GEOMORPHIC AND CLIMATIC DRIVERS OF WHITE SPRUCE GROWTH NEAR THE FOREST-TUNDRA ECOTONE IN SOUTHWESTERN ALASKA

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A
THESIS

Presented to the faculty
of the University of Alaska Fairbanks

in Partial Fulfillment of the Requirements
for the degree of

MASTER OF SCIENCE

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Fairbanks, Alaska
August 2015

Abstract

Three types of treelines occur in Alaska: a latitudinal treeline running east-west along the Brooks Range, alpine treelines in mountainous regions, and a longitudinal treeline running north-south along the Bering Sea coast. Latitudinal and alpine treelines in Alaska have been extensively studied; however, little is known about longitudinal treeline in western Alaska. Here I describe the associations between a longitudinal treeline in southwestern Alaska and geomorphology, soils, and climate. This diffuse, lowland treeline is dominated by white spruce (*Picea glauca* (Moench) Voss) and is presently expanding rapidly westward. Tree age and stand structure vary markedly according to geomorphic position and soil characteristics but generally fall into four vegetation-landscape associations. I cored spruce growing in these four associations to determine limiting germination dates and compare tree growth with climate records. Results show that timing and rate of establishment has varied between vegetation-landscape associations; however, once established, white spruce growth responds positively to warmer summer temperatures with minor variations between sites. Unlike drought-stressed white spruce in Interior Alaska, under likely near-term temperatures, spruce in southwestern Alaska will probably continue to respond positively to warming temperatures. My data suggest this treeline will continue to move westward across varying topographic features and soil conditions, resulting in a complex spatial mosaic of forested and nonforested communities behind the expanding forest margin.

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Acknowledgements

Thank you Patricia, for taking me to Dillingham as an undergraduate to poke around at tree cores and ponder on all manner of things, inspiring me to come back to pursue a graduate degree. Thank you for the mentorship, the skiing and Ivorys breaks, for introducing me both to Bristol Bay and to teaching undergraduates, the two experiences that have made graduate school most worthwhile. Thank you to Dan for all of the guidance, hard questions, and for jumping in after a long hiatus to see this through. Thank you to Glenn for all of the tree core conversations, the knowledge shared, and the opportunity to conduct fieldwork in some spectacular places. Thank you to the Alaska Quaternary Center for funding my research through the David and Rachel Hopkins Fellowship. David Hopkins was my own advisor's advisor and for that reason especially, I hope this thesis contributes something of value to the field of Quaternary research in Beringia.

To Louise Farquharson and Patricia (and solar powered radio named Salvation)- I suspect there are no better people to conduct field work with, and my perpetual offer to be your field assistant any time, any place still stands. Thank you Leif and Claudi for sharing your home and salmon.

Many thanks to Dave Higdon of Dave's World for lodging and creative transportation in King Salmon. Thanks to the Alaska Peninsula Corporation for access to lands on which I conducted my research. Thank you David Spencer assistance in the tree ring lab and to darleen masiak and Bob Van Veldhuizen for help in the soils lab. Thomas Grant helped translate the technical wonders of statistical software, saving me both time and headaches. Many thanks to those who provided 'office spaces' during my frequent wanderings: Patricia for my Montanan office, Rachael for letting me turn every inch of our home at one time or another into a Minnesotan office, and to Erika and Emily for the Idahome and canine surgery recovery unit. Thank you dear friends (you know who you are) for the delicious meals, dog walks, ski breaks, and Settling of Catan. Thank you to my Canine Support Crew, led by Ella, for the reminders never to work too hard or too often without a walkabout or ski break. Thank you to my wonderful family for the endless amount of love and support, and for the gentle and not so gentle reminders to see this through to the end.

1.0 Introduction and Research Objectives

Climate is changing rapidly in Alaska and other parts of the circumpolar north, and these changes are causing rapid shifts in the form and position of treeline ecotones (Wiles et al., 1998; Lloyd et al., 2002; Hinzman et al., 2005; Harsch et al., 2009). Studies throughout the circumpolar north have identified widespread vegetation changes in recent years including shrub expansion (Sturm et al., 2001; Tape et al., 2006; Myers-Smith et al., 2011), northward and upslope movement of treeline (Viereck, 1979; Dial et al., 2007), and infilling of spruce trees in previously low density sites (Danby and Hik, 2007). Changes in the geographical range of white spruce (*Picea glauca* (Moench) Voss)), the dominant treeline species in Alaska, have been documented over the past century through repeat photography both in southwest and northern Alaska (Jorgensen et al., 2006). Ongoing climate change is also affecting the growth patterns of spruce trees throughout Alaska, though in regionally distinct patterns (Beck et al., 2011; Juday et al., 2015). Understanding the factors controlling growth and structure at treeline ecotones can help to refine models of future vegetation change in both tundra and boreal forest communities.

Three distinct types of treelines occur in Alaska today (Figure 1). Latitudinal (arctic) treeline runs east to west across the southern slopes of the Brooks Range and alpine treeline occurs on mountains throughout the Interior and Coastal mountain ranges. In addition, a longitudinal treeline runs south to north paralleling the Bering Sea coast of western Alaska. Many previous studies of treeline have focused on latitudinal (e.g. Lloyd et al., 2002; Lloyd et al., 2005) and alpine treelines (e.g. Körner and Paulsen, 2004; Dial et al., 2007), but very little attention has been paid to the longitudinal treeline occurring in western Alaska (Lloyd and Fastie, 2002; Winslow, 2008; Beck et al., 2011).

The longitudinal treeline of western Alaska has several unusual features. First it extends far south of the arctic treelines present in northern Alaska and northeastern Siberia (Figure 1). Second, it lies near sea level - well below the elevational limits of tree growth in the same region. Third, unlike most altitudinal treelines in northern parts of Alaska and all latitudinal (arctic) treelines in the state, treeline in southwestern Alaska lies in the zone of isolated permafrost where perennially frozen ground has a scattered distribution, is relatively warm in temperature, and is highly susceptible to thaw (Jorgenson et al., 2008). Isolated permafrost is often "ecosystem-protected", meaning it can persist only if the overlying vegetation and soils remain undisturbed (Shur and Jorgenson, 2007; Johnson et al., 2011). These characteristics of the forest-tundra ecotone in southwestern Alaska suggest treeline there could be highly dynamic and very sensitive to ongoing climate change; however, this part of Alaska remains one of the least understood ecosystems in the Subarctic, despite its broad geographic extent (Brubaker et al., 2001).

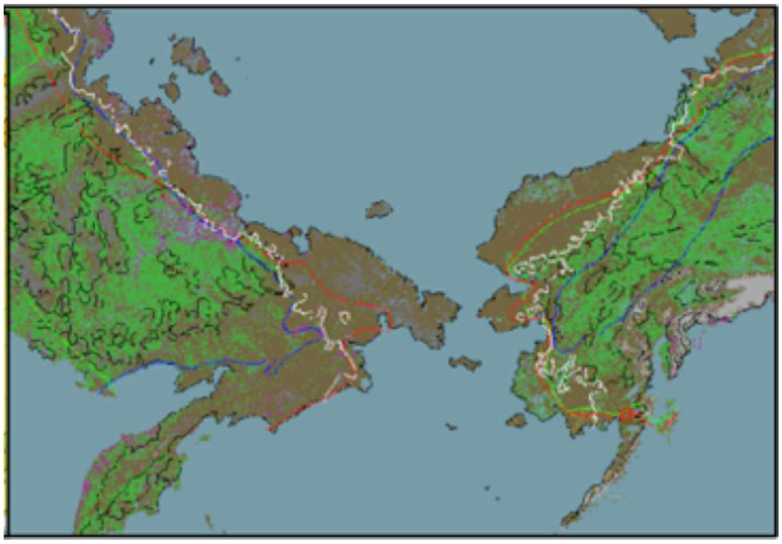

Figure 1 Circumpolar treeline. The red line shows the position of the 10°C mean July isotherm. B. Circumarctic treelines as adapted by Hustich for three different tree species (red, green, and blue lines), the Circumpolar Arctic Vegetation Map (white line), the WWF (black line), and the USGS/UNL/JRC global landcover database (green shaded boundary). My study area is indicated by the red circle. (NSIDC, 2015).

The primary objective of my research is to explore the nature of the longitudinal treeline in southwest Alaska. My overall hypothesis is that unlike most other treelines worldwide (Körner and Paulsen, 2004), growing season temperature is not the dominant factor controlling treeline in the lowlands of southwest Alaska. Instead, because of its low altitude location in a region of isolated permafrost, the proximate controls over treeline are geomorphology and soils, which mediate temperature and moisture in the soil during the growing season. Temperature and hence climate remain critical, but the mediating effects of geomorphology and soils assume an unusually large importance in controlling the dynamics of the lowland, longitudinal treeline in southwestern Alaska. To test this hypothesis, I seek to answer the following question:

How do soil conditions and geomorphology influence stand patterns and growth dynamics of white spruce at the forest-tundra ecotone in southwestern Alaska?

Specific research objectives include:

1. *Identify, describe, and classify geomorphic surfaces and soil conditions in the King Salmon area of southwestern Alaska*
2. *Describe forest stand types and the growth dynamics of individual trees growing on different geomorphic surfaces*

   a. *Map and describe vegetation type and community structure on classified geomorphic surfaces*
   b. *Use tree age and tree-ring growth measurements to determine timing of colonization and growth responses on different geomorphic surfaces*
3. *Determine if differences in forest community structure and/or in tree growth responses are related to soil condition and landscape position.*

1.1 Study Area

This study focuses on uplands on either side of the Naknek River, beginning on the shores of Kvichak Bay and extending 5 km eastward towards Naknek Lake (Figure 2).The Naknek River flows approximately 56 km from Naknek Lake (58°41'0.40"N, 156°25'50.25"W) to Kvichak Bay (58°43'2.81"N, 157° 3'46.76"W) and flows by the communities of King Salmon, Naknek, and South Naknek. A ~26 km road connecting Naknek to King Salmon along the northern bank of the river provides access to the study sites.

1.1.1 Vegetation

The lowlands of southwest Alaska (hereafter "SWAK") support a mosaic of forest stands and tundra (Figure 3). The forest-tundra ecotone here is dominated by alternating patches of forest (needleleaf, broadleaf, and mixed white spruce and Kenai birch (*Betula kenaica* (W.H. Evans) Henry), willow shrubland (tall, low, and dwarf), herbaceous vegetation (dry, moist, wet, and aquatic herbaceous, mosses and lichens), barren lands, and water, all of varying structures and sizes (USGS, 1987). Treeline in SWAK is diffuse in nature with tree density gradually decreasing over a distance before disappearing altogether and dominated by white spruce. Cottonwoods (*Populus balsamifera* L.) are restricted to floodplains and so are not involved in this study. The Naknek River is near the southwestern most extent of black spruce (*Picea Mariana* (Mill) B.S.P.) in Alaska, and this species it is uncommon in the study area (Viereck and Little, 1986). Non-forested areas are dominated by wet sedge tundra that includes freshwater sedge meadows, sedge-moss bog meadows, and halophytic sedge wet meadows (Gallant, 1995). Tundra communities tend to be hummocky with high soil moisture, though overall the soils tend to be better drained than those of the Arctic Coastal Plain (Gallant, 1995). Lakes are present throughout the non-forested area but are not as common as on the Arctic Coastal Plain (Gallant, 1995).

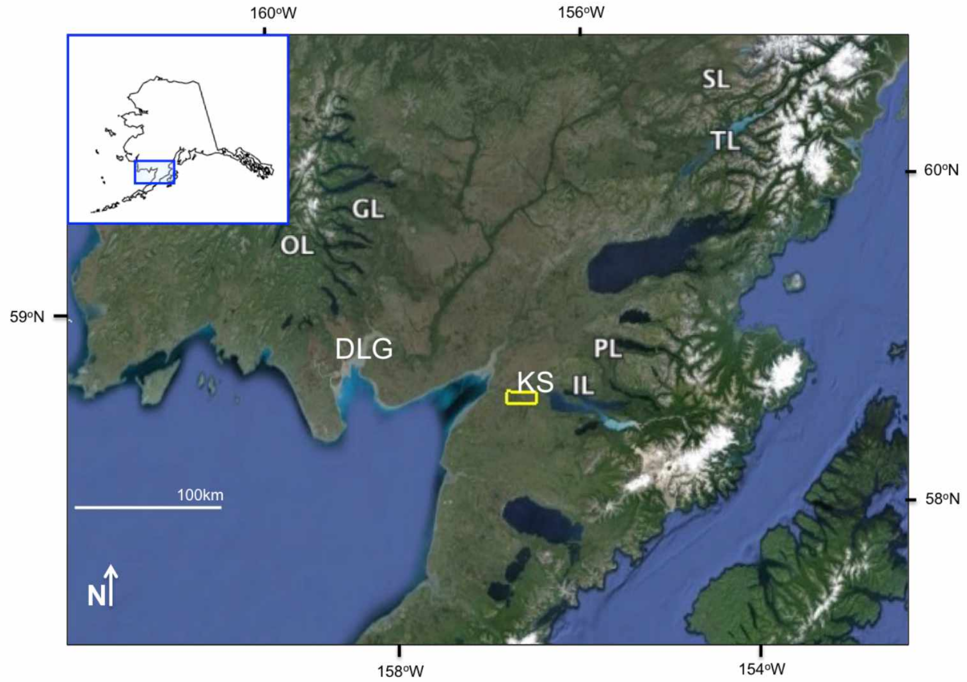

Figure 2 Map of King Salmon field location. All sites are located within yellow 20km x 8km boundary. Pollen records from nearby lakes show timing of post-glacial re-vegetation at Grandfather Lake (GL), Ongivinuk Lake (OL), (Hu et al., 1995), Idivain Lake (IL), Snipe Lake (SL) (Brubaker et al., 2001), Tommy Lake (TL), Pikelet Lake (PL) (Heiser, 2007), and Beaver Pond (BP) (not shown, <0.1km east of SL) (Kaltenreider et al., 2011).

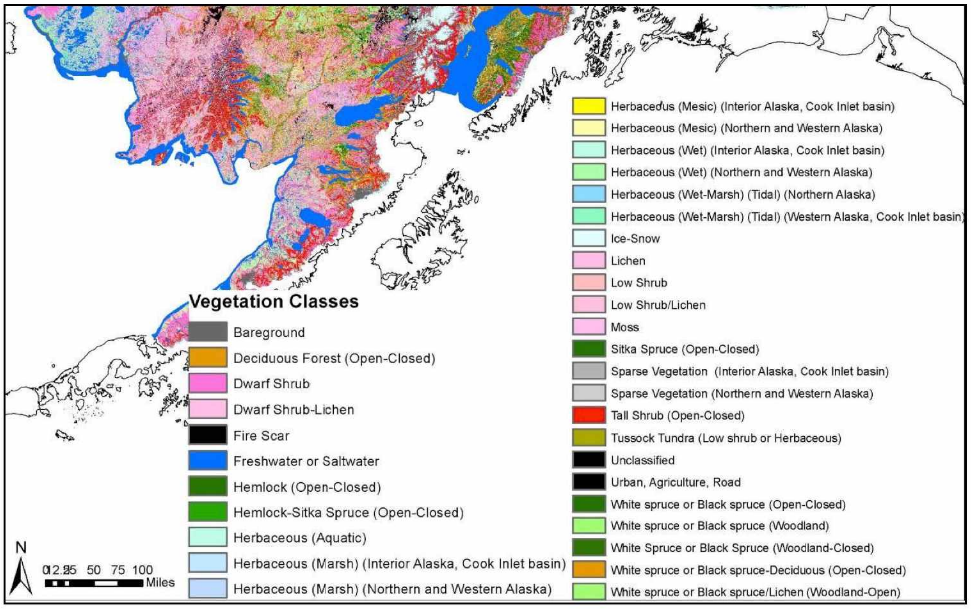

Figure 3 Vegetation map of Southwest Alaska. Modified from Boggs et al., 2012. Red and pink hues depict tundra, shrub, and lichen communities while forests are shown in green.

1.1.2 Climate

Today the climate SWAK is the outcome of a mixture of maritime and continental influences and is characterized by cool, wet summers and cold winters (Furbush, 1969). From September through April, weather is dominated by the Aleutian Low, while between May and August it is dominated by high-pressure systems (Shulski and Wendler, 2007). Sea ice forms in Kvichak Bay in mid-November and persists until mid-April (Shulski and Wendler, 2007). Mean monthly air temperatures in the region range from -13° C in January to 18° C in July (ACRC, 2015a) with historical (1961-1990) average annual temperatures ranging between 0.1 ° C and 2.3 ° C (SNAP, 2015a). The lofty Aleutian Range isolates the Bristol Bay region from much of the moisture carried by the Aleutian Low across the Gulf of Alaska. King Salmon receives an average of 48 cm of precipitation annually, most of it falling as rain during the late summer and fall (Shulski and Wendler, 2007; ACRC, 2015a; SNAP, 2015b). King Salmon's location near the coast results in frequent days with thick cloud cover and strong winds (Shulski and Wendler, 2007). The growing season averages ~100 days, beginning in late May and extending through September (Shulski and Wendler, 2007). The Pacific Decadal Oscillation (PDO) and the El Nino Southern Oscillation (ENSO) influence the climate of Southwestern Alaska through decadal scale (~20-year interval) oscillations in sea surface temperatures in the North Pacific and Gulf of Alaska (D'Arrigo et al., 2001). The prominent positive regime shift in the PDO toward warmer temperatures in 1976 has been documented throughout Alaska (Wiles et al., 1998; D'Arrigo et al., 2001). Instrumental weather data in the King Salmon area begins in A.D. 1917 and extends through the present. Data continuity is poor in the early period (1917-1947) and excellent since then (ACRC, 2015b).

1.1.3 Glacial and Geologic Landforms and Sediments

The landscape of the study area is a complex mosaic of glacial features eroded and deposited during multiple glaciations during the middle and late Pleistocene (Mann and Peteet, 1994). The King Salmon landscape is underlain by multiple moraines, kettle lakes, outwash channels and plains, sand dunes, and dune blowouts along with a diversity of unconsolidated fluvial, beach, and glacial deposits (Riehle, 2002). Periods of glacial advance and retreat during the late Pleistocene have left four distinct moraines in the area; the Iliamna moraine formed ~13000 cal yr BP), the Newhalen moraine (ca. formed ~19000 - 16000 cal yr BP, the Iliuk moraine (deposited ~11,000 cal yr BP, and moraines formed as recently as 8000-10000 cal yr BP near the Ukak River (Figure 4); (Stilwell and Kaufman, 1996; Reihle, 2002). The complex geomorphology of the study area is the product of this complex glacial history.

1.1.4 Soils

In general the soils of the King Salmon area are sandy, gravelly, and well-drained. The parent materials of soils in the study area are glacial till, outwash gravel, loess, sand, and silty alluvium (Furbush, 1969; Gallant, 1995). A 1969 survey mapped soils on the north side of the Naknek River between the mouth of the river and the town of King Salmon, as well as around the community of South Naknek (Furbush, 1969). Soils are a complex mixture of Typic Haplocryands, Typic Vitricryands, Fluvaquentic Cryofibrists, Histic Pergelic Cryaquepts, Pergelic Cryaquepts, and Typic Cryochrepts (Gallant, 1995). Recent glaciation has resulted in a spatial complex of parent materials and topography, contributing to the spatial complexity of soil types and vegetation patterns.

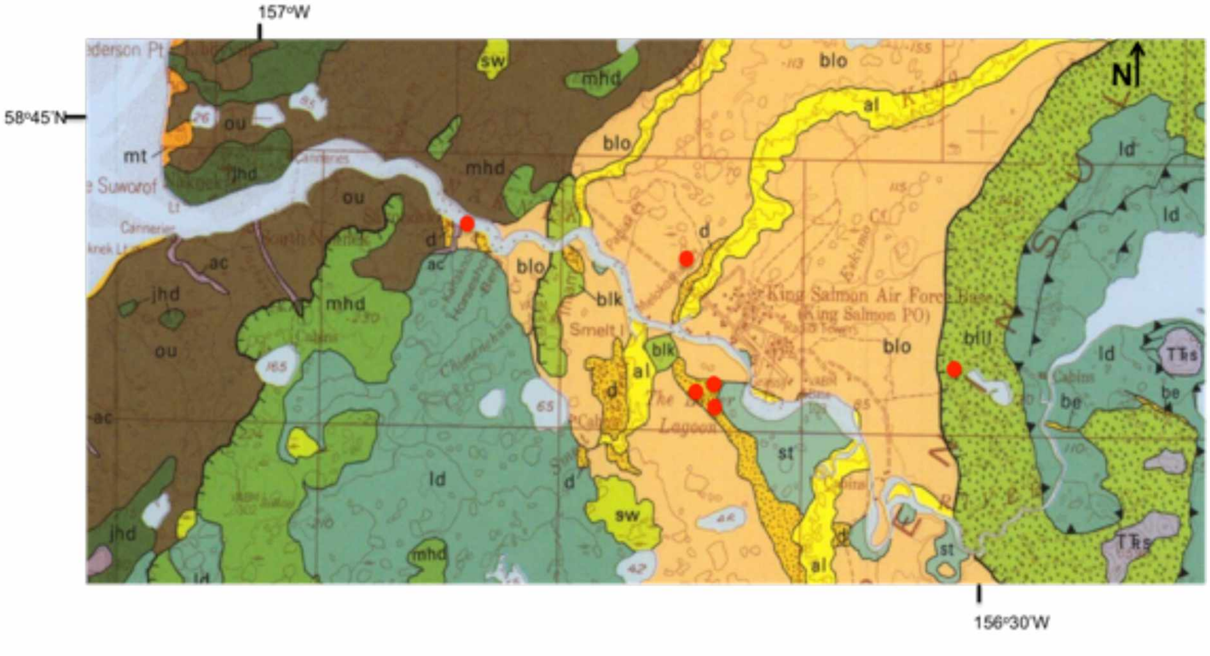

Figure 4 Quaternary geology of the Naknek River. Modified from Riehle and Detterman, 1993. The landscape is dominated by outwash deposits (ou, blo), dunes (d), alluvium (al), and lake deposits (ld). Moraines are shown as black lines with east facing hash marks pointing upglacier and include drifts from Johnston Hill advance (jdh), the Mak Hill Moraine (mhd), the Kvichak advance (blk), and the Iliamna advance (blil). Red circles indicate field sites in this study.

1.1.5 Permafrost

SWAK is located within the zone of isolated permafrost (Jorgenson et al., 2008). Soil surveys in the King Salmon area in 1969 found permafrost within two different soil types, the Naknek and Tolsona series. These loamy and sandy soils are poorly drained and occupy low hills and low floodplain slopes. In the Naknek series, the bottom of the active layer was found a few inches below a thick peat mat. In the Tolsona series, the annual depth of thaw varied from 10-61 cm below the top of the mineral surface (Furbush, 1969). It is possible that permafrost was present in other soils, and the pedologists failed to find it.

Evidence for more extensive distribution of permafrost in prehistoric times is seen in remnant ice-wedge polygons near the site of the village of Savonoski on the south bank of the Naknek River as well as in the valley of King Salmon Creek (Figure 5). In these treeless or sparsely treed sites, high-centered ice wedge polygons are evident on aerial imagery. Based on the fact that these polygonal networks are crosscut by post-glacial streams (Figure 5), I infer these are relict

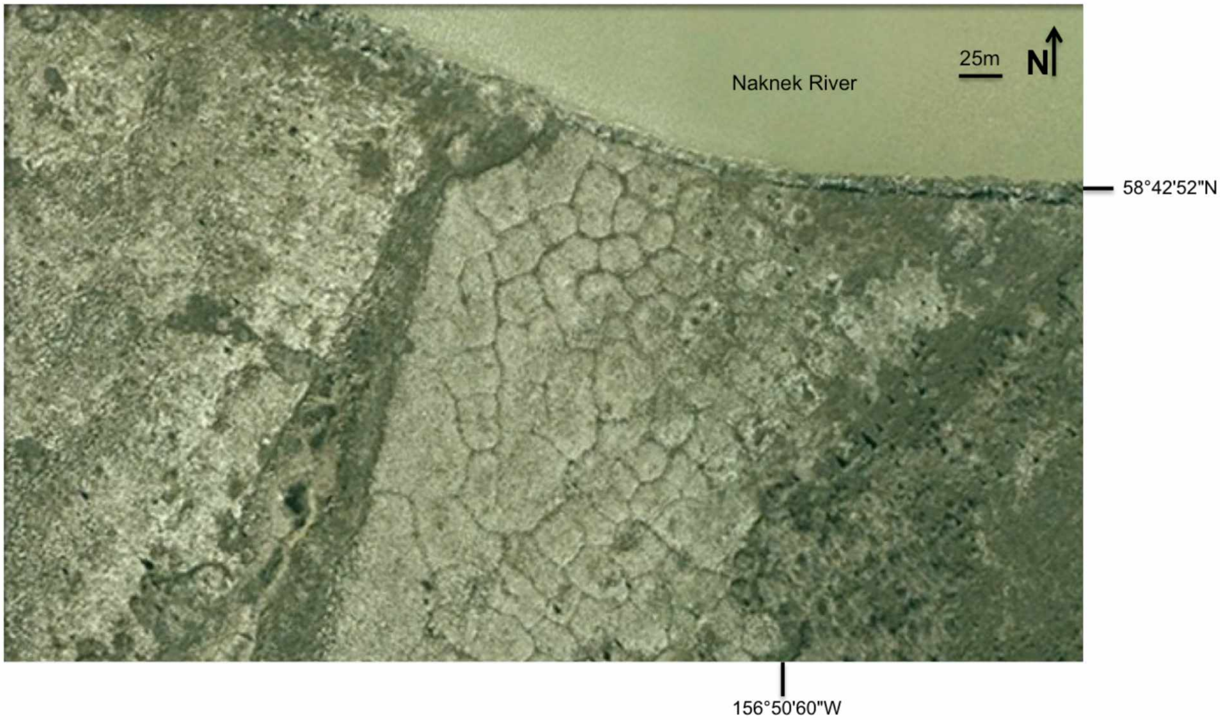

Figure 5 High centered ice wedge polygons along the Naknek River (58°42’52”N, 156°50’60”W).

features dating to the last glacial maximum; however, it is possible that permafrost has persisted - protected by thick organic matter - up to the present day.

