	0.4696
Tave_at	0.3007	0.3689	0.5604	0.073	0.237	0.0707	0.0933	0.6645
PPT_wt	0.2909	0.3855	0.0818	0.811	-0.1253	0.3443	-0.0852	0.6921
PPT_sp	0.4091	0.2115	-0.1455	0.6696	0.2123	0.1065	0.1339	0.5326
PPT_sm	0.1909	0.5739	0.2091	0.5372	0.0551	0.6787	-0.0718	0.7389
PPT_at	0.4091	0.2115	0.0545	0.8734	-0.0239	0.8575	0.1218	0.5709

* Significant results ($p<0.05$) in bold

Table B8.6 cont. Results of Spearman’s rho correlation with continuous variables for lakes in the Pacific Maritime ecozone. See Appendix B2 for climate definitions

	Stowell	
	Spearman's rho	p value
%TOC	-0.2118	0.4311
MAR	0.75	**0.0008**
CN	0.3059	0.2493
GDD5	0.0294	0.9138
MAP	0.1618	0.5495
MAT	0.2682	0.3151
MCMT	0.3235	0.2216
MWMT	0.1595	0.5551
SHM	-0.4088	0.1159
DDB0	-0.2706	0.3108
NFFD	0.4265	0.0995
FFP	0.3063	0.2485
Tave_wt	0.3953	0.1297
Tave_sp	0.2025	0.4519
Tave_sm	-0.0815	0.764
Tave_at	0.2198	0.4135
PPT_wt	-0.1853	0.4921
PPT_sp	0.3029	0.2541
PPT_sm	0.2618	0.3274
PPT_at	0.1794	0.5061

* Significant results ($p<0.05$) in bold

Table B8.7. Results of Spearman's rho correlation with continuous variables for lakes in the Boreal Plains ecozone. See Appendix B2 for climate definitions

	Clear		Katherine		Long		McPhee	
	Spearman's rho	p value	Spearman's rho	p value	Spearman's rho	p value	Spearman's rho	p value
%TOC	0.7912	**<.0001**	-0.2802	0.1569	0.8142	**<.0001**	0.3382	0.2001
MAR	0.9719	**<.0001**	0.9567	**<.0001**	0.5909	**0.003**	0.8	**0.0002**
CN	0.0053	0.9829	-0.007	0.9828	-0.7	0.1881	0.022	0.9432
GDD5	0.2053	0.3992	-0.0379	0.8513	-0.4259	**0.0427**	0.3912	0.1341
MAP	-0.3633	0.1263	0.1764	0.3787	-0.2292	0.2927	0.234	0.3831
MAT	0.4459	0.0557	0.3768	0.0527	-0.1083	0.6229	0.324	0.2209
MCMT	0.3256	0.1738	0.2525	0.2039	-0.2016	0.3563	-0.1252	0.6441
MWMT	0.3307	0.1667	0.0786	0.6967	-0.5802	**0.0037**	0.3127	0.2383
SHM	0.4511	0.0526	-0.1166	0.5624	-0.2559	0.2385	-0.2824	0.2893
DDB0	-0.2456	0.3108	-0.4799	**0.0113**	-0.0296	0.8932	-0.3647	0.1649
NFFD	0.2524	0.2971	0.1674	0.404	-0.1732	0.4294	0.395	0.13
FFP	0.0527	0.8303	-0.0128	0.9494	-0.0959	0.6633	0.5287	**0.0352**
Tave_wt	0.1904	0.4349	0.2042	0.3068	-0.1102	0.6166	-0.0015	0.9957
Tave_sp	0.2888	0.2304	0.4425	**0.0208**	-0.041	0.8525	0.1678	0.5346
Tave_sm	0.206	0.3975	-0.1378	0.4931	-0.6551	**0.0007**	0.4307	0.0958
Tave_at	-0.0176	0.9431	0.2658	0.1803	0.3919	0.0644	0.2701	0.3116
PPT_wt	-0.2141	0.3787	0.0428	0.8321	-0.1622	0.4596	-0.291	0.2742
PPT_sp	-0.1572	0.5203	-0.1939	0.3325	-0.4627	**0.0262**	0.2373	0.3762
PPT_sm	-0.1702	0.4861	0.1603	0.4245	0.0603	0.7846	0.2647	0.3218
PPT_at	0.0123	0.9602	0.3151	0.1094	-0.1271	0.5633	0.0515	0.8496

Table B8.7 cont. Results of Spearman's rho correlation with continuous variables for lakes in the Boreal Plains ecozone. See Appendix B2 for climate definitions

	Moon		Shady	
	Spearman's rho	p value	Spearman's rho	p value
%TOC	-0.6727	**0.0233**	0.3554	0.1615
MAR	0.9792	**<.0001**	0.9951	**<.0001**
CN	-0.5599	**0.0019**	0.2033	0.5053
GDD5	0.124	0.5295	-0.299	0.2437
MAP	0.0958	0.6276	-0.2502	0.3329
MAT	0.4238	**0.0246**	-0.1735	0.5053
MCMT	0.2976	0.124	-0.2882	0.262
MWMT	-0.1671	0.3953	0.1423	0.5858
SHM	0.1321	0.6986	0.2146	0.4082
DDB0	-0.5818	0.0604	0.2721	0.2908
NFFD	0.7608	**0.0065**	0.2683	0.2978
FFP	**0.6909**	**0.0186**	0.1631	0.5317
Tave_wt	0.7818	**0.0045**	-0.1691	0.5164
Tave_sp	0.5421	0.0849	0.1864	0.4738
Tave_sm	0.3418	0.3035	-0.0553	0.833
Tave_at	0.5604	0.073	-0.1977	0.447
PPT_wt	0.0818	0.811	0	1
PPT_sp	-0.1455	0.6696	0.1952	0.4527
PPT_sm	0.2091	0.5372	-0.4338	0.0819
PPT_at	0.0545	0.8734	0.2457	0.3418

* Significant results (p<0.05) in bold

B9 - Average C Accumulation Rates estimated for 30-year Period for every lake

Table B9.1 Average C Accumulation Rate ($g/m^2/yr$) for 30-year Time Periods and Supporting Data Table to Figure 2.3a

