

RECENT PALEOENVIRONMENTAL CHANGES RECORDED IN THREE NON-
ANADROMOUS LAKES IN SOUTHWEST ALASKA: EFFECTS OF CLIMATIC
AND VEGETATION DYNAMICS ON LAKE PRODUCTIVITY

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Abstract

Paleolimnological investigations, landscape analyses, and repeat photographs were used to provide a long-term view (~150 yrs. BP to present) of nutrient dynamics and lake ecosystem change in southwest Alaska. Recent major changes in lake ecology and landscape are generally attributed to climate warming since the end of the Little Ice Age and to the recent warm phase of the Pacific Decadal Oscillation. Disturbances driven by climate, glacial retreat, and volcanism also contribute to changes in aquatic-driven processes. Sediment cores reveal a complex yet progressive set of changes that are expressed in the study lakes. Changes in the biogeochemical proxies began in the mid-19th to early-20th century, but major inflections occurred significantly later, most pronounced after 1950. Among these changes are increases in biogenic opal, and indicators of enhanced C and N cycling. These systems act as integrators of climatic, terrestrial, and aquatic processes without additions of marine-derived nutrient subsidies from spawning salmon and thus allow us to isolate and identify factors (e.g. productivity, spawning and rearing success of salmonids, or terrestrial nutrient inputs) important for interpreting sediment records in anadromous systems.

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CHAPTER 1

1.1 General Introduction

Watersheds of Bristol Bay, Alaska, support the vital resources necessary for the spawning and rearing of sockeye salmon (Donaldson 1967). About 50% of sockeye salmon caught annually originate in Bristol Bay watersheds, representing 33% of the entire U.S. salmon catch, and 16% of the total world salmon catch. In 1980, President Carter within the Alaska National Interest Lands Conservation Act set aside a portion of the greater Bristol Bay watershed lands, now Lake Clark (LACL) and Katmai (KATM) National Parks and Preserves in part to "...protect the watershed necessary for the perpetuation of the red [sockeye] salmon fishery in Bristol Bay..." and to "...protect habitats for populations of fish and wildlife..."(ANILCA 1980).

Many of the issues addressed in this study center around the lack of basic information (i.e. baseline data) that would better assist the National Park Service's (NPS) current understanding and management of the aquatic and terrestrial resources within these lands, which are part of the greater Southwest Alaska Network of National Parks (SWAN). The SWAN includes Katmai, Lake Clark, Aniakchak and Kenai Fjords National Parks and Preserves. Increasing pressure from resource development, subsistence, commercial, and recreational use in addition to human-altered atmospheric changes and deposition has the potential to alter the health and function of these ecosystems. Moreover, potential changes in the use of lands conterminous to watersheds pose a very real risk to the aquatic resources of the SWAN and the valuable fisheries of the region.

The absence of long-term climatic and environmental monitoring data within the SWAN generates the need for paleoecological studies where proxy data from the sediments of lakes and ponds can be used to lengthen baseline data sets and provide long-term perspectives of environmental change. In this thesis, I explored the use of carbon and nitrogen isotopes ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$), total phosphorus, and biogenic opal as proxy indicators of lake production in Southwest Alaska lakes. Stable isotope data from three ^{210}Pb -dated sediment cores were compared stratigraphically with established proxies for historical trophic state (e.g. biogenic opal, and mass ratios of C/N). Furthermore, we examined the vegetation history; (1) qualitatively by examining repeat photography spanning the 20th century; (2) quantitatively by determining the palynological stratigraphy in sediment cores; and (3) using digital datasets created from extensive NPS vegetation inventory and monitoring. In order to more fully assess the watershed components, salmon history, and environmental change within the boundaries of LACL and KATM Parks it is imperative to establish a baseline for natural systems where salmon are not present (i.e. non-anadromous lakes). This will provide a better understanding of how the biogeochemical signatures in various ecosystems, with differing watershed characteristics, respond to natural disturbances, vegetation distribution, and the impending influences of climate change on long and short-time scales.

1.2 Previous Research / Background

1.2.1 Terrestrial Ecosystem Response to Climate and Environmental Change

In northern or boreal regions, the ecological effects of climate change or more specifically warming are predicted to include: general tree line advance in both elevation and latitude, the retreat of glaciers and colonization of formerly glaciated lands, and the transitions in tree species and ecotypes (ACIA 2004; IPCC 2007). Terrestrial vegetation type and distribution on the landscape are potentially important drivers influencing lake productivity (Engstrom and others 2000). Consequently, disturbance (e.g. fire) or climate-driven landscape changes (e.g. glacial advance/retreat) that influence plant community composition or species abundance may drive changes in nutrient acquisition, retention, or loss at the watershed scale (Stottlemyer 1992; Compton and others 2003). Understanding the role of watershed biogeochemical processes in global element cycling is becoming increasingly important as average temperatures increase (IPCC 2007) and much attention has been focused on elemental fluxes between the terrestrial ecosystem and atmosphere. However, considerably less is known about the flux of carbon (C), nitrogen (N) and other major solutes from watersheds to adjacent water bodies. Climate or disturbance-induced hydrologic changes could affect an array of factors that, in turn, control overall elemental fluxes in lake systems. These include: soil water storage, evapotranspiration due to large-scale vegetation changes, and the timing and contribution of runoff from snow melt water and precipitation (Sturm and others 2005). Certain elements may increase in concentration along flow-paths due to leaching from soils or weathering of bedrock whereas other elements may decrease along the same flow path

due to adsorption into soils and uptake by vegetation (Rhoades and others 2001; Compton and others 2003; Fritz and others 2004; Engstrom and Fritz 2006).

The nitrogen (N) and carbon (C) cycles are intimately connected because of the energy necessary to acquire nitrogen and other nutrients from C sources (Binkley 1986). Therefore, shifts in global climate and atmospheric composition are likely to be manifested in the N-cycle (Stottlemeyer 1992). Moreover, a warmer climate has been linked to increasing shrub abundance in northern Alaska (Sturm and Racine 2001; Tape and others 2006). In south-central Alaska a multiple-scale analysis by Klein and others (2005), documents extensive changes across the landscape of the Kenai Peninsula Lowlands since 1950. Landscape changes there include a substantial increase in woody cover, shrinkage of water bodies and vegetation expansion into pre-existing lakebeds. These types of vegetation expansion will ultimately result in an increase in the amount of C stored in the region (ACIA 2004; IPCC 2007). The expansion of vegetation may also play an integral role in the energy budget and hydrologic cycle as the land surface albedo is changed and as snow storage increases via vegetation trapping (Sturm and others 2005).

Climate-driven landscape change, coupled with the linkage between the aquatic and terrestrial ecosystem, is also significant in an historical / paleoenvironmental context. Pollen records show that early Holocene warming was accompanied by establishment and substantial increase in alder shrubs in Alaska and Canada between circa 9,000 and 8,000 years BP (calibrated ^{14}C years before present) (Anderson and Brubaker 1994; Cwynar and Spear 1995; Hu and others 2001; Brubaker and others 2001). Of particular

significance to the study presented here, is the multiple proxy paleolimnological and biogeochemical data collected from lake-bottom sediment cores from Grandfather Lake in southwest Alaska. The Grandfather Lake record depicts an overall increase in lake productivity corresponding with rapid alder (*Alnus*) expansion circa 8,000 years BP (Hu and others 2001). This supports the hypothesis that increased aquatic productivity can occur as a result of nutrient input resulting from vegetation establishment, specifically the expansion of *Alnus* across the landscape.

A study in northern Alaska along the Colville River (Tape and others 2006) showed that both larger and smaller shrub species have increased in size, abundance and extent over the last 50 years. Several ongoing scientific investigations and repeat photography (Jorgenson and others 2004; Jorgenson *unpublished*) throughout the more southerly subarctic SWAN region indicate that there are areas of shrub expansion occurring today in these National Parks. The factors driving this observed rapid change in vegetation are postulated to be consequences of post-Little Ice Age (LIA) warming (e.g. landscape disturbance from glacial recession) combined with anthropogenic-related climate change. In addition, the effect of volcanic ash deposition across the landscape from several active volcanoes in the region remains unclear (Poe 1980; Stottlemyer 1990). All of these factors have the potential to impact terrestrial and aquatic biogeochemical cycles and ecosystems at different spatial and temporal scales.

The high densities of *Alnus* (*A. fruticosa* and *A. tenuifolia*), characteristic of the region today, are attributed to post-LIA glacial retreat. Abandoned moraines and fresh scree slopes allowed the establishment and expansion of these nitrogen-fixing (N₂-fixing)

alder shrub thickets on mountain slopes and high valleys. *Alnus* have reportedly expanded in riparian and forested areas as well (pers. com. John Branson).

Although somewhat anecdotal, the observations of increased alder proliferation as well as willow, and birch species in just the last half century warrants further investigation of the landscape changes and the impact this may have on the vegetation community and adjacent water bodies.

The present distributions of plant communities, ecological boundaries, and transition zones have been mapped in SWAN by the NPS. These land cover maps allow us to quantify the present landscape, and establish a baseline to which future studies can be compared. Together, historical photographs compared with current vegetation allow us to document past change in plant distribution regionally throughout the SWAN. Repeat photography, in a few cases spanning greater than a century, provide convincing qualitative evidence of landscape and vegetation change in the SWAN (Jorgenson *unpublished*). These photographs clearly document that a general trend of glacial recession; post-fire increase in terrestrial primary production; and tree and shrub expansion has occurred in the region (Jorgenson *unpublished*). The existing set of photographs also chronicles periodic disturbances from volcanism amongst other natural changes.

1.2.2 Aquatic Ecosystem Response to Climate and Environmental Change

In northern aquatic ecosystems, both *in situ* primary production within a lake and imported organic matter from surrounding terrestrial ecosystems can be important sources of energy to fuel aquatic food chains. In fact, the magnitude and quality of

terrestrial-derived nutrients (C, N, P) exported to aquatic systems are recognized as the primary drivers of aquatic ecosystem productivity and trophic structure (Karlsson and others 2005). Integrated research linking terrestrial and aquatic interactions is needed in order to understand the impacts of environmental change, specifically at the more sensitive high latitudes.

The impacts of recent short-term climatic oscillations such as the Pacific Decadal Oscillation (PDO) and El Nino Southern Oscillation (ENSO) have been reported around the Gulf of Alaska and other regions near SWAN (Mantua and others 1997; Wiles and others 1998). The PDO alternates between El Nino-like (moderately warmer-than-normal sea surface temperatures) or La Nina-like (moderately cooler-than-normal sea-surface temperatures) patterns of Pacific climatic variability that appear to persist for ~20–30 years (Mantua and others 1997). The climatic fingerprints of the PDO are most visible in the northeast Pacific/North American sector. Several independent studies found evidence for just two full PDO cycles in the past century: ‘cool’ (negative) PDO regimes prevailed from 1890 to 1924 and again from 1947–76, while ‘warm’ (positive) PDO regimes dominated from 1925–46 and from 1977 through (at least) the mid- 1990’s. Some evidence points to the 1976–1977 PDO shift from the cool (negative) to the warm (positive) phases (Mantua and others 1997) as the largest such shift in the historical records. While the shift in PDO between positive and negative phases has been suggested to have some control on salmon productivity in the marine environment (Mantua and others 1997; Finney and others 2000, 2002), the PDO variability is strongly expressed in the historical climate records of temperature and precipitation throughout

southwestern Alaska (Western Regional Climate Center 2008). Changes in temperature or precipitation may in turn drive changes in lake thermal conditions, nutrient delivery and uptake, glacial retreat or advance, water clarity, all of which may influence the availability of nutrients and the physical conditions of a lake.

In other lakes of North America, changes in temperature and other ecological variables have been linked to the ENSO index and the PDO index (e.g. Lake Washington, WA; Lake Tahoe and Castle Lake, CA; Karluk Lake, AK; Hallet Lake, AK) (Finney and others 2000; Park and others 2004; McKay and others 2008). Possible evidence of PDO influence in SWAN may be observed in glacier response. The termini of most glaciers in the Tlikakila River Basin at the northern extent of LACL have retreated between 1957 to and the present (Brabets 2002). Loss in volume of the three main glaciers in the basin (Tanaina, Glacier Fork, and North Fork) ranged from 1.7×10^9 to 6.1×10^9 m³ from 1957–2001. The retreat and thinning of the glaciers is at least partially attributed to the positive shift in the Pacific Decadal Oscillation (PDO) index from 1977 to 1998 (Brabets 2002).

1.2.3 Salmon-Derived Nutrients vs. Terrestrial Derived Nutrients

The park units within the SWAN, Lake Clark in particular, were founded partially with the mission to protect the aquatic habitat that is so vital to the Bristol Bay sockeye salmon. As mentioned above, while many researchers have studied and recognized the importance of salmon inputs to the nitrogen and phosphorus budgets of their natal streams and lakes, few studies have incorporated landscape factors such as vegetation cover and watershed characteristics that also influence water chemistry. This study

focuses on the linkages between terrestrial landscape and non-anadromous lakes in order to better understand nutrient dynamics in lakes that are not influenced by returning salmon. Our investigation into nitrogen balance and sources in non-anadromous lakes will aid in understanding the influence and record of salmon abundance in anadromous lakes.

Although recent studies have increased our understanding of the linkages between Salmon-Derived Nutrients (SDN) and the terrestrial and aquatic communities which rely on them, many questions remain regarding nutrient inputs from the terrestrial ecosystem (Kline and others 1993; Ben-David and others 1997; Finney and others 2000; Helfield and Naiman 2001; Gende and others 2002; Helfield and Naiman 2002; Naiman and others 2002; Bartz and Naiman 2005; Schindler and others 2005). Specifically, it has been suggested that salmon may be a minor source of nitrogen entering riparian and aquatic ecosystems in watersheds where *Alnus* dominate riparian areas and hill slopes (O’Keefe and Edwards 2002). It has also been observed in many studies that the relative importance of SDN between sockeye nursery lakes and thus the productivity of some systems may be less impacted by changes in SDN loading (e.g. Finney and others 2000, 2002; Gregory-Eaves and others 2003, 2004; Schindler and others 2003; Finney 2006). This is postulated to be the situation for the large salmon lakes that feed Bristol Bay, where SDNs are a low proportion of total nutrient input in comparison to input from their watersheds (Finney and others 2000). In other cases, declining salmonid returns have reduced inputs of SDN in Pacific watersheds upward of an order of magnitude and nitrogen isotopes ($\delta^{15}\text{N}$) have been used successfully to reconstruct historical changes in

salmon abundance (Finney and others 2000; Gregory-Eaves and others 2003). Recently, increased awareness and attention have been placed on the need to assess the implications of both climatic change and altered nutrient cycles in determining management strategies for Pacific salmon stocks.

1.2.4 Terrestrial and Aquatic Environments Recorded in Lake Sediments

Terrestrial input such as sediments, pollen, volcanic ash, and plant fragments are preserved in lake bottom sediments. The links between terrestrial ecosystems and lake nutrient dynamics can be observed through the collection and analysis of lake sediments. Likewise, the contemporaneous lacustrine deposition of diatoms and other geochemical and isotopic proxies can record lake nutrient, temperature, and chemical conditions (Smol and Cumming 2000).

Both anadromous and non-anadromous lakes within the Park (LACL and KATM) boundaries lack long-term limnological data making it difficult to ascertain their baseline nutrient status and primary productivity. Despite a few baseline studies (Goldman 1960; Russell 1980; Stottlemeyer and Chamberlain 1987; Brabets 2002; Wilkens 2002) the absence of long-term climatic and environmental monitoring data within the SWAN generates the need for paleoecological studies. Proxy data from the sediments of lakes and ponds can be used to lengthen baseline data sets and provide long-term perspectives of environmental change.

The study of historically recent (100- 200 years BP) sediments in natural lake systems is a valuable tool for assessing regional climate, atmospheric, terrestrial, and aquatic ecosystem changes (see Finney and others 2000; Smol and others 2005; Wolfe

and others 2006; Engstrom and Fritz 2006). With the lack of continuous long-term climatic and environmental monitoring data over the last few centuries (especially in sparsely populated areas like Alaska), proxy data from lake sediments may provide the only historical record of environmental change (Smol and others 2005). These recent historical paleoenvironmental records create an opportunity for comparison to longer paleoenvironmental (e.g. sediment, ice, and tree) records while at the same time developing a baseline for modern studies.

The main objectives of this study were to (1) establish baseline data to assist in inventory and future monitoring efforts, and also (2) gain a better understanding of the longer-term trajectory in SWAN lakes by reconstructing past lake changes, and (3) gain insight of external and internal factors driving change and/or potential responses to change. This was accomplished by measuring a suite of geochemical, isotopic and ecological proxies in dated sediment cores. The rationale behind these measurements is briefly described below.

1.3 Paleoenvironmental Reconstruction

Analyses of lake sediments can provide proxy records of environmental change through time. The following is a review of the origin and determination of different proxy data that have been analyzed in the SWAN lake cores. Detailed methods of laboratory analysis are described in the Methods section.

1.3.1 Pollen / Paleoecology

The study of pollen assemblages recorded in lake sediments is one of the most widely used tools for reconstructing past environmental changes. In fact, defining patterns of vegetation change through time and at different spatial scales has become critical in determining the primary factors and driving forces behind vegetation change (Bartlein and Edwards 1998). Recent studies show significant spatial and temporal variability in Holocene vegetation across Southwest Alaska (Brubaker and others 2001, Hu and others 2001, Heiser and Bigelow *unpublished*)

Pollen records collected from Grandfather and Ongivinuk lakes illustrate the general vegetation history of the northern Bristol Bay region (Anderson and Brubaker 1994). Studies of vegetation change are limited in the SWAN with the exception of two pollen records obtained from Idavain and Snipe Lakes in KATM and LACL, respectively (Brubaker and others 2001).

In this study we focused on the pollen history of the last 150 years. We chose watersheds that differed in geography and vegetation type, and were therefore able to evaluate the significance of vegetation distribution, and recent change occurring in local watersheds over this time. The value of integrating the study of multiple short pollen cores with other biogeochemical proxy is two fold. First, short pollen records located in varied but defined ecotypes provide necessary data that improve our understanding of how local dynamics operate under regional climatic and atmospheric changes. Second, comparison of last-century high-resolution pollen records with historical photographs and

land cover mapping products may prove to be a useful method for lengthening the historical record of vegetation dynamics on the landscape.

1.3.2 Biogenic Opal

Siliceous microfossils, particularly diatoms, are commonly used as proxies in paleoecological studies related to eutrophication of surface waters and hydrologic and climate change on a regional scale. The abundance of Biogenic Opal (BSi) has been used for interpreting sediment source areas, sedimentation processes, and paleoclimate (Leinen and others 1986). Biogenic Opal content is a chemical measure of amorphous silica of sediments and is a proxy of diatom abundance (Conley and others 2001). Wet chemical digestion techniques provide a reasonable estimate of the BSi content of sediments (Conley 1988).

Diatoms are commonly the dominant primary producers in temperate and boreal lakes (Wetzel 2001). Productivity of diatoms in the water column is often proportional to their deposition in sediments, and will ultimately affect the abundance of biogenic opal recorded in lake sediment layers through (Conley and Schelske 1993). Therefore, sedimentary BSi content reflects the abundance of the remains of diatoms, and is used as a proxy for aquatic productivity (Conley and Schelske 1993).

1.3.3 Stable Isotopes ($\delta^{15}\text{N}$ and $\delta^{13}\text{C}$)

Many of the SWAN lakes occupy deep, glacially carved lakes that still receive heavy loads of sediment from braided streams and alpine glaciers. Paleoenvironmental investigations in these deep, glacially influenced oligotrophic systems create a unique

challenge because the organic content of the sediments is very low ($< 0.5\%$ N and $<1\%$ C). In fact, this situation often tests the limits of analytical techniques and instrumentation. Nevertheless, the organic matter that is preserved retains its original source signature and reflects the past environmental conditions occurring in the watershed at the time of deposition (Meyers 1994; Gälman and others 2008).

The differential rate of uptake of stable chemical isotopes results in different isotopic composition of matter. Because the isotopes are stable and will not decay over time, the isotopic composition can be used as a natural chemical marker to trace ecological processes and assess fluxes in organisms, communities, and ecosystems (Peterson and Fry 1987). An understanding of nitrogen uptake, and response of phytoplankton to nutrient changes can aid in interpreting lake response to environmental change (Smol 2001). Discrimination against the heavier ^{15}N isotope, during uptake of inorganic nitrogen, is reduced as plant demand for nitrogen increases relative to nitrogen supply (Peterson and Fry 1987; Evans 2001). In other words, when nitrogen in the lake is in limited supply, less fractionation might be expected because the demand for the resource makes organisms less discriminatory. Jones and others (2004) applied this concept to upland lakes by measuring nitrogen isotope ratios of surface sediments, epilithic biofilm, and aquatic macrophytes to evaluate lake nutrient status. Their results suggest that the sediment can be viewed as a cumulative and integrated response of spatial, temporal and functional variation in nutrient conditions. The $\delta^{15}\text{N}$ ratio can also reflect nutrient sources, as shown in the case of anadromous systems where transport of

marine (^{15}N enriched) SDN is reflected in higher ratios ($^{15}\text{N}/^{14}\text{N}$) (Finney and others 2000).

Total organic carbon (TOC) in lake sediments can be composed of a mixture of autochthonous and allochthonous matter. Assimilation of CO_2 by algae in lakes results in a fractionation of the stable carbon isotope ratio $^{13}\text{C}/^{12}\text{C}$ ($\delta^{13}\text{C}$) of about 20‰ (Hecky and Hesslein 1995). The $\delta^{13}\text{C}$ decreases more during assimilation by algae when productivity is low and CO_2 is abundant in water. Differences in phytoplankton ^{13}C are strongly influenced by their growth rate and dissolved CO_2 concentrations (Laws and others 1997). Thus $\delta^{13}\text{C}$ is a commonly used proxy for inferring aquatic productivity trends in lakes. Phytoplankton $\delta^{13}\text{C}$ values can have a wide range (-42‰ to -18‰) relative to that of high-latitude terrestrial plants (-29‰ to -26‰) (Dean and Stuiver 1993). Due to the overlap and wide range of aquatic and terrestrial end members it is necessary to investigate multiple proxy records (e.g. $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, C/N, BSi) to determine the sources of organic matter and the overall trajectory of primary production overtime.

1.3.4 Mass Ratios of Carbon to Nitrogen (C/N)

To identify the different sources of organic matter in lake sediments the $\text{C}_{\text{org}}/\text{N}_{\text{org}}$ ratios (mass or molar) are compared to each other (Meyers 2003). Algae and phytoplankton have high protein content, lack cellulose, and have low mass ratios of C/N (4–12). On the other hand, terrestrial plants have high mass ratios of C/N (≥ 20) because of their low protein content and abundance of cellulose (Meyers 1994). Thus, increases in mass ratios of C/N within sediment stratigraphy generally indicate sediments received

a high proportion of terrestrial organic matter. In contrast, a decrease in mass ratios of C/N has been used to identify periods when lake sediments receive a higher proportion of algal matter from in-lake (autochthonous) production.

1.3.5 Total Phosphorous

Phosphorus (P) may enter a water body through inflow, precipitation, dry fallout, and diffusion from sediments, and it may be removed by sedimentation or outflow. Lake productivity, particularly algal growth in lakes, has been widely regarded as being principally phosphorus limited (Dillon and Rigler 1974; Vollenweider 1976). It is becoming increasingly common for investigators to find lakes that are primarily N-limited or co-limited with by both N and P (Goldman 1960; Carvalho 1994; Maberly and others 2002; Wilkens 2002). Of particular interest to our study region, N and or P were found to be the limiting nutrient for algal growth at different sampling periods of the growing season in both Lake Clark and one of its major upstream water sources Lake Kontrashibuna (Wilkens 2002). Nitrogen concentrations were shown to increase near the outlet of the Tlikakila River in Lake Clark and postulated to be a function of the abundance of *Alnus* within the watershed (Brabets 2002). Nitrate (NO_3^-) was found to be the most common nutrient limiting primary production in Lake Clark (Wilkens 2002). In Lake Clark phosphate (PO_4^-) was found to also stimulate productivity, especially at lower lake stations.

Goldman (1960) found that the cation magnesium was the most limiting factor for phytoplankton production in two KATM lakes, Naknek and Brooks Lakes, and Becharof Lake further south. During July and August it was shown through both culture and in-

situ experiments that nitrate deficiency was limiting the primary production of the plankton. Although phosphorus additions stimulated photosynthesis it was not as critical in these lakes as magnesium or nitrate until mid-August when other factors such as length of daylight also began to influence production.

Sub-arctic oligotrophic lakes are subject to N limitation, since they generally lack the high nitrogen loadings associated with anthropogenic sources. However, the presence of N₂-fixing *Alnus* in riparian corridors and hillsides may augment N sources where they are present on the landscape (Engstrom and Fritz 2006; Rhodes and others 2001; Compton and others 2003; Fritz and others 2004). Crocker and Major (1955) were the first to recognize the importance of *Alnus* to terrestrial plants in recently de-glaciated areas of Glacier Bay in southeast Alaska. In southwest Alaska, during a period of limiting nitrogen levels it was demonstrated that the primary productivity of Brooks Lake near the major tributary increased. The source of this increase was attributed to the presence of *Alnus* because rainfall concentrations of N and the volcanic ash, which covered the landscape after the 1912 eruption of Mt. Katmai, were N deficient (Goldman 1960).

It is plausible that potential benefits resulting from high densities of alder (i.e. higher nitrogen) may be lost because of the depletion of the phosphorus-pool. Either nitrogen or phosphorus can limit autotrophic production, and therefore, high inorganic nitrogen loads could produce high mass ratios of N/P in the water column and foster phosphorus limitation in the aquatic system.

