# Vegetation succession and environmental relations at the Illisarvik drained lake experiment, western Arctic coast, Canada

by

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# ABSTRACT

Illisarvik is a lake basin on Richards Island, NWT, that was experimentally drained in 1978. Surveys were conducted in 2016 at 110 sites within and surrounding the basin to study vegetation succession. These surveys extended previous records provided by L. Ovenden for 1985, 1993, and 2001. The vegetation at Illisarvik indicated a gradual shift towards undisturbed tundra species but was still compositionally distinct in 2016. Early colonizing species were rarely observed in 2016. Grasses and sedges have steadily increased in cover since drainage. Erect willows have become well-established since 1993, and the increased vegetation height has resulted in deeper snow packs. Surveys of other environmental characteristics in the basin indicated that volumetric water content and vegetation height were the primary factors controlling active-layer thickness and ground temperatures at Illisarvik. The vegetation height likely acts as a proxy for the insulating influence of the snow.

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# Chapter 1
# Overview and Objectives

## 1.1 Introduction

This thesis examines vegetation composition and succession over a 38-year period at the Illisarvik drained lake basin, NWT. In the rapidly warming circumpolar North, there is growing evidence that vegetation is responding to increases in temperature, moisture, and length of the growing season: this may result in shifts of species distributions (Tape *et al.* 2006; Myers-Smith *et al.* 2011). A transition in the tundra from low-lying species to taller woodier shrub communities will increase snow thickness and warm the ground (Sturm *et al.* 2005). Changes to surface conditions will influence the underlying permafrost (Sturm *et al.* 2001; Morse *et al.* 2012; Lantz *et al.* 2013). The greatest changes in vegetation composition at Arctic sites currently occur due to disturbance (Hernandez 1973; Truett and Kertell 1992; Forbes *et al.* 2001; Lantz *et al.* 2009).

The field investigations described in this thesis were conducted at the Illisarvik experimental drained lake basin, near the western Arctic coast (Fig. 1.1 and 1.2). Illisarvik is a long-term field site, originally drained in 1978 by Dr. J. Ross Mackay (1997) to study growth of permafrost *ab initio*. A large amount of data on ground surface conditions is available from the site, e.g., on vegetation change, active-layer thickness, and permafrost temperatures (Ovenden 1986; Mackay and Burn 2002a). These offer a unique context to study vegetation succession and the influence of vegetation development on the near-surface thermal regime, both on active-layer development and the near-surface ground thermal regime.

Illisarvik is a drained thermokarst lake basin. Lake Illisarvik was drained

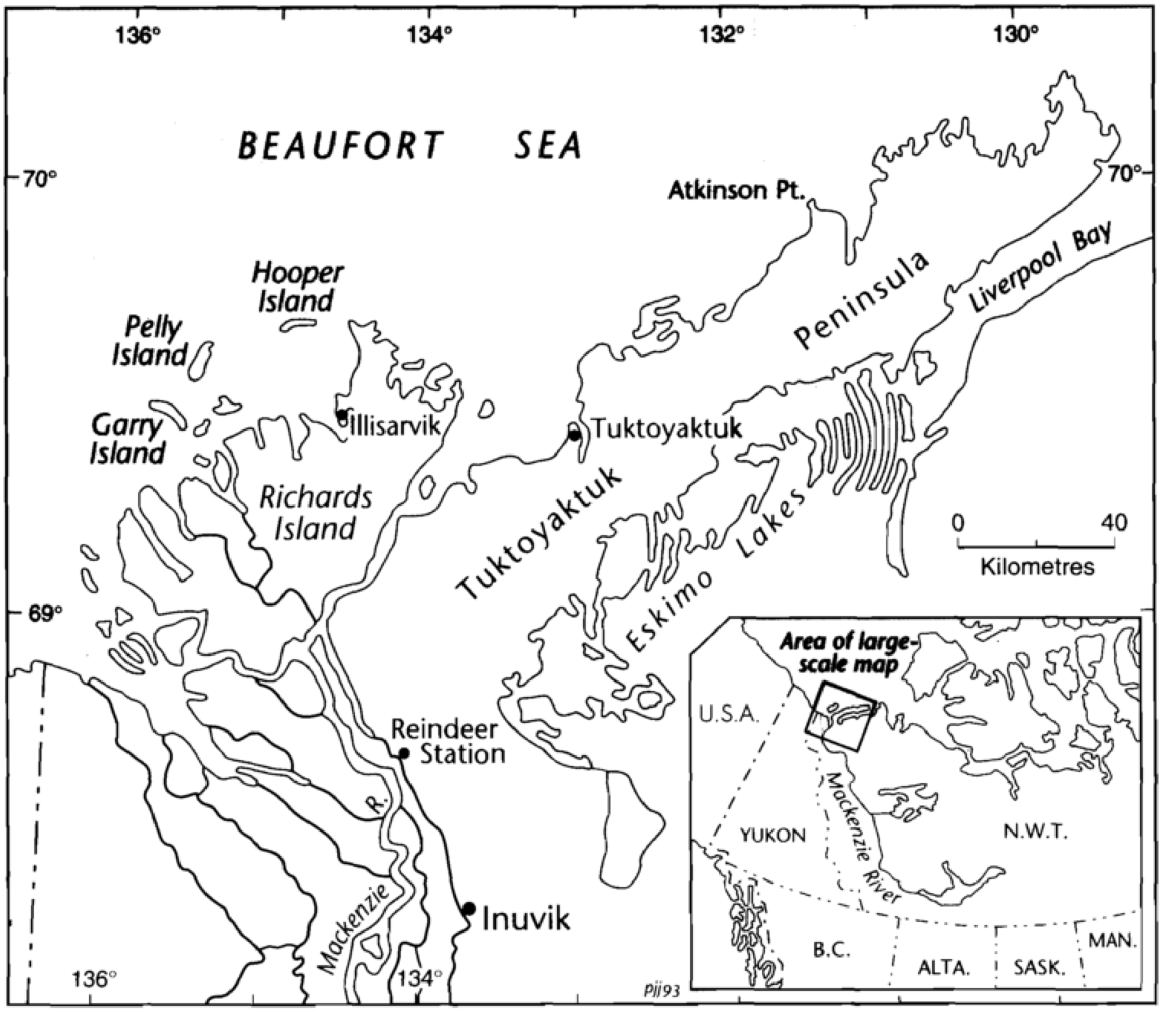


Figure 1.1 - Location of Illisarvik within the Mackenzie Delta region (Mackay and Burn 2002a, Fig. 1). © 2008 Canadian Science Publishing or its licensors, reproduced with permission.

Figure 1.2 - Illisarvik drained lake basin in August 2015 (Photo courtesy of Sam Cornish 2015).

artificially, by excavation of a small channel that enlarged when water began to flow along it (Mackay 1997). Drainage of thermokarst lakes may be catastrophic, initiated by several processes normally involving the overtopping of snow dams (Mackay 1988; Lantz and Turner 2015). Once drained, primary succession may occur *ab initio*. This thesis builds on observations of vegetation development at Illisarvik by Dr. Lynn Ovenden (1986) and her further (unpublished) surveys in 1993 and 2001.

**1.2 Vegetation composition and succession**

Vegetation succession is a directional process describing the changes in species composition over time at a site, theorized to lead to a more stable community with increased structure (Clements 1916; Bliss and Peterson 1991). In the Arctic, succession is relatively slow due to short growing seasons, low growing-season air and ground temperatures, little ground thawing, and nutrient-poor soils. Vegetation succession following disturbances has been studied at several locations in the western Arctic, e.g., Mackenzie Delta area (Ovenden 1986; Kemper and Macdonald 2009; Lantz *et al.* 2009), Yukon coast (Cray and Pollard 2015), and northern Alaska (Billings and Peterson 1980). In these regions early vegetation succession occurs at thaw slumps (Lambert 1976; Lantz *et al.* 2009), surficial disturbances from development (Hernandez 1973; Kemper and Macdonald 2009), and drained lake basins (Billings and Peterson 1980; Ovenden 1986). These studies indicated a general pattern in which early successional species, primarily composed of graminoids, transition to shrub-dominated communities over time. All of these studies employed a chronosequence approach. Illisarvik provides a unique research opportunity to take a longitudinal approach using Ovenden's (1986; unpublished) vegetation surveys. These data and the survey described in this thesis (2016) present four points in time from which to assess vegetation change over the 38 years since drainage of the lake basin.

### 1.3 The active layer and near-surface ground temperatures

The ground above permafrost that freezes and thaws each year is the active layer (Muller 1947). Surface characteristics, such as vegetation, topography, and snow cover, all influence spatial variations in the ground thermal regime and the active layer (Sturm *et al.* 2001; Burn *et al.* 2009; Ukraintseva *et al.* 2011; Roy-Léveillée *et al.* 2014). This thesis will examine data collected in 2016 and 2017 and investigate relations between vegetation and active-layer depth and near-surface ground temperatures.

### 1.4 Snow cover

In tundra regions, distribution of snow cover is influenced by vegetation, wind, and topography (Smith 1975; Morse *et al.* 2012). Vegetation catches snow by reducing wind speeds near the surface and trapping blowing snow particles. Shrubs are more structurally complex and taller than most tundra plant species and may trap more snow than adjacent tundra vegetation (Sturm et al. 2001; Thompson *et al.* 2004; Morse *et al.* 2012). Once a site's snow retention capacity has been filled, snow will be re-distributed by the wind to depressions and wind-sheltered locations. Topographic variability is, therefore, a key determinant of snow depth in tundra regions (Liston and Hiemstra 2011; Morse *et al.* 2012).

The snow pack is comprised primarily of air, which has low thermal conductivity, commonly allowing the snow cover to be an effective insulator limiting heat loss from the ground to the atmosphere (Sturm *et al.* 1997). Areas with deeper snow have higher soil temperatures in winter than areas with thinner or denser snow cover, and, as a result, the permafrost is commonly warmer and the active layer thicker (Mackay and Burn 2002a; Morse *et al.* 2012; Palmer *et al.* 2012). A prime effect of change in vegetation is the influence on the snow cover and its density that may follow from adjustments to the physical structure of the vegetation (Sturm et al. 2001; Morse *et al.* 2012).

### 1.5 Research objectives

This thesis aims to provide a better understanding of vegetation succession following disturbances, and the influence of the vegetation on the ground thermal regime. The purposes of this thesis are: (1) to determine the vegetation succession that has occurred at Illisarvik since drainage in 1978; and (2) to determine environmental relations associated with vegetation succession and composition within the Illisarvik drained lake basin.

The specific research objectives of this thesis are to investigate:

1. vegetation development since drainage;
2. relations between vegetation distribution and nutrient availability, soil moisture, organic matter (OM) thickness, and soil characteristics in 2016;
3. effects of willow distribution within the basin on snow depth and active-layer thickness; and
4. differences in vegetation communities and active-layer thicknesses between the lake basin and surrounding undisturbed tundra.

### 1.6 Research methods

Vegetation surveys were conducted throughout the drained lake basin and the surrounding tundra in July and August 2016. These surveys were completed at pre-established grid points established by the Geological Survey of Canada in 1979 within the basin, i.e., at the same sites as surveyed by Ovenden in 1985, 1993, and 2001 (Ovenden 1986). At each of these sites, active-layer thickness, soil moisture, leaf-area index (LAI), and organic-matter thickness were measured, and soil samples were collected from each vegetation community within the basin and from the tundra. A year of near-surface ground temperatures was recorded within each vegetation community from August 2016.

### 1.7 Thesis structure

This thesis is composed of seven chapters. The following chapter reviews the processes of vegetation succession at drained lakes and other disturbed areas in permafrost environments and the variables that influence ground thermal regimes. Chapter 3 provides a summary of the study area and the study design and methodology. Chapter 4 describes the vegetation distribution, composition, and succession within the drained lake basin using data collected by Lynn Ovenden in 1985, 1993, and 2001 as well as surveys in 2016. Chapter 5 examines the relations between vegetation, environmental variables, active-layer thickness, near-surface ground temperatures and snow thickness. Chapter 6 provides a summary of the results, presents conclusions, and makes suggestions for future research.

# Chapter 2
# Background

## 2.1 Introduction

Illisarvik is a well-documented, long-term field experiment on the growth of permafrost (Mackay 1997). The drained lake is on Richards Island near the western Arctic coast (Fig. 2.1). Vegetation is a key influence on the surface energy regime, active-layer thickness, and ground temperature at Illisarvik (Mackay and Burn 2002a). An examination of vegetation succession at Illisarvik requires an understanding of the factors that influence vegetation establishment and development in the Arctic.