	1830-1860	1860-1890	1890-1920	1920-1950	1950-1980	1980-2010
Babine	3.8	3.9	3.9	4.2	6.7	12.4
Muriel	11.9	15.2	20.9	18.6	20.4	40.4
Kennedy	0.9	2.2	2.1	1.2	1.3	2.1
Quamichan	34.2	41.8	44.8	55.5	76.6	196.3
Stowell	11.8	17.2	28.1	33.1	31.6	47.6
Roe	18.3	20.2	31.9	51.3	53.3	54.2
Marion	6.9	7.2	20.3	12.6	12.5	29.0
Dog	13.7	10.5	6.8	28.6	45.8	80.9
Crandell	26.3	19.0	17.4	25.4	25.8	42.2
Antler	27.2	30.3	26.9	34.4	49.0	107.1
Little Tawayik	144.5	138.5	79.6	75.4	75.0	110.4
Shady	18.9	17.9	20.3	28.9	44.7	47.3
Moon	25.3	21.2	35.7	43.3	52.0	140.4
Long	12.4	16.4	41.8	27.5	5.3	12.1
South	22.8	NA	24.5	26.4	44.4	45.4
Clear	5.3	8.2	11.6	31.9	38.7	73.6
Katherine	21.5	19.2	27.9	35.9	33.9	93.5
McPhee	25.8	25.4	19.8	21.0	19.5	29.9

B10 Pairwise Correlation

Table B10.1. Pairwise correlation analysis using a Spearman rank correlation coefficient (ρ) comparing changes in climate, lake morphometry, and land use variables with modern and historical C accumulation rates (TOC MAR) across all lakes used in this study.

	Modern TOC MAR		Historical TOC MAR		Modern/Historical TOC MAR	
	ρ	p value	ρ	p value	ρ	p value
%TOC	**0.4572**	**0.0565**	**0.5588**	**0.0197**	-0.1299	0.6192
C/N Ratio	-0.3292	0.1822	-0.0237	0.9255	-0.2157	0.4057
			Geographic Variables			
Latitude	-0.0753	0.7664	0.1716	0.5103	-0.1985	0.445
Elevation	0.0723	0.7756	0.3483	0.1707	-0.0392	0.8811
Distance from Pacific Coast	0.1496	0.5534	0.2059	0.4279	-0.0441	0.8665
			Land Use Variables			
CA % Water	-0.0279	0.9126	NA	NA	-0.3106	0.2096
CA % Exposed Land	-0.2690	0.2804	NA	NA	0.2073	0.4091
CA % Shrubland	-0.3191	0.1969	NA	NA	-0.0733	0.7725
CA % Wetland	-0.1373	0.5871	NA	NA	-0.0382	0.8804
CA % Grassland and Native Grass	0.2860	0.2499	NA	NA	0.0606	0.8112
CA % Coniferous Forest	-0.1744	0.4888	NA	NA	0.2962	0.2327
CA % Deciduous Forest	0.1166	0.6449	NA	NA	-0.2941	0.2361

	Modern TOC MAR	Historical TOC MAR	Modern/ Historical TOC MAR		Modern TOC MAR	Historical TOC MAR
	ρ	p value	ρ		ρ	p value
CA % Mixed Forest	-0.2533	0.3104	NA	NA	-0.0862	0.7338
CA % All Agriculture	0.3240	0.1896	NA	NA	-0.0465	0.8548
CA % Total Development and Agriculture	0.2481	0.3209	NA	NA	-0.1797	0.4754

			Climatic Variables			
MAT	-0.0291	0.9089	NA	NA	0.1777	0.4951
MWMT	0.3295	0.1817	NA	NA	0.1276	0.6255
MCMT	-0.1187	0.6390	NA	NA	0.0784	0.7648
MAP	-0.2817	0.2574	NA	NA	0.3431	0.1775
GDD5	0.1496	0.5534	NA	NA	0.1887	0.4682
SHM	0.2303	0.3580	NA	NA	-0.0540	0.8371
DDB0	0.1580	0.5313	NA	NA	-0.1275	0.6257
NFFD	-0.0052	0.9837	NA	NA	-0.0246	0.9254
FFP	0.1147	0.6505	NA	NA	-0.0822	0.7538
Tave_wt	-0.1571	0.5336	NA	NA	0.0724	0.7823
Tave_sp	0.0341	0.8930	NA	NA	0.0577	0.8258
Tave_sm	0.3830	0.1167	NA	NA	0.1900	0.4651
Tave_at	0.1536	0.5428	NA	NA	0.1073	0.6818
PPT_wt	-0.2490	0.3191	NA	NA	0.2922	0.2550
PPT_sp	-0.1497	0.5532	NA	NA	0.2943	0.2515
PPT_sm	-0.0919	0.7169	NA	NA	-0.1006	0.7010
PPT_at	-0.2844	0.2527	NA	NA	0.2654	0.3033

	Modern TOC MAR	Historical TOC MAR	Modern/ Historical TOC MAR		Modern TOC MAR	Historical TOC MAR
	ρ	p value	ρ		ρ	p value
			Lake Morphometric Variables			
LA	-0.0423	0.8676	-0.1495	0.5668	0.0833	0.7505
CA	-0.2487	0.3196	**-0.500**	**0.041**	0.3064	0.2317
CA/LA Ratio	-0.1207	0.6332	-0.1054	0.6873	0.1936	0.4565
MDR	0.0723	0.7755	0.0564	0.8296	0.1227	0.6390
Max Depth	**-0.5142**	**0.0290**	**-0.6070**	**0.0098**	0.0883	0.7361
LGR	**0.5831**	**0.0111**	**0.6740**	**0.0030**	-0.0270	0.9182

* Significant results ($p<0.05$) in bold

Variable Definitions

%TOC: Percentage of Total Organic Carbon

C/N Ratio: Carbon to Nitrogen Ratio

Geographic Variables

Latitude: Latitude of lake (decimal degrees)

Elevation: Elevation of lake (m)

Distance from Pacific Coast: Distance (km) of lake from the Pacific Coast

Land Use Variables

CA % Water: Catchment area % of water bodies (lakes, reservoirs, rivers, stream, etc.)

CA % Exposed Land: Catchment area % of non-vegetated and non-developed land. Includes: exposed lands, bare soil, snow, glacier, rock, sediments, burned areas, rubble, mines, other naturally occurring non-vegetated surfaces.