1.4 General Introduction Summary

Human-induced changes in biological diversity and the modification of ecosystem processes, including primary productivity and element cycling, are two of the most pronounced ecological trends of the last century (Vitousek and others 1997). The success of documenting 20th century environmental change in northern lake sediments has gained much attention in recent years as demonstrated by the increasing number of publications (e.g. Finney and others 2000; Smol and others 2005; Wolfe and others 2006). The study of recently deposited sediments in lake systems with minimal anthropogenic impact or presence makes it possible to extend and record regional climate, terrestrial, and aquatic ecosystem changes. Because of the absence of continuous long-term climatic and environmental monitoring data, proxy data from lake sediments can be used to provide a historical perspective of environmental change (Smol and others 2005). These recent historical paleoenvironmental records create an opportunity for comparison to longer historical (e.g. sediment, ice, and tree) records while at the same time developing a baseline for modern studies and future comparisons.

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CHAPTER 2

2.1 ¹Introduction

High-resolution organic geochemical records from marine and lacustrine depositional basins indicate the variability and magnitude of oceanic and continental environmental responses to abrupt and decadal-scale climate change (Bradley 1999; ACIA 2004; IPCC 2007). Recent recognition of widespread ecosystem changes in the oceans (phytoplankton assemblage, productivity, etc.) and on the continents (terrestrial vegetation, etc.) associated with abrupt climate change during the Last Glacial Maximum (LGM), deglaciation and the transition to Holocene provides insight into the mechanisms responsible for ecologic change and the coupled interactions between oceanic and continental environments (IPCC 2007).

This investigation integrates the study of landscape-scale environmental changes with multi-proxy studies of lake sediment cores in selected watersheds of the Southwest Alaska Network of the National Park Service (SWAN) (Figure 2.1a, b, c, d). More specifically, we combined observations of terrestrial ecological patterns in area watersheds with an analysis of limnologic conditions recorded in lake sediments to better understand the linkages between landscape processes and lake productivity. Historically documented landscape changes and the paleolimnologic records allowed us to observe how changes in the environment through time may influence changes in lake productivity

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and nutrient cycling.

We combined paleolimnological studies and landscape analysis on selected lake ecosystems in the SWAN in order to: (1) establish baseline trophic states in non-anadromous lakes selected along an environmental gradient, and (2) gain a better understanding of how environmental conditions have changed in the past, how lakes have responded to these changes, and how they may change in the future.

The SWAN park units of Southwest Alaska encompass a distinct range of physiographic, climatic, and ecologic provinces and gradients. Ecosystem types show strong variation across the landscape and include: relatively dry interior boreal forest, alpine herbaceous tundra, shrub tundra lowlands, and cool coastal forests. As climate ameliorated after the last ice age, significant changes have occurred in the dominant vegetation assemblages in the area. Little Ice Age (LIA) moraines are prominent in many valleys and suggest that recent and even short-term Holocene climatic events are recorded on the landscape. Oral accounts from local residents, and studies of historical photos indicate that significant changes in vegetation have occurred over the past century (Figure 2.2) (Jorgenson *unpublished*; Branson *pers. comm.*).

Lakes in the SWAN region are numerous and highly variable in geomorphic origin, size, location, depth, limnology and source waters. Many lakes directly or indirectly receive glacial meltwater while others occupy small isolated basins with limited inflow and outflow. Many of the larger and lower elevation lakes of SWAN (e.g. Nanknek, Kukaklek, Kijik, and Lake Clark) are critical rearing and spawning areas for returning (anadromous, semelparous) Bristol Bay sockeye salmon (*Oncorhynchus*

nerka), a key species of the region. The high concentrations of native runs of sockeye salmon to the protected freshwater lakes and streams of the SWAN have thus been the subjects of previous although not extensive limnologic and ecologic studies (e.g. Donaldson 1967; Poe 1980; Kline and others 1993; Woody and Ramstad 1999; Wilkens 2002). Additionally, only a handful of non-anadromous lakes have been studied, though they clearly function as critical components of the watershed and often provide source waters for salmon habitat.

Thus, Bristol Bay in southwest Alaska, along with the SWAN units in the Bristol Bay watershed (LACL and KATM), is of exceptional conservation importance. The nearly pristine headwaters for five major drainage basins are located within LACL boundaries (the Kvichak River, Nushagak River, Kuskokwim River, Chakachatna River and Coastal basins). LACL also includes the sixth largest lake in Alaska, Lake Clark, and three river segments designated as Wild Rivers; Chilikadrotna, Mulchatna, and Tlikakila. The Kvichak River drainage basin is the world's most productive spawning and rearing habitat for sockeye salmon (Weeks 2001). The headwaters of this watershed are contained in the drainage of Lake Clark, which in turn enters Ilimana Lake via the Newhalen River. Iliamna Lake flows into Bristol Bay via the Kvichak River.

The factors affecting and controlling the cyclic populations and historically recent declines in sockeye salmon returns to some watersheds are still poorly understood despite ongoing research and more recent attention (Kline and others 1993; Finney 1998; Woody and Ramstad 1999; Schindler and others 2005; Naiman and others 2002). Many of the non-anadromous waters in the SWAN generally drain to and feed the relatively more

productive anadromous systems. Understanding how the chemical and physical properties of the non-anadromous freshwaters respond to variations in climate, disturbance, and landscape can help identify specifically what changes in ecosystem function are not directly related to salmon. These systems act as an analog for climate, terrestrial, and aquatic ecosystem interactions without additions of SDN subsidies. It is important to understand the effect of climate and landscape evolution on the lakes and the surrounding watersheds to infer how these systems evolve and how they react across and under different climate regimes. However, little work has tested how other factors such as vegetation patterns and watershed processes influence stable isotope signatures in SWAN lakes or how these signatures could be used to evaluate nutrient status and limitation. While the potential influence of SDN (nitrogen, carbon, phosphorus) from anadromous salmon, and the terrestrial input of nitrogen from vegetation have been investigated in numerous studies, distinguishing between the two sources or the potential influence of these two different sources on aquatic productivity has only begun to receive attention (Helfield and Naiman 2001; O'Keefe and Edwards 2002; Holtham and others 2004). Our objective is to develop a baseline understanding of land-lake interactions, decipher the recent limnologic history of non-anadromous lakes in the region, and gain insights into how future landscape change may impact both non-anadromous and anadromous lake systems.

2.2 Study Area

There are five physiographic regions within the SWAN (Racine and Young 1978): *Coastal* region, *Montane* region (Aleutian Range, Alaska Range), *Lake Clark–Kontrashibuna* region, *Foothill Lakes* region, and *Interior Lowlands* region. Three non-anadromous study lakes were chosen specifically for their distinct differences in precipitation, geomorphic position, and vegetation distribution (Figure 2.1d). Specific details on each lake study site are included within the Results of this thesis.

Three non-anadromous (no salmon) lakes and their surrounding watersheds within the boundaries of LACL are the major focus of the detailed paleo-investigation presented here. We broadened the size and scope of our study by examining surface sediments and several biological compartments in an additional 6 non-anadromous lakes in both LACL and KATM. This effort enabled us to include a wider range of sites (n=9) such as the lowlands region, which commonly drain to larger anadromous systems downstream. The study lakes transverse physiographic regions that exhibit vast differences in precipitation and temperature (Figure 2.3a, b), in addition to a vegetation gradient most prominent in the SWAN region (Figure 2.1b, c, d). A summary of the study site locations, basin characteristics and surface water chemistry can be found in Table 2.1. A summary of land cover and vegetation distribution at these three study sites can be found in Table 2.2 and Table 2.3.

2.2.1 Hickerson Lake

The *Coastal* region comprises the southeastern part of LACL on the western boundary of Cook Inlet. This region includes the lowlands between Cook Inlet and the upper elevations of the Aleutian Range (1200 – 1500 m). Hickerson Lake (59°55.84' N, 152°55.063' W) is located on the southeastern flank of Mount Iliamna in the coastal drainage basin, immediately south of the Chakachatna *River Basin*. The other major lake in this region, Crescent Lake lies just to the north of Hickerson Lake, the largest coastal lake in the park and supports a strong run of anadromous salmon.

The elevation of Hickerson Lake is 193 m, and its surrounding watershed drains an area of 40 km² (Table 2.1). Hickerson Lake is approximately 4.5 km long and on average 1 km wide. Depth soundings by Russell 1980, indicated the deepest basin is about 41 m. Overland flow and definable cascading streams supply water from precipitation, glaciers and snowfields to this turquoise blue oligotrophic lake. A small snow-fed tributary (Boulder Creek) drains the northern portion of the watershed. Notably either a terminal moraine from the Hickerson Lake watershed or lateral moraine from remnant glacial activity in the adjacent basin form a large boulder pile extending across the eastern boundary of the watershed. This feature apparently forces subterranean discharge of the lake water; there is no surface outlet from the lake. Although there is no record of spring break-up and fall freeze-up for Hickerson Lake the open-water period for nearby Crescent Lake lasts about 5 months, from June through October, which is probably similar for Hickerson Lake (Brabets and Ourso 2006). Recreationally, Hickerson Lake is

known as a great Dolly Varden fishing lake, and this is the only species of fish found in the lake during past surveys (Russell 1980).

Precipitation averages approximately 110 cm over the entire basin, with approximately half of that falling as snow (Western Region Climate Center 2008). Soils are mostly inceptisols with the lower part of the basin near the mouth primarily entisols. The physiographic characteristics of the basin are those of moderately high, rugged mountains. Bedrock consists of sedimentary and metamorphic rocks. At the present time only four major land cover components account for more than 90% of the Hickerson Lake watershed area including: 50% alder (predominantly *A. fruiticosa* on the hill side and higher elevations and *A. tenuifolia* in riparian corridors and lower elevations), 15% prostrate shrub tundra (dwarf species of willow, blueberry, cranberry, and several fruiticose lichens), 12% exposed bedrock or bare soil and 13% permanent ice and snow (data derived from GIS analyses of NPS land cover mapping products). In the coastal mountainous region, *Alnus* covers nearly all surfaces from riparian corridors to steep mountain slopes and areas of disturbance. Only the steepest high elevation cliff faces are bare from coverage.

2.2.2 Kontrashibuna Lake

Kontrashibuna Lake (60° 11' 13.92"N, -154° 1' 54.12"W) is glacial in origin and fed by snowfields, small steep gradient tributaries, and a major inlet stream at its east end. It is the source of the Tanalian River, a major tributary stream, entering Lake Clark along its eastern boundary south of the town site of Port Alsworth. Tanalian Falls, a major

waterfall located just downstream from Kontrashibuna Lake, is an impressive barrier that prevents upstream migration of adult sockeye salmon.

The elevation of Kontrashibuna Lake is 140 m, and the lake is approximately 21 km long and 1 km wide. The maximum surveyed depth is 108 m. The U.S.G.S. operated a gauging station at the outlet of Kontrashibuna Lake from 1951 -1956 (USGS station No.15298000). The average annual discharge for this limited period of recorded flow data was $18 \text{ m}^3 \text{ s}^{-1}$. Maximum discharge occurs in July due to snowmelt runoff, and reaches a mean maximum discharge of $\sim 60 \text{ m}^3 \text{ s}^{-1}$ (Weeks 2001). A second (smaller) peak in discharge, from rainfall runoff, occurs in October after increased precipitation common from late August through October. This is the only lake in our study set that has recorded discharge data.

Within the *Lake Clark–Kontrashibuna region* of the Park Kontrashibuna Lake occupies an area immediately west of the Chigmit Mountains (meeting point of the Alaska and Aleutian Range). This area is more characteristic of the interior and Western Alaska than the coastal region. Precipitation is less than half of that in the coastal region (50 cm yr^{-1}), with colder winters and warmer dryer summers than the coast to the east.

Along the shores of the Kontrashibuna Lake are primarily stands of white spruce mixed with birch and or balsam poplar. Openings in the canopy are often filled with alder (*Alnus Fruitcosa*), which extends to the understory of the stand. On the north-facing slopes of Kontrashibuna Lake are extensive stands of black spruce (*Picea Mariana*) with understory of ericaceous shrubs, sedges and mosses. On the western side of the Chigmit Mountains, dense communities of alder (with crown cover 75% - 100%)

dominate the hillsides and riparian corridors. This vegetation pattern is typical of many lakes within the SWAN boundaries. Alder shrubs dominate the landscape of LACL and are the most extensive vegetative land cover type and overall second in land cover area only to ice and snow.

2.2.3 Portage Lake

Portage Lake (60° 30.294'N 153° 51.852'W) is a major water source for the Kijik River. The Kijik River is a tributary to Lake Clark and originates in a glacial valley to the north of Portage Lake. Portage, Lachbuna, and Kijik Lakes all drain to the Kijik River as it descends to the larger Lake Clark.

This is the deepest clear (maximum recorded depth of 52 m) lake in LACL with a Secchi depth of 19+ m during our site visit in 2004 (Table 2.1). Portage Lake sits in a heavily forested pass at a considerably higher elevation than the other study lakes (447 m). The lake has an approximate length of 2 km and width of 0.5 km. This lake has long been highly regarded by sport fishers for its northern pike and lake trout. The Portage watershed and Portage Pass area are located in the same transition zone as parts of the Kontrashibuna watershed, however, further inland. Boreal forest vegetation is well represented at this location and elevation throughout LACL. The absence of major tributaries leading into the lake and glaciers, along with its small watershed area (Table 2.1), are at least partially responsible for the remarkable clarity of this lake.

2.2.4 Lowlands Region

As part of an effort to expand on the biogeochemical information in the region we included analyses from 6 additional non-anadromous lakes in the LACL and KATM Parks and Preserves. The Nushagak lowland area is representative of watersheds of these lakes and has been previously described in detail by Brubaker and others (2001).

2.3 Methods

2.3.1 Physical Limnology

Water samples were collected for phytoplankton, chlorophyll a, and other cations/anions in a sanitized plastic gallon container. Samples were filtered within 24 h of sampling. All samples were kept at 4°C. Upon returning to the laboratory all water samples and filters (phytoplankton and chlorophyll a) were frozen until later analysis. Water samples for ammonium and nitrite plus nitrate were analyzed using automated colorimetric continuous flow autoanalyzer (Lachat method 10-107-06-3-D for ammonium and USEPA [1987] method 353.2 for nitrate/nitrite; Lachat Instruments, Milwaukee, WI, USA) at the University of Alaska Fairbanks, Chemical Oceanography Laboratory. DON was analyzed from water filtered on 0.45 micron whatman filters following standard methods Total dissolved nitrogen was determined using persulfate digestion (Cabrera and Beare 1993), followed by automated colorimetric analysis for nitrate as described above. DON was calculated as total dissolved N minus nitrate and ammonium. Cation concentrations were determined by ion chromatography (Dionex Corporation, Sunnyvale, CA, USA). Sampled zooplankton represents one 30 m vertical tow haul from each lake. All samples were taken over the course of two summers (2004-

2005) at the same time the sediment surface samples and sediment cores were collected for each lake. Sub-samples of phytoplankton and zooplankton were freeze dried and prepared for later stable isotope analysis.

2.3.2 Sediment Coring

Lake sediments are often well suited for high-resolution paleoenvironmental analysis due to relatively high rate of sedimentation, low bioturbation, and continuous deposition (e.g. Schelske and Hodell 1991; Charles and others 1994). Coring sites for this study were initially selected using topographic maps and aerial photographs followed by onsite assessment. Potential coring areas with steep and/or complicated bottom topography (typically a result of debris from mass wasting, avalanches or flood events) were avoided.

At least two cores were retrieved from the deepest basin in each study lake. The initial cores were short gravity cores intended specifically to preserve the water sediment interface and underlying several tens of centimeters. To obtain a precise and intact record at the sediment-water interface, a Glew type corer, specifically designed for sampling unconsolidated sediments, was used (Glew 1988). A second, longer core was obtained using a hammer corer at the same site as the Glew cores. Specific details of each core are presented in the Results section for each site. Highly unconsolidated material present near the sediment-water interface of the core was dewatered and sub-sampled by extrusion of 0.5 cm core segments in the field. The remaining unconsolidated material was packaged for safe handling and shipment. All sediment was stored at the Geological Oceanography cold room on the University of Alaska Fairbanks

campus. In the lab, cores were split, described and photographed. Specific analytical sampling methods are described in detail below. One half of each core was retained as an archive.

2.3.3 Chronology

2.3.3.1 ^{210}Pb Dating

Core chronologies were developed using ^{210}Pb and volcanic tephra identifications. The ^{210}Pb method is commonly used to determine the accumulation rate of sediments in lakes and oceans over the past 100 – 150 years. The chronology of individual lake records was based on vertical down-core profiles of excess ^{210}Pb in sediments. One cubic centimeter samples of sediment were freeze-dried, homogenized, and analyzed for ^{210}Pb age determination using alpha-spectrometric analysis by Flett Research Ltd., Winnipeg, Manitoba, Canada. From the accumulation rate calculations, the age of sediment from a particular depth in the sediment column can be estimated. Sediment ages and chronological errors were estimated by using the constant rate of supply (CRS) method based on excess or unsupported ^{210}Pb activity (Appleby and Oldfield 1978; Binford 1990). All dates are reported as year After Dominion (AD). Typically, accumulation rate over a period of 80 -100 years were obtained. Ages of sediments beyond the maximum obtainable ^{210}Pb analyses were estimated by a combination of extrapolation of mass accumulation rates or tephra identification down to ca. 1600 AD depending on the core stratigraphy and sedimentation rate.

2.3.3.2 Magnetic Susceptibility

The entirety of each core was scanned for magnetic susceptibility. Magnetic susceptibility, a measure of the abundance of magnetic materials, provides important incremental, stratigraphic, and sedimentologic information. For example magnetic susceptibility is often sensitive to volcanic ash often allowing otherwise visually undetected tephra layers to be detected in susceptibility profiles. The positive identification of regionally recognized ash layers can aid in establishing a core chronology and sedimentation rate as discussed. Magnetic susceptibility was measured in the laboratory using a Bartington Instruments magnetic susceptibility meter on individual samples.

2.4 Paleolimnology and Paleoproductivity

Laboratory analyses of lake sediments included multiple components, which when combined, describe the physical properties and biogeochemical components over time. Cores were first generally described for lithology and then sub-sampled at 0.5 or 1 cm intervals for measurement of bulk density and organic content following standard methods (PALE 1999).

2.4.1 Biogenic Opal

Biogenic Opal was determined following a modification of the method outlined by Mortlock and Froelich (1989) with a single extraction using a 0.1 M Na_2CO_3 solution at 85°C for 5 hours. Smear slides were extracted at irregular intervals at the transition between sediment facies and examined under a microscope. Based on these observations

diatoms appear to be the main opal constituent in the studied cores. Two homogenized internal reference samples were analyzed with each batch and used to account for batch effects and to calculate within-batch precision, which is better than 5% of measured value.

2.4.2 Stable Isotopes ($\delta^{15}\text{N}$ and $\delta^{13}\text{C}$)

The percentages and stable isotopes of C and N in lake sediments was determined on freeze dried, finely ground, homogenized samples by elemental analysis-isotope ratio mass spectrometry (EA-IRMS, Carlo Erba Elemental Analyzer coupled with a Finnigan Delta V Plus Mass Spectrometer at the University of Alaska, Fairbanks and EA-IRMS, Carlo Erba Elemental Analyzer coupled with a Finnigan Delta ^{XP} Plus Mass Spectrometer at the University of Alaska, Anchorage). ^{15}N and ^{13}C are expressed in δ notation, indicating the difference between a sample and a standard (Peterson and Fry 1987):

$$\delta^{15}\text{N} \text{ or } \delta^{13}\text{C} (\text{‰}) = [\text{R}_{\text{sample}} - \text{R}_{\text{standard}}] \times 1000$$

Where R is the ratio of $^{15}\text{N}/^{14}\text{N}$ or $^{13}\text{C}/^{12}\text{C}$. All isotope results were expressed relative to the international standards: Vienna PeeDee Belemnite (VPDB) for $\delta^{13}\text{C}$ and atmospheric N_2 (AIR) for $\delta^{15}\text{N}$. As carbonate is not present in appreciable quantities in these lakes, acid washing was not conducted. Analytical precision associated (SD) with the EA-IRMS for $\delta^{13}\text{C}$ was $< 0.2\text{‰}$ and $< 0.1\text{‰}$ for $\delta^{15}\text{N}$ ($\text{C}\% \leq 0.2$ and $\text{N}\% \leq 0.1$). Precisions were typically lower for replicate ($n \geq 4$) analyses.

2.4.3 ‘Suess’ Corrections to $\delta^{13}\text{C}$ Values

Part of recent $\delta^{13}\text{C}$ trends are potentially attributed to the fact that in the past 200 years $\delta^{13}\text{C}$ in atmospheric CO_2 ($\delta^{13}\text{CO}_{2\text{atm}}$) has been declining at an increasing rate as a result of the accelerating release of CO_2 to the atmosphere from fossil fuel burning ($\sim 2\text{‰}$) (Verburg 2007). The $\delta^{13}\text{C}$ content of the atmosphere has been lowered substantially over the course of this time period, which can result in lower $\delta^{13}\text{C}$ signatures in lake sediments (Verburg 2007). The change in $\delta^{13}\text{C}$ in atmospheric CO_2 owing to anthropogenic activities (the Suess effect) is well known and thus corrections were applied to all $\delta^{13}\text{C}$ core records for this study using a 6th order polynomial, adapted from Verburg, 2007.

$$\begin{aligned} &7.7738118 * 10^{-6} * Y^6 - 1.2222044 * 10^{-11} * Y^5 \\ &+ 7.1612441 * 10^{-8} * Y^4 - 2.1017147 * 10^{-4} * Y^3 \\ &+ 3.3316112 * 10^{-1} * Y^2 - 273.715025 * Y \\ &+ 91703.261 \end{aligned}$$

Such a correction assumes that dissolved inorganic carbon (DIC) in waters in the lake euphotic zone is in equilibrium with the atmosphere.

2.4.4 Total Phosphorous

All forms of extractable phosphorus, including organic phosphorus compounds, were converted to orthophosphate using an acid-persulfate digestion. Orthophosphate ion reacts with ammonium molybdate in an acidic solution to form phosphomolybdic acid, which upon reduction with ascorbic acid produces an intensely blue complex. Antimony potassium tartrate is added to increase the rate of reduction (Murphy and Riley 1962;

Gales and others 1966; Pai and others 1990). Samples were analyzed on a Technicon Auto Analyzer II, configured with a GC-PAL auto-sampler, analytical cartridge, peristaltic pump, colorimeter, voltage stabilizer, and data station at the University of Alaska at Fairbanks, Forest Soils Research Laboratory. All PO_4^{3-} determinations were made by flow-injection colorimetry described by Keeney and Nelson (1982) (Bran-Luebbe®; Norderstedt, Germany). Analytical precision associated with this method is $\pm 5\%$.

2.4.5 Pollen Records

In this study we focused on the pollen records over the last ~150 years from the selected local watersheds. Each of the sediment cores recovered from the selected lakes was sub-sampled in 1 cm^3 for pollen analysis according to standard techniques (Faegri and Iversen 1989; Shane 1992). The basic pollen sum consists of the total counts of terrestrial trees, shrubs, and herbs. Pollen percentages of particular tree, shrub, and herb taxa were based on the sum of the count for each genus or species divided by the basic pollen sum. Percentages of terrestrial spores were based on the basic pollen sum plus the terrestrial spores and percentages of aquatic spores were based on the basic pollen sum plus aquatic spores. Pollen calculations were done using TILIA and diagrams plotted using TILIA.VIEW (E. Grimm, Illinois State Museum, Springfield, Illinois).

All pollen studies and interpretation were conducted at the University of Alaska Fairbanks, Quaternary Center, under the supervision of Andrea Krumhardt and Dr. Nancy Bigelow.

2.4.6 Vegetation Distribution and Landscape Patterns

The composition and distribution of vegetation types in selected watersheds was assessed using a combination of NPS land cover mapping products, high altitude aerial photography, historical and repeat photographs, and *in situ* confirmation. The extensive GIS resource database enabled a rapid analysis of vegetation, land cover type, slope, elevation, watershed area, and lake characteristics.

Repeat photography was used for qualitative assessment of landscape change. The NPS SWAN and ABR, Inc. collaborated on a project that provided a past and future photographic record of biophysical changes that are occurring in the SWAN parks. They compiled historical and repeat pairs of landscape features in the SWAN parks. Of the compiled set, 39 photographs were considered suitable for studying plant succession (12), shrub expansion (8), and tree expansion (19), and only a proportion of these were repeated by ABR, Inc.

Richard Russell (Alaska Department of Fish and Game) provided another historical photograph set from his personal archive. Russell documented baseline water quality and fish species composition in Lake Clark National Park and Preserve during 1978-1979, prior to the parks inception by President Carter in 1980 (Russell 1980). Russell took many pictures in and around watersheds of key interest to this and related studies including but not limited to, Kontrashibuna, Hickerson, Portage, Kijik, Fish Trap, Two Lakes, and Telaquana (Russell *unpublished*). The photographs and repeat photographs in this study were primarily used qualitatively to support our more detailed palynological and land cover analysis.

2.5 Results

2.5.1 Limnological Surveys

During our site visits in August 2004, some basic limnological parameters of the lakes were measured. All lakes were dilute, with specific conductivity ranging from 42.1 to 354 $\mu\text{S cm}^{-2}$ (Table 2.1). Conductivities were lower in the montane glacial lakes. All lakes were circum-neutral at the time of measurement, pH ranged from 8.0 to 8.5. Phosphorus measured as dissolved ortho-phosphate (PO_4^{-3}) in the surface waters was just above the detection limit ranging from 0.08 – 0.01 $\mu\text{mol L}^{-1}$. Nitrate + Nitrite ($\text{NO}_3^- + \text{NO}_2^-$) ranged from 4.6 $\mu\text{mol L}^{-1}$ in Hickerson Lake to 25.3 $\mu\text{mol L}^{-1}$ in Portage Lake. In contrast, NH_4^+ was very low ranging from 0.1 – 0.58 $\mu\text{mol L}^{-1}$ in all lakes. The N values for the turbid glacial lakes (Kontrashibuna and Hickerson Lakes) were lower than that of the clear and higher elevation Portage Lake. Surface concentrations of SiO_4 ranged from 38.0 to 76.2 $\mu\text{mol L}^{-1}$, suggesting that none of the lakes were SiO_4 depleted and diatom growth in the near surface water (~1 m) would not be hindered.

