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Differential Response of Alaska Peatlands to Climate Changes of the Last Millennium

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Differential Response of Alaska Peatlands to Climate Changes of the Last Millennium

by

Eric S. Klein

A Dissertation

Presented to the Graduate and Research Committee

of Lehigh University

in Candidacy for the Degree of

Doctor of Philosophy

in

Earth and Environmental Sciences

Lehigh University

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Differential Response of Alaska Peatlands to Climate Changes of the Last Millennium

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Abstract

Northern peatlands in boreal and subarctic regions store about 500 Gt of carbon (C). Understanding the fate of this large C pool under a warmer climate is important, as temperatures in northern latitudes have increased quicker than the global averages over the past 100 years. Both regional climate (e.g., temperature and precipitation) and local factors (e.g., topography) influence peatland response to climate changes. To better understand peatland response to climate changes, paleoecological techniques were used to study the C accumulation and paleohydrology of peatlands in different Alaskan climate regions. In addition, local-scale factors were studied through comparison of two nearby peatlands in different surficial geologic settings within the Southcentral Alaska climate region. Peatland responses to relatively well-documented climate changes over the last 1100 years, such as the Medieval Climate Anomaly (MCA) at ~1000-600 and Little Ice Age (LIA) at ~600-200 cal yr BP, were analyzed. Regional-scale results indicate that peatlands in relatively warmer and wetter Southeast Alaska accumulated the most peat over the last millennium. Average apparent peatland C accumulation rates in all regions were greatest during the warmer MCA than the cooler LIA, suggesting a possible negative C cycle feedback to climate change because peatlands may sequester more atmospheric C under a warmer climate, reducing the greenhouse effect. However, results also indicate that local-scale factors, like surficial geology, can lead to a heterogeneous response of peatlands to climate change, even within the same region, which has important implications for C cycling and peat-based paleoclimate studies. A better understanding of local-scale controls is necessary to help account for some of the

unexplained variability present in studies of northern peatland response to climate changes.

Chapter 1

General Introduction

Temperatures in northern latitudes have increased quicker than the global averages over the past 100 years (IPCC, 2007). Northern latitudes contain about 500 Gt (1 Gt = 10^9 tons) of C (GtC) stored in peatlands (e.g., Yu, 2012). Peatlands are a specific type of wetland where the long-term rate of biological production exceeds that of decomposition, which results in the accumulation and storage of carbon-rich organic matter (Clymo, 1984). As 500 GtC is equivalent to about 1/3 of the world's soil C (Jobbagy and Jackson, 2000) and more than 1/2 today's atmospheric CO₂ (Battle et al., 2000) there is interest in understanding how this northern latitude peatland C reservoir will respond to climate change (Davidson and Janssens, 2006; McGuire et al., 2010; Grosse et al., 2011; Turetsky et al., 2011; Charman et al., 2013).

It is possible that higher temperatures could lead to greater decomposition of peatland organic matter (Ise et al., 2008; Dorrepaal et al., 2009), which could release previously sequestered C into the atmosphere and make peatlands part of a positive C cycle feedback (e.g., Friendlingstein et al., 2006). However, higher temperatures could also lead to a longer growing season and greater production, which could increase C storage (e.g., Gorham, 1991). Peatland hydrology is a key factor in determining whether higher temperatures will lead to greater peatland decomposition or productivity. Lower peatland water tables can lead to increased rates of organic matter decomposition and the release of C into the atmosphere (e.g., Gorham, 1991; McGuire et al., 2006). Thus higher temperatures coupled with drier peatland hydrology could likely result in increased C

release, but relatively stable peatland hydrology during warming could lead to production rates greater than those of decomposition and increased C storage.

Peatland hydrology is influenced by regional precipitation. Therefore, the climate zone that a peatland occupies is likely an important control on its response to climate change. However, peatlands in the same region that receive similar amounts of precipitation might still have differences in peatland hydrology due to local-scale variability in factors such as hydrogeologic setting and peatland type. For example, the hydrogeologic setting can impact how water cycles through a peatland and might lead to a differential peatland response to climate change even within the same climate zone (e.g., Klein et al., 2013). Therefore, both regional-scale factors, such as climate, and local-scale factors, such as hydrogeologic setting, are important to understanding how northern peatlands might respond to climate change.

Peatlands in Alaska are found across multiple different climate zones and various hydrogeologic settings that likely influence their response to climate changes. Therefore, a study of different Alaska peatlands can provide insight as to how temperature and precipitation patterns, as well as hydrogeologic differences, influence the response of northern peatlands to climate change. To investigate the influence of climate on peatland response, a comparative study of peatland C accumulation and hydrology from peatlands in the different Southcentral (SC), Southeast (SE), and Southwest (SW) Alaska climates was developed (Table 1.1; Figure 1.1). To study local-scale variation in peatland response within the same region, peatland C accumulation, paleohydrology, and seasonal hydrology were examined at sites occupying different hydrogeologic settings in the SC Alaska climate region.

The SW, SC, and SE regions occupy different positions along a temperature and precipitation gradient (Figure 1.2). The SW Alaska region is influenced by the Bering Sea, changes in inter-annual sea-ice, and strong winds from ocean storms. It is in a transitional temperature and precipitation region that is also influenced by large air masses in the Interior zone. The SC region has some influence from the North Pacific, which makes temperatures relatively moderate, relative to the rest of the state. The SE region is heavily influenced by the Gulf of Alaska, which leads to the warmest temperatures and highest precipitation levels of anywhere in Alaska. Moreover, the SE Alaska climate region is among the warmest and wettest of northern latitude peatland climates (Stafford et al., 2000; Figure 1.2).

At each peatland site, hydrological and C accumulation responses to well-documented climate changes of the past 1100 years, such as the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) were investigated using paleoecological techniques. Previous studies have generally indicated higher peatland C sequestration rates during the MCA than during the LIA, which has been associated with a decrease in temperatures and lower productivity during the LIA (e.g., Charman et al., 2013). As the Alaska peatland study sites are along a climate gradient, and in different topographic settings, the study objectives were to compare peatland response to climate changes of the last millennium to better understand how it was influenced by: 1) temperature and precipitation patterns; and 2) hydrogeologic setting. It is hypothesized that all peatlands had higher C accumulation rates during warmer periods (i.e., MCA) than during cooler periods of the last millennium (i.e., LIA) due to increased productivity. It is also predicted that a relatively warm and wet climate provides the conditions needed to drive

maximum peatland productivity and minimum peatland decomposition. As these conditions could be expected at northern climates that have a combination of relatively high temperatures and precipitation it is also hypothesized that peatlands in SE Alaska accumulated more peat over the last millennium than peatlands in cooler and drier regions of Alaska such as SC Alaska.

Alaska Region: Peatland Site	Latitude	Longitude
Southcentral: Lowland	62.37657	-151.0831
Southcentral: Moraine	62.37271	-151.0896
Southeast: Point Lena	58.3363	-134.5550
Southeast: Fish Creek	58.3365	-134.5552
Southwest: Kwethluk	60.5230	-161.0927

Table 1.1: Location and region of peatland study sites in Alaska.

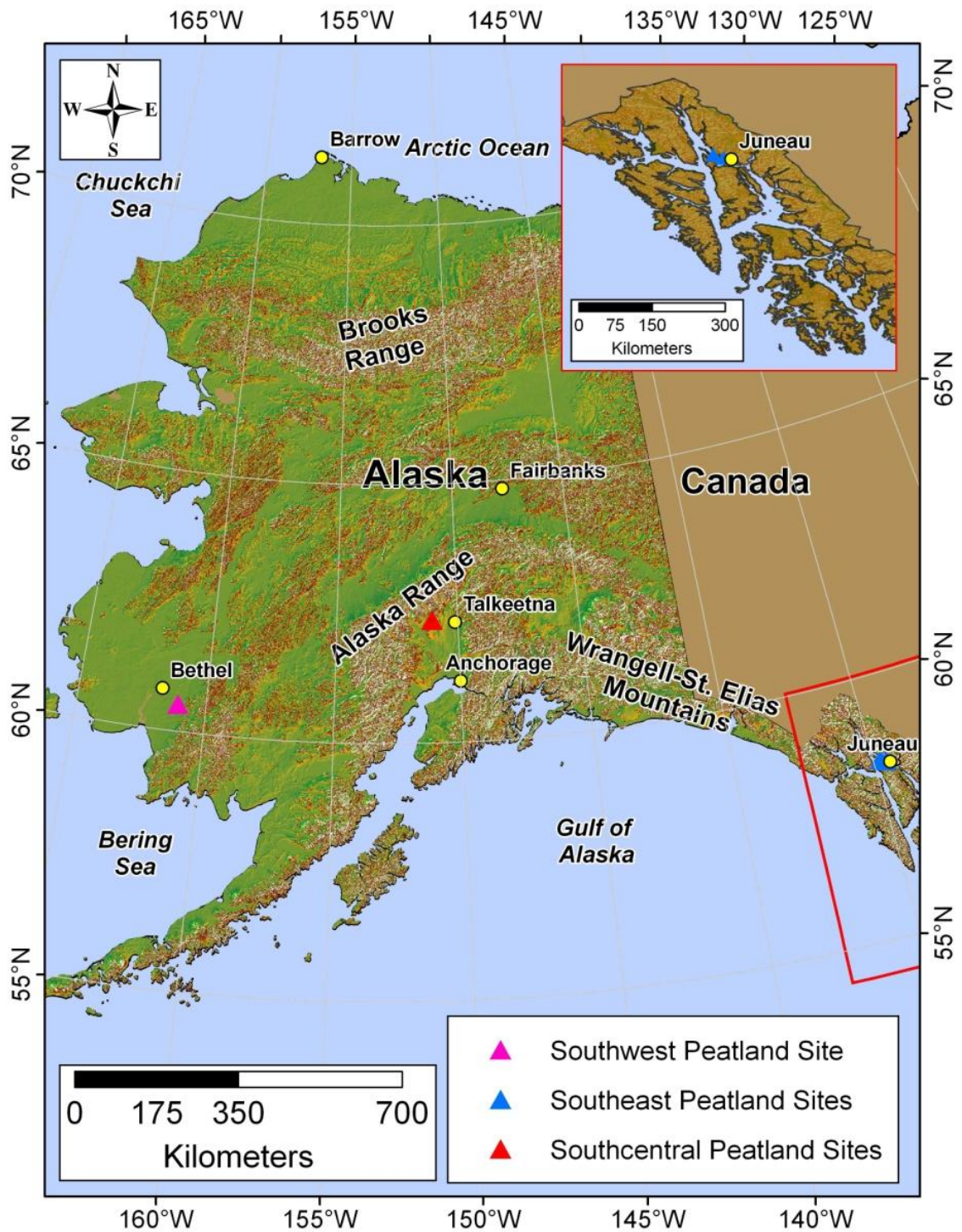


Figure 1.1: Map of Alaska and northwestern Canada showing the location of the peatland study sites. The inset on the upper right depicts the SE Alaska region as shown in the red rectangle on the main figure.

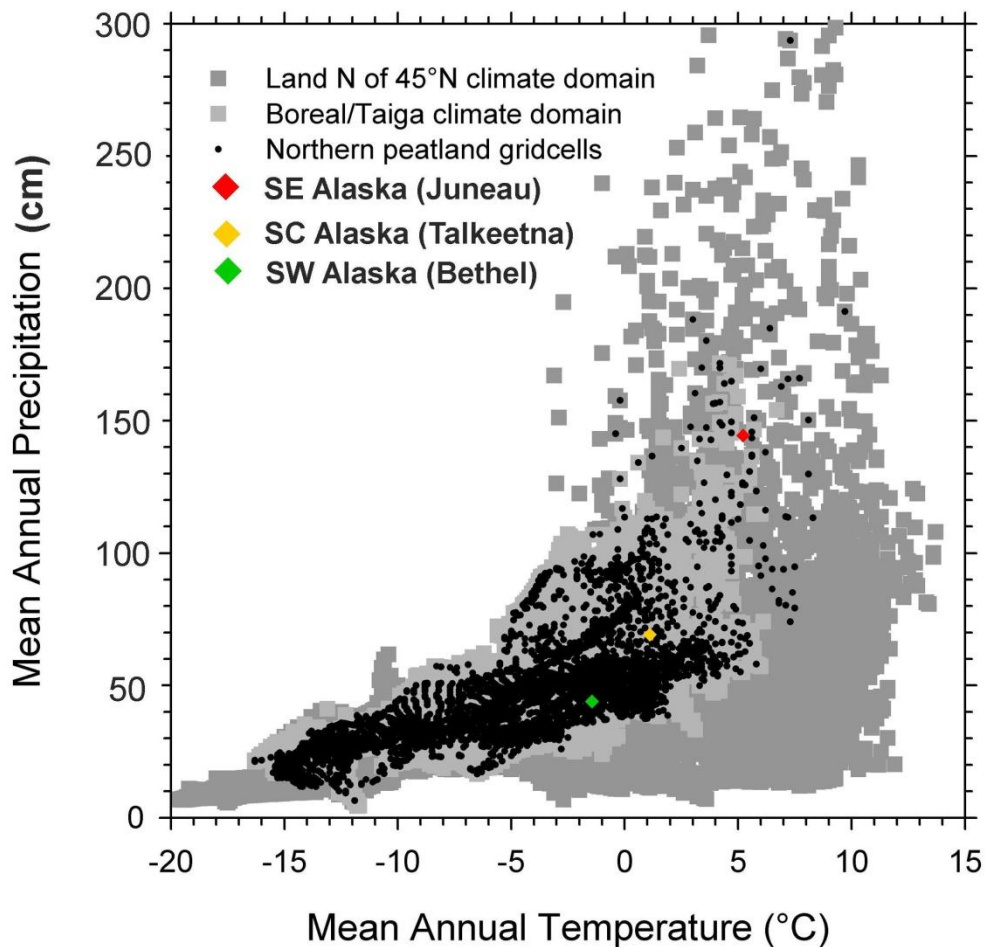


Figure 1.2: The climate space of mean annual temperature and precipitation (adapted from Yu et al., 2009) of total land area north of 45°N latitude (dark gray), the boreal/taiga biome (light gray), and northern peatland regions based on 0.5° x 0.5°-gridded instrumental climate data for the period 1960–1990 (Rawlins and Willmott, 1999). The climate space location of the different Alaska climate regions studied (based on data from 1950-2010 long term weather stations in Juneau for SE Alaska, Talkeetna for SC Alaska, and Bethel for SW Alaska) are represented by the upper right (relative to the other diamonds) red diamond (SE region), the mid-range orange diamond (SC region), and the lower left green diamond (SW region).

Chapter 2

Hydrology-mediated Differential Response of Carbon Accumulation to Late Holocene Climate Change at Two Peatlands in Southcentral Alaska

Summary

Peatlands are among the largest reservoirs of terrestrial carbon in the northern hemisphere. Understanding how this reservoir will respond to climate changes is critical to assessing potential climate feedbacks. Peatland carbon accumulation rates (PCAR) are controlled by the difference between production and decomposition, which is affected by local and climatic factors including hydrology and temperature. To better understand how local controls can influence the response of PCAR to climate change, we investigated modern hydrology, paleohydrology, and PCAR at two nearby *Sphagnum*-dominated peatlands with different surficial geology (lowland and moraine settings) in Southcentral Alaska. Modern hydrological data indicated a higher rate of subsurface drainage at the lowland site, suggesting greater hydrologic sensitivity to prolonged dry periods of the past. We investigated past responses of these peatlands to well-documented climatic changes, like the Medieval Climate Anomaly (MCA) at ~1000-600 cal yr BP and Little Ice Age (LIA) at ~600-200 cal yr BP, using water-table depth (WTD) inferred from testate amoebae and PCAR calculated from loss-on-ignition and ¹⁴C-dating analyses. Our results indicate that WTD and PCAR remained relatively stable at the moraine site throughout the last 1100 years, including the MCA and LIA. However, the lowland site experienced relatively stable WTD and higher PCAR during the MCA, but highly variable WTD and lower PCAR during the LIA. These differences suggest that hydrology and likely decomposition were the primary control on PCAR at these

peatlands. Our results highlight the importance of local-scale controls, like surficial geology, in mediating the response of peatland hydrology and carbon accumulation to climate change.

2.1 Introduction

Peatlands are wetlands where the long-term rate of biological production exceeds that of decomposition, resulting in the accumulation and storage of carbon-rich organic matter (Clymo, 1984). High latitude northern peatlands cover about 4 million km² and store up to 550 Pg (1 Pg = 10¹⁵ g) of carbon (C) (e.g., Gorham, 1991; Turunen et al., 2002; Yu et al., 2010), equivalent to about 1/3 of the world's soil C (Jobbagy and Jackson, 2000) and more than 1/2 today's atmospheric CO₂ (Battle et al., 2000). The response of this globally important C reservoir to global climate change and the potential for climate feedbacks is currently an area of much active debate and research (Davidson and Janssens, 2006; McGuire et al., 2010; Gross et al., 2011; Turetsky et al., 2011). Although there have been broad-scale syntheses looking at the influence of climate changes on carbon-rich peatlands (MacDonald et al., 2006; Jones and Yu 2010; Yu et al., 2011), the influence of hydrogeologic setting on the response of peatland C accumulation to climate change remains largely unstudied. Given the importance of peatland hydrology in controlling C accumulation rates, and the potentially complex hydrogeologic setting of peatlands in topographically and geologically variable landscapes, the responses of peatland C accumulation rates to climatic change might be expected to vary among peatlands in geologically heterogeneous settings.

Rates of production and decomposition in peatlands are sensitive to changes in climate, although understanding relative changes in the rates of these processes is not always straightforward. For example, decreased precipitation may lead to a lower peatland water-table, a thicker aerobic zone at the peat surface, and a faster decomposition rate (McGuire et al., 2009). However, temperature changes could

potentially increase or decrease peat accumulation rates by affecting both production and decomposition. Increased temperatures could lengthen the growing season and lead to greater production (Gorham, 1991), but could also increase evapotranspiration rates and microbial metabolic rates (Gillooly et al., 2001), which could promote greater decomposition and release of carbon (Gorham, 1991; McGuire et al., 2006). Additionally, the seasonality of precipitation and temperature changes may influence the relative rates of production and decomposition.

Local-scale peatland hydrology, which likely varies among peatland settings, also affects the magnitude of water-level change experienced in response to climatic change, further complicating the assessment of linkages between carbon-accumulation rates and climate change. The relative influences of ground, surface, and meteoric water are critical features of peatland water budgets, and likely vary among peatland systems in a region, particularly in topographically and geologically heterogeneous settings. Much of the variability in hydrologic setting has been linked to changes in geologic characteristics (Freeze and Witherspoon, 1967; Winter, 1988; Winter et al., 2001). For example, differences in bedrock type and landforms influence the distance of groundwater movement and the arrangement of flow paths (Freeze and Witherspoon 1967; Winter et al., 2001). This is particularly true in glacially influenced landscapes, where complex configurations of groundwater movement can occur within till moraines and outwash plains (Meyboom et al., 1966; Lissey, 1971; Winter, 1999; Winter et al., 2001).

Peatlands are the largest C reservoir of any North America ecosystem type, and Alaskan peatlands contain more than half of the C storage of United States' peatlands (CCSP, 2007). Alaskan peatlands exist in a geologically heterogeneous landscape in

which average air temperatures over the past 100 years have increased more quickly than global averages (Watson, 2001). This warming has been linked to melting glaciers (Arden et al., 2002), expansion of woody shrubs (Silapaswan et al., 2001; Sturm, 2001), and drying of wetlands and lakes (Klein et al., 2005; Riordan et al., 2006).

Understanding the response of peatlands in this region to warming and associated land cover and hydrological changes is critical to assessing potential changes in C storage.

To better understand how surficial geology might influence the response of peatland C accumulation to climate variability, we conducted a comparative study of peatland C accumulation and hydrology at two proximate peatlands in the Susitna Basin of Southcentral Alaska (Figure 2.1). Surficial geology is defined here as the layer between bedrock and peat, such as gravel or till. The study was set up as a natural experiment using two peatlands that differed in their underlying surficial geology, but experienced the same climatic shifts. Hydrological and C accumulation responses to well-documented climate changes of the past 1100 years, such as the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) were investigated using paleoecological techniques. The modern hydrology and climate of the two sites were observed as an analogue for interpreting the longer term changes indicated by the paleoecological and paleohydrological records. Specifically, water-table and temperature loggers and a remote weather station were installed and data were collected over a full year to track the annual hydrological response of the two peatlands to temperature and precipitation changes. Finally, to further characterize and compare the hydrology of these sites, water isotopes ($\delta^{18}\text{O}$ and δD) were measured in samples of summer and winter precipitation, surface water on peatlands, and water from saturated layers in peat. Water samples were

also collected from nearby rivers, streams and glacial melt to establish the range of local meteoric isotopic variability.

2.2 Study Region and Sites

Climate of Southcentral Alaska is characterized by the maritime influence of the North Pacific, which moderates temperatures (Stafford et al., 2000). The most recent 30-year (1980-2010) climate period from the nearest long-term weather station in Talkeetna (~50 km east) reveals annual average precipitation of 71 cm and temperature of 1.8°C, average July temperature of 14.7 °C, and average January temperature of -12.5°C. Precipitation during summers (June, July, and August) comprises 38% of the annual value, while winters (December, January, and February) account for only 17% (Alaska Climate Research Center, 2011).

The two studied peatlands are located at an altitude of approximately 250 m in a valley ~58 km south of the Kahiltna Glacier and the Alaska Range in the Susitna Basin (Figure 2.1). The study site is on the left-lateral side of the Kahiltna glacier trough, downhill from Peters Hills, and is an area without permafrost (Olszewski, 1986; Clark and Duffy, 2006). One of the peatlands is on a moraine (hereafter referred to as the moraine peatland) and the other is situated approximately 20 m below and 500 m to east (hereafter referred to as the lowland peatland) (Figure 2.2). The moraine peatland is located within a heterogeneous cover of pebble-cobble gravel, smaller amounts of sand and silt, and boulders deposited directly from glacial ice (Reger et al., 1999). The lowland peatland overlies an abandoned-channel deposit with a variable composition ranging from slightly washed drift with thin, local surface cobbles and boulders to well-sorted, pebble-cobble gravel and gravelly medium to coarse sand with scarce to

numerous boulders (Reger et al., 1999). The deposits underlying both sites were formed during the end of the Last Glacial Maximum, named regionally as the Naptowne glaciations that began about 25,000 years ago and ended about 9,500 years ago (Reger, 1999).

Both peatlands are relatively open and *Sphagnum*-dominated with small shrubs such as dwarf birch (*Betula nana*) and bog rosemary (*Andromeda polifolia*), and common grasses and forbs of oligotrophic peatlands including cloudberry (*Rubus chamaemorus*), sundew (*Drosera* spp.), and cottongrasses (*Eriophorum* spp.) (Figure 2.3). Scattered black spruce (*Picea mariana*) trees occur on both peatlands, although they are somewhat more common on the lowland site, at least in the vicinity of the coring location.

Vegetation of the surrounding interior boreal forest ecozone is dominated by white spruce (*Picea glauca*), aspen (*Populus tremuloides*), birch (*Betula neoalaskana*), and alder (*Alnus* spp.) (Viereck and Little, 2007).

2.3 Methods

2.3.1 Modern Hydrology

At both the lowland and moraine sites water level and temperature loggers (Solinst 3001 LT Levellogger Junior) were installed in summer 2010 to better understand potential hydrological differences between the two sites. Measurements were collected every hour for one year, from 24 July 2010 to 24 July 2011. The wells housing the loggers were constructed of PVC pipe approximately 6 cm in diameter and 1.1 m in length. The bottom ~40 cm of the wells contained mesh-covered holes, to allow for equilibration with groundwater and to prevent clogging of PVC pipe by surrounding peat. Pressure loggers were positioned at ~70 cm depth in the wells and both ends of the wells were capped. In

order to determine peatland water-table depths, the pressure data from the loggers were corrected using atmospheric pressure data collected from a barometric logger placed ~1.5 m above ground in a tree ~1 km northeast of the peatlands.

A remote, automated weather station (Campbell Scientific Custom with CR1000 Datalogger and various sensors) was established near the peatland sites (~750 m to the northeast) in order to record weather variables including snow depth (ultrasonic distance sensor), precipitation (tipping bucket), temperature (thermistor), relative humidity (capacitive sensors), and shortwave solar radiation (thermopile pyranometer).

Complications with the snow depth and precipitation data at the weather station near the sites resulted in the use of data from another project's remote weather station installed approximately 25 km away, at a similar altitude and environmental setting. In the months July through January (the temporal overlap between the two stations before complications began) the average monthly difference in precipitation between the two stations was only 0.2 cm. Therefore, the precipitation and snow data from the station 25 km away are assumed to be quite similar to those near the two peatlands. Sensors scanned at 0.5 hour intervals and the average of two 0.5 hour readings was logged every hour for one year, from 24 July 2010 to 24 July 2011, similar to the peatland loggers. Since precipitation falls in frozen form throughout part of the year, and snowfall data provide only a first order approximation of water-equivalent accumulation, weather station data from Talkeetna (~50 km to the east) was also included for comparison purposes.

Water from the two peatlands was collected in March and July, 2010 and analyzed for stable isotope ratios ($^{18}\text{O}/^{16}\text{O}$ and D/H) in order to better understand the

cycling and recharge of peatland waters (Rozanski et al., 1992; Mark and McKenzie, 2007;). Additionally, water samples were collected from Kahiltna Glacier meltwater, summer and winter precipitation, nearby rivers and lakes, and other regional peatlands in order to further characterize the local meteoric water isotopes. Values of $\delta^{18}\text{O}$ and δD were measured with a mass spectrometer (Finnigan MAT Delta Plus coupled to a HDO water equilibrators) at the Byrd Polar Research Center at The Ohio State University. The results of stable isotope analysis are presented using the δ -notation reported relative to the Vienna-Standard Mean Ocean Water (VSMOW) standard, with an accuracy of $\pm 0.2\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 2\text{‰}$ for δD . Isotopic results were partitioned into two groups: local peatland water (lowland, moraine, and other regional peatlands) and local meteoric waters (all other non-peatland water samples, such as glacier meltwater and precipitation). These local peatland and local meteoric waters were compared to the global meteoric water line (Craig, 1961).

2.3.2 Peat Core Analysis

An 85-cm long peat core was collected from the lowland peatland in August 2009 (HRC 09-2) and a 96-cm long peat core was collected from the moraine peatland in July 2010 (HRC 10-2), both using a rectangular box corer approximately 1-m long and 32-cm² in cross sectional area. Peat cores were collected near well locations. Peat characteristics were noted in the field and described in detail in the laboratory. The cores were wrapped in plastic wrap and aluminum foil and placed in PVC containers for transportation back to the laboratory at Lehigh University, where they were stored in a cold room at 4°C.

The cores were cut into 1-cm increments, and from each of these increments 1 cm³ of peat was collected for loss-on-ignition (LOI) analysis. These subsamples were first dried for 12 h at 105°C to determine dry peat weight. LOI analysis was then performed and weight loss after 4 hr of combustion at 550°C was used to estimate organic matter content (Dean, 1974). The difference between peat dry weight and weight after combustion was divided by the fresh peat volume to estimate ash-free bulk density.

Radiocarbon dates were used to constrain age-depth models. Subsamples of 1-cm thick sections were sieved, and *Sphagnum* stems were picked from the sieved material, cleaned with distilled water, dried, and sent to the Keck-CCAMS facility at the University of California, Irvine for pretreatments and AMS radiocarbon dating analysis. Four AMS ¹⁴C dates from the lowland peatland and five dates from the moraine peatland were calibrated using the IntCal09 data set (Reimer et al., 2009) (Table 2.1), and age-depth models were developed using the age-depth modeling software, CLAM (Blaauw, 2010). Using linear interpolation, CLAM performed 10,000 iterations of age-depth models through the ranges of calibrated radiocarbon dates, which resulted in most probable ages and 95% probability range for every depth. Cryptotephra layers, from eruptions of Mt. Redoubt at 1990 AD (-40 cal yr BP) (Scott and McGimsey, 1994) and ~600 cal yr BP (Schiff et al., 2010), present at both peatlands helped to assess the consistency of the age-depth models. The cryptotephra were determined by correlating decreased organic matter spikes with the spatial coverage and dates of known volcanic events.

Carbon accumulation rates at both peatlands were estimated for the past 1100 years from loss on ignition (Dean, 1974) ash-free bulk density measurements using an

average carbon content of peat organic matter of 51% (Vitt et al., 2000) and peat vertical growth rates based on both the most probable age estimate from the CLAM age-depth model and intervals between median calibrated radiocarbon dates (Table 2.1). The age-depth model for a core influences the estimation of C accumulation rates between the dated horizons, so in order to use the most conservative C accumulation rates, the accumulation rates were analyzed based on intervals between median calibrated radiocarbon ages (Yu et al., 2003; Beilman et al., 2009).

Testate amoebae, a group of shell-producing amoeboid protists, were used as a proxy to reconstruct peatland water-table depth at 1-cm resolution at both sites (e.g., Booth, 2008; Charman, 2001, Markel et al., 2010; Woodland et al., 1998). Preparation and analysis of testate amoebae followed standard sieving methods (Booth et al., 2010). One cm³ of peat was collected for analysis and the size fraction between 355 and 15 µm was analyzed, as this interval sufficiently collects the species necessary for water-table depth reconstruction. Slides were prepared and scanned at 400x magnification until a total of at least 100 tests were identified and counted following the taxonomy of Charman et al. (2000) and the modifications of Booth (2008). However, *Cyclopyxis arcelloides* type and *Phryganella acropodia* type were grouped in this study. A transfer function for North America (Booth, 2008), developed from samples collected in the Rocky Mountains, Upper Midwest, and Eastern North America, was combined with a calibration set from Alaska peatlands (Markel et al., 2010) to reconstruct water-table depth changes from testate amoeba assemblages using a weighted averaging (WA) model. A range of other transfer function models were explored, and all produced similar reconstructed water-table depths from the fossil data, so only the results of the WA transfer function are

reported in this paper. Sample specific standard error estimates were made using bootstrapping techniques ($n=1000$) and the software program C2 (Juggins, 2003). Stratigraphically constrained cluster analysis, using the program CONISS (Grimm, 1987), was performed on the testate amoeba data to help in zonation and assist in discussion of the record.