CA % Shrubland: Catchment area % of woody vegetation of relatively low height (<2m).

CA % Wetland: Catchment area % of land with a water table near/at/above soil surface for enough time to promote wetland or aquatic processes.

CA % Grassland and Native Grass: Catchment area % of native grasses and other herbaceous vegetation may include some shrubland cover.

CA % Coniferous Forest: Catchment area % of predominately coniferous treed areas.

CA % Deciduous Forest: Catchment area % of predominately deciduous treed areas.

CA % Mixed Forest: Catchment area % of mixed coniferous and deciduous treed areas.

CA % All Agriculture: Catchment area % that combines the categories of agriculture land, perennial cropland (periodically cultivated cropland (e.g., alfalfa and clover)), annual cropland (annually cultivated cropland (e.g., corn), and pasture.

CA % Total Development and Agriculture: Catchment area % of developed land is predominately built-up; including vegetation associated with these cover conditions. This may include road surfaces, railway surfaces, buildings and paved surfaces, urban areas, parks, industrial sites, farmsteads, golf courses, and ski hills. Developed land is combined with the category of agriculture to form this category.

Climatic Variables

MAT: Mean Annual Temperature (ºC)

MWMT: Mean Warmest Month Temperature (ºC)

MCMT: Mean Coldest Month Temperature (ºC)

MAP: Mean Annual Precipitation (mm)

GDD5: Growing Degree-days above 5ºC

SHM: Summer Heat Moisture index (MWMT)/(Mean May-to-September Precipitation/1000)

DDB0: Degree-days Below 0ºC

NFFD: Number of Frost-free Days

FFP: Frost-free Period

Tave_wt: Winter (December - February) Mean Temperature (ºC)

Tave_sp: Spring (March – May) Mean Temperature (ºC)

Tave_sm: Summer (June – August) Mean Temperature (ºC)

Tave_at: Autumn (September – November) Mean Temperature (ºC)

PPT_wt: Winter Precipitation (mm)

PPT_sp: Spring Precipitation (mm)

PPT_sm: Summer Precipitation (mm)

PPT_at: Autumn Precipitation (mm)

Lake Morphometric Variables

LA: Lake Area (ha)

CA: Catchment Area (ha)

CA/LA Ratio: Catchment Area to Lake Area Ratio

MDR: Modified Dynamic Ratio (Sqrt(LA)/Max Depth)

Max Depth: Maximum Depth of lake (m)

LGR: Lake Geometry Ratio (LA^0.25/Max Depth)

B11. Mineralization

Table B10.1. Analysis of TOC MAR (g/m2/yr) data with upper 10cm of sediment removed to address mineralization affects.

Lake	TOC MAR (g/m2/yr) 1830-present	U10 Removed TOC MAR 1830-present	TOC MAR n	U10 Removed TOC MAR n
Anler	71.75	35.64	26	16
Babine	6.41	NA	9	0
Clear	28.37	19.49	38	27
Crandell	27.29	22.20	24	13
Dog	49.08	35.05	36	25
Katherine	54.38	35.63	37	26
Kennedy	1.80	2.03	17	6
Little Tawayik	105.98	103.05	35	26
Long	24.50	26.61	36	26
Marion	21.07	18.48	24	14
McPhee	24.37	22.23	24	13
Moon	72.28	43.75	37	28
Muriel	21.90	16.62	19	14
Quamichan	115.70	85.01	69	58
Roe	42.67	38.76	32	22
Shady	35.79	26.10	23	12
South	34.82	NA	6	0
Stowell	33.56	26.84	19	9

Appendix C. Supplemental material to Chapter 3

C1. ^{210}Pb and ^{14}C dates for Dog and Marion Lake

Table C1.1. ^{210}Pb and ^{14}C dates for Marion Lake

Depth (cm)	Age (cal yr BP)	Standard Deviation (± years)	^{210}Pb or ^{14}C
0	0	0	^{210}Pb
1	1	0	^{210}Pb
4	7	0	^{210}Pb
8	24	2	^{210}Pb
12	61	9	^{210}Pb
16	89	25	^{210}Pb
20	121	206	^{210}Pb
24	134	159	^{210}Pb
86	8118	46	^{14}C
141	10512	47	^{14}C
197	11283	39	^{14}C
210	12592	43	^{14}C

Table C1.2 ^{210}Pb and ^{14}C dates for Dog Lake

Depth (cm)	Age (cal yr BP)	Standard Deviation (± years)	^{210}Pb or ^{14}C
0	4	1	^{210}Pb
3	8	1	^{210}Pb
6	14	1	^{210}Pb
9	20	2	^{210}Pb
12	26	2	^{210}Pb
15	33	2	^{210}Pb
18	41	2	^{210}Pb
21	51	3	^{210}Pb
24	63	4	^{210}Pb
27	76	5	^{210}Pb
30	94	7	^{210}Pb
98	1139	196	^{14}C
194	2812	103	^{14}C
315	6355	115	^{14}C
395	7960	142	^{14}C

Table C1.3. Bacon generated dates for Marion Lake. ^{210}Pb and ^{14}C dates for Marion Lake referenced as tie points from Table C1.1.

Depth	Bacon Age (cal yr BP)	Tie Point Age (cal yr BP)
0	0	0
1	1	1
2	3	
3	5	
4	7	7
5	11	
6	16	
7	20	
8	24	24
9	34	
10	43	
11	53	
12	63	61
13	77	
14	91	
15	106	
16	120	89
17	161	
18	202	
19	246	
20	290	121
21	345	
22	400	
23	454	

24	507	134
25	619	
26	730	
27	849	
28	969	
29	1099	
30	1229	
31	1354	
32	1479	
33	1599	
34	1720	
35	1835	
36	1951	
37	2075	
38	2198	
39	2323	
40	2449	
41	2567	
42	2685	
43	2815	
44	2944	
45	3062	
46	3181	
47	3309	
48	3437	
49	3559	
50	3681	

51	3810	
52	3940	
53	4052	
54	4164	
55	4295	
56	4426	
57	4547	
58	4668	
59	4786	
60	4904	
61	5027	
62	5151	
63	5271	
64	5391	
65	5517	
66	5643	
67	5758	
68	5873	
69	5994	
70	6116	
71	6233	
72	6351	
73	6468	
74	6586	
75	6709	
76	6832	
77	6965	