1.1.6 Post-Glacial Vegetation Change

Changes in vegetation in SWAK during postglacial times are both spatially complex and poorly understood (Brubaker et al., 2001). Idavain Lake (~45 km east of King Salmon) and Pikelet Lake (~65 km northeast of King Salmon) are the nearest pollen records (Figure 2). They, in addition to three lake core records from Lake Clark National Park ~210-250 km to the northeast and two lakes in the Ahklun Mountains ~160-190 km to the northwest, record several distinct episodes of post-glacial vegetation change, although the timing of these episodes varies between lakes (Hu et al., 1995; Brubaker et al., 2001; Heiser, 2007; Heiser and Bigelow, 2008; Kaltenrieder et al., 2011). Pollen records show that much of the Bristol Bay vegetation was initially comprised of herb tundra, followed by a rise in birch pollen between 14500 cal yr BP and ~10000 cal yr BP (Brubaker et al., 2001; Heiser, 2007). The arrival of alder - probably *Alnus sinuata* ((Reg.) Rybd.) - started around 10000 cal yr BP at Tommy Lake (Heiser, 2007), but alder only arrived around 7400 cal yr BP at Grandfather Lake (Hu et al., 1995; Heiser, 2007).

At the regional scale, white spruce expanded its range from northeast to southwest across SWAK starting in the middle Holocene. The timing of spruce establishment ranges from 5000 cal yr BP- 3000 cal yr BP in Lake Clark National Park (Brubaker et al., 2001; Heiser and Bigelow, 2008; Kaltenrieder et al., 2011), 4200 cal yr BP at Idavain Lake nearest King Salmon (Brubaker et al., 2001), 4000 cal yr BP in the Ahklun Mountains (Hu et al., 1995), and most recently at Pikelet Lake ~ 1000 cal yr BP (Heiser and Bigelow, 2008). Because Idavain Lake and Pikelet Lakes are nearest to King Salmon; it is therefore reasonable to conclude that spruce first arrived in the King Salmon area after 4200 cal yr BP , likely around 1000 cal yr BP based on the arrival dates from Pikelet Lake (Heiser, 2007) but possibly more recently.

Studies by Robert F. Griggs in the early part of the 20th century noted very few spruce trees on the shoreline of Naknek Lake, but remarked those that were there were young and healthy (Griggs, 1934). Griggs also remarked on the absence of stumps and fallen logs in the area, concluding that the trees in the Naknek region represented the beginnings of forest expansion into the tundra. Repeat photography corroborates Griggs' observations, noting an increase in spruce in the Katmai and Naknek Lake areas over the past century (Jorgenson et al., 2006).

1.1.7 Holocene Climate History

The climate of Alaska has varied markedly during the Holocene, with periods of prolonged cold as well as periods of dramatic warming. In the early Holocene, from about 12000 to 8600 cal yr BP, Alaska experienced more pronounced seasonality than today with warmer summers, colder winters, and was overall drier, as evidenced by lower lake levels (Jones and Yu, 2010). During the Holocene Thermal Maximum (HTM), which occurred with some temporal and spatial variability across Alaska roughly between 12000 and 8000 cal yr BP (Kaufman et al., 2004), climate in many areas of the far north was 1.6± 0.8°C warmer than the approximate average of the 20th century (Kaufman et al, 2004). The HTM coincides with expansion of *Populus balsamifiera* at many sites in Interior and Northern Alaska, and expansion *Alnus sinuata* along the Gulf of Alaska coastline (Kaufman et al., 2004). Additionally, evidence of expanded beaver and insect ranges as well as ice-wedge thaw on the Seward Peninsula, decreases in glacial extent in the Ahklun Mountains (Kaufman et al., 2004) the development of thaw lakes on the Arctic Coastal Plain and the expansion of peatlands throughout Alaska (Jones and Yu, 2010) indicate the widespread occurrence of a HTM, although the onset and duration varies locally. The extent to which the HTM affected SWAK is unclear (Kaufman et al., 2004). There is no indication of the HTM in the pollen records from Grandfather Lake and Ongivinuk Lakes in the Ahklun Mountains north of King Salmon, or at Snipe Lake northeast of King Salmon in Lake Clark National Park (Kaufman et al., 2004). This may be due to the moderating effects of a newly maritime climate in Southwestern Alaska, as the extensive continental shelf in Beringia was flooded at the terminus of the Last Glacial Maximum (Kaufman et al., 2004). The disappearance of glaciers in the Ahklun Mountains between 9100 and 3200 cal yr BP and palynological evidence between 10000-9400 cal yr BP at Idavain Lake suggest that the HTM may have had local effects in parts of Southwest Alaska (Kaufman et al., 2004).

Temperature reconstructions at SWAK pollen sites indicate warming during the Medieval Warm Period (MWP) between ~ A.D. 950 and 1250; however; the magnitude of warming during the MWP in SWAK appears to have been less than the temperature changes of recent decades (Loso, 2009). Evidence for cooling in the Chugach Mountains of southern Alaska between A.D. 1350 and 1850 coincides with Little Ice Age (LIA) (Loso, 2009). Evidence from glacial geology in Prince William Sound and dendrochronology on the Seward Peninsula places the most significant LIA cooling in two pulses, once in the early to mid-1600s, and again in the late 1700s to mid-1800s, with a brief warming from the mid-1600s to early 1700s (Wiles et al., 1999; D'Arrigo et al., 2005). Over the past 150 years, climate has gradually warmed, marking the end of the Little Ice Age and the beginning of new, unprecedented warming, with a high rate of warming throughout Alaska, and the rate of warming in the high Arctic north of 65°N now being nearly double the global average (Solomon et al., 2007).

1.1.8 Volcanic Ashfall Regimes

Post-glacial times in SWAK have seen a series of volcanic eruptions (Nelson, 2004). The most recent of these was the eruption of Mt. Katmai in June, 1912, the largest volcanic eruption of the 20th century (Hildreth and Fierstein, 2012). This eruption deposited 1-3 cm layer of ash in the King Salmon area, the thickness of which thins with distance from the volcano (Hildreth and Fierstein, 2012). The impact of ash deposition on vegetation in the King Salmon area remains unclear; however, the large (20-50cm) deposit of tephra in Kodiak 170 km to the southeast of the eruption, where Sitka spruce (*Picea sitchensis*) had already established, proved to be beneficial in the long term for Sitka spruce by reducing interspecific competition from seedlings, saplings, and shrubs (Tae, 1997). A study of revegetation after ash fall in Aniakchak found that ash deposits < 5cm had no immediate effect on vegetation growth, although there may be additional nutrient input depending on the chemistry of the tephra (Nelson, 2004). The Lethe tephra, which fell sometime between 16000 and 8000 ^{14}C yr BP is frequently found in discontinuous, 1-5 cm lenses within soil profiles in the Bristol Bay region (Riehle et al., 2008). The Lethe and Novarupta ashes are the two most commonly occurring tephras in the Bristol Bay lowlands, but somewhere between ten and twenty other volcanic ashes have fallen there since the end of the last ice age (D.H. Mann, personal communication).

1.1.9 Fire History

Few wildland fires have been recorded in the 20th century, most of those being less than 10 acres in size (Alaska Fire Service, 2015).

1.2 Characteristics of the Forest-Tundra Ecotone in Alaska

1.2.1 Natural History of White Spruce

White spruce is often the treeline species in boreal Alaska (Viereck and Little, 1986). Currently, the latitudinal limit of treeline in Alaska follows the south side of the Brooks Range, reaching a latitude 68.7°N in the Firth River drainage (Wilmking and Juday, 2004). Both alpine and longitudinal treelines exist in SWAK with alpine treelines ranging from 400-580 m above sea level in the Chigmit Mountains of Lake Clark National Park (Driscoll et al., 2005) to 275-305 m above sea level closer to Naknek Lake (Heiser, 2007).

White spruce grows best on well-drained soils, on south-facing slopes, and on deeply thawed soils along riverbanks and tends to be rare at sites underlain by permafrost (Viereck and Little, 1986). White spruce reaches maturity at 100-200 years of age (Viereck and Little, 1986) but begins producing seeds much earlier at around 10 years of age. In ideal growing environments, white spruce can grow upwards of 24-35 m tall, with diameters of up to 76 cm (Viereck and Little, 1986).

Across most of its range, the growth of white spruce is limited by growing season temperature (Thompson et. al., 1999; Korner and Paulson, 2004; Wilmking and Juday, 2004). At some sites, its growth is strongly modified by substrate and disturbances such as wildfire (Lloyd et al., 2005; Lloyd et al., 2007). Recent studies suggest that at well-drained sites that have seen an increase in temperature without a concurrent increase in precipitation, drought-stress limits the growth of white spruce more than temperature (Barber et al., 2000; Lloyd et al., 2013). In Alaska today, white spruce grows at sites where mean July temperature ranges from 8°C to 21°C, and July precipitation ranges from 20-200 mm (Thompson et al., 1999; Barber et al., 2004). In western Canada, this species' growth is restricted at its northern range limit by summer warmth and at its southern limit by moisture stress (Thompson et al., 1999; Barber et al., 2004).

White spruce trees in Alaska are genetically distinct from those in the contiguous United States (Brubaker et al., 2005; Anderson et al., 2006; Anderson et al., 2011). This suggests that isolated pockets of white spruce survived the last ice age in cryptic refugia and so preserved genetic diversity overall and unique genes in particular. Given this history of survival in refugia, white spruce native to Alaska may be better adapted to cold temperatures than previously thought and for this reason drought stress rather than temperature may be the most important physiological factor controlling its range limits in northwestern North America. That said, temperature is often an important modifier of water stress.

1.2.2 Factors Controlling Arctic, Alpine, and Longitudinal Treelines

Globally, alpine treelines have diverse controls related to their geographic diversity, yet a 6.7°C seasonal, mean soil temperature seems to be important in many cases (Korner and Paulsen, 2004). Recent work suggests that the response of alpine treelines to changing climate is controlled by their physical structure (diffuse, abrupt, or krummholz treelines) (Harsch et al., 2009). Diffuse treelines are usually limited by summer temperature and so will advance upslope as summers warm. In contrast, krummholz and abrupt treelines are usually limited by winter conditions detrimental to growth, such as deep snow packs and abrading wind regimes, which makes them able to expand upslope only if winter conditions ameliorate (Harsch et al., 2009).

Many latitudinal (arctic) treelines are controlled mainly by growing season temperature (Lloyd, 2005; Andreu-Hayles et al., 2011) though other climate effects such as moisture stress, disturbances like wildland fires, and non-climatic factors such as thermokarst, permafrost, and nutrient availability are often important modifiers of treeline position (Epstein et al., 2004; Juday et al., 2005; Lloyd et al., 2005; Lloyd et al., 2007). Current predictive models for vegetation response to climate change in the Arctic and Subarctic assume that temperature is the limiting factor for growth at latitudinal treelines and that an increase in temperature will correspond with an increase in radial growth and recruitment of white spruce, except in those sites limited by drought stress (i.e. Barber et al., 2000; Rupp et al., 2001; Lloyd et al., 2013).

Extensive work has been done investigating the factors controlling tree growth in Alaska (Viereck, 1979; Lloyd et al., 2003; Driscoll et al., 2005; Dial et al., 2007; Beck et al., 2011). Arctic treeline in Alaska exists roughly at the 10-12°C isotherm, indicating seasonal temperature exerts a large control over its position (Epstein et al., 2004). Reforestation experiments, using seeds, seedling or sapling transplants to areas north of present-day arctic treeline suggest that it in recent decades it has been possible for white spruce to grow well beyond its current range (Viereck, 1979; Hobbie and Chapin, 1998). While survival of white spruce beyond its range has been demonstrated, evidence of white spruce producing viable seedlings beyond treeline remains inconclusive (Viereck, 1979).

In contrast to arctic and alpine treelines, little is known about controls over growth at southwestern Alaska's longitudinal treeline. Comparisons between the geographic limits of white spruce and the distribution of mean summer temperatures suggests that July mean temperature may be important, just as it is for latitudinal (arctic) treeline (Figure 1). Additionally, the longitudinal treeline of SWAK is diffuse in form and so by analogy to the alpine treelines described by Harsch et al (2009), treeline in SWAK is likely to respond positively to warming summer temperatures rather than milder winter conditions. Fire disturbance is rare in SWAK (Gallant, 1995), and likely does not play a strong modifying role in treeline position there like it does in arctic treelines and Interior Alaska (Lloyd et al., 2007; Payette et al., 2008). Temperature gradients are likely to be less pronounced across longitudinal treelines than across alpine treelines. Gradients in drought stress are probably also less steep at longitudinal treelines than they are on south-facing bluffs in Interior Alaska where azonal treelines occur (Lloyd et al., 2013).

1.2.3 Growth Divergence in Alaskan Treelines

As previously mentioned, the radial growth of white spruce trees growing at arctic, alpine, and boreal forest sites is highly sensitive to climate, particularly to growing season temperature (Epstein et al., 2004; Lloyd and Bunn, 2007; Juday and Alix, 2012; Lloyd et al., 2013). Recent studies show that at many sites, the responses of white spruce growth to climate changed starting in the mid-1970s. Although some white spruce trees continued to show positive growth sensitivity to temperature during warmer than usual summers, other trees began to show negative growth sensitivity during the same summers (Wilmking and Juday, 2004; Driscoll et al., 2005; Wilmking et al., 2005; Beck et al., 2011). A number of studies have looked into what has become known as the 'divergence problem' and have identified a number of possible factors that could change the way a tree growing at treeline responds to the same environmental driver (Barber et al., 2000; Grossnickle, 2000; D'Arrigo et al., 2008; Juday et al., 2015).

In many cases, it appears there is a threshold in the positive growth response to summer temperature, above which growth declines either due to overheating effects or to temperature-induced drought stress (Barber et al., 2000; Lloyd and Bunn, 2007; Lloyd et al., 2013; Juday et al., 2015). Temperature and precipitation in the year prior to growth are important factors for annual ring growth throughout the range of white spruce; however, optimal growing conditions for white spruce in dry sites occur most often during and in the year following cool, wet years (Lloyd et al., 2013). Other studies have found correlations between white spruce growth and winter warming, autumn precipitation, spring snow melt, and temperature and precipitation in varying months, all of which suggest that white spruce's relationship to climate is far more complex than simply growing faster in warmer summers (Driscoll et al., 2005; D'Arrigo et al., 2008; Harsch et al., 2009). Other factors that may drive forest growth at the forest-tundra ecotone include heating-degree days, net radiation and cloud cover, as well as disturbances caused by insects, fire, and ash fall (Viereck, 1979; Tae, 1997). The complexity of factors interacting with each other and influencing growth make it very difficult to generalize about the factors that control arctic, alpine, and longitudinal treelines.

1.2.4 Productivity and Recent Changes in Alaskan Treelines

Over the last several decades, treelines have advanced at many sites globally (Harsch et al., 2009). In Alaska, some alpine treelines such as those growing on north- facing mesic sites in the Kenai Peninsula have advanced upward, while on other sites vegetation density has increased without upward expansion of treeline (Dial et al., 2007). Trees at arctic treeline in the Noatak National Preserve in northwest Alaska have advanced 80-100 m upslope over the past 200 years (Suarez et al., 1999). Currently throughout Alaska, studies indicate northward and upslope advance of trees and increased greening of shrubs at arctic treeline, and an increase in browning throughout the Interior (Sturm et al., 2001; Goetz et al., 2005; Tape et al., 2006; Lloyd and Bunn, 2007). This is corroborated by normalized difference vegetation index (NDVI) and tree ring data that show a recent shift in spruce primary productivity along a longitudinal gradient across Alaska, with productivity decreasing in Interior Alaska while increasing in western Alaska (Wilmking and Juday, 2004, Beck et al., 2011). These changes are thought to reflect the threshold effect of summer temperature with the Interior trees suffering from drought stress while the western trees grow faster in response to summers that are warmer, but have more available water than trees at arctic treeline (Juday et al., 2015).

In conclusion, while trees growing at high latitude treelines are often limited by low temperatures during the growing season, their responses to changing climate can be strongly modified by a suite of other factors including ecological disturbances like fires, water stress caused by droughty conditions, and localized edaphic factors affecting moisture supply and temperature. Treeline types in every geomorphic setting will respond differently to climate change. Understanding the responses of different geomorphic settings and vegetation communities to climate change is important for predicting and planning for ecological changes that may occur in the future.

2.0 Methods

2.1 Site Selection and Description

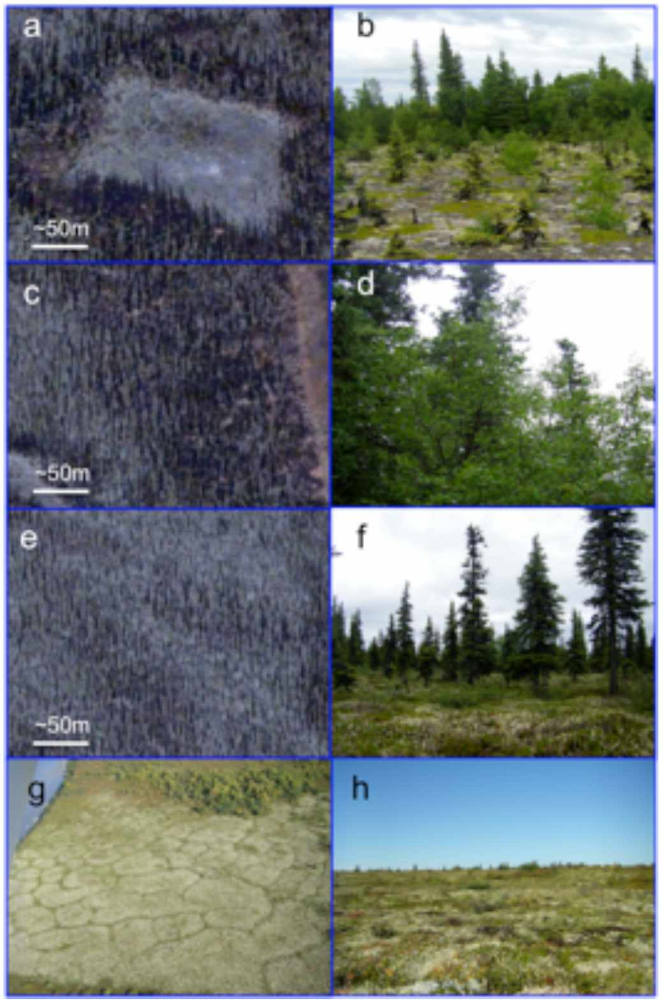

Figure 6 Aerial and ground photos of vegetation-landscape associations. *Open dwarf basins* (a-b), closed forest hillslopes (c-d), open forest flats (e-f), and polygon plateaus (g-h).

This study focuses on twelve field sites representing four, upland vegetation-landscape associations that contain white spruce trees (Figure 6). 'Uplands' are defined as non-floodplain settings occurring 10-30 m above sea level. I chose twelve intensive study sites that are representative of these four forest-landscape associations (Figure 7, Table 1). Seven of these sites are located along a 150-m long and 5-m wide transect south of King Salmon on the southern side of the Naknek River. I specifically chose sites distant from human trails with no signs of human disturbance. In total, the twelve intensive study sites include three *open dwarf basin* associations, six *closed forest hillslopes* associations growing on stabilized sand dunes and glacial moraines, two *open forest flats*, and one *scattered spruce polygon* association (Figure 7). The 'Kite Basin Transect' contains three *open dwarf basin* associations, three *closed forest hillslope* associations, and one *open forest flats* association, all in close proximity to one another. While sites were selected to be representative of the surrounding terrain, due to access and transportation limitations, all sites are located within a small geographical area, which should be noted if spatially extrapolating the results of this study.

At each study site, I recorded species occurrence, the stem density of the dominant tree species, and the approximate abundance of tree and understory plant species. I also recorded slope, aspect, geomorphic landform, microtopography, latitude, longitude, and elevation. Aerial photos were taken from a small aircraft 120-180 m above the ground wherever possible.

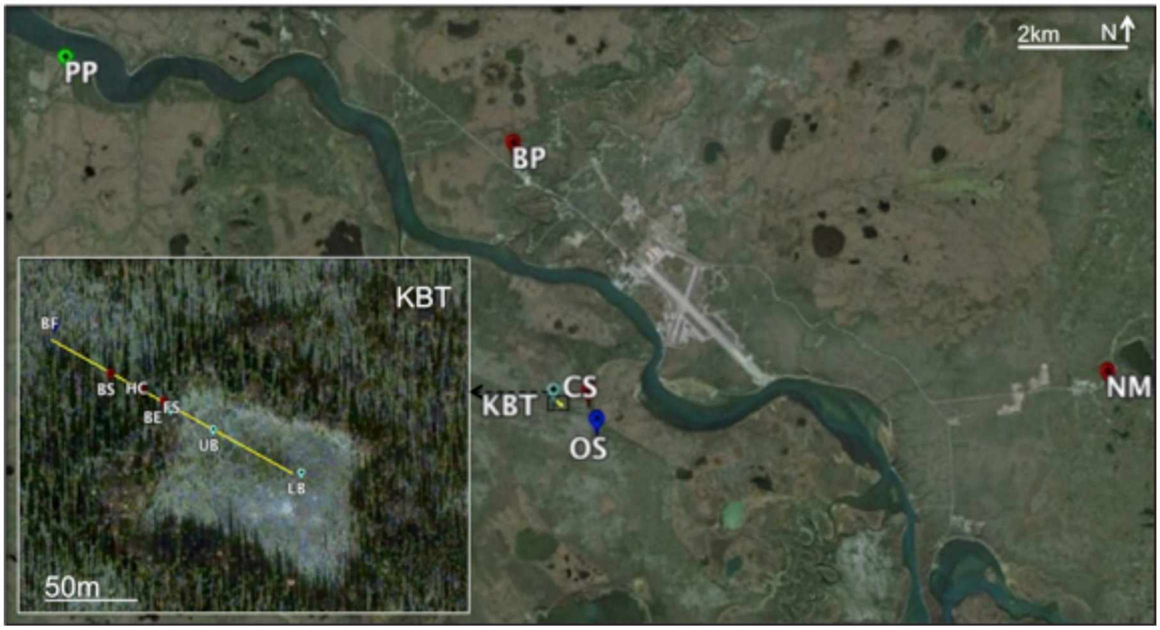

Figure 7 Location of field sites. Inset: Seven sites are located along a 150m Kite Basin transect (KBT).

Table 1 Name, vegetation-landscape association, and location of field sites.

	Field Site	Vegetation-Landscape Association	Latitude	Longitude
Kite Basin Transect	Lower Basin (LB)	open dwarf forest basins	N 58.660294	W 156.689133
	Upper Basin (UB)	open dwarf forest basins	N 58.660500	W 156.689963
	Basin Edge (BE)	open dwarf forest basins	N 58.660597	W 156.690366
	Foreslope (FS)	closed forest hillslopes	N 58.660633	W 156.690430
	Hillcrest (HC)	closed forest hillslopes	N 58.660688	W 156.690641
	Backslope (BS)	closed forest hillslopes	N 58.660766	W 156.690933
	Backflats (BF)	open forest flats	N 58.661000	W 156.691466
	Closed Spruce (CS)	closed forest hillslopes	N 58.662222	W 156.681111
	Open Spruce (OS)	open forest flats	N 58.657400	W 156.678200
	Polygon Plateau (PP)	scattered spruce polygons	N 58.714366	W 156.851783
	Naknek Moraine (NM)	closed forest hillslopes	N 58.668033	W 156.515950
	Bonfire Pit (BP)	closed forest hillslopes	N 58.702761	W 156.707852

2.1.1 Landcover and Vegetation Patterns

To map land cover, I obtained aerial imagery from GoogleEarth and georeferenced it to an imagery baselayer obtained on May 1, 2010 from http://www.alaskamapped.org/data/arcgis-layer-files (GINA, 2012). I then manually digitized the polygons, drawing boundaries between the four vegetation-landscape associations as well as non-forested floodplain, tundra and river polygons. I then re-projected the image, converted the file to ASCII format, and ran landscape metrics through FRAGSTATS spatial analysis (McGarigal and Marks, 1995) to obtain data describing landcover, patch density, and patch size.