## 2.2 Thaw-lake basins

The Tuktoyaktuk Peninsula and Richards Island in the western Arctic are home to thousands of lakes covering 15-50% of any given area (Mackay 1988) (Fig. 2.1). Lake drainage in the Tuktoyaktuk Peninsula area has been estimated at approximately two lakes per year from 1950-1986 (Mackay 1988), and one lake per year between 1985 and 2000 (Marsh *et al.* 2009). Many of these drainages occurred catastrophically and were completed within a few hours, usually associated with the erosion of a drainage channel along interconnecting ice wedges (Mackay 1988).

Upon drainage, exposed lake bottom sediments provide an area for vegetation colonization. The initiation requirements for drainage (Mackay 1997; Jones *et al.* 2012) and the vegetation composition of basins of varying ages (Ovenden 1986; Hinkel *et al.* 2003; Bockheim *et al.* 2004; Jones *et al.* 2012; Lantz 2017) have both been analyzed, but there are no studies from the region known to the author that have examined vegetation

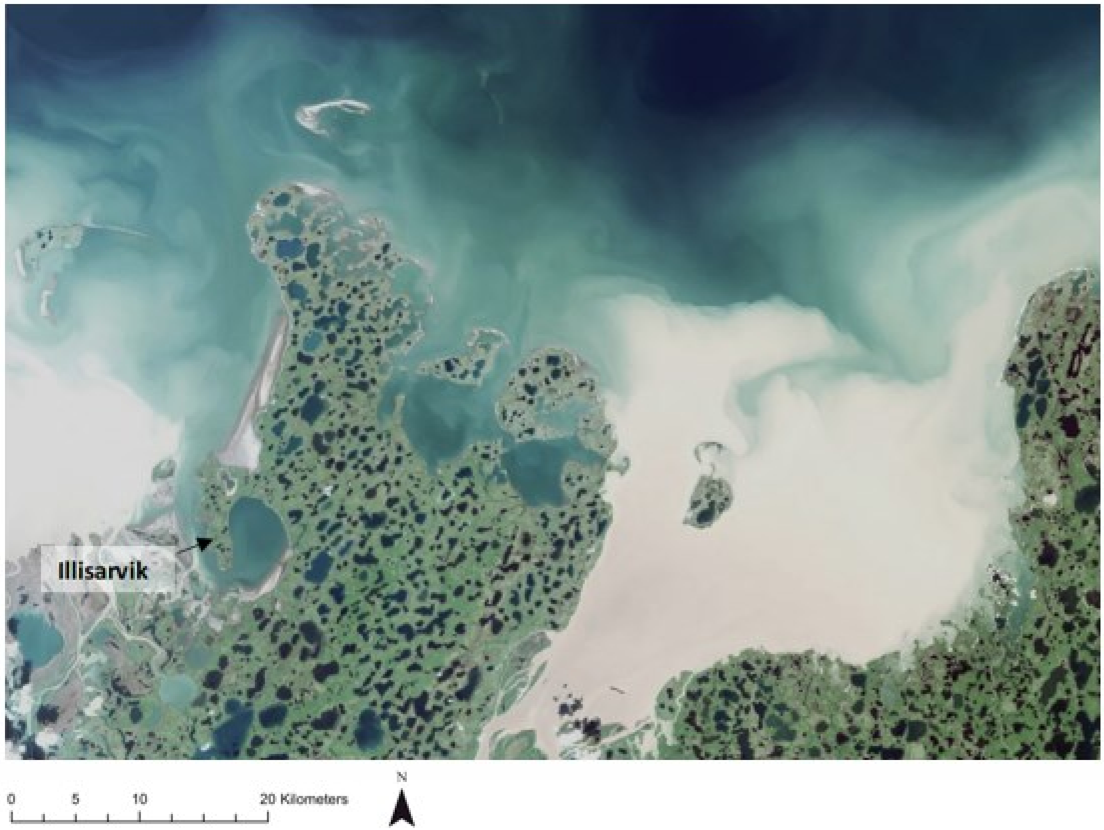


Figure 2.1- Satellite image of northern Richards Island in the Tununuk and Kittigazuit low hills. Imagery from Sentinel-2, July 10th, 2016.

succession at one site on a multi-decadal time scale.

### 2.3 Permafrost and vegetation

The Arctic tundra biome is north of treeline and is characterized by vegetation of low species diversity and low annual productivity (Forbes *et al.* 2001). The Arctic has a range of climatic and hydrologic conditions and is often classified into the High Arctic and Low Arctic. The Low Arctic has higher air temperatures and a longer growing season than the High Arctic. The Canadian Low Arctic contains more erect shrubs and, with about 700 species extant, a higher vascular plant cover and diversity (Forbes *et al.* 2001).

The treeline is an ecotone comprising a mosaic of tundra and forest (Timoney *et al.* 1992). The latitudinal position of treeline is controlled by climate; it is determined by the median position of the Arctic front in summer, which is generally the northern limit of the 10 °C isotherm in July (Bryson 1966). Treeline is close to the southern boundary of continuous permafrost, which occurs where the mean annual air temperature (MAAT) is -6 to -8 °C (Smith and Riseborough 2002; French and Slaymaker 2012). Smith and Riseborough (2002) indicate that treeline is a critical boundary for permafrost because of its effects on snow cover.

The presence of permafrost generally limits rooting of plants to within the active layer, thus reducing the presence of trees. The active layer limits larger vegetation to shrubs such as *Salix* spp. (willow) and *Alnus* spp. (alder). Vegetation is an important factor that influences local microclimates. Vegetation change is expected to affect environmental variables such as moisture and surface temperature (Oke 1987). Changes in these variables may then influence the ground thermal regime.

## 2.4 Vegetation establishment

Vegetation succession is recognized as an important concept in understanding ecological systems and for improving our ability to predict the impact of disturbances on the landscape. The low species diversity of Arctic ecosystems makes them particularly susceptible to disturbance from industrial activity and climate warming. Arctic systems are generally characterized by limited heat, short growing seasons, and nutrient poor soil, so recovery from disturbances is impeded by the available environmental resources (Bliss and Peterson 1991; Forbes and Jeffries 1999).

The term vegetation "succession" was first coined by Clements (1916) who viewed the vegetation system as a superorganism in terms of growth, development, and reproduction. It was solely directional, culminating in a final fixed community assemblage termed "the climax". Succession can be either primary or secondary, in which primary succession begins on a newly formed or exposed soil, such as a drained lake basin, while secondary succession is the re-establishment of vegetation on land that had been previously vegetated but was destroyed, such as after a forest fire. Pickett *et al.* (1987) established a set of working definitions separating the study of succession into three categories: pathways, mechanisms, and models of succession. Successional *pathways* refer to the temporal patterns of vegetation succession, while the *mechanisms* of succession refer to the processes or interactions that contribute to the successional change. A *model* of vegetation succession is a construct to explain successional pathways by combining mechanisms and specifying the relations among the mechanisms along the various stages of the pathway (Pickett *et al.* 1987). Egler (1954) states that succession is either Relay Floristic, corresponding to the classical Clements (1916) model of succession or, alternatively, results from Initial Floristic Composition (IFC), and vegetation develops through changes in species dominance. Based on IFC, Huston and Smith (1987) simulated succession based on species interaction and described five possible outcomes: 1) patterns or replacement, 2) divergence, 3) convergence, 4) suppression, or 5) pseudo-cyclic replacement.

Numerous mechanisms explain observed patterns of succession, including vegetation competition (Grime, 1977; 1979), facilitation/inhibition (Connell and Slatyer 1977), life history characteristics (Egler 1954; Huston and Smith 1987), and resource allocation (Tilman 1985). The importance of these mechanisms varies relative to one-another depending on the degree of environmental severity (Svoboda and Henry 1987; Walker and Chapin 1987; Matthews 1992; Chapin *et al.* 1994). Factors that increase the severity of an environment include low nutrient availability, limited moisture, short growing seasons, and low temperatures. Competition is considered a chief agent of classical vegetation succession in low-stress environments. Grime (1977) suggests that in marginal habitats (habitats with stronger environmental stress) there are fewer competitor plant strategies. Potential biological interactions are important in all habitats, yet in environments with severe environmental stressors, such as the Arctic, inherent environmental conditions may be more critical than any biological control. In non-stressed environments, allogenic processes (externally driven processes) are important in the beginning of succession, after which autogenic processes (internal or community driven processes) become more significant (Matthews 1992). In unfavourable conditions for plant growth there are more constraints on biological production so allogenic processes are more important throughout all stages of succession.

Plant functional types (PFTs) used by Arctic ecologists provide a useful framework for predicting vegetation responses to ecosystem processes (Chapin *et al.* 1996; Ustin and Gamon 2009). The PFTs (e.g. deciduous and evergreen shrubs, forbs, graminoids, mosses, and lichens) have been widely used to describe plant responses to the environment (Webber 1978; Walker *et al.* 1989; Chapin *et al.* 1996). PFT classifications vary depending on the research and ecosystem studied but are generally grouped by their response to the environment and perturbations through the same mechanisms (Chapin *et al.* 1996; Gitay and Noble 1997).

### 2.4.1 Environmental controls

There is a suite of interacting factors that influence the growth of different species in a plant community at the local level (Scott and Billing 1964; Chapin and Shaver 1985) (Fig. 2.2). Plant production in an area is the aggregate response of many species reacting independently to many environmental factors (Scott and Billings 1964; Chapin and Shaver 1985; Chu and Grogan 2010). Environmental factors that have the largest influence on production in the tundra are moisture availability, temperature, and nutrient availability (Bliss and Wein 1972; Svoboda and Henry 1987; Myers-Smith *et al.* 2011).

#### 2.4.1.1 Moisture

The Arctic is drier than environments south of the treeline. For example, there is an increase in precipitation at Inuvik (241 mm) (south of treeline) versus Tuktoyaktuk (161 mm) (north of treeline) (Environment Canada 2016). Summer precipitation plays a reduced role in annual precipitation in comparison with snow. Despite snowmelt being the largest potential source for water, most of it runs off or evaporates due to limited percolation into the frozen ground. During the growing season, light rains are more

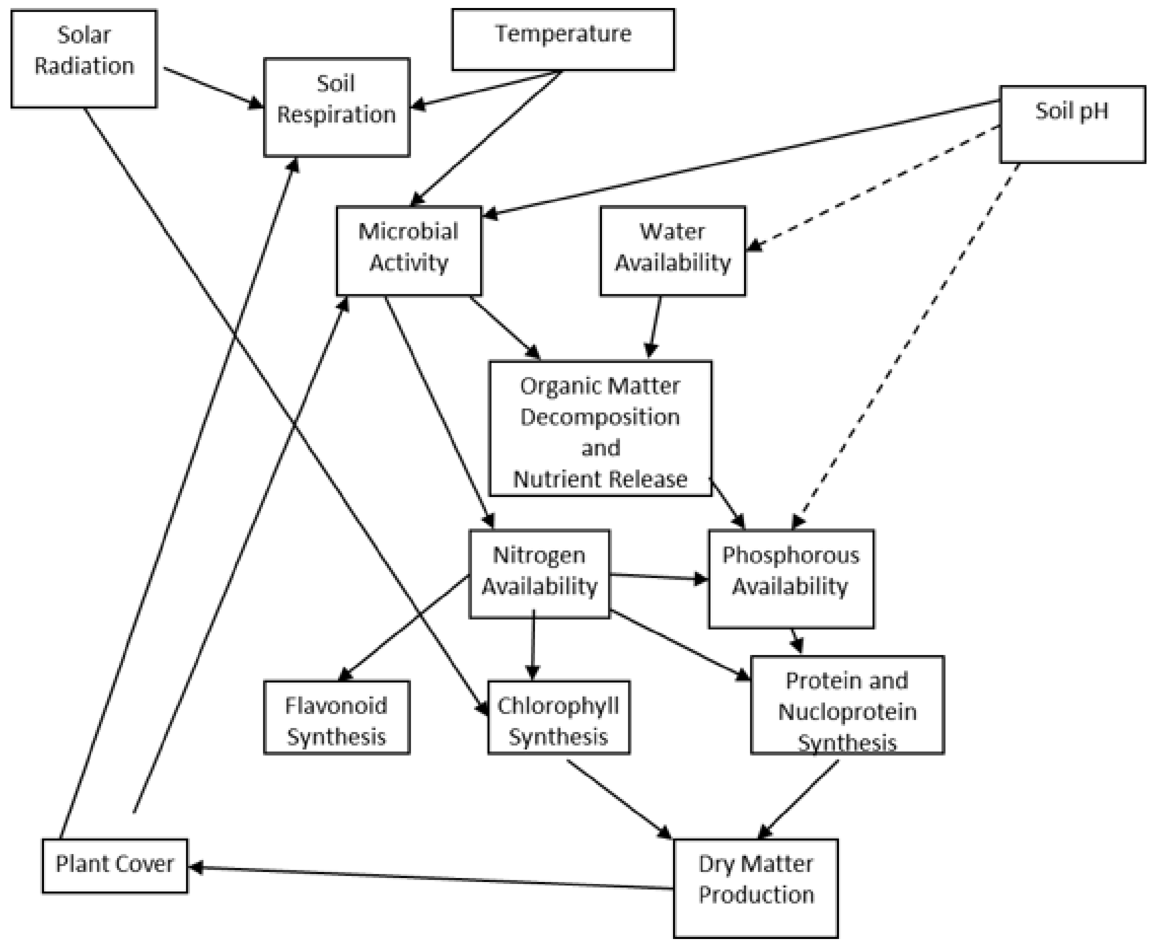


Figure 2.2 - Compartment model showing the interactions between environmental factors and plant metabolism in the limitation of primary production. (Modified from Haag 1974, Figure 2, p. 111).

common than heavy rainfalls (Bliss *et al.* 1981).