78	7098	
79	7219	
80	7340	
81	7469	
82	7599	
83	7731	
84	7863	
85	7979	
86	8094	8118
87	8144	
88	8194	
89	8238	
90	8281	
91	8324	
92	8366	
93	8407	
94	8448	
95	8492	
96	8535	
97	8578	
98	8622	
99	8666	
100	8710	
101	8753	
102	8796	
103	8841	
104	8886	

105	8929	
106	8973	
107	9016	
108	9058	
109	9102	
110	9145	
111	9187	
112	9230	
113	9272	
114	9315	
115	9357	
116	9399	
117	9442	
118	9485	
119	9528	
120	9571	
121	9616	
122	9661	
123	9703	
124	9746	
125	9790	
126	9833	
127	9877	
128	9920	
129	9963	
130	10005	
131	10049	

132	10093	
133	10137	
134	10181	
135	10223	
136	10266	
137	10308	
138	10351	
139	10393	
140	10435	
141	10475	10512
142	10515	
143	10547	
144	10578	
145	10608	
146	10639	
147	10671	
148	10702	
149	10734	
150	10765	
151	10797	
152	10828	
153	10859	
154	10889	
155	10920	
156	10952	
157	10983	
158	11014	

159	11047	
160	11079	
161	11111	
162	11143	
163	11174	
164	11206	
165	11237	
166	11268	
167	11300	
168	11332	
169	11363	
170	11394	
171	11426	
172	11457	
173	11489	
174	11520	
175	11552	
176	11584	
177	11615	
178	11646	
179	11678	
180	11710	
181	11741	
182	11771	
183	11803	
184	11834	
185	11865	

186	11896	
187	11927	
188	11958	
189	11989	
190	12021	
191	12060	
192	12100	
193	12148	
194	12195	
195	12244	
196	12293	
197	12341	11283
198	12389	
199	12438	
200	12488	
201	12536	
202	12584	
203	12633	
204		
205		
206		
207		
208		
209		
210		12592

Table C1.3. Bacon generated dates for Dog Lake. ^{210}Pb and ^{14}C dates for Marion Lake referenced as tie points from Table C1.2.

Depth	Bacon Age (cal yrs BP)	Tie Point Age (cal yrs BP)
0	3	4
1	5	
2	6	
3	8	8
4	10	
5	12	
6	14	14
7	16	
8	18	
9	20	20
10	22	
11	24	
12	26	26
13	28	
14	31	
15	33	33
16	36	
17	39	
18	41	41
19	44	
20	48	
21	51	51
22	55	
23	59	

24	63	63
25	67	
26	72	
27	78	76
28	83	
29	90	
30	96	94
31	114	
32	131	
33	148	
34	166	
35	184	
36	201	
37	219	
38	237	
39	254	
40	272	
41	290	
42	307	
43	325	
44	343	
45	361	
46	378	
47	396	
48	414	
49	431	
50	449	

51	466	
52	484	
53	502	
54	519	
55	537	
56	555	
57	573	
58	591	
59	608	
60	626	
61	644	
62	662	
63	679	
64	697	
65	715	
66	732	
67	750	
68	769	
69	786	
70	804	
71	821	
72	839	
73	856	
74	874	
75	891	
76	909	
77	927	

78	945	
79	963	
80	980	
81	997	
82	1015	
83	1033	
84	1050	
85	1068	
86	1086	
87	1104	
88	1121	
89	1139	
90	1157	
91	1175	
92	1193	
93	1210	
94	1228	
95	1245	
96	1263	
97	1281	
98	1299	1139
99	1318	
100	1337	
101	1356	
102	1376	
103	1395	
104	1415	

105	1434	
106	1454	
107	1473	
108	1491	
109	1511	
110	1530	
111	1549	
112	1568	
113	1587	
114	1607	
115	1626	
116	1645	
117	1664	
118	1684	
119	1702	
120	1721	
121	1740	
122	1759	
123	1778	
124	1798	
125	1816	
126	1835	
127	1854	
128	1873	
129	1892	
130	1911	
131	1930	

132	1950	
133	1969	
134	1987	
135	2007	
136	2026	
137	2045	
138	2064	
139	2083	
140	2101	
141	2121	
142	2140	
143	2159	
144	2179	
145	2198	
146	2217	
147	2236	
148	2256	
149	2275	
150	2294	
151	2313	
152	2332	
153	2351	
154	2370	
155	2390	
156	2409	
157	2427	
158	2446	

159	2465	
160	2484	
161	2503	
162	2522	
163	2542	
164	2561	
165	2580	
166	2599	
167	2618	
168	2637	
169	2657	
170	2676	
171	2695	
172	2714	
173	2732	
174	2751	
175	2770	
176	2790	
177	2809	
178	2828	
179	2847	
180	2867	
181	2885	
182	2904	
183	2923	
184	2942	
185	2961	

186	2981	
187	3000	
188	3019	
189	3038	
190	3057	
191	3075	
192	3094	
193	3113	
194	3133	2812
195	3156	
196	3179	
197	3205	
198	3230	
199	3255	
200	3280	
201	3306	
202	3331	
203	3357	
204	3382	
205	3408	
206	3433	
207	3458	
208	3484	
209	3509	
210	3534	
211	3560	
212	3585	

213	3611	
214	3636	
215	3662	
216	3687	
217	3712	
218	3737	
219	3763	
220	3788	
221	3814	
222	3840	
223	3865	
224	3890	
225	3916	
226	3941	
227	3966	
228	3991	
229	4017	
230	4042	
231	4068	
232	4094	
233	4118	
234	4143	
235	4169	
236	4194	
237	4219	
238	4245	
239	4270	

240	4295	
241	4320	
242	4346	
243	4371	
244	4396	
245	4422	
246	4447	
247	4472	
248	4497	
249	4523	
250	4549	
251	4574	
252	4599	
253	4625	
254	4650	
255	4676	
256	4701	
257	4726	
258	4752	
259	4777	
260	4802	
261	4828	
262	4853	
263	4879	
264	4905	
265	4931	
266	4957	

267	4982	
268	5007	
269	5032	
270	5058	
271	5082	
272	5107	
273	5133	
274	5158	
275	5183	
276	5208	
277	5233	
278	5259	
279	5284	
280	5309	
281	5335	
282	5361	
283	5386	
284	5412	
285	5437	
286	5462	
287	5487	
288	5513	
289	5538	
290	5564	
291	5589	
292	5615	
293	5640	