2.5.2 Sediment Description and Chronology

The recovered surface sediment cores ranged in length from 10 to 20 cm and consisted of a thin veneer of greenish-brownish lacustrine gyttja overlying denser gray silt. The contact between the two sedimentary units was fairly sharp, with the lacustrine sediments becoming increasingly flocculent and organic-rich toward the top of the cores (Figure 2.4 a, b, c). Although organic matter was also estimated by the loss on ignition (LOI) technique we found that the organic carbon content (C%) measured on an Elemental Combustion System provided more precise and accurate results. Therefore,

we report our findings as C% for this study (Figure 2.4a, b, c).

Organic C content increased up core in both Kontrashibuna and to a lesser extent in Hickerson Lake. The increase in C% for the Kontrashibuna Lake sediment core is ~ 0.5 – 2% in post 1860 AD sediments, increasing abruptly nearing the top 4 cm of the core (circa 1975 to the present). Water content and dry bulk density showed (Figure 2.4a, b, c) that in Hickerson and Kontrashibuna Lakes, sediments are highly unconsolidated in comparison to that of Portage Lake. Water content profiles in the two largely glacially fed systems ranged from 45 -75% while Portage Lake ranged from 45-55%. Magnetic susceptibility ranged between 5 – 15 SI units g^{-1} and no volcanic ash layers could be positively identified using this technique. Further examination of smear slides of sample with high masses did not positively identify any major tephtras in the surface core stratigraphies.

All of the ^{210}Pb profiles indicate an approximately exponential decrease in activity as a function of depth (Figure 2.5a, b, c). In some cases, such as Hickerson Lake, the activity profile has irregular variation superimposed on the exponential decline, which appears to follow variation in dry bulk density (Figure 2.4a). Variable sediment accumulation rates were indicated in all of the cores by the CRS model described in Methods (Figure 2.5a, b, c). However, the average sediment accumulation rates estimated by the CRS and linear regression models were reasonably close for Kontrashibuna and Portage Lakes, the age difference estimated by both model applications was less than ~10 years. In contrast, these conditions were not met in Hickerson Lake where the age difference was greater than ~10 years. CRS modeled chronologies are used in this study, and ages greater than ~80 years are based on the mean CRS accumulation rates.

2.5.3 Sediment Organic Matter and Stable Isotope Characterizations

2.5.3.1 Hickerson Lake – Eastern Coastal Montane Region

Carbon and nitrogen in the Hickerson Lake sediments range from 0.45% to 1.1% and 0.06% to 0.12% of dry sediments, respectively (Figure 2.6a). Over the last century both C% and N% show a marked increase, and their stratigraphic variations are highly correlated ($R^2 = 0.99453$; $n=15$). The mass ratios of C/N range between 10.1 and 11.8, with a decreasing trend toward the top of the core. However, the decreasing trend appears to begin much earlier in the core record at a depth of 40 cm (Figure 2.6a). The mean C/N ratio since circa 1860 AD (0–15 cm) is 11.0. The C/N ratio in Hickerson Lake indicates the sediment is primarily composed of autochthonous organic matter and the decreasing trend in the C/N ratio implies a relative increase in aquatic sources or less degraded material.

The BSi content is very low in the Hickerson Lake core with values ranging from 1.2 to 3.4 Wt. %. Typical for oligotrophic lakes, the content is low, but significantly greater than the within batch precision obtained for our internal standard with low BSi (better than $\pm 5\%$ of the measured value).

The low organic and opal contents reflect the high proportions of allochthonous inorganic materials in the sediments, which likely are derived from the watershed through runoff, and mountain glacial processes, contributing high mineral loads to the lake. Generally, BSi increased over the last century with some fluctuations. BSi concentrations reach a maximum of 3.4% near the surface at 1.5 cm depth. Although BSi is in low concentrations, the trend was analytically significant and the 2% increase

overall was a large relative increase. The post ~1860 AD values (Figure 2.6b) are well above those found in the complete core. BSi was positively correlated with both C% and N% ($R^2 = 0.7$ $n=15$).

The uncorrected $\delta^{13}\text{C}$ of sediments deposited since circa 1860 (upper 15 cm) in Hickerson Lake range between -25.7‰ to -27.6‰ SD 0.38‰, and does not follow a regular trend with depth. Based on the corrected data the most depleted period occurred circa 1920 to 1940 and enrichment of $\delta^{13}\text{C}$ (~1‰) occurred shortly after circa 1950. A depletion trend occurred shortly thereafter reaching a minimum of -27.7‰ circa 1979 (3 cm). Post 1980 sediments (upper 3 cm) became more enriched through 2003 consistent with other proxy data and our other core stratigraphies, indicating increased productivity in post 1980 sediments.

Sediments deposited since 1860 are marked by relatively low $\delta^{15}\text{N}$ values with minor variation ($\delta^{15}\text{N}_{\text{mean}} = 1.9\text{‰}$, SD = 0.16‰) (Figure 2.6b). The largest change in the $\delta^{15}\text{N}$ record is the increase from ~1975 to 1990 (1.5‰) (Figure 2.6b). Reduced variability is observed in sedimentary $\delta^{15}\text{N}$ levels before this time (Figure 2.6b). The $\delta^{15}\text{N}$ levels are weakly positively correlated with BSi ($R^2 = 0.3$). Following this period $\delta^{15}\text{N}$ values declined to a low ~1965 (6 cm), again coincident with a low BSi, C/N, C%, and N% (Figure 2.6a, b). The late 1970s increases in sedimentary $\delta^{15}\text{N}$ represented the greatest change and, with the highest sedimentary $\delta^{15}\text{N}$ levels occurring for both the surface (0-15 cm) and deeper hammer core (15-135 cm) core.

2.5.3.2 Kontrashibuna Lake –Transition Region (west of coastal mountain range)

In samples from Kontrashibuna Lake, C% (mean = 0.76%, SD = 0.31) and N% (mean= 0.085%, SD = 0.03) increase sharply in sediments postdating 1975, reaching peak values at the surface. Percentages of C and N are highly correlated indicating that the N is mainly organic in origin ($R^2=0.96$) (Figure 2.7a). Importantly, the C/N mass ratios suggest the organic material has remained primarily autochthonous over the last century (mean = 9, SD = 0.7). The stratigraphies of C and N parallel those of BSi in post ~1860 sediments, suggesting a close association between diatom production and organic matter sedimentation ($R^2 = 0.77$ and 0.78 ; $n=19$, respectively) (Figure 2.7a, b).

In the Kontrashibuna Lake surface core, $\delta^{13}\text{C}$ (corrected) values range from -26.7 to -23.9‰ (SD = 0.17 $n=19$), and reveal stratigraphic changes that broadly parallel those of BSi, N%, C% since circa 1860 AD (Figure 2.7a, b). The enrichment of the C isotopic signal in Kontrashibuna Lake sediments compares well with increased BSi, N%, and C% (Figure 2.7a, b). In Kontrashibuna Lake all the productivity proxies support the interpretation that, over this interval, BSi, N%, C%, and $\delta^{15}\text{N}$ are primarily influenced by lake primary production, of which diatoms represent a major component. It is important to note that after 1975 the corrected $\delta^{13}\text{C}$ values became far more enriched than at anytime prior in the sedimentary record by ~1.5‰ (Figure 2.7b).

Sediment $\delta^{15}\text{N}$ values ranged between 1.9‰ and 2.9‰ with a small declining trend moving up core from circa 1860 to the present (Figure 2.7b). Mean values prior to circa 1960 were 2.7‰ and 2.0‰ thereafter.

2.5.3.3 Portage Lake – Inland Montane Region (subalpine)

Portage Lake sits at the highest elevation and is located ~2 km west of Lake Clark, the farthest inland site in our study transect. Although glacial in origin the lake no longer receives glacial or permanent snowfield contributions and does not have large tributaries that feed into it. This results in its nearly clear waters and a lower sedimentation rate ($0.04 \text{ g cm}^{-2} \text{ yr}^{-1}$) compared to Hickerson and Kontrashibuna Lakes, 0.11 and $0.08 \text{ g cm}^{-2} \text{ yr}^{-1}$, respectively. Additionally, the Portage Lake watershed is much smaller (10 km^2) than that of Hickerson and Kontrashibuna Lakes. The watershed to lake area ratio for Portage Lake is about the same as Hickerson Lake, 7 and 9 respectively. Organic C% and N% in the Portage Lake sediment core range from 0.85% to 1.4% and 0.07% to 0.13% of dry sediments, respectively (Figure 2.8a). The stratigraphic variations of C and N are positively correlated ($R^2 = 0.68$; $n=12$) (Figure 2.8a). Both C% and N% showed slight increases from circa 1930 to the present. The mass ratios of C/N, range from 8.9 to 13.0, and increased briefly from circa 1900 to 1928 AD (8-10 cm), then generally decreased to the present (Figure 2.8a). BSi content (0.85%–3.74% dry sediment) is negatively correlated with the mass ratio of C/N ($R^2 = 0.74$). A decrease in C/N mass ratios may suggest increased aquatic productivity, reduced terrestrial input or better preservation of OM. An interpretation of higher productivity is thus supported by the increases in the BSi content of the sediment.

Sediment $\delta^{15}\text{N}$ values range between 2.5 and 3.7‰, generally tracking down-core changes in BSi (Figure 2.8a, b). The $\delta^{15}\text{N}$ signature in Portage Lake is consistently more enriched than the other lakes in the transect. In contrast to the depleting trend observed

in Kontrashibuna Lake, there is a small but reproducible trend in the $\delta^{15}\text{N}$ values up core with an increase of $>1\text{‰}$ circa 1860 to 2000. In the Portage Lake core, $\delta^{13}\text{C}$ (Suess corrected) values ranged from -30.73 to -23.95‰, and revealed stratigraphic changes that have a high negative correlation with BSi concentrations ($R^2 = 0.90$; $n=12$), and are not correlated with $\delta^{15}\text{N}$ over the 1860–2004 AD period (Figure 2.8b).

2.5.4 Watershed Vegetation History

Pollen diagrams for Hickerson, Kontrashibuna, and Portage Lakes are used as a qualitative index of relative changes in their major vegetation assemblages (Figure 2.9). Pollen data reveals distinct differences in vegetation development among the study sites. This likely compares to the different trajectories of primary succession that occurred across the physiographic gradient between the ocean climate and mountain divide. Down core plots of the four major pollen types, *Alnus* (alder) and *Picea* (spruce), *Betula* (birch) and *Salix* (willow) show high percentages of *Alnus* ($>50\text{--}90\%$) across all three sites (Figure 2.9). In Hickerson Lake, *Alnus* is present in very high percentages throughout the length of the core. Both Kontrashibuna and Portage Lakes show a slight decline. At Kontrashibuna Lake the decline in *Alnus* is more abrupt after ~ 1940 and accompanied by increases in *Picea* sp. At Portage Lake, the *Alnus* decline is less sudden and begins near the turn of the century; a delayed rise in *Picea* (~ 1940) corresponds well with trends from the Kontrashibuna Lake core. The Portage Lake and Kontrashibuna Lake pollen trajectories are very similar despite minor differences of pollen percentages (Figure 2.9). Hickerson Lake, on the other hand, shows steady rates of *Alnus* throughout the entire sequence, with percentages equal to those found in surface sediment samples.

2.5.4.1 Hickerson Lake

The low percentages of all taxa other than *Alnus* are a result of the watershed vegetation in Hickerson Lake being dominated by *Alnus* (mean abundance 90%) over the record. The palynological assemblage is dominated by *Alnus* (92%), *Betula* (<5%) and *Picea* (<1%). *Alnus* appears to be well established and the primary vegetation type in the Hickerson watershed and along the coastal uplands before 1860 (Figure 2.9). *Betula* reaches a maximum for the record by circa 1880 (12cm) and percentages decline only slightly thereafter reaching a minimum by 1920 (8cm). Over this same time period a further increase of *Alnus* is not observed in the pollen percentage data. However, photographic evidence along the coastal region depicts establishment of *Alnus* on hillsides and in recently deglaciated terrain along the glacial margins. The fact that *Alnus* make up nearly 90% of the pollen assemblage makes it plausible that recent changes in vegetation abundance would not be readily observed in the palynological record. Expansion of *Betula* by 1880 is observed with increasing pollen percentages to a maximum in the record of ~5% by 1920 (Figure 2.9). The *Betula* pollen percentage are only 3% in near surface sediments and are most likely not in the watershed in significant abundance today (Figure 2.9 and Table 2.2). From circa the late 1870s to circa 1950 (14-8 cm) an abrupt decline in *Betula* pollen percentage is followed by increases and maximum concentration in *Artemisia*, and then *Cyperaceae* pollen. These changes indicate a reduction in *Betula* shrubs and expansion of herb tundra plants in and around the Hickerson watershed. *Salix* and *Picea* pollen remain low throughout at approximately 1%. Increases in *Salix*, *Picea*, and *Betula* shrubs are presumably dwarfed by the high

concentration of *Alnus*. The higher concentration of *Picea* indicates its expansion on the landscape, but percentages remain low ($\leq 3\%$) potentially marking only the beginning of the local presence of *Picea* in the watershed. Holocene investigations of lake sediment pollen (Hu and others 1995, 1996, 1998, 2001) and studies of *Picea* in modern lake sediments (Anderson and Brubaker 1986, 1994) suggest that *Picea* pollen reaches 3-10% where *Picea* trees are present in lake watersheds. The circa 1980 - 2000 pollen assemblages compare well with the modern land cover mapping data (Table 2.2). *Alnus* pollen percentages have comparatively large increases in contrast to other species throughout the core stratigraphy. The repeat photography (Figure 2.2a) from coastal regions of the SWAN depict that the distribution and expansion of *Alnus* followed the post LIA advances, colonizing bare rocks and almost all surfaces except shear cliff faces.

2.5.4.2 Kontrashibuna Lake

Trends in pollen at Kontrashibuna Lake while similar to those found at Hickerson Lake, contain some major differences in the evolution of the vegetation in this watershed between the turn of the 20th century to the present. Specifically, the percentage of *Alnus* pollen dominates the entire record, but experiences a marked decrease from approximately 1940 to the present (Figure 2.9). Despite this decrease, *Alnus* pollen remains a major component throughout the core profile comprising ~75% of the pollen taxa at a depth of 4 cm where *Picea glauca* and then *Picea mariana* increase markedly, values of ~10% and 5%, respectively (Figure 2.9). This shows an increase in *Picea* from ~1960 to present. The reduction in the percentage of *Alnus* pollen after circa 1960 (~40%) appears to be a result of dilution by the increases in *Picea* indicating that forested

areas are expanding across the landscape and within the watershed (Figure 2.2) (Jorgenson *unpublished*). Interestingly, increases in *Alnus* (from 40 – 50%) and *Betula* (from 10 – 20%) suggest that shrub expansion may also be occurring in the watershed from circa 1970 to the present. Repeat photography from the Kontrashibuna Lake site shows a large increase in *Picea sp.* following a fire circa 1930s (Figure 2.2) (Jorgenson *unpublished*).

2.5.4.3 Portage Lake

While the general patterns of vegetation distribution and pattern of succession observed in the other study lakes is similarly present in the Portage Lake pollen stratigraphy, the *timing* of colonization and vegetation distribution are much different. Additionally, the slow sedimentation rates at Portage Lake result in lower stratigraphic resolution than the other study lakes. Once again the pollen record is dominated by *Alnus* (range 80 – 65%) throughout the core stratigraphy (Figure 2.9). Prior to circa 1900 (~14 – 10 cm depth) the pollen percentage of *Picea* (5%), indicate probable presence of Spruce within the watershed. *Betula* pollen percentage increased rapidly in the late 1800s (~10 cm) reaching maximum peak percentages circa 1940. *Betula* pollen percentages in Portage Lake (mean = 10%) approximates that of Kontrashibuna Lake (mean = 12%), both are much greater than Hickerson Lake (mean = 4.4%). Additionally, several herb taxa (e.g. *Poaceae*, *Artemisia*, and *Cyperaceae*) contained in the stratigraphy are at much higher concentrations throughout the 20th century. These vegetation types are typical at higher elevations (sub-alpine to alpine) of the lake and lake watershed. Indication of vegetation succession and expansion is more pronounced earlier in the century with the

marked establishment of *Picea*, *Betula* and herbs. This is augmented by marked declines in *Alnus* pollen percentages. It is possible that increases in *Picea*, which are prolific pollen producers, may be masking the *Alnus* trends. *Picea*, *Salix* and a consistent presence of *Betula* pollen are observed on the landscape post circa 1950 to the present.

2.5.5 Surface Sediment, POM, and Zooplankton Regional Lake Comparisons

To expand the study region and incorporate information from other non-anadromous lakes we collected surface sediments, phytoplankton, and zooplankton from an additional six lakes (totaling $n=9$) in the SWAN (Figure 2.1b, c). When the lakes were categorized within their physiographic regions, consistent cross-lake relationships emerged for sediment $\delta^{15}\text{N}$, BSi, C and N, but not for $\delta^{13}\text{C}$ or P. Both N and C had a positive correlation with BSi ($R^2 = 0.87$ and 0.92 , $n = 9$, respectively) (Figure 2.10), as might be expected for lakes with increasing content of biogenic material. A strong positive correlation was observed between $\delta^{15}\text{N}$ and BSi ($R^2 = 0.76$) and a strong negative correlation was observed between $\delta^{15}\text{N}$ and C/N mass ratios ($R^2 = -0.76$) in the surface sediment comparisons when Pringle Lake, the outlier was removed from the data set (Figure 2.11). The content and source of sediments in Pringle Lake are generally inconsistent and anomalous in comparison to the other lakes in the region.

These studies of surface sediments in lakes that vary in morphology and watershed characteristics across physiographic gradients help define how biogeochemical markers are related to physical and biological processes. Clear demarcations exist between the heavy rainfall and glacier/snow fed lakes of the warmer-coastal montane

regions (e.g. Hickerson Lake) and the cooler-inland sites (e.g. Nushagak lowland lakes). Additionally, this analysis shows marked differences between the small and shallow inland lakes (e.g., Idavain and Klosterman) and the large and deep coastal-montane and montane lakes (e.g., Hickerson and Kontrashibuna). However, the lakes just to the east of the Chigmit mountains (e.g. Kontrashibuna and Tazimina) serve as a transition region consisting of a mixture of larger and smaller watersheds and lakes, which may or may not be fed by glacial runoff and whose biogeochemical proxy may often overlap those of the coastal or inland lakes. The non-anadromous lakes in KATM are typically smaller-shallow inland lakes characterized by more enriched $\delta^{15}\text{N}$ (mean = 3.7‰) values compared to the large-deep montane and coastal non-anadromous lakes more typical of LACL (mean = 2.2‰). Typically, $\delta^{15}\text{N}$ values are more enriched along a gradient from coastal-montane to montane to inland-lowland lakes. The glacially-fed systems such as Hickerson, Kontrashibuna, and Devils Cove Lakes had lower $\delta^{15}\text{N}$ values and higher C/N mass ratios in surface sediments than the other study lakes. BSi followed a similar trend to that of $\delta^{15}\text{N}$, with the exception of Kontrashibuna and Devils Lakes, which had higher percent BSi than the non-glacial Portage Lake and the lowland Jo Jo Lake. The physiographic, temperature, and precipitation gradients, along with lake morphometric differences appear to compare well with trophic and productivity proxies.

Although zooplankton samples represent only a single point in time (one 30 m vertical tow haul), the sediment and zooplankton $\delta^{15}\text{N}$ values were positively correlated ($R=0.60$ $n=8$; no zooplankton data for Tazimina Lake). The zooplankton $\delta^{15}\text{N}$ samples were on average 1.5‰ greater than the sediments in the corresponding lakes.

Finney and others (2000) showed that lake sediments and zooplankton closely track each other along a gradient in SDN loading. Thus, it is interesting to note that in non-anadromous systems a similar relationship might be viable where both sediments and zooplankton accurately track the trophic relationship and perhaps nutrient limitations based on geomorphic, climatic and watershed characteristics.

When the sediment and phytoplankton biogeochemical markers were compared there were no strong relationships. Nor did C and N stable isotope values in phytoplankton show any relationship to that of surface sediments or zooplankton. Finally, there were no clear relationships observed for any of the phytoplankton proxies when compared to each other. This is potentially due to the differences between the longer time scales that zooplankton and sediment integrate their signature compared to phytoplankton.

2.6 Discussion

This multi-lake comparison of lake biogeochemistry reveals similar recent paleolimnological histories for all three-study lakes, despite their differences in lake morphology, watershed size, landscape position, and regional climatic influences. This degree of coherence implies that although differences exist at the local scale and within individual core stratigraphies, environmental change is occurring across the region. While some of the proxy data show only small fluctuations or trends reproducibility of the trends was such that they merit further interpretation and discussion.

2.6.1 Lacustrine Biogeochemistry and Nutrient Cycling Records

Hu and others (2001) demonstrated Holocene changes in lake productivity as a result of climate-driven landscape processes and the expansion of vegetation. Increases of *Alnus*, in particular, may result in N-isotopic enrichment due to either increased rates of N cycling (Gu and others 1994), or weakened physiological fractionation of ^{15}N during dissolved inorganic nitrogen (DIN) uptake when N becomes limiting for primary production (Goericke and others 1994). Recent increases in primary productivity proxies such as BSi and % organic C and N, and decreasing trends in C/N mass ratios, are generally expected to be accompanied by enriched $\delta^{15}\text{N}$ values.

Similarly our unpublished data at Idavain Lake in KATM (see Finney 2006) covering the entire Holocene at very high resolution, suggests that N isotopes are sensitive to climate (e.g. medieval warming period and Younger Dryas) and other pre-industrial changes (e.g. Volcanic eruptions) that drive lake productivity (Finney 2006; Cohn *unpublished data*). In this study we observed only minor enrichment of $\delta^{15}\text{N}$ ($\sim 0.5\text{‰}$) in the Hickerson and Portage Lake cores and a small reproducible depletion trend in Kontrashibuna Lake. It should be noted that the study sites are highly oligotrophic systems relative to some other studies.

There are a number of depositional and post depositional processes that can cause enrichment or depletion of $\delta^{15}\text{N}$ values in lake sediments. Early-digenetic processes such as denitrification strongly favor the lighter and more weakly bonded ^{14}N leaving the remaining material more enriched in ^{15}N (Hodell and Schelske 1998; Talbot 2001). It is reasonable that the water column is not a significant factor in denitrification as most of

the lakes in the SWAN can be thoroughly mixed by prevailing winds when ice-free and are subject to only small periods of thermal stratification in the summer (Stottlemeyer and Chamberlain 1987; LaPerriere 1997; Wilkens 2002). LaPerriere (1997) classified many of the lakes of KATM as discontinuous-cold-polymictic, in the ice-free season the lakes may mix to great depths due to frequent winds and coastal storms. Thus it seems unlikely that recent increases in lake denitrification can explain the observed trends. In addition we did not see a strong positive relationship between N concentration and $\delta^{15}\text{N}$ in the down core stratigraphy of the lake cores. Based on controlled experiments it has been shown that diagenetic overprinting of $\delta^{15}\text{N}$ in both oxidized or reduced sediments occurs over much shorter timescales (weeks to years) than our century-scale study (Lehmann and others 2002). Nitrogen isotope ratios of surface sediments suggest that the sediment can be viewed as a cumulative and integrated response of spatial, temporal and functional variation in nutrient conditions (Jones and others 2004). In addition, it has been concluded elsewhere that $\delta^{15}\text{N}$ can record changing sources of N more strongly than diagenetic processes (see Brenner and others 1999; Finney and others 2000; Teranes and Bernasconi 2000; Wolfe and others 2006). Our down core assessments and our surface sediment survey are therefore consistent with the general interpretation that $\delta^{15}\text{N}$ is recording the sources of N and the rate of N cycling.

Despite the fact that the trend is not uniform in all lakes and relatively small for $\delta^{15}\text{N}$, the observed increases in landscape primary production over the ~80 years including that of N_2 -fixing *Alnus* and the post 1960 increases in the N% concentration implies possible increases in N loading relative to P. Thus, any nitrogen limitation would

be reduced or alleviated in recent decades, allowing lake autotrophs to fractionate more strongly against ^{15}N , and resulting in the progressive depletion of $\delta^{15}\text{N}$ in sedimented autochthonous organic matter.

An alternative hypothesis is that increased atmospheric N concentrations from anthropogenic emissions are driving depletion trends in sedimentary $\delta^{15}\text{N}$ signatures due to their lighter isotopic signatures (Baron and Campbell 1997; Baron and others 2000; Wolfe and others 2001, 2003, 2006; Saros and others 2003). Moreover, studies of high-latitude lakes in the Canadian Arctic have suggested that decreasing trends of $\delta^{15}\text{N}$ in sediments are a result of increasing N deposition in pristine environments from distant sources (Wolfe and others 2006). Again, Wolfe and others (2006) presented further evidence from studies regarding increased concentrations of NO_3^- in Arctic and high Arctic ice cores. The watershed and landscape position of Kontrashibuna Lake located on the western side of the Chigmit Mountains are potentially an area for 'rain out' events produced as a result of orographic lifting. This could deposit higher concentrations of N across this east-west divide. Relatively high rates of atmospheric N deposition west of the divide in the SWAN could potentially alter terrestrial plant community composition and nutrient limitation of phytoplankton. This possibility needs to be tested more directly, by measuring atmospheric N deposition rates across the Chigmit Mountain region.