As the summer progresses, the presence of permafrost aids plant growth by preventing deep infiltration and retaining water for root transpiration. However, the soil moisture in more well-drained soils may decrease throughout the summer as active-layer thickness increases. Ninety-six percent of the rooting mass of Arctic tundra vegetation is found in the top 30 cm of the soil profile, in comparison with 52-85% in temperate and tropical biomes (Jackson *et al.* 2000). The confinement of the plants' rooting depth to the upper soil horizons indicates that although a warming climate may cause a deepening of the active layer, some species may not successfully extend roots downwards to effectively access moisture throughout the summer (Björk *et al.* 2007).

Soil moisture is important in structuring vegetation communities. Hydrophilic plants with aerenchyma, such as sedges, grow in hypoxic conditions provided by saturated soils, commonly found in poorly drained depressions in tundra environments.

**2.4.1.2 Temperature**

The presence of impermeable permafrost leads to lower ground temperatures even in summer. Low temperatures reduce plant root respiration and limit the ability for root uptake of water and nutrients (Chapin and Shaver 1981). A majority of soluble nutrients are flushed through the ecosystem during spring runoff through overland and near surface flow, which plant roots within the frozen soil cannot take up. Additionally, low temperatures limit organic matter decay rates and microbial transformation of organic matter. In return, this limits the N available for primary production (Haag 1974). An increase in ground temperatures may raise microbial activity and nutrient cycling (Chu and Grogan 2010), which may also accelerate shrub growth, as observed in the Low

Arctic (Hollister *et al.* 2005; Zamin and Grogan 2012; Fraser *et al.* 2014).

**2.4.1.3 Nutrients**

Nutrient availability is important to Arctic plant survival and growth (Bliss and Peterson 1991). Nutrient availability to plants depends on source, strategy, and delivery. Soil moisture and temperature influence the biological processes that result in nutrient cycling and nutrient availability for plants. Nutrients in tundra landscapes accumulate in the soil organic matter and recycle slowly due to waterlogged conditions and/or high acidity (Dowding *et al.* 1978). In tundra environments, evergreen vegetation predominates at nutrient-poor sites where nutrient retention and conservation are of high importance (Small 1972) whereas forbs, graminoids, and deciduous shrubs tend to dominate more nutrient-rich sites. Vegetation with higher nutrient concentrations attract herbivores, which may, in turn, increase nutrient inputs into the soil (Schultz 1968; Jeffries 1988). Forbs and deciduous shrubs predominate at drier microsites where soils are less acidic, have greater soil organic matter, and mycorrhizal fungi. The associated mycorrhizal fungi may explain their capacity to take up a large amount of phosphorus in a phosphorus-poor environment (Smith *et al.* 2011; Zamin and Grogan 2012). Plants require macro- and micronutrients for survival, but nitrogen and phosphorus are the greatest limiting nutrients in tundra environments.

Nitrogen is a major limiting nutrient for vegetation production in the tundra (Haag 1974; Bliss *et al.* 1981). Most nitrogen enters the soil through nitrogen fixation; primarily by bacteria, lichens, and fungi (Bliss *et al.* 1981). Nitrogen is available to plants in the mineral forms of ammonium ($NH_4^+$) and nitrate ($NO_3^-$), and soluble organic nitrogen such as glycine (Atkin 1996). $NH_4^+$ is the predominant form taken up by plants but may also be taken up as amino acids and $NO_3^-$ (Chapin *et al.* 1993; Nadelhoffer *et al*. 1996; Clemmensen *et al.* 2008). The relative availability of mineral versus organic N can vary among ecosystems (Atkin 1996; Sorensen *et al.* 2008), and there are conflicting reports on the importance of mineral N compared with organic N (Chapin *et al.* 1993; Schimel and Chapin 1996; Henry and Jefferies 2003; Näsholm *et al.* 2009). Tundra typically has acidic, infertile, anaerobic, and cold conditions that tend to result in low $NO_3^-$ compared with $NH_4^+$ and organic N (Atkin *et al.* 1993; Kielland 1994; Gebauer *et al.* 1996; Keuper *et al.* 2012).

There may be a species-specific difference in the preference of N for uptake in different forms; species in the *Carex* (sedge) genus preferentially take up $NO_3^-$, whereas other sedges, grasses and shrubs have increased uptake of organic N and $NH_4^+$ (Iversen *et al.* 2015). This is consistent with the consensus that $NH_4^+$ is preferred over $NO_3^-$ in most northern plants (McCown 1978; Chapin *et al.* 1982; Bliss and Peterson 1991).

Phosphorus is tightly conserved in Arctic ecosystems, even when it is not the main limiting nutrient (Chapin *et al.* 1980). Phosphorus may be just as limiting as nitrogen, as found in the experiment by Zamin and Grogan (2012) in which birch shrubs were equally limited by nitrogen and phosphorus availability. In moist and wet tundra environments, phosphorus inputs are small, primarily from rainfall. In dry tundra environments with thin organic horizons, phosphorus input is influenced more by the properties of the mineral soil horizon. Most phosphorus uptake occurs early in the growing season, shortly after snowmelt, when the competition with microbial communities is reduced (Chapin *et al.* 1978). Phosphorus is more likely to be limiting in lowland communities where dilution of the soil solution may decrease its availability

(Haag 1974). Slowly cycling soil phosphorus and limited phosphorus availability may drive the distribution of a number of important graminoid species (Webber 1978). Sedges (especially the *Carex* genus) can have rates of phosphorus uptake that are an order of magnitude greater than other tundra species (Chapin and Slack 1979; Shaver *et al.* 1979; Chapin and Tryon, 1982; Kielland and Chapin 1994).

A low cycling rate of nitrogen and phosphorus limits production rather than the supply itself (Haag 1974). Differences in plant rooting depths may have important future implications with a warming climate, for deeply rooted plants may have an advantage if nutrients are released from thawing permafrost as the active layer deepens (Keuper *et al.* 2012). Available nitrogen may increase with a warming climate, which will be advantageous to tundra species that prefer more nutrient-rich environments such as forbs, graminoids, and deciduous shrubs. In particular, increased nutrient availability may favour shrubs over other tundra plants (Bliss and Matveyeva 1991; Chapin *et al.* 1995; Arft *et al.* 1999; Tape *et al.* 2006; Zamin and Grogan 2012). Soils with large amounts of decomposable carbon, commonly found in cold wet soils in tundra ecosystems, may have increased respiration in response to warming, likely releasing nutrients from decomposing organic matter (Nadelhoffer *et al.* 1991). Species that have greater rooting depths such as sedges and deciduous shrubs will be able to more effectively compete for nutrients released from thawing permafrost (Björk *et al.* 2007; Myers-Smith *et al*. 2011; Iversen *et al.* 2015)

### 2.4.2 Vegetation competition

Differences in vegetative growth, seed production, and plant mortality are observed wherever plants grow in close proximity. It would be wrong to attribute all differences in vegetation establishment to competition since variations in success of neighbouring plants may arise from differences in capacity to exploit features of the physical or biotic environment. For this thesis, competition is defined as “the tendency of neighbouring plants to utilize the same quantum of light, ion of a mineral nutrient, molecules of water, or volume of space” (Grime 1973).

Dry-matter production is subject to environmental constraints, such as shortages or excesses in solar energy, water, and mineral nutrient, but also sub-optimal temperatures and growth-inhibiting toxins such as heavy metals within the soil. These stresses may operate in the same environment and may be complicated when certain stresses either originate or are intensified by the vegetation itself (Grime 1977). The most important types of plant-induced stress are shading and reduction of mineral nutrients in the soil following plant biomass accumulation (Grime 1977).

The vegetation that is best adapted to take advantage of the nutrients and light will succeed. For example, *Dupontia fisheri*, *Arctophila fulva*, and *Carex aquatilis* all have similar life-history adaptations that lead to competitive sorting along spatial patterns of habitat. *Dupontia* and *Arctophila* grow rapidly except in nutrient-poor conditions. *Carex aquatilis* has slow growth, but can tolerate nutrient-poor conditions, and it appears to eliminate rapidly growing species by forming density distributed roots which absorb nutrient and reduce the nutrient availability for other species (Billings and Peterson 1991). Additionally, species requiring significant amounts of solar radiation would not be found in the understorey of willow or alder shrubs.

Herbivory is another stress applied to species success. Feeding by herbivores such as caribou, voles, and lemmings can inhibit plant growth (Olofsson *et al.* 2009). When the herbivores are present at a site they prefer nutrient-rich, fast-growing species, which are more commonly found in early stages of succession. The importance of herbivory varies spatially and temporally in the Low Arctic due to the relatively low population of herbivores (Walker and Chapin 1987).

### 2.4.3 Succession following disturbances

The frequency and extent of disturbances may increase in the Arctic following climate warming (Anisimov *et al.* 2002; ACIA 2005). These conditions may cause a differential response in disturbed and undisturbed tundra, and the response of plants to increased temperatures following a disturbance may be intensified (Lantz *et al.* 2009). Hydrologic, nutrient, and thermal regimes are altered following a disturbance and are reflected in soil and vegetation characteristics within disturbed areas (Walker 1996). The removal of vegetation following a disturbance may reduce albedo by up to a factor of two (Haag and Bliss 1974; Babb and Bliss 1974), increase soil temperatures and deepen the active layer (Bliss and Wein 1972; Auerbach *et al.* 1997; Lantz *et al.* 2009). A deeper active layer may lower the water table, thus reducing the rate of vegetation regeneration. Forbes *et al.* (2001) found that vegetation regeneration was faster at wet sites. Slower regeneration rates in drier tundra environments are also associated with aeolian erosion in which vegetation has difficulty establishing on a continuously eroding substrate. Additionally, moisture and temperature influence nutrient availability; therefore, disturbances will change the constraints on plant production (Chapin and Shaver 1981; Ebersole and Webber 1983; Walker and Walker 1991; Forbes *et al.* 2001).

At disturbed sites, species that are available to colonize do so through surviving site disturbances, emerging from a seed or bud bank, or by vegetative spread and seed dispersal from adjacent sites (Kemper and Macdonald, 2009). Drained lake basins are considered a primary succession site as they produce a previously unvegetated surface to colonize. In primary succession, seed dispersal mechanisms promoting seeds from distant sources are more important than in secondary succession paths (Viereck 1966; Davis et al. 1985; Del Moral and Clampitt 1985). These species that are commonly early colonizers are ruderal plants. Ruderal plants are short-lived perennials or annuals with high rates of dry matter production that commonly exploit environments intermittently favorable for rapid plant growth and maximize seed production (Grime 1977). Ruderals are often colonizing species that establish shortly after a disturbance and are subsequently replaced by vegetation that will compose the more stable "climax" community (Grime 1977). *Senecio congestus* is a ruderal commonly observed at recently disturbed sites in northwest Canada (Burn 2012).

Vegetation succession following disturbances has been studied in the western Arctic in thaw slumps (Lambert 1976; Lantz *et al.* 2009), at surficial disturbances from development projects (Bliss and Wein 1971; Hernandez 1973; Johnstone and Kokelj 2008; Kemper and Macdonald 2009), and in drained lake basins (Billings and Peterson 1980; Ovenden 1986, Lantz 2017). The majority of these studies consider a short time period, a few years to a decade, and all observed similar colonizing species, especially the colonizing grasses *Festuca rubra*, *Arctagrostis latifolia*, *Poa lanata,* and *Calamagrostis canadensis*. The forb *Senecio congestus* commonly colonizes within the first year following disturbance (Bliss and Wein 1972; Lambert 1976; Kemper and Macdonald 2009). In wet environments, *Carex aquatilis* and *Arctophila fulva* are common, while *Equisetum* spp. dominate moist environments (Bliss and Wein 1972; Gill

1973). None of these species are as common in undisturbed tundra (Bliss and Wein 1972; Kemper and Macdonald 2009).