2.4 Results

2.4.1 Seasonal Changes in Water-table and Hydroclimate

Weather station data revealed variations consistent with seasonal changes (Figure 2.4). Seasonal temperature averages were 12.03°C for summer, 3.65°C for fall, -12.16°C for winter, and 4.29°C for spring. Relative humidity (RH) exhibited the greatest seasonal difference in average values between winter (82%) and spring (66%) and RH during the nights was typically greater than during the days. Over 65% of total precipitation occurred in summer (34.1 cm) with nearly 18 cm recorded in August alone. Fall had the second highest rainfall total (7.3 cm) and the majority of it came in September. Winter accounted for about 10% of total rainfall and over 40% of this amount occurred in the early winter month of November (Table 2.2; Figures 2.4A and 2.4C). Average shortwave solar radiation was greatest in the spring (181 W/m^2) and summer (161 W/m^2), with values over 6 times greater than in the winter (26 W/m^2). Snow accumulation began at the end of October and reached its highest maximum depth (120.8 cm) in early April, when it began melting (Table 2.3; Figure 2.4B). The one year of weather data at the study site was similar to the 30-year averages from Talkeetna (Figure 2.4C). Precipitation in colder winter months like December was below the averages, but as evident from the winter snow depth (Figure 2.4B), this was likely due to the weather

station tipping bucket not recording some frozen winter precipitation, and not lack of precipitation.

The water-table fluctuations during the year were similar at the two sites, but the lowland site had a substantially lower water-table during the late fall, winter, and early spring when precipitation levels decreased (Figures 2.4A and 2.4D). The water-logger data revealed that during July and August of 2010, a period of higher precipitation, both peatlands experienced relatively similar hydrological changes, with water-table depths fluctuating from ~1 cm to 14 cm below the peatland surface. In mid-September precipitation began to decrease and the water-table depth at the lowland peatland began to drop more than at the moraine site. The lowland peatland water-table reduced its level considerably more during the low precipitation winter months and by the end of March the lowland water-table depth (29 cm) was nearly twice that of the moraine site (15 cm). Both peatlands quickly became wetter at the end of April from a spring freshet caused by melting snow and increased precipitation; standing water occurred on both sites through early May. The two sites continued to experience similar water-table fluctuations into June when the moraine water-level logger stopped recording data, perhaps because of disturbance by an animal.

Peatland water temperatures varied more at the lowland than the moraine, including the colder late-fall and winter period. Overall, the average moraine peatland water temperature (3.8°C) was warmer than the lowland average water temperature (3.4°C) (Figure 2.4D). Progressing from mid-July, 2010, water temperatures at both sites increased until a fall cooling trend began in September, 2010. The cooling trend was more rapid at the lowland site, and in mid-to-late September, water temperatures at both

sites were approximately the same. Similar to the water-table patterns, water temperatures at the lowland peatland decreased faster than the moraine peatland throughout the fall, with the greatest winter-temperature difference (1.2°C) between the two sites occurring in early-to-mid December. After this, the water temperatures at both sites began to converge, but with the lowland maintaining a lower temperature, before reaching the same value (0.9°C) in May after spring snowmelt.

The $\delta^{18}\text{O}$ and δD values measured for water samples are presented on a bivariate plot (Figure 2.5). The lowest (most depleted) values from the local meteoric waters were from snow ($\delta^{18}\text{O}$ values from approximately -30 to -17‰), while rainwater had the highest (most enriched) ($\delta^{18}\text{O}$ values from approximately -17 to -13‰). The glacial meltwater $\delta^{18}\text{O}$ value is intermediate of meteoric precipitation values, but is the depleted endmember of the remaining rivers and lakes. The $\delta^{18}\text{O}$ values of peatland waters ranged from approximately -18 to -13‰ and within this group, the moraine peatland had the highest (most enriched) values of all peatland waters (Figure 2.5). The local meteoric water samples fall along a line located just below the global meteoric water line (slope = 8) on Figure 2.5, but with a nearly identical slope of ~7.8. The peatland water samples have a shallower slope (~3.6), which is usually indicative of waters that have been influenced by evaporation (Clark and Fritz, 1997).

2.4.2 Peatland Carbon Accumulation

Peatland growth rates at the two sites differed during various periods, but were relatively similar throughout the course of the record. Over the past 1100 years the moraine had an average peat growth rate of 0.50 mm/yr, while the lowland averaged 0.52 mm/yr. The

average peat growth rate at the lowland site increased to 0.62 mm/yr from ~950 to 600 cal yr BP, while the rate at the moraine peatland remained relatively unchanged during this period. Beginning ~600 cal yr BP the average growth rate at the lowland decreased, and from ~600 to 200 cal yr BP the moraine peat accumulation rate (0.43 mm/yr) was nearly twice that of the lowland peatland (0.24 mm/yr). These differences in average growth rates are apparent through comparison of slopes in the age-depth models from each core. For example, from the ~950 to 600 cal yr BP period the lowland has a greater average growth rate and steeper slope than the moraine (Figure 2.6).

The results of LOI analysis indicated that the average organic matter content of both *Sphagnum*-dominated cores was about 90%, but during certain periods LOI values were much different than this average (Figure 2.7A). Both cores had two minima at ~1990 AD (-40 cal yr BP) and ~600 cal yr BP in which the organic matter dropped below 60%, reflecting tephra layers. The ash-free bulk densities, excluding the last 50 years of freshly produced plant fragments and peat, varied between 0.09 g/cm³ and 0.20 g/cm³, with an average of 0.14 g/cm³ for the lowland peat core and 0.13 g/cm³ for the moraine peat core. The ash-free bulk densities at both sites are relatively similar until diverging ~500 yr BP, when lowland values became higher than those at the moraine (Figure 2.7B).

Carbon accumulation rates were more variable at the lowland peatland and quite similar with and without incorporation of the age-depth model (Figure 2.7C and 7D). The main difference was an increase at ~150 cal yr BP at the moraine peatland that coincides with the portion of the age-depth model that has the largest 95% probability range (Figure 2.6). Excluding the last 50 years of freshly produced plant fragments and peat, the estimated C accumulation rates for the lowland peatland ranged from ~22 to 68

gC/m²/yr, with an average of ~38 gC/m²/yr. At the moraine peatland the estimated C accumulation rates varied from ~24 to 34 gC/m²/yr, with an average of 29 gC/m²/yr. An increase in C accumulation observed at the lowland peatland (~68 gC/m²/yr) between ~950 and 600 cal yr BP did not occur at the moraine peatland (~24 gC/m²/yr). At ~600 cal yr BP, the C accumulation rate at the lowland peatland decreased substantially to ~22 gC/m²/yr, while the rate at the moraine remained relatively unchanged (Figure 2.7C).

2.4.3 Testate Amoebae and Water-table Depth Reconstruction

Twenty-nine testate amoeba taxa were identified in the lowland peatland core and 31 testate amoeba taxa were identified in the moraine peatland core. The number of identified taxa from both cores includes the rotifer, *Habrotrocha angusticollis*, which is commonly found with testate amoebae (e.g., Mitchell et al., 1999). Major changes in community composition occurred within 2-3 cm in several parts of both records (Figure 2.8). Three zones were defined with help from a stratigraphically constrained cluster analysis (Grimm, 1987) for each of the peatlands, and descriptions of the zones are presented in Table 2.4. The transition from Zone 2 to Zone 3 at the lowland peatland occurred at 22 cal yr BP and 156 cal yr BP on the moraine, which are statistically indistinguishable given the 95% probability ranges associated with the age-depth models (15 to 23 cal yr BP for the lowland and -17 to 291 cal yr BP for the moraine). Conversely, the transition from Zone 1 to Zone 2 at the lowland peatland (628 cal yr BP, 576 to 674 cal yr BP 95% error range) and the moraine peatland (411 cal yr BP, 314 to 490 cal yr BP 95% uncertainty ranges) may have occurred at different times based on our age-depth models (Table 2.4; Figure 2.8).

The testate amoeba-inferred water-table reconstruction at the moraine peatland indicates relatively minor fluctuations in average water-table depth, with most variability well within the uncertainty of the transfer function. However, the reconstruction for the lowland peatland indicates more variability between 200 and 600 cal yr BP (Table 2.4), with several significant wet and dry fluctuations when water-table depths changed by more than 20 centimeters (Figure 2.8). These fluctuations were primarily driven by changes in the relative abundance of *Archerella flavum*, *Arcella catinus*, *Diffugia pulex*, *Heleopera sphagni*, and *Trigonopyxis arcuata* (Figure 2.8).

2.5 Discussion

2.5.1 Contrasting Hydrology Dynamics at Lowland and Moraine Peatland Sites

Modern hydrological data spanning one year revealed differences in peatland hydrology between the lowland and moraine sites. Isotopic ratios of peatland water, modern water-table depth changes recorded by the loggers, and precipitation data from the weather station all suggest that the primary recharge of peatland waters is due to precipitation. Although both peatlands receive most of their water through precipitation and runoff, they experienced seasonal differences in water-table depths. For example, during the summer both the lowland and moraine peatlands had similar water-table depths, but in the fall and winter the lowland peatland became drier as the position of its water-table dropped substantially more than at the moraine (Figure 2.4D). This difference between the two peatlands in water-table depths during the fall and winter suggests that the lowland peatland experienced subsurface drainage at a higher rate than the moraine peatland.

Peatland water temperature patterns are consistent with the hypothesis of increased subsurface drainage at the lowland peatland. Water temperatures at the lowland peatland during fall and winter (Figure 2.4D) decreased more than at the moraine peatland, indicating advection of heat through the loss of water (Fetter, 2001). Summer had nearly three times the precipitation of fall and winter combined (Table 2.2; Figure 2.4A), so although the lowland peatland likely experiences higher rates of water loss throughout the year, it only becomes apparent when the rate of recharge becomes less than the rate of discharge, that is, when there is water deficit. Less subsurface drainage at the moraine peatland is also supported by the presence of lakes and ponds on the moraine (Figure 2.2).

Examined collectively, isotopic ratios of $\delta^{18}\text{O}$ and δD , modern water-table depth changes, and weather data suggest that: 1) peatland recharge at both sites is primarily controlled by precipitation; and 2) the lowland site is more hydrologically sensitive to precipitation deficits than the moraine. The sensitivity to precipitation is consistent with the oligotrophic vegetation composition of the two sites, and the increased sensitivity to the fall and winter moisture deficit at the lowland site is consistent with the geologic settings. The surficial geology of the lowland peatland, which overlies an abandoned outwash channel (Reger et al., 1999), would be expected to be more permeable than the moraine till surrounding the moraine peatland (Winter et al., 2001). The isotope values for the peatland surface water samples are consistent with these surficial geological differences, as the moraine peat waters are more evaporatively enriched relative to the lowland site, perhaps further suggesting a longer residence time of these waters in response to a less permeable subsurface layer. Additionally, the lakes and ponds on the

moraine, whose presence is influenced by surficial geology, may help buffer peatland water-table decreases during reduced precipitation events, while the lack of such water bodies at the lowland (Figure 2.2) would likely increase its hydrologic sensitivity. These patterns suggest that similar to the water table differences at the two sites when precipitation decreased in the fall and winter during our single year of measurements (Figure 2.4), a past prolonged drought would likely have a greater hydrological impact on the lowland peatland than the moraine peatland.

2.5.2 Differential Hydrological Responses to Climate Change During the Last Millennium

Since past periods with prolonged dry conditions could have had a greater hydrological impact on the lowland peatland, the reconstructed lowland water-table depth would likely be more variable on average than the moraine peatland through the course of the record. The more variable water-table depths at the lowland (5.6 SD) compared with the moraine (2.8 SD) and the larger range of variability in reconstructed water-table depths at the lowland (~23 cm) relative to the moraine (~14 cm) over the 1100 year record support that the lowland peatland has greater hydrologic sensitivity to past climate change than the moraine (Figure 2.9).

Reconstructed water-table depths at the lowland peatland indicate a change at ~600 cal yr BP from stable to more variable peatland hydrology, although the moraine peatland was not as sensitive and its hydrology apparently did not change considerably (Figure 2.9). Moreover, the increase in ash-free bulk density values beginning ~550 cal yr BP at the lowland (Figure 2.7B) is also indicative of more variable peatland hydrology

and greater peat decomposition. The timing and magnitude of shifts in testate amoeba assemblage-based zones (Figure 2.8) further underscores the differences in hydrologic responses between sites. The change in testate amoeba assemblages at the lowland at ~600 cal yr BP was characterized by the disappearance of *Hyalosphenia papilio*, a sharp decrease in *Archerella flavum*, and an increase in *Diffflugia pulex* and *Trigonopyxis arcuata*. These shifts suggest a transition from a more stable, and relatively wet, peatland surface to one that is more variable, and relatively dry (Table 2.4; Figure 2.8) (Booth, 2008; Markel et al., 2010). Moreover, recent work has indicated that some taxa, such as *Diffflugia pulex*, may be favored by highly variable environmental conditions at the peatland surface (Sullivan and Booth, 2011). The changes at this time are consistent with increased short-term variability in surface conditions of the lowland site, as evident from the ratio of taxa likely indicative of relatively variable and stable environmental changes (Figure 2.9). Interestingly, although reconstructed water-table depths at the moraine site do not experience marked change at this time, significant compositional changes occur at a similar time and are characterized by increased abundance of *Diffflugia pulex* and *Hyalosphenia papilio* (Figure 2.8). Although our interpretation of the testate amoeba data is focused on hydrology, the potential impact of tephra on testate amoebae cannot be completely ruled out, and we note that changes at ~600 cal yr BP occur near a tephra layer at both sites. However, Payne and Blackford (2008) suggest that while some peatlands might be sensitive to outlying volcanic events, definitive data linking these events to changes in peatland microbial communities are lacking. The fact that the two peatland sites show such differences in variability for an interval spanning several hundred years suggests a paleoclimatic cause.

A comparison with regional paleoclimate records can help understand the past climate changes associated with the observed response of the more hydrologically sensitive lowland peatland. The relatively stable reconstructed peatland water-table depths from ~1000 – 600 cal yr BP correlate well with the ~1000 – 700 cal yr BP MCA identified by Loso (2009) using a varve record from Iceberg Lake in Southcentral Alaska and the MCA seen in the Farewell Lake record (Hu et al., 2001) on the north side of the Alaska Range (Figures 2.1A and 2.9). Similarly, the changes in reconstructed peatland water-table depth and the increased hydrological variability that began ~600 cal yr BP correlate well with the start of the LIA as identified by Iceberg Lake (Loso, 2009), Farewell Lake (Hu et al., 2001), and Hallet Lake in the Chugach Range of Southcentral Alaska (McKay et al., 2008) (Figures 2.1A and 2.9). As changes in precipitation tend to be more spatially and temporally variable and less clear than temperature changes (Miller et al., 2010), the more variable LIA in our record is associated with drier conditions at Blue Lake (Bird et al., 2009) in the central Brooks Range, Marcella Lake in the Yukon (Anderson et al., 2007), and Farewell Lake (Hu et al., 2001), but wetter conditions in records from the Sand Dunes (Mann et al., 2002) and Takahula Lake (Clegg et al., 2010) in the Brooks Range (Figure 2.1A).

Although the response of various Earth systems to the LIA is temporally variable, records indicate that in Alaska it ended between ~300 and 125 cal yr BP (Hu et al. 2001; McKay et al., 2008; Kaufman et al., 2009; Loso, 2009). The lowland peatland water-table depth reconstruction indicates reduced variability after about ~200 cal yr BP. Thus, our records suggest a relatively wet MCA from ~1000 – 600 cal yr BP and a more variable and perhaps drier LIA from ~600 – 200 cal yr BP (Figure 2.9) in this area of

Southcentral Alaska (Figure 2.1). While these MCA and LIA climate changes influenced the hydrology of the lowland peatland, there were not any significant changes in reconstructed water-table depths at the moraine peatland (Figure 2.9). These differences in hydrological response might be expected to lead to differences in peatland C accumulation rates.

2.5.3 Response of Peatland Carbon Accumulation to Hydrology and Temperature Changes

The response of C accumulation rates to past climate changes varied between these two sites. At the hydrologically less sensitive moraine peatland where water tables were relatively stable, C accumulation rates were relatively consistent throughout the record, ranging from ~24 to 34 gC/m²/yr. Conversely, C accumulation rates at the hydrologically more sensitive lowland peatland, where water tables varied more, varied by more than a factor of three. C accumulation rates at the lowland peatland increased to ~68 gC/m²/yr at ~950 cal yr BP during the MCA as reconstructed water-table depths were relatively stable and shallow, but at ~600 cal yr BP, rates at the lowland site decreased to ~22 gC/m²/yr as water-table depth became more variable (Figure 2.9).

Both sites experienced the same past climate changes, but the peatland hydrology and C accumulation responses varied. Previous studies have indicated that when peatlands become drier, peatland organic matter accrued under wet hydrology can be lost to drying-induced decomposition at a faster rate than it was accumulated (Belyea and Baird, 2006). This suggests that it is not merely peatland water-table depth that influences C accumulation rate, but the fluctuation of that water-table depth is also

critical. Therefore, the lowland, with a more variable water-table depth, which would lead to more decomposition of carbon-rich organic material, should also have greater variability in C accumulation rates overall. Conversely, the moraine with less hydrologic sensitivity and lower water-table depth variability should have less fluctuation in overall C accumulation rates and little response during past climate changes. Our results support these relationships. Excluding the last 50 years of freshly produced plant fragments and peat, the range of variability of estimated C accumulation rates at the lowland peatland ($46 \text{ gC/m}^2/\text{yr}$) was over four times greater than the range of variability at the moraine ($10 \text{ gC/m}^2/\text{yr}$) (Figure 2.7C). The SD of C accumulation rates at the lowland (21) was over five times greater than the SD of rates at the moraine (4) (Figure 2.7C). Additionally, the lowland C accumulation rates appeared to be influenced by the onsets of MCA and LIA climate changes around 950 and 600 cal yr BP, respectively, while the moraine did not show a response to these climate changes (Figure 2.9). Peatland modeling simulations found that seasonal and interannual variability of water-table depth influences C fluctuation, and on a time scale from decades to centuries increased water-table depth variability can decrease peat depth and C accumulation (Frolking et al., 2010). These peatland core results are consistent with this simulation, as lower C accumulation rates are generally present during periods of higher water-table depth variability and increased C accumulation rates occur during periods of reduced water-table depth variability (Figure 2.9).

As hydrological variability influences decomposition, the seasonal differences in water-table depth measured between the two sites can help further explain the disparities in C accumulation rates. The modern hydrological data indicate that peatland water

tables at both sites were not frozen at depths up to 30 cm throughout the winter (Figure 2.4D). Shallower depths closer to the surface of both sites might have frozen during parts of the winter, but as snow cover can easily accumulate in relatively open and non-forested areas and substantially insulate soils (Ping, 1986), it is possible that both peatlands remained unfrozen all the way down to 30 cm during the winter. The exact depth at which freezing occurred in the peatlands may not be known, but a portion of each peatland was both above the water table and not frozen throughout the winter. As freezing conditions, which would substantially reduce microbial activity (Gillooly et al., 2001), were not present during this period, the discrepancy in water-table depths between the two sites was likely differentially affecting decomposition.

Decomposition of organic matter usually increases in the oxic zone above the water-table (Clymo, 1984). So during this late-fall and winter period the drier lowland peatland with its larger oxic zone would expose more soil C to aerobic decomposition and potentially release more CO₂ into the atmosphere (McGuire et al., 2006). Conversely, during this same period, the larger anoxic zone at the moraine would experience less decomposition, which could lead to C storage (Moore and Knowles, 1989). Although these potential differences at the two peatlands are relatively small on a single year scale, the cumulative impact of these combined differences over decades to centuries could have influenced the varying C accumulation rates observed in the peat core data (Figure 2.7C). In particular, the differences in water-table depth at the two sites during the low-precipitation late-fall and winter periods (Figure 2.4D) could be analogous to the more variable hydrology and colder climate conditions during the LIA at ~600 –

200 cal yr BP, which exhibit increased ash-free bulk density values at the lowland (Figure 2.7B), consistent with greater decomposition.

Peatland hydrology is one of several factors that control peatland C accumulation rates (Yu et al., 2009). Temperature can also influence peatland C accumulation, as warmer temperatures increase production (Beilman et al., 2009). However, these peatland core data suggest that C accumulation rates at these sites are primarily controlled by hydrology and decomposition, as variable water-table depths induced greater decomposition of organic matter and reduced C accumulation. The relative influences of decomposition and production can be seen in the different responses of C accumulation between the two sites. Carbon accumulation rates at the moraine did not increase during the warmer MCA, even though peatland hydrology was relatively stable (Figure 2.9). If production was a dominant control on C accumulation, then a more stable moraine peatland hydrology, as indicated by both the paleo and modern data, combined with a longer growing season afforded by warmer conditions, could have led to increased C accumulation rates during the MCA. However, the C accumulation rates showed little change throughout the entire moraine peatland record, including during the warmer MCA period.

These results suggest that the greatest peatland C accumulation rates are likely to occur during periods of high and stable water table under warmer conditions, but the relatively warm and wet MCA conditions only resulted in higher C accumulation rates at the lowland site (Figure 2.9). This relative lack of change in C accumulation rates at the moraine site during the MCA at ~950 – 600 cal yr BP, a time of increased C accumulation rates at the lowland, may indicate that a shift to a wetter and warmer

climate has negligible influence on decomposition, and thus C accumulation, in hydrologically less sensitive peatlands. Essentially, C accumulation rates at the less hydrologically sensitive moraine remain stable during periods of optimal accumulation (e.g., the MCA), as well as periods that would favor decomposition in more sensitive peatlands (e.g., the LIA). Conversely, the lowland peatland exhibits the opposite pattern, as C accumulation rates increase during periods of optimal growth, but then decrease during periods that favor decomposition in more hydrologically sensitive peatlands. The lowland peatland has a larger range of C accumulation values and is more sensitive to changes in climate, but due to the C accumulated during the MCA, its average C accumulation rate is greater than the moraine for the length of our record. Overall, these results show that inter-site variability in local-scale controls like surficial geology can influence the response of peatland hydrology and C accumulation to climate change. Also, the results indicate that even during colder periods, like the LIA, C accumulation rates of Southcentral Alaskan peatlands appear to be controlled more by the variability of peatland hydrology and its influence on decomposition of carbon-rich organic matter, than low production caused by a cold climate.

2.6 Conclusions

This study of modern and paleo hydrology and peatland C accumulation data from two nearby *Sphagnum*-dominated peatlands in Southcentral Alaska indicates that different local surficial geology results in differences in peatland subsurface drainage that in turn impacts peatland hydrologic sensitivity and water-table depth variability. This water-table depth variability influences decomposition of organic matter and peatland C accumulation rates, resulting in a heterogeneous peatland response to climate change,

even within the same region. These results suggest that peatland hydrology is a primary control on C accumulation rates by influencing decomposition of organic matter, while temperature and related production play a secondary role. The data imply that an understanding of inter-site variability in local-scale controls like surficial geology, particularly in glacial terrain, is necessary when peatland C storage and paleohydrology values are extrapolated from single peatland data points for use in global C cycle and climate change studies. The results from this study have important implications for peatland-based paleoclimate studies, as surficial geological controls can influence how a peatland responds to climate change. Future research should continue to investigate the influence of geological controls on peatland response to climate change in this and other regions.

Dated Depth (cm)	Lab Number^a	$\delta^{13}\text{C}$ (‰)	^{14}C date \pm 1 SD (yr BP)	Median Calibrated Age (cal yrs BP)	Calibrated 95% Age Range (cal yrs BP)
<u>Lowland Peatland</u>					
19-20	UCIAMS-84633	-26.8	10 \pm 20	-4	-5-52
32-33	UCIAMS-76275	-27.6	570 \pm 20	605	534-637
52-53	UCIAMS-76276	-24.9	990 \pm 20	922	801-956
74-75	UCIAMS-84631	N/A ^b	1520 \pm 45	1407	1326-1521
<u>Moraine Peatland</u>					
21-22	UCIAMS-84638	-26.3	160 \pm 20	167	-2-283
40-41	UCIAMS-84637	-25.3	660 \pm 15	594	563-667
52-53	UCIAMS-84636	-27.3	1030 \pm 20	945	924-967
70-71	UCIAMS-84635	-26.1	1580 \pm 15	1465	1414-1521
91-92	UCIAMS-84634	-27.7	2010 \pm 15	1962	1904-1997

Table 2.1: AMS radiocarbon dates, median calibrated ages, and calibrated 95% age range from lowland and moraine peatland sites in Southcentral, Alaska

a UCIAMS - University of California, Irvine Accelerator Mass Spectrometry Facility

b Unable to measure due to small sample size

Season	Temperature (°C)			Relative Humidity (%)			Precipitation (cm)
	Average	Max.	Min.	Average	Max.	Min.	Total
Summer (June, July, August)	12	25	-1	81	100	25	34.1
Fall (September,	4	23	-13	79	100	12	7.3
Winter (November, December, January, February, March)	-12	11	-32	82	100	12	5.2
Spring (April, May)	4	28	-15	66	100	16	4.8

Table 2.2: Modern temperature, relative humidity, and precipitation climate data, as recorded by remote automated weather station from July 24th 2010 to July 24th 2011. To reflect Southcentral Alaska's climate, the winter season includes the months of November and March.

Season	Snow depth (cm)			Solar Radiation (W/m ²)
	Average	Maximum	Minimum	Average
Summer (June, July, August)	0	0	0	162
Fall (September, October)	14	55	0	68
Approximate first fall snow accumulation:	October 28 th , 2010			
Winter (November, December, January, February, March)	78	110	52	26
Spring (April, May)	35	120	0	181
Approximate first spring snow melt:	April 8 th , 2011			

Table 2.3: Modern snow depth and solar radiation climate data, as recorded by remote automated weather station from July 24th 2010 to July 24th 2011. To reflect Southcentral Alaska's climate, the winter season includes the months of November and March.

Lowland Peatland Core Testate Amoebae Zones						
Zone	Depth (cm)	Age Range (95% probability error range), cal yr BP:	Major Taxa	Zone Description	Average Water-Table Depth (cm)	Water-Table Depth Standard Deviation
3	0-20	-59 to 22 (-59 to 23)	<i>Archerella flavum</i> , <i>Hyalosphenia elegans</i>	<i>Archerella flavum</i> , <i>Assulina</i> spp., <i>Diffugia pulex</i> , and <i>Hyalosphenia elegans</i> are variably abundant in this zone. <i>Heleopera sphagni</i> is nearly absent from this zone.	18.09	3.46
2	21-35	22 to 628 (15 to 674)	<i>Heleopera sphagni</i> , <i>Diffugia pulex</i> , <i>Trigonopyxis arcula</i>	Sharp decrease in <i>Archerella flavum</i> . Increase in <i>Diffugia pulex</i> , <i>Heleopera sphagni</i> , and <i>Trigonopyxis arcula</i> . <i>Hyalosphenia papilio</i> is absent from this zone.	14.06	6.64
1	36-59	628 to 1085 (593 to 1101)	<i>Archerella flavum</i>	Increase in <i>Archerella flavum</i> and <i>Hyalosphenia papilio</i> . Decrease in <i>Diffugia pulex</i> , <i>Heleopera sphagni</i> , and <i>Trigonopyxis arcula</i> .	10.49	3.88

Moraine Peatland Core Testate Amoebae Zones						
Zone	Depth (cm)	Age Range (95% probability error range), cal yr BP:	Major Taxa	Zone Description	Average Water-Table Depth (cm)	Water-Table Depth Standard Deviation
3	0-21	-60 to 156 (-60 to 291)	<i>Archerella flavum</i> , <i>Heleopera sphagni</i>	<i>Archerella flavum</i> , <i>Diffflugia pulex</i> , <i>Heleopera sphagni</i> , and <i>Phryganella acropodia</i> , are variably abundant in this zone.	12.56	1.84
2	22-32	156 to 411 (1 to 490)	<i>Diffflugia pulex</i> , <i>Heleopera sphagni</i> , <i>Hyalosphenia papilio</i>	Decrease in <i>Archerella flavum</i> . Increases in <i>Diffflugia pulex</i> , <i>Heleopera sphagni</i> , and <i>Hyalosphenia papilio</i> .	12.06	2.39
1	33-62	411 to 1219 (343 to 1252)	<i>Archerella flavum</i> , <i>Heleopera sphagni</i> , <i>Trigonopyxis arcula</i> ,	Variable abundances of <i>Archerella flavum</i> , <i>Trigonopyxis arcula</i> and <i>Phryganella acropodia</i> . Decreases in <i>Diffflugia pulex</i> and <i>Hyalosphenia papilio</i> and increases in <i>Trigonopyxis arcula</i> and <i>Arcella catinus</i> .	12.26	3.52

Table 2.4 (previous pages): Descriptions of testate amoebae zones^a

a Zones were derived from a constrained cluster analysis. Average water-table depth and standard deviation for each of the zones are also presented (these values are based on the estimated water-table depths and do not include error estimates).