2.2 Soil Sampling and Description

Probing for permafrost with a tile probe in July of 2009 identified a number of sites underlain by frozen ground. To avoid seasonal ice, all soil samples were collected in September 2010, when the active layer was near its maximum depth. At each of the ten sites where I collected tree cores, I dug a soil pit to at least 1.5m depth or until an unaltered C horizon was reached, whichever was shallower. In total, I described one pit representing scattered spruce polygons, five pits representing closed forest hillslopes, two pits representing open forest flats, and two pits representing open dwarf basins. Soils were described using standard procedures (Birkeland, 1999; Schoeneberger et al., 2002). From each soil horizon, I collected soil samples for laboratory analysis and described field color, structure, boundary, roots, mottling, ice content (if any), presence of gravels, grain size, and consistency. Additionally I made note of any unique features, such as cryoturbation and the presence of volcanic ashes. I also recorded air temperature, soil temperature at the ground surface, and soil temperature within at least one horizon at depth.

I collected soil samples in the field from each horizon in the soil pits. Samples were processed following standard procedures in the laboratory (Birkeland, 1999). Moist color was recorded using the Munsell soil color system, and percent soil moisture was calculated for each sample by removing particles >2 mm in diameter, heating soils at 105°C for 24 hours, and then comparing wet and dry weights. Soil moisture in this study is directly a result of drainage and precipitation conditions at the time of collection; however, this method does allow for relative soil moisture comparisons across different vegetation-landscape associations as all samples were collected within 10 days of each other with no rainfall event occurring during collection. pH and EC were recorded following standard procedures, and grain size was described using the Bouyoucos Hydrometer method (Birkeland, 1999).

2.3 Tree-Core Sampling

In the summers of 2009 and 2010, I collected 300 cores from 200 white spruce trees at twelve different field sites. Because this study is concerned not only with climate correlations but also on the effects of local site factors, I cored canopy trees from multiple size classes. I cored between 15 and 45 trees per site, and collected a bark-to-pith core at breast height for growth response to climate as well as a core near the root crown to estimate germination date. For each tree, I measured diameter at breast height (dbh), estimated tree height, and recorded tree location. I avoided trees with obvious signs of damage such as those with scars and/or tilted or twisted trunks. Additionally, I recorded presence of dead trees and stumps and any signs of ecological disturbance.

After being mounted on wooden holders, trees cores were incrementally sanded to 600 grit. Ring widths were measured to 0.001mm on a Velmex® sliding bench micrometer. Samples were crossdated and verified using the computer program COFECHA (Grossino-Mayer et al., 1992). Once cores were cross-dated and ring counts corrected, individual ring widths as well as site-series averages per year were calculated and plotted. Cores that included branches, scars, or that contained unreadable rings were not included. This analysis only includes cores in which the pith was reached. In total, my analysis includes cores from 148 white spruce trees representing each of the four vegetation-landscape associations; 17 *open dwarf basins*, 51 *open forest flats*, 72 *closed forest hillslopes*, and 8 *scattered spruce polygons*. To remove age-related influences on diameter growth, I used the dplR software package in R to de-trend the ring width data using a modified negative exponential growth curve for each of the 148 usable chronologies (Bunn, 2008).

2.3.1 Timing of Establishment

To estimate germination date, I cored a smaller subsample of tree birch at sites where they were present. These cores were dated by counting annual rings under a dissecting microscope after sanding the mounted cores with 600-grit sandpaper. These birch cores are included in the establishment portion of this study but are not included in ring-width analysis. First year of growth (FYOG) dates for white spruce were grouped by landscape position. Trees that were both shorter than 137 cm and with a basal diameter too small to safely core were not sampled, so it should be noted that the rarity of trees with FYOG dates after 1980 is the result of this sampling bias. Corrections for rings below the basal core height were not made, and therefore tree ages are slightly underestimated for germination; instead, first year of growth is used for this study.

2.3.2 Ring Width Measurements

I took the detrended mean ring widths for each site and grouped them according to their vegetation-landscape association. This resulted in a mean ring-width index for each association; mRWI (ring-width index for all King Salmon samples), bRWI (for *open dwarf basins*), fRWI (for *open forest flats*), sRWI (for *closed forest hillslopes*), and pRWI (for *scattered spruce polygons*). I then plotted each RWI and calculated the r^2 value of a linear least squares fit and the resulting slope equation. I then visually assessed patterns of growth in the period of record, noting years with large and small growth rings.

To assess variability among the different vegetation-landscape associations, I calculated the standard deviation ($\pm 1\sigma$ of mRWI) and plotted annual growth at each vegetation-landscape association compared to the standard deviation of the pooled ring widths of all trees from all sites (mRWI).

In what follows, a *strong positive* refers to a year when the growth in one vegetation-landscape association was greater than one standard deviation of the mean growth of all trees in that year. A *strong negative* response is noted in years when the radial growth in one of the vegetation-landscape association at least one standard deviation less than the mean ring width of all trees in that year. *Non-responsive* refers to years when radial growth at any given vegetation-landscape association fell within the range of the mean growth of all trees in that year, plus or minus one standard deviation of the mean of all trees.

2.3.3 Ring Width and Climate Correlations

I compared ring width indices for trees growing in each vegetation-landscape association with mean annual air temperature (MAAT), mean July temperature, mean monthly temperature (MMT), mean July precipitation, mean monthly precipitation (MMP) and mean annual precipitation (MAP) from the King Salmon weather station for the period 1917-2009 (ACRC, 2015).

I performed a preliminary analysis of correlation and response of ring width indices with weather data using the program Dendroclim2002 (Biondi and Waikul, 2004). To account for years with missing temperature and precipitation data from the King Salmon weather station, I used weather data from the Dillingham weather station 111 kilometers to the northeast across Kvichak Bay; 'DLG' on Figure 2) as needed. No weather data was recorded at either King Salmon or Dillingham in 1946; for that year I used the mean annual temperature at King Salmon for the years 1917-2009. Other sites around Alaska do report a strong cooling period in 1946; as such, my estimate may be higher than actual temperature in that year. In addition to data missing from the early part of the record, instrumental techniques for recording weather data greatly improved after the 1940s and, consequently, the early part of the record may not be as accurate as the data in later years. Following my analysis with Dendroclim2002, I also tested Pearson Product Correlation Coefficients in MS Excel for MMT and MMP in the year of growth and one and two years prior to growth, as well as a Flood Plain Temperature Index (FPTI) developed to predict growth at flood plain sites in the Interior and Western boreal forests (Juday et al., 2015).

3.0 Results

3.1 Description and Spatial Extent of Vegetation-Landscape Associations

White spruce growth occurs in four distinct and widespread vegetation-landscape associations in southwestern Alaska: low density and low stature mixed spruce and shrub birch grow in gravelly blow-out basins, opens spruce forests grow on hummocky upland flats and slight slopes, closed canopy mixed forest grow on low relief ridges and dunes, rising above the surrounding uplands by 1-3m, and scattered white spruce appear associated with formerly permafrost-dominated polygon sites, particularly in the cracks between high-centered polygons (Figure 8). Vegetation classes follow the Alaska Vegetation Classification Index (Table 2) (Viereck et al., 1992) and vegetation-landscape associations are given names unique to this paper based on geomorphic substrate and vegetation classification (Table 3, Table 4). Vegetation-landscape association are named as follows:

a) open, dwarf forest growing in topographic basins ("*open dwarf basins*")

b) open forest on topographic flats ("*open forest flats*")

c) closed forest growing on hillslopes ("*closed forest hillslopes*")

d) scattered spruce growing in ice-wedge polygons ("*scattered spruce polygons*")

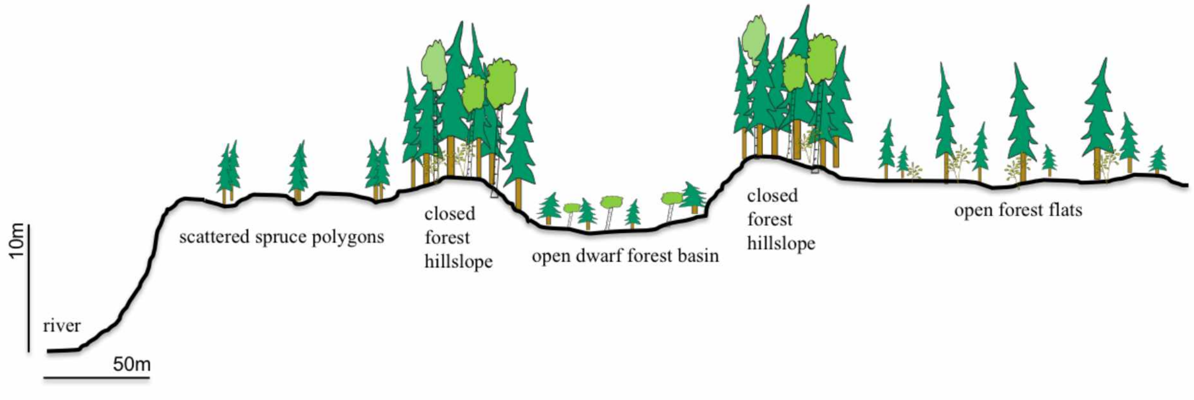

Figure 8 Idealized schematic of vegetation-landscape associations in King Salmon. Scale is approximate.

Table 2 Vegetation patterns described from Viereck et al., 1992 and terms used in this study

Alaska Vegetation Classification Index (Viereck et al., 1992)	Vegetation-Landscape Association (This study)
open dwarf tree scrub	open dwarf basins
open white spruce forest	open forest flats
closed spruce-paper birch forest	closed forest hillslopes
spruce dwarf tree woodland/open low willow-birch shrub	scattered spruce polygons

Additionally, I identified two prominent non-forested landscape types, upland tundra and floodplain. A landscape patch analysis using Fragstats showed that within the 2-km^2 area encompassing most of our field sites, the most extensive forested vegetation-landscape associations by area are *closed forest hillslopes* (45% landcover) and *open forest flats* (12%) (Figure 9). *Open dwarf basins* account for very little area (0.2%) but are included in this study because of their unique form. *Scattered spruce polygons* are included in upland tundra in the FRAGSTATS analysis due to the difficulty in distinguishing them from surrounding tundra on aerial imagery.

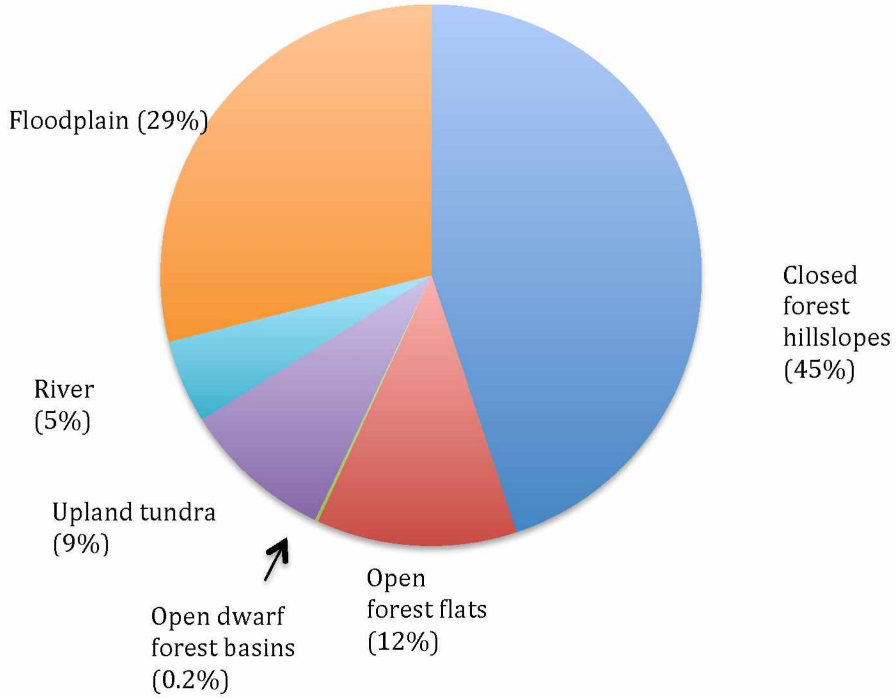

Figure 9 Percent landcover of a 2km^2 area representative of the surrounding King Salmon landscape. *Scattered spruce polygons* are included in upland tundra.

Table 3 Geomorphology and topography of landscape-vegetation classes. Bolded field sites indicate locations where soil pits were dug.

Vegetation-Landscape Association	Field Sites	Geomorphology	Topography
open dwarf forest basins	**LB**, UB, **BE**	dune blow-out basins	flat
open forest flats	**BF, OS**	outwash gravels, sand	hummocks 5-50cm
closed forest hillslopes	**FS, HC, BS, CS, NM**, BP	sand dunes, moraines	1-3m relief
scattered spruce polygons	**PP**	outwash gravels, remnant ice wedge polygons	<1m relief

3.1.1 Soil Conditions in Vegetation-Landscape Associations

Soils in the study area are sandy, slightly acidic, and fairly well-drained. There is some variability in texture, moisture, and acidity between different associations (Table 4). Permafrost was not found at any of the sites; however, the occurrence of cryoturbated soils in one of the *open forest flats* sites and the presence of cryoturbation and ice-wedge cracking at the *scattered spruce polygons* site suggest that some time in the past, permafrost played a role in soil processes there. I did not find charcoal in any of the soil pits, suggesting the occurrence of large fires has historically been low.

Table 4 Soil properties of vegetation-landscape associations.

Vegetation-Landscape Association	Field Sites with Soil Pits	Mean Soil Moisture %	% Sand	% Silt	% Clay	Mean Acidity
open dwarf basins	LB, UB	9.94	75-92	3.5-18.5	2.5-6	5.93
open forest flats	BF, OS	26.04	58-94	5-25	2-15	5.92
closed forest hillslopes	FS, HC, BS, CS, NM	19.26	52-94	2-25	3-19	5.36
scattered spruce polygons	PP	27.67	55-92	5-28	5-25	6.13

Open dwarf basins

Open dwarf basins are small (50-200 m diameter), dune blow-out basins associated with stabilized dune fields. They are characterized by a thin organic horizon (< 2 cm) and alternating bands of oxidized and reduced sand in the B and BC horizons. They are sometimes underlain by gravelly, well-drained parent material probably deposited as proglacial outwash or moraines (Figure 10). At the time of sampling in August 2010, soils were moist, with soil moisture at 10% water by weight. I encountered the water table within 2 m of the ground surface. Near-surface horizons are finer in texture than deeper horizons. Soils are sandy, with sand content ranging from 75.5% near the surface to 91.5% mid-profile, and averaging 89%-91% at depth in the C horizon. Silt content ranges from 3.5-18.5% at the ground surface but decreases with depth, as does clay content, which is highest near the surface at 6%, decreasing to 2.5% with depth. Open dwarf basin sites are slightly acidic with a mean pH of 5.9 (n=2).

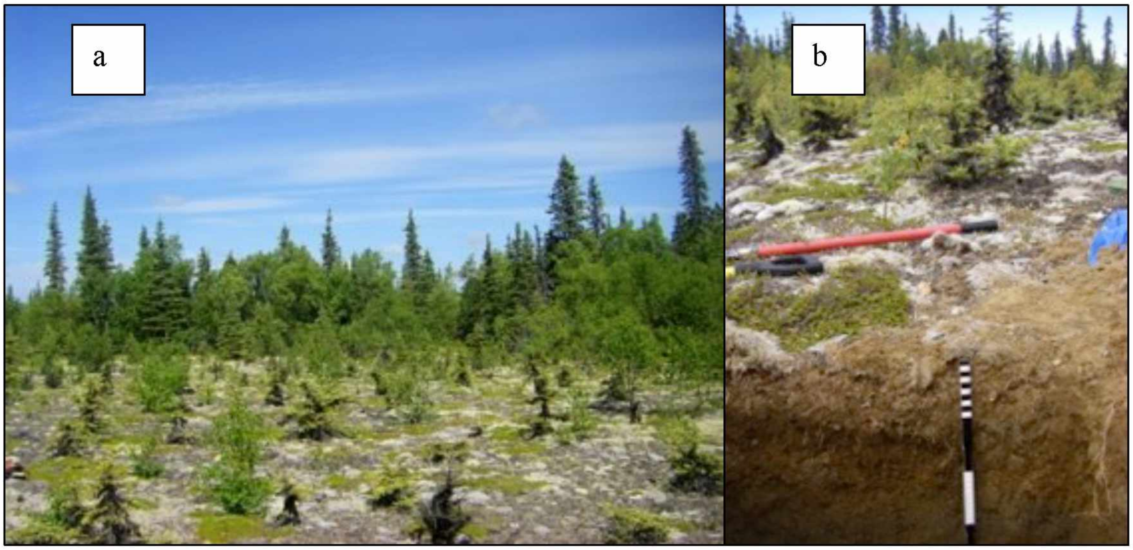

Figure 10 Landscape and soils characteristic of *open dwarf basins.* (a) photo of open dwarf basin. (b) Soil pit in Kite Basin showing a thin O horizon and alternating layers of oxidized and reduced sandy parent material, likely representing stabilized dune blowout.

Open forest flats

Soils in the *open forest flats* are characterized by organic hummocks underlain by thin (~2 cm) organic horizons and only limited soil development. Mottling occurs in the B horizons (Figure 11). Textures are sandy with 58-94% sand, increasing with depth; 5-29% silt decreasing with depth; and 2-15% clay, also decreasing with depth. At the time of sampling, soils in the *open forest flats* had higher soil-moisture contents than either the *open dwarf basin* or the *closed forest hillslope* sites (26% water by weight). Soils in the open forest flats are slightly acidic with a pH of 5.9 (n=2).

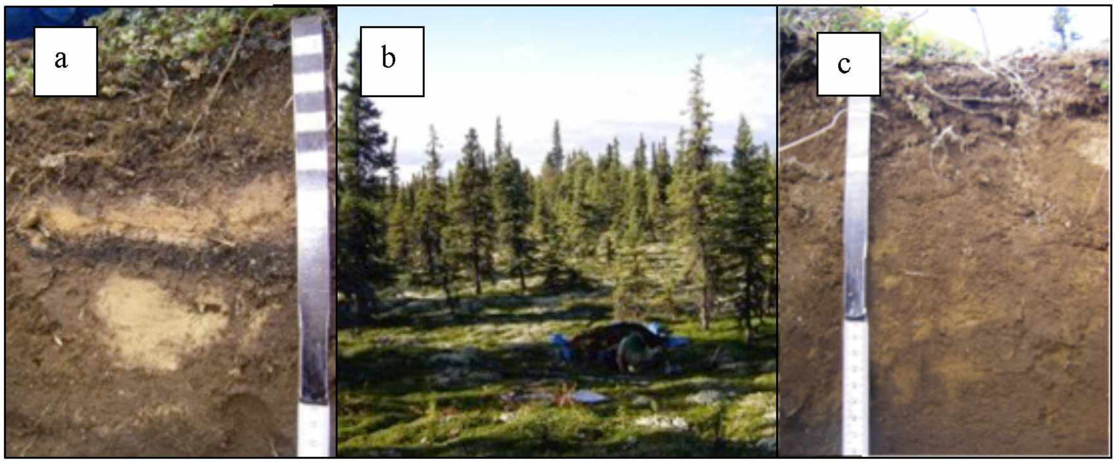

Figure 11 Landscape and soils characteristic of *open forest flats.* (a) top of soil profile from *open forest flat* site BF showing O horizon and presence of tephra (b) photo of site BF, characteristic of *open forest flats* and (c) soil profile at *open forest flats* site OS showing mottling in the B horizons.

Closed forest hillslopes

Closed forest hillslope associations occur on stabilized sand dunes and glacial moraines and are characterized by sandy soils with limited horizon development (Figure 12). Organic horizons range from 0.5 cm to 6 cm thick. Sand accounts for 52-94% of the soil, typically increasing with depth; while silt accounts for 2-29%; and clay accounts for 3-19%, both decreasing with depth. In the soil pit dug on the Naknek Moraine, glacial till, overlain by aeolian sand, appeared at a depth of 80 cm. The mean soil moisture content of soil pits sampled at closed

Figure 12 Landscape and soils characteristic of *closed spruce hillslopes.* (a) top of soil profile at *closed forest hillslope* site HC showing thin O horizon and sandy B horizons, (b) vegetation at site CS, characteristic of *closed forest hillslope* associations and (c) soil profile at NM, a moraine *closed forest hillslope* site.

forest hillslope sites was 19%. Soils in closed forest hillslopes tend to be slightly more acidic than other landscape types with a mean pH of 5.4 (n=4).

Scattered spruce polygons

Scattered spruce polygons occur in isolated patches on proglacial outwash plains, and are named for the presence of ice-wedge networks, 5-40 m in diameter (Figure 5, Figure 13b). They are characterized by slightly cryoturbated soils (Figure 13a), relatively high soil-moisture (28%), and organic horizons ~3 cm thick (Figure 13a). We did not find permafrost within 1.5m of the ground surface either in the soil pit or in the surrounding area. In terms of classification, this suggests that these soils are not gelisols, though they may have been in the past. Soils are sandy loams, with sand accounting for 55-92% of mineral material. Most of the soil profile has sand percentages in the 60-70% range, increasing with depth to 92% in the C horizon. Silt accounts for 5-28% near the surface, but decreases with depth. Clay content ranges from 5-25%, also decreasing with depth. Of the landscape types we sampled, polygons had the highest pH at 6.1 (n=1). Gravels up to 6 cm in diameter occur below a depth of 11 cm. Two tephras, probably the Katmai and Lethe Ashes, are present in the soil profile we described in this vegetation-landscape association.

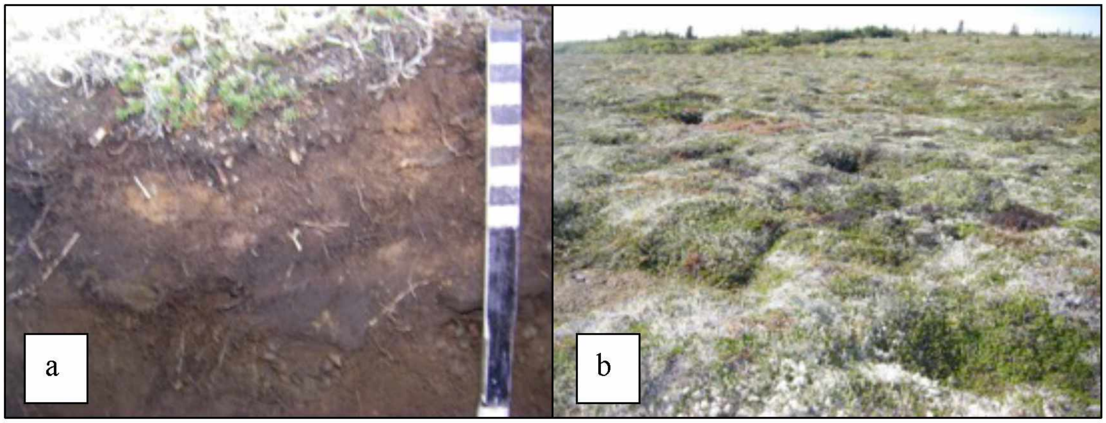

Figure 13 Landscape and soils characteristic of *scattered spruce polygons.* (a) soil pit dug across a low crack between adjacent high-centered polygons. (b) vegetation characteristic of *scattered spruce polygon* association. Figure 5 shows aerial view of polygonal networks.

3.1.2 Forest Community Composition and Structure

Open dwarf basins

Forest vegetation in *open dwarf basins* is Open Spruce Dwarf Tree Scrub and is characterized by a mixture of *Picea glauca* and *Betula kenaica*, the latter accounting for less than 10% of the canopy cover (Viereck et al., 1992). Vegetation is sparse overall, and trees are dwarfed, with few surpassing 3 m in height (Figure 14a). Both spruce and birch are sparsely distributed (0-1 stems/m^2), and they are co-dominant, with *P. glauca* averaging 2.7 cm diameter at breast height with a mean height of 1.8 m and *B. kenaica* averaging 2 cm diameter at breast height with a mean height of 2.5 m. No stumps or dead trees were found at any of the open dwarf basin sites. All trees are relatively young, ranging from 14 to 63 years old. The mean age of the 17 *P. glauca* cored for this study is 43 years, while the mean age for *Betula sp.* is 33 years. Understory vegetation cover is comprised of *Empetrum nigrum* (50%), *Polstrus* moss in 10-40cm diameter clumps (15%), and lichens, predominately *Stereocaulon sp.* and *Cladina sp.* (5%) (Figure 14b).