Increased primary production results in the enrichment of sediment $\delta^{13}\text{C}$, directly reflecting the consequence of sustained exploitation of $^{12}\text{CO}_2$ and reduced discrimination under productive regimes. Thus, increased lake production often results in enrichment of

sediment $\delta^{13}\text{C}$ on a variety of timescales (Hodell and Schelske 1998). Sediment $\delta^{13}\text{C}$ can also change as a result of varying mixtures of aquatic and terrestrial organic matter, which often have different $\delta^{13}\text{C}$ signatures. Aquatic-derived organic matter can be either heavier or lighter than terrestrial organic matter (which has a more restricted range in high latitude terrestrial C_3 environments) depending on the $\delta^{13}\text{C}$ of lake water DIC (Laws and others 1997). Suess-corrected $\delta^{13}\text{C}$ in Hickerson and Kontrashibuna Lake sediment cores are more enriched than Portage Lake illustrating that the sources of C or C-cycling processes are potentially quite different between glacial-fed lakes and non-glacial-fed lakes in the region. Similar to trends reported in this region by Hu and others (2001), results from two of our three study lakes have consistently shown that $\delta^{13}\text{C}$ is weakly negatively correlated with BSi. For example, in Hickerson Lake the correlation between $\delta^{13}\text{C}$ and BSi ($R^2 = -0.33$) was weaker than that of Portage Lake ($R^2 = -0.91$) and positive correlations between $\delta^{13}\text{C}$ and the mass ratios of C/N ($R^2 = 0.52$ and $R^2 = 0.66$, respectively) despite the application of the Suess correction factor (Figure 2.12). Additionally, we observed fairly depleted $\delta^{13}\text{C}$ values in algae and zooplankton collected during our site visit to Portage Lake (Table 2.4). In the Kontrashibuna Lake sediments we observed a positive correlation between BSi and $\delta^{13}\text{C}$ ($R^2 = 0.55$) and no correlation between the C/N ratio and $\delta^{13}\text{C}$.

In Hickerson Lake, and especially in Kontrashibuna Lake, enhanced productivity alone could be causing enrichment of $\delta^{13}\text{C}$ values of the sediments because fractionation is reduced when phytoplankton productivity is high (Laws and others 1997). This is generally the case where particulate or dissolved organic matter (OM) is dominated by

aquatic sources ($C/N < 10$). In general, $\delta^{13}C$ values lighter than ~ -26 to -27‰ such as in Portage Lake may reflect a lack of equilibrium with the atmosphere. This could be the result of input of respired CO_2 from organic matter decomposition in soils around the lake and then input via streams and groundwater. However, we hypothesize that the protected watershed of Portage Lake and its continuous clarity may suggest that this lake becomes stratified thermally for longer periods of time in summer (no data). In this scenario a dimictic lake would experience a seasonal turnover and mixing of the hypolimnion, which is typically depleted in $\delta^{13}C$ due to decomposition of OM during stratification. The turnover of the lake water could then provide the more depleted $\delta^{13}C$ to the algal communities, which would in turn have more depleted values of $\delta^{13}C$ as we see in our sediments, phytoplankton and zooplankton from Portage Lake. Therefore even if the lake was becoming more productive, as several proxies suggest, the $\delta^{13}C$ may not reflect this overall change because the sources of C change seasonally.

The BSi content and the C/N mass ratios through time are important indications of the relevant changes occurring in the aquatic system. Increases in C/N mass ratios are expected as the sediments age because of bacterial preference for degradation of N-rich compounds (Fenchel and others 1998). Newly deposited sediment typically contains easily degradable material from algae which, has a C/N mass ratio of $\sim 6-8$ (Meyers and Ishiwatari 1993; Meyers and Teranes 2001; Talbot 2001). As this material is degraded, the influence of more resilient terrestrial material leads to an increase in the C/N mass ratio with time. A major part of the C and N loss from the sediment occurs within the first 5 years after deposition (20% and 30%, respectively) after which the loss rate is low,

and thus the C/N mass ratios below that zone reflect that of the initial accumulation of organic matter (Gälman and others 2008). However, these loss rates are highly dependent on initial composition of the sediment, the condition of the lake – sediment interface (oxic or anoxic), and processes such as mixing, bioturbation, fragmentation, and further consumption.

That the increasing trends in C /N mass ratios in recently deposited sediments reflect an increase in aquatic derived organic material are further supported by increases in BSi content and $\delta^{13}\text{C}$ enrichment. The BSi and $\delta^{13}\text{C}$ proxies generally suggest that primary productivity increased during the last century. These proxies are potentially less susceptible to decomposition or diagenetic alteration than C_{org} and N_{org} . ^{13}C of organic matter is resistant to isotopic alteration during water-column or post-burial diagenesis (Schelske and Hodell 1995). Silica concentrations in near surface waters proved to be near saturation during our site visit indicating that silica is not limited in the euphotic zone (Table 2.1). Thus, it is plausible that opal is near saturation at the water-sediment interface and the increasing BSi signal is authentic. The C/N as a proxy for productivity further supports this if not affected much by decomposition. The stability of these proxies in near surface sediments along with coherent patterns between several biogeochemical proxies further demonstrates that overall, lake production has increased across our study sites over last half century.

2.6.2 Vegetation Expansion and Increased Aquatic Productivity

Vegetation is integral to ecosystem function, energy transfer, and element cycling, and has the potential to both impact and respond to environmental drivers. Changes in the pollen percentages from circa 1900 AD to the present indicate rapid vegetation succession of SWAN watersheds in a post LIA environment. Along with these rapid landscape changes our lake sediment biogeochemical analysis of BSi and $\delta^{13}\text{C}$, in general, suggest a trend towards higher lake productivity. The decline in C/N mass ratios supports this interpretation if not affected much by decomposition processes. The decreasing trends in C/N mass ratios in our study are further supported by increases in BSi content and $\delta^{13}\text{C}$ enrichment. The trends of these proxies in near surface sediments along with coherent patterns between several biogeochemical proxies further demonstrate that overall, lake production has increased in at least the last half century.

More dramatically, the repeat photographs illustrate the dynamics of the SWAN landscapes over a relatively short time scale (~80-100 years). In comparing the old and recent photographs, it is evident that a variety of changes associated with vegetation succession and geomorphic processes have occurred within the parks. Although we note increased vegetation and biomass across many landscapes in the SWAN, the volcanic eruption of 1912 in KATM buried parts of the landscape in meters of ash creating many barren landscapes that have seen only a small amount of re-colonization. However, our detailed study lakes lie outside the zone of thick ash deposition, as we see only minimal evidence of the 1912 tephra in our cores. Most glaciers have shown dramatic retreat since the early 1900s, with newly exposed surfaces becoming rapidly vegetated by tall

shrubs and trees at low elevations but remaining sparsely vegetated at higher elevations. Expansion of trees and shrubs was observed in western KATM, and altitudinal increase in treeline was observed at many locations in LACL and KATM.

In LACL the extant of ecosystems is gradient driven by the Chigmit Mountains, which divide the subpolar marine climate of Cook Inlet from the continental climate of interior Alaska. Local climatic conditions transecting this divide from east to west vary with elevation and the distance from mountains and large bodies of water. In addition to observed climate warming ocean climate variability (e.g. PDO) can potentially enhance or impair optimum aquatic and terrestrial conditions over time (e.g. higher rates of photosynthesis or drought stress).

Although the post LIA expansion of *Alnus* is much less dramatic than the early Holocene expansion circa 8000-7000 BP (calibrated ^{14}C years before present) (Hu and others 1995, 2001), *Alnus* pollen percentages and accumulation rates (in this study and a number of other studies in southwestern Alaska (see Brubaker and others 2001), reflect the high density of *Alnus* shrubs that characterize the region. *Alnus* are typical pioneer species that invade nutrient-poor soils. They benefit from a nitrogen-fixing association with a bacterial symbiont, while supplying the symbiont with photosynthetic products. In LACL and KATM, *Alnus* colonize recently deglaciated or highly disturbed areas, riparian corridors, and are nearly ubiquitous on hillsides and sub-alpine areas. The presence of *Alnus* has been suggested to be the principal source of N for the establishment and expansion of other vegetation types in other Alaskan terrestrial ecosystems (Crocker and Major 1955; Chapin and others 1994; Rhoades and others 2001; Engstrom and Fritz

2006), and the primary source of N to the aquatic ecosystems (Goldman 1961; Stottlemeyer 1992; Helfield and Naiman 2002; Bartz and Naiman 2005). The N from *Alnus* in turn may be a very important attribute of these systems; previous studies suggest the larger Lake Clark and Kontrashibuna Lake proper are co-limited by N or P seasonally and at different depths within the euphotic zone (Stottlemeyer and Chamberlain 1987; Wilkens 2002). Marked changes in the biogeochemical proxies (e.g. BSi, C/N, and $\delta^{13}\text{C}$) suggest that increased aquatic productivity and accelerated nutrient cycling at our study lakes began as early as the end of the LIA. This compares favorably with pollen records and photographic evidence that suggest increased vegetation expansion over the same time period. On the landscape at all of our sites, *Alnus* along the margins of rapidly receding glaciers and in disturbed areas (Figure 2.2), has the potential to supply substantial N to both the terrestrial and aquatic ecosystems.

Twentieth century warming of northern latitudes, especially those above 50°N has been well established by both instrumental and paleo-investigations (Overpeck and others 1997; Serreze and others 2000). Surface changes include one to two week increases in growing season, earlier timing of ice out for lakes, increases in the disturbance regime by insects and fire as well as deglaciation (IPCC 2007). In the high arctic cold-limited systems are responding to warming where plant growth and establishment are increasing along with temperature (see Sturm and Racine 2001; Tape and others 2006). These changes are strongly linked to changes in albedo and energy budgets (Chapin and others 2005; Sturm and others 2005). However, recent declining terrestrial vegetation productivity has been observed in tree ring studies and linked to increasing drought stress

at one of our study sites, the Portage Lake watershed (see Driscoll and others 2005). Declines in boreal forest greenness and vegetation productivity have also been detected by recent satellite observations and modeling efforts (Goetz and others 2005). Growth responses of vegetation to climate seem to diverge more and more since the 1950s (D'Arrigo and others 2008). This challenges our understanding of climate change responses and climate reconstructions. Nonetheless, a variety of data indicate an overall increase in vegetation cover and alder abundance since the end of the LIA. Increases in soil decomposition and plant-available nitrogen coinciding with regional warming trends and increased vegetation cover are likely to result in positive productivity responses in many landscapes (IPCC 2007).

Increasing vegetation abundance on the landscape corresponds with in-lake biogeochemical proxies that denote increased aquatic productivity. Increasing trends in BSi, N%, $\delta^{13}\text{C}$, and decreasing ratios of C/N suggest that lake primary production has increased coincident with increases in pollen concentrations within each lake system. Despite the differences in vegetation type and distribution within each watershed, this initial rise of increasing lake primary production is consistent with factors relating to lake ontogeny (Pearsall 1921; Fritz and others 2004), and likely morphology and watershed size.

2.6.3 Does the Landscape Distribution of *Alnus sp.* Influence Sedimentary N and Primary Productivity?

N-fixing organisms release fixed N to their surroundings (Millbank 1982; Millbank and Olsen 1986), mostly as nitrate and ammonium (Belnap 2001) that can be sequestered by soil microorganisms and plants. Concentrations of nitrate and dissolved organic nitrogen were shown to be strongly correlated with broadleaf cover of *Alnus rubra* (Red Alder) within entire watersheds of the Pacific Northwest, indicating that *Alnus* stands play a critical role in N export (Compton and others 2003). Thus, leaching of N from alder and mixed alder–conifer stands clearly has the potential to influence water chemistry (Stottlemeyer 1992; Rhodes and others 2001; Compton and others 2003). Most published rates of N₂-fixation range from 100 to 200 kg N ha⁻¹ y⁻¹ for pure stands (Binkley and others 1994). This suggests that N inputs by *Alnus* can result in very high rates of N export. In our study focused on lake sediments we found that the relationship between *Alnus* biomass and distribution was not clearly reflected in the N content of the sedimentary record. The N content of sediments was not related to percentage of *Alnus* cover in individual watersheds despite the fact that *Alnus sp.* generally dominate the landscape ranging from 70% to 24% of the total vegetation in the study watersheds (Table 2.3). In addition, there does not appear to be a direct relationship between percent N in lake sediments and the concentration of N as Nitrate + Nitrite (NO₃⁻+NO₂) from our one-time surface water samples. DIN was negatively correlated to *Alnus* distribution with the highest concentration of N present in Portage Lake, the watershed with the lowest *Alnus* distribution. The surface sediment comparison of non-anadromous lakes

(n=9) also did not correspond with the *Alnus* percent distribution across the transect (*Alnus* dominated in coastal and boreal sites and herbs dominated at interior sites). In general, N content of the sediments increased from coastal to non-coastal areas (Figures 2.7a, 2.8a, 2.9a, and 2.10). The observation that both the organic N pool in the sediments and the inorganic N pool in the lake waters are unrelated to alder distribution suggests that other factors control concentrations in these pools (e.g. rate N-cycling or uptake). The percent of N in sediments is likely a poor proxy for N deposition rates across the many different lake types because of lake-specific organic and inorganic sedimentation rates. Likewise, summer nitrate concentrations are likely not a good indicator of watershed N loading.

In contrast, the use of stable isotopes, which are not subject to dilution from inorganic materials, may give better insight into nutrient sources and cycling in these systems in the absence of detailed monitoring. For example, Portage Lake had the most enriched $\delta^{15}\text{N}$ values of the three study lakes indicating that N cycling is higher and thus N is in greater demand in comparison to availability. Less fractionation of N indicates less discrimination against the heavier isotope, or lower relative N limitation. In Hickerson Lake, an *Alnus* dominated system, we observed very low $\delta^{15}\text{N}$ values, which potentially reflect that of N-fixing species and/or substantial N concentrations are available in comparison to nutrient demand. The small but discernable declining trend in Kontrashibuna $\delta^{15}\text{N}$ values from circa 1850 to the present, along with increased N content of the sediments is indicative of increased N availability to the aquatic ecosystem. This is likely due to landscape processes and potentially significant contributions of

Alnus expanding on hillsides and along riparian corridors. The coherent pattern between increasing BSi, C%, N%, $\delta^{13}\text{C}$ and decreasing $\delta^{15}\text{N}$ suggests that the increased availability of N on the landscape from vegetation expansion is transported via runoff to the lake system and aids in the stimulation of primary production in the lake-water in Kontrashibuna Lake and perhaps to a lesser extent in Hickerson Lake. Both Kontrashibuna Lake and Lake Clark can be co-limited by N or P seasonally. The nutrient limitation in these studies suggest dependence on seasonal variation and/or proximity to stream outlets with an abundance of *Alnus* situated along the riparian corridors (Stottlemeyer and Chamberlain 1987). Seasonal patterns of inorganic and organic N pool concentrations in surface waters and inflowing waters are necessary to further elucidate the causal factors for the patterns observed in the sediments.

2.6.4 Climatic forcing influences on vegetation and aquatic ecosystem dynamics

Winter climate variables such as precipitation and air temperature affect summer primary productivity through ice-out timing, water temperatures and runoff. Other studies have shown that nutrient availability in the spring is influenced by the previous year's primary productivity, which influences primary productivity in the following summer. For example, a 42-year study of Castle Lake, California suggested that nutrient availability was related to ice-out timing as well as primary productivity in the proceeding year (Park and others 2004). The study demonstrated that the positive phase of the PDO was positively correlated to increases in water temperature and lake primary production. A PDO polarity reversal in 1977 significantly affected air temperatures and precipitation across our study region (Figure 2.3a, b) (Western Regional Climate Center

2008). The instrument record shows that the coastal area is most influenced by these changes (See Figure 3b - Kodiak Island station) as demonstrated by a mean annual increase of 1°C air temperature and a large increase in annual precipitation of >75mm of precipitation from ~1950 to 2000 (Western Regional Climate Center 2008). Positive-PDO-year discharge from the Kenai River in the central Gulf of Alaska region is on average about 18% higher than during the negative polarity PDO years indicating higher precipitation of which a large proportion is snow (Mantua and others 1997).

Since no long-term lake temperature or productivity data exist for the study time period in this region, paleolimnological analyses are critical for examining how changes in air temperature and precipitation patterns are related to lake biogeochemistry and landscape vegetation patterns. In the northern latitudes significant warming began circa 1850 at the close of the LIA, representing the coldest interval of the mid- to late Holocene over many regions. However, the 20th century has been shown to be the warmest of the last 400 years (Overpeck and others 1997). Overlaying this general warming trend in the north Pacific region are decade-scale periods of PDO variability. During the time period from 1900 to the present the PDO has gone through two negative and positive phases. BSi, N, C and C/N in all lakes generally positively correlate with the latest positive polarity regime from 1977 - ~1999 and the patterns, although less distinct, are still discernable down core. Overall our data suggest the PDO has had the most influence on the primary productivity in the study lake systems during the most recent polarity reversal (Figure 2.13). Increased BSi in the post 1977 interval of all cores shows inflections in the same direction to shifts that might be expected from warming

and/or increases in precipitation. This interpretation is further strengthened by observing that the fluctuation in the BSi record is less pronounced at the furthest in-land site (Portage Lake) in comparison to that of the coastal and montane sites.

Disentangling causal factors for these productivity increases is complicated due to the variety of factors that are driving or influenced by change over similar time intervals. Collectively, the landscape analysis, repeat photography and pollen data from the sediments imply vegetation changes over the same time interval. While the observed 20th century biogeochemical changes and vegetation expansion are at least partially attributable to climatic processes, it is difficult to determine the role of the feedback of vegetation change on lake productivity.

2.6.5 Biogeochemical proxies in non-anadromous lake systems - an aid for interpreting the influence of climate, landscape, and lake morphology in anadromous lake systems

Early marine survival of sockeye salmon is related to their size at the time they enter the ocean (Pearcy 1992; Koenings and others 1993). Therefore, it has been hypothesized that factors influencing the size of smolts such as, increases in nutrients, primary productivity and resultant prey may encourage higher survival rates of juvenile sockeye salmon and subsequent increases in their production over the long term (Koenings and Burkett 1987; Uchiyama and others 2008). Perhaps the most important variable with respect to tracing SDN in lake systems is $\delta^{15}\text{N}$. Upon returning to their natal streams to spawn and then die, semelparous anadromous Pacific salmon transport biogenic N virtually 100% marine in origin (Kline and others 1993). This marine source

of N has been shown to be isotopically distinguishable from terrestrial and freshwater N (Kline and others 1993; Ben-David and others 1997; Finney 1998; Finney and others 2000; O'Keefe and Edwards 2002; Schindler and others 2005). This is in part due to the large difference in $^{15}\text{N}/^{14}\text{N}$ in returning salmon compared with that in the terrestrial environment (driven by N_2 -fixation).

Our study of surface sediments from nine non-anadromous lakes within the SWAN region reveals a range of $\delta^{15}\text{N}$ values in the different biological and biogeochemical compartments that define the natural variation across SWAN parks. Predictably the larger and deep glacial fed systems contain depleted $\delta^{15}\text{N}$ signatures in contrast to the clear or organically stained shallow lakes. The concentration of OM in the sediments and the increased rate of nutrient cycling are thus reflected in the stable isotope signatures; generally higher $\delta^{15}\text{N}$ values occur in the systems with higher production regimes. Importantly, all of these lakes drain to, and thus supply, the anadromous systems and therefore may play a role in the resulting isotopic signatures in anadromous lake studies. Thus, the proportion of glacially derived or non-glacially derived waters flowing to the non-anadromous systems could potentially affect the downstream $\delta^{15}\text{N}$ signatures in an anadromous system. The innumerable small and shallow kettle ponds that cover the landscape in SWAN could be draining relatively high concentrations of N and enriched $\delta^{15}\text{N}$ into the major anadromous systems. The sediments in the shallower organically stained lakes (e.g. Idavain Lake) from our study have $\delta^{15}\text{N}$ values nearing 4‰ and zooplankton values nearing 9‰. These values are similar to those found in many anadromous systems (Finney and others 2000). Understanding the overall

contribution of these small organically stained lakes with enriched $\delta^{15}\text{N}$ values to the overall $\delta^{15}\text{N}$ signature found in the deep basins of anadromous systems might be an important consideration in salmon system N isotope balance, as the terrestrial $\delta^{15}\text{N}$ end member strongly influences calculations of SDN importance (Schindler and others 2005). The larger lakes that are often glacial fed, provide much of the overall water and sediment supply to anadromous systems downstream, have much smaller $\delta^{15}\text{N}$ values (range = 1.5 to 2‰ in sediments and -1.5 to 4‰ for zooplankton) and are generally more similar in morphology to the anadromous systems within the SWAN. This work illustrates the importance of selecting an appropriate control system for comparative studies focused on SDN subsidies to freshwater systems.

The quantity of nutrients exported from watersheds into lakes rises with increasing watershed area (Kalff 2002). The important anadromous lakes for sockeye salmon in the SWAN system are very large and incorporate inputs from watershed areas that far exceed the lakes in our study. The lakes with large watershed areas are more likely to experience large inputs of terrestrial nutrients relative to the nutrients derived from spawning salmon despite the magnitude of the run size. In such lakes, SDN has been postulated, in a number of studies, to be of secondary importance to the productivity of the system and to the growth of juvenile salmon (e.g. Finney and others 2000; Naiman and others 2002; Schindler and others 2003). Because the stable isotope signature of terrestrial nitrogen is much lighter than nitrogen derived from adult salmon, all of the biological compartments (phytoplankton to juvenile salmon) and the sediments in a lake in which nutrients from terrestrial sources are abundant have a lower $\delta^{15}\text{N}$ value.

Perhaps the most interesting and important aspect of the comparison between non-anadromous lakes in this study and anadromous lake studies including unpublished data from this region (e.g. Naknek Lake) lies in the down core profiles of BSi, C/N, and the isotopic signatures. In all three of our lake cores we observed marked increases during the 20th century in proxies related to primary production. In contrast, anadromous systems that likely have similar regional climate forcing often show a distinct reduction in productivity indicators in addition to decreasing trends in the stable isotope measurements of C and N, all reflecting a 20th century decline in primary production. Declines in SDN due to commercial fishing and fluctuations in the PDO have been postulated to explain these trends (Finney and others 2000). Climate mediated or disturbance driven increases in terrestrial and aquatic production appear to be occurring in most watersheds and non-anadromous systems. However, the reliance of anadromous systems on SDN to maintain higher rates of autochthonous production is quite clear and the recent inferred declines in primary production are noteworthy. The large fluctuations and recent declines in $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ in the anadromous systems of the SWAN are on the order of 2-6‰ and 1-3‰, respectively (Finney 2006). In our study lakes, recent changes generally trending toward enrichment, record a much smaller range for $\delta^{15}\text{N}$ (~0.5-2‰) and $\delta^{13}\text{C}$ (0-3‰). The importance of these contrasting trends with regard to salmon productivity is unclear but highly relevant to salmon management.

2.7 Conclusion

The aim of this research was to establish a better understanding of the links between the varying landscape processes across the SWAN region and the response of the aquatic community to these environmental factors. By comparing biogeochemical proxies and palynology of lake-bottom sediments with a study of current and historical landscape vegetation structure and composition we made an effort to document the types and rates of change occurring response to environmental drivers (e.g. climate, biotic interactions, and anthropogenic influences). This study has improved our understanding of environmental and landscape influence on aquatic ecosystems in the SWAN.

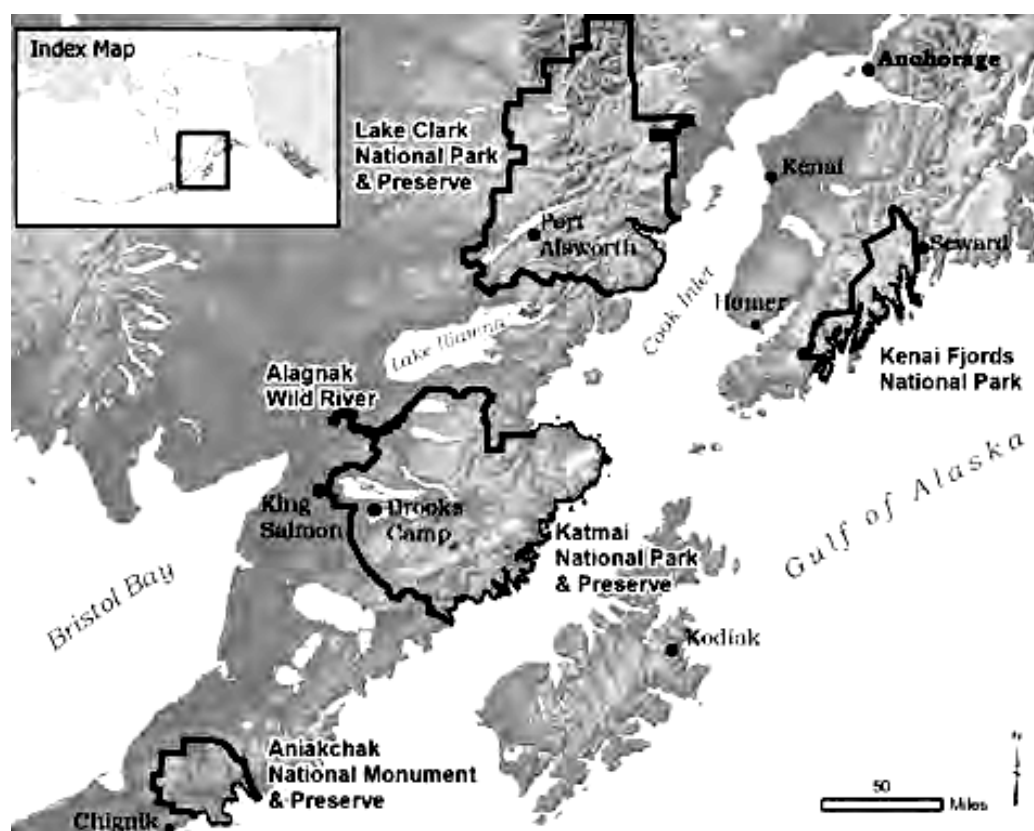
Kontrashibuna Lake provided the best overall record of recent paleoproductivity and contained the most robust data for our overall assessment and conclusions. The record from Kontrashibuna Lake was not confounded by the anomalous factors Hickerson Lake (e.g. steep cliff faced watershed with a single predominant vegetation type and no surface outlet) or Portage Lake (e.g. clear, 19 m secchi depth, with no major tributaries) presented. The landscape position of Kontrashibuna Lake and its watershed spans two physiographic gradients (coastal-montane and montane) of LACL, and the large size of the watershed and lake make it a representative control for the numerous large glacially-fed anadromous systems of the southwest Alaska region.