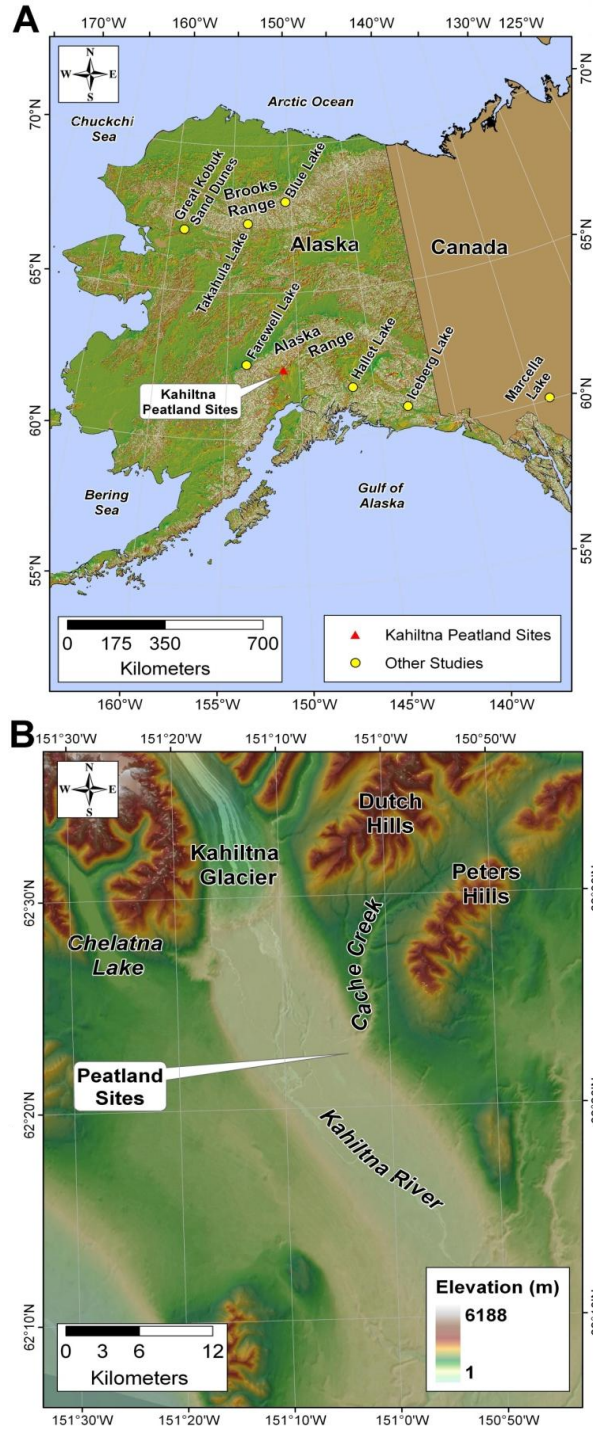


Figure 2.1: A) Map of Alaska and northwestern Canada showing the location of the Kahiltna Peatland sites from this research study as well as other records discussed; and B) Location of peatlands studied in the Kahiltna Glacier Valley, south of the Alaska Range, Southcentral Alaska.

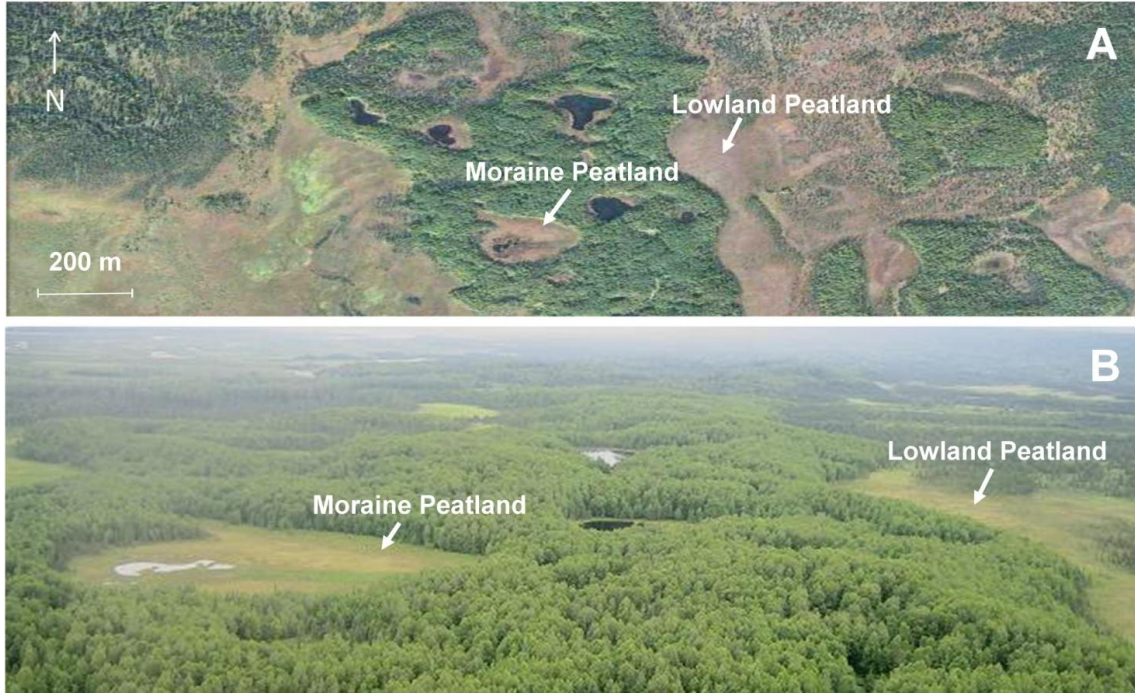


Figure 2.2: Location of lowland and moraine peatlands from satellite (A) and oblique aerial (B) views. The moraine peatland is raised ~20 m above the lowland peatland. (photos: A, QuickBird satellite imagery; B, ESK)

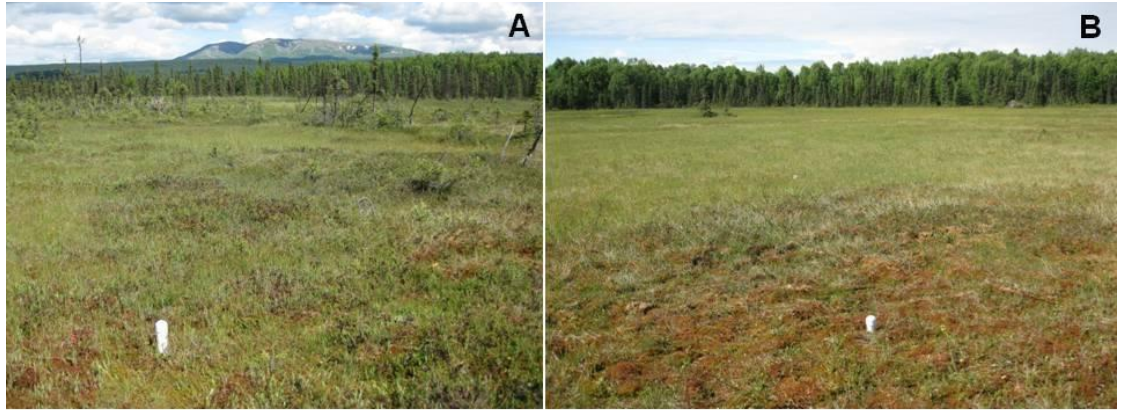


Figure 2.3: Panel A) Looking northeast from the lowland peatland. The Peters Hills are visible in the background. Panel B) Looking west from the moraine peatland. The wells that house the loggers (white capped tubes) used for water-table depth and temperature measurements are visible at both locations. (photos: ESK)

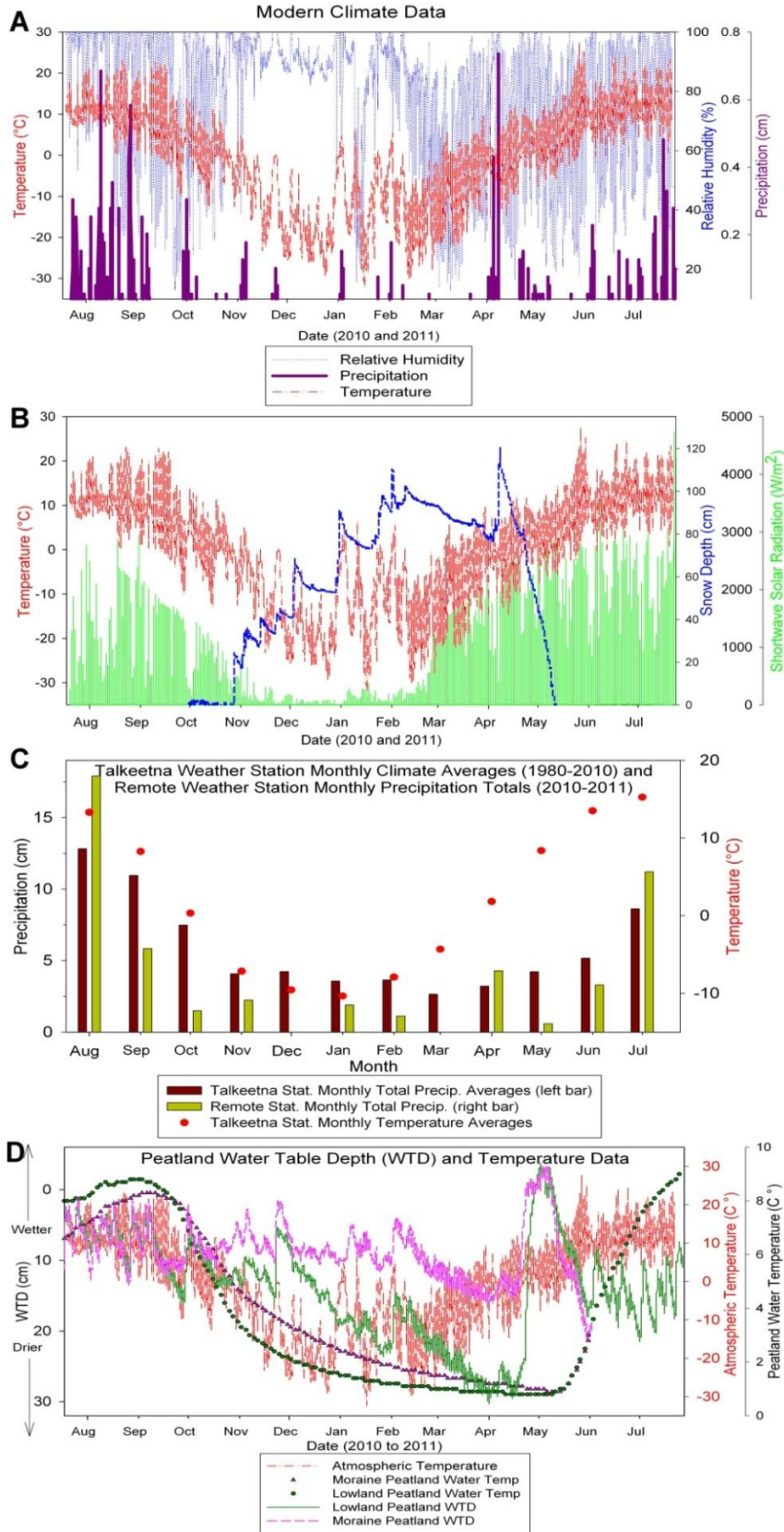


Figure 2.4 (previous page): Panel A) Relative humidity, precipitation, and temperature data from remote weather station near the lowland and moraine peatlands. Climate data extend for a full year (24 July 2010 – 24 July 2011); Panel B) Shortwave solar radiation, snow depth, and temperature data; Panel C) 30-year (1980-2010) monthly temperature and total precipitation averages from Talkeetna, Alaska (Alaska Climate Research Center, 2011) and monthly precipitation totals (2010-2011) from remote weather station; and Panel D) Level logger water-table depth and water temperature data for a full year (24 July 2010 – 24 July 2011) from the lowland and moraine peatlands and atmospheric temperature from the remote weather station. The moraine logger data ends in June 2011 likely due to animal disruption. Transient increases in winter water-table depth (i.e., at the end of November) appear to be influenced by changes in snow depth and are unrelated to the longer-term differences between sites.

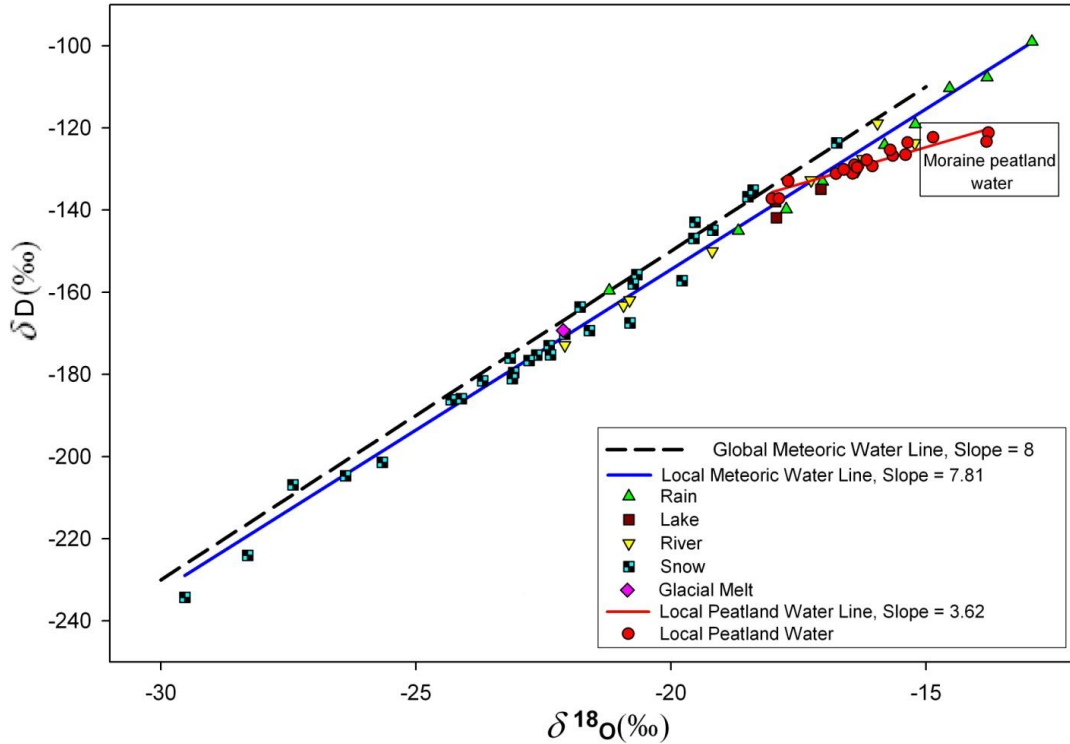


Figure 2.5: Isotopic ratios ($\delta^{18}\text{O}$ vs δD) of water samples separated into two groups: local meteoric water (rain, lakes, rivers, snow, and glacial melt) and local peatland water (lowland, moraine, and other regional peatlands). The global meteoric water line, $\delta\text{D} = 8 \cdot \delta^{18}\text{O} + 10$ (Craig, 1961), is presented for comparison. The peatland water samples have a shallower slope, which usually is indicative of waters that have been influenced by evaporation (Clark and Fritz, 1997). Of the peatland waters, the moraine peatland waters are the most evaporatively enriched, relative to the lowland site, potentially suggesting a longer residence time of these waters in response to a more impermeable subsurface layer.

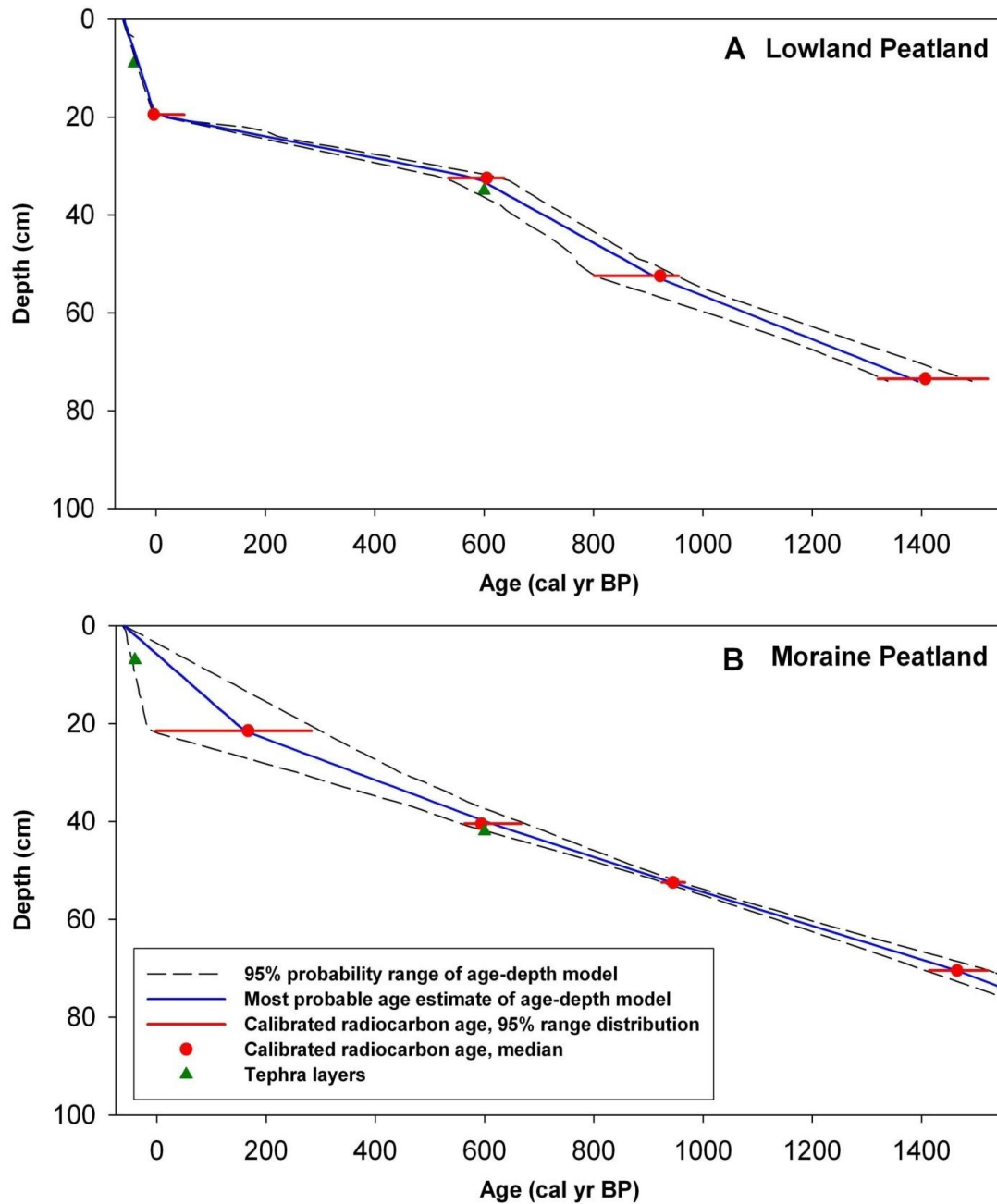


Figure 2.6: Age-depth models for lowland (A) and moraine (B) peatlands. Radiocarbon ages were calibrated using the IntCal09 data set (Reimer et al., 2009). The age-depth modeling software CLAM was used to create age-depth models (Blaauw, 2010). The tephra layers are consistent with the calibrated radiocarbon ages and age-depth model ranges.

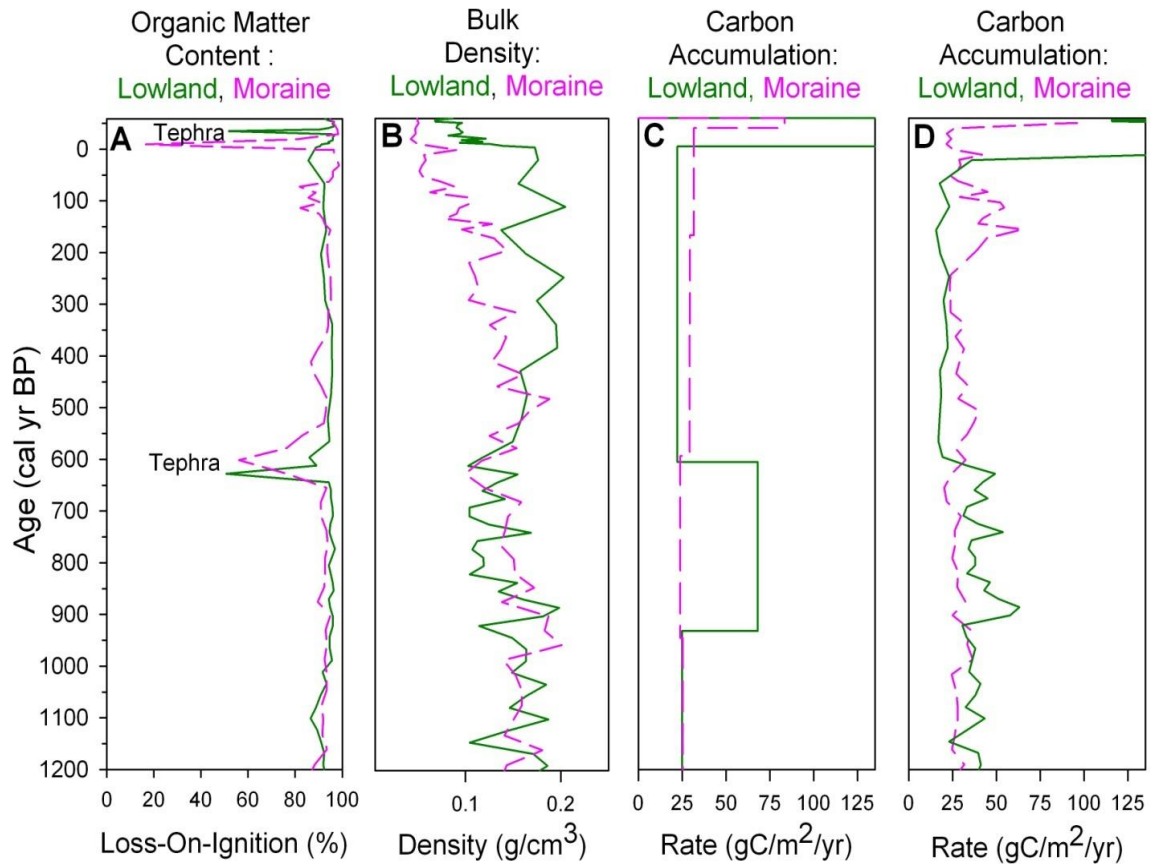


Figure 2.7: Lowland (solid line) and moraine (dashed line) peatlands: Panel A) Organic matter content (%); Panel B) Ash-free bulk density (g/cm³); Panel C) carbon accumulation rates (gC/m²/yr) based on intervals between median calibrated radiocarbon dates (Table 2.1); and Panel D) carbon accumulation rates based on the most probable age estimate from the age-depth model (Figure 2.6).

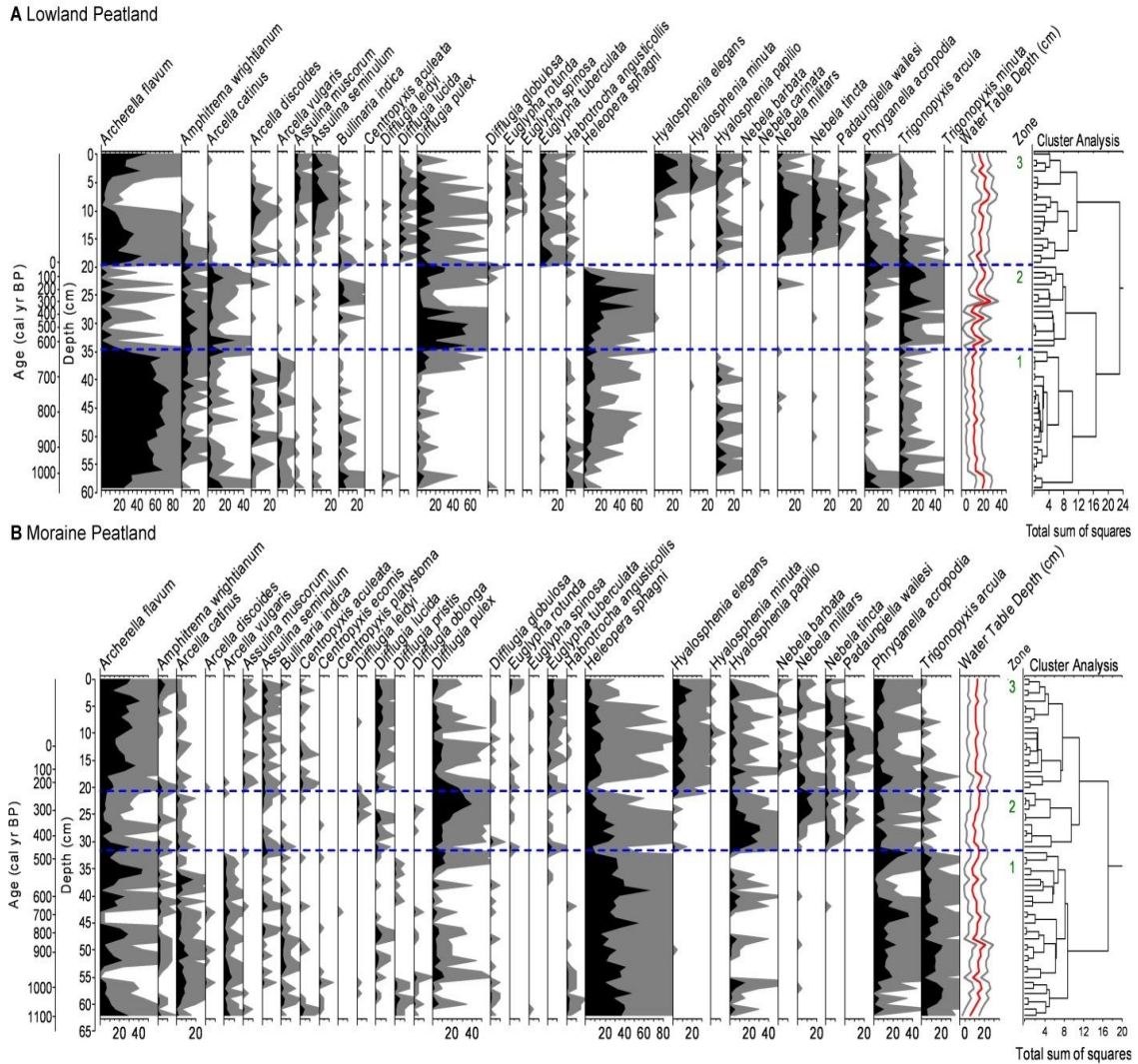


Figure 2.8: Testate amoebae species assemblage composition graphs from the lowland (A) and moraine (B) peatlands. Reconstructed water-table depths are presented; gray lines represent estimated prediction error bars based on bootstrapping. Testate amoebae assemblages were divided into zones based on a CONISS cluster analysis (Grimm, 1987).

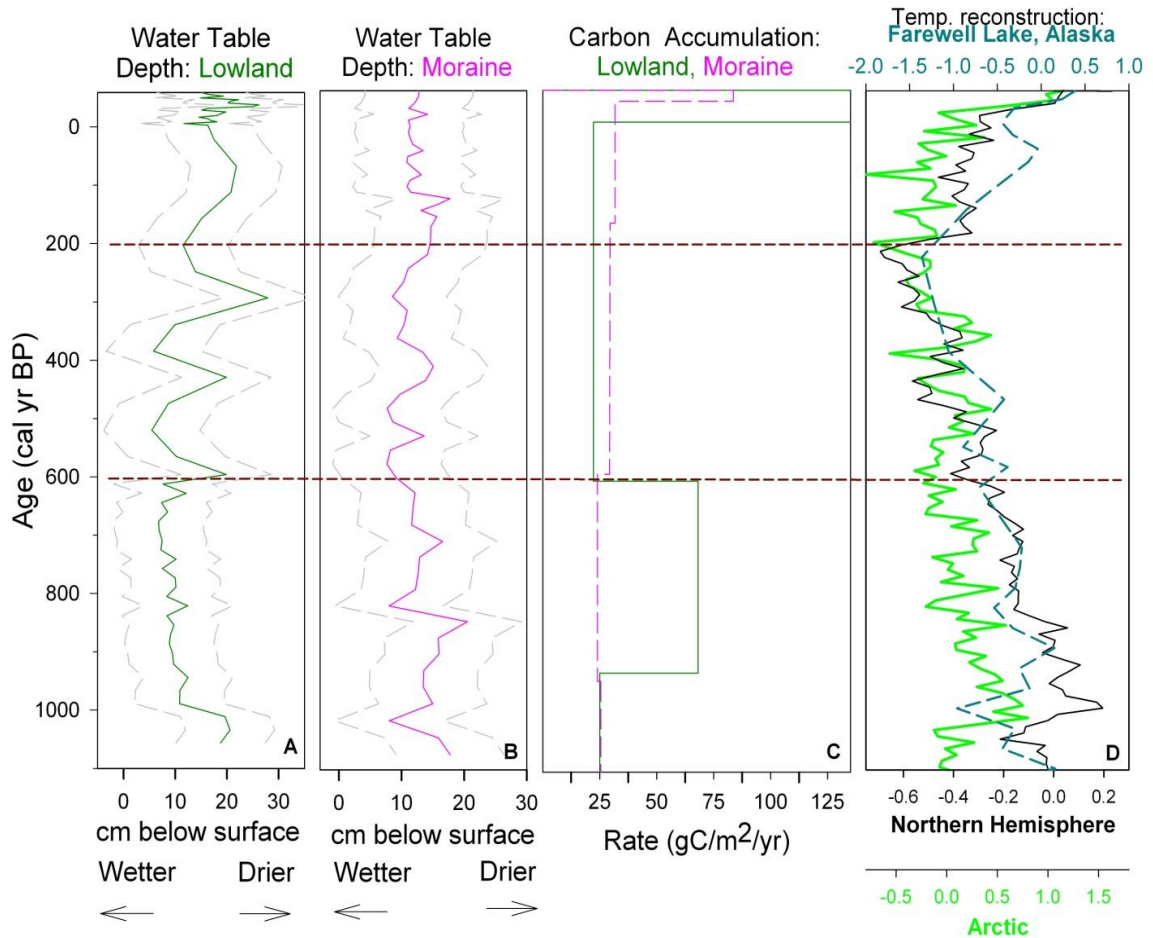


Figure 2.9: Testate amoeba-based reconstruction of water-table depth (WTD) for lowland (A) and moraine (B) peatlands. Dashed gray lines represent estimated prediction error bars based on bootstrapping. C) A ratio of testate amoebae taxa associated with high environmental variability to those taxa associated with low environmental variability. Testate amoebae were included in the two categories if they were found to be more abundant in highly variable or highly stable surface environments, using the environmental variability index of (EVI) Sullivan and Booth (2011) (taxa most abundant in the upper or lower ~30% of EVI values). D) Peatland C accumulation for lowland (solid line) and moraine (dashed line) rates based on intervals between median calibrated radiocarbon dates (Table 2.1). E) Geochemical proxy temperature reconstruction from Farewell Lake, Alaska (dashed line) (Hu et al., 2001); multiproxy Arctic region temperature reconstruction (thick line) (Kaufman et al., 2009); and multiproxy northern hemisphere temperature reconstruction (thin line) (Ljungqvist, 2010). Horizontal dashed red lines indicate the 600-200 cal yr BP period in which differences in WTD variability are beyond the reconstruction error estimates.