Kemper and Macdonald (2009) and Johnstone and Kokelj (2008) studied vegetation at seismic lines and drilling sumps 30 years after oil and gas exploration. They noted erect *Salix* establishment north of treeline at these disturbances. Overall, 30 years following disturbance, the vegetation was still distinct from the surrounding undisturbed tundra (Kemper and Macdonald 2009). Variations in species composition were primarily due to moisture availability and disturbance type. In areas where vegetation was not completely removed by the disturbance, the original vegetation may re-colonize through rhizomatic growth (Johnstone and Kokelj 2008; Kemper and Macdonald 2009).

#### 2.4.3.1 Succession following thaw lake drainage

In northern Alaska, Hinkel *et al.* (2003), Bockheim *et al.* (2004), Jones *et al.* (2012), and Lantz (2017) have described the vegetation of thaw lake basins of ages ranging from ~50 to ~2000 years. This research indicates that lake basin succession begins with highly productive fen vegetation that is succeeded by sedge meadows and develops into shrub bog and tussock-dominated ecosystems after several hundred years. This supports the thaw lake cycle in which over hundreds of years the following occurs: a lake drains, vegetation establishes, low-centered polygons with ice-wedges develop, there is thaw and coalescence of polygons, and finally a thaw lake develops (Billings and Peterson 1980). Jorgensen and Shur (2007) argue that a smaller lake may form in the basin or a series of infilling ponds.

The vegetation succession determined in northern Alaska following lake drainage is supported by studies in other disturbed Low Arctic environments. *Dupontia fisheri* and

*Arctophila fulva* rapidly colonize wet areas, while *Carex aquatilis* dominates in older disturbed areas with lower nutrient availability (Bliss and Peterson 1991) (Fig. 2.3). Successional trends for thaw lake basins that have drier environments unable to support *Dupontia*, *Arctophila,* or *Carex* colonization have not been investigated. Additionally, all the successional research on lake basins uses an ergodic hypothesis with the successional model inferred from basins of varying age.

Paired succession studies examine basins of different ages to represent the stages of succession (ergodic hypothesis); this assumes that under certain circumstances, sampling in space can be the equivalent to sampling through time (Chorley and Kennedy 1971). This method ignores process and spatial variation within sites, and that contingent factors, such as boundary conditions, and the particular order of events over time at a given site may all affect the subsequent trajectory of the system (Pickett 1989). Space-time substitution has an implicit assumption that soil conditions, microclimate, and history of the sites are the same. This is not a valid assumption as climate is not constant over time: a 2000-year-old drained lake would have been influenced by different initial climatic conditions than one that drained in the past year. Space-time substitution is common due to a lack of long-term study sites from which to obtain data and is required at present to consider changes over time scales that are longer than about a century.

Lantz (2017) discusses vegetation succession following catastrophic lake drainage in Old Crow Flats, Yukon. Two distinct communities developed over the short-term (≤ 83 years): dense stands of willows (primarily *Salix pulchra* and *Salix glauca*) in well-drained areas and *Carex aquatilis* in areas with high soil moisture. The willow stands were likely a seral community and in the long-term trajectory of the basin would not be

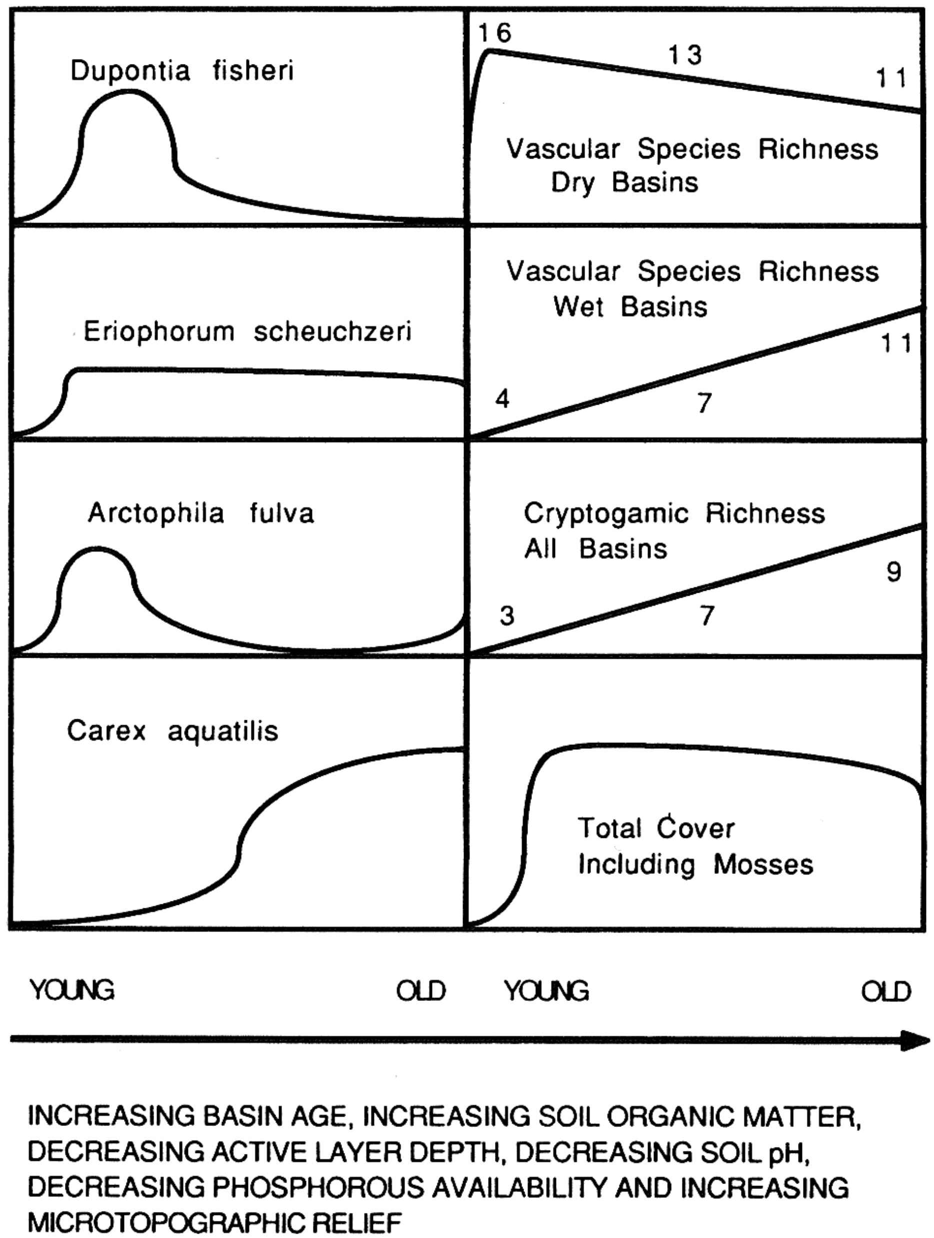


Figure 2.3 - In drained lake basins near Barrow, Alaska, well-dispersed plants dominate early succession. Tolerance of high stress environments (low-fertility) characterizes late successional species. Numbers associated with species richness curves represent average number of species with cover exceeding 1% (Bliss and Peterson 1991, Fig. 3). © Elsevier Book, reproduced with permission.

the dominant species (Lantz 2017). Lantz (2017) was unable to determine whether the transition from willow-dominated communities would be to tussock and dwarf shrub communities common in the treeline ecotone of Old Crow Flats or take another successional trajectory in response to the changing climate.

**2.5 Shrubification and greening of the Arctic**

Deciduous shrubs respond to warming on decadal time scales (Tape *et al.* 2006), and shrubs such as alders are expected to show improved growth and recruitment in response to disturbance and climate change (Sturm *et al.* 2001b; Lantz *et al.* 2009). Tundra disturbances may create microsites where tall shrubs may establish and remain dominant for decades to centuries. Disturbances may also be a precondition for shrubs to take advantage of improved environmental conditions (Myers-Smith *et al.* 2011).

Increases in shrub biomass, cover, and abundance (colloquially termed *shrubification*) have been observed in many tundra environments in the last century (Smith *et al.* 2001b; Tape *et al.* 2006; Myers- Smith *et al.* 2011). Increases in alder and willow cover have been observed in northern Alaska, western Canadian Arctic, Canadian High Arctic, northern Quebec and Arctic Russia (Myers-Smith 2011, review paper). Increases in the western Canadian Arctic have been primarily of alder and willow species (Lantz *et al.* 2010; Myers-Smith *et al*. 2011b). The snow-shrub-climate hypothesis suggests that warmer climate, earlier snowmelt, and longer growing seasons support increased shrub growth. The shrub growth in turn increases snow depth, thus increases water availability and soil temperatures. Increased temperatures promote microbial activity which in turn accelerates nutrient cycling and further supports shrub growth (Fig.

2.4) (Sturm *et al.* 2001).

Sturm *et al.* (2005) found that active-layer temperatures around shrubs are higher than in shrub-poor locations, resulting in enhanced winter microbial activity that increases nitrogen mineralization (Fig. 2.4) (Truett and Kertell 1992; Sturm *et al.* 2005). Increased nutrient availability favours growth of shrubs and grasses over other tundra plant functional types (Dormann and Wodin 2002; Gough and Hobbie 2003; Wang *et al.* 2017). Larger and more abundant shrubs will trap more snow, increasing the snow depth and lead to even greater soil warming, thus creating a positive feedback loop (Sturm *et al.* 2001; Sturm *et al.* 2005; O'Neill and Burn 2017 a,b). The vegetation succession and shrub growth within Illisarvik lake basin may modify the aggradation of permafrost through impacts on the surface energy balance and ground thermal regime.

### 2.6 Surface energy balance and vegetation

The ground above permafrost that freezes and thaws each year is called the active layer (Muller, 1947). The thickness of the active layer is controlled by a number of environmental factors such as vegetation, snow cover, substrate, and water content (French 2007). Thawing of the active layer is one-sided, occurring from the surface downwards, while autumn freeze back is two-sided from the surface downwards and top of permafrost upwards (French, 2007). The energy for thawing depends on the surface energy balance which is influenced by vegetation cover among other factors.

The surface energy balance describes how radiative energy is partitioned at Earth's surface (Oke 1987). The *surface* in this thesis will refer to the ground surface, either soil or organic matter in summer, unless otherwise specified.

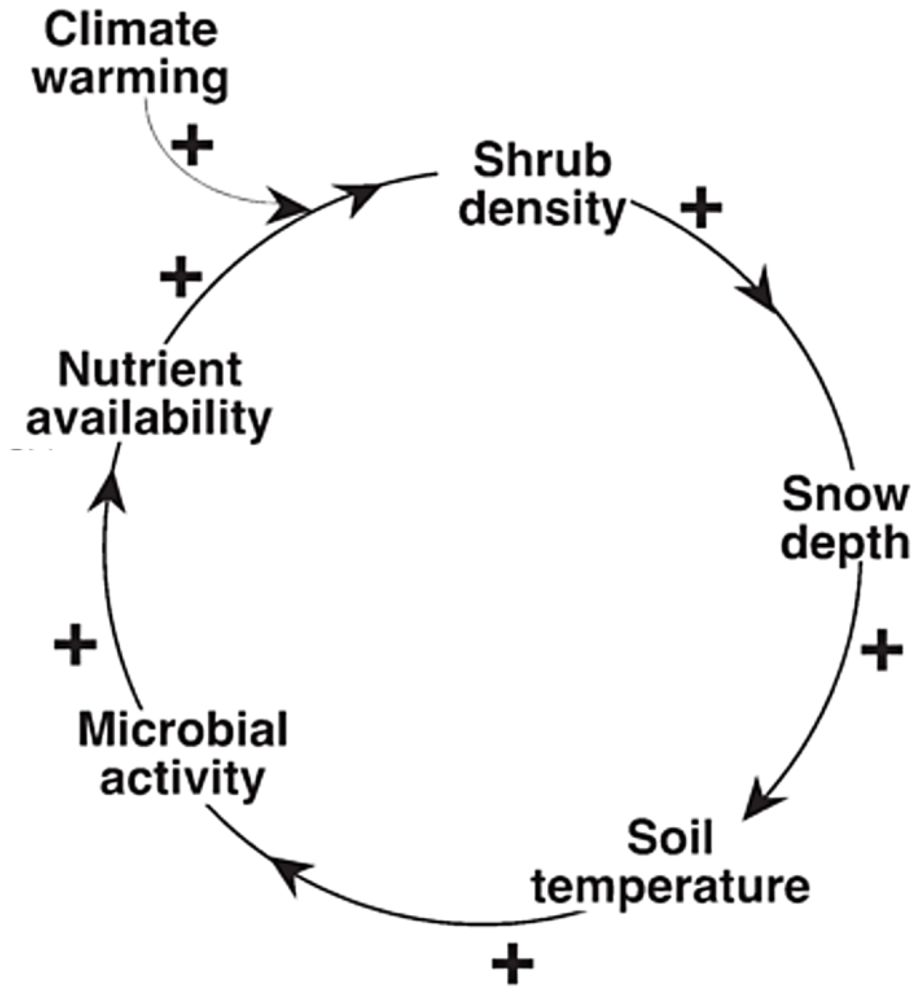


Figure 2.4 - Snow-shrub-soil-microbe feedback loop (based on Sturm et al. 2005, fig. 9). © Oxford University Press, reproduced with permission.