These results suggest limnological and landscape response, associated first with the end of the LIA and secondly to fluctuations of the PDO. Foremost is the observation that BSi in lake sediments began to change directionally before anthropogenic effects to the region (e.g. pre-1900), but pronounced changes in lake biogeochemistry have

occurred in subsequent decades, primarily since the 1950s. The PDO polarity reversal in 1977 significantly affected air temperatures and precipitation across our study region and accelerated the biological primary productivity in the lake systems. The effects of climate change were also observed in the terrestrial vegetation type and community structure across the landscape. Thus vegetation is potentially an important intermediary of lake development and primary productivity. This can be inferred by correlation of paleolimnological trends with those occurring during succession in the terrestrial system. Vegetation may play a key role in how climate affects productivity in this region by enhancing nutrient input. *Alnus* likely plays a key role due to N₂-fixation and its influence on overall terrestrial productivity and watershed nutrient export.

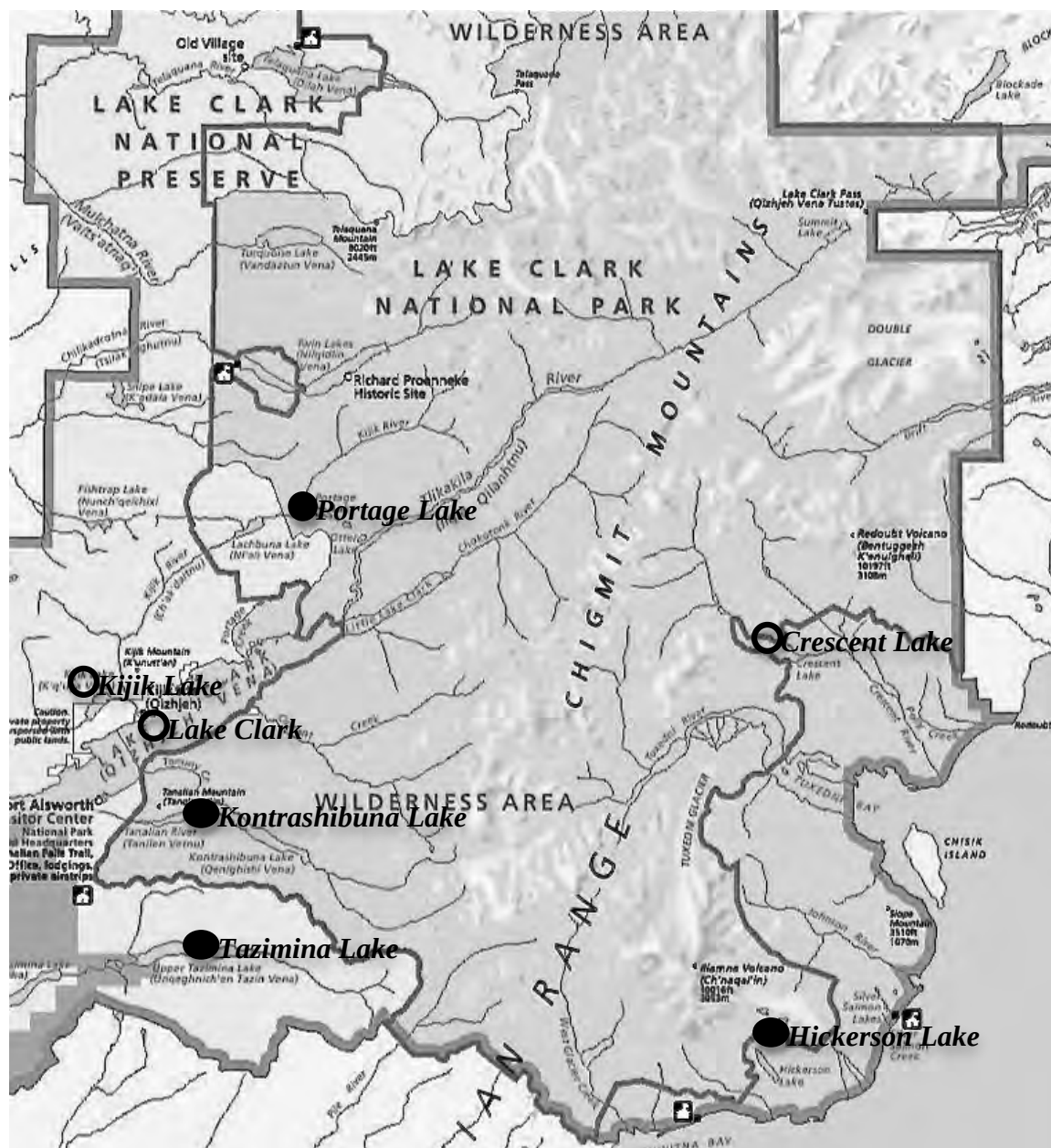
The trajectory of these oligotrophic lakes, trending toward a higher productive regime, is in sharp contrast to anadromous systems facing general decreases in aquatic primary productivity. The influence of the PDO and warming on lake 'ice-out' timing and in lake primary production may be a critical component of understanding rearing and survival of juvenile salmonids under a changing climate regime. The importance of understanding the historical productivity and ensuing changes in non-anadromous aquatic ecosystems of the SWAN and the southwest Alaska region is that these waters generally feed the relatively more productive anadromous systems. These systems act as an analog for climate, terrestrial, and aquatic ecosystem interactions without additions of marine-derived nutrient subsidies (e.g. SDN) and give us further information on factors (e.g. productivity, spawning and rearing success, terrestrial nutrient inputs) important for interpreting sediment records in anadromous systems. Furthermore, influences from

anthropogenic increases in atmospheric CO₂, N and climate warming may also be imbedded in the patterns and trends we have identified in the paleo-record.



Adapted from National Park Service Inventory and Monitoring Program Southwest Alaska Network base map

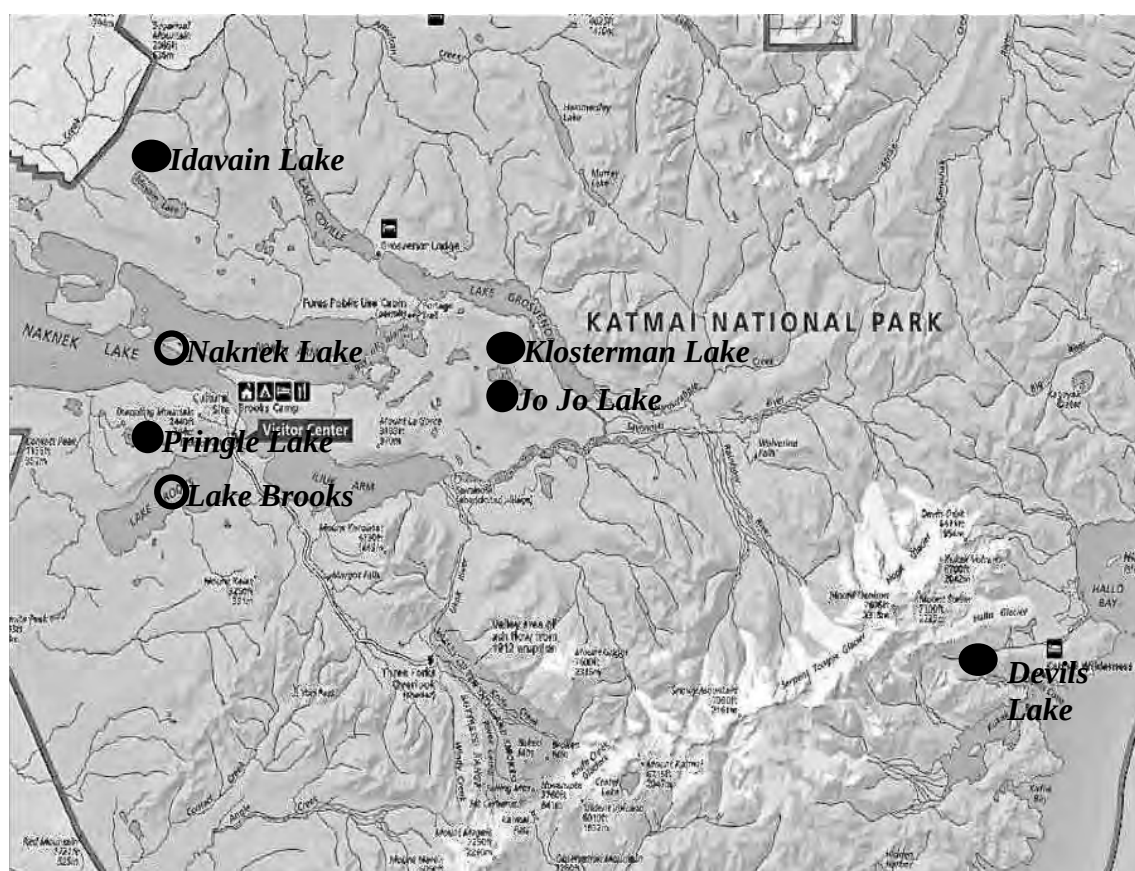
Figure 2.1a Location of the Southwest Alaska Network (SWAN) National Parks and Preserves.



Key

- Important Anadromous Lakes
- Non-anadromous study Lakes

Figure 2.1b Location of important anadromous lakes and non-anadromous study lakes within the boundaries of Lake Clark (LACL) National Park and Preserve.



Key

- *Important Anadromous Lakes*
- *Non-anadromous study Lakes*

Figure 2.1c Location of important anadromous lakes and non-anadromous study lakes within the boundaries of Katmai (KATM) National Park and Preserve.

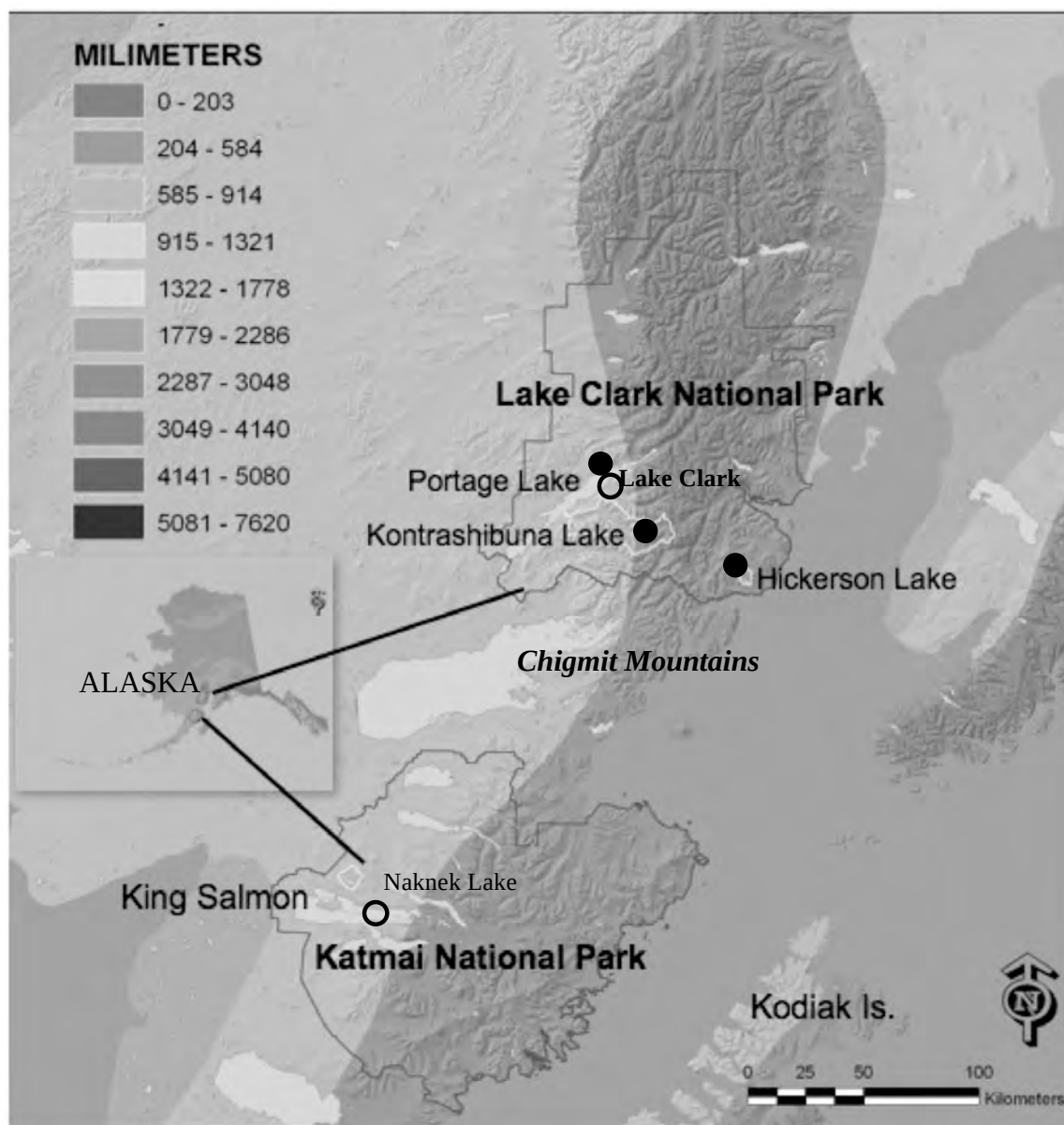


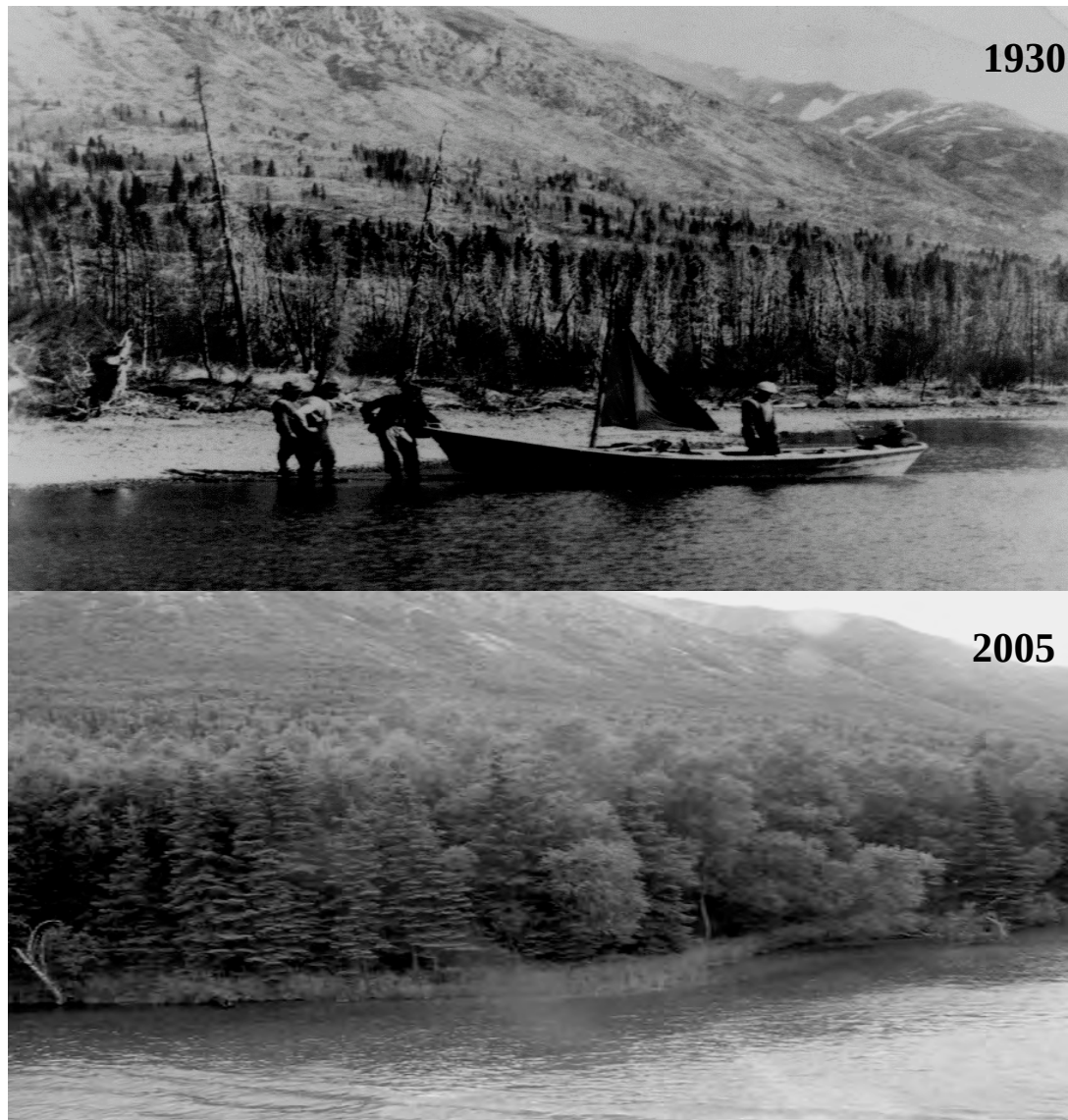
Figure 2.1d The physiographic gradient and the resulting precipitation pattern (decreasing west to east) across the north-south divide created by the Chigmit Mountains.

A



Repeat photography along the coast of KATM shows the beginning of post-LIA recession of the Four Peaked Glacier in 1894 in comparison to the Alder (*Alnus sp.*) covered glacial margins and mountainside (> 1000 m in elevation) along the coastal region at today.

Figure 2.2 A suite of repeat photographs spanning more than a century depict large-scale regional changes across different landscapes and climatic regions of LACL and KATM. All photographs are courtesy of the Alaska National Park Service and Torre Jorgenson ABR, INC Fairbanks, Alaska.

B

Repeat photography at Kontrashibuna Lake, LACL, illustrates revitalization of the watershed after fire. Foreground: Hillside and shoreline stabilization with the re-establishment and expansion of Spruce (*Picea Mariana*) and Poplar. Background: Alder (*Alnus fruticosa*) has advanced considerably upslope (>1000 m elevation).

Figure 2.2 (continued) A suite of repeat photographs spanning more than a century depict large-scale regional changes across different landscapes and climatic regions of LACL and KATM. All photographs are courtesy of the Alaska National Park Service and Torre Jorgenson ABR, INC Fairbanks, Alaska.

C



Repeat photography of hillside shrub expansion over 86 years near Grosvenor Lake, KATM, within an area of minimal disturbance. Note establishment and expansion of mixed shrub types including: *Salix*, *Betula*, and *Alnus* replacing dwarf prostrate shrub tundra

Figure 2.2 (continued) A suite of repeat photographs spanning more than a century depict large-scale regional changes across different landscapes and climatic regions of LACL and KATM. All photographs are courtesy of the Alaska National Park Service and Torre Jorgenson ABR, INC Fairbanks, Alaska.

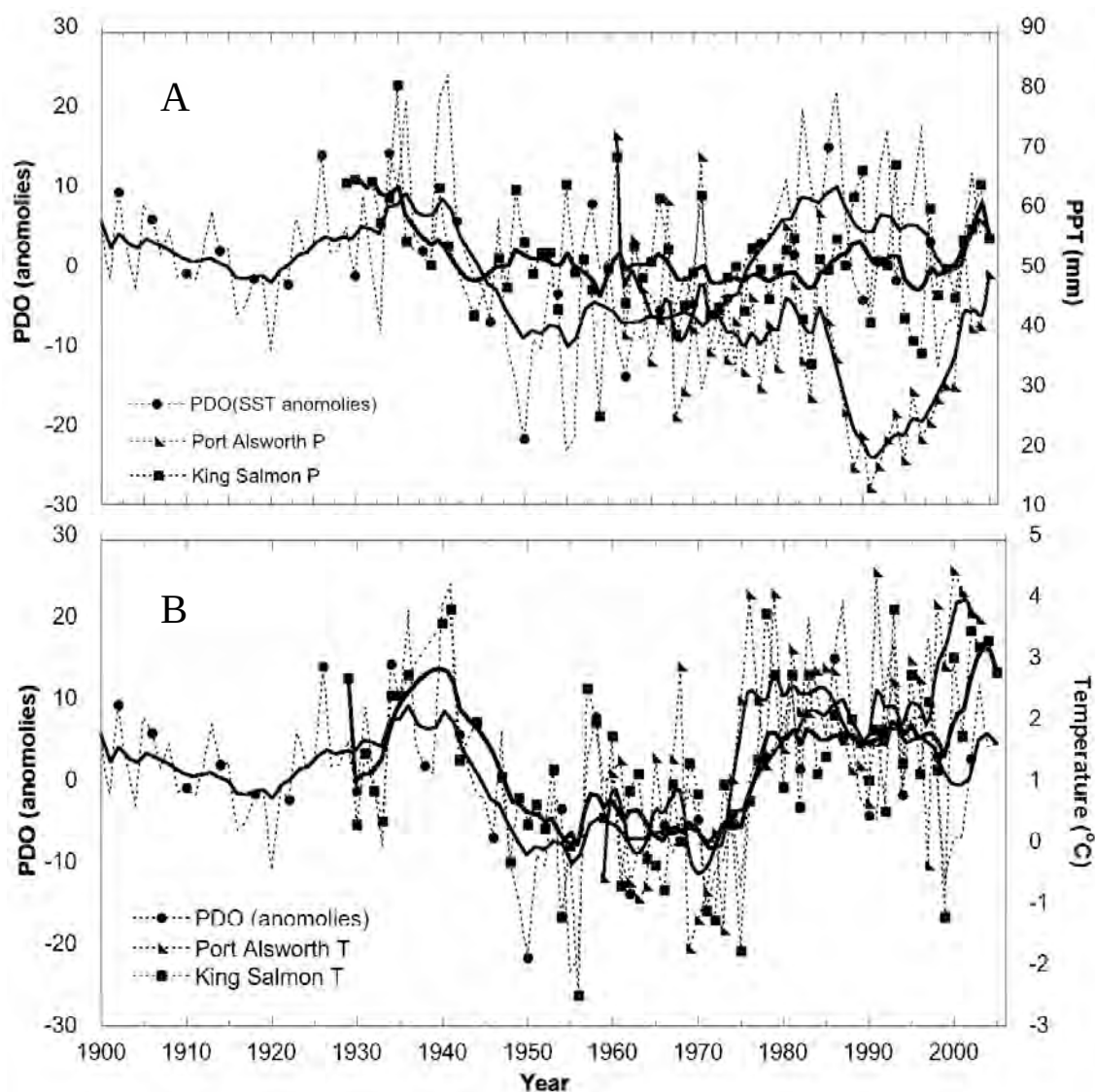
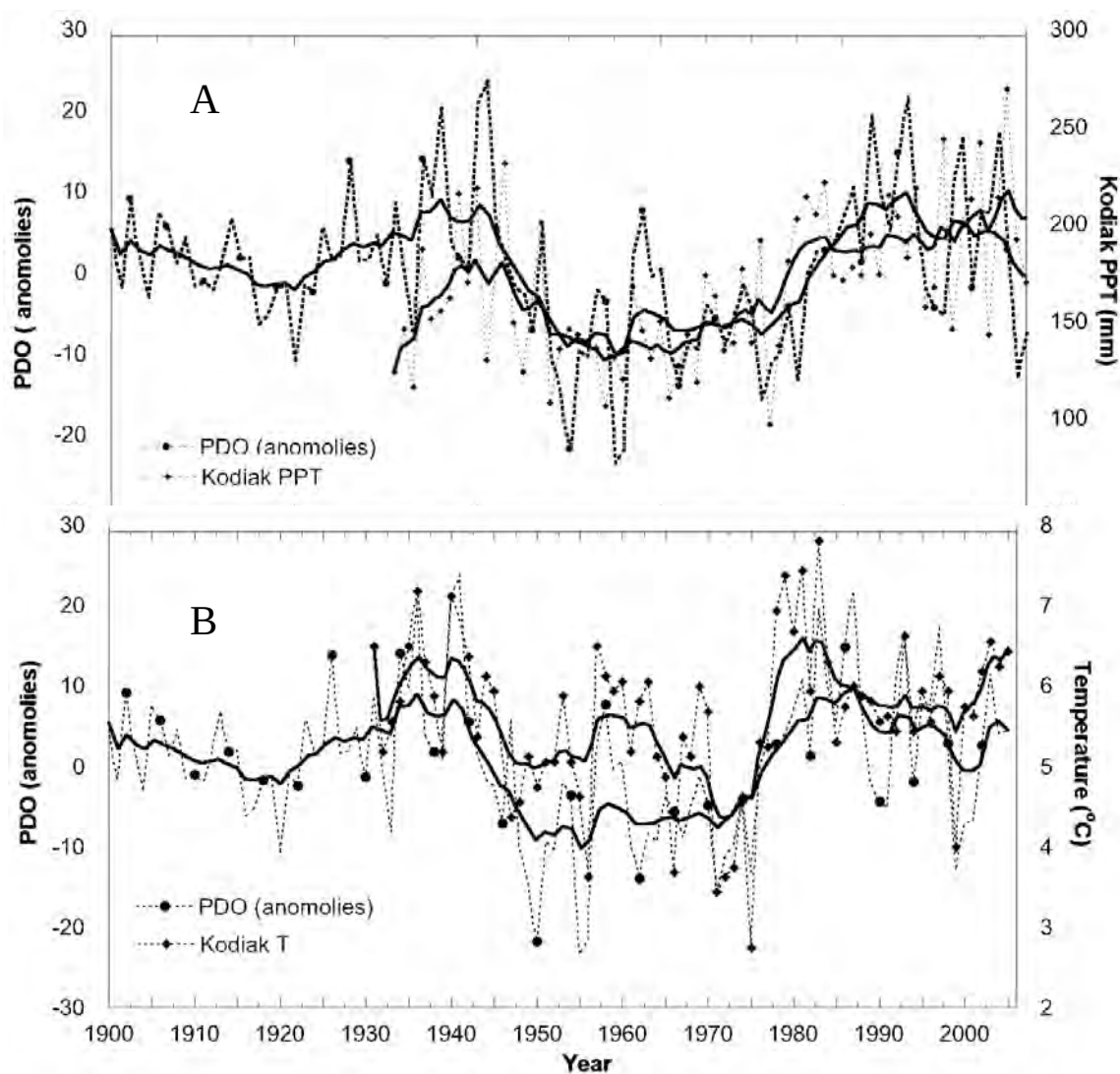


Figure 2.3a (A) Precipitation and (B) temperature records compared to PDO anomalies at Port Alsworth and King Salmon, AK weather stations. The station at Port Alsworth best represents climate on the eastern side of the Chigmit Mountains. However, the King Salmon weather station contains a longer and more continuous record and is representative of inland and lowland areas. Major late 20th century decreases in Port Alsworth's precipitation record are observed (A). Adapted from data provided by Western Regional Climate Center 2008.