Chapter 3

Recent Increase in Peatland Carbon Accumulation in a Thermokarst Lake Basin in Southwestern Alaska

Summary

Drained thermokarst lake basins cover large areas of northern high latitude lowlands. However, the importance of peat accumulated in these drained basins to carbon (C) cycling is poorly understood. Here we present results from a permafrost sediment core aimed at investigating site history, lake drainage, apparent carbon accumulation, and paleohydrology in a thermokarst basin on the Yukon Kuskokwim Delta in southwestern Alaska. Our results show that a thermokarst lake existed for about 2,300 years before it drained and a peatland established in the early 1600s. Average apparent C accumulation rate (CAR) was 12 gC/m²/yr over the 2,300 years before lake drainage, but increased to 120 gC/m²/yr following peatland initiation. After transitioning to a *Sphagnum*-dominated peatland at ~1700 AD, CAR reduced gradually before more than doubling from the mid-1970s to the early 1980s. This abrupt increase in CAR was possibly in response to a Pacific climate regime shift in the late 1970s, a transition characterized by a nearly 1.5°C increase in regional average annual temperature. Even after considering the differential decay of recent peat, there was an increase in C accumulation after 1977. Reconstructed water-table depths from subfossil testate amoeba show little change throughout the past three centuries, but there was a pronounced shift in testate amoeba composition after the 1977 temperature change. If the results from peatlands in other drained thermokarst lake basins are consistent with the results from this study, then the C accumulated in these

vegetated drained basins under current warming might help offset some of the C released from thawing permafrost and thermokarst features in northern regions.

3.1 Introduction

Temperatures at northern high latitudes have risen more quickly than the global average (IPCC, 2007), increasing the potential of permafrost thaw and release of stored organic carbon (C) (Schuur et al., 2009; Tarnocai et al., 2009; Grosse et al., 2011). However, the magnitude of its potential impact on the global C cycle and climate change is uncertain (Zimov et al., 2006; Schuur et al., 2008). An understudied and important component of the permafrost organic C pool is the accumulation of peat in drained thermokarst lake basins, as large portions of northern high latitude landscapes presently contain vegetated drained lake basins (e.g., Nowacki, 2002; Grosse et al., 2012).

Formation of thermokarst lakes occurs after ice-rich permafrost thaws and the ground surface subsides. This progression releases labile C previously stored in frozen soil (Schirrmeister et al., 2011), which increases methane (CH₄) production and atmospheric emissions (Zimov et al., 1997; Walter et al., 2008). Drainage of thermokarst lakes, which can be induced by internal (e.g., increased thaw zone beneath a lake) or lateral processes (e.g., lake enlargement toward a drainage gradient), can lead to the formation of permafrost on the basin floor, which creates a confining layer and water-saturated soils. Subsequently, most drained thermokarst lake basins become vegetated about 5 years after drainage and can accumulate peat within 20 years of drainage (Billings and Peterson, 1980; Bliss and Peterson, 1992). However, the C accumulation potential of post-lake drainage remains unclear.

A better understanding of the processes that impact peat accumulation rates in drained vegetated thermokarst basins is important for assessing how permafrost thaw dynamics could influence C cycling. After thermokarst lake drainage and peatland

initiation, the peatland C accumulation rate could be impacted by various factors such as changes in vegetation or temperature. The accumulation of C in these drained thermokarst lake basins could also be influenced by changes in peatland hydrology, but these factors have not been adequately assessed. Therefore, more information is needed about the processes that influence C accumulation rates in peatlands occupying drained thermokarst lake basins so that the net C balance associated with thawing permafrost can be better estimated. To help address this need, a sediment core was collected from a thermokarst basin on the Yukon-Kuskokwim Delta (hereafter referred to as YK Delta) in southwestern Alaska (Figure 3.1A). This sediment core was analyzed to understand the ecological and hydrological history of the site, and specifically to determine: 1) the timing of thermokarst lake drainage and peatland initiation; 2) the C accumulation rates of both the lake and peatland; and 3) changes in the peatland water-table depth.

3.2 Regional Setting and Study Site

The YK Delta is greater than 25 million acres in area, which is second only to the Mississippi Delta in North America (USFWS, 2004). This low-lying landscape, heavily influenced by permafrost and thermokarst features, is dominated by wetlands, lakes, and rivers (Nowacki, 2002; USFWS, 2004). The YK Delta forms where the two largest rivers in Alaska, the Yukon and Kuskokwim, reach the southwestern coast of Alaska. The YK Delta landscape, which is generally lower than 35 m above sea level in elevation, stretches from the Norton Sound in the north to Kuskokwim Bay in the south and from the coast in the west to the Kuskokwim Mountains in the east (USFWS, 2004) (Figure 3.1A). Peatlands of the YK Delta are generally found within the Yukon-

Kuskokwim Coastal Plain soil survey major land resource area, which is primarily characterized by old alluvium from the Yukon and Kuskokwim rivers and includes broad organic-rich plains. Permafrost is common and discontinuous, and thermokarst lakes and vegetated thermokarst depressions are abundant (USDA, 2008). YK Delta modern vegetation is classified as Bering Taiga (Nowacki et al., 2002); coastal vegetation primarily consists of brackish marshes and wet meadows dominated by birch (*Betula* spp.) and willow (*Salix* spp.) shrubs and sedges (e.g., *Eriophorum* spp.), while the permafrost-influenced landscapes of the inland are characterized by Ericaceous shrubs (*Ledum palustre*, *Empetrum nigrum*, *Vaccinium* spp.), dwarf birch (*Betula nana*), willows (*Salix* spp.), sedges (*Carex* spp., *Eriophorum vaginatum*) and peat mosses (*Sphagnum* spp.) (Viereck and Little, 2007; Nowacki et al., 2002). The YK Delta is in the Western region climate zone, a transitional zone between continental and coastal zones impacted by cold interior air, changes in sea ice extent, and low pressure from the Bering Sea (Stafford et al., 2000). A recent 30-year (1980-2010) climate period from the long-term weather station in Bethel shows mean annual precipitation of ~46 cm and mean annual temperature of -0.7°C, with average July temperature of 13.3 °C and average January temperature of -14.2°C. Precipitation during June, July, and August comprised 40% of the annual total, while December, January, and February accounted for only 14% (Alaska Climate Research Center, 2012).

The peatland study site (Latitude 60°31'23" N & Longitude 161°5'34" W, hereafter referred to as the Kwethluk peatland) is ~25 m in altitude in a drained thermokarst basin in the southeast portion of the YK Delta (Figure 3.1A), about 45 km southeast of Bethel, south of Three Step Mountain (Figure 3.1B) and ~60 m west of the

Kwethluk River (Figure 3.1C). The basin is ~75 m in diameter, and its basin floor is ~2 m lower than the surrounding upland surface (Figure 3.2). Visible cracks near the basin edge and intact permafrost in the surface surrounding the basin, as well as below the basin floor, suggest that permafrost thaw and collapse resulted in this thermokarst depression, which is similar to other features common in this region (USDA, 2008). The vegetation includes Ericaceous shrubs like Labrador tea (*Ledum palustre*), dwarf birch (*Betula nana*), small cranberry (*Vaccinium oxycoccos*), sedges like water sedge (*Carex aquatilis*) and tussock cottongrass (*Eriophorum vaginatum*), and mosses (*Sphagnum* spp., *Tomenthypnum nitens*) (Figure 3.2). Although the YK Delta was not glaciated at any time during the last three million years, including maximum extent of the Cordilleran Ice Sheet and the Last Glacial Maximum ~20 ka, the Ahklun Mountains to the east of the site (Figure 3.1B) experienced cycles of glacial activity during this period (Briner and Kaufman, 2008; Kaufman et al., 2011). The study site is near glacial outwash from glaciers in the Ahklun Mountains, but is in the Kwethluk River floodplain and is underlain by alluvial silt (NPS, 1999).

3.3 Methods

3.3.1 Sediment Core Collection

A 111-cm long core (YD 10-2) was collected from the Kwethluk peatland in late August 2010. The top 41 cm of the core was collected as a monolith (8-cm long and 10-cm wide) by cutting to the bottom of the active layer with a knife, while the remaining 70 cm of frozen sediment was collected using a 2-cm diameter hand operated permafrost corer (also known as a Modified Hoffer probe) (Zoltai, 1978). The upper 41 cm of the core

was covered in plastic wrap and aluminum foil and placed in PVC containers. The lower 70 cm of the core was subsampled on site in 1 to 3 cm intervals, placed in plastic bags, and covered with aluminum foil. Sediment characteristics were noted in the field and described in detail in the laboratory. The samples were transported back to the laboratory at Lehigh University, where they were stored in a cold room at 4°C.

3.3.2 Sediment Properties and Radiometric Dating

The upper 41 cm of the core were cut into 1-cm increments, and from each of these increments, as well as the field sampled increments of the lower 70 cm, 1 cm³ of peat was collected for loss-on-ignition (LOI) analysis in accordance with standard methods (Dean, 1974). The difference between sediment dry weight and weight after combustion was used to estimate organic matter content, which was then divided by the fresh sediment volume to estimate ash-free bulk density. Sediments from the core were sampled for radiometric dating. At seven different depths (23 to 107 cm) 1-cm³ subsamples were sieved and *Sphagnum* stems were picked (as well as woody fragments at two depths), cleaned with distilled water, dried and then sent to the Keck-CCAMS facility at the University of California, Irvine for pretreatments and AMS radiocarbon dating analysis. Peat from the first 40 cm was sampled at a 2-cm interval, dried at 60°C, ground, and at least 600 mg from each interval was sent to MyCore laboratories in Ontario, Canada for ²¹⁰Pb analyses. Results from ²¹⁰Pb analyses and the constant-rate-of-supply (CRS) model (Appleby and Oldfield, 1979) were used to estimate ages for 0-22 cm (Table 3.1). IntCal09 (Reimer et al., 2009) and CALIBomb (Reimer et al., 2004) were used to calibrate the seven AMS ¹⁴C dates (Table 3.2).

The chronology of the record combines the ages estimated by the ^{210}Pb CRS model with an age-depth model from a polynomial regression for the ^{14}C samples (Figure 3.3). As the radiocarbon dates from 23-40 cm are almost statistically the same based on their 95% calibrated ranges (Table 3.2), the age-depth model curve through this section is as shallow as possible given the calibrated radiocarbon ranges and connection to ^{210}Pb -dated section of the core. This approach represents the most conservative age-depth model and attempts to minimize the uncertainty from the radiocarbon dates at 23-40 cm. Age-depth model error ranges were extrapolated from the 95% ranges of the calibrated radiocarbon dates. The CRS model used to estimate ages from 0 to 22 cm resulted in most probable ages and a 68% probability range. Samples with excess modern carbon and/or a mid-20th century median calibrated age (i.e., at 57 cm, 71 cm, and 90 cm depths; Table 3.2) were excluded from age-depth modeling as they represented age reversals, which is not uncommon in peatlands in permafrost influenced basins (e.g., Jones et al., 2012). Ages are presented on the BC/AD timescale. Apparent C accumulation rates were estimated from LOI, ash-free bulk density measurements using a carbon content of peat organic matter of 51% (Vitt et al., 2000), and sediment deposition rates based on the age-depth model.

3.3.3 Macrofossil and Testate Amoebae Analyses

Macrofossil analysis helped to better understand the history of the study site and objectively determine the transition from lacustrine sediments, which included aquatic-plant remains, to peatland sediments, which had greater proportions of *Sphagnum* (e.g., Mauquoy and van Geel, 2007; Ireland and Booth, 2011). Two cm³ of sediment

subsamples were sieved, and the size fraction greater than 125 μm was analyzed down to a depth of 99 cm. Three cm above and below 35 cm (a potential depth of transition from lake to peatland as suggested by LOI data) were analyzed at 1-cm resolution, while most of the record was analyzed at 2-cm resolution (three samples from the lower portion of the core necessitated 3-cm resolution). Peat subsamples were dispersed into a custom-designed tray with four equal-sized quadrants for examination under a stereo-microscope. The percent cover (in 5% increments) was estimated in each quadrant to produce a semi-quantitative estimation of relative abundance of eight macrofossil categories: *Sphagnum* moss, brown moss, large herbaceous fragments, herbaceous rootlets, ligneous roots or stems, shrub leaves, aquatics (*Nuphar* spp. seeds), mineral material, and unidentifiable organic debris. The presence of chironomid fragments was also noted, as they can be indicative of lacustrine sediments (e.g., Walker, 2001). Stratigraphically constrained cluster analyses, using the program CONISS (Grimm, 1987), was used to analyze the similarity of macrofossil samples and aid in objectively determining the transition between lake and peat sediment. The date of the lowest cm of peat above the lacustrine sediments (as determined by macrofossil analysis) was used to estimate the timing of lake drainage and peatland initiation (e.g., Hinkel et al., 2003).

Testate amoebae, a group of shell-producing amoeboid protists, were used as a proxy to reconstruct peatland water-table depth at 1-cm resolution (e.g., Charman, 2001; Booth, 2008; Markel et al., 2010). Preparation and analysis of testate amoebae followed standard sieving methods (Booth et al., 2010). One cm^3 of peat was collected for analysis and the size fraction between 355 and 15 μm was analyzed, as this interval captures most species and was used for the calibration dataset (Booth, 2008; Markel et al., 2010).

Slides were prepared and scanned at 400x magnification until a total of at least 100 tests were identified and counted following the taxonomy of Charman et al. (2000) and the modifications of Booth (2008). However, *Cyclopyxis arcelloides* type and *Phryganella acropodia* type were grouped in this study. Additionally, *Diffflugia pristis* type was not used for the water-table depth reconstruction as a lack of sufficient modern ecological data and uncertain taxonomy make it an unclear indicator species. A transfer function for North America (Booth, 2008) was combined with a calibration set from Alaska peatlands (Markel et al., 2010) to reconstruct water-table depth changes from testate amoeba assemblages using a weighted averaging (WA) model. Sample specific standard error estimates were made using bootstrapping techniques ($n = 1000$) and the software program C2 (Juggins, 2003). Stratigraphically constrained cluster analysis, using the program CONISS (Grimm, 1987), was performed on the testate amoeba data to help in zonation and assist in discussion of the record.

3.4 Results

3.4.1 Peat Properties and Carbon Accumulation Rates

Organic matter content shows the sharpest changes at 35 cm or ~1700 AD (Figure 3.4). Less pronounced shifts in organic matter also occurred at depths of 67 and 108 cm. Average organic matter content was 37% (ranging from 11 to 47%) below 35 cm, but increased to 94% (61-99% range) above 35 cm. About 90 years prior to the shift in organic matter, the C accumulation rate also changed dramatically (Figure 3.4). The C accumulation rate averaged 12 gC/m²/yr from ~775 BC until 42 cm or ~1610, when it increased substantially to reach 120 gC/m²/yr by the late 1600s. Similarly, ash-free bulk

density also increased from 0.10 to 0.22 g/cm³ in the late 1600s. Carbon accumulation rates then declined gradually, before doubling from the late 1970s to the early 1980s.

3.4.2 Macrofossils

The macrofossil data also show the largest changes at 35 and 42 cm or ~1700 and ~1610, respectively (Figure 3.4). The cluster analysis of the macrofossil data helped define two different primary zones and one subzone. The transition from Zone 1 to Zone 1a occurs at 42 cm and is associated with a decrease in unidentifiable organic debris, which are common in lake sediments (e.g., Schnurrenberger et al., 2003), and an increase in *Sphagnum* moss. Zone 1a, a subzone from 42 cm to 35 cm within Zone 1, is most specifically characterized by increased amounts of herbaceous rootlets. At the transition from Zone 1a to 2 at 35 cm, the abundance of herbaceous rootlets dropped while the amount of *Sphagnum* increased sharply. Chironomid fragments were found at five depths from 90 to 57 cm and aquatic plant seeds were found at depths of 82, 49, and 45 cm in the core, all within Zone 1.

3.4.3 Testate Amoebae and Water-table Depth Reconstruction

There were 25 testate amoeba taxa identified in the upper 35-cm of the core, and *Archerella flavum* was the most dominant species (Figure 3.5). The number of testate amoebae dropped sharply to zero at depths below 35 cm. Three zones were defined using the stratigraphically constrained cluster analysis. Shifts between these zones are evident in changes in the abundance of testate amoeba species, like the decrease in *Hyalosphenia papilio* and increase in *Archerella flavum* that occurred from Zone 1 to Zone 2 and

absence of *Phryganella acropodia* type in Zone 3. The transition between zones 3 and 2 occurred ~1989 AD, while the transition between zones 2 and 1 occurred ~1790 AD. However, changes in testate amoeba assemblages were only associated with small changes in reconstructed water-table depths, which are relatively stable. In fact, most changes in water-table depth estimates are within the error of the transfer function except for the change that occurred at the transition from Zone 1 to Zone 2.

3.5 Discussion

3.5.1 Evidence for the Presence of a Thermokarst Lake Before Peatland

Establishment

The sharp decrease in unidentifiable organic matter coupled with increases in both *Sphagnum* and herbaceous rootlets at 42 cm or ~1610 AD was likely the result of either permafrost thaw and collapse (e.g., Kokfelt et al., 2010) or drainage of a thermokarst lake (e.g., Jones et al., 2012). Patterns in the macrofossil data provide evidence that these changes were most likely the result of thermokarst lake drainage. For example, submerged aquatic plant (*Nuphar* spp.) seeds were present in Zone 1 (Figure 3.4). These aquatic plant seeds are also consistent with the presence of chironomid fragments in Zone 1 at five depths from 90 to 57 cm. Chironomids are primarily aquatic, but they can also be found in peatlands. However, permafrost soils are not considered potential chironomid habitat (Walker, 2001). Therefore if changes in the macrofossils were the result of terrestrial permafrost soil thaw and collapse, then chironomid fragments would not likely be present in the lower core sediments of Zone 1.

Thermokarst lakes are usually shallow, and the relatively small size of this basin (Figure 3.1) coupled with the macrofossil data from the core (Figure 3.4) suggest that the lake that occupied this thermokarst basin was likely shallow. The relatively small amount of *Sphagnum* (8.5 %), large herbaceous fragments (e.g., graminoid leaves), and ligneous roots and stems are consistent with this interpretation, as these plants are unlikely to survive under deep water (e.g., Mauquoy and van Geel, 2007). Additionally, the location where the core was taken might have been in or near relatively shallow water in the lake basin. The core was not collected near the edge of the basin (Figure 3.2), but prior to lake drainage this location might have been near a topographic high point in the lake basin. Examples of topographic high points in lake basins were seen in other regional lakes near the Kwethluk River during examination of aerial photos and aerial observations during field work. Water-level fluctuations may have allowed for the accumulation of lake indicators (e.g., *Nuphar* spp. seeds) as well as smaller quantities of plants like *Sphagnum* and herbaceous material prior to peatland establishment at the coring site.

3.5.2 Peatland Initiation Following Drainage of the Thermokarst Lake

The macrofossil and testate amoeba data combined with radiometric dating suggest that thermokarst lake drainage occurred at 42 cm or ~1610 AD and was followed by establishment of a peatland with increased herbaceous vegetation (i.e., a fen) before transitioning to a *Sphagnum*-dominated peatland (i.e., a bog or poor fen) at 35 cm (Figure 3.4). The amount of *Sphagnum*, indicative of peatland sediment (e.g., Mauquoy and van Geel, 2007), increased while unidentifiable organic debris, representative of lacustrine

sediment (e.g., Schnurrenberger et al., 2003), decreased from Zone 1 to Zone 1a. This change indicates a shift from a lake environment in Zone 1 to a peatland environment in Zone 1a. Another increase in *Sphagnum* at 35 cm, over three times larger in magnitude than the previous change at 42 cm, coupled with a sharp decrease in herbaceous rootlets, indicates a major transition from Zone 1a to Zone 2 that likely represents a change from a more fen-like peatland to a *Sphagnum*-dominated system (Figure 3.4). The presence of herbaceous rootlets in Zone 1a suggests more fen-like characteristics than the *Sphagnum*-dominated peatland (Mitsch and Gosselink, 2000) of Zone 2. Additionally, the density of testate amoebae increased sharply in Zone 2, which could be expected following transition to a *Sphagnum*-dominated peatland (Figure 3.5) (e.g., Warner, 1990). In summary, the macrofossil data indicate that lake (Zone 1) drainage occurred at 42 cm or ~1610 AD and was followed by a mixed *Sphagnum* and herbaceous peatland (Zone 1a) until ~1700 AD, when there was a transition to a *Sphagnum*-dominated system (Zone 2).

Determining the causal mechanism for thermokarst lake drainage is important, but can be difficult. Thermokarst lake drainage can be caused by either internal or lateral processes, but both mechanisms are associated with the degradation of permafrost that serves as a confining layer. Lateral drainage is most common in continuous permafrost areas and can be caused by various factors that often leave drainage channels, such as the expansion of a lake until it reaches the top of a hydraulic gradient, which can cause water to flow downward out of the lake (Hopkins, 1949; Marsh et al., 2009; Grosse et al., 2012). Conversely, in discontinuous permafrost areas internal drainage is more common and can occur when the talik (unfrozen ground under a lake) expands into the permafrost and leads to subterraneous drainage (Hopkins, 1949; Yoshikawa and Hinzman, 2003).

As the basin containing the Kwethluk peatland did not have a clear drainage channel and the YK Delta has discontinuous, intermittently shallow, and relatively warm permafrost (Nowacki, 2002), it is likely that this thermokarst lake drained internally through an open talik. Due to relatively large 95% error range of the age-depth model at 42 cm, the transition from lake to peatland likely occurred between 1541 and 1764 (Figure 3.3). Climate reconstructions from Farewell Lake north of the Alaska Range (Hu et al., 2001) and the northern hemisphere (Ljungqvist, 2010) indicate that post-Little Ice Age (LIA) warming began ~1750 AD. So it possible that a warmer climate contributed to drainage of this basin, similar to results from a study of drained thermokarst basins on the Seward Peninsula that suggested past warmer climates led to more permafrost degradation and increased lake drainage (Jones et al., 2012). However, due to the uncertainty of the estimated start of drainage based on our results from this single core, additional regional samples are necessary before climate forcing can be considered a likely cause for YK Delta thermokarst lake drainage.

It is also possible that the nearby Kwethluk River (Figure 3.1B) influenced drainage of the lake. Erosion along the upper banks of the Kwethluk River was observed while collecting the core. The river could have eroded away material that was preventing water flow out of the river bank, which could lead to drainage of the lake. Additionally, the post-LIA warming might have led to quicker erosion of the riverbank due to decreased soil stability associated with soil thawing.

3.5.3 Post-Drainage Peatland Carbon Accumulation

Apparent carbon accumulation rates increased dramatically following lake drainage. The apparent C accumulation rate (CAR) was $12 \text{ gC/m}^2/\text{yr}$ over the $\sim 2,300$ year period prior to lake drainage, but increased to $120 \text{ gC/m}^2/\text{yr}$ following lake drainage (Figure 3.4). The sharp rise in peatland CAR in Zone 1a correlates with an increase in herbaceous rootlets. Also, the start of the gradual decline in peatland CAR appears to correspond with the subsequent decrease in herbaceous rootlets (Figure 3.4). This suggests that highly productive early successional herbaceous peatland vegetation, such as *Calamagrostis canadensis*, potentially influenced the higher peatland CAR present after lake drainage and peatland initiation. When herbaceous vegetation cover likely decreased and *Sphagnum* increased, as seen in the transition from Zone 1a to Zone 2, peatland CAR began to decrease as well. This relationship between CAR and vegetation type might be expected, as herbaceous vegetation is generally more productive (e.g., Jones et al., 2012) and has a higher organic-carbon content than *Sphagnum* (e.g., Beilman et al., 2009). Moreover, this pattern in which a drained thermokarst lake accumulates C at the greatest rate immediately following drainage and then the accumulation rates decrease with the time since drainage, is similar to patterns seen in peat accumulation in drained thermokarst lake basins north of our study site on the northern Seward Peninsula (Jones et al., 2012) and Arctic Coastal Plain (Bockheim et al., 2004) and is not uncommon in Arctic peatlands (Oksanen et al., 2001).

Average apparent peatland CAR since lake drainage at the Kwethluk peatland was $120 \text{ gC/m}^2/\text{yr}$, which is over three fold greater than the average rate of sites on the Seward Peninsula ($35 \text{ gC/m}^2/\text{yr}$) and twice the average rate of sites on the Arctic Coastal

Plain ($60 \text{ gC/m}^2/\text{yr}$) in a comparable age class (50-500 years since drainage). Regional climate differences likely explain the high rates of CAR in the YK Delta relative to these other northern locations. Recent 30-year climate averages in summers (months of June, July, and August) from weather stations representative of the northern Seward Peninsula (Kotzebue), Arctic Coastal Plain (Barrow), and YK Delta (Bethel) study sites show that the YK Delta had both the warmest and wettest climate (Alaska Climate Research Center, 2012). These relatively warmer and wetter climate conditions could be beneficial for peatland C accumulation, as warm temperatures increase production (e.g., Beilman et al. 2009), while wet hydrology can minimize C released through decomposition (e.g., Moore and Knowles, 1989). Additionally, a study of bioclimatic zones across the low Arctic indicated that vegetation productivity levels were higher in basins in warmer bioclimatic zones than in basins in colder zones (Walker et al., 2003).

3.5.4 Peatland Carbon Accumulation and Recent Climate Warming

There was also an increase in apparent peatland CAR in the late 1970s, which was temporally similar to the Pacific Decadal Oscillation (PDO) regime shift in 1977 (e.g., Mantua et al., 1997) that increased temperatures in southwestern Alaska (Figure 3.6). Analysis of records from the long-term weather station in Bethel revealed an average annual temperature of -2.07°C for the 32 years prior to the 1977 PDO shift (1945-1977), but the annual average for the following 32 years after the PDO shift (1978-2010) increased substantially to -0.75°C . The peatland CAR more than doubled from the mid-1960s ($\sim 62 \text{ gC/m}^2/\text{yr}$) to the early-1980s ($\sim 138 \text{ gC/m}^2/\text{yr}$). Similarly, the ash-free bulk density increased after the 1977 PDO shift, suggesting rapid peat accumulation and

reduced decomposition and compaction. The cluster analysis of the testate amoeba species data (Figure 3.5) reveals a shift in the community composition and transition from Zone 2 to 3 in the late 1980's. This shift is mostly attributable to an expansion of *Hyalosphenia elegans* and suggests a possible response in testate amoeba communities to the 1977 PDO shift. However, no major change in reconstructed water-table depths occurred at this time, suggesting that the community changes may have been unrelated to the average surface moisture. Temperature or changing seasonality of precipitation may have led to the testate amoeba community change. Alternatively, the patterns may be explained by differential preservation; however, *Hyalosphenia elegans* is preserved in high percentages deeper in the core. The cluster analysis of macrofossil data indicates little change after 1977 (Figure 3.4), suggesting that vegetation was an unlikely cause of the testate amoeba community change. This lack of change in the macrofossil data also suggests that the increase in apparent CAR was less likely due to a structural change in the peatland and more likely related to greater productivity stimulated by warmer average temperatures and a longer growing season. Moreover, instrumental records from Bethel indicate that precipitation remained largely the same after the 1977 PDO shift (Alaska Climate Research Center, 2012), which is also apparent in the reconstructed water-table depths (Figure 3.5), so increased temperatures are possibly the primary driver for higher apparent CAR values.

This increase in apparent CAR following the 1977 PDO shift was likely partially influenced by incomplete decomposition of fresh plant organic matter, as suggested by the relatively low ash-free bulk density values toward the top of the core (Figure 3.4), but this impact was probably minimal. Comparison of peat masses (g of organic matter

(OM) /m²) accumulated over equal time periods before (1948-1975) and after (1982-2009) the 1977 PDO shift supports these differences in peatland CAR. Even though both of the comparative sections of the core were in the acrotelm, and thus subject to similar decay rates, the plant materials prior to the 1977 PDO shift had more time to decay. To account for this difference in decay time, an estimated acrotelm decay constant of 0.0244 yr⁻¹, as established from a recent peatland study in southcentral Alaska (Loisel and Yu, 2013) was applied to the OM from the pre-1977 section for a period of 60 years. After factoring in these decay time differences, which allows for a more equal comparison of the two sections, the estimated OM accumulated after the 1977 PDO shift (42.7 g/m²) is 50% greater than the OM accumulated during an equal time period prior to 1977 (28.4 g/m²). Even with a more conservative decay estimate, which increased the decay period for OM in the post 1977 section 25% to 75 years (well beyond the time difference between the two sections), the OM accumulated in the section after 1977 (37.1 g/m²) is still over 30% greater than during the commensurate time period prior to the 1977 PDO shift.

Apparent peatland CAR also increased in response to warmer temperatures in 2000 (Figure 3.6). The instrumental temperature records from Bethel reveal an increase in average annual temperature starting in 2000. During this increase the average annual temperature from 2000-2010 (-0.43 °C) was more than 1°C warmer than the mean annual temperature from 1930-1999 (-1.53 °C). This recent (2000-2010) increase in temperature is supported by a recent global climate reconstruction based on 73 records that indicates the decade from 2000-2010 was warmer than at least 75% of the temperatures from the last 11,300 years (Marcott et al., 2013). Similar to the response to warmer temperatures

after the 1977 PDO shift, apparent peatland CAR values again more than doubled from the late-1990s (~170 gC/m²/yr) to the mid-2000s (~350 gC/m²/yr). Again, some of these recent increases in peatland CAR are likely influenced by incomplete decomposition of fresh plant tissues, but even for fresh material these recent CAR values are unusually high (e.g., Loisel and Yu, 2013). Future studies of other regional peatlands are needed for comparison, but peatlands in drained lake basins across the YK Delta might serve as substantial and relatively persistent C sinks under future warming conditions, which could offset some of the C released from permafrost thaw.

3.6 Conclusions

This study analyzed a permafrost sediment core from a thermokarst basin on the Yukon-Kuskokwim Delta in southwestern Alaska to: 1) determine when a thermokarst lake drained and a peatland initiated; and 2) estimate changes in lake and peatland CAR. The study site was a thermokarst lake for at least 2,300 years, before it drained and changed to a peatland in the early 1600s (1541-1764 AD). The average apparent CAR increased tenfold following lake drainage, from ~12 to 120 gC/m²/yr after peatland establishment. After transition to a *Sphagnum*-dominated peatland ~1700, CAR reduced gradually before more than doubling from the mid-1970s to the early 1980s, potentially in response to a 1977 PDO shift that saw average annual temperatures increase nearly 1.5°C. Even after accounting for differences in decay time, organic matter accumulation after 1977 was more rapid than a similar time period before 1977. The testate amoeba-based reconstructed water-table depth changed very little throughout the past three centuries, but there was a pronounced shift in testate amoeba communities in the late 1980s, after the 1977 PDO temperature change.