### 2.6.1 Radiation balance

The radiation balance considers short-wave (K) and long-wave (L) radiation. Short-wave radiation emanates from the Sun. It may be absorbed by the ground surface or atmosphere and may be reflected back to space or scattered to create diffuse radiation. Long-wave radiation is the spectrum of radiation emitted by bodies near the Earth's temperature, such as clouds, and the Earth's surface. The radiation balance describes how radiant energy at the Earth's surface is reflected, absorbed, and reemitted:

$$(1)\quad Q^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow$$

where $K\downarrow$ is the incoming short-wave radiation and $K\uparrow$ is the outgoing short-wave radiation. $L\downarrow$ is the incoming long-wave radiation, and $L\uparrow$ is the outgoing long-wave radiation. $Q^*$ is the radiative surplus or deficit at that location (W $m^{-2}$).

#### 2.6.1.1 Vegetation controls on radiation balance

The short-wave radiation flux varies through the day and over the year (Oke 1987). Objects ranging in size from vegetation to mountains may shade the surface from incoming short-wave radiation. Increased vegetation cover may increase shading of the surface, thereby decreasing $K\downarrow$ at the surface.

$K\uparrow$ is the energy reflected from a surface. The surface reflectivity or albedo ($\alpha$, the ratio of $K\uparrow$ to $K\downarrow$) ranges from near 0 to near 1. In the late winter, taller vegetation, such as shrubs that are above the snowpack, reflect less short-wave radiation than snow ($\alpha$ approaching 1 when fresh and clean) due to their lower albedo (~ 0.2). Increased shrub density and expansion across the tundra landscape is projected to reduce albedo and may accelerate snow melt (Sturm *et al.* 2005; Loranty *et al*. 2011). There is a divergence in air temperature at Tuktoyaktuk and Inuvik beginning in February due to differences in albedo between treeline and tundra (Palmer 2012).

L↓ is emitted by surface objects and the atmosphere. The amount of long-wave emitted by the atmosphere is controlled by the temperature and emissivity (Oke 1987). This relation is given by the Stefan-Boltzman equation:

$$(2)\ L = \varepsilon\sigma T^4$$

where ε is the surface emissivity, σ is the Stefan Boltzman constant (W $m^{-2}$ $K^{-4}$), and T is the surface temperature (K). Emissivity (ε) is the ability to absorb or emit energy in comparison with a perfect radiator. Vegetation can contribute to L↓ within a forest canopy, or at the level of shrubs. Natural surfaces, including leaves, are almost perfectly full radiators, with emissivities of 0.94-0.99, as a result, L↑ is primarily controlled by T.

**2.6.2 Surface energy balance**

The surface energy balance describes the fluxes of energy to or from the surface:

$$(3)\ Q^* = Q_E + Q_H + Q_G$$

where $Q_E$ is the latent heat flux, $Q_H$ is the sensible heat flux, and $Q_G$ is the ground heat flux (Oke 1987). $Q_E$ is the transport of heat captured or released during the phase change of water. $Q_H$ is heat transferred by convection to or from the overlying air. $Q_G$ is the conduction of heat to or from the underlying surface. The relative partitioning of $Q_E$, $Q_H$, and $Q_G$ are dependent upon the surface characteristics. In northern environments, Q* is small and negative through much of the year, during the snow-covered winter months when there is little incoming radiation and high albedo. During the rest of the year, incoming radiation exceeds outgoing and Q* is positive (Weller and Holmgren 1974).

**2.6.2.1 Controls on latent heat flux ($Q_E$)**

Positive $Q_E$ is a result of transpiration, evaporation, and sublimation (Beringer *et al.*

2005). The energy used in $Q_E$ does not contribute to warming the soil. It is primarily controlled by the availability of surface water, the temperature gradient between the air and ground surface, the vapour concentration gradient between the surface and air, the turbulence near the ground surface, and stomatal resistance of the vegetation cover (Oke 1987). $Q_E$ may be high at wet sites during the thaw season and during snowmelt when there is a large supply of water. An increase in vegetation cover may raise transpiration, cooling the ground surface in the summer beyond the effects of shading (Oke 1987).

#### 2.6.2.2 Controls on sensible heat flux ($Q_H$)

$Q_H$ is controlled by the temperature gradient between the ground surface and the overlying air (Oke 1987). Ground temperature and the wind speed gradient control $Q_H$ because wind speed gradient influences turbulent transfer. Turbulence is influenced by the size and structural complexity of vegetation near the ground surface (and the roughness) of the surface boundary layer (Oke 1997; Kimble 2004). With an increase in surface roughness, the fraction of $Q^*$ partitioned to $Q_H$ rather than $Q_G$ increases.

#### 2.6.2.3 Controls on ground heat flux ($Q_G$)

The ground heat flux is a conductive flux and refers to the amount of heat that enters and leaves the ground. The partitioning of $Q_G$ and $Q_H$ is controlled by the surface ($\mu_s$) and the atmospheric thermal admittances ($\mu_a$):

$$(4)\quad \mu_s/\mu_a = Q_G/Q_H$$

The thermal admittance is the ease by which a body releases or accepts heat. This is controlled by the heat capacity of air or soil, and the ability of the air and soil to transfer heat.

The magnitude of $Q_G$ is controlled by the temperature gradient between the surface and sub-surface and the thermal conductivity of the soil (Oke 1987). The conductivity of a soil is determined by its constituents, and so changes with water content (Table 2.1). In the summer, the surface is warmer than the ground at depth and, therefore, $Q_G$ is positive and heat moves from the atmosphere into the ground. In permafrost regions, sensible heating of the ground in summer is reduced as there is a large amount of energy required to melt the ice in seasonally frozen ground. In winter, the gradient is reversed and $Q_G$ is negative. The presence of snow cover may minimize ground heat loss in winter (Goodrich 1982; Williams and Smith 1989; Zhang 2005). A snowpack of 0.5 m has comparable thermal properties to a fibreglass-insulated wall 6 inches thick (Sturm 2005). As the snow pack increases throughout the winter, the magnitude of $Q_G$ decreases, and the temperatures beneath the snowpack tend to be higher (Mackay and Mackay 1974; Goodrich 1982; Sturm *et al.* 2001).

Several factors influence the partitioning of available energy to the ground heat flux, including the thermal properties of the ground material (Table 2.1) (Goodrich 1982; Williams and Smith 1989; Karunaratne and Burn 2004), canopy shading (Beringer *et al.* 2005), and the temperature gradient within the soil. The temperature gradient is strongly influenced by the presence of permafrost which maintains lower ground temperatures in summer (Karunaratne and Burn 2004). Canopy shading reduces Q* at the ground surface in summer (Beringer *et al.* 2005), but perhaps the most significant role for vegetation is snow trapping in winter (Sturm *et al.* 2001). On an annual scale, daily or weekly variations in winter conditions are of less importance to the ground heat balance because the winter is long and the presence of a thick snow pack provides great insulation. $Q_G$ is greater in winter at sites with thin snow packs (Sturm *et al.* 1997).

Table 2.1 - Thermal properties of soil constituents and snow. From Oke (1987, Table 2.1, p. 44) and Williams and Smith (1989, Table 4.1, p. 90).

| | Heat Capacity ($J\ kg^{-1}\ K^{-1}$) | Thermal Admittance ($J\ m^2 s^{-1/2}\ K^{-1}$) | Thermal Conductivity ($W\ m^{-1}\ K^{-1}$) | Thermal Diffusivity ($x\ 10^{-6}\ m^2 s^{-1}$) |
|---|---|---|---|---|
| Soil Constituents | | | | |
| Quartz | 800 | - | 8.80 | 4.14 |
| Clay minerals | 900 | - | 2.92 | 1.22 |
| Organic matter | 1920 | - | 0.25 | 0.10 |
| Water (0 °C) | 4180 | 1545 | 0.56 | 0.13 |
| Ice (0 °C) | 2100 | 2080 | 2.24 | 1.16 |
| Air (still) | 1010 | 5 | 0.025 | 20.63 |
| Snow | | | | |
| Fresh snow | 2090 | 130 | 0.08 | 0.10 |
| Old snow | 2090 | 595 | 0.42 | 0.40 |
| Peat | | | | |
| Dry peat | | | 0.06 | 0.10 |
| Wet peat | | | 0.50 | 0.12 |
| Frozen, wet peat | | | 1.10 | 0.68 |

### 2.6.3 Subsurface temperatures

The temperature at the surface and the thermal properties of the subsurface materials predominately control subsurface temperatures. The thermal conductivity, and the heat capacity of the active layer materials, including latent heat content, all influence the ground temperature. The heat capacity of the active layer changes seasonally as the water content of the soil varies in the summer, and the proportion of water and ice varies throughout the winter. The apparent heat capacity is larger as it includes the latent heat in soils near 0 °C (Williams and Smith 1989).

The active layer generally has a lower thermal conductivity in the summer than winter due to the change in thermal conductivity of soil pore contents. The low thermal conductivity in summer helps maintain permafrost even as the surface temperatures increase. When thermal conductivity is high in winter, even with a gentle temperature gradient, the temperatures at the top of permafrost will decrease (Burn 2004).

Peat has a high ratio of frozen to thawed thermal conductivities (Table 2.1). In the summer, if the peat dries out, it is primarily composed of air and is an effective insulator. This effectiveness results in steep temperature and vapour pressure gradients which drive non-conductive heat transfer processes within the active layer (Hinkel and Outcalt 1994). Evaporative cooling at the surface of peaty soils will reduce the amount of energy directed to the ground heat flux, thereby reducing soil warming (Hinkel and Outcalt 1994). Reduced evaporation in fall makes the peat wetter and, upon freezing, the peat may have a high thermal conductivity due to its high water content.

Snow cover influences subsurface temperatures. Distribution of snow cover is influenced by vegetation, wind, and topography (Smith *et al.* 1998). Snow accumulates near vegetation due to reducing wind speeds near the surface and by trapping snow particles. In the tundra, snow cover is generally thinner than south of treeline as there is less precipitation, snow is readily distributed by wind, and because snow is suspended for long periods of time the amount is reduced by sublimation (Sturm *et al.* 2001).

The presence of shrubs may lead to localized increases in snow cover as deep drifts of snow often surround and extend downwind from shrubs (Sturm *et al.* 2001; Sturm *et al.* 2005; Myers-Smith *et al.* 2011). The snow trapped by shrubs has a lower thermal conductivity due to lack of dense, wind-compacted snow layers, further insulating the ground, and leading to the snow-shrub hypothesis described in section 2.5 (Sturm *et al.* 2001; Sturm *et al.* 2005; Bewley *et al*. 2010).

### 2.7 Summary

The environmental controls and limitations on vegetation have been investigated at various locations throughout the circumpolar Arctic. Vegetational success is limited by the temperature and nutrient and soil availability, factors that vary following disturbances. Vegetation influences the ground surface and, therefore, the surface energy balance and the ground thermal regime. Therefore, following the drainage of lake Illisarvik vegetation establishment may have been influenced by environmental factors, which may then have influenced the ground thermal regime.

# Chapter 3
# Study Area and Methods

## 3.1 Introduction

This thesis examines the establishment and succession of vegetation at Illisarvik since lake drainage in 1978. Relations between vegetation and active-layer development and controlling factors such as soil moisture, soil texture, soil temperature, nutrient availability, snow, vegetation height, and organic matter accumulation were investigated.