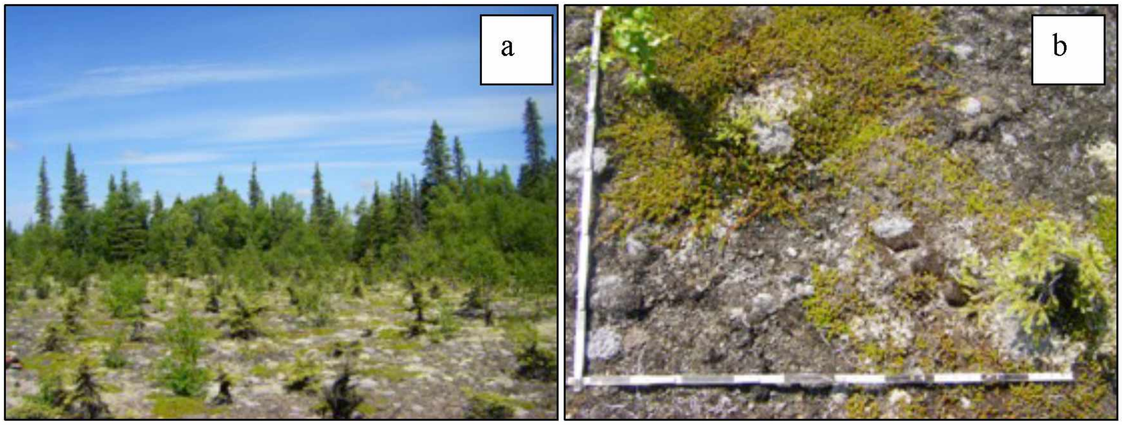

Figure 14 *Open dwarf basin* vegetation communities. a. Stand is comprised of low-density and low-stature mixed *P. glauca* and *B. kenaica*. b. Understory composition in 1m^2 frame characterized by mosses, lichens, *E. nigrum*, and bare soil.

Open forest flats

Open forest flats contain Open White Spruce Forest where *Picea glauca* accounts for 40-60% of canopy cover (Viereck et al., 1992). *Betula kenaica* is absent from all *open forest flats* sites. Spruce occur in three distinct size classes; small (<2 m) medium (2 m – 6 m) and tall (6-10 m) with a mean height of 4 m. Stems are spatially distributed singly or in clusters, with an average of 0-3 stems/m^2(Figure 15a). Spruce trees have a mean diameter at breast height of 8 cm and range in age from 34 to 173, with a mean stand age of 101 years. Understory vegetation is hummocky and dominated by *E. nigrum* (30%), *Ledum decumbens* (20%), lichens, predominately *Stereocaulon sp.* and *Cladina sp.* (20%), feathermosses (10%), and *Vaccinium vitis-idaea* (5%) (Figure 15b). Rare plants of *Equisetum sp.*, *Arctostaphylos uva-ursi,* and *Salix sp.* are present in most *open forest flats* sites. *Salix sp.*, when present, grows around the base of *P. glauca*, and are typically <50 cm tall and occur with a stem density of 0-2 stems/m^2.

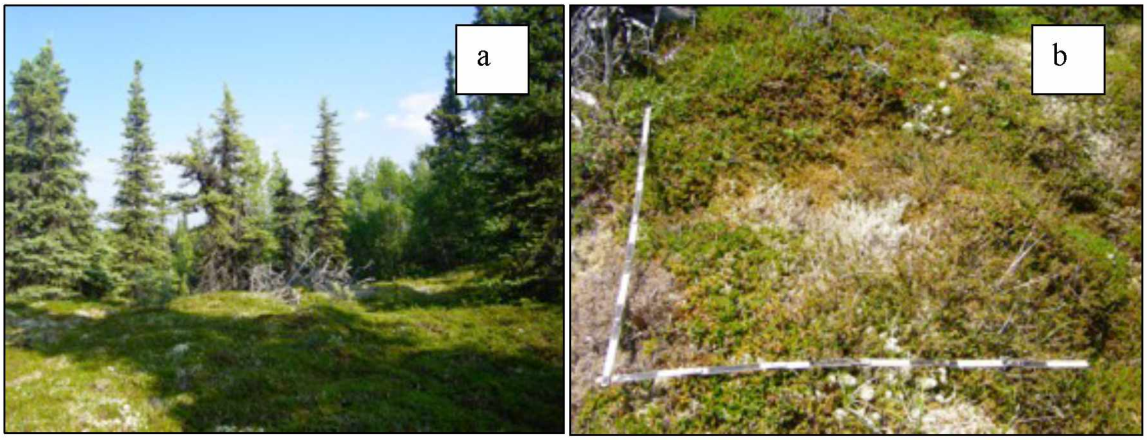

Figure 15 ***Open forest flat*** **vegetation communities.** a. Stand is characterized by low-density *P. glauca*. b. Understory is hummocky with *E. nigrum, L. decumbens,* and lichen species dominating.

Closed forest hillslopes

Closed forest hillslopes are Closed Spruce-Paper Birch Forests, typical of Interior Alaska's boreal forest (Viereck et al., 1992). They have a canopy cover of nearly 100% shared between two co-dominant species, *Picea glauca and Betula kenaica*, each accounting for 40-60% of the canopy (Figure 16a). Mean diameter at breast height of *P. glauca* is 7 cm and 8 cm for *B. kenaica.* Mean height is 5.5 m for *P. glauca* and 5 m for *B. kenaica,* with 0-2 stems of either co-dominant species per m^2. White spruce growing in closed forest hillslope sites range in age from 15 to 168 with a mean age of 64 years old. At two of my sites, Closed Spruce (CS) and KB Backslope (BS), white spruce average 84 and 93 years respectively; while at the other two sites, Naknek Moraine (NM) and Bonfire Pit (BP) they are much younger, 43 and 35 years respectively. Birch at both CS and BS averaged 51 years. Birch was not cored at NM or BP, although it was present, so it is unclear if birch is younger at these two sites compared to CS and BS. Understory composition in *closed forest hillslope* sites is comprised of *E. nigrum* (60%), *V. vitis-idaea* (20%), *A. uva-ursi* (10%), *Equisetum sp.* (5%), and *Vaccinium uliginosum* (5%) (Figure 16b). Rare species include mosses, lichens, leaf litter, *Betula nana* (<30cm tall), *Salix sp.* (20-70 cm tall), and *Epilobium angustifolium.*

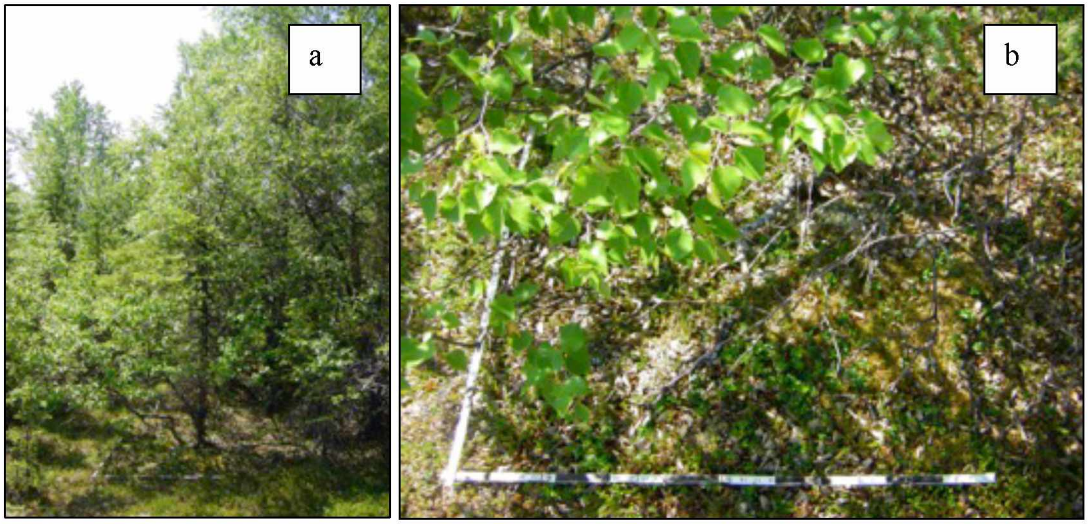

Figure 16 ***Closed forest hillslope*** **vegetation communities.** a. Stands are closed canopy mixed *P. glauca* and *B. kenaica*. b. Understory is predominately *E. nigrum* with shrub *B. nana* and *Salix sp.* present.

Scattered spruce polygons

Scattered spruce polygons are mostly treeless, with a few scattered *P. glauca* growing in the cracks between ice-wedge polygons (Figure 17a). *Betula kenaica* is not present. Spruce here range in height from 0.7m to 2.5 m and average 1.8 m tall and 1.6 cm diameter at breast height. Maximum density of white spruce stems is 1 stem/m^2. Trees in the scattered spruce polygons are young, ranging in age from 15 to 67 and averaging 33 years old. We noted presence and absence of understory species but did not make detailed observations on percent cover, therefore we are unable to classify the vegetation type according to the Alaska Vegetation Classification system (Viereck et al., 1992). That said, s*cattered spruce polygons* can likely be categorized as either White Spruce Dwarf Tree Woodlands, as canopy cover is less than 10%, or Open Low Willow-Birch Shrub. *Salix sp.* and *Betula nana* are present as low shrubs, along with *E. nigrum, V. uliginosum,* and lichens (Figure 17b).

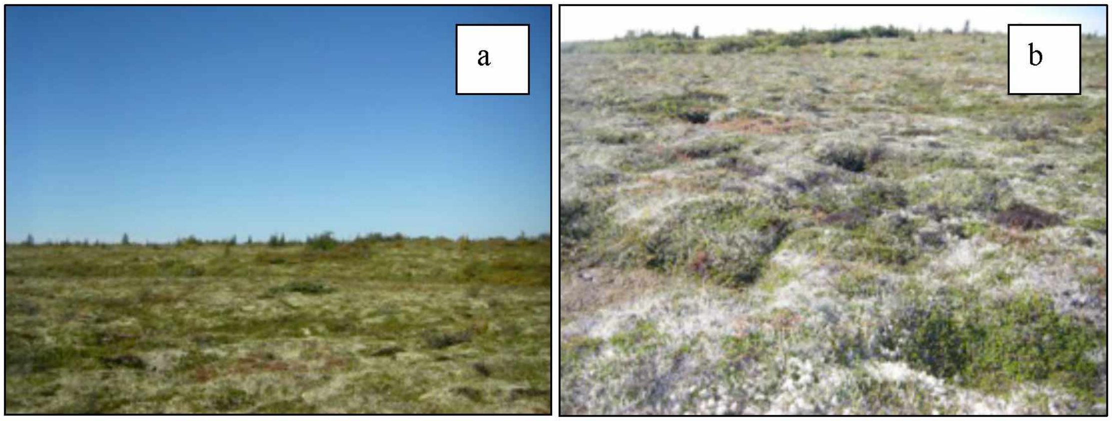

Figure 17 ***Scattered spruce polygon*** **vegetation communities.** a. Spruce are scarce on the landscape, scattered mostly in the cracks between high-centered polygons and near the transition with denser forest. b. Understory is lichen dominated with *Salix sp., B. nana, E. nigrum,* and *V. uliginosum.*

3.2 Tree-Ring Chronologies and First Year of Growth

3.2.1 Timing of Forest Establishment

The oldest *P. glauca* trees in the study sites originated in or before the A.D. 1820s, but most trees appear to have germinated in the past century (Figure 18). *P. glauca* growing in *open forest flats* show the earliest dates of first year of growth, with the number of trees with FYOG increasing to a peak between A.D. 1900 and 1909, and then declining since then. No trees in the *open forest flats* had FYOG dates after 1980, but germination is probably ongoing because scattered saplings were present. Establishment of *P. glauca* in *closed forest hillslope* sites began by the A.D. 1840s or earlier, and gradually increased until 1920-1929. The apparent tree establishment rate then declined for several decades until increasing again between 1940 and 1949. After that the rate of establishment declined until another peak between 1960 and 1979. None of the *P. glauca* samples from the *open dwarf basins* or *scattered spruce polygon* sites contained FYOG dates prior to the 1940s. *Open dwarf basins* show an increase in successful tree establishment that peaked in the 1960s and decreased through 2009 (Figure 18). One tree in the *scattered spruce polygon* site germinated in or before the 1940s, but no other *scattered spruce polygon* trees became established until some time before the 1970s, with most of the population having FYOG between 1970 and 1989. Seedlings were present in all vegetation-landscape associations, suggesting germination in all sites is ongoing. Vegetation-landscape associations are spatially mixed on the landscape, with none consistently situated further west toward the final limit of white spruce extent than the others, suggesting that timing of germination relates to timing of landscape favorability within a large moving front.

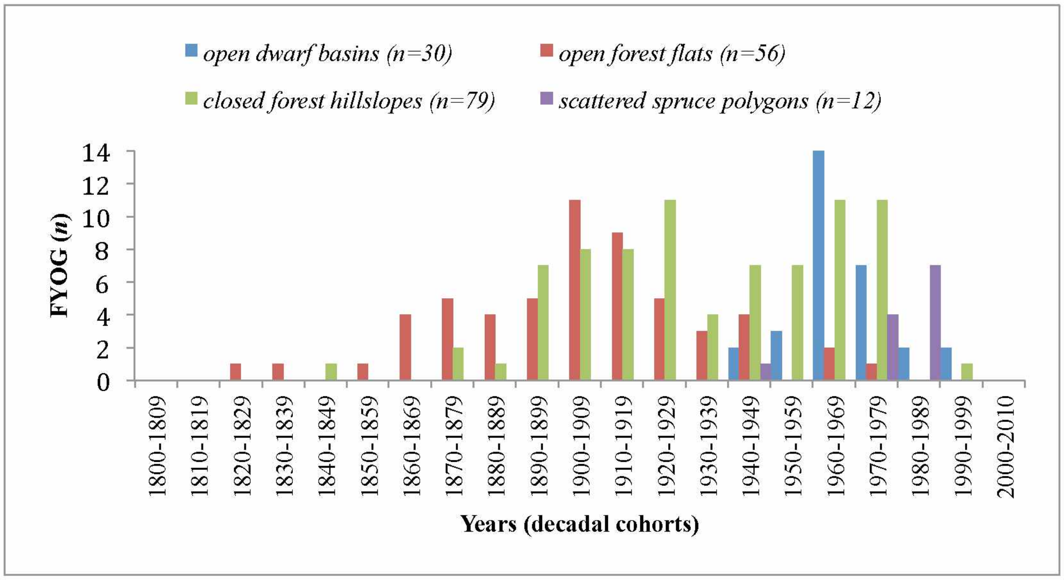

Figure 18 White spruce FYOG (*n*) in decadal cohorts (years).

3.2.2 Radial Growth Patterns of *P. glauca*

The mean radial growth rate of all measurable white spruce prior to detrending was 0.76 mm per year between 1845 and 2007 (n=148). Mean raw radial growth for the period where instrumental weather data is available (1917-2009) was 0.99 mm per year (n = 148) and varied over time from a minimum of 0.66 mm in 1975 to a maximum of 1.77 mm in 2007 (Figure 19, Figure 20). Following detrending, relative growth in the study area has been mostly constant throughout the period of record ($r^2 = 0.038$ for years 1917-2008) and positive throughout the common period of record ($r^2 = 0.501$ for years 1950-2008), with a few notable periods of elevated and decreased growth (Figure 20). Most prominently, a period of markedly increased growth occurs in the mean growth response of all vegetation-landscape associations after the year A.D. 2000. Overall, even when divided by vegetation-landscape association, the growth pattern of white spruce shows an overall positive trend that is particularly pronounced from the mid-1970s to the present, with an especially strong positive surge in all sites after the year 2000 (Figure 20). Following 2007, growth rates declined in all vegetation landscape associations; however, this decline ingrowth may be the result of a decrease in sample size after A.D. 2008.

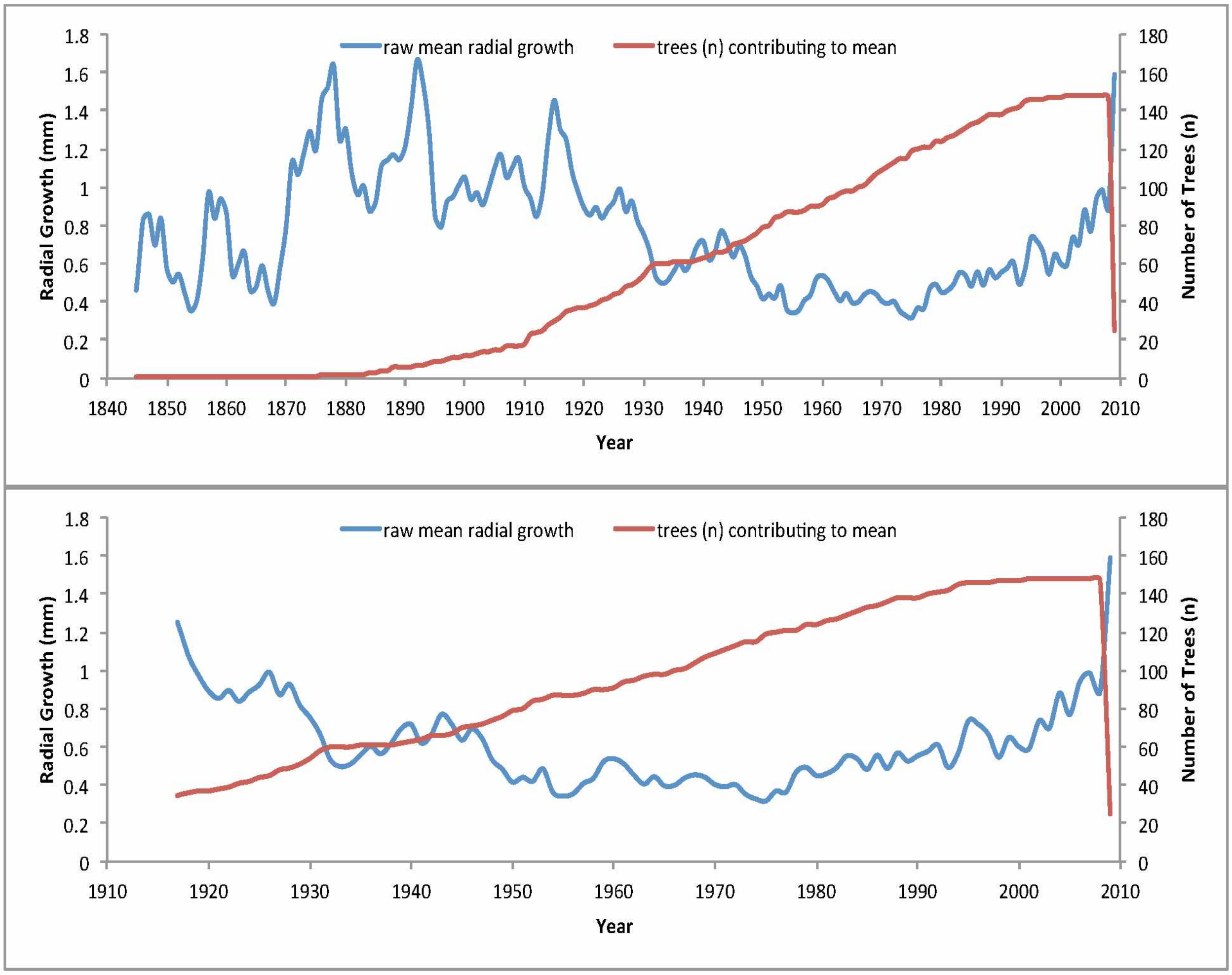

Figure 19 Radial growth rates over time. Blue line indicates raw (uncorrected) mean radial growth for all cores, red line shows number of trees (n) contributing to the mean for entire period of record (top) and for period when instrumental weather data is available (bottom, 1917-2009).

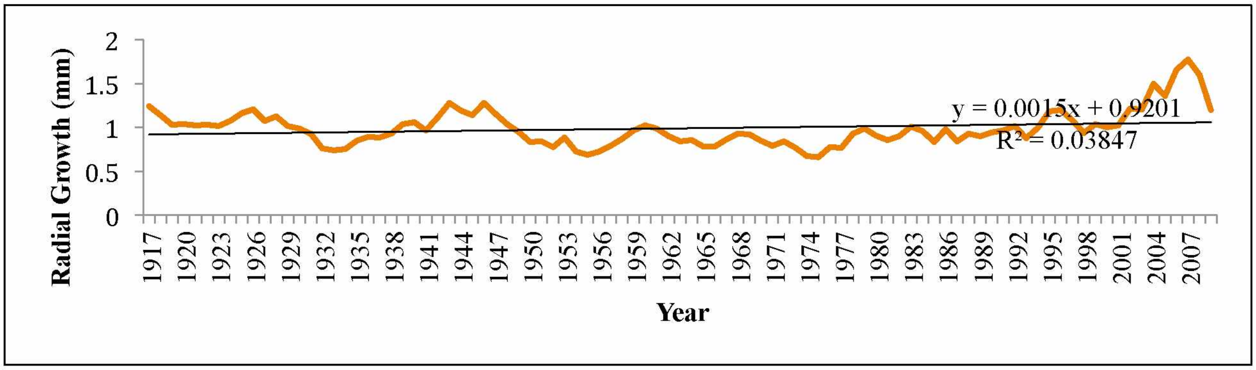

Figure 20 De-trended mean radial growth from 1917-2007 of all white spruce trees.

Open dwarf basins

Of the 17 white spruce in *open dwarf basins,* no FYOG was recorded prior to 1950. The growth trend from 1950-2010 in the *open dwarf basins* is positive, with an R^2 value of 0.205 (Figure 21a). The years of lowest growth are early in the record, in 1950, 1954, 1970, and 1974. Increased growth can be seen in wide ring widths between 2002 and 2006. Other years of high growth include 1956 and 1982.

Open forest flats

White spruce in the *open forest flats* is relatively constant over time, with only a slight positive trend with an R^2 value of 0.052. For the common period of record across all vegetation-landscape associations (1950-2008), the R^2 value is 0.415. The smallest ring widths are recorded in the mid-1930s, 1955, and 1974, with all of the largest ring widths occurring since 1998 (Figure 21b). Increased growth occurred in *open forest flats* post-1998.

Closed forest hillslopes

White spruce in the *closed forest hillslope* sites is constant over time, with a slight positive growth trend with an R^2 value of 0.068 (Figure 21c). For the common period of record across all vegetation-landscape associations (1950-2008), the R^2 value is 0.561. Spikes in growth, either high or low, over the period of record are rare; most wide ring widths occurred since 1995, with the exception of an additional spike in 1943. There are no years with notably small ring widths, and the years of lowest radial growth are 1954 and 1975 (Figure 21c). Similar to growth in *open forest flats*, the radial growth at *closed forest hillslope* associations increased after 1998.

Scattered spruce polygons

Of the eight spruce growing in the *scattered spruce polygon* site, no FYOG was recorded prior to 1944 and all show a positive linear growth trend with an R^2 value of 0.417. For the common period of record across all vegetation-landscape associations (1950-2008), the R^2 value is 0.346. Years with lowest growth are early in the record in 1945, 1956, and the early to mid-1970s. The years with the greatest growth include 1984, 1986, and all years between 2002 and

2006 (Figure 21d). There is a marked increase in radial growth after 2000, as in the other vegetation-landscape associations.

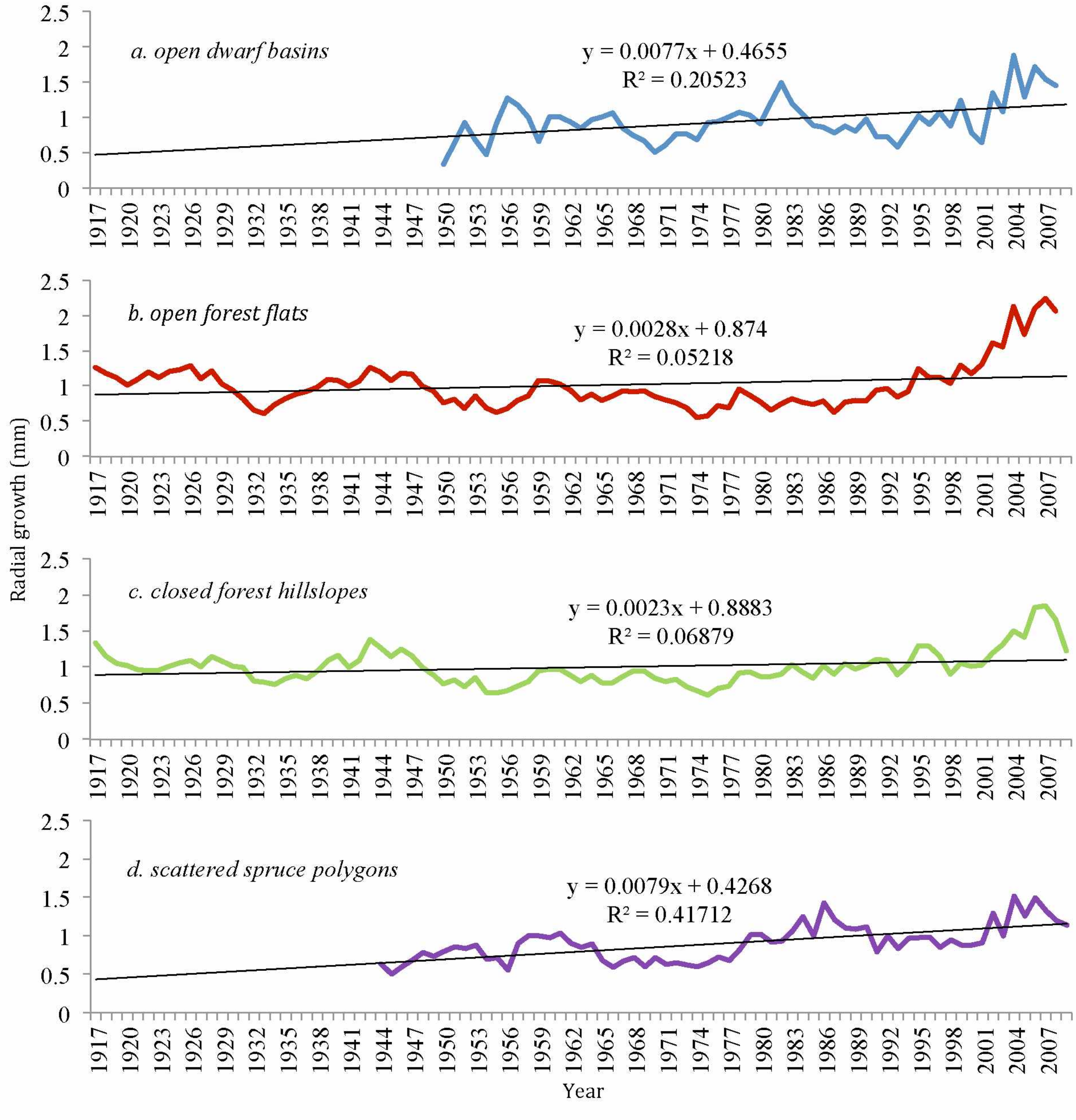

Figure 21 De-trended radial growth and linear growth curves for white spruce growing in different vegetation-landscape associations. a) *open dwarf basins*, b)*open forest flats*, c) *closed forest hillslopes*, and d) *scattered spruce polygons*. In the *open dwarf basin* and *scattered spruce polygon* associations, no spruce contained FYOG dates prior to 1950 and 1944, respectively. Black line is linear growth curve.