Results from this study suggest that drainage of thermokarst lakes in northern regions could produce basins that accumulate organic-rich peat. These vegetated basins might be a persistent C sink that increases with warming. In some regions however, warming temperatures might also cause peatland hydrology to become drier, which could increase decomposition of organic matter in these basins. Therefore, additional studies of both peatland hydrology and C accumulation rates are needed from vegetated drained thermokarst lake basins in other northern regions. If the results from peatlands in other drained thermokarst lake basins are consistent with the results from this study, then the C accumulated in these vegetated drained basins under current warming might help offset some of the C released from thawing permafrost and thermokarst features in northern regions.

Depth (cm)	²¹⁰ Pb activities (Bq/g)	Year (AD)	68% Date Range ^a
0-1	0.243	2010	2010
2-3	0.196	2008	2008
4-5	0.220	2005	2005
6-7	0.211	2003	2003
8-9	0.239	2000	1999 to 2001
10-11	0.287	1996	1995 to 1997
12-13	0.242	1989	1987 to 1991
14-15	0.309	1982	1980 to 1984
16-17	0.274	1968	1964 to 1972
18-19	0.211	1948	1944 to 1952
20-21	0.110	1921	1912 to 1930
22-23	0.055	1881	1860 to 1902
24-25	0.017	NA	NA
26-27	0.016	NA	NA
28-29	0.014	NA	NA
30-31	0.010	NA	NA
32-33	0.013	NA	NA
34-35	0.013	NA	NA
36-37	0.013	NA	NA
38-39	0.015	NA	NA
40-41	0.019	NA	NA

Table 3.1: ²¹⁰Pb analysis results from Kwethluk peatland in southwestern Alaska.

^a Samples below 24 cm show ²¹⁰Pb activities are at background level so no ages can be determined.

Lab ID Number ^a	Depth (cm)	Material dated	$\delta^{13}\text{C}$ (‰)	^{14}C Fraction Modern	^{14}C date \pm 1 SD (yr BP)	Median Calibrated Year (BC/AD)	Year (BC/AD) Calibrated 95% Range
UCIAMS - 94433	23-24	<i>Sphagnum</i> stems	-25.7	0.9902	80 \pm 15	1879	1696 to 1954
UCIAMS- 94434	33-34	<i>Sphagnum</i> stems	-26.8	0.9898	85 \pm 15	1848	1695 to 1918
UCIAMS- 112292	39-40	<i>Sphagnum</i> stems	-25.7	0.9817	150 \pm 20	1772	1668 to 1879
UCIAMS- 112293	57-58	<i>Sphagnum</i> stems and woody fragments	-27.1	0.9975	20 \pm 20	1953	1893 to 1955
UCIAMS- 112294	71-72	<i>Sphagnum</i> stems	-28.1	1.0080 ^b	-60 \pm 20	1954 ^b	1952 to 1955
UCIAMS- 112295	90-91	<i>Sphagnum</i> stems	-28.4	1.1410 ^b	-1055 \pm 20	1958 ^b	1957 to 1993
UCIAMS- 85701	107-108	<i>Sphagnum</i> stems and woody fragments	-29.1	0.7244	2590 \pm 15	793 BC	774 to 803 BC

Table 3.2: AMS radiocarbon data from Kwethluk peatland in southwestern Alaska.

a UCIAMS - University of California, Irvine Accelerator Mass Spectrometry Facility

b Presence of excess radiocarbon suggests a post-bomb sample age

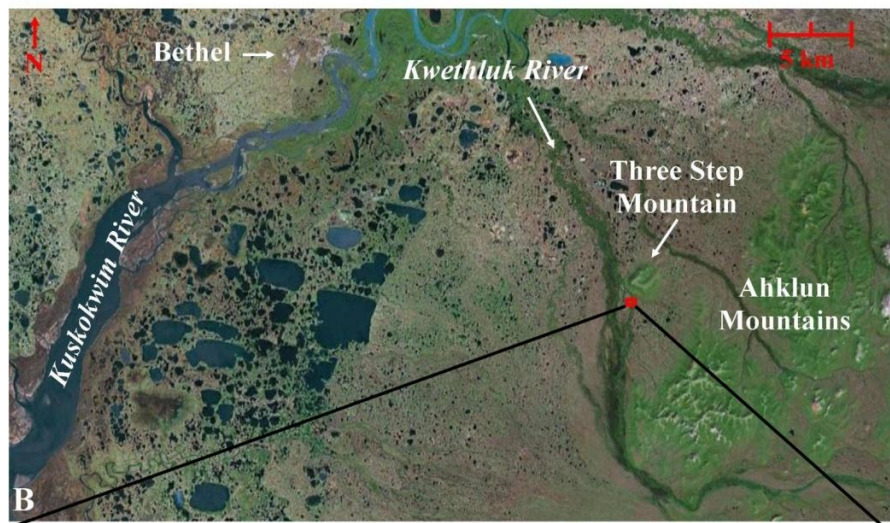
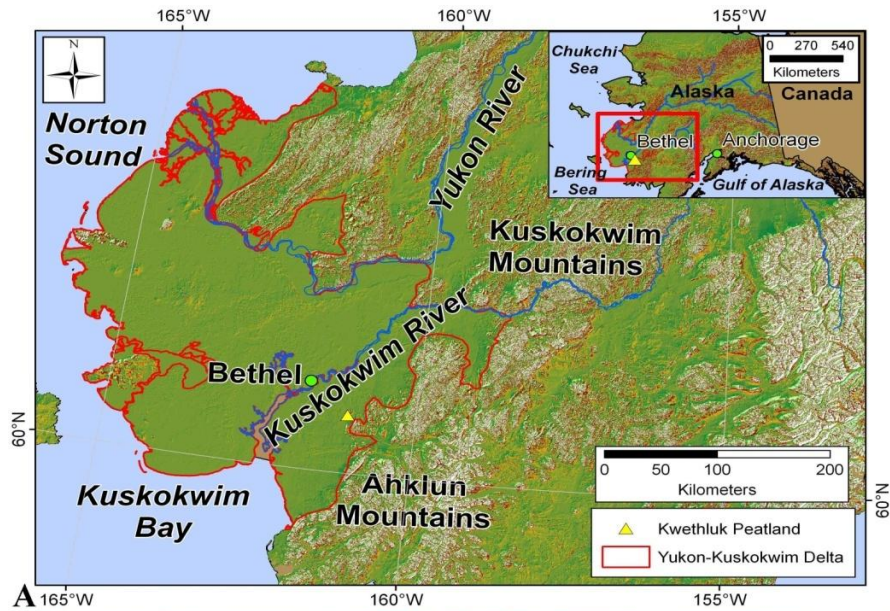


Figure 3.1 (previous page): Location of study site. A) Yukon-Kuskokwim Delta and Kwethluk peatland study site in Southwestern Alaska (inset in upper right corner depicts location relative to rest of Alaska). B) Location of thermokarst basin peatland studied, south of Three Step Mountain and west of Ahklun Mountains; and C) Closer view of the study site west of the Kwethluk River. (photos: B & C, QuickBird satellite imagery)

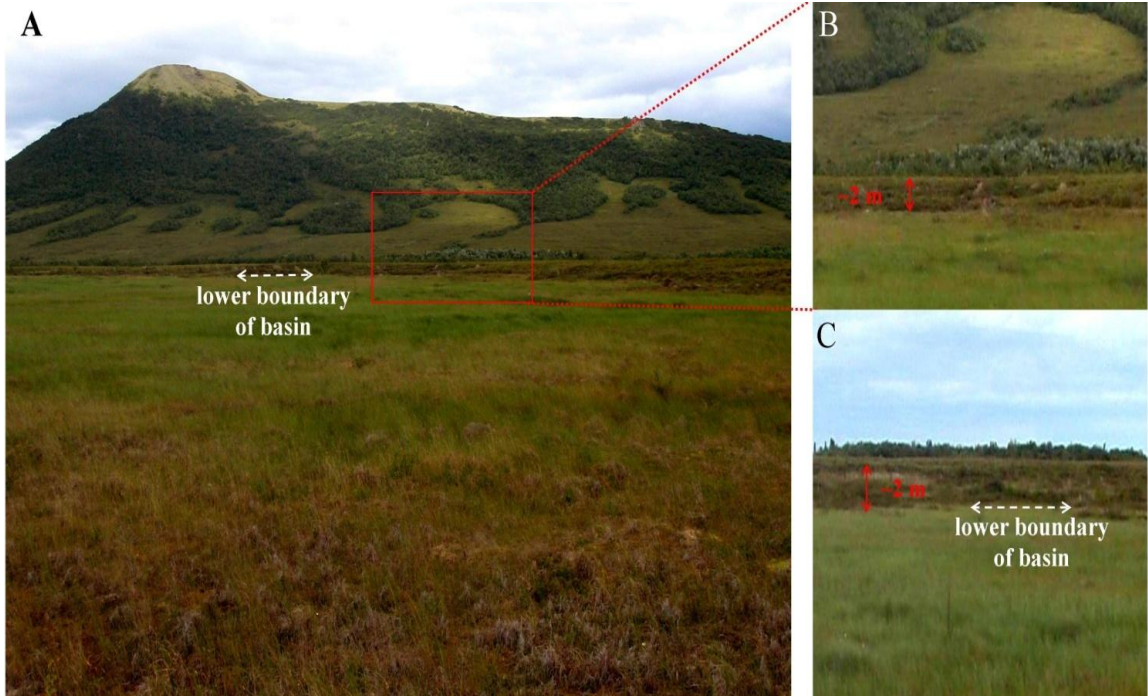


Figure 3.2: Ground photos of the study site. A) Looking northeast from the peatland. Three Step Mountain, on the other side of the Kwethluk River, is visible in the background. The boundary of the thermokarst basin is highlighted in the middle of the photo at the border of the peatland; B) Closer view of the boundary, and estimated vertical relief, of the basin. C) Looking northwest from the peatland, the boundary of the basin is highlighted. The basin was approximately 2 m lower than the ground surface around it. (photos: ESK)

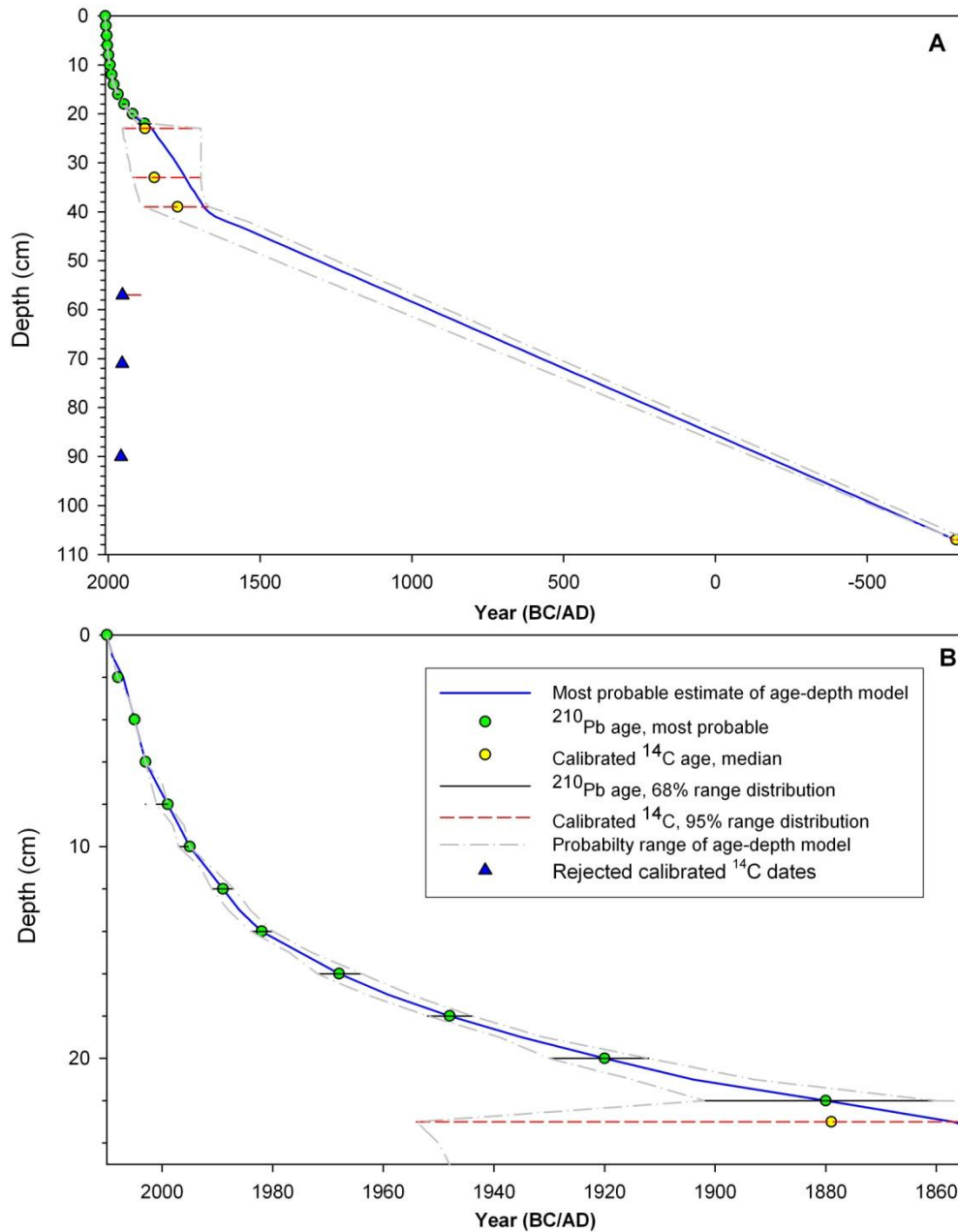


Figure 3.3: A) Age-depth model of the Kwethluk peatland core. B) ^{210}Pb section of the core. ^{210}Pb analyses and the constant-rate-of-supply (CRS) model determined ages for 0-22 cm and IntCal09 (Reimer et al., 2009) was used to calibrate the AMS ^{14}C dates. Samples with excess modern carbon and/or a mid-20th century median calibrated ages (i.e., 57, 71, and 90-cm depths; Table 3.2), were excluded from age-depth modeling as they represented age reversals.

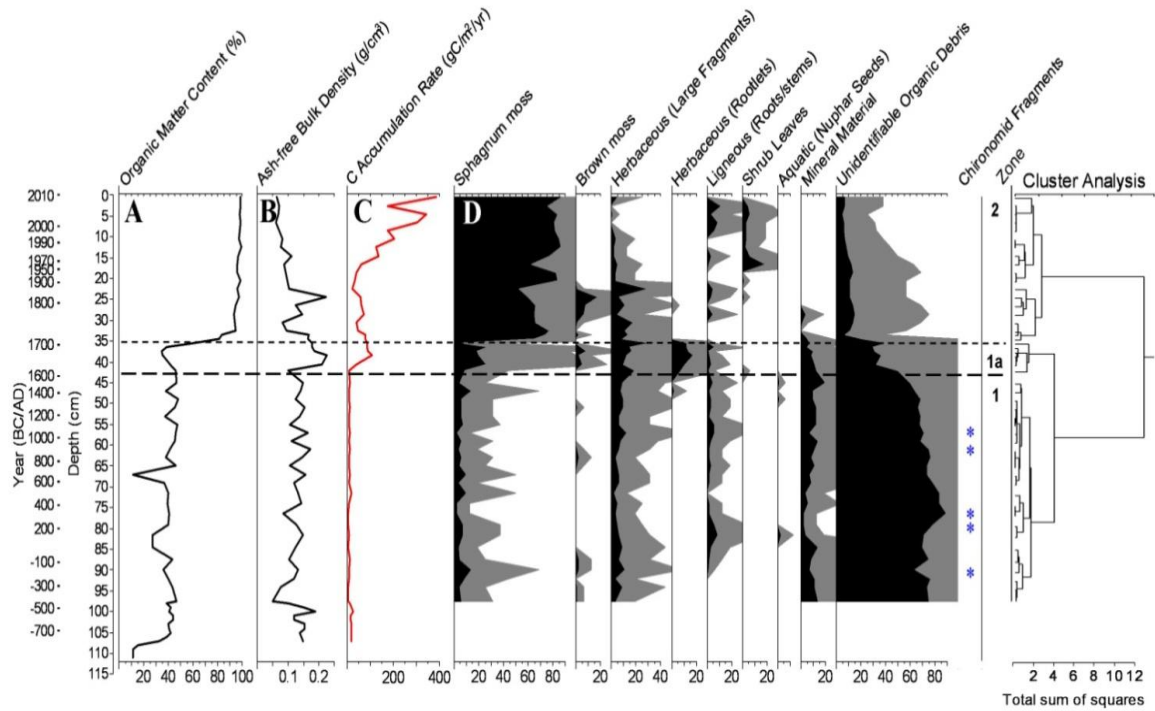


Figure 3.4: A) Organic matter content (%); B) Ash-free bulk density (g/cm^3); C) Carbon accumulation rate ($\text{gC/m}^2/\text{yr}$); and D) Macrofossil relative assemblage graphs and cluster analysis. Blue stars represent chironomid fragments and negative values on the year axis represent year BC. The long-dashed horizontal black lines (lower) depict the transition from Zone 1 (lake sediment) to Zone 1a (herbaceous peat), while the short-dashed horizontal black lines (upper) show the transition from Zone 1a (herbaceous peat) to Zone 2 (*Sphagnum*-dominated peat).

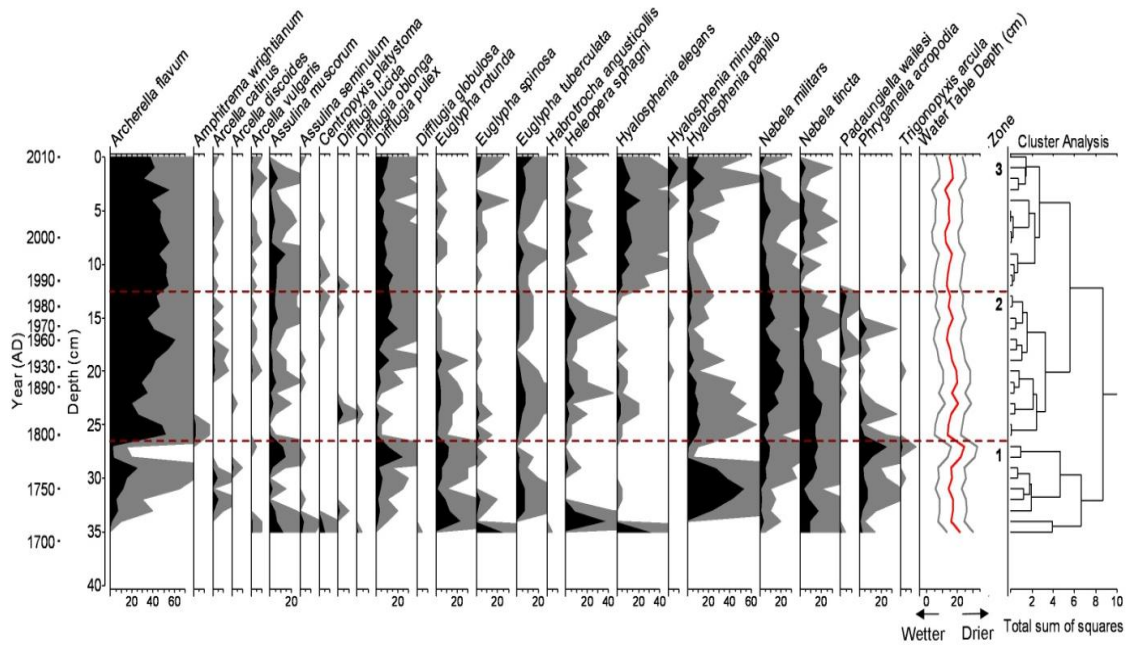


Figure 3.5: Relative abundance of testate amoebae in the upper portion of the peat core. Reconstructed water-table depths are presented; gray lines represent estimated prediction error bars based on bootstrapping. Three zones were defined and the transitions between these three zones are indicated by the dashed brown lines.

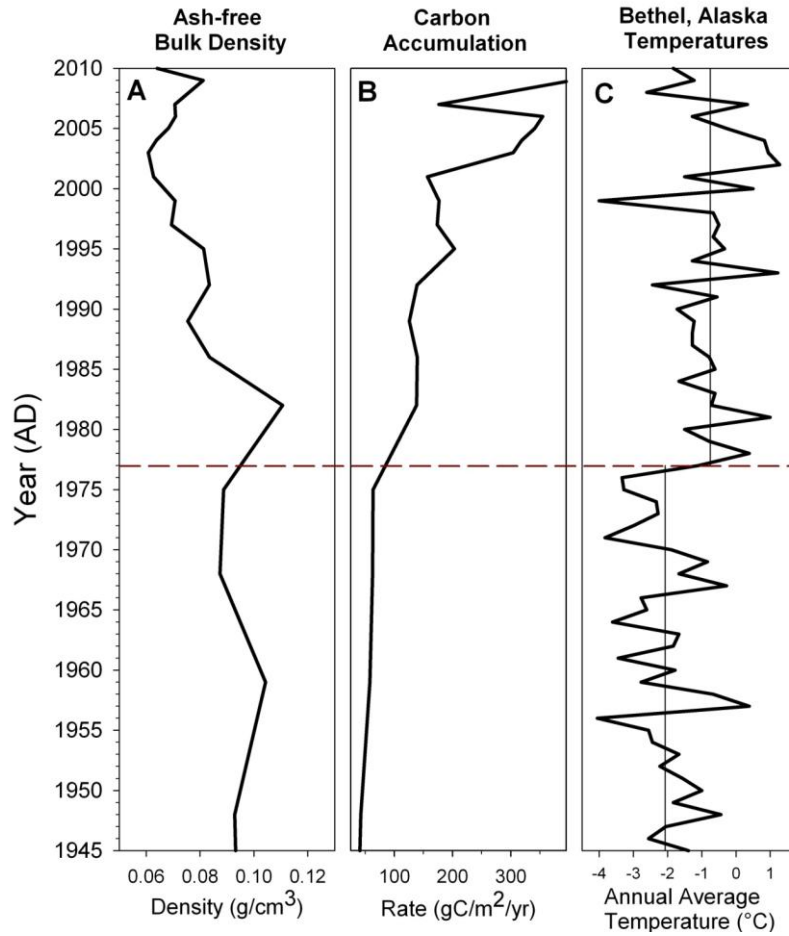


Figure 3.6: A) Ash-free bulk density (g/cm^3); B) Carbon accumulation rate ($\text{gC}/\text{m}^2/\text{yr}$); C) Mean annual temperatures from Bethel, Alaska (Alaska Climate Research Center, 2012) from 1945-2010. The solid vertical black lines represent the mean annual temperatures from 1945 to 1977 (-2.07°C) and 1978 to 2010 (-0.75°C). The dashed horizontal red line represents the 1977 PDO regime shift (e.g., Mantua et al., 1997).

Chapter 4

Climatic Controls of Peatland Hydrology and Carbon Accumulation in Southeastern Alaska over the Last Millennium

Summary

North American peatlands are the largest carbon (C) reservoir of any ecosystem type, and Alaskan peatlands contain greater than half of the C storage of United States' peatlands. Peatland C accumulation rates (PCAR) are controlled by the relative rates of production and decomposition, which are influenced by climate conditions. Understanding how the response of this peatland C pool to climate changes varies among different climate zones is important for evaluating potential earth-system feedbacks. Here we developed a coupled study of peatland paleohydrology and PCAR from two *Sphagnum*-dominated peatlands in the relatively warm and wet climate of southeast Alaska. Past apparent PCAR and hydrology, inferred from loss-on-ignition analyses and testate amoebae, were compared to well-documented climate changes of the past 1100 years, like the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA). Our results indicate that one of the peatlands was wetter during the warmer MCA than during the cooler LIA, but drier during recent warming in the last ~100 years. Interpretation of the paleohydrology of the second site was problematic due to poor modern analogue testate amoeba communities. PCAR at both sites was higher during the MCA than the LIA, but was highest during the recent warming period (88.5 gC/m²/yr average), despite drier conditions than during the MCA. Increased PCAR during a period warmer, but drier, than the MCA suggests that

temperature was the dominant control on PCAR. The relatively abundant precipitation in Southeast Alaska, which may minimize the impact of changes in peatland water-table depth on PCAR, could also amplify the importance of temperature. Higher average PCAR rates during warm periods suggest that peatlands in warmer and wetter climates could accumulate greater C under future warming conditions, creating a negative feedback to climate change.

4.1 Introduction

The response of large carbon (C) reservoirs to climate changes is important for understanding earth-system feedbacks and the global C cycle. High latitude peatlands in the northern hemisphere are one of the largest C reservoirs in the biosphere, storing up to 500 gigatons of C (GtC) ($1\text{Gt} = 10^9 \text{ t}$) (e.g., Gorham, 1991; Turunen et al., 2002; Yu, 2012). As this is greater than 1/2 the C pool of CO_2 that is currently present in the atmosphere (Battle et al., 2000), the response of this northern peatland C reservoir will likely impact future climate changes. Previous studies have looked at how peatland C stocks have responded to climate changes in various northern latitude climate regions such as Western Siberia (Sheng et al., 2004), Continental Western Canada (Vitt et al., 2000), the Mackenzie River Basin (Vitt et al., 2005; Beilman et al., 2008), and Southcentral Alaska (e.g., Jones and Yu, 2010; Klein et al., 2013; Loisel and Yu, 2013). However, C accumulation data from peatlands in relatively warm and wet northern climates are lacking (Yu et al., 2009; Charman et al., 2013). The SE Alaska region, with its abundant precipitation and relatively warm climate (Stafford et al., 2000), presents an opportunity to learn more about how northern peatlands in comparatively wet and warm climates responded to past climate change. This ~20 million acre region with many peatlands (USDA, 2008) is of particular importance because it is generally warmer and wetter (Stafford et al., 2000) than other northern peatland areas (Figure 1.2; Yu et al., 2009), which can influence peatland productivity (e.g., Yu, 2012).

Peatlands accumulate C when the rate of biotic production is greater than the rate of decomposition (Clymo, 1984). The rates of these processes can be impacted by the climatological setting. However, the influence of climate variables on the relative rates

of accumulation and decomposition is not always straightforward. For example, less precipitation may lower the peatland water-table, resulting in a larger aerobic zone in the peat and a faster decomposition rate (McGuire et al., 2009), while simultaneously allowing for increased vegetative production and C sequestration. Additionally, a rise in temperatures could extend the growing season and increase production (Gorham, 1991), but could also increase microbial respiration (Gillooly et al., 2001), which could release more C (Gorham, 1991; McGuire et al., 2006).

North American peatlands contain the largest C reservoir of any ecosystem type, and Alaskan peatlands contain greater than half of the C storage of United States' peatlands (CCSP, 2007). Alaskan peatlands are found across different climate zones ranging from the dry and cold Arctic to the comparatively warm and wet Southeast (Stafford et al., 2000; Nowacki et al., 2002). These different climate zones likely mediated the response of Alaska peatlands to average northern latitude air temperatures that have increased faster than global averages over the past 100 years (IPCC, 2007). How peatlands in relatively warm and wet climates, such as SE Alaska, responded to climate change is currently understudied. There have been previous studies of peatland paleohydrology in SE Alaska (e.g., Payne and Blackford, 2008), but these were relatively low-resolution records and they were not linked with records of C accumulation. In fact, there have not been any studies of long-term PCAR in the SE Alaska region. In order to have a comprehensive understanding of how the large store of C in northern peatlands may respond to climate change, it is important to examine peatlands in northern climates with comparatively wet and warm conditions.

To help address the need for peatland data in relatively wet and warm northern climate conditions, we assessed the response of SE Alaska peatland C accumulation and hydrology to past climate changes. Cores were collected from two *Sphagnum*-dominated peatlands in SE Alaska. Hydrological and C accumulation responses to well-documented climate changes of the past 1100 years, such as the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA) were investigated using paleoecological techniques. One peatland is likely ombrotrophic in a small basin while the other is a sloping peatland, likely with some non-meteoric input, near the bottom of a larger basin. It is hypothesized that PCAR values from peatlands in climates that have abundant precipitation, such as those found in SE Alaska, would be more sensitive to changes in temperature than precipitation. Therefore, C accumulation might be greater during warmer climate periods.

4.2 Regional Setting and Study Sites

Southeastern Alaska is a heavily glaciated and mountainous area in the Gulf of Alaska (GOA) (Figure 4.1). Modern vegetation is classified as Coastal Rainforest (Nowacki et al., 2002); dominant species include Sitka spruce (*Picea sitchensis*), white spruce (*Picea glauca*), mountain hemlock (*Tsuga mertensiana*), yellow cedar (*Chamaecyparis nootkatensis*), Sitka alder (*Alnus sinuata*), and willow (*Salix* spp.) (Nowacki et al., 2002; Viereck and Little, 2007). Southeastern Alaska has a maritime climate that is influenced by the GOA in the North Pacific, which moderates temperatures and results in relatively high levels of precipitation (Stafford et al., 2000). Temperatures in the GOA in the winter and spring months are mainly controlled by the Aleutian Low, a semi-permanent low pressure center near the Aleutian Islands that is an important element of North

Pacific decadal variability (Wilson and Overland, 1987; Trenburth and Hurrell, 1994). Thus winter and spring GOA temperatures correlate well with changes in the Pacific Decadal Oscillation (PDO) Index, the primary mode of North Pacific monthly sea surface temperature variability (Mantua et al., 1997; Hare et al., 1999), and the North Pacific Index, a gauge of the strength of the Aleutian Low pressure cell (Trenburth and Hurrell, 1994).