## 3.2 Study area

### 3.2.1 Regional setting

The study site is in the Mackenzie Delta area within the southern Arctic ecozone. It is on western Richards Island, 60 km west of Tuktoyaktuk, Northwest Territories, the closest community to the site. The site is in the Tununuk Low Hills subdivision of the Tuktoyaktuk Coastlands physiographic region near the western Arctic coast (Rampton 1988). Tununuk Low Hills is underlain by variable sediments ranging from fine-grained till to glaciofluvial gravel, while surface sediments range from clays to sandy gravels (Burn 2002). Western Richards Island is characterized by irregular rolling topography, with many drowned or poorly-drained valleys (Mackay 1963). Tuktoyaktuk Coastlands contains over 5000 lakes of thermokarst origin, which may drain catastrophically, or provide lake shores vulnerable to thaw slumping (Mackay and Burn 2002a).

### 3.2.2 Climate

The climate of the western Arctic is characterized by long, cold winters, and short, cool summers. The annual mean air temperature at Tuktoyaktuk is currently -10.1°C (Environment Canada 2016), the warmest month at Tuktoyaktuk is July (11°C), and the coldest month is January (-26.6°C) (Fig. 3.1). Annual precipitation at Tuktoyaktuk is relatively low (160.7 mm), and the majority falls in the summer and autumn. The snow cover usually begins to accumulate in September or October and melts by late May. Mean annual air temperatures have increased in the last 30 years (Fig. 3.2)

### 3.2.3 Vegetation

Vegetation in the Tununuk Low Hills varies with soil moisture, topography, and nutrient conditions (Mackay 1963). Tuktoyaktuk Coastlands are covered mainly by low Arctic tundra vegetation (Rampton 1988), with good drainage in the uplands resulting in *Salix* spp. (low willows) and *Betula glandulosa* (ground birch), lichen, and moss. Willows and *Alnus viridis* subsp. *crispa* (alders) are found on slopes and valleys, while *Carex* spp. (sedges) dominate poorly drained areas (Mackay 1963). The sedge dominated environments can be further sub-divided. *Eriophorum vaginatum* (cottongrass) is found in poorly-drained areas and is also associated with *Carex lugens* (sedge), *Salix pulchra* (willow), *Betula glandulosa* (ground birch), and *Vaccinium uliginosum* (crowberry) (Ritchie 1984). Second, sedge meadows are found in areas with water tables at or above the soil surface in the thaw season, commonly near margins of ponds and thermokarst lakes where drainage is poor (Ritchie 1984). The dominant species is *Carex aquatilis* (water sedge), with combinations of other sedges, willows, ground birch, *Eriophorum angustifolium* (cottongrass) and *Calamagrostis canadensis* (Ritchie 1984).

### 3.2.4 Permafrost and the active-layer

The study site is located within the continuous permafrost zone (Heginbottom *et al.*

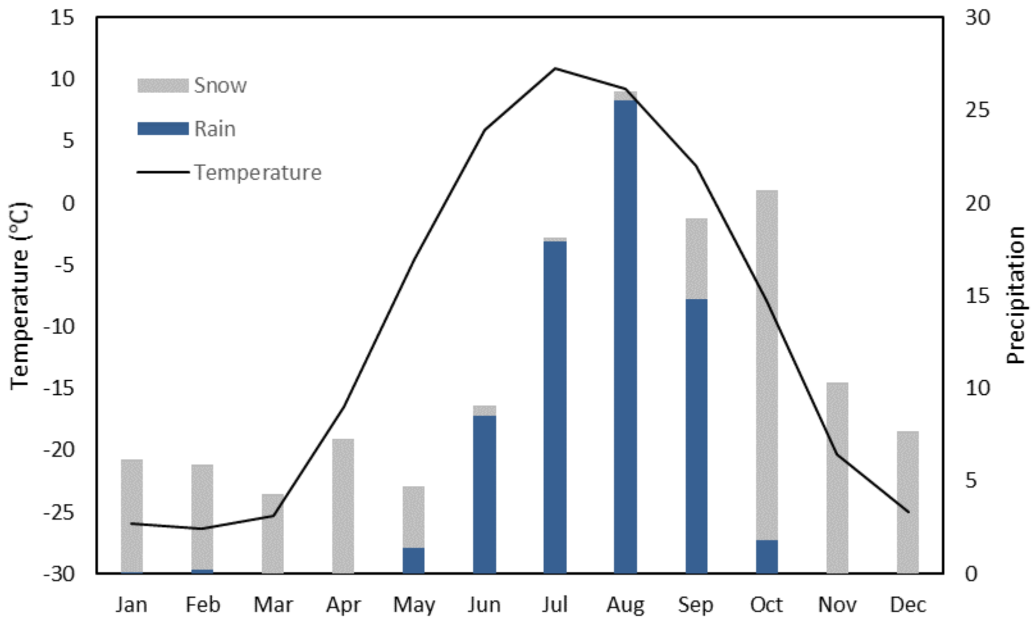


Figure 3.1- Monthly climate normal (1981-2010) for Tuktoyaktuk Airport. Data from Environment Canada. The snow data is in centimeters and the rainfall is in millimeters. (http://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?stnID=1700&autofwd=1).

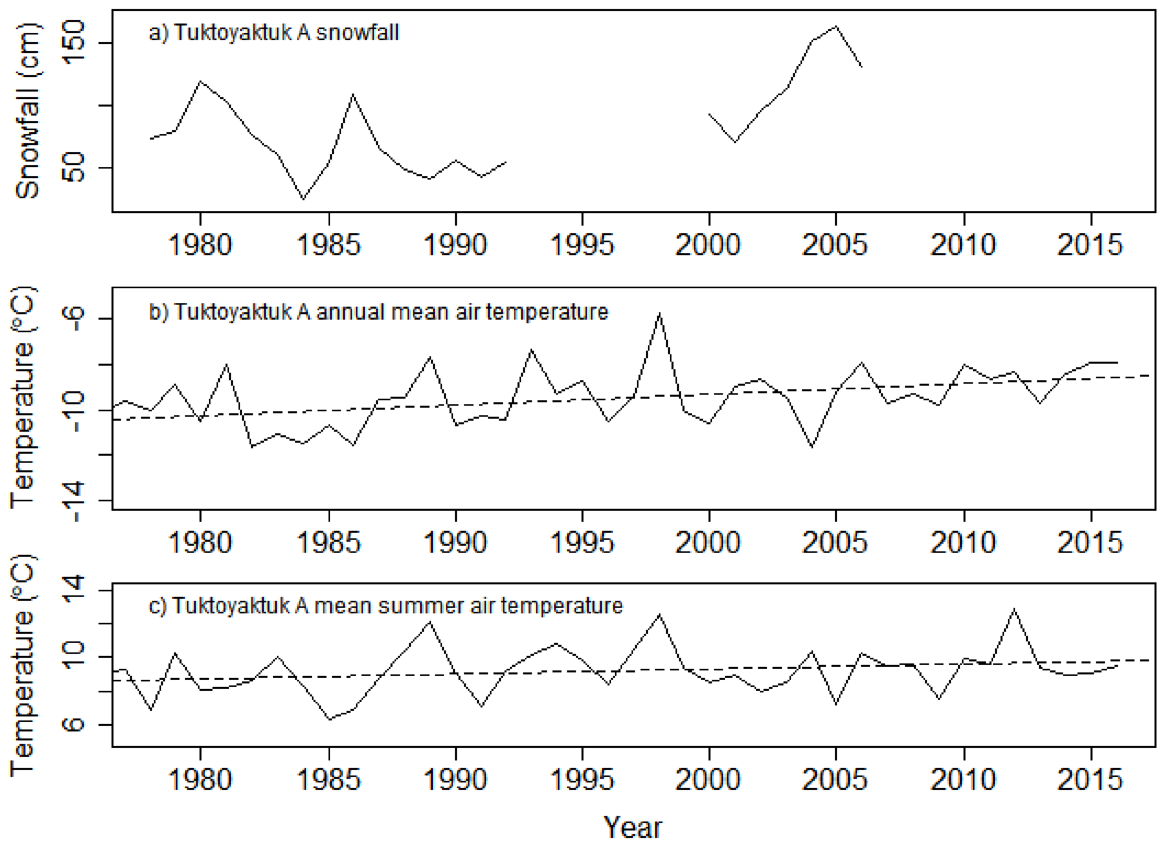


Figure 3.2 - a) available snowfall record for Tuktoyaktuk A, b) annual mean air temperature for Tuktoyaktuk A, increasing by 0.046 °C/ year, and c) annual mean summer air temperature (June, July, and August) for Tuktoyaktuk A, increasing 0.032 °C/ year (Environment Canada, 2016). Dashed lines in the temperature records represent the regressions of temperature on year.

1995). Richards Island was glaciated between ~22 000 and 16 000 years ago (Murton *et al.* 1997). The time since glacial retreat has resulted in permafrost thicknesses generally greater than 400 m (Judge *et al.* 1987). Near-surface permafrost temperatures in the region range from -6 to -7 °C (Burn and Kokelj 2009).

Ground ice occurrence is concentrated in the near surface of Richards Island, with ice-wedges accounting for approximately one third of the excess ice (Rampton and Mackay 1971; Pollard and French 1980). The greatest mean excess-ice content is found in the upper 50-60 cm of permafrost in wetter locations (Morse *et al.* 2009; O'Neill and Burn 2012). The ice-rich permafrost renders the area susceptible to thermokarst activity, which is evident from the abundance of lakes that cover ~ 23.5% of the island (Burn 2002).

Active-layer thickness varies in the region, primarily due to soil organic matter and moisture content. A tundra active-layer course at Illisarvik with 12 sites in various topographic settings showed an increase in mean thaw depth of 8 cm from ~42 to 50 cm from 1983- 2008 (Burn and Kokelj 2009). Smith *et al.* (2009) obtained similar results at several other sites in the region.

The dominant soil type in the region is Turbic Cryosol. Crysosols are mineral soils with permafrost within 2 m of the surface. Organic or organic-rich mineral horizons are common near the permafrost table throughout the uplands of the outer Mackenzie Delta region (Tarnocai 2004). The frost susceptible till results in much of the tundra being covered by earth hummocks (Mackay 1980).

### 3.3 Lake Illisarvik

The research site is the Illisarvik experimentally drained lake basin (Mackay 1997), located at 69° 28' 51" N, 134° 35' 04" W. Prior to drainage, Illisarvik measured 600 x 350 m and was underlain by a bowl-shaped talik 32 m deep at the center of the lake (Mackay and Burn 2002a). A talik is a layer of unfrozen ground in a permafrost area (ACGR 1988). The lake formed approximately 9500 years ago, expanding until reaching its maximum size roughly 6000 years ago (Michel *et al.* 1989). Lake depths for most of the basin ranged between 2 and 3 m prior to drainage (Mackay and Burn 2002a). Professor J. R. Mackay drained the lake on August 13th 1978, in a full-scale field experiment to investigate permafrost aggradation *ab initio* (Mackay 1997). The lake almost completely drained over an eight-hour period, leaving two residual ponds termed the North Pond and South Pond.

Studies have been ongoing at Illisarvik for the past four decades, making Illisarvik Canada's longest-running northern field experiment. Prior to drainage, studies were initiated on ground temperatures, the position of the permafrost table, and composition of the basin sediments. Following drainage, research developed on ground temperatures (Burgess *et al.* 1982; Mackay and Burn 2002a), active-layer development (Mackay and Burn 2002a), ice-wedge growth and cracking (Mackay 1993; Mackay and Burn 2002b), aggradational ice development (O'Neill and Burn 2012), stable isotopes (Michel *et al.* 1989), frost heave, and vegetation succession (Ovenden 1986) (see Burn and Burgess 2000).

#### 3.3.1 Lake basin

The lake bed surface was soft and wet after drainage (1979) but gradually hardened over the following years. The hardened ground surface was attributed to continued drainage, evaporation, and freeze-thaw consolidation (Mackay 1997). By August 1985, most of the lake bed was very dry with desiccation cracks in a few areas. A white salt crust covered much of the basin surface except for a large eroded area on the eastern side (Ovenden 1986).

Today, the lake basin sediment profile can be divided into four units, which are overlain with peat in some areas. The deepest unit is a thick layer of fine-medium sand that contains some organic fragments (Michel *et al.* 1989). Interbedded layers of clay-silt and sand lie above this unit. A middle unit of clay-silt with variable sand content lies above the interbedded layers (Michel *et al.* 1989). The uppermost unit is organic-rich silt; this unit is thickest in the center of the basin and thins towards the margins, where sand dominates. Silt is the dominant substrate across the basin (Michel *et al.* 1989; O'Neill and Burn 2012).