3.2.3 Variability in Growth Rates Between Different Vegetation-Landscape Associations

To compare how white spruce growth in different vegetation-landscape associations varied through time, I compared them with the mean growth rate of all trees from all sites (Figure 22). The early period of record (1917-1943) contains only trees growing in *open forest flats* and *closed forest hillslopes*. During this period, growth is congruent among trees growing in both these associations. Growth in either of these two different vegetation-landscape associations did not diverge from the mean growth of all trees until the mid-1940s (Figure 22). Sample sizes vary between vegetation-landscape associations; while growth anomalies are reported here, it is of note that coefficient of variation scores across most of the record are low, suggesting bias in the expression of anomalies when sample size is small.

Trees in *open dwarf basins* first enter the record in 1950 and display *strong negative departures in growth* compared to the mean in 1950, 1959, and 2001 (Figure 23a). *Strong positive anomalies in growth* occurred among trees in open dwarf basins in 1956, 1957, 1966, and after 1981-1982 (Figure 23a).

Growth in *open forest flats* is never *strongly below the mean*, and for most of the period of record, remains within one standard deviation of the mean of all trees growing in all associations (Figure 23b). Only in recent years do trees in *open forest flats* begin to diverge, experiencing *strong positive departures from the mean* in all years between 2001 and 2007 (Figure 23b).

Throughout the period of record, radial growth in *closed forest hillslope* associations was never *strongly above the mean* or *strongly below the mean* but instead remained within one standard deviation of the mean of all trees (Figure 23c).

The establishment of trees in the *scattered spruce polygons* association marked the earliest strong departures from the mean. Trees in the *scattered spruce polygons* displayed *strong negative departures in growth* in 1944-1947 and again in 2005, and 2007-2008 (Figure 23d). Only in 1986 did the trees in the *scattered spruce polygon* association display *strong above mean* growth.

Throughout the period of record, growth at vegetation-landscape associations fell outside of the pooled mean of all trees by <1 standard deviation multiple times; however, divergence was not equally distributed between vegetation-landscape associations (Figure 22). Trees growing in *open dwarf basins* diverged from the mean of all trees eight times between 1950-2009, five times with *strong positive departures* and three times with *strong negative departures* from the mean (Figure 23a). Trees have been growing in the *open forest flats* since 1917, and have yet to have a year in which the growth response is *strongly negative* compared to the mean of all trees. Trees in the *open forest flats* have shown *strong positive growth anomolies* seven times between 1917 and 2009, all occuring since A.D. 2000 (Figure 23b). Trees in *closed forest hillslopes* have not diverged >1 SD from the mean of all trees in any direction over the period of record (1917-2009) (Figure 23c). Spruce in the *scattered spruce polygons,* like *open dwarf basins*, diverged eight times between 1944 and 2009; however, all but one of these years (1986, which displayed *strong positive growth anomoly*) showed a *strong negative response* (Figure 23d).

Overall, variability between vegetation-landscape classes was low, with congruent growth patterns, likely the result of shared environmental restraints dominating over differences in microclimate or edaphic site conditions, occurring for most of the period of record for trees in all vegetation-landscape associations (Figure 22). Coefficient of variation values for anomolous years are relatively low, suggesting that most of the population participated in the departure from the long term mean; however, coefficient of variation scores for *open dwarf basins* in the 1950s are high, suggesting that either not all trees in the sample experienced a similar strongly negative response or, more likely, that the small samples size limits the ability to detect the response with confidence.

Spruce in all vegetation-landscape associations showed a striking increase in radial growth since A.D. 2000. Within this trend of increasing growth, trees in the *open forest flats* show the most *strongly positive* growth trend while trees in the *scattered spruce polygons* are the most *negative* in trend.

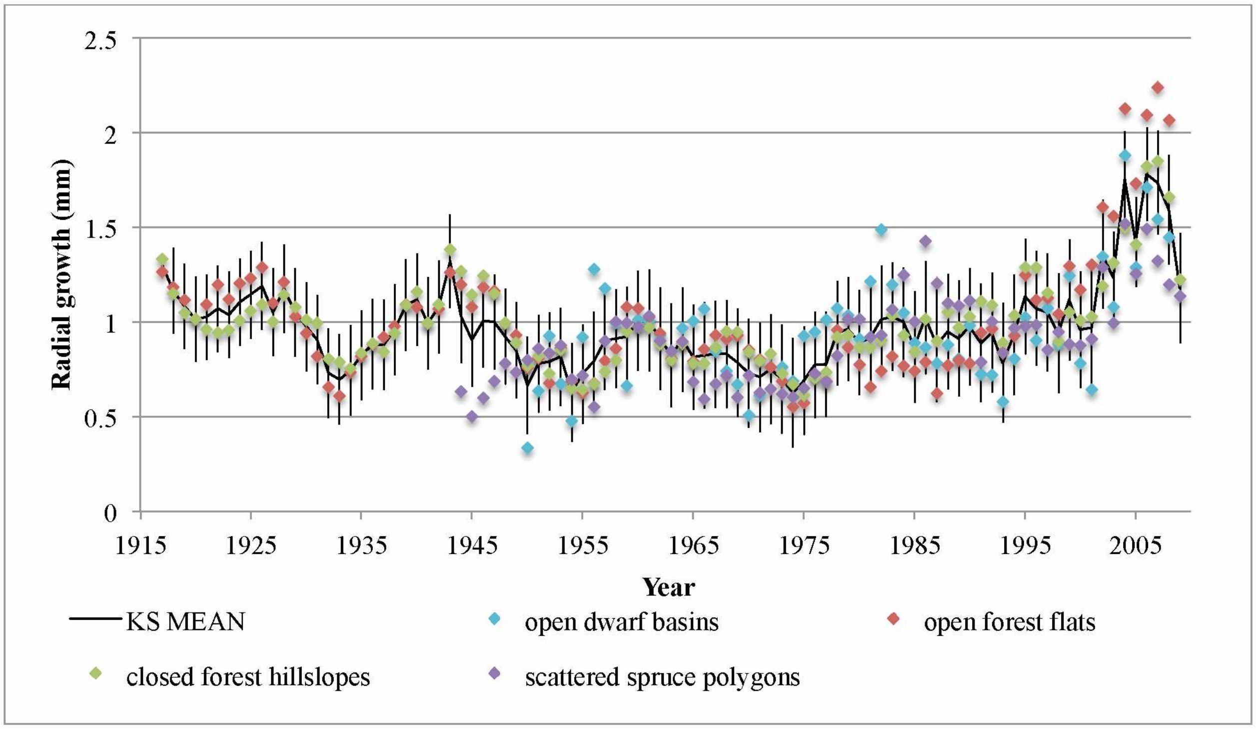

Figure 22 Variability in radial growth at vegetation-landscape associations. Black line is King Salmon mean growth with error bars at one sigma standard deviation.

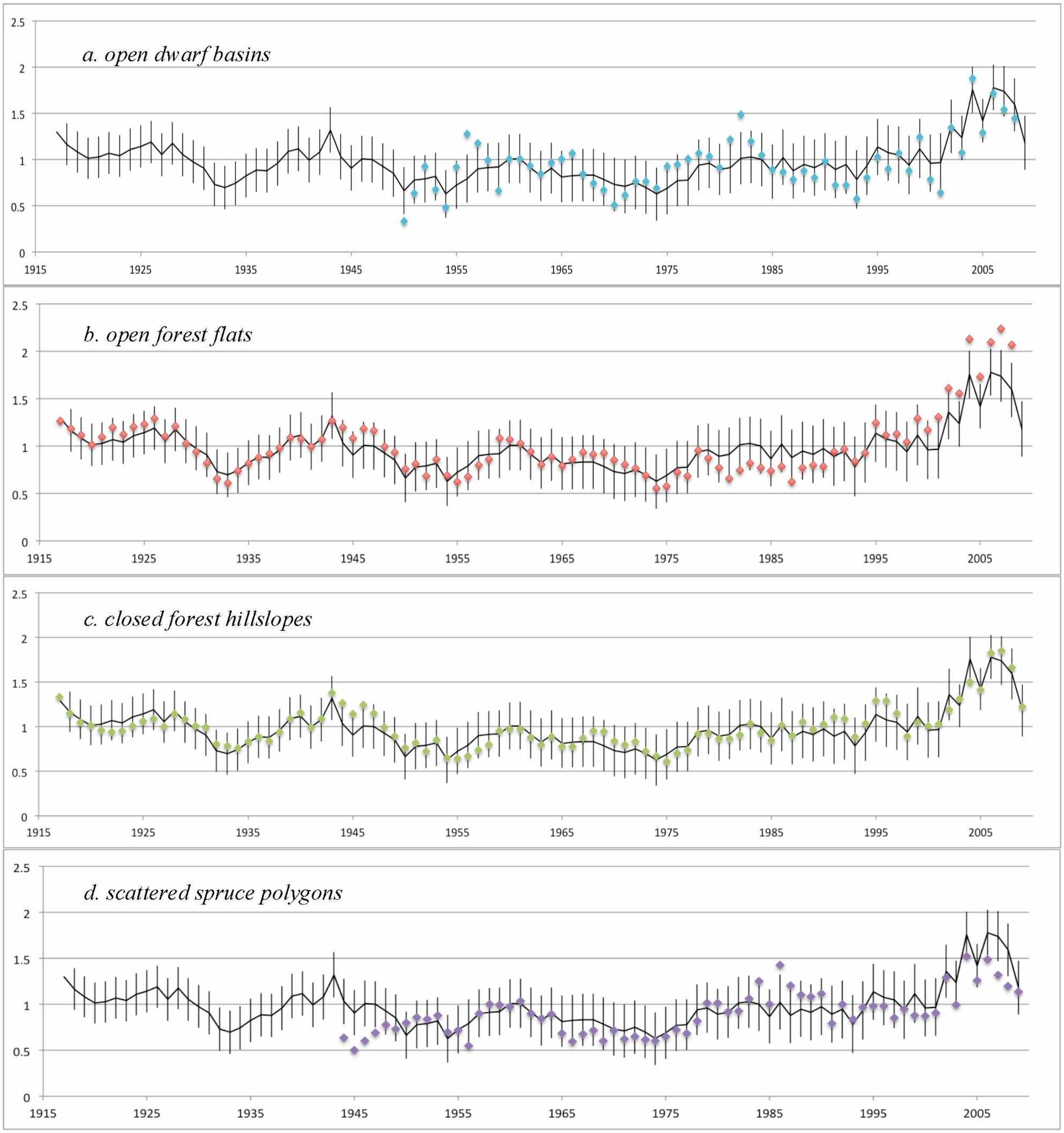

Figure 23 Radial growth and standard deviation of *P. glauca* at vegetation-landscape associations. (a) *open dwarf basins* (b) *open forest flats* (c) *closed forest hillslopes,* and (d) *scattered spruce polygons* compared to mean KS growth and standard deviation (black line and error bars in a-d).

3.3 Climatic Influence on Radial Growth

3.3.1 Forest Patterns and Growth Response to Temperature

Mean radial growth for all sites is broadly positively related to mean annual air temperature and mean July temperature (Figure 24); however, much of the variability in growth response is not explained by temperature, suggesting temperature exerts a dominant but not exclusive control on radial growth.

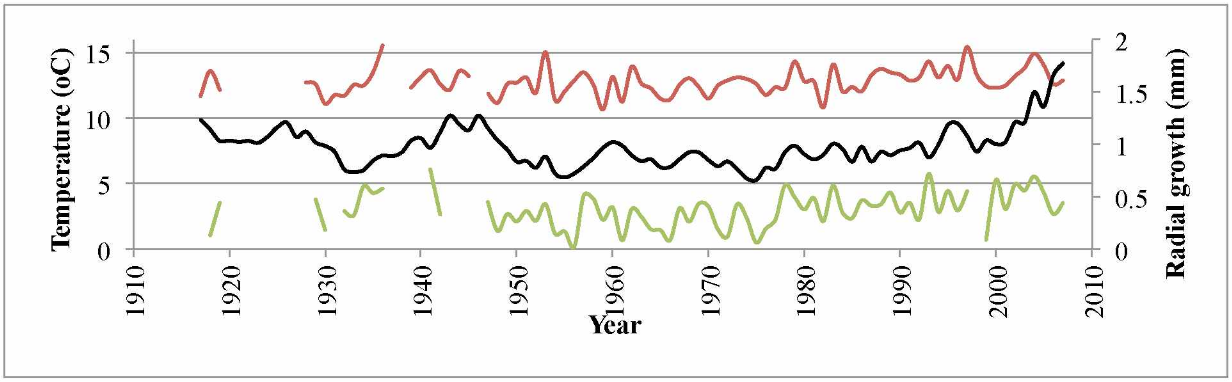

Figure 24 Temperature and mean radial growth. Mean radial growth (black line), MAAT from 1917-2010 at King Salmon (green line), and mean July temperature at King Salmon (red line).

3.3.2 Forest Patterns and Growth Response to Precipitation

Similarly to temperature, mean radial growth for all sites is somewhat positively related to both mean annual precipitation as well as growing season precipitation, suggesting that precipitation does exert some control over growth (Figure 25). This is particularly evident in cases where growth was more rapid in dry summers (i.e., the 1940s, though records indicate these years were warm in many parts of Alaska) and slower during wet summers (i.e., the early to mid-1930s, which were notably cool years throughout the state).

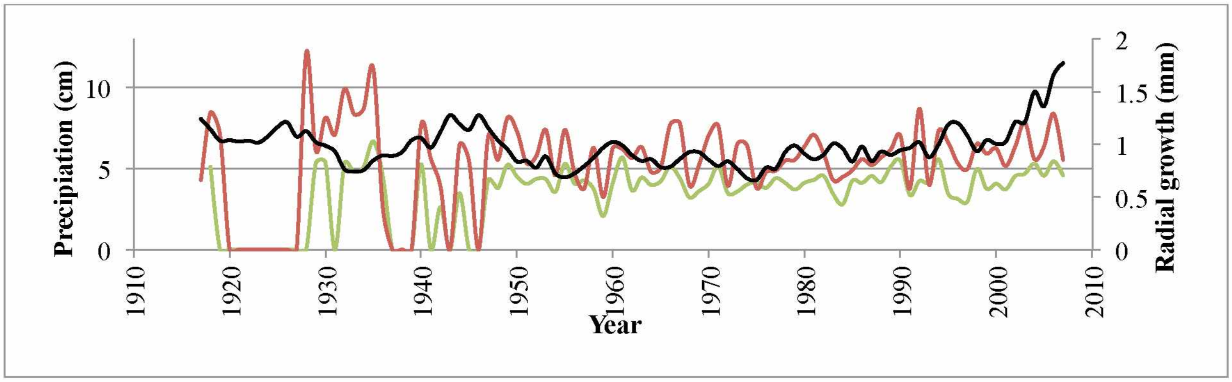

Figure 25 Precipitation and mean radial growth. Mean radial growth (black line), growing season precipitation at King Salmon (red line), and mean annual precipitation at King Salmon (green line).

3.3.3 Correlation Between Radial Growth and Climate Variables

When plotting radial growth against mean July air temperature (MJAT), mean annual air temperature, mean July precipitation (MJP), and mean annual precipitation, positive correlation between radial growth and temperature (both MJAT and MAAT), and negative correlation between precipitation (both MJP and MAP) emerge (Figure 26).

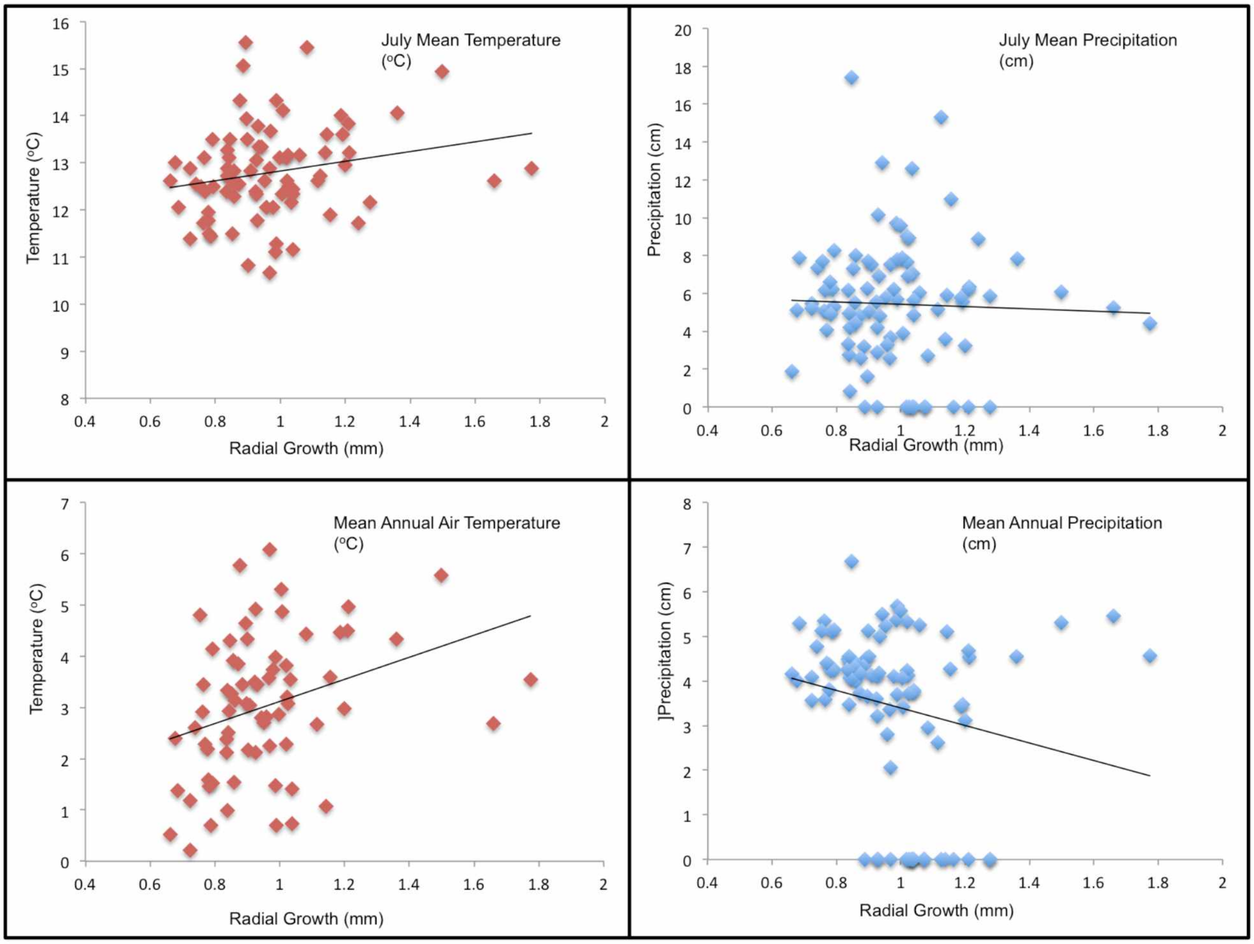

Figure 26 Scatter plots comparing radial growth and climate variables. Radial growth is the mean of all sites and may be influenced by small sample size in early years; however, the do preliminarily suggest relationships between growth and climatic variables, further analyzed below with Dendroclim and Pearson product correlation coefficients.

The results of my analysis using Dendroclim show that the radial growth of white spruce trees near King Salmon is positively correlated with growing season temperature (June-August) in the year of growth as well as with growing season temperature one year prior (Figure 27). The RWI is negatively correlated with March precipitation both in the year of growth and the year prior to growth. When separated into vegetation-landscape associations, there are some differences in correlation between temperature and precipitation and ring-width indexes (Figure 27). In all vegetation-landscape associations, some aspect of growing season temperature is positively correlated with growth. Thus trees growing in *open forest flats* and *closed forest hillslopes* were positively correlated to growing season temperature (June-August), trees in *open dwarf basins* responded positively to June temperature, and trees in *scattered spruce polygons* respond positively to extended growing season temperature (May-August) in the year prior to growth and early growing season (April-July) in the year of growth. In addition to growing season temperature, spruce growth in *open forest flats* and *closed forest hillslope* associations respond positively to late winter (February) temperature in the year of growth and year prior, and negatively to March precipitation in both the year of growth and year prior to growth. Spruce growing in *open dwarf basins* are most highly correlated with winter (January-February) temperatures in the year prior to growth and June in the year of growth. In addition to growing season temperatures, trees growing in *scattered spruce polygons* also responded to late winter (January-March) and early winter (December) temperature in the year prior to growth as well as late winter (February) temperature in the year of growth. Additionally, trees growing in *scattered spruce polygons* are negatively correlated with March precipitation in the year prior and February-March precipitation in the year of growth (Figure 28).