Thirty-year (1980-2010) climate normals from the long-term weather station in Juneau reveal a mean annual precipitation of 157 cm, a mean annual temperature of 5.5°C, average July temperature of 13.7 °C, and average January temperature of -2.2°C. Precipitation during the autumn (September, October, and November) comprised the largest portion (37%) of the annual average, while March, April, and May accounted for only 16% (Alaska Climate Research Center, 2012). The temperature and plentiful precipitation generate a landscape composed of carbon-rich peatlands among coniferous forests. In total, wetlands comprise ~30% of the land area in the Tongass National Forest, which covers 80% of Southeast Alaska (USDA, 2008; Figure 4.1).

The entire Alexander Archipelago, including both peatland sites, was glaciated during the Last Glacial Maximum ~20 ka (Briner and Kaufman 2008; Kaufman et al., 2011). The Point Lena peatland (Figure 4.2A; Latitude 58°23'13" N, Longitude 134°44'47" W), north of Juneau and about 13 km southwest of the current terminus of the Mendenhall Glacier, is likely a raised ombrotrophic peatland dominated by meteoric inputs (Payne 2003; Payne and Blackford 2004) at an altitude of ~30 m. The Fish Creek peatland (Figure 4.2B; 58°20'11" N, 134°33'18" W) is a gently sloping peatland at an altitude of ~40 m and is part of a larger peatland complex on the northeastern portion of

Douglas Island. Both sites are underlain by alluvium and colluvium (NPS, 1999) and are *Sphagnum*-dominated with trees like lodgepole pine (*Pinus contorta* var. *contorta*), shrubs like Labrador tea (*Ledum palustre*), dwarf birch (*Betula nana*), small cranberry (*Vaccinium oxycoccos*), and herbs like cotton grass (*Eriophorum* spp.).

A geographic information system (GIS)-based analysis was used to approximately delineate basins in the vicinity, and understand the potential hydrologic connectivity to higher elevation non-meteoric waters (e.g., runoff from rain or snow melt), of each peatland site. The portion of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) (30-m horizontal and 20-m vertical resolution) (METI and NASA, 2011) that covered the Point Lena and Fish Creek peatland sites was used with Environmental Systems Research Institute's (ESRI) ArcGIS 9.3 Spatial Analyst Hydrology tools to help delineate the basins and the potential of non-meteoric surface water flow to influence peatland hydrology. In a GIS the elevations in the DEM helped estimate the location of hydrological basins and where water might flow through and drain out of these basins, based on the assumption that water flows down gradient. This analysis was not done to try and estimate specific basin discharge calculations (which would also require groundwater flow estimates), but instead to determine if runoff of non-meteoric waters would likely pass through the vicinity of the study sites and impact peatland hydrology.

The GIS-based hydrologic analyses indicated that the Point Lena peatland did not have any drainages for non-meteoric waters within its estimated basins (Figure 4.2C), while the Fish Creek peatland was in a topographic position that could be hydrologically influenced by runoff accumulated in higher elevation basins (Figure 4.2D). These

differences suggest that the Point Lena peatland is not likely to be influenced by runoff as it is not hydrologically connected to the one substantial drainage basin in its vicinity. Further, the Point Lena peatland is less likely to receive any potential runoff as it is at a higher elevation than the bottom of the hydraulic gradient that begins atop the steep slopes northeast of it (Figure 4.2C). Any potential runoff from the north or east would drain to the coastal areas before reaching the Point Lena peatland and the potential input from the locally higher point to its west would be minimal. Conversely, the Fish Creek peatland is down gradient from the runoff of the combined outflow of the basins that occupy the valley to its southeast (Figure 4.2D). The basin and hydrologic analyses confirm that the Point Lena peatland is dominated by meteoric inputs (e.g., Payne 2003; Payne and Blackford 2004), while Fish Creek is likely hydrologically connected to runoff from non-meteoric waters.

4.3 Methods

4.3.1 Sediment Core Collection

A 466-cm long peat core was collected from the Point Lena peatland and a 346-cm long core from the Fish Creek peatland using a modified Livingstone piston-corer 10.2 cm in diameter (Wright et al., 1984) in May of 2011. Peat characteristics were noted in the field and described in detail in the laboratory. Each core was wrapped in plastic wrap and aluminum foil and placed in PVC containers for transportation back to the laboratory at Lehigh University, where they were stored in a cold room at 4°C.

4.3.2 Sediment Properties and Radiometric Dating

The cores were cut into 1-cm increments and from each of these increments 1-cm³ of peat was collected for analysis. Subsamples of bulk peat were first dried for 12 h at 105°C to determine dry peat weight. Loss-on-ignition (LOI) analysis was then performed and weight loss after 4 hr of combustion at 550°C was used to estimate organic matter content (Dean, 1974). The difference between peat dry weight and weight after combustion, which is the organic matter, was divided by the fresh peat volume to estimate ash-free bulk density.

Radiocarbon and ²¹⁰Pb dates were used to constrain age-depth models.

Subsamples of 1 cm sections were sieved for terrestrial plant macrofossils to be used for ¹⁴C dating. *Sphagnum* stems were picked from the sieved material, cleaned with distilled water, dried, and sent to the Woods Hole AMS lab in Massachusetts for processing and AMS radiocarbon dating. For the time period of interest in this study, approximately the last 1100 years, seven samples were selected from the Point Lena peatland core, while five were selected from the Fish Creek core. Radiocarbon dates were calibrated using the IntCal09 (Reimer et al., 2009) data set (Table 4.1). Also, peat subsamples from every other cm for the first 30 cm from both the Point Lena and Fish Creek cores were dried at 60°C, ground, and at least 600 mg were sent to MyCore laboratories in Ontario, Canada for ²¹⁰Pb dating using the constant-rate-of-supply (CRS) model (Appleby and Oldfield, 1979) (Table 4.1). The chronology of the record combines the ages estimated by the ²¹⁰Pb CRS model with ages developed using the Bayesian-based age-depth modeling software Bacon (Blaauw and Christen, 2011) for the ¹⁴C samples. Incorporating prior knowledge about estimated accumulation rates, 50,000 iterations of possible age-depth

models were developed from the calibrated radiocarbon dates, and these were used to calculate most probable ages and 95% probability range for depths below the oldest ^{210}Pb date. The CRS model used to estimate ages from the ^{210}Pb samples resulted in most probable ages and a 68% probability range. The oldest ^{210}Pb date was then connected to the youngest ^{14}C date through linear interpolation to produce an age-depth model for each of the Point Lena and Fish Creek cores (Figure 4.3). Carbon accumulation rates were estimated from LOI (Dean, 1974), ash-free bulk density measurements using an average carbon content of peat organic matter of 51% (Vitt et al., 2000), and sediment growth rates based on both the most probable age estimate from the age-depth model and intervals between median calibrated radiocarbon dates (Table 4.1). The age-depth model for a core influences the estimation of C accumulation rates between the dated horizons, so in order to use the most conservative C accumulation rates, the accumulation rates were analyzed based on intervals between median calibrated radiocarbon ages (e.g., Yu et al., 2003; Beilman et al., 2009).

4.3.3 Testate Amoeba Analysis

Testate amoebae, a group of shell-producing amoeboid protists, were used to assess the timing of microbial community changes and as a proxy to reconstruct peatland water-table depth at 1-cm resolution (e.g., Booth, 2008; Charman, 2001; Markel et al., 2010; Woodland et al., 1998). Preparation and analysis of testate amoebae followed standard sieving methods (Booth et al., 2010). One cm^3 of peat was collected for analysis and the size fraction between 355 and 15 μm was analyzed. Slides were prepared and scanned at 400x magnification until a total of at least 100 tests (Payne and Mitchell, 2009) were

identified and counted. However, at certain depths in both cores the density of tests was low, and only counts of 50 individuals were obtained. However, this count total may still be adequate for transfer function applications (Payne and Mitchell, 2009). For two depths (61 and 62 cm) in the core from Fish Creek a count total of 50 could not be reached and these samples were therefore excluded from analysis. Testate amoeba taxonomy generally followed Charman et al. (2000) with the modifications of Booth (2008). However, *Cyclopyxis arcelloides* type and *Phryganella acropodia* type were grouped in this study.

A transfer function for North America (Booth, 2008), developed from samples collected in the Rocky Mountains, Upper Midwest, and Eastern North America, was combined with a calibration set from Alaska peatlands (Markel et al., 2010) to reconstruct water-table depth changes from testate amoeba assemblages using a weighted averaging (WA) model. A range of other transfer function models was explored, but all produced similar reconstructed water-table depths from the fossil data, so only the results of the WA transfer function are reported in this paper. Sample specific standard error estimates were made using bootstrapping techniques ($n=1000$) and the software program C2 (Juggins, 2003). *Diffugia pristis* type was excluded from the transfer function because of taxonomic uncertainty of this morphologically variable grouping, and limited information on its modern ecology. Stratigraphically constrained cluster analysis, using the program CONISS (Grimm, 1987), was performed on the testate amoeba data to help in zonation and identify major times of testate amoeba community change, based on total sum of squares values. All taxa, including *D. pristis* type, were used in the cluster analysis.

Non-metric multidimensional scaling (NMS) ordination was used to summarize the major patterns of variability in testate amoeba assemblages (McCune and Grace, 2002), and was compared to water-table depth reconstructions based on the modern calibration dataset. NMS can be favorable over other ordination techniques for ecological data because it incorporates fewer assumptions (Clark, 1993; McCune and Grace, 2002). An appropriate solution, with the necessary number of dimensions, was determined by using Sorenson's distance measurement with the automatic search feature found in PC-ORD (McCune and Medford, 1999). This feature executed 40 runs with real data, each with a random starting configuration, as well as solutions for one to six dimensions. After completing this, 50 runs with randomized data were carried out and statistics on the final stress for each dimensionality were created. The best solution for each dimensionality was chosen through a comparison of the final stress values.

4.4 Results

4.4.1 Peatland Carbon Accumulation

The results of LOI analysis indicated that the average organic matter content of both cores was about 95%, but during certain periods LOI values were much different from this average (Figure 4.4A). Each core had a minimum in which the organic matter dropped below 50%, but these minima occurred at different times. The minimum LOI from the Point Lena core (9%) was at ~870 cal yr BP, while the Fish Creek minimum (47%) occurred at ~450 cal yr BP. It is possible that these minima reflect cryptotephra layers, but this is uncertain as the organic matter minima occurred at different times at each site. The 95% age error range at the depth of the Fish Creek minimum (321 to 511 cal yr BP) was near the ~300 cal yr BP cryptotephra found in multiple peatlands in this

area, including Point Lena and a site near Fish Creek, during a previous study (Payne and Blackford, 2008). It is believed that the most likely source of this tephra was an eruption of Mt. Churchill ~300 cal yr BP (Payne et al., 2008). However, the 95% age error range of the minimum at Point Lena (812 to 952 cal yr BP) was much different than the ~300 cal yr BP Mt. Churchill eruption age (Payne et al., 2008). Given the relatively large estimated age range (within the last 600 yrs) of this Mt. Churchill eruption (Payne et al., 2008), it might be possible that this minimum at Point Lena represents the Mt. Churchill cryptotephra layer, but this is unknown without further geochemical analyses. Due to the uncertainty of this potential cryptotephra layer, it was not incorporated into the age-depth models. The ash-free bulk densities varied between 0.04 g/cm³ and 0.17 g/cm³, with an average of 0.10 g/cm³ for the Point Lena peat core and 0.09 g/cm³ for the Fish Creek peat core. The ash-free bulk densities at both sites are relatively similar except for a slight divergence from ~300 to ~150 cal yr BP, when Point Lena values became higher than those at Fish Creek (Figure 4.4B).

Carbon accumulation rates were more variable at the Point Lena peatland and relatively similar with and without incorporation of the age-depth model (Figure 4.4C and 4D). The main difference was that the increases in rates at both sites ~1100 to 1000 cal yr BP, apparent with incorporation of the age-depth model, were less pronounced when the intervals between median calibrated radiocarbon dates were used for estimation of C accumulation rates. The apparent PCAR for the Point Lena peatland ranged from ~21 to 227 gC/m²/yr, with an average of ~94 gC/m²/yr. At the Fish Creek peatland the estimated PCAR varied from ~7 to 334 gC/m²/yr, with an average of 110 gC/m²/yr. PCAR at both peatlands increased ~800 to 900 cal yr BP and decreased about 550 cal yr

BP, but the magnitude of change at Point Lena was greater. For the period of ~800 to 500 cal yr BP, Point Lena had an average PCAR of 52 gC/m²/yr while Fish Creek had an average PCAR of 24 gC/m²/yr (Figure 4.4C).

4.4.2 Testate Amoebae and Water-table Depth Reconstruction

Twenty-eight testate amoeba taxa were identified in the Point Lena peatland core and 33 testate amoeba taxa were identified in the Fish Creek peatland core. Major changes in community composition occurred within 2-3 cm in several parts of both records (Figure 4.5). Using the results of stratigraphically constrained cluster analysis (Grimm, 1987), four zones were defined for the Point Lena peatland and five zones were defined for the Fish Creek peatland. Descriptions of these zones are presented in Table 4.2. Several of the testate amoeba community changes represented by the zone changes occurred at statistically indistinguishable times at the two peatlands (Figure 4.6).

The Fish Creek peatland contained a high abundance of *Diffflugia pristis* type in many samples, which is problematic as samples with high percentages of this taxon are not well represented in the modern calibration dataset. Also, the group is extremely morphologically variable, making ecological inferences even more uncertain. Therefore, *D. pristis* type was not used to estimate water-table depths. However, the abundance of the taxon creates considerable uncertainty in the interpretation of the Fish Creek testate amoeba record.

To further examine both testate amoebae records, and better assess the strength of the water-table depth reconstructions, we compared the NMS axis one and two scores to the water-table depth reconstructions. Given that these axes summarize the major patterns

of assemblage variability, we would expect to observe correlations with the reconstructed water-table depths if surface moisture was the primary control on assemblage variability. However, the reconstructed water-table depths at Fish Creek show little association with the main patterns of variability in the record, as summarized by NMS axis one and two (Figure 4.7). Conversely, at Point Lena a strong correlation occurred between reconstructed water-table depths and axis one scores ($R^2=0.72$). Therefore, the water-table depth reconstruction at Fish Creek (Figure S4.1) is likely unreliable, as other factors may be influencing the structure of testate amoeba communities. We therefore focus our interpretation of the testate amoeba data at Fish Creek on the timing of community changes, whereas at Pt. Lena we have more confidence in the water-table depth reconstruction. Throughout the course of the record Point Lena experienced a general change toward drier peatland hydrology, which included several wet and dry shifts outside the uncertainty of the transfer function (Figure 4.8A). These fluctuations were primarily driven by changes in the relative abundance of *Archerella flavum*, *Diffflugia pulex*, *Hyalosphenia papilio*, and *Nebela militaris* (Figure 4.5).

4.5 Discussion

4.5.1 Response of Peatland Hydrology and Testate Amoebae Communities to Climate Changes

Reconstructed water-table depths at Point Lena indicate a gradual, millennial scale drying of peatland surface moisture over the course of the record (Figure 4.8A). Moreover, after accounting for the estimated error range, the average water-table depth prior to ~500 cal yr BP (17.4 cm) was wetter than after this date (27.1 cm). Based on topographic position, hydrology at the relatively flat and apparently ombrotrophic Point Lena peatland is likely

dominated by atmospheric inputs. Therefore, warmer temperatures would likely increase evapotranspiration, which should lower the water-table depth. Instead, average peatland water-table depth at the Point Lena site was wetter during the warmer MCA from ~1000 to 600 cal yr BP (16.8 cm) than during the cooler LIA from ~600 to 200 cal yr BP (25.1 cm) (Figure 4.7). However, as even raised peatlands can experience long-term changes related to autogenic processes, in addition to external (allogenic) factors like climate change (e.g., Charman et al., 2006), it is possible that the Point Lena hydrologic response was not entirely climate driven.

Testate amoeba-inferred reconstructed water-table depths from the Point Lena peatland suggest that hydrology has been relatively stable for the past 100 years, including the 1977 PDO climate shift (e.g., Manuta et al., 1997; Figure 4.9). Juneau instrumental records from 1950 to 2010 reveal an increase in average summer temperature after 1977 of 0.9°C (from 12.3 to 13.2°C) while average summer precipitation increased ~9% from 31.0 cm to 33.9 cm after 1977 (Alaska Climate Research Center, 2012). However, Point Lena did not become wetter as a result of this PDO climate shift; instead it remained drier than during the MCA, on average. This difference in peatland hydrology between two warm periods might be attributable to recent temperatures (including both before and after the 1977 PDO shift) that were warmer than those during the MCA (Loso, 2009). These increased temperatures might have led to greater evapotranspiration rates during recent warming than during the MCA, which may have caused the drier (relative to the MCA) peatland hydrology. Moreover, the average reconstructed water-table depth during recent warming (26.4 cm, from 1950 to 2010) was drier than the average reconstructed water-table depth from the less warm

MCA (16.8 cm, from ~1000 to 600 cal yr BP) (Figure 4.8). The possibility remains that these hydrologic responses to different warm periods are influenced by autogenic factors, but it appears that the abundant precipitation in SE Alaska may cause temperature (due to increased evapotranspiration during warmer temperatures) to be a dominant control on peatland hydrology.

The testate amoeba data indicate similar timing of some changes in communities at both the Point Lena and Fish Creek sites, suggesting a microbial community response to climate changes. Accounting for the probability ranges, the transition from Zone 3 to 2 at Fish Creek (542 to 672 cal yr BP, 95% error range) and Zone 2 to 1 at Point Lena (554 to 619 cal yr BP, 95% error range) occurred at statistically indistinguishable times (Figure 4.6). These zone transitions and associated shifts in species composition at both the Point Lena and Fish Creek sites suggest a change occurred at ~600 cal yr BP. The timing of these community changes at both sites correlates with the approximate onset of the LIA (e.g., Loso, 2009). Additionally, the transition from Zone 5 to 4 at Fish Creek (1964 to 1970 AD 68% error range) and Zone 4 to 3 at Point Lena (1964 to 1971 AD 68% error range) occurred at statistically similar times. These age ranges for transitions between zones at both Point Lena and Fish Creek are similar in timing to the 1977 PDO regime shift (e.g., Mantua and Hare, 2002). Further, according to the cluster analysis, Zone 1 at Point Lena could be split into subzones with a transition between them placed at 90 cm (953 to 1028 cal yr BP, 95% error range) (Figure 4.5). This Point Lena transition would be statistically the same, according to error ranges, as the transition from Zone 2 to 1 at Fish Creek (872 to 1037 cal yr BP, 95% error range) (Figure 4.6), which is similar to the approximate start of the MCA (e.g., Loso, 2009) (Figure 4.8C).

It is also possible that a local structural change independent of climate (i.e., autogenic change), caused these changes in testate amoebae communities. However, both cores were *Sphagnum*-dominated, which would reduce the likelihood that a peatland vegetation shift was responsible for the change in testate amoebae communities. Additionally, both the shift from Zone 5 to 4 at Fish Creek and the shift from Zone 4 to 3 at Point Lena involved a decrease in *Trigonopyxis arcula* and increase in *Hyalosphenia papilio* (Figure 4.5). Modern ecological data suggest that *Trigonopyxis arcula* is more likely to be found in drier environments than *Hyalosphenia papilio* (e.g., Booth, 2008), suggesting a possible transition to wetter peatland hydrology. Although, there was little change in reconstructed water-table depths associated with these changes in testate amoeba communities, which might indicate that the community shifts were influenced by warming associated with the 1977 PDO regime shift.

The shifts from Zone 3 to 2 at Fish Creek and Zone 2 to 1 at Point Lena (Figure 4.6) were primarily driven by changes in the abundance of *Hyalosphenia papilio* (Figure 4.5), but these changes varied between peatlands. At Fish Creek, the abundance of *Hyalosphenia papilio* decreased ~ 600 cal yr BP, while at Point Lena the abundance increased. This differential response might have been influenced by differences in landscape positions and hydrologic connectivity between the peatlands. Further, as there was not a strong association between the primary pattern of testate amoeba variability and reconstructed water-table depths at Fish Creek (Figure 4.7), the shift in species at Fish Creek ~ 600 cal yr BP might be related to temperature changes. Conversely, the species shift ~ 600 cal yr BP at the Point Lena peatland might have been associated with water-table depth changes (Figure 4.8A). Although it is uncertain what caused the testate

amoeba community transitions, the multiple changes recorded in communities at similar times across both a sloping and raised peatland suggest that these are large-scale changes and not local factors that would likely only be represented at one site (e.g., Charman et al., 2006). Moreover, the timing of these statistically indistinguishable changes at different sites within the same region is similar to relatively well-documented climate changes of the last millennium (e.g., Loso, 2009), which suggests that climate change was likely the primary driver for these community shifts.

4.5.2 Response of Peatland Carbon Accumulation to Change in Hydrology and Temperature

The rates of apparent peatland C accumulation at Point Lena appeared to be more sensitive to MCA and LIA temperature changes than the rates from Fish Creek. The apparent PCAR values at Point Lena were greatest from ~800 to 550 cal yr BP (52 gC/m²/yr on average) during the latter portion of the warmer MCA period, when peatland hydrology was wetter (Figure 4.8). However, apparent PCAR values at Point Lena decreased to 28 gC/m²/yr after the start of the cooler LIA at ~600 cal yr BP (e.g., Loso, 2009) and remained around these levels as peatland hydrology was drier. Apparent PCAR values at Fish Creek also increased during the warmer MCA, but less than at Point Lena. These data suggest that the greatest PCAR values occurred under relatively warm and wet conditions, as indicated by Point Lena during the MCA, which had the highest average PCAR values between the sites. Warm temperatures coupled with relatively wet peatland hydrology could be beneficial for peatland C accumulation, as warm temperatures help maximize production (e.g., Beilman et al., 2009) and allow for a longer growing season, while wet hydrology can minimize C released through decomposition

(e.g., Moore and Knowles, 1989). However, apparent PCAR values at both sites were also relatively high ($> 20 \text{ gC/m}^2/\text{yr}$) during the cooler and potentially drier LIA. This could be due to the moderate, Gulf of Alaska-influenced SE Alaska climate, which is relatively warm with abundant precipitation (Stafford et al., 2000). Thus even during the relatively drier LIA, the SE Alaska climate was potentially still wet enough to mitigate the impact of a lower peatland water-table depth on C accumulation.

In addition to the SE Alaska climate, the PCAR response of these peatlands may have also been influenced by localized differences between the sites. Both peatlands are similarly underlain by alluvium and colluvium (NPS, 1999), but they are located in different topographic positions. The GIS-based hydrologic analyses of these topographic differences indicated that the Fish Creek peatland likely has hydrologic connectivity to upper basin waters (Figure 4.2D), while Point Lena does not (Figure 4.2C). As wetter peatland hydrology is likely to minimize decomposition (e.g., Moore and Knowles, 1989), it might be expected that due to greater decomposition rates the likely drier Point Lena accumulated less peat than Fish Creek, but our results do not support this. A potential reason for this could be differential availability of nutrients. Both peatlands were *Sphagnum*-dominated, so neither was truly minerotrophic, but Fish Creek likely had greater connectivity to waters with potentially higher nutrient levels than Point Lena. If nutrient availability was a limiting factor to productivity, then the likely ombrotrophic Point Lena site should have a lower PCAR than the seemingly more minerotrophic Fish Creek peatland. Instead, throughout the course of the record, Point Lena accumulated more peat (102-cm) than Fish Creek (73-cm) and had a higher average PCAR, which suggests that nutrient availability may not be a primary factor influencing productivity.

However, nutrient availability could also influence decomposition (e.g., Aerts et al., 1999), which is the other primary factor controlling peat accumulation (e.g., Clymo, 1984). Decomposition at the Fish Creek peatland, with its greater hydrologic connectivity, is less likely to be influenced by nutrient limitations than Point Lena. Therefore, it is possible that higher nutrient levels might have increased decomposition rates at Fish Creek and led to lower total peat accumulation than at Point Lena, but this is uncertain. Without a comparative reconstructed water-table depth from Fish Creek and modern hydroclimate data regarding potential differences in water cycling (e.g., Klein et al., 2013), it is difficult to develop a detailed understanding of how the likely hydrological differences between these two sites differentially influenced peat accumulation.

4.5.3 Recent Warming and Increased Peatland Carbon Accumulation

Both the Point Lena and Fish Creek peatlands exhibit increased apparent PCAR in response to recent warming that began ~50 cal yr BP (~1900 AD). From ~50 to -60 cal yr BP (1900 to 2010 AD) the average apparent PCAR at Point Lena was 134 gC/m²/yr while the average at Fish Creek during the same time period was 143 gC/m²/yr (Figure 8B). These recent average PCAR values are over 5 fold greater at Point Lena, and nearly 3 fold greater at Fish Creek, than the average PCAR values over the rest of the record prior to ~50 cal yr BP. This increase in PCAR occurred during a warm period considered greater than any in at least the last 2000 years, based on a synthesis of proxy temperature reconstructions from 23 sites north of 60° latitude (Kaufman et al., 2009). Some of these

recent increases in peatland CAR are undoubtedly influenced by fresh plant fragments and incomplete decomposition of plant tissues, but even for fresh material these recent apparent CAR values are relatively high. Moreover, the CAR values at Point Lena and Fish Creek are about 50% higher than those from a Southcentral Alaska study that found recent acceleration of C accumulation to a rate of 96 gC/m²/yr over the last ~100 years (Loisel and Yu, 2013).

As mentioned previously, these warmer recent temperatures were associated with drier peatland hydrology at Point Lena than the peatland hydrology during the less warm MCA. However, despite peatland hydrology during recent warming that was drier than the MCA, and actually more similar to the water-table depths during the LIA, the apparent PCAR values were substantially higher than during the MCA (Figure 4.7). This relationship suggests that temperature was a dominant control on apparent PCAR values at Point Lena. As the abundant precipitation in SE Alaska likely results in temperature being the most important control in determining peatland hydrology, this precipitation likely also causes temperature to be the dominant environmental factor influencing apparent PCAR values. This importance of temperature on C accumulation in SE Alaska is evident in Point Lena apparent PCAR values, which were higher during the recent warming period beginning about ~50 cal yr BP (with relatively drier peatland hydrology and warmer temperatures) than during the MCA (with relatively wetter peatland hydrology and cooler temperatures) (Figure 4.7). Therefore, even though peatland hydrology could become drier during current warming, the ample precipitation in SE Alaska (and potentially the high relative humidity associated with it) could help minimize the impact of drier peatland hydrology on peatland C accumulation.

4.6 Conclusions

The water-table depth reconstruction from the raised, ombrotrophic Point Lena peatland in this study suggests that the peatland surface underwent a gradual, millennial scale drying trend with a potentially wetter MCA and a drier LIA. The recent warming period beginning about 50 cal yr BP (~1900 AD) had drier peatland hydrology than the relatively cooler MCA ~1000 to 600 cal yr BP, likely due to increased evapotranspiration associated with warmer temperatures, which suggests that temperature was a dominant control on peatland hydrology. This recent warm period, however, had average apparent PCAR rates higher than during the MCA. This increase in apparent PCAR during a period warmer than the MCA, but with drier peatland hydrology, suggests that temperature was also the most dominant control on apparent C accumulation rates. This importance of temperature could be due to the relatively high humidity and abundant precipitation in SE Alaska, which may minimize the impact of changes in peatland water-table depth on PCAR.

The approximate average apparent PCAR rates during the recent and MCA warm periods were 93.4 gC/m²/yr at Point Lena and 83.7 gC/m²/yr at Fish Creek. As this is the first study of C accumulation in SE Alaska, more investigations of peatlands in this region need to be undertaken to have a more comprehensive understanding of how these peatlands could impact C cycling and climate change in the future. However, the abundant precipitation found in climates such as SE Alaska appears to result in PCAR values that are primarily controlled by temperature. Additional data need to be collected from other peatlands in relatively wet and warm northern regions, but under current warming, peatlands in wet northern climates could maximize productivity while

minimizing decomposition and thus contribute to a negative feedback to climate change through increased C storage.