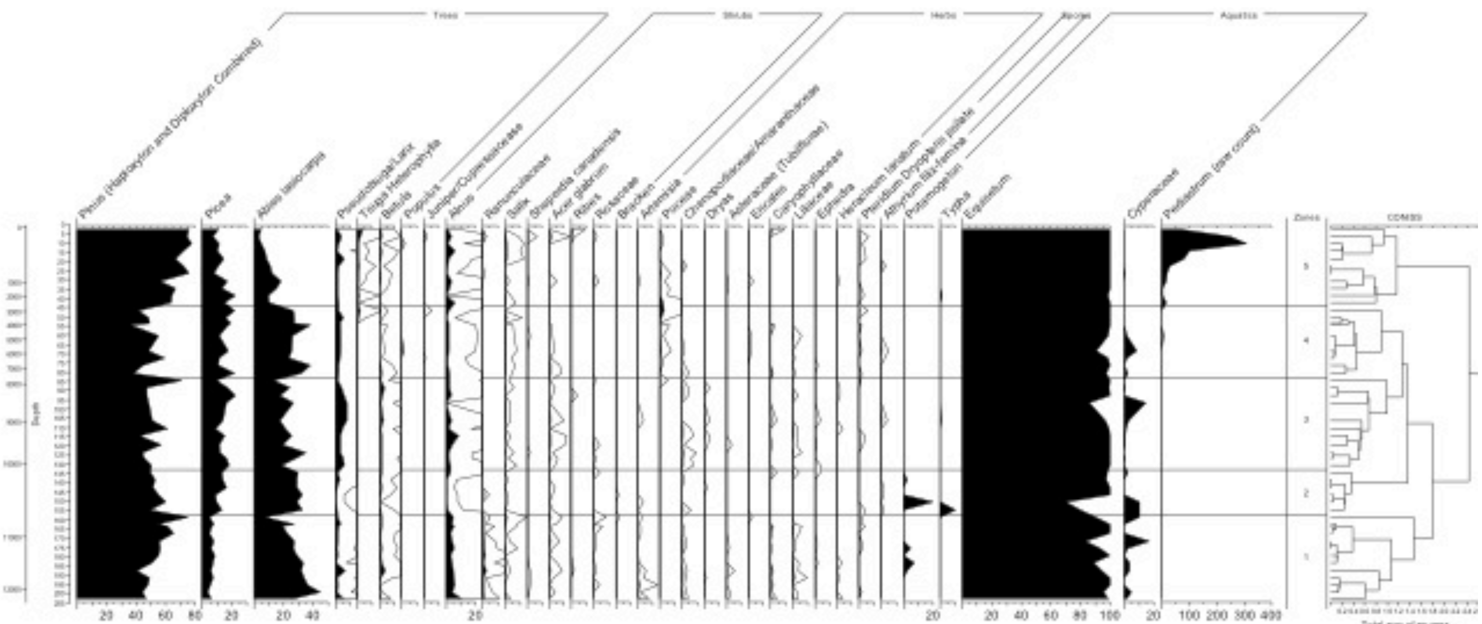
294	5665	
295	5690	
296	5716	
297	5742	
298	5767	
299	5793	
300	5819	
301	5845	
302	5870	
303	5895	
304	5921	
305	5946	
306	5971	
307	5997	
308	6022	
309	6047	
310	6072	
311	6096	
312	6121	
313	6146	
314	6172	
315	6196	6355
316	6221	
317	6242	
318	6263	
319	6284	
320	6305	

321	6326	
322	6347	
323	6368	
324	6389	
325	6410	
326	6432	
327	6452	
328	6473	
329	6494	
330	6515	
331	6537	
332	6558	
333	6579	
334	6600	
335	6621	
336	6642	
337	6663	
338	6685	
339	6706	
340	6727	
341	6748	
342	6769	
343	6791	
344	6812	
345	6833	
346	6854	
347	6875	

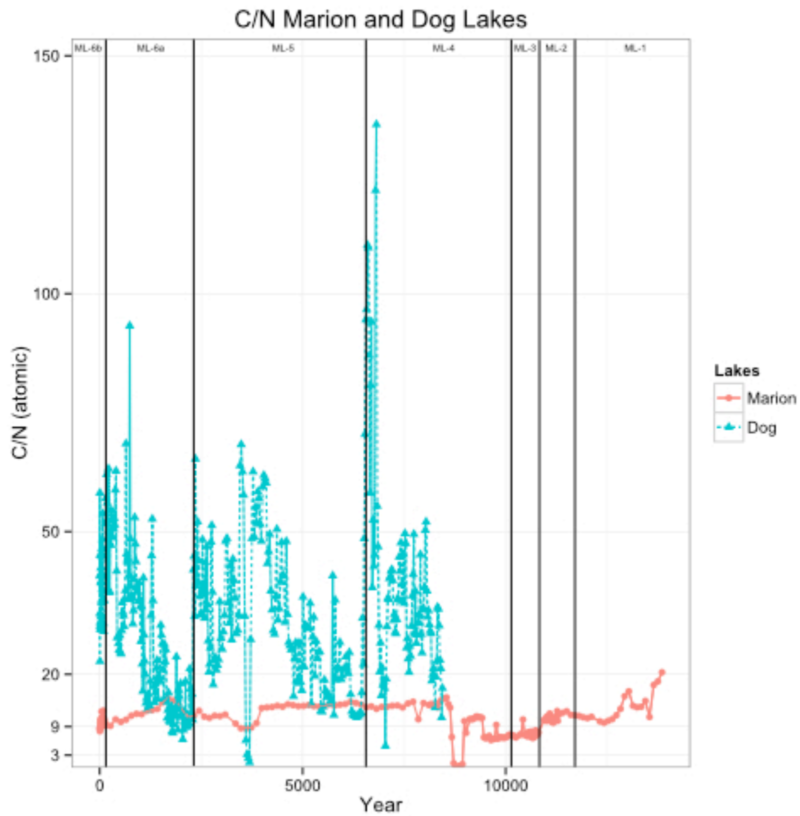
348	6896	
349	6917	
350	6938	
351	6959	
352	6980	
353	7002	
354	7023	
355	7044	
356	7066	
357	7087	
358	7108	
359	7129	
360	7150	
361	7171	
362	7192	
363	7214	
364	7235	
365	7256	
366	7278	
367	7299	
368	7321	
369	7342	
370	7364	
371	7385	
372	7406	
373	7427	
374	7448	