Adapted from data provided by Western Regional Climate Center 2008.

Figure 2.3b Coastal precipitation (A) and temperature (B) records from Kodiak Is., AK compared to PDO anomalies. Note that coastal precipitation is much greater than that recorded at inland stations and temperatures are generally milder annually. Adapted from data provided by Western Regional Climate Center 2008.

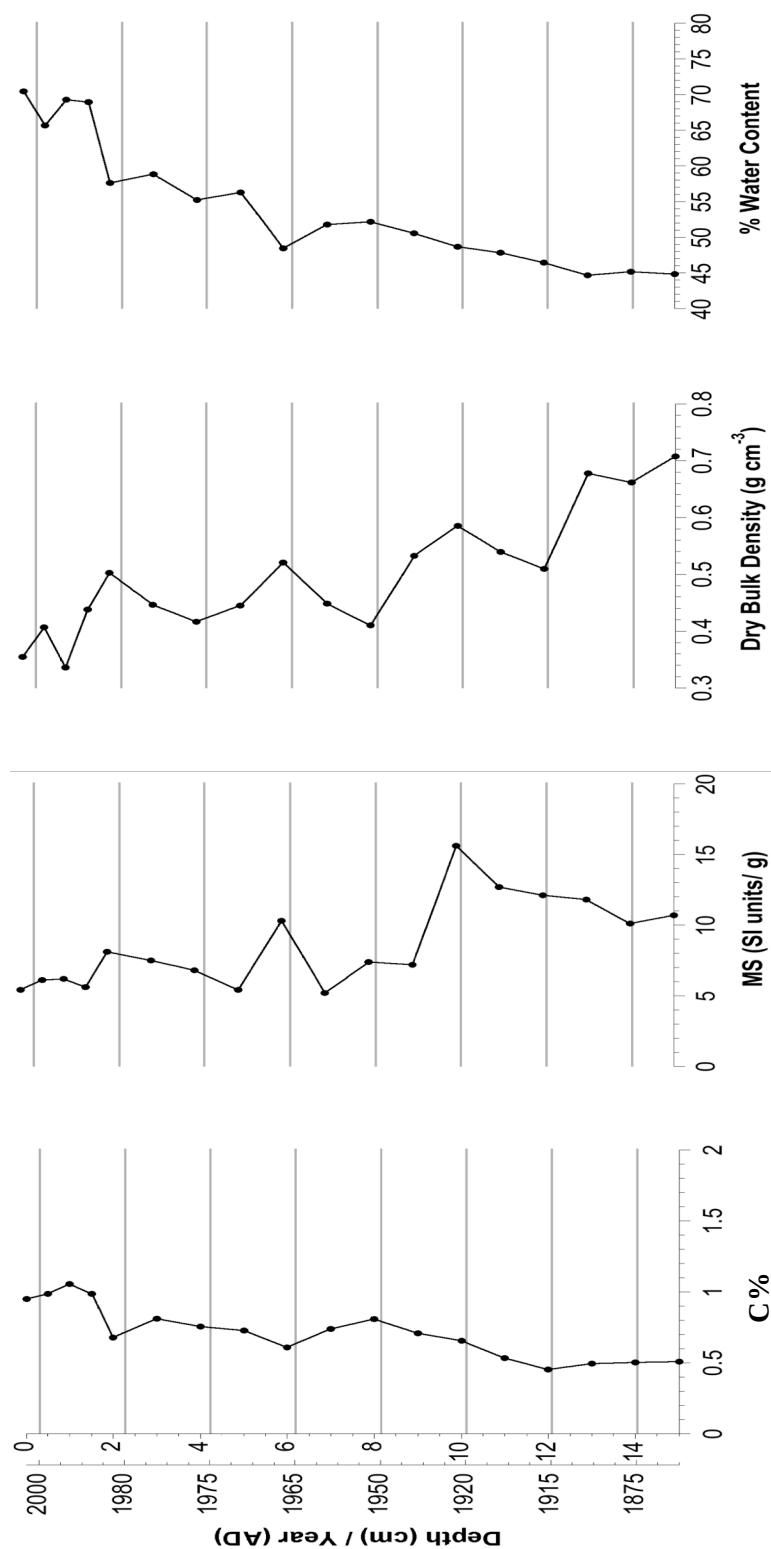


Figure 2.4a Comparison of physical properties and carbon percent (C%) from the Hickerson Lake sediment core.

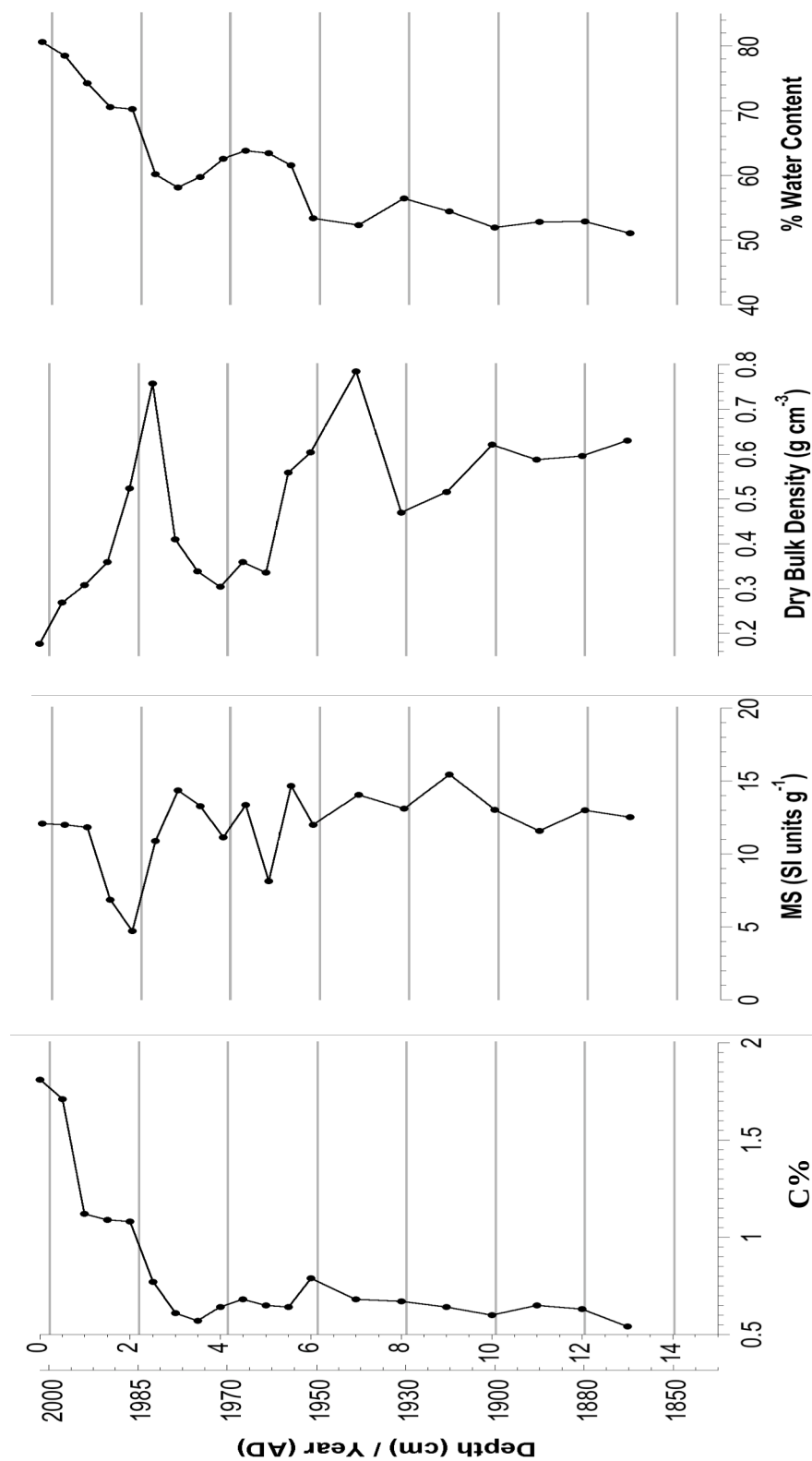


Figure 2.4b Comparison of physical properties and carbon percent (C%) from the Kontrashibuna Lake sediment core.

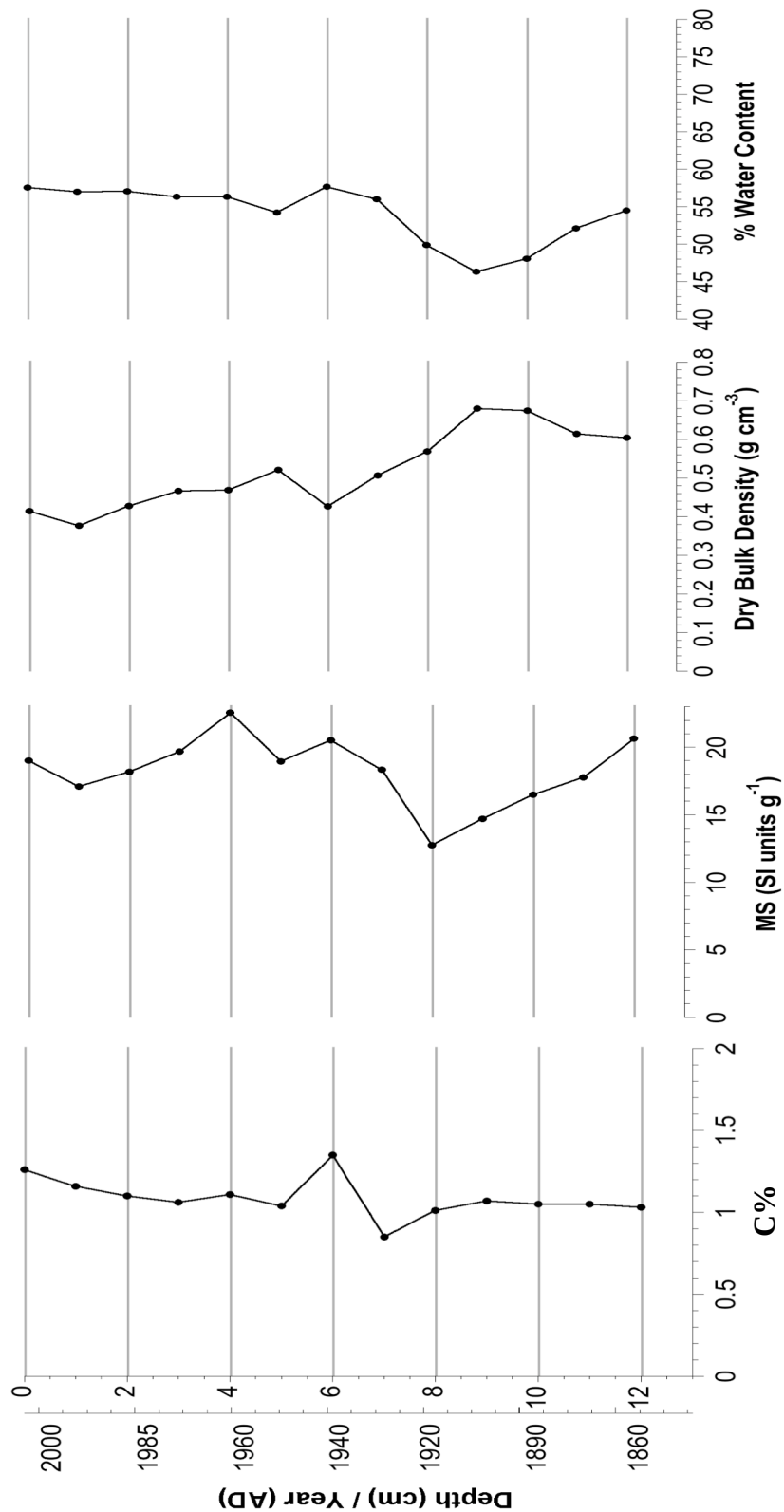


Figure 2.4c Comparison of physical properties and carbon percent (C%) from the Portage Lake sediment core.

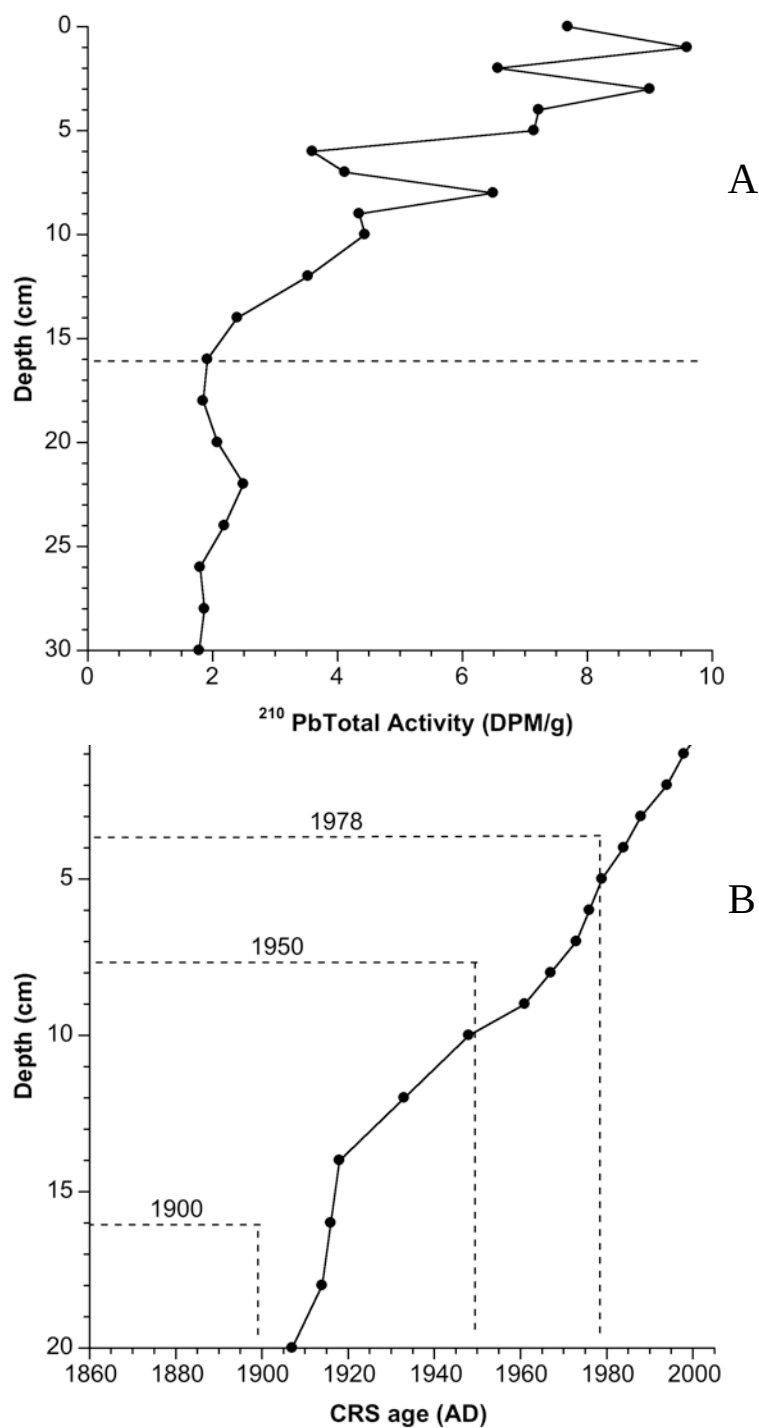


Figure 2.5a Down-core sediment ^{210}Pb activities (A) and corresponding CRS age-depth models (B) for the Hickerson Lake sediment core. Dashed horizontal lines (A) indicate the estimated depth of exhaustion of unsupported ^{210}Pb .

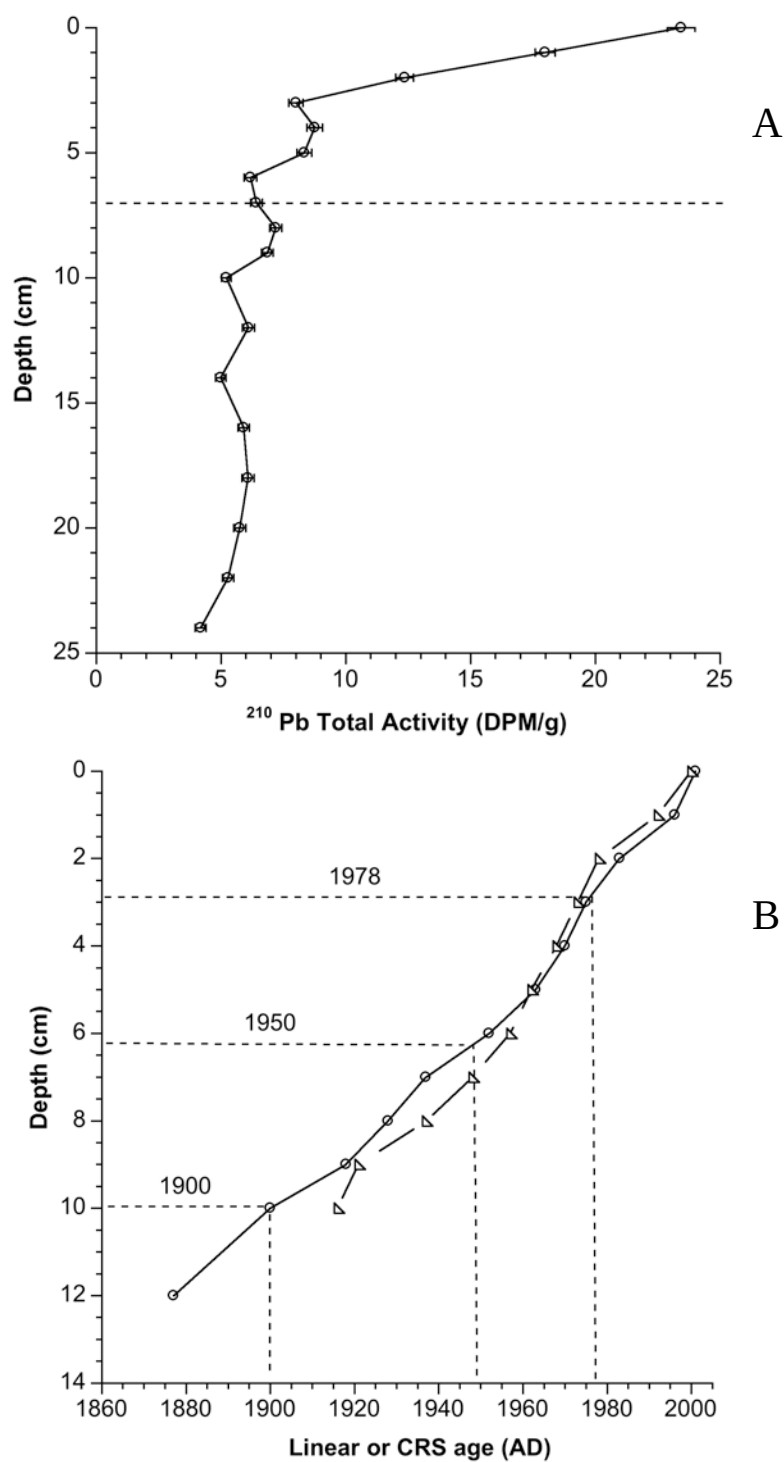


Figure 2.5b Down-core sediment ^{210}Pb activities (A) and corresponding linear (triangles) and CRS (circles) age-depth models (B) for the Kontrashibuna Lake sediment core. Dashed horizontal lines (A) indicate the estimated depth of exhaustion of unsupported ^{210}Pb .

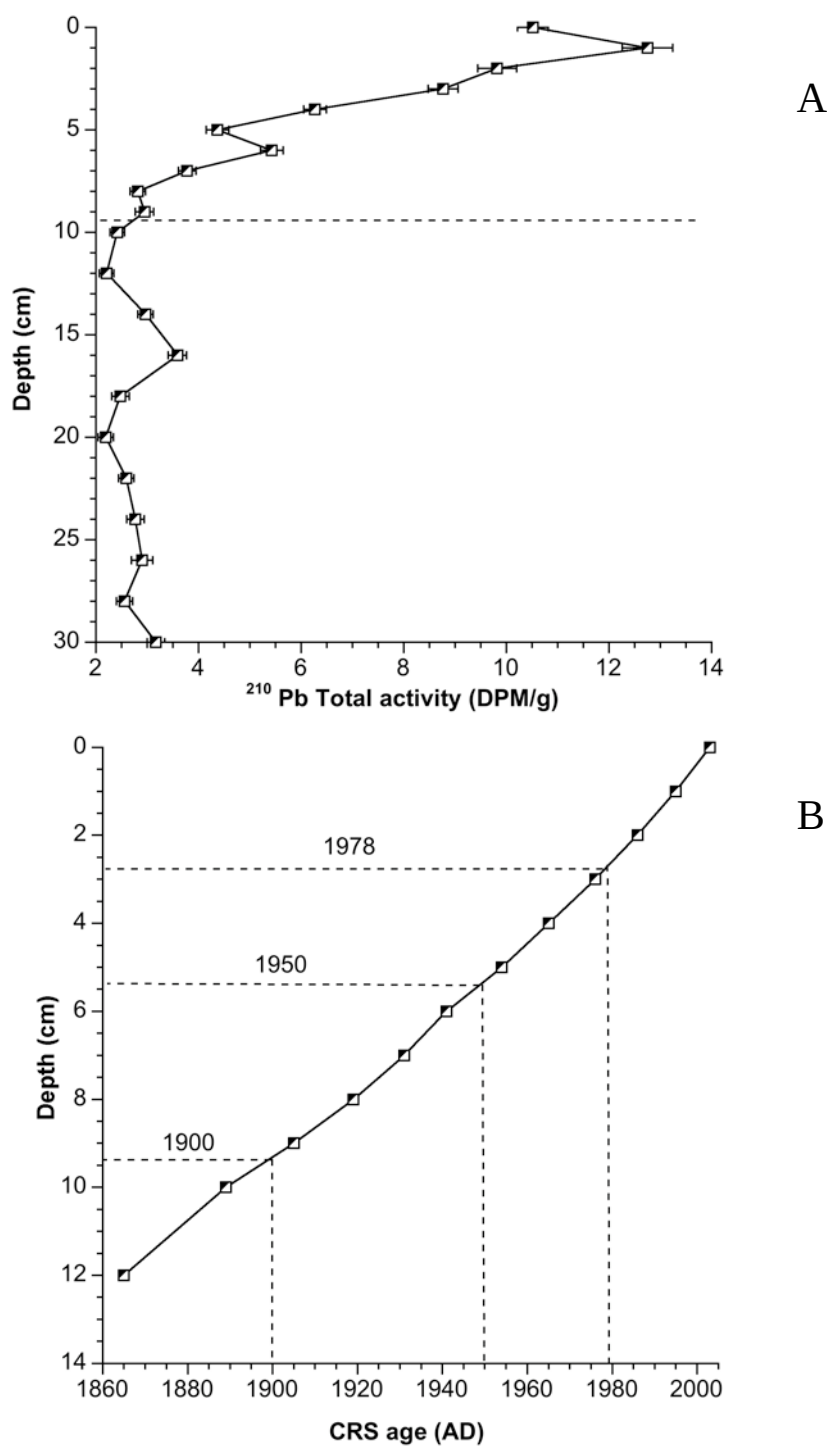


Figure 2.5c Down-core sediment ^{210}Pb activities (A) and corresponding CRS age-depth models (B) for the Portage Lake surface core. Dashed horizontal lines (A) indicate the estimated depth of exhaustion of unsupported ^{210}Pb .