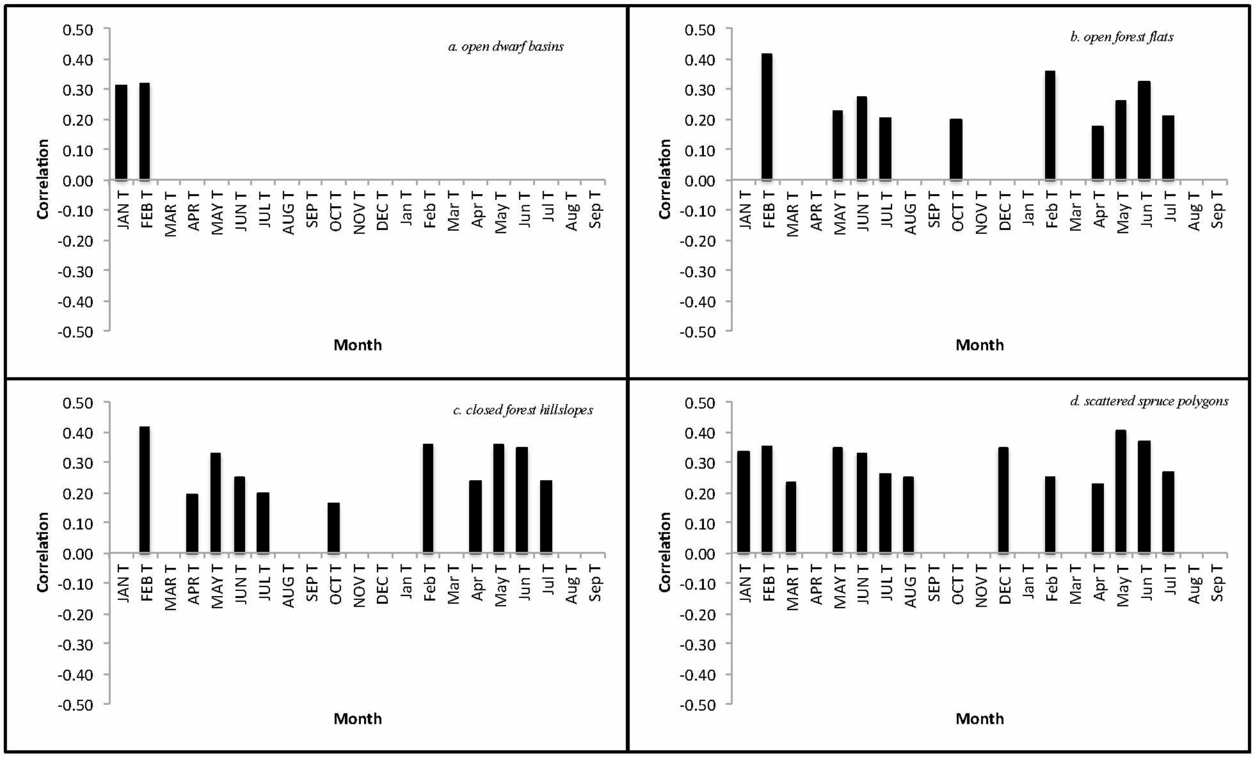

Figure 27 Correlation (α = 0.05) between growth and monthly temperature in the year of growth and the year prior to growth. Months in the year of growth appear in lower case letters while those in the year prior are in upper case letters. a. *open dwarf basins,* b. *open forest flats,* c. *closed forest hillslopes,* and d. *scattered spruce polygons.*

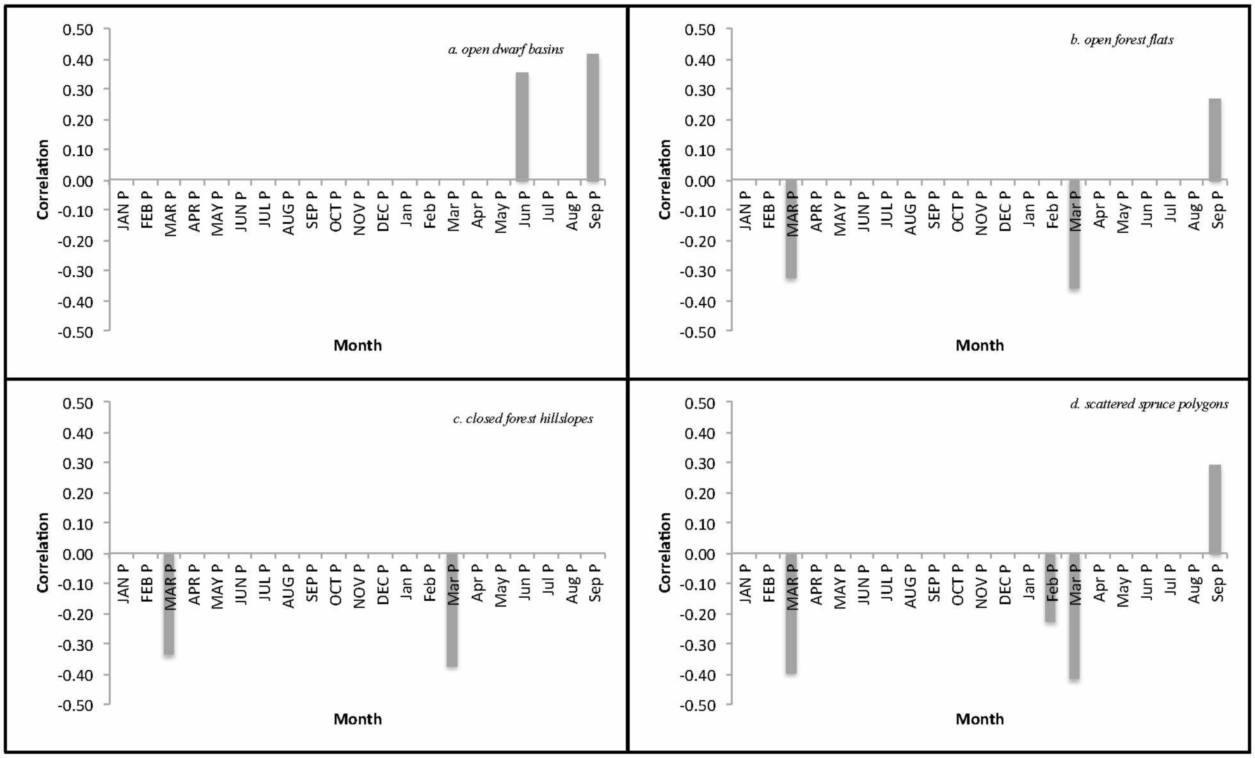

Figure 28 Correlation (α = 0.05) between growth and monthly precipitation in the year of growth and year prior to growth. Months in the year of growth appear in lower case letters while those in the year prior are in upper case letters. a. *open dwarf basins,* b. *open forest flats,* c. *closed forest hillslopes,* and d. *scattered spruce polygons.*

Pearson product correlation coefficients that test correlations between ring width and temperature and precipitation yield a similar result as the Dendroclim results. Dendroclim data is limited to the year of growth and the year prior to growth. Using Pearson product correlation in Excel, I assessed correlation with climate records two years prior to growth. Many temperature variables throughout the year of growth, year prior to growth, and two years prior to growth are significant to radial growth at all four vegetation-landscape associations as well as the mean (Table 5, Table 7). As seen in the Dendroclim results, growing season temperature in the year of growth, year prior to growth, and two years prior to growth is positively correlated with radial growth in all vegetation-landscape associations, although the strength is much less in *open dwarf basins* than in the other associations. Additionally, these results show strong correlation between February temperature in the year of, year prior, and two years prior to growth across all vegetation landscape associations (Table 5). When radial growth is compared with the Flood Plain Temperature Index (FPTI) (Juday et al., 2015) where $\mathrm{FPTI} = (\mathrm{MMT}_{\mathrm{May}} + \mathrm{MMT}_{\mathrm{Mar\text{-}1}} + \mathrm{MMT}_{\mathrm{Apr\text{-}2}} + \mathrm{MMT}_{\mathrm{Feb\text{-}2}})/4$, developed to best predict growth in negative responders along flood plain sites in Interior Alaska, positive correlation is strong across all vegetation-landscape classes, most strongly and best correlated in *closed forest hillslopes* (Table 6).

Table 5 Pearson Product Correlation Coefficients of Radial Growth and Temperature. Bold numbers indicate significance (p >0.05). Red numbers highlight the five temperature variables most strongly correlated with radial growth for each vegetation-landscape association.

	Temperature in the Year of Growth											
	Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan
King Salmon mean	NA	NA	NA	NA	**0.20**	**0.31**	**0.42**	**0.44**	**0.32**	-0.05	**0.36**	**0.06**
open dwarf basins	NA	NA	NA	NA	**0.12**	**0.16**	**0.10**	**0.15**	**0.05**	-0.05	**0.18**	**0.16**
open forest flats	NA	NA	NA	NA	**0.17**	**0.20**	**0.32**	**0.26**	**0.17**	**-0.12**	**0.35**	0.03
closed forest hillslopes	NA	NA	NA	NA	**0.10**	**0.21**	**0.34**	**0.34**	**0.23**	-0.05	**0.35**	**0.07**
scattered spruce polygons	NA	NA	NA	NA	**0.17**	**0.25**	**0.36**	**0.40**	**0.22**	**0.17**	**0.21**	**0.17**
	Temperature in the Year Prior to Growth											
	Dec-1	Nov-1	Oct-1	Sep-1	Aug-1	Jul-1	Jun-1	May-1	Apr-1	Mar-1	Feb-1	Jan-1
King Salmon mean	**0.20**	0.01	**0.26**	**0.16**	**0.24**	**0.24**	**0.33**	**0.35**	**0.27**	0.01	**0.45**	**0.19**
open dwarf basins	**-0.11**	**-0.07**	**0.10**	**0.12**	**0.15**	**0.07**	0.02	**0.16**	**0.07**	0.03	**0.33**	**0.28**
open forest flats	**0.06**	0.05	**0.19**	**0.09**	**0.20**	**0.20**	**0.25**	**0.21**	**0.16**	-0.02	**0.39**	**0.11**
closed forest hillslopes	**0.15**	-0.03	**0.17**	**0.12**	**0.17**	**0.19**	**0.23**	**0.31**	**0.21**	0.05	**0.40**	**0.19**
scattered spruce polygons	**0.35**	0.02	**0.16**	**0.17**	**0.27**	**0.26**	**0.31**	**0.34**	**0.19**	**0.17**	**0.35**	**0.32**
	Temperature 2 Years Prior to Growth											
	Dec-2	Nov-2	Oct-2	Sep-2	Aug-2	Jul-2	Jun-2	May-2	Apr-2	Mar-2	Feb-2	Jan-2
King Salmon mean	**0.23**	0.04	**0.28**	**0.12**	**0.31**	**0.29**	**0.43**	**0.42**	**0.31**	**0.14**	**0.44**	**0.18**
open dwarf basins	**0.11**	0.05	**0.31**	**0.13**	**0.15**	**0.24**	**0.22**	**0.32**	**0.14**	**0.13**	**0.31**	**0.14**
open forest flats	**0.12**	**0.10**	**0.27**	**0.12**	**0.26**	**0.27**	**0.34**	**0.29**	**0.21**	**0.13**	**0.41**	**0.06**
closed forest hillslopes	**0.22**	**0.07**	**0.24**	**0.16**	**0.28**	**0.32**	**0.35**	**0.35**	**0.26**	**0.13**	**0.44**	**0.19**
scattered spruce polygons	**0.38**	**0.14**	**0.14**	-0.04	**0.25**	**0.18**	**0.28**	**0.34**	**0.15**	**0.27**	**0.24**	**0.35**

Table 6 Correlation between growth and Flood Plain Temperature Index. (p > 0.05)

	FPTI
KS Mean	0.39
Open dwarf basins	0.25
Open forest flats	0.33
Closed forest hillslopes	0.43
Scattered spruce polygons	0.29

Correlation between precipitation variables and radial growth using Pearson Product Correlation are similar to the results from Dendroclim, with the added variables of monthly precipitation two years prior to growth (Table 8). Growth is most strongly negatively correlated with March precipitation in the year of, year prior to, and two years prior to growth. Additionally, September precipitation one and two years prior to growth is positively correlated with growth. Growing season precipitation is positively correlated with growth at all sites; however, the strength of the correlation is slight compared to correlation with other variables such as growing season temperature and March precipitation (Table 7). While all vegetation-landscape associations display a negative correlation with March precipitation in the year of and both years prior to growth, the strength of the correlation is lower in *open dwarf basins* then in other vegetation-landscape associations.

Table 7 Pearson Product Correlation Coefficients of Radial Growth and Precipitation. Bold numbers indicate significance (α >0.05). Red (positively correlated) and blue (negatively correlated) numbers highlight the five precipitation variables most strongly correlated with radial growth for each vegetation-landscape association.

	Precipitation in the Year of Growth											
	Dec	Nov	Oct	Sep	Aug	Jul	Jun	May	Apr	Mar	Feb	Jan
King Salmon mean	NA	NA	NA	NA	-0.02	**0.08**	**0.19**	-0.03	0.04	**-0.41**	**-0.22**	**-0.14**
open dwarf basins	NA	NA	NA	NA	**-0.11**	0.01	**0.20**	**0.07**	**0.09**	**-0.14**	**-0.09**	**0.10**
open forest flats	NA	NA	NA	NA	-0.03	**0.08**	0.05	-0.04	-0.02	**-0.35**	**-0.08**	**-0.13**
closed spruce hillslopes	NA	NA	NA	NA	-0.01	**0.09**	0.03	-0.04	-0.04	**-0.36**	-0.03	**-0.18**
scattered spruce polygons	NA	NA	NA	NA	**-0.12**	**0.11**	**0.12**	**0.13**	**0.09**	**-0.40**	**-0.23**	**0.17**
	Precipitation in the Year Prior to Growth											
	Dec-1	Nov-1	Oct-1	Sep-1	Aug-1	Jul-1	Jun-1	May-1	Apr-1	Mar-1	Feb-1	Jan-1
King Salmon mean	0.04	**0.07**	**0.25**	**0.30**	0.04	**0.14**	**0.16**	**0.15**	**0.09**	**-0.38**	**-0.10**	**-0.10**
open dwarf basins	**-0.13**	0.05	**0.17**	**0.26**	**-0.09**	**0.07**	**0.10**	**0.20**	**0.15**	**-0.19**	**0.17**	-0.02
open forest flats	-0.05	0.02	**0.17**	**0.21**	-0.02	**0.06**	**0.07**	**0.11**	**0.08**	**-0.32**	0.00	**-0.08**
closed spruce hillslopes	0.02	0.03	**0.16**	**0.23**	-0.05	**0.11**	**0.06**	**0.11**	**0.07**	**-0.33**	-0.02	**-0.07**
scattered spruce polygons	0.00	**0.22**	**0.25**	**0.19**	**0.19**	0.03	**0.08**	**0.18**	**0.09**	**-0.37**	**-0.24**	0.03
	Precipitaiton 2 Years Prior to Growth											
	Dec-2	Nov-2	Oct-2	Sep-2	Aug-2	Jul-2	Jun-2	May-2	Apr-2	Mar-2	Feb-2	Jan-2
King Salmon mean	**0.06**	**0.14**	**0.18**	**0.33**	0.04	**0.24**	**0.07**	**0.13**	0.00	**-0.34**	-0.03	**-0.06**
open dwarf basins	**-0.17**	**-0.07**	0.04	**0.24**	-0.03	**0.14**	**0.12**	**0.08**	**0.12**	**-0.23**	0.05	0.02
open forest flats	**-0.07**	0.05	**0.12**	**0.21**	-0.03	**0.07**	0.01	**0.11**	0.02	**-0.30**	0.00	-0.02
closed spruce hillslopes	0.02	**0.15**	**0.09**	**0.24**	**-0.09**	**0.09**	0.03	**0.16**	0.00	**-0.32**	0.03	-0.04
scattered spruce polygons	**0.06**	**0.21**	**0.16**	**0.24**	**-0.14**	0.05	**0.18**	**0.18**	**-0.06**	**-0.31**	**-0.24**	**0.17**

4.0 Discussion

4.1 Variability in Timing of Forest Establishment and Expansion

White spruce establishment in the King Salmon lowlands began around A.D. 1800 but its timing varied widely between different landscape positions. The oldest spruce found in the study area dates to the 1820s and is found in the *open forest flats* association. Logs and dead trees are rare in the study area; it is possible that there was an earlier scattered generation of scattered individual trees, but that forest development is more recent. Trees probably established first on well-drained substrates including hummocky flats and stabilized sand dunes (Figure 18). Peaks in establishment rates in the *closed forest hillslopes* during or just before the 1930s and the onset of establishment of the *scattered spruce polygons* in the 1940s could be related to the relatively warm temperatures experienced statewide in the late 1930s, which was then followed by a relatively cool period statewide in the late 1940s. Establishment was delayed by more than a century in dune blow-out basins and outwash gravels, perhaps because sandy soils and low organic matter content were unfavorable for spruce establishment and early survival. Fluctuating water tables in *open dwarf basins* would have created ice-rich environments and microsites that were too wet during after cold winters for seeds to germinate and seedlings to survive post-germination. White spruce did not become established in the *scattered spruce polygon* association until the 1944. High soil moisture content in *scattered spruce polygons* is likely to have impeded establishment. These sites, notable for the presence of ice-wedge polygon casts, relatively thick organic mats and high soil moisture, were probably unfavorable for spruce establishment. These sites may have experienced permafrost thaw in the warm peak of the 1940s, or experienced adequate viable seedfall for the first time after the same warm interval. As temperature and evaporation has increased over the past century, soil moisture has probably decreased, and permafrost may have disappeared, allowing spruce to establish. As temperatures have warmed over the past century (Figure 21), particularly winter temperatures, all four vegetation-landscape associations in this study have become habitable by white spruce. Currently, floodplains and thaw lake uplands remain suboptimal for white spruce establishment.

4.2 Variability and Congruency in Radial Growth

Following establishment, radial growth of white spruce in King Salmon remained within a relatively narrow range, with some variation among vegetation-landscape associations, until

A.D. 2000-2006. At that time, trees in all vegetation-landscape associations experienced a rapid increase in growth, followed by a decrease in radial growth post-A.D. 2006, though the apparent decrease is partly due to a drop in sample size (Figure 22, Figure 23). While there is some divergence in the record between trees growing at different vegetation-landscape associations, trends in growth have been largely congruent between associations, suggesting a common environmental or climatic control, with the exception of divergence in the white spruce growing in *open dwarf basins*. Growing season temperature is a significant limiting factor for white spruce growth at all vegetation-landscape associations in the year of, year prior to, and two years prior to growth, except for trees growing in *open dwarf basins,* which positively respond primarily to June precipitation in the year of growth and winter temperature in the year prior to growth (Figure 27, Figure 28, Table 6, Table 8).

The trees growing in *open dwarf basins* are unique in their growth form and in their growth response to climate, and they represent only a small subset of the forested landscape of SWAK. It may be that the fluctuating water table in the *open dwarf basins* is too deep in the summer for water to be available at root level, and that early summer rain might provide needed water in the most well-drained of our sites. The other three vegetation-landscape associations do not show a positive correlation of white spruce radial growth with summer precipitation, possibly as a result of higher soil moisture content, and therefore more water available at the root level.

Trees growing in *open forest flats, closed forest hillslopes,* and *scattered spruce polygons* show a negative correlation with March precipitation in the year of and the year prior to growth. The mechanism resulting in this relationship remains unclear, but it is of note that the driest site, *open dwarf basins,* does not show the same response. It is possible that heavy late winter precipitation (though it is not recorded in the existing climate records whether the precipitation fell as snow or rain) saturates soils and negatively impacts growth in that year and the following year or, if it falls as snow, retards spring thaw and thus shortens the growing season. Alternatively, the observed negative response to March precipitation may be a negative response to a climatic factor correlated with March precipitation, such as warm temperatures during March storms. White spruce growth at *open forest flats, closed forest hillslopes,* and *scattered spruce polygon* sites is also positively correlated with February temperature. Warm February temperatures may lessen the maximum depth of freeze (usually at its maximum in February), allowing for a quicker thaw and earlier onset of the growing season, which then may contribute positively to growth. Further research is needed to assess this mechanism; however, while growth in *open dwarf basins* is interesting, it comprises a small geographic area, constrained on all sides by *closed forest hillslopes*. Therefore, increasing germination of white spruce in *open dwarf basins* is likely to be through infilling rather than outward expansion.

4.3 Recent Unidirectional Growth Across All Vegetation-Landscape Associations

Regardless of differences in *vegetation-landscape associations*, all associations show a clear and strong increasing growth signal between A.D. 2000 and 2006 and a decrease in growth from A.D. 2006 through 2009. If temperatures continue to increase, white spruce growth in SWAK appears likely to continue to respond with increased growth across all vegetation-landscape associations, assuming that these fundamental relationships of temperature and growth do not change.

4.4 Testing the Initial Hypothesis

My data indicate that the growth of white spruce and hence the overall position of this longitudinal treeline in SWAK appears to be largely controlled by growing season temperature, like other treeline sites in arctic and alpine environments. This overall climatic control is then modulated at smaller spatial scales by the particular pedologic, microclimatic, and geomorphic setting where individual trees grow. The results of my research indicate that climatic influence of growing season temperature is strong enough to largely negate microsite differences in terms of growth. Unlike treeline sites in Interior Alaska where water stress is important in regulating the growth of white spruce, decreases in effective moisture in SWAK is not likely to negatively impact growth due to the maritime climate and the relatively high, soil moisture content. Therefore, microsite differences in SWAK are likely to continue to be overpowered by influences of growing season temperature in the future.

On the other hand, the important role of climate in the lives of these trees does not extend to the level of seedling establishment. This is evident from the different rates of tree establishment in the different landscape-vegetation associations (Figure 18). Regional climate largely controls growth, but local factors related to soils, microclimate, soil moisture, and permafrost collaborate in determining where forest establishes itself at spatial scales of kilometers and less.

4.5 Projected Changes in Vegetation Under Continued Warming

Temperatures in the King Salmon area are projected to rise between 0.1 °C to 4.5 °C by 2050, even under scenarios of low and/or decreasing emissions (SNAP, 2015c). Winter warming will probably increase more than warming during other months (SNAP, 2015c). Under low or declining emission scenarios, precipitation is projected to maintain current rates or increase by up to 243 mm by A.D. 2050. For medium and high emission scenarios, precipitation is projected to increase an additional 1-243mm by 2050, with the greatest increases in winter and late summer (SNAP, 2015d). This rise in precipitation may prevent white spruce in western Alaska from experiencing the effects of drought-stress reported in Interior Alaska's forests (i.e. Barber et al., 2000, Juday et al., 2015); however, avoidance of temperature-induced drought stress will depend largely on the combined impacts of precipitation and temperature on evapotranspiration rates in relation to plant-available water. It is possible that drought-stress could be experienced in drier sites during particularly warm years in spite of increases in precipitation.

The large unidirectional spike in growth shared by trees at all vegetation-landscape associations after A.D. 2000 is a response to warming that would be expected in a treeline community formerly limited by suboptimally cool temperatures but not limited by moisture. White spruce in the low moisture stress environment of SWAK, lacking the local controls of drought, fire, and insects that are detrimental to ecotonal stands of white spruce in Interior Alaska, appear to have experienced a direct positive growth response to increasing temperature during the growing season. It is reasonable to infer that this increased vigor as a sign of improved environmental suitability in general will allow treeline to continue expanding southwest along the Alaska Peninsula unless a critical threshold of growing season temperature is passed, changing the dominant response of white spruce to temperature from positive to negative. In parts of SWAK where pollen records tell us white spruce has been present for millennia, tree cover is still infilling in non-forested patches.

Driving factors influencing treeline may also change over time. While tundra and forest fires are not driving factors in southwestern Alaska currently, increasing temperatures could increase the rate and severity of fire, which if burning in the forests could impede the expansion of treeline or, if fires occur in the tundra communities, could increase seedling establishment rates by clearing the organic layer and providing raw mineral soil for white spruce to establish in.

As treeline moves westward past the study area, tree forms and stand structures will probably change. White spruce growth in *closed forest hillslopes* and *open forest flats* has been consistent since spruce established in the mid-19th century. These sites are likely to maintain their structure, form, and productivity in the near future. Young, low-density vegetation-landscape associations such as *open dwarf basins* and *scattered spruce polygons*, which previously may have been unfavorable to growth, appear likely to continue experience establishment and survival of white spruce. Due to similar soil characteristics and understory composition between *scattered spruce polygons* and *open forest flats,* it may be possible that *scattered spruce polygons* represent the beginning of a transformation from treeless tundra to *open forest flats* and that if soils continue to dry and trees establish, these sites will begin to resemble the stand structures of *open forest flats*.

5.0 Conclusions

The white spruce-dominated forests growing at the forest-tundra ecotone of SWAK represent a unique, diffuse, longitudinal treeline extending along Alaska's western coast. Longitudinal treeline in southwestern Alaska covers a broad geographical belt beginning at the edge of the dense boreal forests of the interior and extending southwestward to the edge of white spruce range southwest of King Salmon. Similar to diffuse treelines in alpine and arctic communities, much of the physical form of treeline is diffuse in individual tree density. Unlike other treelines, longitudinal treeline in southwest Alaska is also diffuse in patch density, with the number of patches of forest decreasing over a gradient toward the coast and patches of tundra increasing in size until merging into unforested open tundra. White spruce treeline has expanded rapidly across the landscape of the study area since A.D. 1800, mainly in response to changing climate. Correlations between radial growth and climatic variables are largely congruent regardless of where on the landscape the trees are growing, suggesting these trees are well within their ecological tolerance zone and that potential treeline lies further west. Similarly to arctic and alpine treelines, growth in the longitudinal treeline of SWAK is controlled primarily by growing season temperature; however, unlike sites in Interior Alaska, arctic treeline, and alpine treeline, the markedly positive growth trend of white spruce in my study area is seemingly unaffected by drought stress or fire disturbance. While treeline expansion in other regions of Alaska is being complicated by localized fire- and insect-related mortality, as well as die-back caused by water stress, treeline in the King Salmon area appears to be in the early stages of an unrestrained expansion.

At smaller (kilometer) scales near King Salmon, rates of treeline spread appear to vary according to landscape position, as does stand structures behind the spreading front. Sites where tree growth diverges most frequently from the mean growth of all sites are also the places where tree establishment has been slowest. This attests to the important role played by local conditions of soil, drainage, microclimate, and geomorphology in controlling the fine structure of treeline expansion. Under future warming scenarios, it seems likely that white spruce will expand into adjacent areas of tundra that are now unsuitable for its growth. In the most conservative of warming scenarios, increasing temperature will have a positive effect on spruce growth, even as effective moisture decreases, with the possible exception of greater recurrence of short term extreme warm temperature anomalies during the growing season. Increased overall warming is unlikely to have detrimental effects on growth except possibly under the most extreme warming scenarios with projected annual temperature increases up to 4.5°C by the year 2050 (SNAP, 2015e). In this extreme case, systematic warming and drying of the soil in well-drained sites currently favorable for growth could result in extremely low effective moisture content, resulting in low growth and high mortality as a result of temperature-induced drought stress. Without fire and/or drought acting as controls over treeline as they do in Interior forests and Arctic treelines, treeline in SWAK will probably continue its rapid westward expansion as the climate warms, keeping close behind its main environmental constraint of July temperature. The varying dates of germination and rates of establishment at the four different vegetation-landscape associations imply that while this longitudinal treeline may continue expanding westward, the forest established in its wake will be an open-structured forest possessing diverse stand types and numerous nonforest inclusions. Regardless of how exactly the landscape and the white spruce population changes, the rate of change is likely to increase with future warming in the region.