375	7470	
376	7491	
377	7512	
378	7533	
379	7554	
380	7575	
381	7596	
382	7617	
383	7638	
384	7659	
385	7680	
386	7702	
387	7722	
388	7743	
389	7764	
390	7785	
391	7806	
392	7827	
393	7849	
394	7871	
395	7892	7960

C2. Detailed Pollen Diagram for Marion Lake



C3. C/N Ratio of Marion and Dog Lakes



Appendix D. Supplemental material to Chapter 4

D1. Abstract for 2011 BCPARF Session

Title: Starting the Conversation: Climate Change Mitigation in Canada's Protected Areas

Panelists: Thomas Rodengen[1], Wolfgang Haider[1], Marlow Pellatt[2,1], Donald McLennan[2], Eva Riccius[3], Tory Stevens[4]

Panelists' Affiliation:
[1]School of Resource and Environmental Management, Simon Fraser University
[2]Parks Canada
[3]BC Parks
[4]BC Ministry of Environment

Please direct all inquires to tjr3@sfu.ca

Format: Panel Discussion (2 hrs)

With this session we would like to initiate a discussion about the role(s) of protected areas in climate change mitigation, which is an important solution within a larger portfolio of climate change solutions. The session will begin with short background presentations on the current understanding of climate change mitigation from the perspective of the panelists. The subsequent discussion goals are to define climate change mitigation as it relates to protected areas, identify where protected area agencies fit into larger climate change strategies, frame objectives of climate change mitigation in protected areas, and, if time permits, prioritizing climate change management options. Follow up communication will be available with interested participants.

D2. List of questions for semi-structured interviews.

1. *Given Parks Canada's primary mandate for preserving ecological integrity, does Parks Canada have a role to play in contributing to carbon management[1]?*

2. *Given your knowledge, how do Parks Canada's current management activities and programs contribute to carbon management?*

3. *How do XX Park's current management activities and programs contribute to carbon management?*

4. *What new management activities and programs could XX Park do to further contribute to carbon management?*

5. *What specific type of information would help to incorporate carbon management into decisions at XX Park?[2]*

6. *In your opinion, what are the biggest challenges to carbon management and implementation in XX Park?[3]*

7. *Does carbon management fit into any current mandates at XX Park? If yes, what specific mandates?*

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[1] If prompted, carbon management is defined as an activity that protects carbon stocks (articles 3.3 and 3.4 of the Kyoto Protocol). In protecting carbon stocks greenhouse gas emissions are reduced.

[2] If prompted, options might include a carbon map, model results, scorecard/monitoring, etc.

[3] If prompted, options might include, limited resources (e.g., staff and funding), uncertainty in the science of how management activities affect carbon stocks, understanding the various tradeoffs and multiple uses being considered/competing priorities, etc.

D3. Survey launched at 2013 BCPARF

The primary goal of this survey is to investigate how managers and researchers working in protected areas perceive the role of carbon management. This survey is part of a scientific research project and none of the agencies mentioned currently have plans to initiate the activities or scenarios described in this survey.

The survey will take approximately 15 minutes to complete.

To view the privacy policy please click <u>here</u>. By clicking 'BEGIN' you acknowledge that you have read and agree to the privacy policy.

SFU

BEGIN the survey

(•)

1. Which agency do you work for? Please select all that apply

- [x] Parks Canada
- [ ] BC Parks
- [ ] Municipal/Regional Protected Area Agency (e.g., Metro Vancouver)
- [ ] Other *Please specify*

. 2. Which types of ecosystems are represented in your unit's/office's jurisdiction? Please select all that apply

- [x] Terrestrial (Forest, Grassland, and Tundra/Barrens)
- [x] Aquatic (Lakes, Streams/Rivers, Wetlands)
- [x] Coastal/Marine (includes Subtidal)

3. Carbon management refers to any process, activity or mechanism that stores carbon and can reduce greenhouse gas emissions. In your opinion, does your agency have a role in carbon management? Please select one

- (•) Yes
- ( ) No
- ( ) Don't Know/Unsure

4. In your opinion, to what extent do you agree or disagree with each of the following statements. Please choose the response that best describes your opinion

	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree
Carbon management should be a <u>separate ecological integrity</u> measure.	○	○	○	●	○
Carbon management should be a <u>co-benefit</u>, i.e., increasing carbon stores and reducing greenhouse gas emissions should only occur along with activities, processes or mechanisms that further other measures (e.g., biodiversity)	●	○	○	○	○

Imagine that your agency has adopted a new ecological integrity measure for carbon.

The new carbon measure describes any process, activity or mechanism that can store carbon and reduce greenhouse gas emissions.

5. Compared to the new carbon measure, how important is each of these TERRESTRIAL measures listed below? Please choose the response that best describes your opinion

	Unimportant	Of Little Importance	Moderately Important	Important	Very Important	Don't Know
Vegetation Condition -measured by forest community composition, structure, diversity, and primary productivity	○	○	○	○	●	○
Disturbance by Wildfire -measured by area disturbed by fire, condition of remaining forest after a fire, and fire cycle	○	○	○	○	●	○
Disturbance by Prescribed Fire - measured by area burnt versus total area targeted for burning	○	○	○	○	●	○
Invasive Species -measured by non-native flora and fauna presence, distribution, relative abundance, and rates of expansion	○	○	○	○	●	○
Wildlife Population -measured by abundance, birth rate, mortality, species richness, range, and condition	○	○	○	○	●	○
Disturbance by Forest Insects and Disease -measured by insect and disease outbreak, frequency, extent, host species, and age class	○	○	○	○	●	○

6. Compared to the new carbon measure, how important is each of these AQUATIC measures listed below? Please choose the response that best describes your opinion