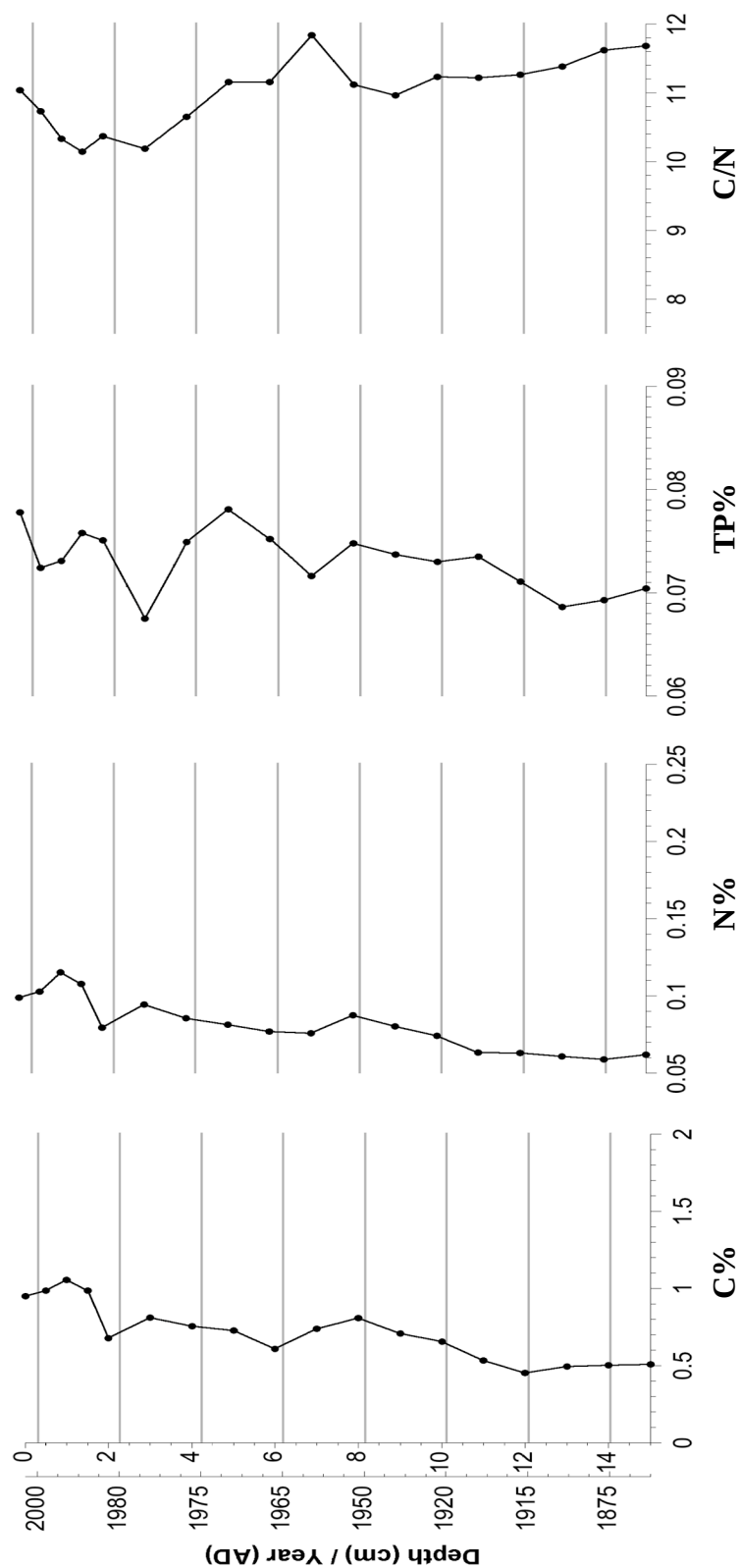


Figure 2.6a Comparison of percentages of carbon (C%), nitrogen (N%), total phosphorus (TP%), and mass ratios of C/N from the Hickerson Lake sediment core.

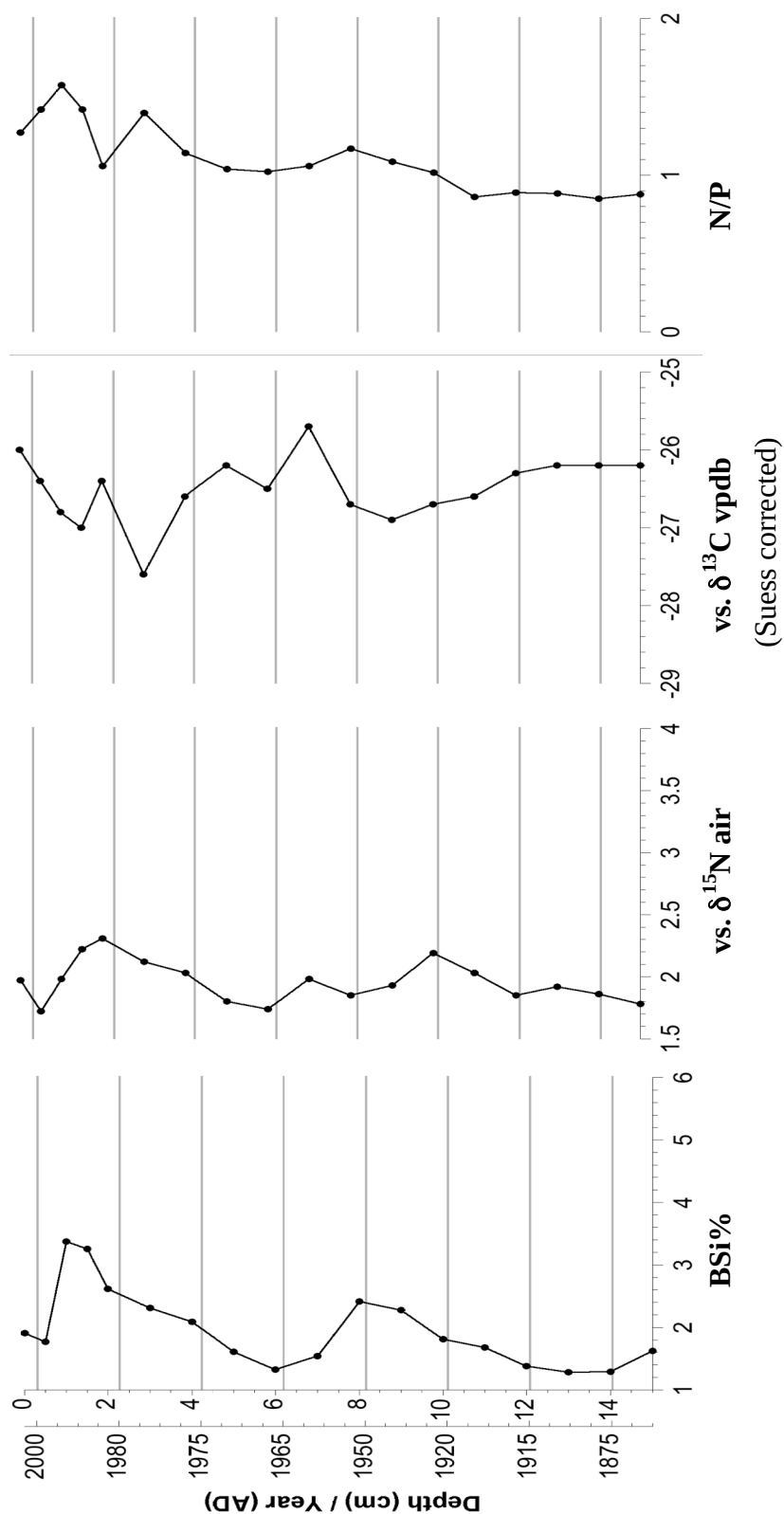


Figure 2.6b Percent Biogenic Opal (BSi%), Isotopic Ratios of $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ reported as ‰, and mass ratios of nitrogen to total phosphorus (N/P) from the Hickerson Lake sediment core.

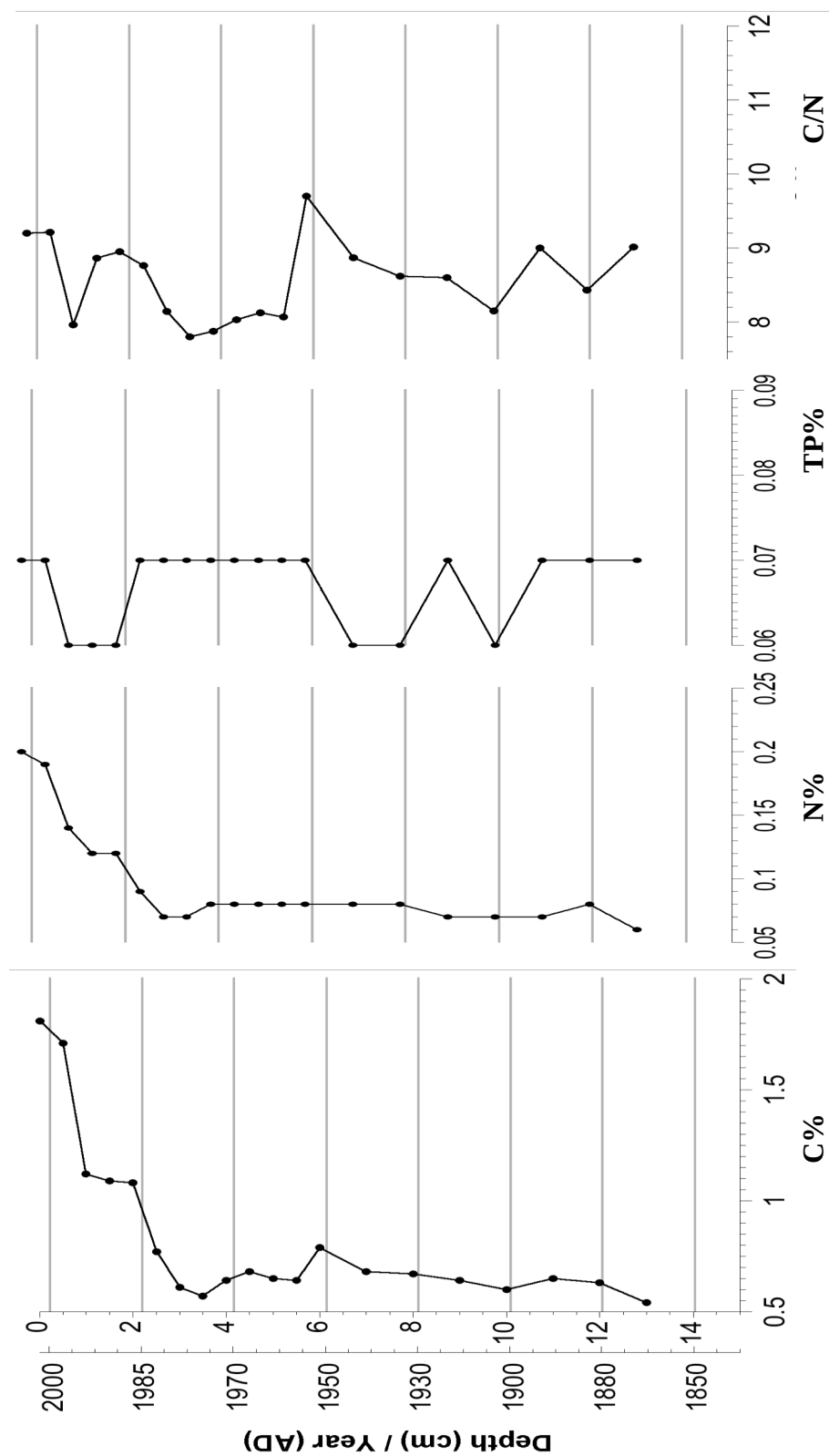


Figure 2.7a Comparison of percentages of carbon (C%), nitrogen (N%), total phosphorus (TP%), and mass ratios of C/N from the Kontrashibuna Lake sediment core.

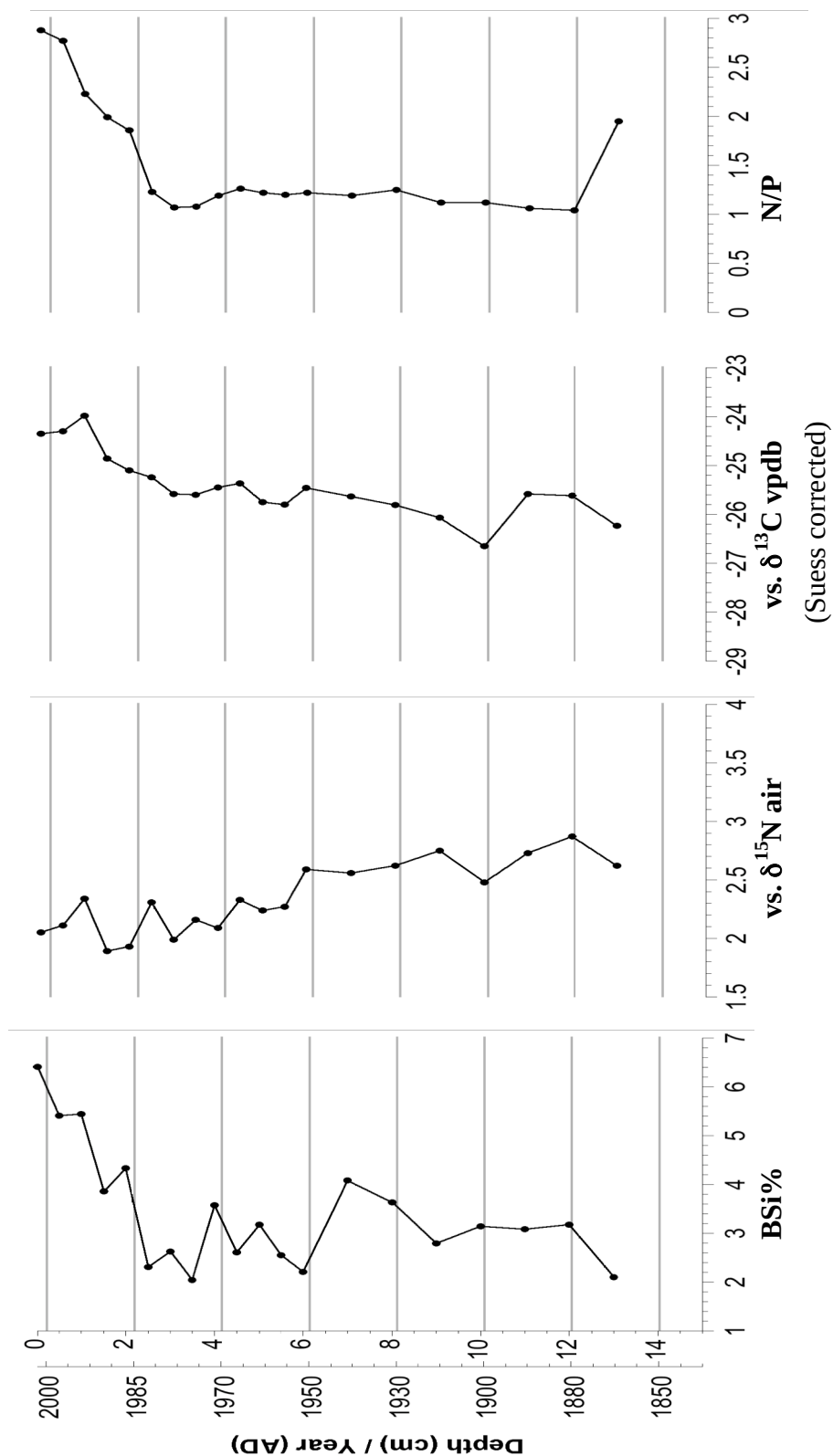


Figure 2.7b Percent Biogenic Opal (BSi%), Isotopic Ratios of $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ reported as ‰, and mass ratios of nitrogen to total phosphorus (N/P) from the Kontrashibuna Lake sediment

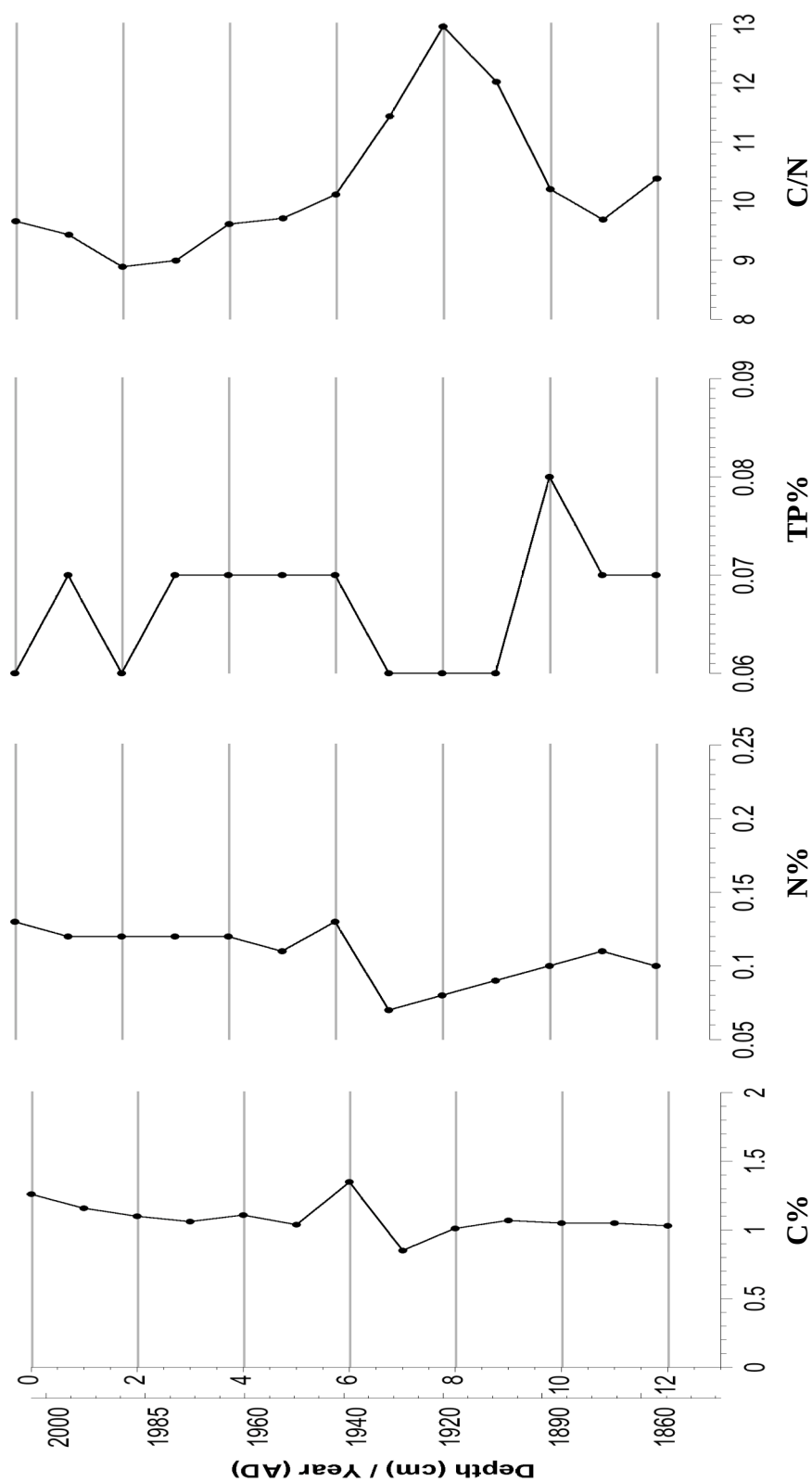


Figure 2.8a Comparison of percentages of carbon (C%), nitrogen (N%), total phosphorus (TP%), and mass ratios of C/N from the Portage Lake sediment core.

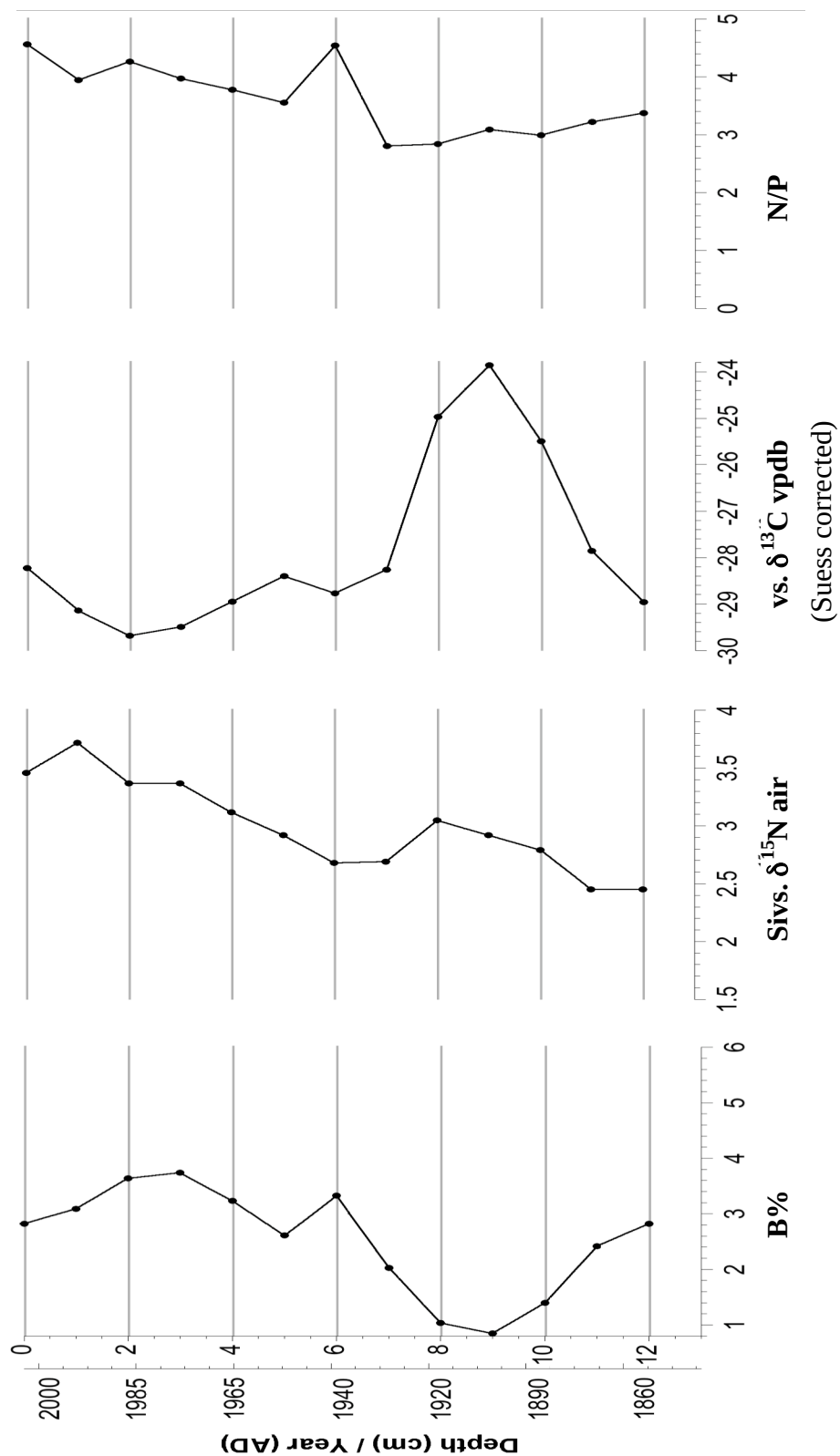


Figure 2.8b Percent Biogenic Opal (BSi%), Isotopic Ratios of $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ reported as ‰, and mass ratios of nitrogen to total phosphorus (N/P) from the Portage Lake sediment core.

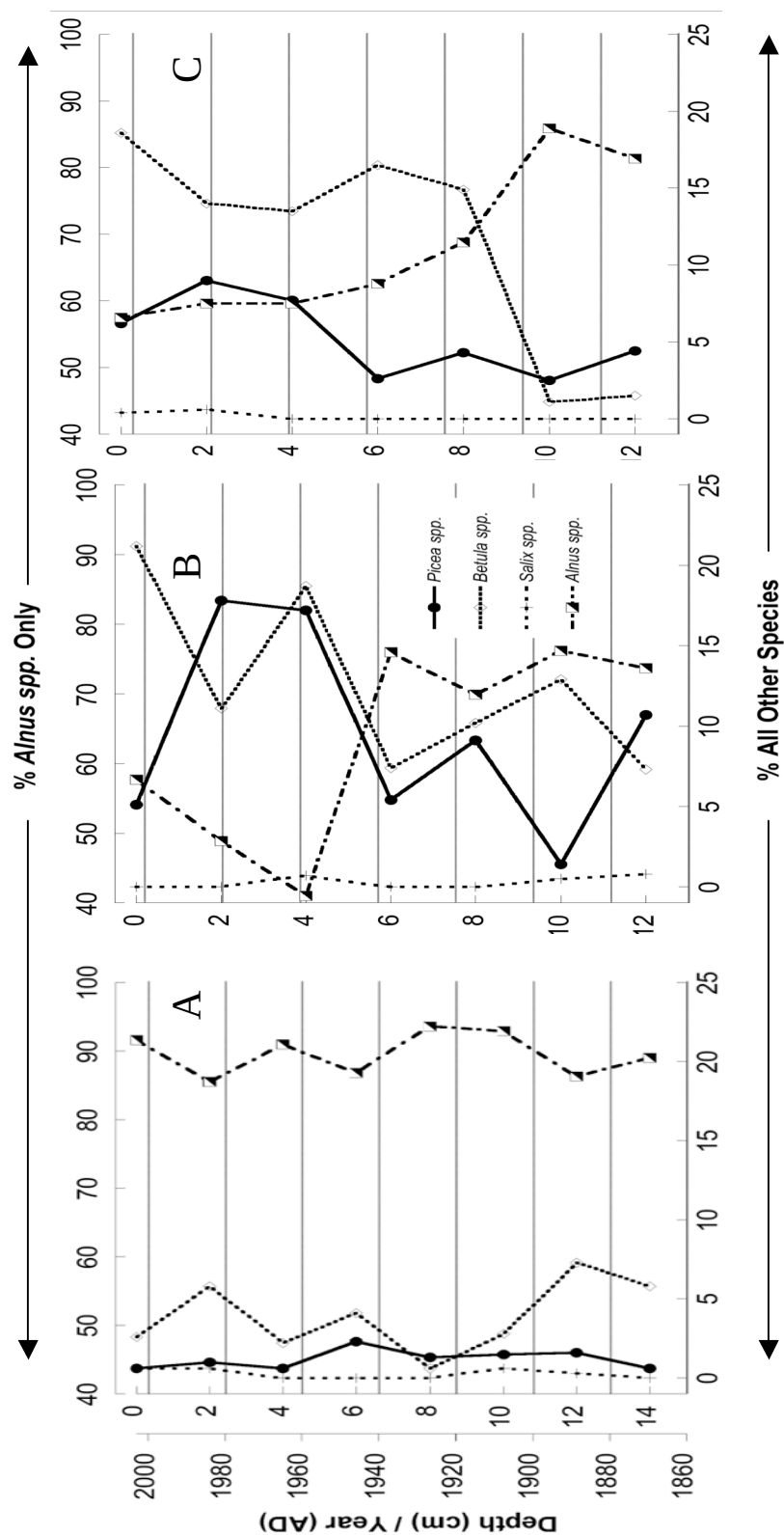


Figure 2.9 Pollen percentages of key taxa (*Picea*, *Betula*, *Salix*, and *Alnus*) from sediment cores of (A) Hickerson Lake, (B) Kontrashibuna Lake, (C) Portage Lake.