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Appendix

Soil Profile Data Sheets: all soil profile data sheets are listed in order of vegetation-landscape associations, with *open dwarf basins* appearing first, followed by soil pits representing *open forest flats, closed forest hillslopes,* and *scattered spruce polygons.*

Open dwarf basins
- Lower Kite Basin (LB)
- Kite Basin Edge (BE)

Open forest flats
- Kite Basin Backflats (BF)
- Open Spruce (OS)

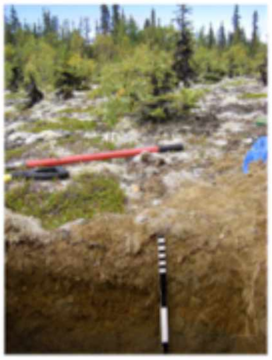
Closed forest hillslopes
- Kite Basin Foreslope (FS)
- Kite Basin Hillcrest (HC)
- Kite Basin Backslope (BS)
- Closed Spruce (CS)
- Naknek Moraine (NM)

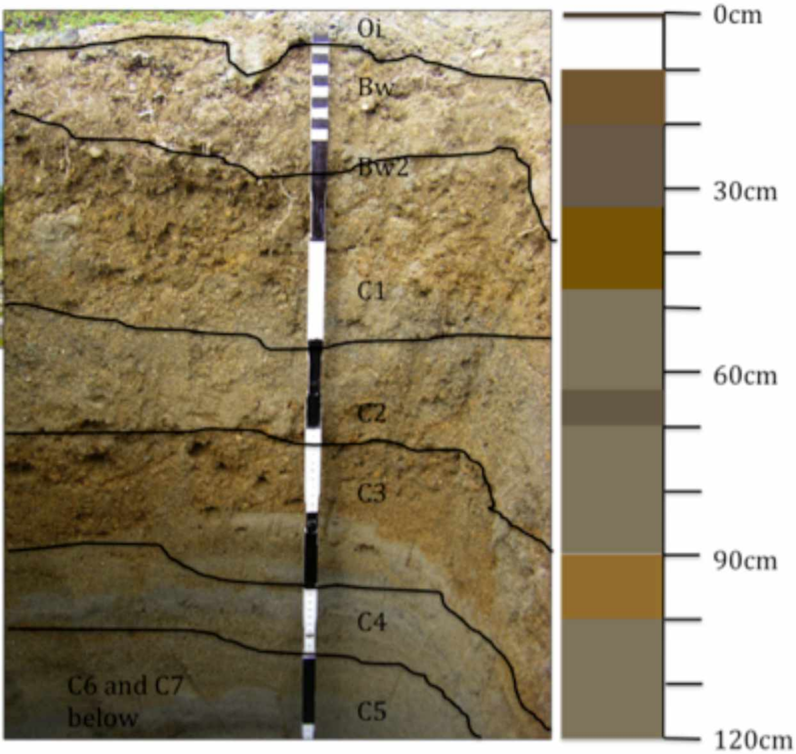
Scattered Spruce Polygons
- Polygon Plateau (PP)

SOIL PROFILE DESCRIPTION

Site Name:	Lower Kite Basin	Lat/Long:	58 °39.607N 156°41.396W
Vegetation-Landscape Association: Open dwarf basin			
Location:	Lower basin across frost crack	Physiography:	Lowland coastal plain
Elevation:	~11-12m a.s.l.	Microrelief:	None
Slope:	Mostly flat	Aspect:	Slight slope North toward river
Parent Material:	Pebbly sand	Drainage:	Good, water table >2m
Geomorphic Surface:	Dune blow-out basin surrounded LGM/Holocene dunes -Holocene blow-out		
Vegetation:	Widely scattered dwarf *P. glauca*, 10-150cm tall and about 1-2m apart. Shrub *B. kenaica,* 20-200cm tall, widely scattered about 2m+ apart. Rare *B. nana*. Understory sp.- mosaic of stereocaulon lichen, cladina, polstrus (cushion moss) 10-40cm in diameter, *E. nigrum* patches to 1m diameter. Veg layer is 0-8cm thick with lichen, pebbles exposed between patches and lichen.		
Described By:	Emily Sousa, Patricia Heiser		
Date/Time: 9/11/10, 14:30	Weather: partly sunny, air temperature 26°C		

Profile Sketch and Notes:





Soil Profile Description

Site Name:	Lower Kite Basin	Lat/Long:	58 °39.607N 156°41.396W

Miscellaneous Notes: alternating reduction/oxidation C horizons- likely from fluctuating water table.

Depth (cm)	Horizon	Properties
0-0.2 (variable)	Oi	Thin organic layer with <75% gravel ≤ 2cm mixed with sand and roots. Surface is flat, boundary is abrupt and smooth. Moist color is 10YR 2/2.
0.2-9	Bw	Brown soil with moist color 10YR 3/3. Massive structure, very friable consistence, 46.29% gravels by weight ≤ 2cm, remaining soil is sandy loam. Soil moisture 10.93%. pH of 5.64 and EC 41.2µS. Contains few fine roots and very few medium roots. Root depth does not extend past this horizon. Soil temp @ 3cm is 19°C. Temp at 6cm, 17°C. Boundary is abrupt and smooth.
9-20	Bw2	Reddish brown soil with wet color 10YR 3/4. Single grain, loose, sandy loam with 37.11% gravels by weight, ≤ 2cm in size. Soil moisture is 7.78% and pH is 6.08, EC 25.2µS. No roots. Soil temperature 16°C. Boundary is abrupt and smooth.
20-32	C1	Grey single grain, loose loamy sand, gravels 0.5-2cm in size 21.55% of sample weight. Moisture content 6.88% of sample and wet color is 10YR 3/2. Boundary is abrupt and smooth. pH of 6.36 and EC of 19.79µS.
32-46	C2	Reddish brown single grain, loose loamy sand, gravels 0.5-2cm in size and 37.31% of sample weight. Moisture content is 5.75% of sample. Wet color 10YR 3/6 with a pH of 6.61 and an EC of 18.8µS. Boundary is abrupt and smooth.
46-62	C3	Grey matrix with reddish brown elongate mottles. Mottles are many large and prominent. Single grain, loose sand, wet color 2.5Y 4/2. Gravels 1.40% of sample weight and moisture content 6.14%. pH of 6.61 and EC of 15.78µS. Boundary is abrupt and smooth.
62-70	C4	Reddish brown with no mottles. Single grain, loose sand with an abrupt and smooth boundary. Moisture content 4.52% with gravels comprising 1.34% of sample weight. Wet color is 2.5Y3/2 and pH is 6.53 with EC of 14.1µS.
70-90	C5	Loose, single grain grey sand with a wet color 5Y 4/2 and moisture content of 8.33%. Trace of gravel at only 0.05% of sample weight. Boundary is abrupt and smooth with a pH of 6.59 and EC 22.3µS.
90-100	C6	Reddish grey and gravelly horizon comprised of single grain, loose loamy sand with a wet color of 10YR 4/6. Gravels are 0.5-2cm in size and 18.25% of sample weight. Soil moisture is 6.0%. Boundary is clear and smooth with a pH of 6.76 and an EC of 21.4µS.
100-120	C7	Grey matrix with many prominent and elongate reddish brown mottles. Texture is single grain, loose, sand. Matrix is 5Y 4/2 when soil is wet and contains no gravel with a soil moisture content of 11.95%. pH is 6.74 and EC is 25.8µS.
120+	Bottom of pit	Sand horizons continue with depth- able to dig deeper but did not. Sample from bottom of the pit had a wet color of 10YR 3/3, soil moisture content of 20.08% of sample with gravels comprising 3.61% of the sample weight. pH is 6.61 and EC is 61.3µS. Temperature at 130cm, 12°C, temp at 200cm (probe depth) 8°C.

SOIL PROFILE DESCRIPTION

Site Name:	Kite Basin Edge	Lat/Long:	58 °39.639N 156°41.429W
Vegetation- Landscape Association: Open dwarf basin			
Location:	Southwest corner of Kite Basin at base of slope	Physiography:	Lowland coastal plain
Elevation:	~11-13m a.s.l.	Microrelief:	None
Slope:	Slight	Aspect:	Northeast
Parent Material:	Sand over gravels	Drainage:	Good, water table >3m
	Base of blow-out dune, Holocene		
Vegetation:	Mixed *P. glauca*, *B. kenaica*, density every 0.1 -1m. Understory - lichen, *Empetrum nigrum*, *Arctostaphylos rubra*, grey bush lichen, cladonia/cladina		
Described By:	Emily Sousa, Patricia Heiser		
Date/Time: 9/14/10, 14:00		Weather: sunny, air temperature 18°C	

Profile Sketch and Notes:

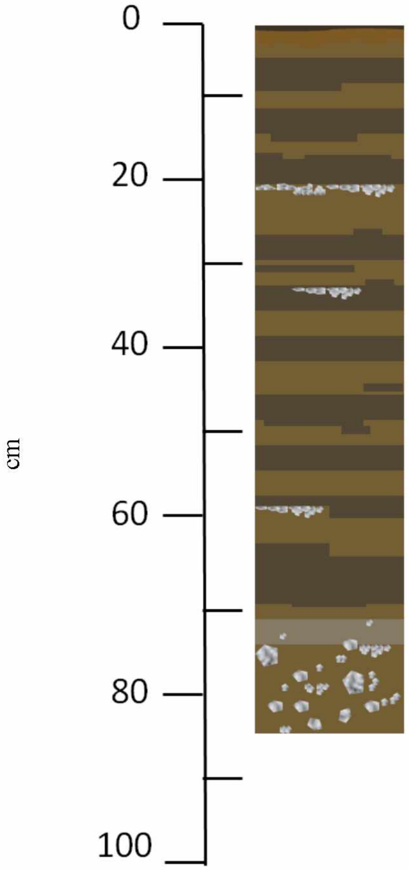


Figure above: white and black lines mark 10cm intervals

Soil Profile Description

Site Name:	Kite Basin Edge	Lat/Long:	58 °39.639N 156°41.429W

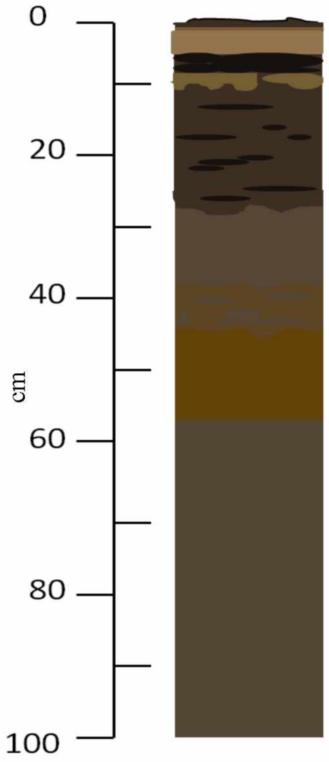
Miscellaneous Notes:

Depth (cm)	Horizon	Properties
0-1	Oi	Peat with moist color 10YR 2/2. Boundary abrupt and smooth with common fine and few medium roots. Soil surface temperature 13°C.
1-3 (variable)	ash	Pinkish tan ash mixed with sand with moist color 10YR 4/6. Structure is massive with no gravel and firm moist consistency. Boundary abrupt and wavy, with few fine roots.
3-72	Bw/C	Alternating bands of reddish brown (moist color 2.5Y 4/4) and grey (moist color 2.5Y 3/2) sand. Texture is single grain with loose moist consistency. Boundary is abrupt and smooth with few fine roots through 25cm. Contains lenses of fine gravels accounting for only 0.06% of sample weight. Soil moisture content is 7.31%. Reddish brown bands have a pH of 5.09 and EC of 43.9μS. Grey bands have a pH of 5.27 and an EC of 15.98.
72-75	2C	Light grayish tan loam with moist color 2.5Y 5/2. Structure is massive with firm consistence when moist with 1.07% gravels and soil moisture of 24.75%. Boundary is abrupt and smooth. pH is 5.56 and EC is 66μS. Possible ash or lake sediments. Soil temperature of 9°C.
75-85+	3C	Reddish brown sand with moist color 2.5Y 4/4. Gravels 51.23% and soil moisture content is 4.79%. Structure is single grain with loose moist consistence. pH is 5.68 and EC of 18.37%.

SOIL PROFILE DESCRIPTION

Site Name:	Kite Basin Backflats	Lat/Long:	58 °39.646N 156°41.456W
Vegetation-Landscape Association: Open forest flats			
Location:	Backflats along SW side of Kite Basin	Physiography:	Lowland coastal plain
Elevation:	~11-12m a.s.l.	Microrelief:	None
Slope:	Mostly flat	Aspect:	Slight slope North toward river
Parent Material:	Gravelly sand	Drainage:	Good, water table >3m
Geomorphic Surface:	Glacial outwash fan, Late Wisconsin		
Vegetation:	Open spruce forest, *Picea Glauca* scattered, 1-4m apart, mostly 1-2m tall with some up to 5m tall, few *Salix sp.* Understory- *E. nigrum, V. vitis-idaea*, lichen		
Described By:	Emily Sousa, Patricia Heiser		
Date/Time: 9/12/10, 14:00		Weather: overcast, air temperature 15°C	

Profile Sketch and Notes:



Figures above: white and black lines mark 10cm intervals

Soil Profile Description

Site Name:	Kite Basin Backflats	Lat/Long:	58 °39.646N 156°41.456W

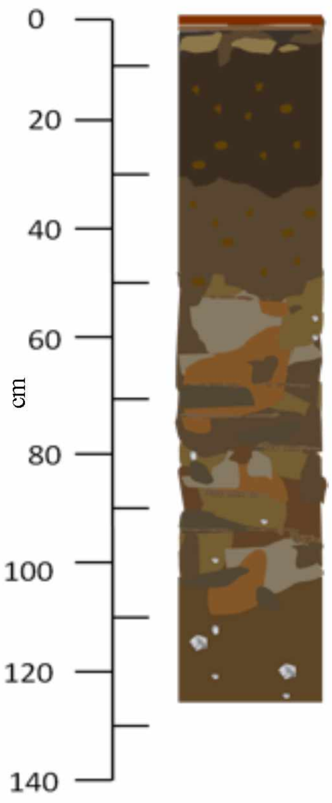
Miscellaneous Notes:

Depth (cm)	Horizon	Properties
0-2	Oi	Fibrous peat with moist color 10YR 2/2. Boundary is abrupt and smooth with common fine and few medium roots. Soil temperature at surface 12°C.
2-2.5	E	Pinkish grey with moist color 10YR 4/4. Structure is massive with no gravels and friable moist field consistency. Boundary is abrupt, wavy, and broken with common fine and few medium roots.
2.5-5	ash	tan ash color 10YR 5/4 when moist. Boundary is abrupt and smooth and ous. Likely Katmai ash. Massive structure with no gravels with common fine medium roots.
5-8	Oeb	Mucky peat with moist color 10YR 2/1. Boundary is abrupt, smooth, and broken with very few fine roots and no gravel.
8-11	ash	Tan buff ash with moist color 2.5Y 4/4. Structure is massive with moist consistence of friable to firm and no gravels. Boundary is abrupt, wavy, and broken with very few fine roots. Likely Lethe ash.
11-27	Bhb	Dark brown sandy loam matrix with moist color 10YR 2/2 containing wavy elongate sandy loam mottles with moist color 10YR 2/1. Structure is massive, angular blocky. No gravels, field consistence is friable when moist. Soil moisture content of matrix sample is 45.56% while mottles have soil moisture content of 43.09%. pH is 5.8 with EC of 22.9μS. Soil temp at 25cm 10°C. Boundary is clear and wavy.
27-38	Bw/Bs	Slightly redder sandy loam than Bhb above, with moist color 10YR 3/2 containing no gravels. Structure is massive, and angular blocky. Boundary is clear and wavy with no roots. Soil moisture of sample is 41.45% with pH of 6.05 and an EC of 25.0μS.
38-45	Bsb	Reddish brown sandy loam with moist color 10YR3/4 containing yellow brown sandy loam mottles with moist color 10YR 3/2. Structure is massive, and angular blocky with a very friable moist field consistence. Contains no gravel. Matrix has soil moisture content of 26.69% whereas mottles have 37.75% soil moisture content. Boundary is clear and wavy with no roots. pH of matrix is 5.86 with an EC of 43.4μS. Mottles have a pH of 5.97 and an EC of 30.9μS.
45-58	2Bw	Reddish yellow/orange/brown loamy sand with moist color 10YR 3/6. Sample is 22.71% gravel with a moisture content of 13.04%. Structure is single grain and loose consistence when moist. Boundary is clear and smooth. pH is 5.22 and EC is 24.3μS.
58-85+	2C	Grey sand with moist color 2.5Y 3/2 with 3.09% gravels. Structure is single grain and consistence is loose when moist. Soil moisture content is 5.98% with a pH of 6.1 and an EC of 21.8μS.

SOIL PROFILE DESCRIPTION

Site Name:	Open Spruce Parkland	Lat/Long:	58°39.444N 156°40.692W
Vegetation-Landscape Association: Open forest flats			
Location:	Near trailhead to Shark Basin	Physiography :	Lowland coastal plain
Elevation:	~11-12m a.s.l.	Microrelief:	Hummocks 15-50cm
Slope:	Flat	Aspect:	Flat
Parent Material:	Sand	Drainage:	Good, water table >3m
Geomorphic Surface:	Glacial outwash fan Last Glacial Maximum		
Vegetation:	*P. glauca*, 1-3m density between *P. glauca*, >75% of spruce heavy with cones. Size cohorts as follows: tall *P. glauca* 4.5-10+m tall, spaced 6-8m apart; medium. *P. glauca*, average 3-4.5m tall with density every 2-4m; small *P. glauca* average 0.5-3m tall spaced 2-8m apart, variable density, with some seedlings grouped 20cm apart. Combined, *Picea glauca* density of 4-7 trees per 5m^2. Understory – *E. nigrum*, *V. vitis-idaea, L. decumbens,*, *B. nana,* shrub *Salix sp.* <1m tall, lichen, moss, cladonia/cladina		
Described By:	Emily Sousa, Patricia Heiser		
Date/Time: 9/15/10, 14:30	Weather: did not record		

Profile Sketch and Notes:



Figures above: white and black lines mark 10cm intervals

Soil Profile Description

Site Name:	Open Spruce Parkland	Lat/Long:	58°39.444N 156°40.692W

Miscellaneous Notes:

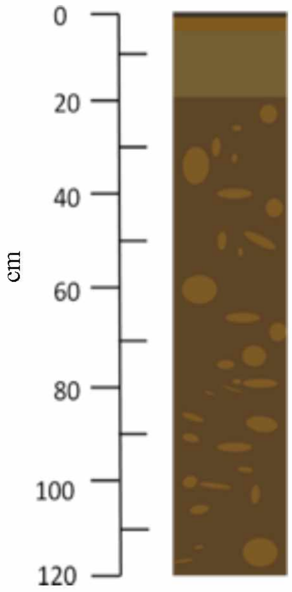
Depth (cm)	Horizon	Properties
0-2	Oi	Peat with moist soil color 5YR 3/1. Boundary is abrupt and smooth, with many fine and few medium roots.
2-3	ash	Pinkish tan ash with moist color 7.5YR 4/4. Structure is massive with firm moist consistence and no gravels. Boundary is abrupt and smooth with many fine and few medium roots. Likely Katmai ash.
3-6 (variable)	Oeb	Peat with moist color 10YR 2/1. Boundary is abrupt, wavy, and broken with many fine and few medium roots.
6-7 (variable)	Bw	Thin reddish yellow brown layer with moist color 10YR 3/3 and soil moisture content of 31.16%. Structure is single grain with loose consistence when moist. Boundary is abrupt, wavy, and broken with many fine and few medium roots.
7-10	ash	Grayish tan ash with moist color 2.5Y 5/4. Appears as 2-4cm wide blobs or lenses within Bw. Structure is massive with firm moist consistence and no gravels. Likely Lethe ash. Boundary is abrupt, irregular, and broken.
10-32	Bh1	Dark sandy loam matrix with moist color 10YR 2/2 with lighter tan/olive mottles with moist color 10YR 3/6 mostly around roots in small blobs. Structure is massive, subangular blocky with no gravels and friable moist consistence. Few fine roots and boundary is abrupt and wavy. Soil moisture content of dark matrix 36.71% with a pH of 5.4 and an EC of 55.9μS. Soil moisture content of light mottles is 28.6% with a pH of 5.9 and EC of 29.3μS.
32-55	Bh2	Brown sandy loam matrix with moist color 10YR 3/3 with same light tan mottles as in Bh1 with moist color 10YR 3/6 mostly around roots and in small blobs. Structure is massive, subangular blocky with no gravels. Boundary is abrupt and irregular with few fine roots with maximum root depth at 55cm. Soil moisture content of brown matrix is 26.89% with mottles containing 28.6% soil moisture. Brown matrix has a pH of 5.71 with an EC of 36.8μS and light tan mottles have a pH of 5.9 and EC of 29.3μS.
55-110	Bhsw	Heavily mottled horizon with no distinct matrix and seven distinct mottles- a red/orange loamy sand mottle with moist color 7.5YR 4/6 with no gravels, soil moisture content 11.6%, pH of 6.03 and EC of 55μS; a dark grey mottle with moist color 2.5Y 3/2, no gravels, soil moisture content of 26.44%, pH of 5.78 and EC 62μS; a brown mottle with moist color 10YR 3/3 with no gravels and soil moisture content 22.4%, pH of 5.69 and EC of 37.7μS; a bright red mottle with moist color 7.5YR3/4 with no gravels, a soil moisture content of 5.99%, pH 6.03 and EC of 55μS; a mustard yellow mottle with moist color 2.5Y 4/4, with gravels comprising 0.78% of sample weight, soil moisture content of 15.38% with a pH of 5.96 and EC of 67.1μS; a light yellow grey mottle with moist color 2.5Y 5/2 with no gravels and a soil moisture content of 30.0%, pH of 6.02 and EC of

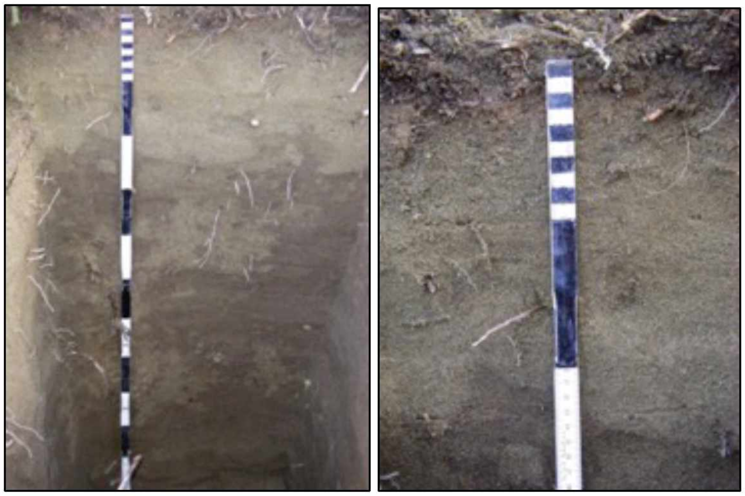
		79.7μS; a pink sandy loam mottle with moist color 10YR 4/3, appearing as irregular lenses of fine gravelly sand, poorly sorted, with gravels to ½ cm diameter, rounded to angular, and mixed lithology. Possibly till- very firm and compact gravel. Structure is massive and soil moisture content of pink sandy loam is 12.9% with a pH of 6.27 with an EC of 37.6μS. Structure of all other mottles is single grain. Boundary is wavy and clear, involuted and highly variable.
110-125 (bottom of pit)	C	Reddish grey sand with moist color 10YR3/4 with soil moisture content of 7.75%. Structure is single grain, with 2.22% gravels by weight, with loose consistence when moist. pH is 6.22 with an EC of 28.4μS.

SOIL PROFILE DESCRIPTION

Site Name:	Kite Basin Foreslope	Lat/Long:	20m toward basin from HC pit at 58°39.633N 156°41.460W
Vegetation-Landscape Association: Closed forest hillslope			
Location:	NE dune slope between HC and LB, foreslope about 20m from hillcrest to basin edge	Physiography:	Lowland coastal plain
Elevation:	~13-14m a.s.l.	Microrelief:	Slight, <5%
Slope:	~6%	Aspect:	Northeast
Parent Material:	Sand	Drainage:	Good, water table >3m
Geomorphic Surface:	Dune foreslope, Holocene blow-out dune		
Vegetation:	*P. glauca* on upper slope, near basin crest and backslope, *B. kenaica* on lower slope. *P. glauca* 3-10m tall, also some seedlings. Occasional *Salix sp. P. glauca* heavy with cones. Understory: *Empetrum nigrum, Vaccinium vitis-idaea*, lichen, moss, *Equisetum sp.*		
Described By:	Emily Sousa, Patricia Heiser		
Date/Time: 9/13/10, 14:20		Weather: sunny, air temperature 19°C	

Profile Sketch and Notes:





Figures above: white and black lines mark 10cm intervals

Soil Profile Description

Site Name:	Kite Basin Foreslope	Lat/Long:	20m toward basin from HC pit at 58 °39.633N 156°41.460W

Miscellaneous Notes:

Depth (cm)	Horizon	Properties
0-2	Oi	Peat with moist color 10YR 2/2. Boundary is abrupt and smooth with common fine and few medium roots.
2-5.5	E/ash	Single grain with moist color 10YR 4/6 with no gravels. Moist consistence is firm. Boundary is abrupt and smooth with common fine and few medium roots. Soil temperature at 5cm is 11°C.
5.5-23	Bw1	Light grayish brown sand with moist color 2.5Y 4/4. Contains no gravel and has a soil moisture content of 7.51%. Structure is single grain and consistence is loose wen moist. Boundary is clear and irregular with common fine and few medium roots. pH is 5.52 with an EC of 9.16μS.
23-120+	Bw2 matrix/Bw1 mottle	Darker reddish brown sand matrix with moist color 10YR3/4 and soil moisture of 8.55%. Contains mottles (possibly Bw1) with moist color 10YR 4/6 and a soil moisture content of 9.38%. No gravel, structure is single grain and loose moist consistency. Roots are few medium and few fine. Mottles occur in blobs 1-10cm across, frequently around roots. pH of matrix is 5.6 with and EC of 11.25μS. pH of mottles is 5.21 with an EC of 28.4μS. Soil temperature at 120cm 7°C.