	Unimportant	Of Little Importance	Moderately Important	Important	Very Important	Don't Know
Water Quality -measured by trophic status	○	○	○	◉	○	○
Fish and Wildlife Population -measured by benthic invertebrate diversity, wildlife abundance, creel census, tagging, and fish counts	○	○	○	◉	○	○
Vegetation Condition -measured by vegetation response to wildlife, primary productivity, and vegetation productivity, macrophyte monitoring, and algal monitoring	○	○	○	◉	○	○
Connectivity of Rivers and Streams - measured by the capacity (full or partial barrier) for fish and terrestrial wildlife passage	○	○	○	◉	○	○
Invasive Species -measured by non-native flora and fauna presence, distribution, relative abundance, and rates of expansion	○	○	○	◉	○	○

7. Compared to the new carbon measure, how important is each of these COASTAL/MARINE measures listed below? Please choose the response that best describes your opinion

	Unimportant	Of Little Importance	Moderately Important	Important	Very Important	Don't Know
Invasive Species -measured by non-native flora and fauna presence, distribution, relative abundance, and rates of expansion	○	○	○	◉	○	○
Erosion and Sediment Transport - measured through beach profiles which include sea level change and storm surge frequency, river and stream output, and eutrophicication	○	○	○	◉	○	○
Fish and Wildlife Population - measured by benthic invertebrate diversity, wildlife abundance, creel census, tagging, and fish counts	○	○	○	◉	○	○
Vegetation Condition -measured by primary productivity (e.g., eelgrass)	○	○	○	◉	○	○

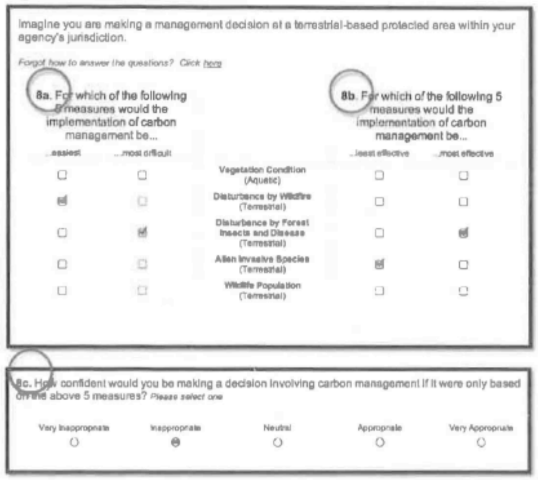
Now you are asked to treat carbon management as a co-benefit.

We will show you several subsets of these measures you just evaluated. There will be a total of 11 subsets of 5 measures at a time. see example below

In each subset please consider questions a, b, and c separately.

Please select only one answer per column for questions a and b.

Example Subset



Imagine you are making a management decision at a terrestrial-based protected area within your agency's jurisdiction.

Forgot how to answer the questions? Click here.

8a. For which of the following 5 measures would the implementation of carbon management be...			**8b.** For which of the following 5 measures would the implementation of carbon management be...	
...easiest	....most difficult		...least effective	...most effective
☐	☐	**Disturbance by Forest Insects and Disease** (Terrestrial)	☐	☐
☐	☐	**Vegetation Condition** (Aquatic)	☐	☐
☐	☐	**Vegetation Condition** (Terrestrial)	☐	☐
☐	☐	**Wildlife Population** (Terrestrial)	☐	☐
☐	☐	**Invasive Species** (Aquatic)	☐	☐

8c. How appropriate would a decision involving carbon management be if it only based on the above 5 measures? Please select one

Very Inappropriate	Inappropriate	Neutral	Appropriate	Very Appropriate
○	○	○	○	○

Imagine you are making a management decision at a terrestrial-based protected area within your agency's jurisdiction.

Forgot how to answer the questions? Click here.

9a. For which of the following 5 measures would the implementation of carbon management be...			**9b.** For which of the following 5 measures would the implementation of carbon management be...	
...easiest	....most difficult		...least effective	...most effective
☐	☐	**Invasive Species** (Terrestrial)	☐	☐
☐	☐	**Vegetation Condition** (Terrestrial)	☐	☐
☐	☐	**Fish and Wildlife Population** (Aquatic)	☐	☐
☐	☐	**Wildlife Population** (Terrestrial)	☐	☐
☐	☐	**Disturbance by Forest Insects and Disease** (Terrestrial)	☐	☐

9c. How appropriate would a decision involving carbon management be if it only based on the above 5 measures? Please select one

Very Inappropriate	Inappropriate	Neutral	Appropriate	Very Appropriate
○	○	○	○	○

Imagine you are making a management decision at a terrestrial-based protected area within your agency's jurisdiction.

Forgot how to answer the questions? Click here.

10a. For which of the following 5 measures would the implementation of carbon management be...			**10b.** For which of the following 5 measures would the implementation of carbon management be...	
...easiest	....most difficult		...least effective	...most effective
☐	☐	**Vegetation Condition** (Aquatic)	☐	☐
☐	☐	**Fish and Wildlife Population** (Aquatic)	☐	☐
☐	☐	**Disturbance by Prescribed Fire** (Terrestrial)	☐	☐
☐	☐	**Wildlife Population** (Terrestrial)	☐	☐
☐	☐	**Water Quality** (Aquatic)	☐	☐

10c. How appropriate would a decision involving carbon management be if it only based on the above 5 measures? Please select one

Very Inappropriate	Inappropriate	Neutral	Appropriate	Very Appropriate
○	○	○	○	○

Imagine you are making a management decision at a terrestrial-based protected area within your agency's jurisdiction.

Forgot how to answer the questions? Click here.

11a. For which of the following 5 measures would the implementation of carbon management be...			**11b.** For which of the following 5 measures would the implementation of carbon management be...	
...easiest	....most difficult		...least effective	...most effective
☐	☐	**Invasive Species** (Terrestrial)	☐	☐
☐	☐	**Disturbance by Prescribed Fire** (Terrestrial)	☐	☐
☐	☐	**Water Quality** (Aquatic)	☐	☐
☐	☐	**Vegetation Condition** (Terrestrial)	☐	☐
☐	☐	**Disturbance by Wildfire** (Terrestrial)	☐	☐

11c. How appropriate would a decision involving carbon management be if it only based on the above 5 measures? Please select one

Very Inappropriate	Inappropriate	Neutral	Appropriate	Very Appropriate
○	○	○	○	○

Imagine you are making a management decision at a terrestrial-based protected area within your agency's jurisdiction.

Forgot how to answer the questions? Click here.