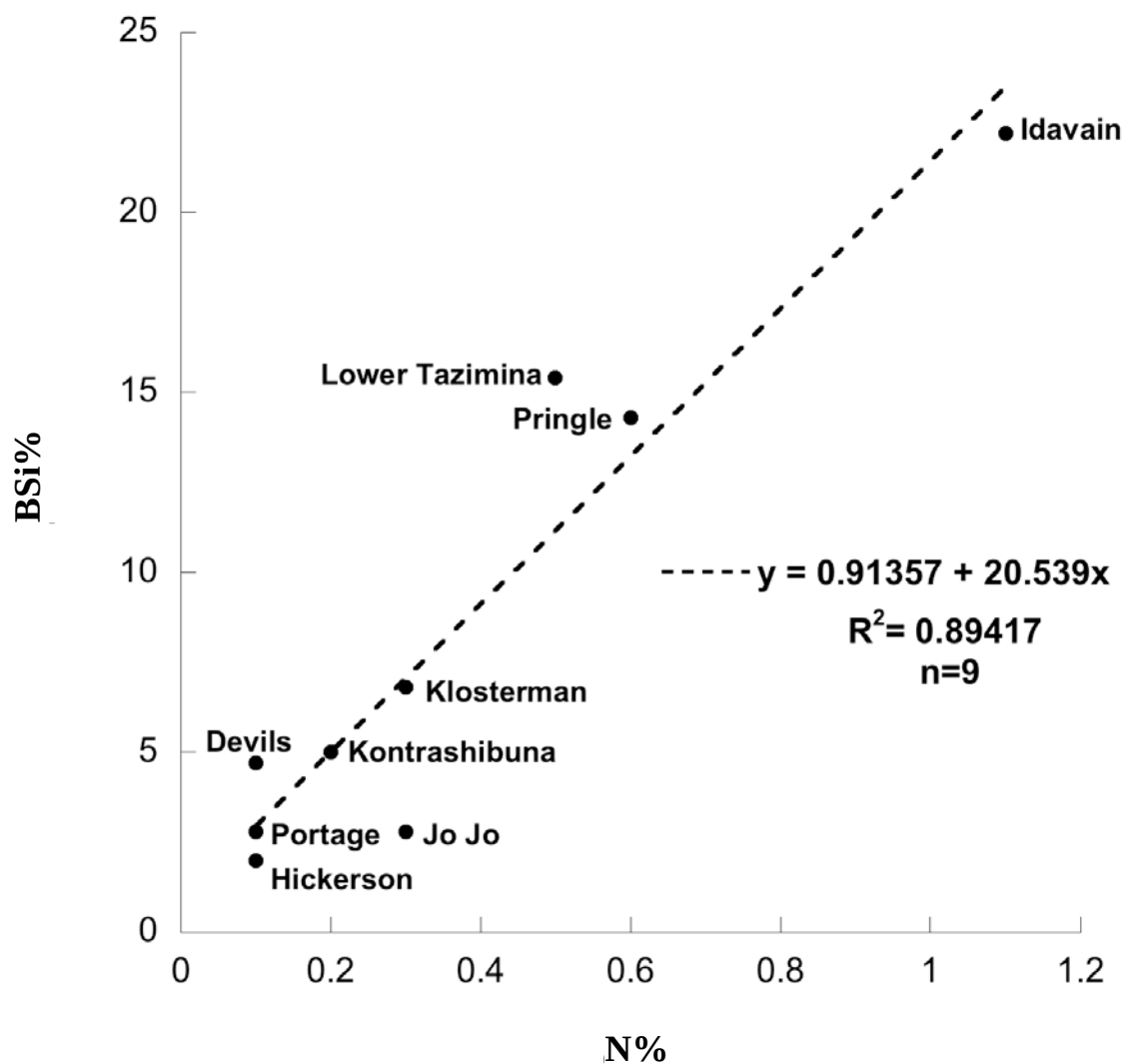


Figure 2.10 Comparison of percent Biogenic Opal (BSi%) to percent nitrogen (N%) in surface sediments from nine lakes in LACL and KATM. The relationship shows the gradient of aquatic productivity as it relates to N content in surface sediments from deep coastal lakes (e.g. Hickerson Lake) to shallow inland lakes (e.g. Idavain Lake).

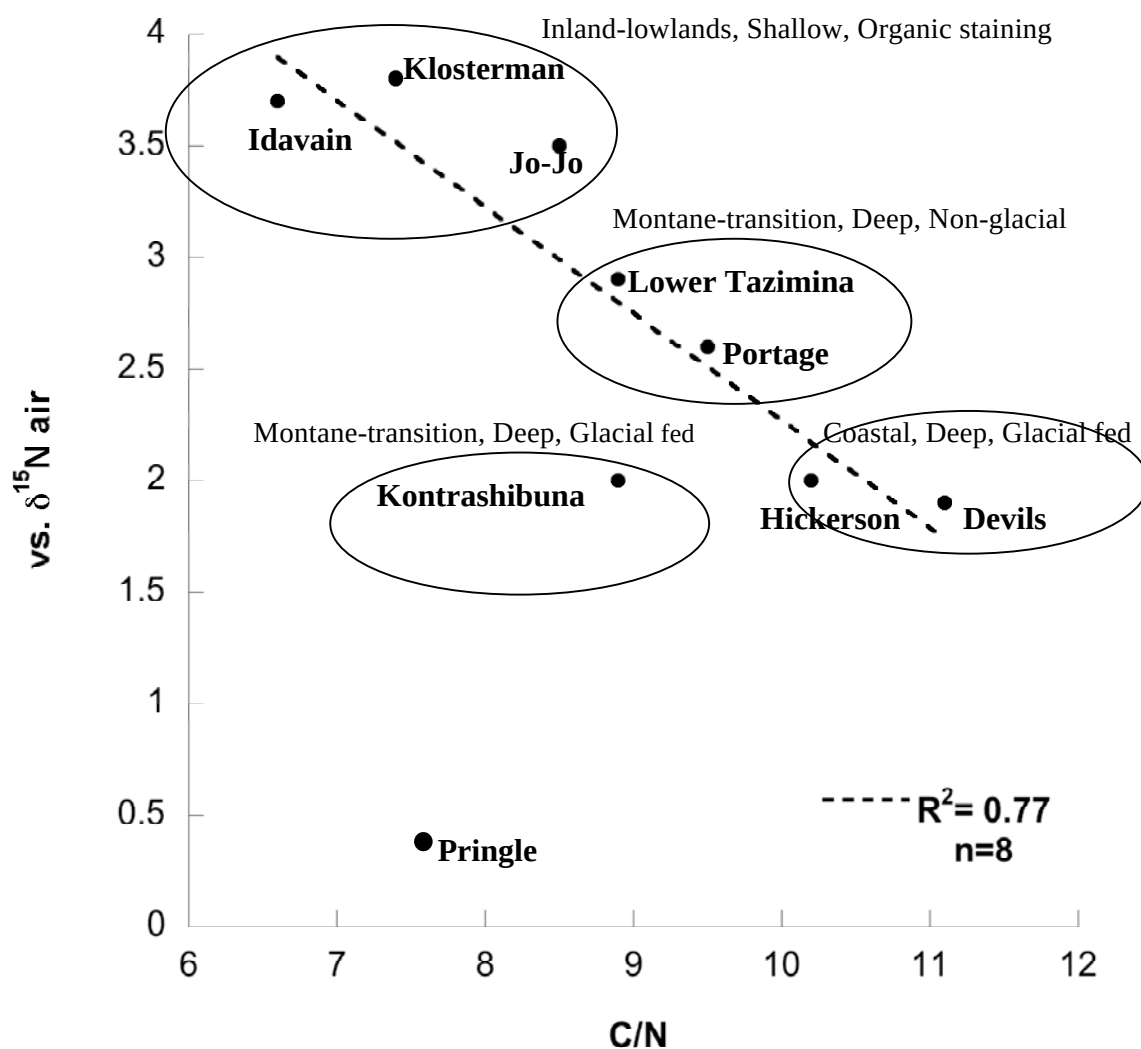


Figure 2.11 Comparison of $\delta^{15}\text{N}$ reported in ‰, to carbon to nitrogen (C/N) mass ratios in surface sediments in LACL and KATM. Note the physiographic zones indicated by the labeled ovals. The apparent outlier Pringle Lake was excluded from analysis for this comparison.

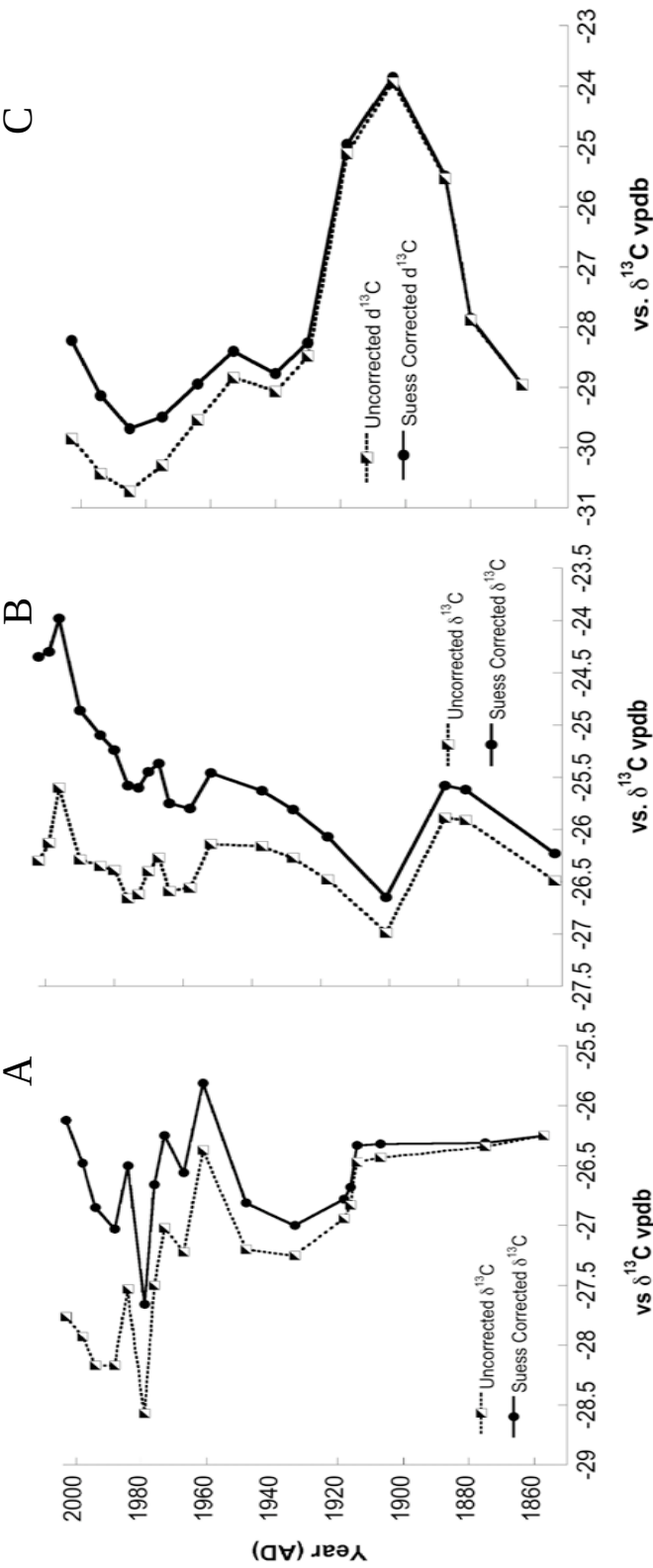


Figure 2.12 Comparison of $\delta^{13}\text{C}$ vs. Suess corrected $\delta^{13}\text{C}$ data in down core sediments. All $\delta^{13}\text{C}$ is reported in ‰ vs. Vienna Pee Dee Belmnte. (A) Hickerson Lake, (B) Kontrashibuna Lake, (C) Portage

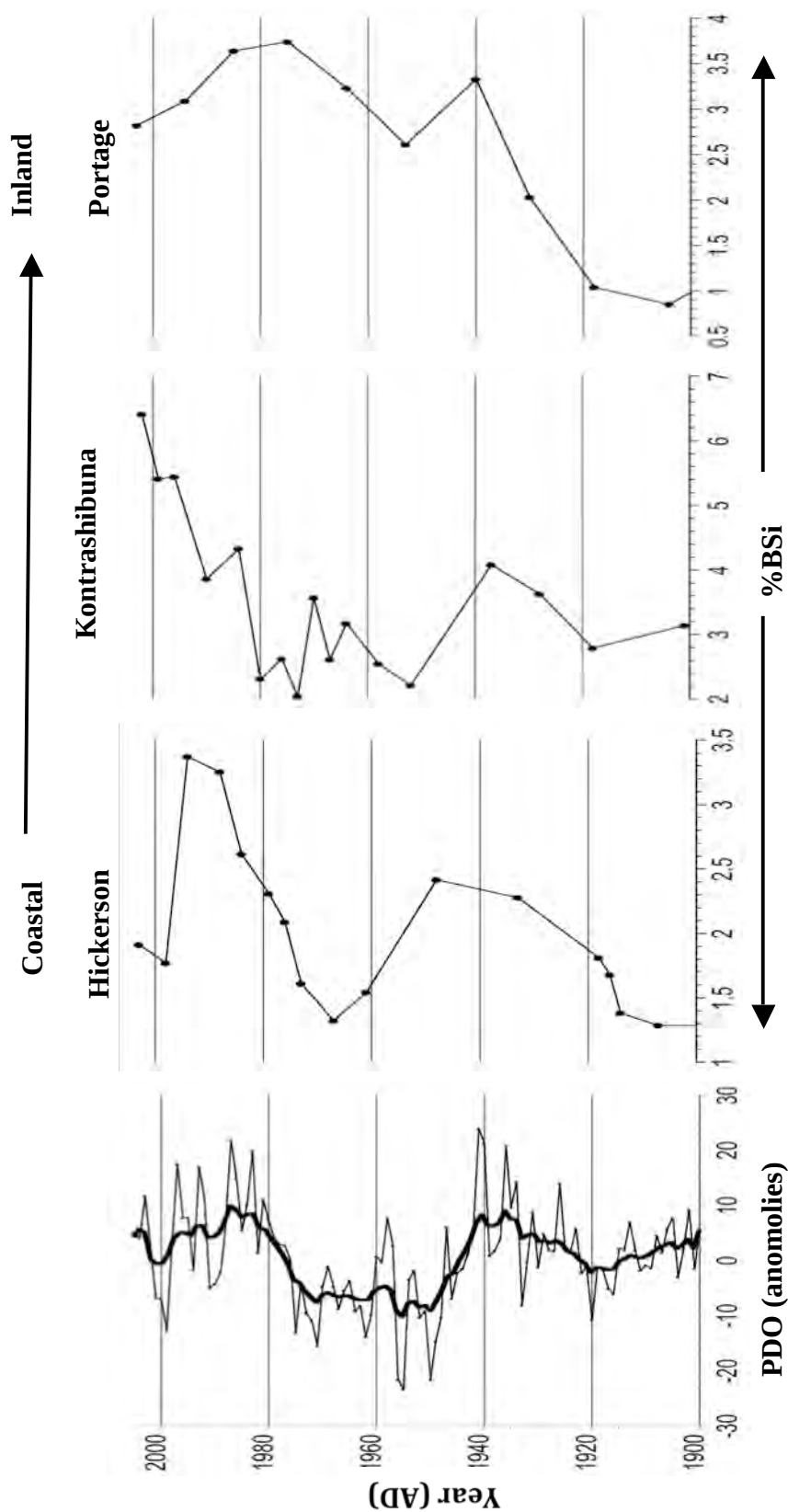


Figure 2.13 Comparisons of Pacific Decadal Oscillation (PDO) and percent Biogenic OPAL (BSi%) from Hickerson Lake, Kontrashibuna Lake and Portage Lake in LACL. The PDO signal is more pronounced in the coastal (Hickerson) and transition (Kontrashibuna) lakes than the inland site.

Table 2.1 Site Location, Basin characteristics, and surface water chemistry. Samples were collected on August 17 – 21, 2004.

Parameter	units	Hickerson Lake	Kontrashibuna Lake	Portage Lake
Latitude		59° 55.84' N	60° 11' 13.92" N	60° 30.294' N
Longitude		152° 55.063' W	154° 1' 54.12" W	153° 51.852' W
Region		Coastal Montane	Montane	Inland Montane
Characteristics		Shrub dominated - cooler and wetter	Boreal forest - transition zone	Boreal forest/ Herb - warmer and dryer
Elevation	m	193	140	447
Watershed Area	Km ²	36	507	10
Lake Surface Area	Km ²	4	21	1.4
Watershed/Lake Surface		9	24	7
Secchi Depth	m	2.5		16+
pH		8.3	8	8.6
Specific Conductance	uS			
PO ₄	cm ⁻¹	69.7	42.1	354
SiO ₄	uM	0.08	0.05	0.01
N+N	uM	76.2	38.0	75.5
NH ₄	uM	4.6	7.6	25.3
	uM	0.45	0.10	0.58

Table 2.2 Percent of Landcover Type by Watershed Area.

Landcover Type	% Cover of Watershed Area		
	Hickerson Lake	Kontrshibuna Lake	Portage Lake
<i>Picea sp.</i> - forest	<1	3	4
<i>Betula sp.</i> - forest	NA	4	1
<i>Populus sp.</i> - forest	1	1	2
<i>Alnus sp.</i> - shrub	48	19	14
<i>Salix sp.</i> - shrub	1	<1	<1
Mixed Forest	<1	7	1
Low Mixed Shrub	<1	<1	14
Dwarf Shrub Tundra	2	2	3
Prostrate Shrub Tundra	14	14	16
Lichen Tundra	<1	2	1
Sedge Shrub Bog Meadow	<1	<1	<1
Wet sedge Meadow	<1	<1	<1
Grasslands	1	<1	<1
Gravel and Sparse Vegetation	9	22	20
Bedrock	2	8	8
Ice/Snow	11	11	<1
Lake Water	10	4	13

Data originating from: 19970603, Land Cover Map of Lake Clark National Park and Preserve: National Park Service, Alaska Support Office, Anchorage Alaska

Table 2.3 Percent of vegetation type distributed across the three study watersheds. Species corresponding to pollen assemblages are highlighted as a reference.

Landcover Type	% of Vegetation Type		
	Hickerson Lake	Kontrshibuna Lake	Portage Lake
<i>Picea sp.</i> - forest	<1	7	7
<i>Betula sp.</i> - forest	NA	2	2
<i>Populus sp.</i> - forest	1	6	3
<i>Alnus sp.</i> - shrub	70	36	24
<i>Salix sp.</i> - shrub	2	1	<1
Mixed Forest	<1	12	2
Low Mixed Shrub	NA	<1	23
Dwarf Shrub Tundra	3	3	6
<i>Prostrate Shrub Tundra</i>	20	27	27
Lichen Tundra	1	4	1
Sedge Shrub Bog Meadow	1	<1	<1
Wet sedge Meadow	<1	<1	<1
Grasslands	<1	<1	<1

Data originating from: 19970603, Land Cover Map of Lake Clark National Park and Preserve: National Park Service, Alaska Support Office, Anchorage Alaska

Table 2.4 Phytoplankton and zooplankton organic matter and isotopic characterization.

Site	Phytoplankton*			Zooplankton**				
	$\delta^{15}\text{N}$	$\delta^{13}\text{C}$	$\delta^{15}\text{N}$	$\delta^{13}\text{C}$	%N	%C	C:N	
Hickerson Lake	0.5	-28.5	2.0	-35.5	4.6	42.6	9.4	
Kontrashibuna Lake	1.9	-27.1	4.5	-33.2	7.9	44.1	5.6	
Portage Lake	5.4	-26.1	5.4	-37.6	4.9	44.0	9.0	

*POM of water collected at ~1 m depth

** Vertical 30 m tow hauls

Samples Collected August 17 -21, 2004

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Chapter 3

3.1 General Conclusion

The information collected in this study provides insight for SWAN monitoring objectives and questions, such as: how are vegetation communities changing across the SWAN region in response to environmental factors or climate change? How is environmental warming affecting primary productivity in lakes?

The significance of this research lies in understanding how the synergistic relationships between climate, disturbance, vegetation structure and composition, and watershed scale processes impact aquatic productivity over time. We have used multi-proxy paleolimnological techniques to explore the trophic histories of several major southwest Alaskan lakes within the SWAN. In addition to acquiring natural baseline trophic state conditions and change in lake state through time, this information will assist with future monitoring and management efforts. These records will assist in the evaluation and assessment of lake productivity and potential impacts from geography, climate change, vegetation distribution, as well as natural and anthropogenic disturbance. The methods, results, and interpretations of this study will be useful to other lake studies, including those interpreting anadromous watersheds facing fluctuations in sockeye salmon.

Although our analytical measurements of many biogeochemical proxies showed small variations, reproducibility and corresponding trends give us confidence in our interpretations. Further efforts to understand changes in the algal communities (e.g. diatom assemblages) within the core stratigraphies would markedly increase our

understanding of the aquatic ecosystems, in regard to nutrient dynamics and physical water parameters.

In the future it may be of interest to determine the significance of the modern vegetation distribution and changes relative to the long-term record of natural variability. Comparing the results of the sedimentary record from the last few centuries to studies focused on early Holocene records from Idavain Lake in KATM, Snipe Lake in LACL (see Brubaker and others 2001), and the aforementioned Grandfather Lake (see Hu and others 2001) may shed insight to recent climatic or atmospheric changes.

The integration of the multiple biogeochemical, physical, and historical photographic observations presented in this study show that it is also beneficial to have site-specific data from potential modern end members that would ultimately influence the sediment record. Although many of the typical plant species found in our study have been examined for their stable isotope content in other studies, future research focusing on senescent plants, soils and freshwater inputs at the watershed or plot level would help in assessing the modern variations in $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and C/N mass ratios. This would further our knowledge of interpreting lake cores and modern limnological investigations within the SWAN, while providing an understanding of the interrelationship between an organism's physical functioning and its environment.

It is important to understand the effect of climate and landscape evolution on the lakes and the surrounding watersheds to infer how these systems react to different climate conditions. Although the systems studied remain highly oligotrophic, their current trajectory and additional nutrient inputs and greater productivity together may enhance

downstream habitats and waters. If current trends persist or intensify these nutrient subsidies could change the level of available nutrients in downstream systems and boost production along the food chain.

As discussed, the results and methods developed as part of this study are useful in interpreting records in anadromous watersheds facing declines in sockeye salmon. The importance of selecting an appropriate control lake is clear. The morphometry, climate, and the role of vegetation and vegetation change in a watershed should be accounted for in reconstructing historical sockeye salmon escapement, as contributions from terrestrial nutrient sources may influence nutrient fluxes and stable isotope signatures through time. However, this study of non-anadromous lakes, suggests that these systems generally have lower productivity regimes and more depleted $\delta^{15}\text{N}$ stable isotopic composition in comparison to anadromous systems. In addition, the influence of the PDO and warming on lake 'ice-out' timing and in lake primary production may be a critical component of understanding rearing and survival of juvenile salmonids.

Furthermore, many valuable lessons for exploring ecological questions were learned throughout the progress of the study presented here. First and foremost, selection of the appropriate lake types to test the hypotheses was perhaps the most challenging and critical issue faced. In hindsight I now realize that it would have been more effective to study smaller lake systems to capture the 'landscape' signal, and minimize the confounding influences of other factors such as the disturbance regime, glacial influences and depth of the lakes. At the onset of the project I was focused on finding good control comparisons for anadromous lakes, however, these larger, non-productive lake systems

are more complex and generally lose a large proportion of the organic component during sedimentation and through recycling. In smaller and more importantly shallower lakes (e.g. Idavain lake) the organic matter may remain in the water column for a shorter period of time resulting in better preservation. Also, as part of site selection, it would have been valuable to have an understanding of basic limnological parameters (e.g., N vs. P limitation) again to minimize differences between sites. Additionally, studying the modern components of the ecosystem is vital for comparison to the historical record preserved in the sediments. Although we were able to capture a snapshot of the limnological and watershed properties when in the field, a more thorough and long-term effort is necessary to determine seasonal and annual biotic and abiotic signatures. A better understanding of the ecosystem compartments would allow more precise estimates of the contribution by the important sources and end members.

3.2 References

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