Two residual ponds were left following drainage. South Pond is the deepest, with 4 m depth (Mackay and Burn 2002a). These have varied in size seasonally and from year to year. The ponds gradually reduced in area following drainage through to the 1990s and North Pond dried up most summers (Ovenden unpublished). Both ponds were larger in 2001 than in 1993, South Pond being ~3 times larger than in 1979 (Ovenden unpublished). South Pond expanded after 1999, due to the drainage channel becoming blocked. A new channel was manually cleared in 2003, after which South Pond's area declined. An unvegetated area east of South Pond was flooded throughout summer 2015 but was exposed in summer 2016, after the new channel was cleared again.

### 3.3.2 Permafrost development

A total of 24 temperature cables were installed to varying depths ranging from 10-84 m following drainage to monitor ground temperatures (Burgess *et al.* 1982). Permafrost aggradation commenced the first winter following drainage (Mackay and Burn 2002a), and where the talik was less than 10 m thick ground temperatures had cooled below 0 °C by two years after drainage (Burgess *et al.* 1982). At the same time, five or six meters of permafrost had formed in the center of the basin (Burgess *et al.* 1982). Three years later, the 0 °C isotherms had nearly converged in the lake center where the pre-drainage talik was deepest. By the 1980s, the talik sediments in the middle of the lake basin were below 0 °C (Mackay 1997).

At the north end of the basin, permafrost cooled in the first 5 - 15 years after drainage, but subsequently warmed with growth of vegetation. Sites closest to the basin margins experienced warming earliest by 1985, and sites ~ 50 m from the margin began warming in 1991 (Mackay and Burn 2002a).

### 3.3.3 Active-layer development

The active-layer thickness at Illisarvik depends on the interaction of many factors including vegetation cover, drainage, soils, exposure, and permafrost temperatures (Mackay 1982). In the summer following drainage, two active-layer transects were established along the basin's axes (Fig. 3.3). From 1979 to 1981 as permafrost aggraded downwards, active-layer depths were similar in magnitude to sites in old undisturbed permafrost (Mackay 1982). No vegetation had established on the transect by 1981, and snow accumulation was minimal (Mackay 1982).

Mackay and Burn (2002a) monitored active-layer depths along the transects for


Figure 3.3 - Illisarvik a year after drainage, August 12, 1979. The active layer transects along the major and minor axes of the basin are marked (Mackay and Burn 2002a, Fig. 2). © 2008 Canadian Science Publishing or its licensors, reproduced with permission.

20 years following drainage (1979-1999) with late summer thaw depth measurements which approximate active-layer thickness. The active layer was thickest by the lake margin with values >90 cm, due to well-drained sandy soils and snowdrifts accumulating and insulating the ground in the winter (Mackay and Burn 2002a). Elsewhere, active-layer depths ranged from 50 - 60 cm in 1980 - 1988. Active-layer depths gradually increased from 1989 to 1993, by an average of 20%. Thaw depths in the nearby tundra course changed little in the same period due to relatively constant summer temperatures (Mackay and Burn 2002a).

### 3.3.4 Lake basin vegetation succession

Initially the lake basin was primarily covered by peaty organic mud, with windblown peat at the south end of the basin (Mackay 1982). Wind continued to relocate peat to the southern margins of the basin until 1999 (Mackay and Burn 2002a).

There was no vegetation development up to the summer of 1981, three years following drainage (Mackay 1982), but by 1982 *Senecio congestus* (marsh fleabane) had established around the margins of North Pond, increasing snow depths to > 60 cm (Mackay and Burn 2002b). By 1983, grasses, sedges, and horsetails colonized the north end of the basin (Mackay and Burn 2002b). The basin center, which had less organic matter, had scattered clumps of grasses spread a few meters apart (Mackay and Burn 2002b).

Dr. Lynn Ovenden (1986) conducted a detailed vegetation survey throughout the lake basin in the summer of 1985. Vegetation composition and distribution varied throughout the basin, predominantly controlled by erosion, surface wetness, and proximity to the former shoreline (Ovenden 1986). The lake bed was dominated by

*Puccinellia borealis* (alkali grass), *Arctagrostis latifolia* (polar grass), *Carex aquatilis* (water sedge), *Senecio congestus* (marsh fleabane), *Matricaria ambigua* (mayweed), and *Descurainia sophioides* (northern tansy mustard) (Ovenden 1986). Ovenden identified four distinct biophysical units (Fig. 3.4): (1) areas within 10 m of the former shoreline, (2) non-eroded lake bed >10 m from shoreline, (3) eroded lake-bed, and (4) wet depressions. Eroded lake-bed refers to areas within the basin that have been eroded by aeolian effects. The near-shore margin had a more diverse and continuous vegetation, with a higher abundance of grass species and willows than elsewhere in the basin. Non-eroded lake bed areas had 40 - 90% vegetation coverage, dominated by alkali grass and up to 20 different vegetation species. Eroded areas had sparsely distributed alkali grass and northern tansy mustard, and the wet depressions were bordered by marsh fleabane and a diverse meadow of moisture tolerant grasses. *Hippuris vulgaris* (horsetail) was found only near the pond (Ovenden 1986).

Between 1985 and 1999, North Pond gradually drained, and vegetation established in the former pond bottom. By 1990, willow had spread over the north end of the basin, and the basin center had ~ 80% vegetation coverage (Mackay and Burn 2002b). Vegetation established in the drier sandy soils at the east end of the basin by 1999, with some alders and willow exceeding 2 m in height. Grasses proliferated and, by 1999, taller willows established in the north and northeast margins of the basin (Fig. 3.5) (Mackay and Burn 2002a). Additional unpublished surveys were completed by Dr. Lynn Ovenden in 1993 and 2001. The results of these surveys will be discussed later in chapter 4.

By the summer of 2010, there were abundant tall willows (>3 m) around North Pond and the lake margins. The basin center was dominated by grasses with scattered

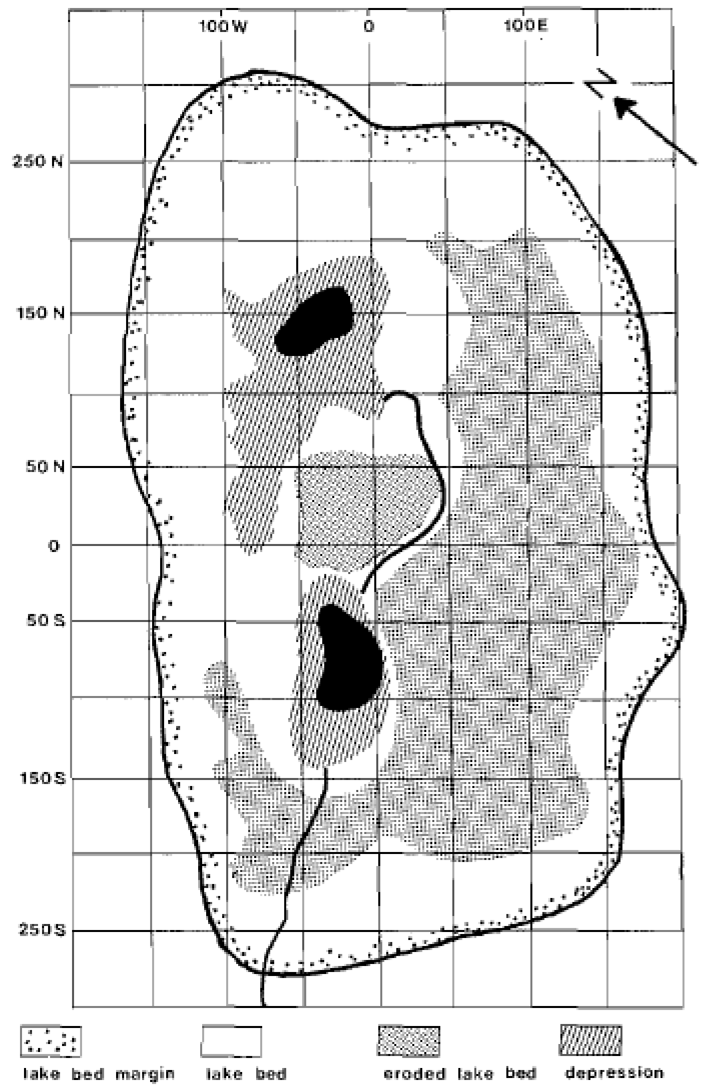


Figure 3.4 - Vegetation units within the basin established by Ovenden (1986, Fig. 2). The black areas are the ponds. The north arrow indicates true north, while the top of the map is the grid north. © 2008 Canadian Science Publishing or its licensors, reproduced with permission.


Figure 3.5 - Looking south towards the outlet along the 600 m transect in 1996 (top) and 2006 (bottom). Note the increase in tall vegetation over 10 years. Photos taken by and reproduced with kind permission of C.R. Burn.

patches of willows (O’Neill 2012). However, vegetation remained sparse near the southern margins and east of the South Pond (O’Neill 2012).

### 3.4 Study design

The Illisarvik drained lake site is an ideal site to study the influence of vegetation succession on permafrost. First, being an experimental drained lake basin, there is continuous monitoring of the active layer and ground temperatures. This is in addition to 4 detailed basin-wide vegetation surveys over 31 years of vegetation establishment. Such a complete dataset has not been examined before: a majority of vegetation succession studies are not longitudinal but use space-time substitution. Illisarvik provides a site in which to study vegetation succession *ab initio*, removing the uncertainties inherent within paired vegetation succession studies.

#### 3.4.1 Site selection

Illisarvik has a permanent 50-m grid established in 1979 by the Geological Survey of Canada (Fig. 3.4). Each grid point is marked by a 2” × 2” wooden stake. Following the methods of Ovenden (1986), surveys were conducted at the stakes within the grid. Long-term active-layer measurements have been made along two perpendicular transects within the basin, and a transect in the adjacent tundra (Fig. 3.3). Ovenden (1986) did not conduct vegetation surveys outside the basin, but the 2016 vegetation surveys were at every stake in the 50-m grid and along 12 stakes on the tundra transect (Fig. 3.4), allowing for a comparison of vegetation between the undisturbed tundra and the basin.

## 3.5 Field methods

### 3.5.1 Vegetation surveys

The growth of vegetation has been recorded by plant collection in 1980 and 1982 and vegetation surveys in August 1985, 1993, 2001 (Ovenden 1986; unpublished), and 2016. At each stake, a species presence list was compiled for all taxa within a 7 m radius. A 1 × 3 m quadrat was used to tally the percent cover of each species. The quadrat was placed with the long axis east-west and the corner closest to the stake 1 m south and west (see Fig. 3.6 and 3.7). Surveys in 2016 were conducted prior to complete knowledge of Ovenden's surveying technique. All previous surveys included 1× 3 m quadrats both 1 m south and west (quadrat 'A') and 1 m south and east (quadrat 'B'). The precise method of surveying was not known before the 2016 field season and only quadrat 'A' was re-surveyed. A list of the species found at Illisarvik and the vegetation surveys are in Appendix A and B. Vascular plant identification followed Cody's *Flora of the Yukon Territory* (2000) and was confirmed by botanists at the National Herbarium of Canada.

Leaf-area index (LAI) was used as a proxy for vegetation structural complexity. LAI was obtained using a gap fraction technique recorded by a Plant Canopy Analyzer (LAI-2000, LI-COR Inc, Lincoln, NE). LAI measurements were collected in the middle of every quadrat three times over the summer using the light scattering correction (Kobayashi *et al*. 2013).

Vegetation heights for each site were determined by measuring the tallest plant part within a 1 m circle and, 2-3 m, 4-5 m, and 5-7 m annuli surrounding the site stake. These four measurements were averaged to provide an average maximum vegetation height for each site.