12a. For which of the following 5 measures would the implementation of carbon management be...			**12b.** For which of the following 5 measures would the implementation of carbon management be...	
...easiest	....most difficult		...least effective	...most effective
☐	☐	**Disturbance by Prescribed Fire** (Terrestrial)	☐	☐

☐	☐	**Vegetation Condition** (Terrestrial)	☐	☐
☐	☐	**Fish and Wildlife Population** (Aquatic)	☐	☐
☐	☐	**Connectivity of Rivers and Streams** (Aquatic)	☐	☐
☐	☐	**Invasive Species** (Aquatic)	☐	☐

12c. How appropriate would a decision involving carbon management be if it only based on the above 5 measures? Please select one

Very Inappropriate	Inappropriate	Neutral	Appropriate	Very Appropriate
○	○	○	○	○

Imagine you are making a management decision at a terrestrial-based protected area within your agency's jurisdiction.

Forgot how to answer the questions? Click here.

13a. For which of the following 5 measures would the implementation of carbon management be...			**13b.** For which of the following 5 measures would the implementation of carbon management be...	
...easiest	....most difficult		...least effective	...most effective
☐	☐	**Vegetation Condition** (Terrestrial)	☐	☐
☐	☐	**Water Quality** (Aquatic)	☐	☐
☐	☐	**Connectivity of Rivers and Streams** (Aquatic)	☐	☐
☐	☐	**Vegetation Condition** (Aquatic)	☐	☐
☐	☐	**Disturbance by Forest Insects and Disease** (Terrestrial)	☐	☐

13c. How appropriate would a decision involving carbon management be if it only based on the above 5 measures? Please select one

Very Inappropriate	Inappropriate	Neutral	Appropriate	Very Appropriate
○	○	○	○	○

Imagine you are making a management decision at a terrestrial-based protected area within your agency's jurisdiction.

Forgot how to answer the questions? Click here.

14a. For which of the following 5 measures would the implementation of carbon management be...			14b. For which of the following 5 measures would the implementation of carbon management be...	
...easiest	....most difficult		...least effective	...most effective
☐	☐	**Disturbance by Forest Insects and Disease** (Terrestrial)	☐	☐
☐	☐	**Disturbance by Prescribed Fire** (Terrestrial)	☐	☐
☐	☐	**Invasive Species** (Terrestrial)	☐	☐
☐	☐	**Vegetation Condition** (Aquatic)	☐	☐
☐	☐	**Invasive Species** (Aquatic)	☐	☐

14c. How appropriate would a decision involving carbon management be if it only based on the above 5 measures? Please select one

Very Inappropriate	Inappropriate	Neutral	Appropriate	Very Appropriate
○	○	○	○	○

Imagine you are making a management decision at a terrestrial-based protected area within your agency's jurisdiction.

Forgot how to answer the questions? Click here.

15a. For which of the following 5 measures would the implementation of carbon management be...			15b. For which of the following 5 measures would the implementation of carbon management be...	
...easiest	....most difficult		...least effective	...most effective
☐	☐	**Invasive Species** (Aquatic)	☐	☐
☐	☐	**Water Quality** (Aquatic)	☐	☐
☐	☐	**Disturbance by Forest Insects and Disease** (Terrestrial)	☐	☐
☐	☐	**Disturbance by Wildfire** (Terrestrial)	☐	☐
☐	☐	**Fish and Wildlife Population** (Aquatic)	☐	☐

15c. How appropriate would a decision involving carbon management be if it only based on the above 5 measures? Please select one

Very Inappropriate	Inappropriate	Neutral	Appropriate	Very Appropriate
○	○	○	○	○

Imagine you are making a management decision at a terrestrial-based protected area within your agency's jurisdiction.

Forgot how to answer the questions? Click here.

16a. For which of the following 5 measures would the implementation of carbon management be...			**16b.** For which of the following 5 measures would the implementation of carbon management be...	
...easiest	....most difficult		...least effective	...most effective
☐	☐	**Invasive Species** (Terrestrial)	☐	☐
☐	☐	**Connectivity of Rivers and Streams** (Aquatic)	☐	☐
☐	☐	**Fish and Wildlife Population** (Aquatic)	☐	☐
☐	☐	**Vegetation Condition** (Aquatic)	☐	☐
☐	☐	**Fish and Wildlife Population** (Aquatic)	☐	☐

16c. How appropriate would a decision involving carbon management be if it only based on the above 5 measures? Please select one

Very Inappropriate	Inappropriate	Neutral	Appropriate	Very Appropriate
○	○	○	○	○

Imagine you are making a management decision at a terrestrial-based protected area within your agency's jurisdiction.

Forgot how to answer the questions? Click here.

17a. For which of the following 5 measures would the implementation of carbon management be...			**17b.** For which of the following 5 measures would the implementation of carbon management be...	
...easiest	....most difficult		...least effective	...most effective
☐	☐	**Invasive Species** (Aquatic)	☐	☐
☐	☐	**Invasive Species** (Terrestrial)	☐	☐
☐	☐	**Water Quality** (Aquatic)	☐	☐

☐	☐	**Wildlife Population** (Terrestrial)	☐	☐
☐	☐	**Connectivity of Rivers and Streams** (Aquatics)	☐	☐

17c. How appropriate would a decision involving carbon management be if it only based on the above 5 measures? Please select one

Very Inappropriate	Inappropriate	Neutral	Appropriate	Very Appropriate
○	○	○	○	○

Imagine you are making a management decision at a terrestrial-based protected area within your agency's jurisdiction.

Forgot how to answer the questions? Click here.

18a. For which of the following 5 measures would the implementation of carbon management be...			**18b.** For which of the following 5 measures would the implementation of carbon management be...	
...easiest	....most difficult		...least effective	...most effective
☐	☐	**Wildlife Population** (Terrestrial)	☐	☐
☐	☐	**Disturbance by Prescribed Fire** (Terrestrial)	☐	☐
☐	☐	**Connectivity of Rivers and Streams** (Aquatic)	☐	☐
☐	☐	**Disturbance by Wildfire** (Terrestrial)	☐	☐
☐	☐	**Disturbance by Forest Insects and Disease** (Terrestrial)	☐	☐

18c. How appropriate would a decision involving carbon management be if it only based on the above 5 measures? Please select one

Very Inappropriate	Inappropriate	Neutral	Appropriate	Very Appropriate
○	○	○	○	○