Dated Depth (cm)	²¹⁰ Pb activities (Bq/g)	Age (cal yr BP)	68% Age Range (cal yr BP)
Point Lena^a			
0-1	0.346	-61	-61
2-3	0.461	-58	-58
4-5	0.409	-54	-54
6-7	0.861	-45	-46 to -44
8-9	0.216	-31	-33 to -29
10-11	0.198	-23	-26 to -20
12-13	0.153	-12	-16 to -8
14-15	0.161	0	-6 to 6
16-17	0.113	22	14 to 30
18-19	0.059	48	28 to 68
20-21	0.031	74	27 to 121
22-23	0.036	97	52 to 143
24-25	0.013	NA	NA
26-27	0.010	NA	NA
28-29	0.004	NA	NA
30-31	0.034	NA	NA
Fish Creek^b			
0-1	0.432	-61	-61
2-3	0.475	-58	-58
4-5	0.403	-54	-54
6-7	0.246	-51	-52 to -50
8-9	0.215	-49	-50 to -48
10-11	0.233	-47	-48 to -46
12-13	0.248	-45	-46 to -44
14-15	0.334	-41	-42 to -40
16-17	0.394	-36	-38 to -34
18-19	0.375	-28	-30 to -26
20-21	0.245	-17	-20 to -14

22-23	0.177	-6	-10 to -2		
24-25	0.250	11	7 to 15		
26-27	0.116	57	43 to 71		
28-29	0.049	NA	NA		
Point Lena ¹⁴C Samples					
Dated Depth (cm)	Lab ID Number^c	Material dated	¹⁴C date ± 1 SD (yr BP)	Median Calibrated Age (cal yr BP)	Calibrated 95% Age Range (cal yr BP)
50	OS-91519	<i>Sphagnum</i> stems	445±25	507	479 to 529
55	OS-95016	<i>Sphagnum</i> stems	545±25	548	518 to 631
67	OS-91551	<i>Sphagnum</i> stems	675±25	651	562 to 675
72	OS-95017	<i>Sphagnum</i> stems	745±25	682	664 to 724
80	OS-95087	<i>Sphagnum</i> stems	905±30	834	742 to 911
88	OS-91552	<i>Sphagnum</i> stems	1060±25	962	928 to 1052
111	OS-91553	<i>Sphagnum</i> stems	1370±25	1295	1268 to 1331
Fish Creek ¹⁴C Samples					
Dated Depth (cm)	Lab ID Number	Material dated	¹⁴C date ± 1 SD (yr BP)	Median Calibrated Age (cal yr BP)	Calibrated 95% Age Range (cal yr BP)
49	OS-91560	<i>Sphagnum</i> stems	370±25	441	319 to 501
60	OS-95034	<i>Sphagnum</i> stems	570±50	595	519 to 653
65	OS-95002	<i>Sphagnum</i> stems	1000±30	925	798 to 967
72	OS-95341	<i>Sphagnum</i> stems	1140±25	1029	970 to 1168
80	OS-94968	<i>Sphagnum</i> stems	1250±30	1206	1082 to 1273

Table 4.1 (previous pages): ^{210}Pb ages and 68% age ranges from Point Lena and Fish Creek; and AMS radiocarbon data from Point Lena and Fish Creek peatlands in Southeast, Alaska.

a ^{210}Pb activity from 24 to 30 cm was below background so estimated ages cannot be determined

b ^{210}Pb activity at 28 cm was below background so estimated age cannot be determined

c OS-Woods Hole AMS Lab

Point Lena Peatland Core Testate Amoebae Zones						
Zone ^a	Depth (cm)	Age Range (95% probability error range), cal yr BP: ^b	Major Taxa	Zone Description	Average Water-Table Depth (cm)	Water-Table Depth Standard Deviation
4	0-11	-61 to -17 (-61 to -14)	<i>Assulina seminulum</i> , <i>Nebela militars</i> , <i>Nebela tinctoria</i> , <i>Phryganella acropodia</i>	<i>Archerella flavum</i> , <i>Hyalosphenia papilio</i> , and <i>Trigonopyxis arcuata</i> are variably abundant in this zone. <i>Paduangiella wailesi</i> is nearly absent in this zone.	24.7	4.8
3	12-26	-17 to 143 (-21 to 285)	<i>Nebela militars</i> , <i>Nebela tinctoria</i> , <i>Phryganella acropodia</i>	Increase in <i>Nebela militars</i> . <i>Hyalosphenia papilio</i> and <i>Assulina seminulum</i> are nearly absent in this zone.	28.4	3.2
2	27-60	143 to 602 (78 to 619)	<i>Archerella flavum</i> , <i>Assulina seminulum</i> , <i>Diffflugia pristis</i> type, <i>Hyalosphenia papilio</i> , <i>Nebela militars</i>	Sharp increase in <i>Hyalosphenia papilio</i> in this zone. <i>Archerella flavum</i> and <i>Nebela militars</i> are variably abundant in this zone.	25.2	7.4

1	61-103	602 to 1123 (554 to 1267)	<i>Archerella flavum</i> , <i>Assulina seminulum</i> , <i>Diffflugia pulex</i>	<i>Archerella flavum</i> and <i>Diffflugia pulex</i> increase in this zone, while <i>Hyalosphenia papilio</i> is reduced in this zone.	16.6	6.2
Fish Creek Peatland Core Testate Amoebae Zones						
Zone ^a	Depth (cm)	Age Range (95% probability error range), cal yr BP: ^c	Major Taxa	Zone Description		
5	0-20	-61 to -17 (-61 to -14)	<i>Archerella flavum</i> , <i>Hyalosphenia papilio</i> , <i>Assulina muscorum</i> , <i>Nebela militars</i>	<i>Diffflugia pristis</i> type, <i>Heleopera sphagni</i> , and <i>Cyclopyxis platystoma</i> are nearly absent in this zone. <i>Trigonopyxis arcula</i> is variably abundant in this zone.		
4	21-46	-17 to 433 (-20 to 487)	<i>Cyclopyxis platystoma</i> , <i>Diffflugia pristis</i> type, <i>Heleopera sphagni</i>	<i>Hyalosphenia papilio</i> , and <i>Nebela militars</i> are nearly absent in this zone. <i>Archerella flavum</i> is variably abundant in this zone.		
3	47-60	433 to 618 (267 to 672)	<i>Archerella flavum</i> , <i>Amphitrema wrightianum</i> , <i>Assulina muscorum</i>	Sharp decrease in <i>Diffflugia pristis</i> type and increase in <i>Amphitrema</i> <i>wrightianum</i> . <i>Hyalosphenia</i> <i>papilio</i> is nearly absent in this zone.		
2	61-69	618 to 1035 (570 to 1037)	<i>Archerella flavum</i> , <i>Hyalosphenia papilio</i> , <i>Assulina muscorum</i>	Sharp increases in <i>Hyalosphenia</i> <i>papilio</i> and <i>Archerella flavum</i> . <i>Diffflugia pristis</i> type is nearly absent in this zone. <i>Amphitrema</i> <i>wrightianum</i> is reduced in this zone. <i>Assulina muscorum</i> is variably abundant in this zone.		
1	70-88	1035 to 1410 (887 to 1539)	<i>Archerella flavum</i> , <i>Amphitrema wrightianum</i> , <i>Habrotracha angusticollis</i> , <i>Heleopera sphagni</i>	Increases in <i>Amphitrema</i> <i>wrightianum</i> , <i>Habrotracha</i> <i>angusticollis</i> , and <i>Heleopera</i> <i>sphagni</i> . <i>Hyalosphenia papilio</i> is absent, and <i>Diffflugia pristis</i> type is nearly absent, in this zone.		

Table 4.2 (previous pages): Descriptions of testate amoebae zones

a Zones were derived from a constrained cluster analysis. Average water-table depth and standard deviation for each of the zones are also presented for Point Lena.

b Age range 23 cm and up has 68% probability error range associated with ^{210}Pb dating

c Age range 26 cm and up has 68% probability error range associated with ^{210}Pb dating

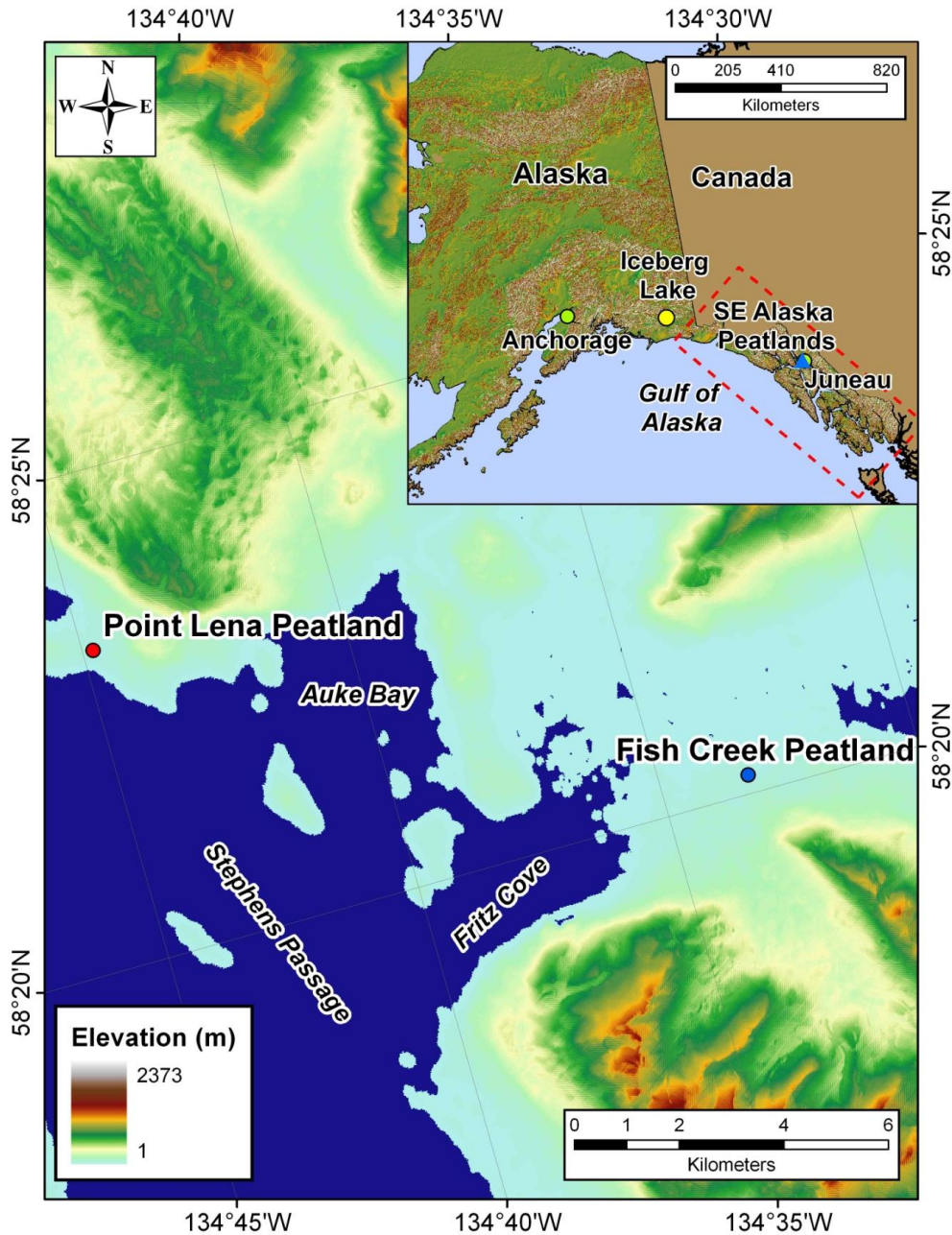


Figure 4.1: Location of the Point Lena and Fish Creek peatlands in SE Alaska. Inset: Map of Alaska and northwestern Canada showing the location of the Point Lena and Fish Creek peatland sites in Southeast (SE) Alaska and the Iceberg Lake record mentioned in the text. The dashed rectangular red box on the inset shows the approximate area of Southeast Alaska and the Alexander Archipelago east of the Gulf of Alaska.

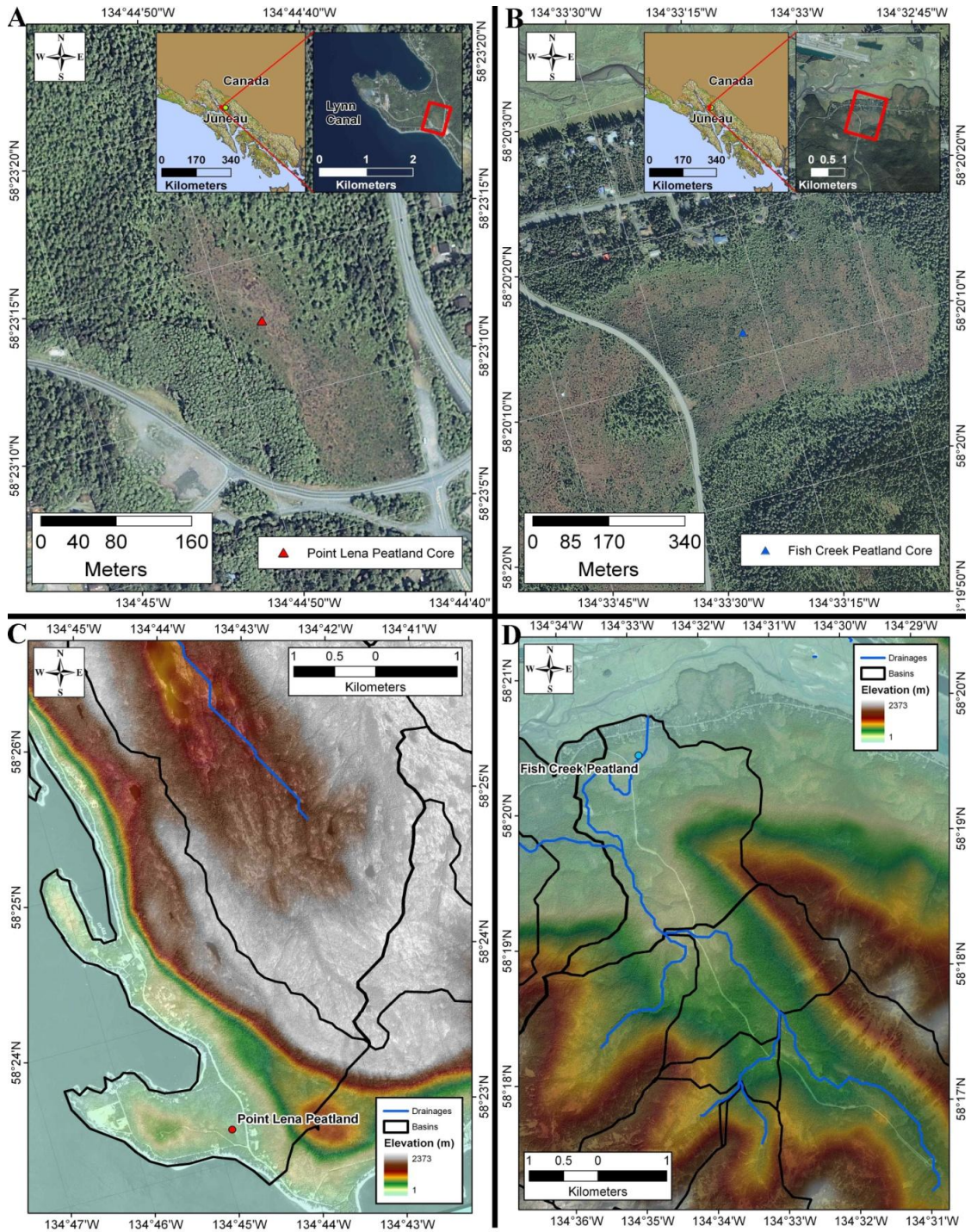


Figure 4.2: A) Location of Point Lena peatland core; B) Location of Fish Creek peatland core; and basins and drainages around the Point Lena (C) and Fish Creek (D) peatlands.

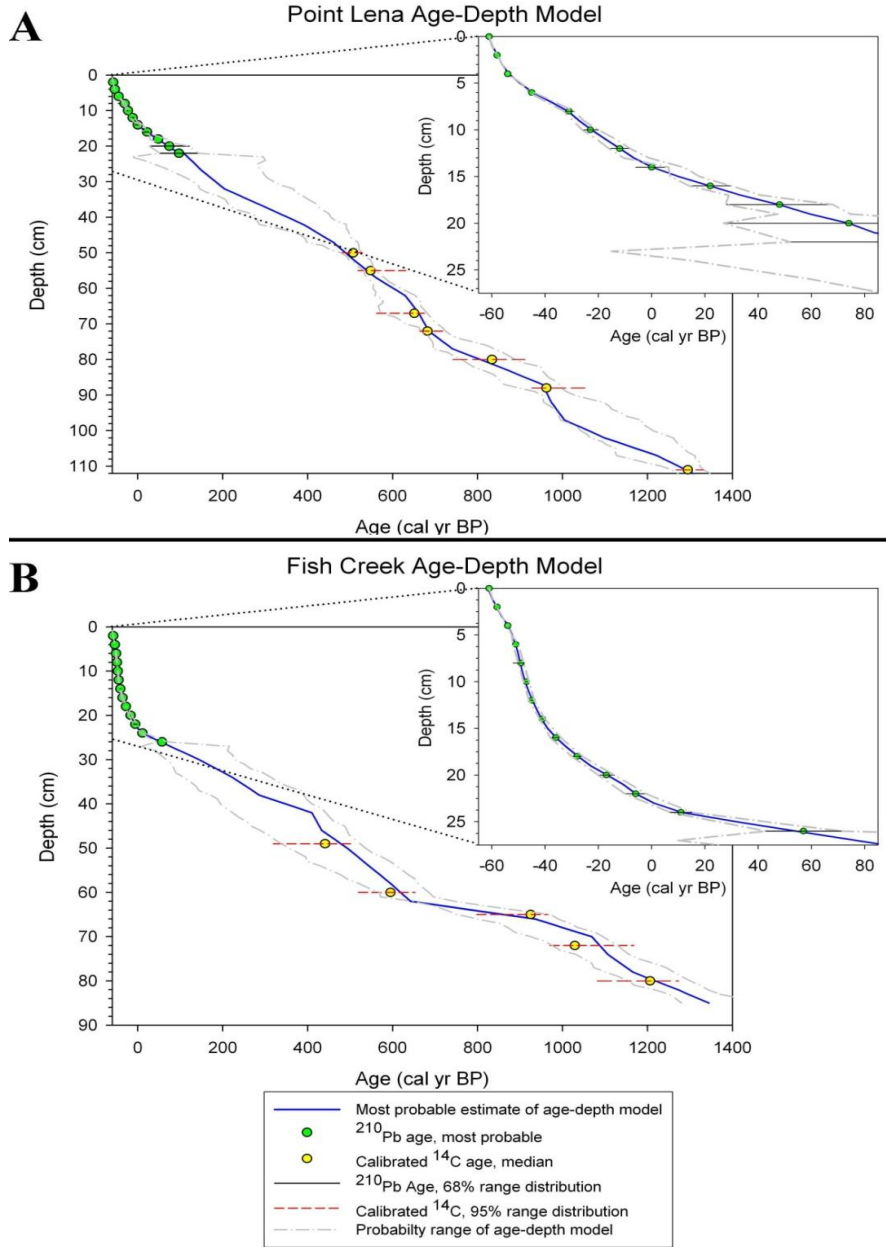


Figure 4.3: Age-depth models for the Point Lena (A) and Fish Creek (B) peatland cores. ^{210}Pb analyses and the constant-rate-of-supply (CRS) model determined ages for 0-23 cm of the Point Lena core and 0-26 cm of the Fish Creek core. IntCal09 (Reimer et al., 2009) was used to calibrate the AMS ^{14}C dates. The chronologies of both records combine the ages estimated by the ^{210}Pb CRS model with ages developed using the age-depth modeling software BACON (Blaauw and Christen, 2011) for the ^{14}C samples. The CRS model used to estimate ages for the ^{210}Pb analyses resulted in most probable ages and a 68% probability range, while BACON resulted in most probable ages and 95% probability range for calibrated ^{14}C dates.

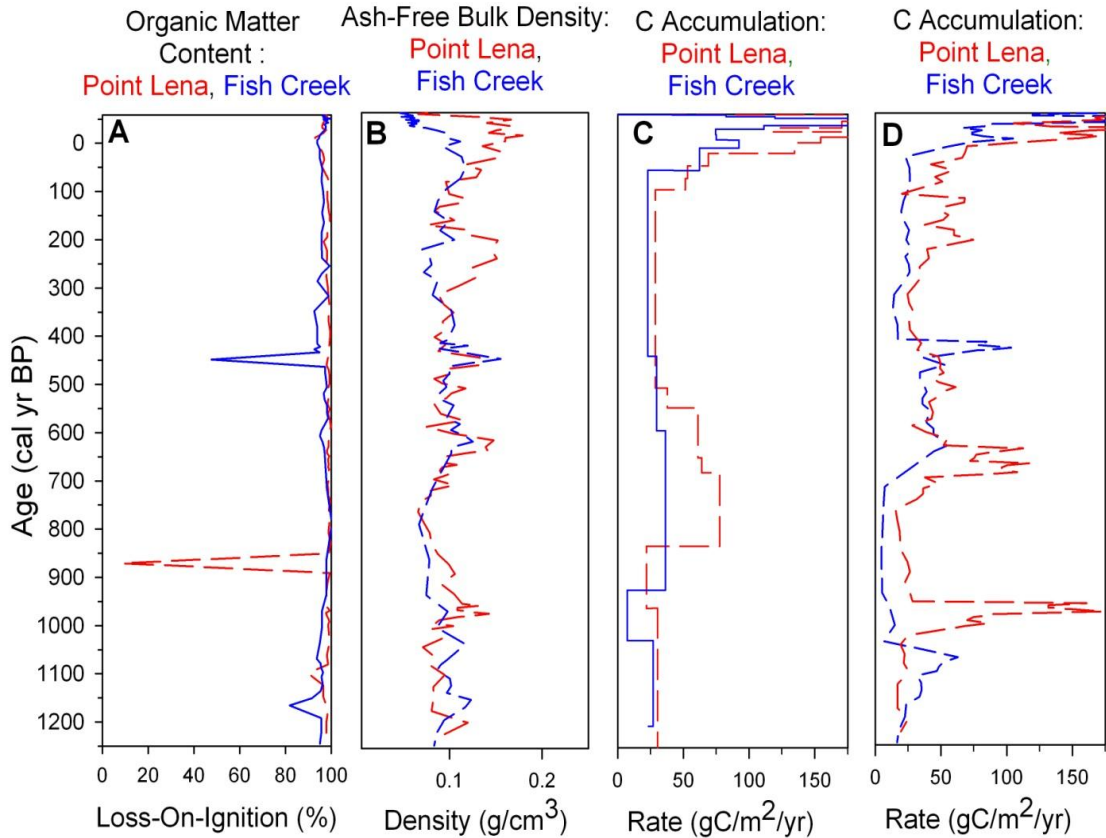
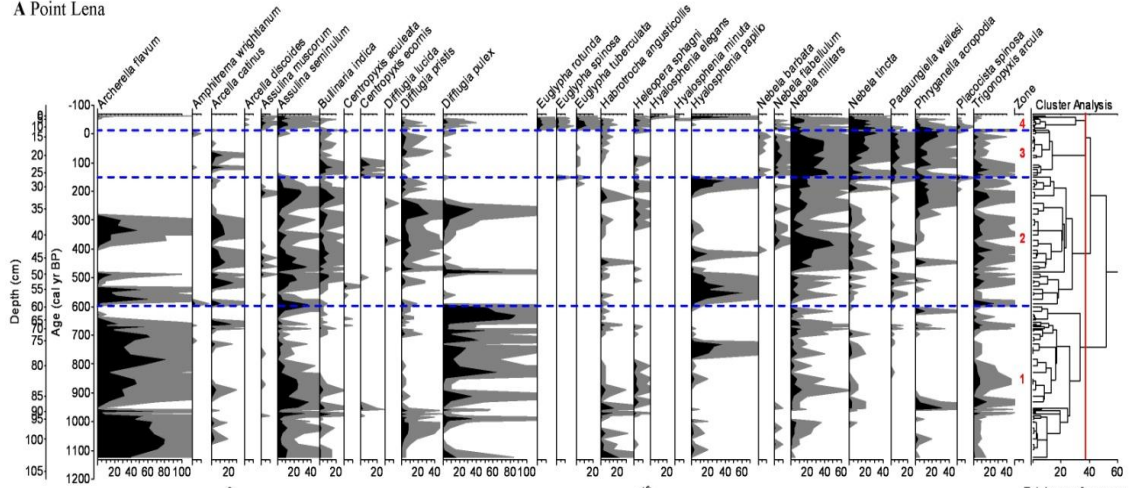


Figure 4.4: Point Lena (dashed red line) and Fish Creek (solid blue line) peatlands. A) Organic matter content (%); B) Ash-free bulk density (g/cm^3); C) Apparent carbon accumulation rates ($\text{gC/m}^2/\text{yr}$) based on intervals between median calibrated radiocarbon dates (Table 1); and D) Apparent carbon accumulation rates based on the most probable age estimate from the age-depth model (Figure 4.3).

A Point Lena



B Fish Creek

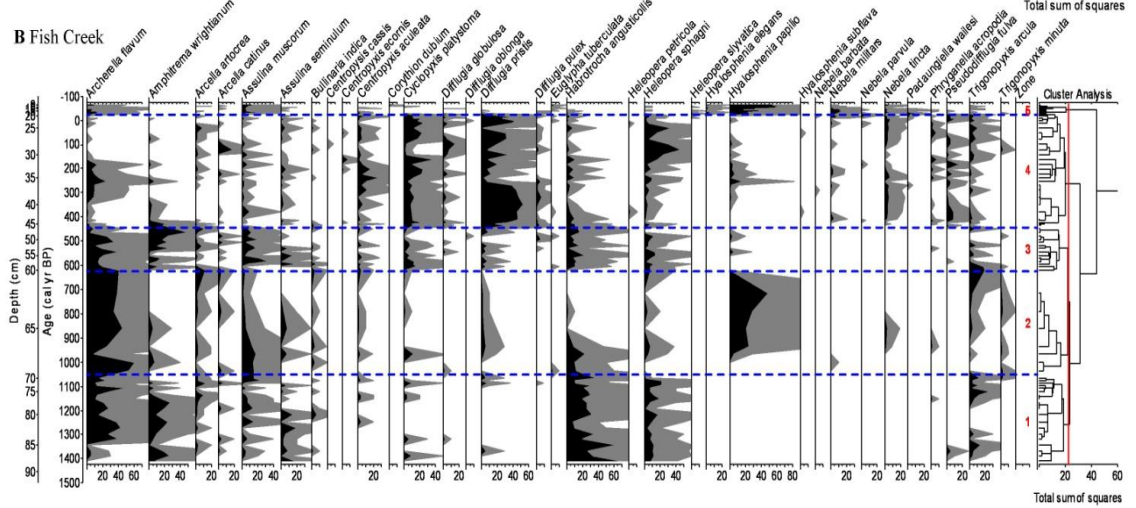


Figure 4.5: Testate amoeba assemblages from Point Lena (A) and Fish Creek (B) peatlands, showing the relative abundance of taxa against time and depth. Testate amoeba assemblages were divided into zones based on a CONISS cluster analysis (Grimm, 1987). The vertical red line in the cluster analysis indicates where the clusters were split to determine the different zones.

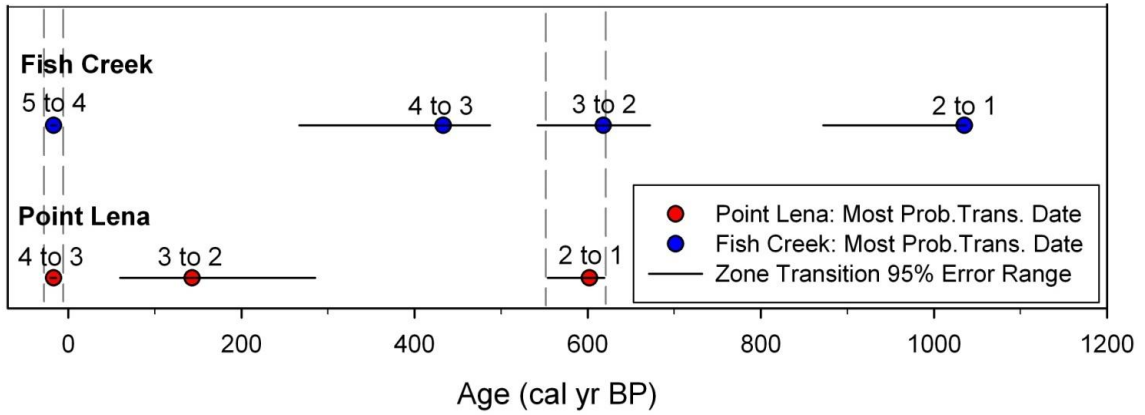


Figure 4.6: Estimated timing of zone transitions between testate amoeba communities (based on the cluster analysis) for Fish Creek and Point Lena. The most probable (blue circle for Fish Creek and red circle for Point Lena) and 95% error range (black lines) of transition dates between zones are shown. Zone transitions that are statistically indistinguishable are highlighted with gray dashed, vertical lines.

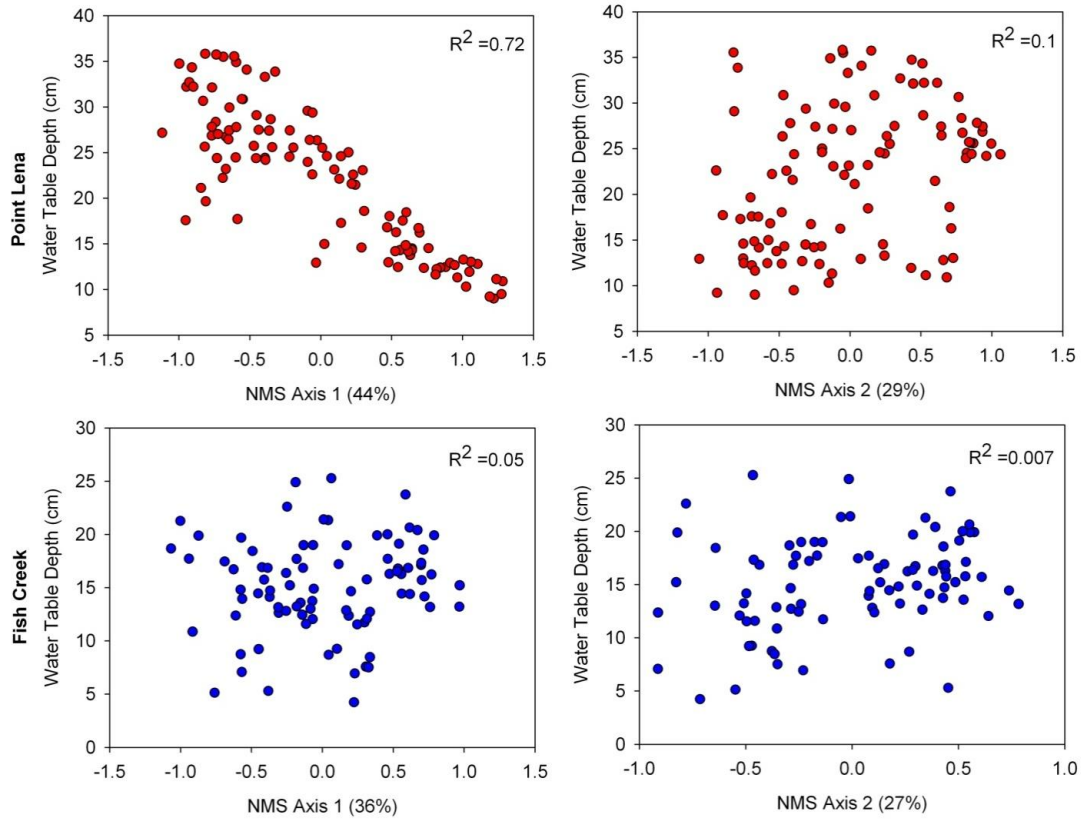


Figure 4.7: Biplot of NMS ordination of testate amoeba community data (Axis 1 and Axis 2) and reconstructed water-table depths for the Point Lena and Fish Creek peatlands. The major pattern of assemblage variability reflects changes in water-table depth at Point Lena, but not at Fish Creek.