SOIL PROFILE DESCRIPTION

Site Name:	Kite Basin Hillcrest	Lat/Long:	58 °39.633N 156°41.460W
Vegetation-Landscape Association: Closed forest hillslope			
Location:	Elevational high in area, top of dune on SW side of Kite Basin	Physiography:	Lowland coastal plain
Elevation:	~14m a.s.l.	Microrelief:	None
Slope:	Flat at top, sloping both sides (toward KBFS and KBBS)	Aspect:	Flat
Parent Material:	Sand	Drainage:	Good, water table >3m
Geomorphic Surface:	Stabilized sand dune (crest), Holocene blowout dune		
Vegetation:	Mixed *P. glauca* scattered 3-6m apart, ranging in height from 5-10m tall, many cones. Few scattered 1-2m tall dead *P. glauca.* Occasional tree *B. kenaica* and *Salix sp.* Understory – *E. nigrum, V. vitis-idaea.,* lichen, moss, *L. decumbens, Equisetum sp.,* cladonia/cladina, few *A. rubra.*		
Described By:	Emily Sousa, Patricia Heiser		
Date/Time: 9/12/10, 17:00	Weather: sunny, air temperature 24°C		

Profile Sketch and Notes:

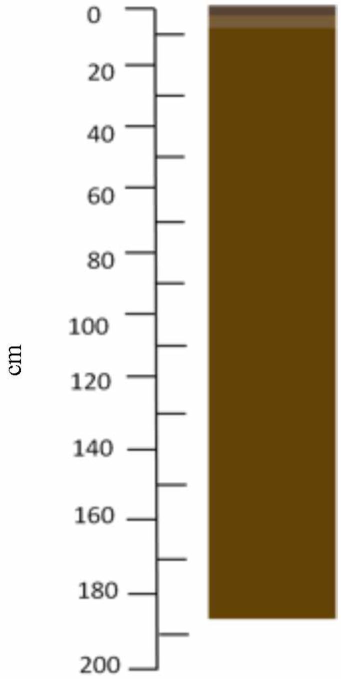


Figure above: white and black lines mark 10cm intervals

Soil Profile Description

Site Name:	Kite Basin Hillcrest	Lat/Long:	58 °39.633N 156°41.460W

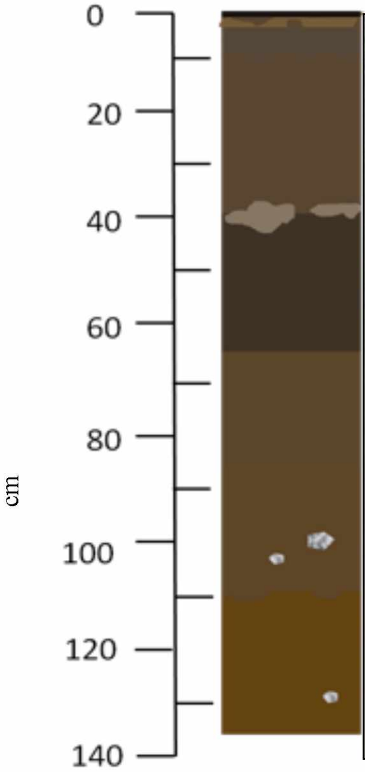
Miscellaneous Notes:

Depth (cm)	**Horizon**	**Properties**
0-4.5	Oi	Peat with moist color 7.5YR 3/2. Boundary is abrupt and smooth with many fine and few medium roots.
4.5-5	E/ash	Thin pinkish grey with moist color 10YR 4/4. Structure is massive and consistence is friable to firm when moist. Contains no gravel.
5-6	ash	Pinkish tan ash, likely Katmai, with moist color 10YR 4/4. Massive structure and firm moist consistence with no gravel. Boundary is abrupt and smooth and continuous in profile.
6-186+	C	Grayish brown sand with moist color 10YR 3/6. Contains no gravels, structure is single grain and consistence is loose when moist. pH is 5.28 with an EC of 20.2µS.

SOIL PROFILE DESCRIPTION

Site Name:	Kite Basin Backslope	Lat/Long:	58 °39.646N 156°41.456W
Vegetation-Landscape Association: Closed forest hillslope			
Location:	Back slope on SW side of Kite Basin	Physiography:	Lowland coastal plain
Elevation:	~13-14m a.s.l.	Microrelief:	Slight, <10cm
Slope:	~5%	Aspect:	SW
Parent Material:	Medium sand	Drainage:	Good, water table >3m
Geomorphic Surface:	Holocene sand dune on LGM glacial outwash fan		
Vegetation:	Open spruce forest, *Picea glauca* 20-40ft tall and spaced 1-3m apart, few *Salix sp.*, understory- *E. nigrum*, *V. vitis-idaea*, lichen		
Described By:	Emily Sousa, Patricia Heiser		
Date/Time: 9/11/10, 18:00		Weather: Sunny	

Profile Sketch and Notes:



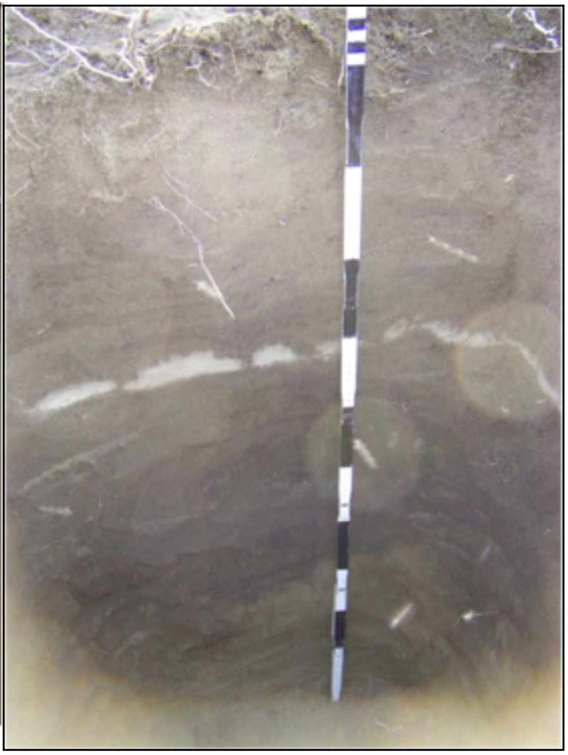


Figure above: white and black lines mark 10cm intervals

Soil Profile Description

Site Name:	Kite Basin Backslope	Lat/Long:	58 °39.646N 156°41.456W

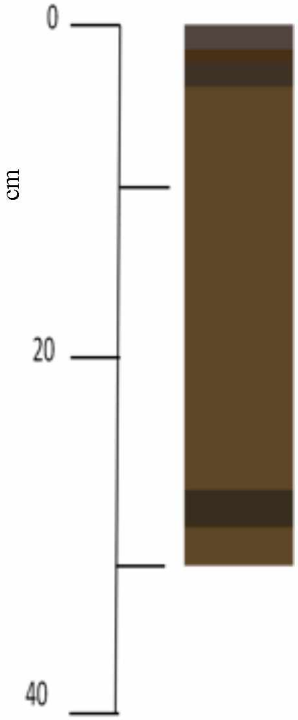
Miscellaneous Notes:

Depth (cm)	Horizon	Properties
0-0.5	Oi	Thin organic layer with few fine roots and very few medium roots. Soil temp at surface 14°C. Moist color is 10YR 2/1.
0.5-1	E	Thin pinkish-grey with massive structure and fine sand with moist color 10YR 3/3. Boundary is abrupt and smooth but broken with few fine and very few medium roots penetrating through.
1-2	Ash	Pinkish-brown ash with wet color 10YR 4/4. Structure is massive and consistence is friable to firm when moist. Boundary is abrupt, wavy, and broken with few fine roots and very few medium roots.
2-10	Bh	Yellowish brown loamy sand with moist color 10YR 3/2. Structure is massive and very friable when moist. Boundary is clear and wavy with few fine roots and very few medium roots. No gravels, moisture content of sample is 10.3%. pH is 5.17 and EC is 18.94μS.
10-40	Bw/Bh	Mottled yellowish brown and dark brown sand with moist color 10YR 3/3. Horizon contains no gravel and has a moisture content of 10.71%. Boundary is abrupt, smooth, and broken. Structure is massive and moist field consistency is very friable. pH is 5.35 and EC is 18.01μS. No roots.
40-43	Ash	Grey buff ash color of 10YR 5/2 when moist. Not enough sample for moisture content, pH, EC or texture. Boundary is abrupt, wavy, broken and discontinuous throughout the section. Structure is massive and firm to friable when moist. No roots.
43-66	Bhb	Reddish brown sandy loam with yellowish, dark brown and light reddish brown mottles. Matrix is 10YR 2/2 when moist and contains no gravel and a moisture content of 12.35%. Boundary is gradual to diffuse and smooth. Structure is massive with moist field consistency very friable. pH is5.69 with an EC of 12.63μS. No roots.
66-87	Bhb2	Similar to Bhb1 but slightly redder with faint brown mottles. Texture is loam with decrease in sand and increase in silt and clay compared to Bhb1. Moist color is 10YR 3/3 and contains no gravel and has a moisture content of 41.99%. pH is 5.75 with an EC of 14.78μS. very few fine to medium roots.
87-110	Bhb/Bsb	Yellowish to yellowish-tan massive sand with moist field consistency very friable. When moist, color is 10YR 3/4. Boundary is diffuse and wavy with 1.36% of sample weight in small gravel. Moisture content is 8.66% and pH is 6.01 with and EC of 8.92μS.
110-135 (bottom of pit)	C/Bw	Light grayish tan sand that is loose when moist and single grain. Moist color is 10YR 3/6 with 0.84% of sample weight in small gravels and a moisture content of 6.6%. pH is 6.02 with an EC of 12.37μS. Soil temp at base of pit 8°C.

SOIL PROFILE DESCRIPTION

Site Name:	Closed Spruce	Lat/Long:	58° 39’ 44”N 156° 40’ 52”W
Vegetation- Landscape Association: Closed forest hillslope			
Location:	Ridge 14m W of small basin on the trail to Kite and Shark Basins	Physiography:	Lowland coastal plain
Elevation:	~11-13m a.s.l.	Microrelief:	None
Slope:	Slight, <2%	Aspect:	West
Parent Material:	Sand	Drainage:	Good, >3m
Geomorphic Surface:	LGM / early Holocene sand dunes (stabilized)		
Vegetation:	Mixed *Picea glauca*, variable size (see 2009 notes), density every 0.5-3m, *Betula kenaica* 4-7m tall, density every 3-6m apart, *Salix sp*. shrub to 1m tall, spaced every 0.5-3m-6m but occurring in clusters. Understory- *Ledum decumbens., Empetrum nigrum, Vaccinium vitis-idaea, moss, Epilobium angustifolium, Carex sp. (rare), Equisetum sp., Betula nana*		
Described By:	Emily Sousa, Patricia Heiser		
Date/Time: 9/15/10, 18:00		Weather: did not record	

Profile Sketch and Notes:



Figures above: white and black lines mark 10cm intervals

Soil Profile Description

Site Name:	Closed Spruce	Lat/Long:	58° 39' 44"N 156° 40' 52"W

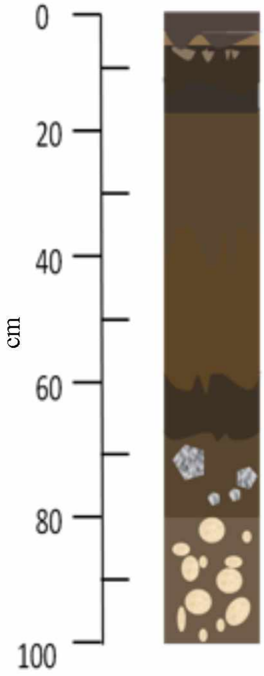
Miscellaneous Notes:

Depth (cm)	**Horizon**	**Properties**
0-2	Oi	Peat with moist color 5YR 2.5/1. Boundary is abrupt and smooth with common to many fine to medium roots. Very few coarse roots to 1.5cm diameter.
2-3	Ash	Pinkish tan ash with moist color 7.5YR 2/4. Structure is massive with no gravel and firm moist consistence. Boundary is abrupt and smooth. Likely Katmai ash.
3-5	Oib	Fibrous peat with moist color 10YR 2/2. Boundary is abrupt and smooth with common fine to medium roots.
5-26	Bw1	Brown sand matrix with moist color 10YR 3/4 with light yellow and brown mottles around roots, circular 2-5cm in diameter. Structure is single grain and loose consistence when moist. Contains no gravel and has a soil moisture of 15.17%, pH of 4.94 and an EC of 40.9μS. Boundary is abrupt and smooth with common fine to medium roots.
26-28	Ash	Tan ash with moist color 2.5Y 5/4. Structure is massive with no gravels and a firm consistence when moist. Boundary is abrupt and smooth with very few fine roots. Likely Lethe ash.
28+	Bw2	Brown sand matrix (possibly the same as Bw1) with a soil moisture content of 9.18% and no gravels. Mottles decrease with depth. Structure is single grain and loose moist consistence. Roots are rare below 30cm. pH is 5.36 with an EC of 26.5μS.

SOIL PROFILE DESCRIPTION

Site Name:	Naknek Moraine	Lat/Long:	58 °40.082 156°30.957W
Vegetation-Landscape Association: Closed forest hillslope			
Location:	Middle distal slope of Naknek Moraine, near Naknek Lake, kettle topography North of Pike Lake	Physiography:	Morainal ridge on lowland coastal plain
Elevation:	~11-12m a.s.l.	Microrelief:	Hummocks 50-100cm
Slope:	Flat	Aspect:	Flat
Parent Material:	Glacial till, gravelly sand	Drainage:	Good, water table > 3m
Geomorphic Surface:	Moraine Crest, Brooks Lake stage (~16000 - 20000 14C yr BP)		
Vegetation:	Mixed *Betula kenaica-Picea glauca* forest, shrub *B. kenaica* to 4m tall, multi stemmed and single stemmed, some slopes solid dense birch, others mixed with open areas. No *Picea* in dense *Betula* stands. Mostly associated with small open areas. *Salix sp.* to 2m tall, *Betula sp.* to 1.5m tall, dwarf *Salix sp.* to 20cm tall. *P. glauca* to 5m, many abundant with cones. Understory- very hummocky/ring structured 1-2m diameter, 50-100cm deep. *E. nigrum* and lichen in low spots. *V. vitis-idaea* in ridges and crests, *E. nigrum, L. decumbens*, lichen, *Spirea sp., A. rubra.*		
Described By:	Emily Sousa, Patricia Heiser		
Date/Time: 9/18/10, 17:00		Weather: did not record	

Profile Sketch and Notes:



Figures above: white and black lines mark 10cm intervals

Soil Profile Description

Site Name:	Naknek Moraine	Lat/Long:	58 °40.082 156°30.957W

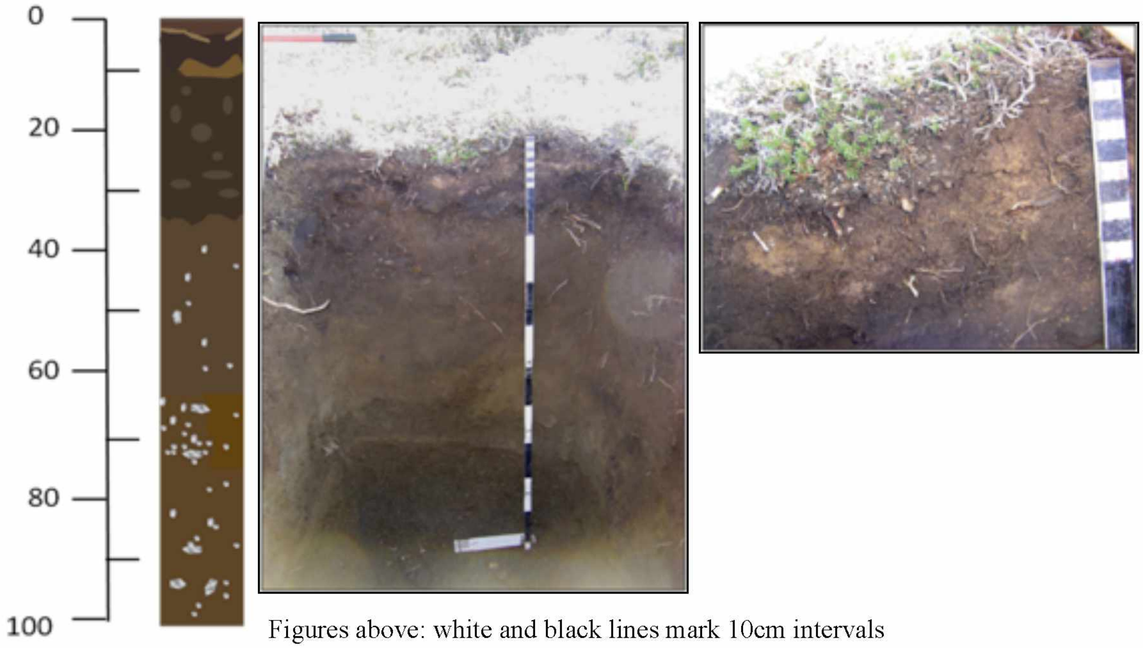
Miscellaneous Notes: probed around with auger- higher areas resemble west side of pit w/ deep Bw horizons to 60+cm, then C. Lows closer to east side of pit where sand C w/in 10-30cm, wet Bw above. Both ashes more obvious in higher areas. Bw horizons drier in higher areas, wetter in lows.

Depth (cm)	Horizon	Properties
0-6	Oi	Peat with moist color 5YR 2.5/1. Boundary is abrupt and wavy. Soil temperature at surface of 9°C. Fine and medium roots common.
6-7	ash	Ash with moist color 10YR 5/4, likely Katmai ash. Structure is massive and singular grained. Boundary is abrupt, wavy, and broken.
7-8	Oeb	Buried peat with moist color 10YR 2/2. Boundary is abrupt and wavy. Fine and medium roots common.
8-9	ash (variable)	Variable 1-2cm thick ash with moist color 2.5Y 5/2. Likely Lethe ash. Structure is massive and singular grained. Boundary abrupt, wavy, and broken.
9-15	Ab1	Dark brown sandy loam with moist color 10YR 2/2. Gravels account for 6.27% of sample weight. Structure is massive and consistence is very friable when moist. Soil moisture of 33.66%. Roots make up 6.71% of sample weight. pH of 4.47 with an EC of 91.2μS. Boundary is abrupt and wavy. Many fine and very fine roots.
15-19	Ab2	Blackish brown sandy loam with moist color 10YR 2/1 and soil moisture content of 59.68%. No gravels, consistence is friable when moist. Boundary is abrupt and wavy. pH of 4.3. Not enough sample for EC. Many fine and very fine roots.
19-42	Bw1	Brown sandy loam with moist color 10YR 3/3 and 0.65% small gravel by weight when cobbles removed. Structure is massive, consistence is very friable when moist. Horizon highly variable in thickness with occasional cobbles. Soil moisture content is 33.92% with pH of 5.12 and an EC of 29.2μS. Boundary is abrupt and irregular. Fine and medium roots common.
42-61	Bw2	Dark brown sandy loam with moist color 10YR3/4 and 1.13% weight in gravel. Soil moisture content of 29.13%. Structure is massive, with occasional boulder/cobbles. Consistence is very friable when moist. Horizon contains 2 large cobbles 30cm in diameter, with 12 smaller cobbles <30cm in diameter. pH is 5.33 with an EC of 26.7μS. Boundary is gradual and wavy. Soil temperature of 8°C. Fine and medium roots common.
61-67	Bw3	Blackish brown sandy loam with moist color 10YR 2/2. Structure is massive to single grained with <10% boulders and cobbles. Small gravels account for 3.82% of sample weight. Moist consistence is very friable with soil moisture content of 34.5%. pH is 5.48 and EC of 30.3μS. Boundary is gradual and wavy. Fine and medium roots common.

67-80	Bw4	Brown sandy loam with moist color 10YR3/3. Structure is massive with gravels accounting for 60.1% of sample weight. Soil moisture content of 41.14% with a pH of 5.26 and an EC of 26.9μS. Soil temperature of 7°C at 80cm. Fine and medium roots common.
80+	C	Loamy sand matrix with moist color 2.5Y 4/2 containing sandy loam blobs (till?) with moist color 2.5Y 5/4. Structure is single grained, large gravels 50%, small gravels 9.22% of sample weight in matrix and 2.52% of sample weight of till. Consistence is loose when moist. Loamy sand matrix has soil moisture content of 11.09% with a pH of 5.36 and an EC of 16.43μS. Till blobs have soil moisture content of 11.29% with pH 5.96 and an EC of 19.16μS. Fine and medium roots common.

SOIL PROFILE DESCRIPTION

Site Name:	Polygon Plateau	Lat/Long:	58°42.862N 156°51.107W
Vegetation-Landscape Association: Scattered spruce polygons			
Location:	Downriver from King Salmon, on south side of river near village site of New Savonoski	Physiography:	Lowland coastal plain
Elevation:	~11-12m a.s.l.	Microrelief:	10-70cm between frost troughs and center of polygons
Slope:	Slight, <2%	Aspect:	North
Parent Material:	Silt-sand-peat over sandy gravel	Drainage:	Poor, water table >1m
Geomorphic Surface:	High-centered polygons on former lake bed, LGM / Holocene		
Vegetation:	Treeless at site of pit, patch of small (1-5m tall) *Picea glauca* by bluff on upstream plateau (10m lower surface than downstream plateau), low density, growing in cracks between polygons. Understory: shrubs (*Alnus sp., Salix sp., Betula nana*) <1m tall, cladonia/cladina lichens, other lichen, *Empetrum nigrum*, *Arctostaphylos rubra, Ledum decumbens*, occasional rush		
Described By:	Emily Sousa, Patricia Heiser		
Date/Time: 9/17/10, 12:00	Weather: air temperature 16 °C		



Figures above: white and black lines mark 10cm intervals

Soil Profile Description

Site Name:	Polygon Plateau	Lat/Long:	58°42.862N 156°51.107W

Miscellaneous Notes:

Depth (cm)	**Horizon**	**Properties**
0-1	Oi	Peat with moist color 7.5YR 3/2. Boundary is clear and wavy.
1-3	Oe	Peat with moist color 5YR 3/2. Boundary is abrupt and wavy. Soil surface temperature of 10°C.
3-4 (variable)	ash	Pinkish tan ash with moist color 10YR 5/4. Likely Katmai ash. Structure is massive with no gravels and consistence is firm when moist. Boundary is abrupt, wavy, and broken.
4-9	Oebjj	Peat with moist color 5YR 2.5/1. Possibly two separate Oebjj horizons separated by ash. Boundary is broken and variable.
9-11	ash	Tan ash with moist color 2.5Y 4/4. Structure is massive with no gravels and a firm moist consistence. Boundary is abrupt, smooth, and broken. Likely Lethe ash. Boundary varies with depth with Oebjj. Soil temperature at 10cm is 10 °C.
11-35	Bh	Dark brown sandy loam with moist color 10YR 2/2 with very wet, reddish brown blob-like mottles with sandy clay loam texture and moist color 10YR 3/2. Structure is massive with a friable moist consistence. Matrix contains 8.79% gravels by weight with soil moisture content of 50.87%. Mottles contain 4.12% gravels by weight with soil moisture content of 36.22%. Matrix has pH of 5.83 with an EC of 30.2μS. Mottles have pH of 6.06 and EC of 32.3μS. Gravels, where present, up to 6-7cm in diameter. Roots do not extend past 35cm. Boundary is gradual and wavy. Soil temperature in wet mottles is 9 °C at 30cm.
35-63	Bw	Reddish brown sandy loam with moist color 10YR 3/3. Gravels account for 5.65% of sample weight with soil moisture content of 33.2%. Consistence is very friable when moist, no wet blobs or mottles. Boundary is clear and smooth. pH 6.03 and EC of 26.6μS. Soil temperature at 50cm of 9 °C.
63-75	Bw/C1	Horizon appears slightly different on opposite faces of pit. Both are single grain, with coarse gravels greater than 6cm in diameter, loose to very friable when moist and with a clear and smooth boundary. Bw/C1 (face 1) is reddish brown loamy sand with moist color 10YR 3/4 with soil moisture content of 14.57%, 64.32% gravels by weight, with a pH of 5.99 and EC of 31.8μS. Bw/C1 (face 2) is reddish brown sandy loam with moist color 10YR 3/6 and soil moisture content of 25.40%, gravels 11.49% by weight, with a pH of 6.14 and EC of 37.8μS.
75-100+	C2	Reddish and grey-brown bands of sand with moist color 10YR3/4. Structure is single grain with a loose moist consistence and 29.41% gravels by weight, most very coarse. Soil moisture content of 5.77% with a pH of 6.1 and an EC of 18.35μS.