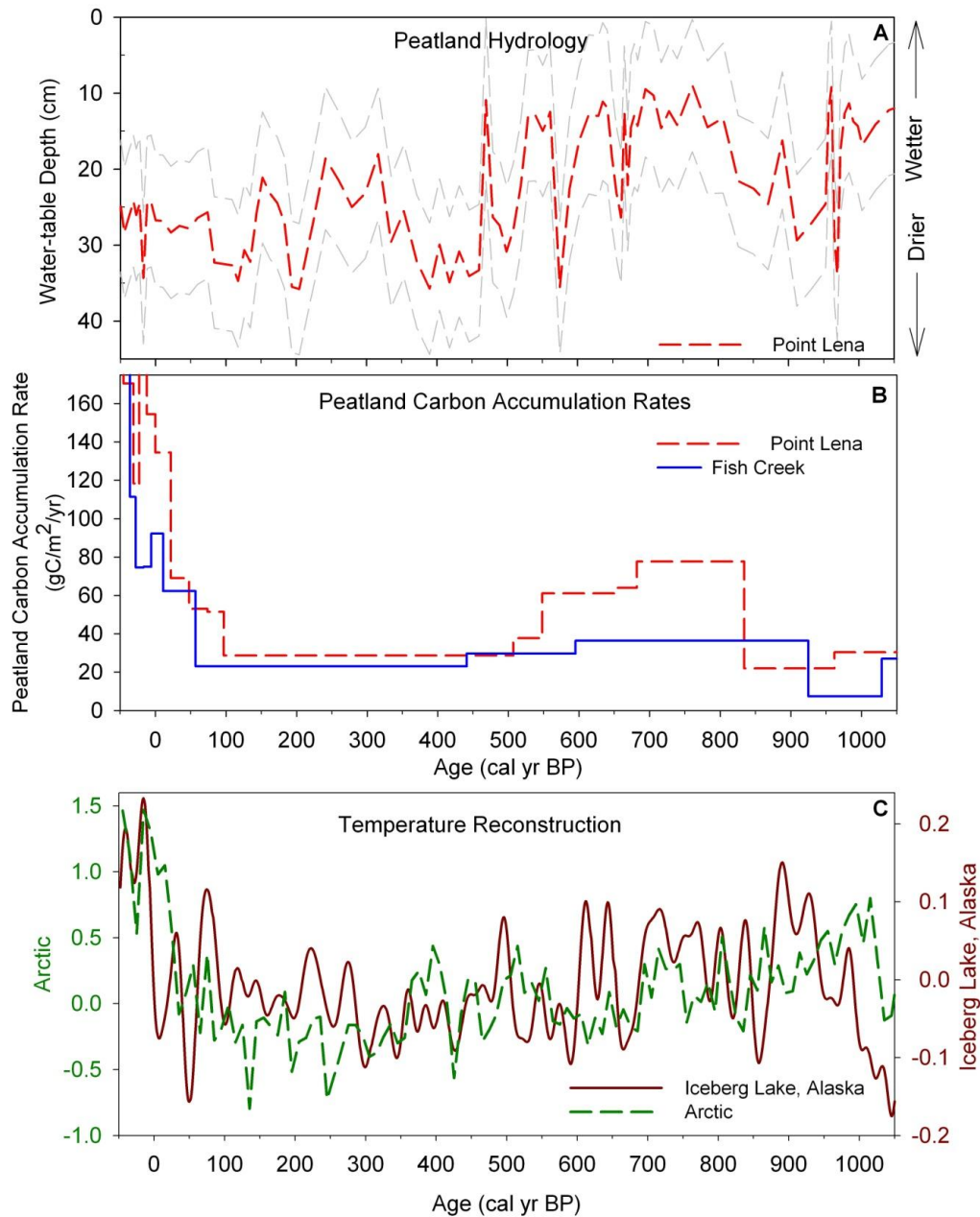


Figure 4.8: A) Reconstructed peatland water-table depths for the Point Lena peatland site, gray lines represent estimated prediction error bars based on bootstrapping; B) Apparent peatland carbon accumulation rates for the Point Lena and Fish Creek peatlands; and C) Varve-based temperature reconstruction from Iceberg Lake, Alaska (solid brown line) (Loso, 2009); and multiproxy Arctic (synthesis of 23 sites above 60° latitude) temperature reconstruction (dashed green line) (Kaufman et al., 2009).

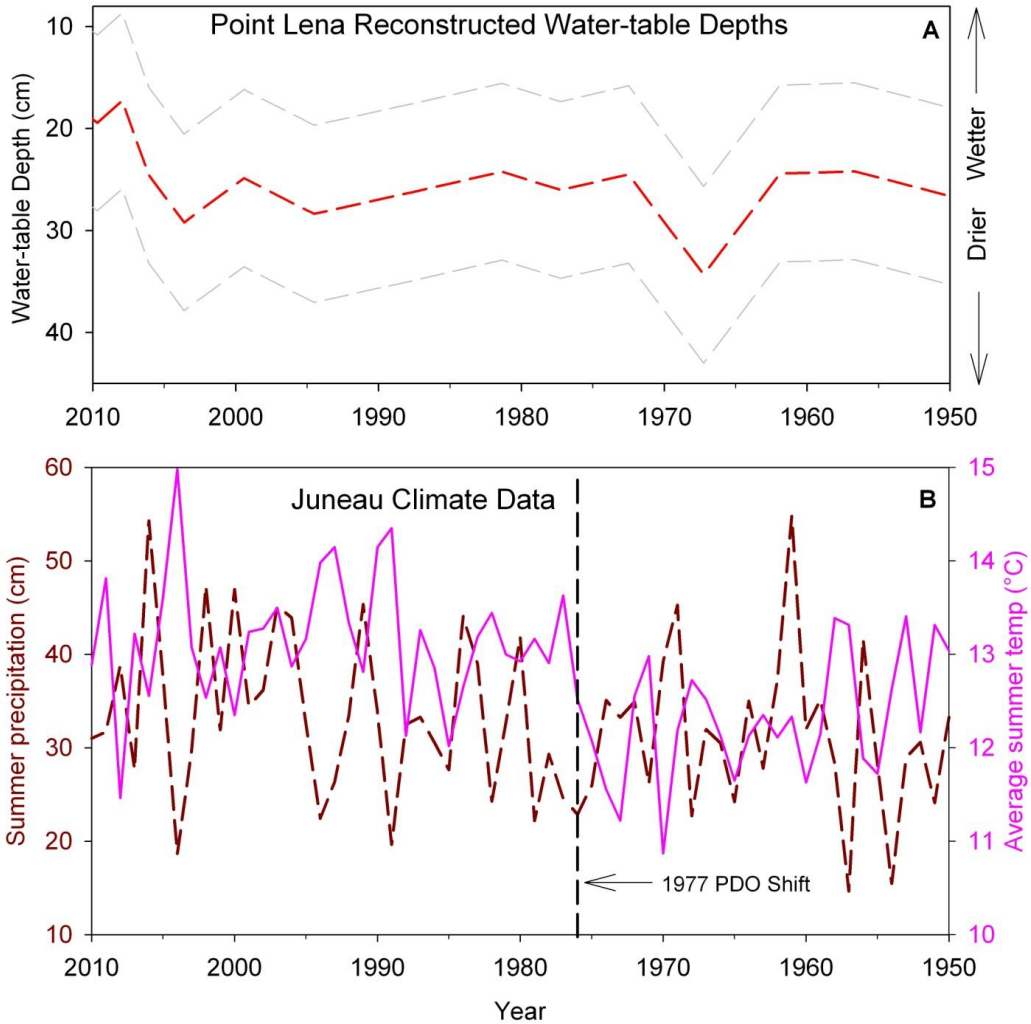


Figure 4.9: A) Reconstructed peatland water-table depths for Point Lena, gray lines represent estimated prediction error bars based on bootstrapping; and B) 30-year (1980-2010) average summer temperature and total precipitation from Juneau, Alaska (Alaska Climate Research Center, 2012). The 1976-1977 PDO shift is represented with a black vertical dashed line.

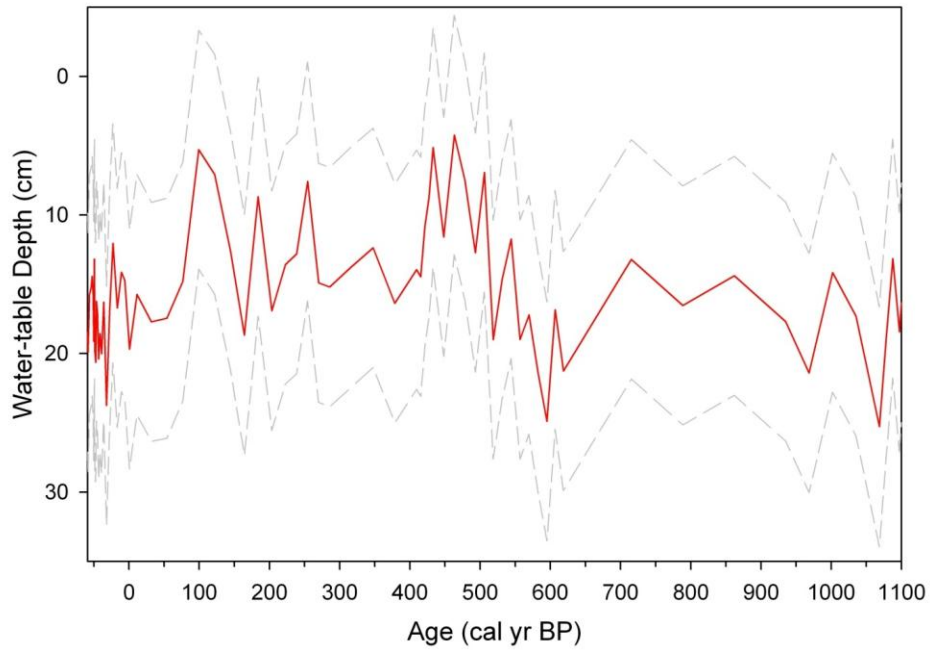


Figure S4.1: A) Reconstructed peatland water-table depths for the Fish Creek peatland site (without *D. pristis* type), dashed gray lines represent estimated prediction error bars based on bootstrapping.

Chapter 5

General Discussion and Conclusions

5.1 Patterns in Peatland Response over the Last Millennium

This discussion focuses on results from the peatlands in SC and SE Alaska, as they had peatland cores that extended through the last millennium. While the core from the Kwethluk peatland (SW Alaska) extended over a millennium, the majority of the core was composed of lake sediments. Even though the Kwethluk peatland core did indicate rapid peatland C accumulation in a drained basin in SW Alaska, it is not discussed here with the other cores from SC and SE Alaska because the peatland portion of the record is not comparable over the last millennium.

5.1.1 Testate Amoeba Data and Climate Changes

A comparison of the timing of the transitions between testate amoeba zones at each of the peatlands in SC and SE Alaska indicates that testate amoeba communities across the climate regions showed the strongest response to changes ~600 cal yr BP (Figure 5.1). The transitions between testate amoeba Zones 2 to 1 at the lowland, Zones 3 to 2 at Fish Creek, and Zones 2 to 1 at Point Lena are statistically indistinguishable and took place ~600 cal yr BP. The oldest age of the 95% error range (510 cal yr BP) of the transition between Zones 2 to 1 at the moraine peatland is close to the ~600 cal yr BP transitions at the other three sites. Although spatially and temporally variable, even within the state of Alaska, for comparative purposes the MCA can be generally defined as 1000 to 600 cal yr BP and the LIA as 600 to 200 cal yr BP (e.g., Hu et al., 2001; Kaufman et al., 2009;

Ljungqvist, 2010). Therefore, the testate amoeba data suggest a pronounced shift in environmental conditions occurred during the transition from the MCA to the LIA. Additionally, the transitions between Zones 5 to 4 at Fish Creek and Zones 4 to 3 at Point Lena are statistically indistinguishable and occurred around the 1977 PDO climate shift. These zone transitions around the 1977 PDO climate shift in SE Alaska, which were not present in SC Alaska, could potentially be influenced by the higher resolution ^{210}Pb dating that was in the most recent (top) section of the cores from only the SE Alaska peatlands.

The shift in testate amoeba communities that appears at three of the four peatland sites ~600 cal yr BP (Figure 5.1) is similar to the estimated timing of the transition from the MCA to the LIA (e.g., Hu et al., 2001; Kaufman et al., 2009; Ljungqvist, 2010). It is likely that this MCA to LIA transition influenced climate conditions in the relatively cooler and drier SC region differently than the warmer and wetter SE region. However, the reconstructed peatland hydrology from both the lowland peatland in SC Alaska (the most hydrologically sensitive of the two SC peatlands) and from the Point Lena peatland in SE suggest that the cooler LIA was might have also been drier (Figure 5.2). Therefore, the testate amoeba community shift ~600 cal yr BP might be in response to this transition to colder and potentially drier LIA conditions.

5.1.2 Regional Climate Controls on C Accumulation

Our results indicate that a warmer and wetter northern latitude climate will accumulate C at an overall greater rate than relatively cooler and drier climate regions. Throughout the course of the record, the average apparent PCAR from both peatlands in the SE Alaska

climate region ($51.7 \text{ gC/m}^2/\text{yr}$) was nearly 20% greater than the two peatlands in the SC Alaska climate region ($43.6 \text{ gC/m}^2/\text{yr}$). These regional differences in PCAR are even more apparent when changes between the MCA and LIA climate periods are compared. Analysis of these climate periods indicates that in the SE Alaska climate region the average apparent PCAR was $44.3 \text{ gC/m}^2/\text{yr}$ during the MCA and $32.8 \text{ gC/m}^2/\text{yr}$ during the LIA. In the SC Alaska climate region, the average apparent PCAR during the MCA was $40.8 \text{ gC/m}^2/\text{yr}$, but then dropped nearly 40% to $25.8 \text{ gC/m}^2/\text{yr}$ during the LIA. This difference in PCAR between climate regions could possibly be attributed to the more moderate SE climate that likely cooled less and probably maintained a longer growing season during the LIA than other colder and drier climate regions. Moreover, the more moderate SE Alaska climate region responded to post-LIA warming at $\sim 200 \text{ cal yr BP}$ with increased PCAR values while PCAR values from peatlands in SC Alaska climate region remained unchanged (Figure 5.2). Overall, the higher PCAR values during warmer periods suggest that Alaskan peatlands, especially those in the SE climate region, could serve as C sink and induce a negative feedback to current climate warming.

A greater average apparent PCAR in the SE Alaska climate zone is in agreement with a recent study that explored climate impact on peatland C accumulation over the last 1000 years across 90 different northern peatlands (Charman et al., 2013). This study found that modern growing season length and photosynthetically active radiation had the strongest relationship with PCAR. These two variables are greatly influenced by regional climate. Thus, the greater (relative to SC) average peatland C accumulation in SE Alaska (Figure 5.2), with its warmer average annual temperature, observed in our results is consistent with expectations. Charman et al. (2013) also found that PCAR

values were lower during the cooler LIA than during the warmer MCA. This decrease in PCAR values across the transition from the MCA to the LIA is consistent with our results in both the SC and SE Alaska climate regions (Figure 5.2). A study of peatland C accumulation in west Siberia over the last 2000 years suggested that lower latitude peatlands generally stored more C than their higher latitude counterparts (Beilman et al., 2009). Again, this is similar to our results that revealed a greater peat depth had accumulated over the last 1100 years (Figure 5.3) at the lower latitude SE Alaska sites (Figure 1.1).

5.1.3 Local-scale Variability in Peatland Response to Climate Change

In addition to regional-scale differences in temperature, local-scale variability within the same region can also influence the response of peatlands to climate changes. These local-scale impacts on peatland response to climate change are apparent through comparison of the two peatlands within the SC climate region. The SC lowland and moraine sites were located in different surficial geological settings, which impacted their subsurface drainage. As the lowland peatland had greater subsurface drainage than the moraine, its hydrology was more sensitive to sustained periods of reduced input (i.e., drought conditions). This greater hydrologic sensitivity during periods of reduced hydrologic input resulted in not only increased water-table depth, but also greater variability of that water-table depth (Figure 5.2). In turn, greater variability in peatland water-table depth led to increased decomposition and release of C (please refer to chapter two for more information regarding the differences between the two SC region peatland sites). The results of this hydrologic sensitivity, which was influenced by surficial

geology, can be observed in the response of the lowland peatland to the MCA (~1000 to 600 cal yr BP) and LIA (~600 to 200 cal yr BP) climate changes (Figure 5.2). During the warmer MCA, lowland peatland hydrology was relatively wet and stable, but during the cooler (and presumably drier) LIA, peatland hydrology became more variable and drier. This change from wet and stable to dry and variable peatland hydrology occurred during the MCA and LIA transition and correlated with a sharp and sustained decrease in PCAR values at the lowland.

A recent study (Charman et al., 2013) found strong relationships with modern growing season length and C accumulation in northern peatlands over the last 1000 years and suggested that some of the unexplained variability could be due to local hydrologic factors. Our analysis from the SC Alaska climate region offers strong support of this idea, as it was found that differences in topography (e.g., surficial geology) can indeed impact the response of peatland hydrology and C accumulation to climate change. With the inclusion of local-scale variables like surficial geology into analyses of many peatlands across different locations, some of this unexplained variability could possibly be accounted for. Moreover, including local-scale variability would likely result in a more comprehensive understanding of how northern peatlands might respond to climate change going forward, which is critically important considering the large amount of C stored in northern peatlands and its potential impacts on the atmosphere and global temperatures.

5.2 Overall Conclusions

This study analyzed the influence of both local- and regional-scale factors on the response of peatlands in SC and SE Alaska to climate change over the last 1100 years. Results indicate that on a regional-scale, peatlands in warmer and wetter modern climate regions (e.g., SE Alaska) accumulated more peat over the last millennium than their cooler and drier counterparts (e.g., SC Alaska). Additionally, average apparent PCAR in both regions was greater during the warmer MCA than the cooler LIA. This suggests that under future warming conditions, northern peatlands could serve as a negative feedback to climate change by increasing their C accumulation rates. Moreover, the potential for a negative climate feedback is particularly relevant in warmer and wetter regions, like SE Alaska. A wetter climate is more likely to maintain the moisture levels needed to accumulate C under warmer temperatures, which is suggested by the increased PCAR values during post-LIA warming in the SE Alaska region. Thus northern peatlands in warmer and wetter climate conditions, which might maximize productivity and minimize decomposition, could represent the largest negative feedback to climate change of all northern peatlands under a warming climate.

However, results indicate that local-scale topographic differences, such as changes in surficial geology, can also influence the response of peatland hydrology and C accumulation to climate changes. These local-scale variables can result in a heterogeneous peatland response to climate change, even within the same climate region. With the inclusion of local-scale variables, like surficial geology, some of the

unexplained variability that currently exists in overarching analyses of the response of different northern region peatlands to climate changes could possibly be accounted for. A more detailed understanding of how northern peatlands might respond to climate change going forward is vitally important considering the large amount (500 Gt) of C stored in northern peatlands and its potential impact on global temperatures.

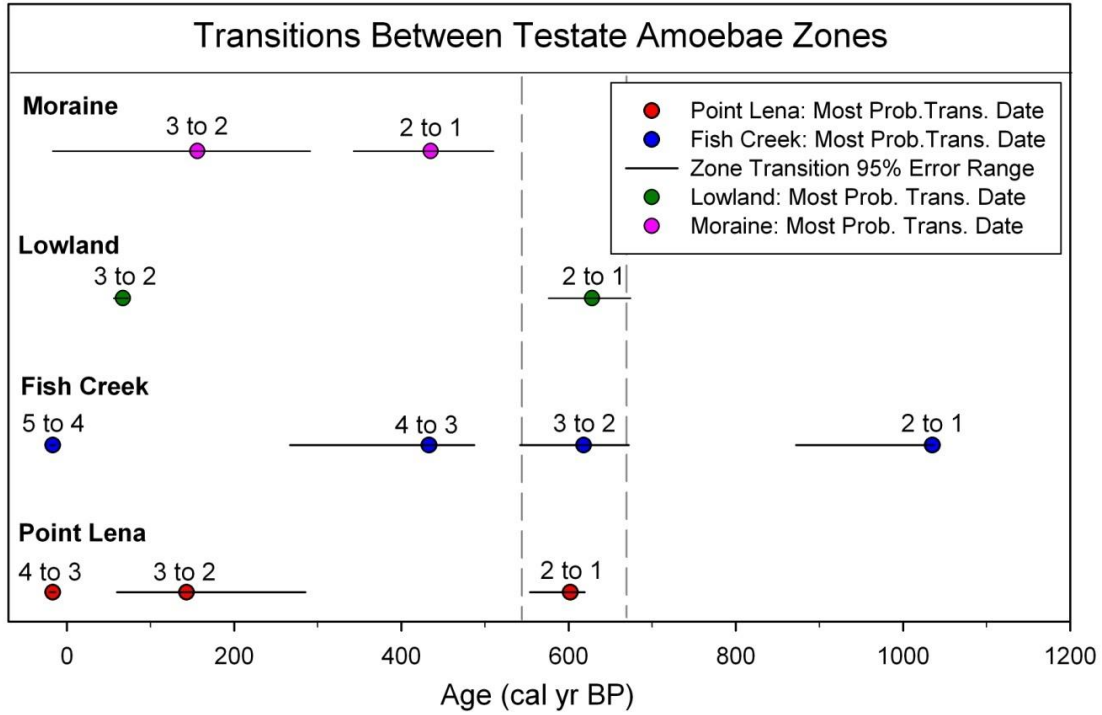


Figure 5.1: Estimated timing of zone transitions between testate amoeba communities (based on cluster analyses) for moraine and lowland peatlands in SC Alaska and the Fish Creek and Point Lena peatlands in SE Alaska. The most probable (purple circle for moraine, green circle for lowland, blue circle for Fish Creek, and red circle for Point Lena) and 95% error range (black lines) of transition dates between zones are shown. The timing of the zone transition ~600 cal yr BP that is statistically indistinguishable at three of the four peatlands is highlighted with dashed gray vertical lines.

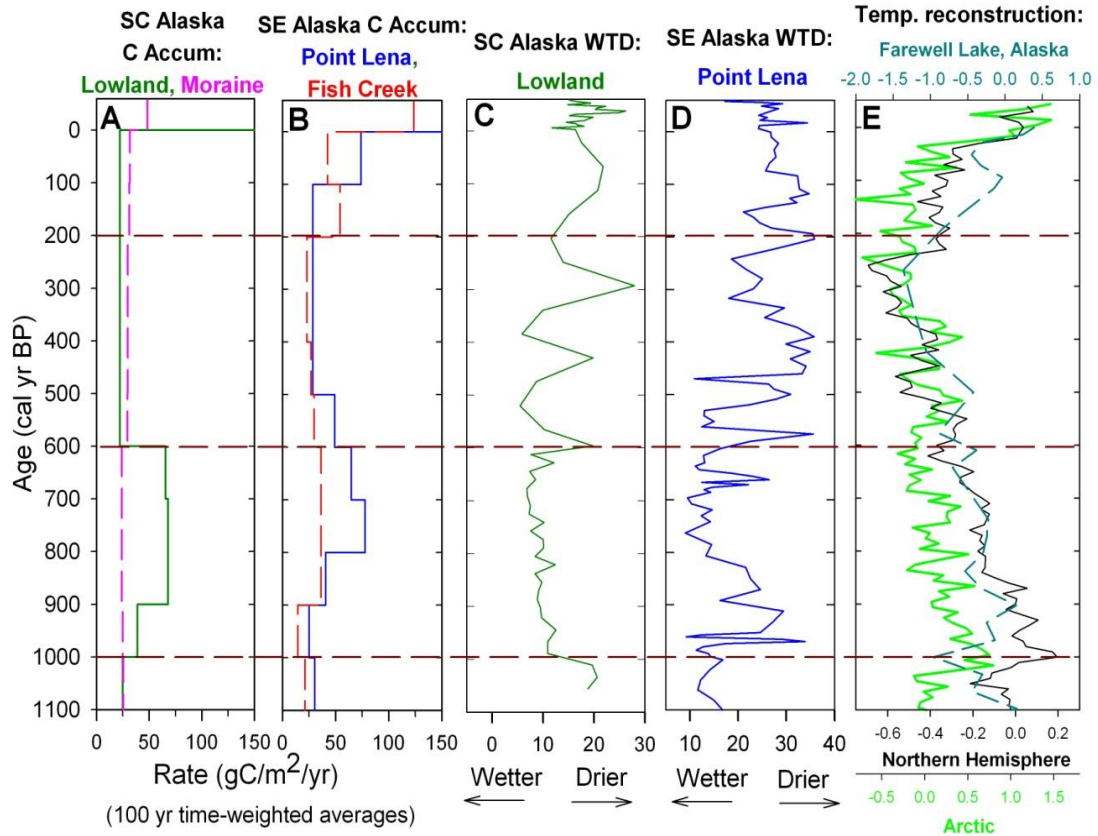


Figure 5.2: Carbon accumulation rates ($\text{gC}/\text{m}^2/\text{yr}$), 100 year time-weighted averages, for SC Alaska region lowland (solid line) and moraine (dashed line) (Panel A) and SE Alaska region Point Lena (solid line) and Fish Creek (dashed line) (Panel B) peatlands. Testate amoeba-based reconstructions of water-table depth for the lowland (solid line) peatland in the SC region (Panel C), and the Point Lena peatland in the SE region (Panel D). Geochemical proxy temperature reconstruction from Farewell Lake, Alaska (dashed line) (Hu et al., 2001); multiproxy Arctic region temperature reconstruction (thick line) (Kaufman et al., 2009); and multiproxy northern hemisphere temperature reconstruction (thin line) (Ljungqvist, 2010). Horizontal dashed red lines indicate the approximate times of the following climate changes: 1) end of the Little Ice Age (LIA) (top line); 2) transition from LIA and Medieval Climate Anomaly (MCA) (middle line), and 3) start of MCA (bottom line).

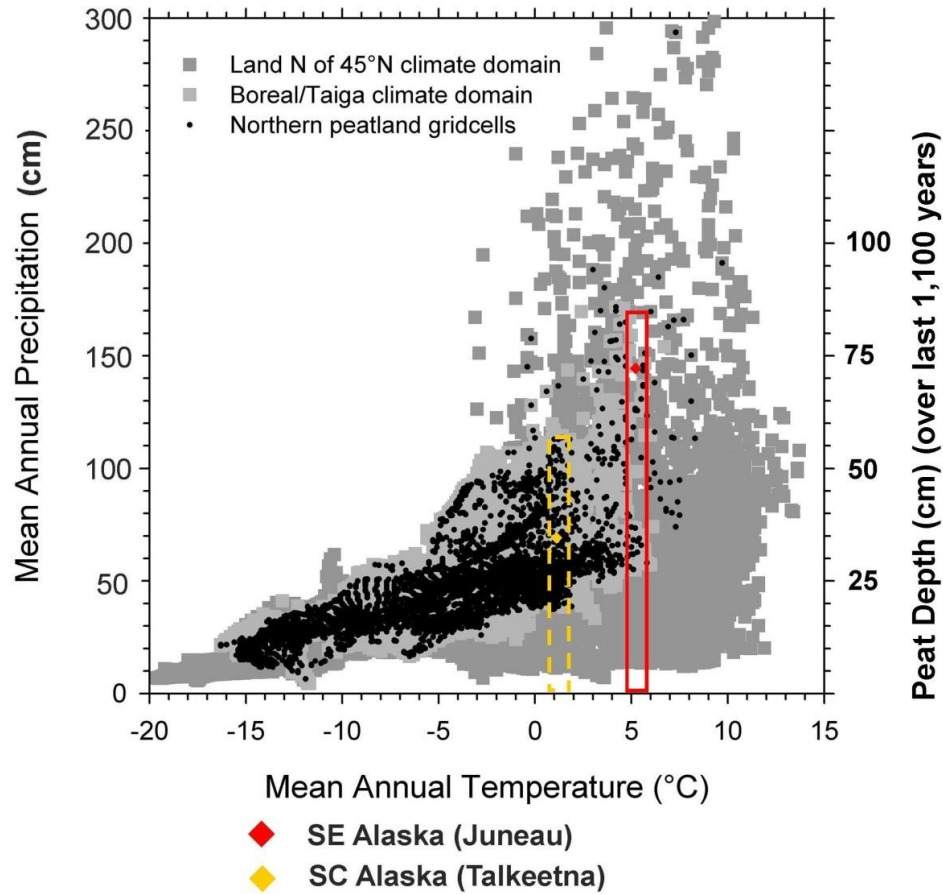


Figure 5.3: The climate space of mean annual temperature and precipitation (adapted from Yu et al., 2009) of total land area north of 45°N latitude (dark gray), the boreal/taiga biome (light gray), and northern peatland regions based on 0.5° x 0.5°-gridded instrumental climate data for the period 1960–1990 (Rawlins and Willmott, 1999). The climate space location of the different Alaska climate regions studied (based on data from 1950-2010 long term weather stations in Talkeetna for the SC, and Juneau for the SE) is represented by the red diamond (SE region) and the orange diamond (SC region). The vertical bars represent average peat depth at 1100 cal yr BP for the SE (red solid) and SC (orange dashed) climate regions.

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Vita

Eric S. Klein was born and raised in Portland, Oregon and graduated from Lake Oswego High School (Oregon) in 1996. He received a BA in Political Science from the University of Puget Sound in Tacoma, Washington in 2000 and a MS in Environmental Science from Alaska Pacific University in Anchorage, Alaska in 2004. His MS research about wetland drying and succession in Southcentral Alaska was one of the first studies to document landscape impacts consistent with climate change in Alaska. He worked for the US Fish and Wildlife Service at the Kenai National Wildlife Refuge in Alaska as a Biological Science Technician from 2002 to 2004. Eric then was employed as an Environmental Scientist and GIS Specialist for URS Corporation in Anchorage, Alaska from 2004 to 2008. In 2008, Eric went to work as a Wetlands Scientist with Arctic Slope Regional Corporation Energy Services in Anchorage, Alaska. Eric began his PhD studies in the Earth and Environmental Sciences Department at Lehigh University in Bethlehem, Pennsylvania in 2009 and completed his doctoral degree in 2013. In the spring of 2013, Eric began a postdoctoral research fellowship at the Environment and Natural Resource Institute at the University of Alaska, Anchorage.

Publications

Klein, E.S., Booth, R. K., Yu, Z., Mark, B.G., Stansell, N. D., 2013. Hydrology-mediated Differential Response of Carbon Accumulation to Late Holocene Climate Change at Two Peatlands in Southcentral Alaska. *Quaternary Science Reviews*. 64, 61-75.

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