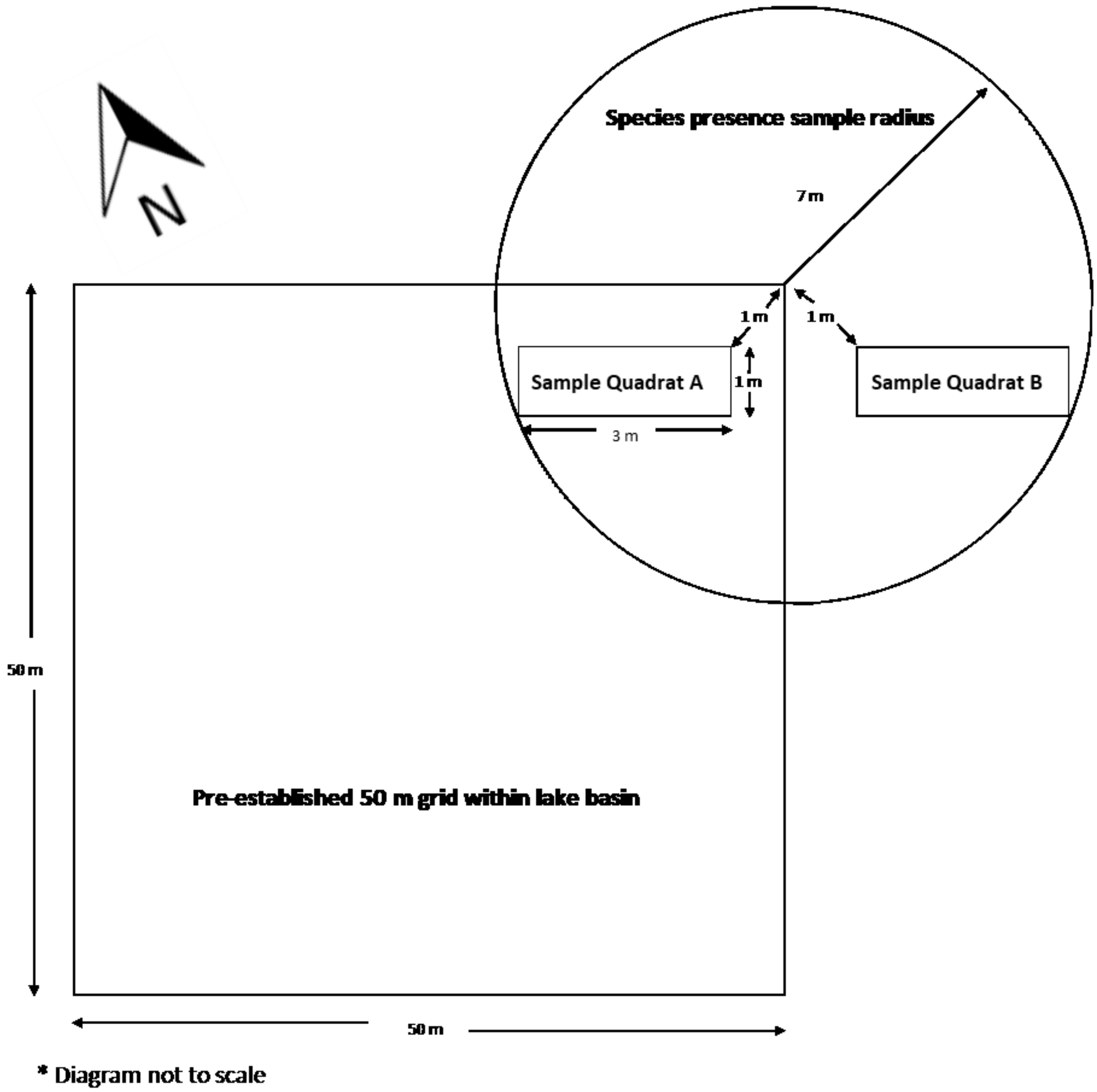


Figure 3.6 - Vegetation sampling diagram illustrating placement of sampling within the established 50-m grid. The 1 x 3 m sample quadrats were located 1 m south and west from established stakes. The 1 x 3 m quadrat corresponds to quadrat “A” in Ovenden’s survey data. Species presence was recorded within 7 m of each stake.

Figure 3.7 - Vegetation sampling. A wooden 1 x 3 m vegetation quadrat was placed 1 m from the wooden stake shown in background by the arrow.

Lastly, a vegetation map for the basin was created while surveying the basin. The units were delineated visually while traversing the grid lines in the lake bottom. The units were distinguished by plant functional type and physical vegetation structure. The classification was generated specifically for the unique context and characteristics of Illisarvik. The fully detailed vegetation map is presented in Appendix C and a slightly simplified version in Chapter 5, Fig. 5.1.

### 3.5.2 Soil characteristics and organic-matter thickness

At each vegetation quadrat, a small hole was made in the ground to measure the organic matter thickness (e.g. the LFH layer in these mineral soils) with a ruler. Volumetric water content of the top 0-20 cm soil layer was measured using a Hydrosense II probe (Campbell Scientific Inc, Logan, UT). Soil samples were collected in 32 locations (Fig. 3.8). Since soil characteristics were investigated in association with vegetation composition, duplicate soil samples were collected from each of the 16 distinct vegetation units (in Appendix C) within the basin and the surrounding tundra. Sites were chosen using judgement in the field to obtain samples from locations representative of the vegetation units. In total, 32 soil pits were excavated. At each soil pit, an aluminum tube was used to extract samples for bulk density from 0-5 and 5-10 cm depths. Bulk samples were also obtained from those depths. An auger was used to obtain a bulk sample from 10 - 30 cm depth. At four sites, a high water table prevented collection of core samples, so only an auger sample was collected.

Anion ($NO^{3-}$, $B^-$) and cation ($K^+$, $Cu^+$, $Mg^{2+}$, $NH_4^+$, $Mg^{2+}$, $Ca^{2+}$, $P^{3-}$, $Fe^{2+}$, $Zn^{2+}$, $S^+$, $Pb^+$, $Al^{3+}$) supply rates were measured in 2016 using 20 paired Plant Root Simulator probes (PRS) (Western Ag Innovations Inc, Saskatoon, SK). The probes were installed as part of a complementary field study being conducted at Illisarvik simultaneously (Laforce 2018). The specific locations of the probes were chosen for that study. Two pairs of probes were placed in 10 different vegetative communities within the basin, as well as the peat plateau and undisturbed tundra. Probes were inserted on July 11th and removed on August 6th. Probes were inserted by cutting a slit in the soil with a saw and inserting the probes to 10 cm depth.

### 3.5.3 Active layer

Active-layer thicknesses were obtained by inserting a graduated steel probe into the ground to point of refusal at every grid point (Fig. 3.8). Measurements were taken in mid to late August each year. Although thaw depth may increase slightly after the date of probing, Mackay (1974) and Osterkamp and Romanovsky (1997) indicate that up-freezing from the bottom of the active layer tends to precede downfreezing from the ground surface. Thus, the August thaw depths are a reasonable approximation of maximum thaw depth. Measurements were taken at each grid point in August 2015 (Fig. 3.8). Thaw depths were measured three times throughout the basin in 2016, upon arrival in early July, in late July, and prior to departure in mid-August, and in late August 2017. Each site was probed five times: the median value has been used as the thaw depth at each location.

### 3.5.4 Ground temperature

Near-surface ground temperatures at 25 cm depth were monitored at 10 sites with data loggers installed in August 2016 (Fig. 3.9). The sites were chosen to represent 8 different vegetative communities within the basin as well as two tundra sites with different peat cover. The loggers in the basin were placed in all of the vegetation units in Fig. 5.1

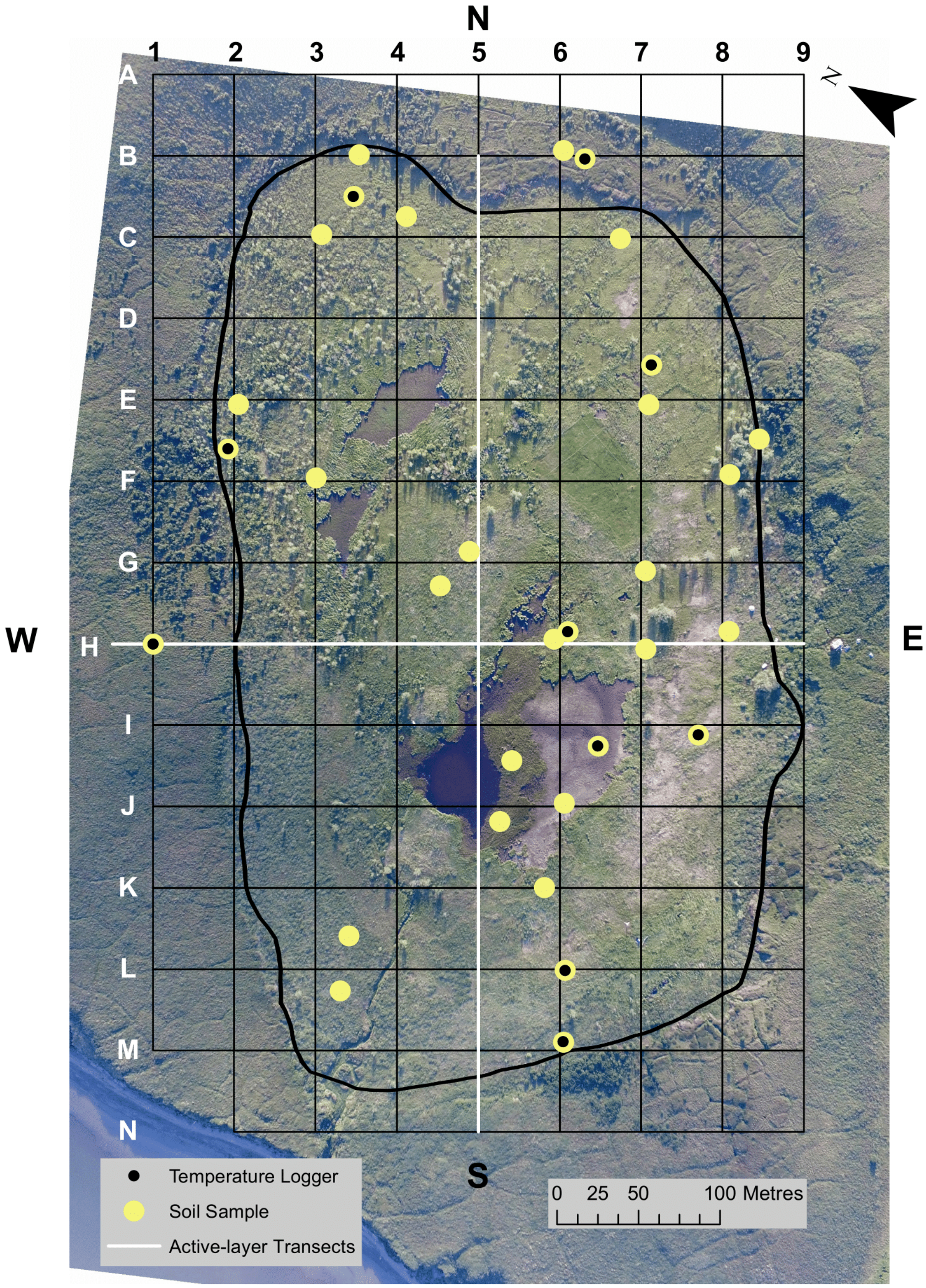


Figure 3.8 - Locations of soil sampling and ground temperature data logger installations. The north arrow indicates true north, and the 'N' label indicates grid north. The active-layer transects have been measured at 25 m intervals every year since 1979. All other measurements were conducted at the grid points; specific sites are noted by an alpha-numeric labelling system. Site N2, existed in 2015 but eroded before the 2016 season. Photo courtesy of A.G. Lewkowicz, University of Ottawa.


Figure 3.9 - Data logger housing for temperature sensors installed at 25 cm depth to log soil temperatures over one year at 10 vegetation sites.

except Pendant Grass, and the Grass unit had two loggers in a drier grass dominant area and a cotton grass area in the north end of the unit. Measurements were made with HOBO H8 series miniature data loggers attached to TMC6-HD thermistors (Onset Corp., Bourne, MA). Ground temperatures were recorded every four hours from August 5$^{th}$, 2016 to August 4$^{th}$, 2017.

### 3.5.5 Snow survey

Snow depths were measured in April 2017 to determine the effect of vegetation on snow characteristics. Snow depths were measured at each stake within the lake basin (on the 50 m grid), and snow density was measured at 49 sites, selected from both the basin and adjacent tundra. In addition, snow depth and density were measured at the temperature logger sites.

## 3.6 Laboratory and analytical methods

### 3.6.1 Soil physical characteristics

Soil samples of known volume (147.59 cm$^3$) were weighed and dried for 12 hours at 105 °C at the Aurora Research Institute in Inuvik. The dried samples were re-weighed to calculate volumetric water content (VWC, cm$^3$ cm$^{-3}$):

$$(1)\quad VWC = (W_w - W_d)/(V_t\, \rho_w)$$

where $W_w$ is the wet weight of the soil sample (g), $W_d$ is the oven-dried weight of the sample (g), $V_t$ is the total volume of the sample (cm$^3$), and $\rho_w$ is the density of water (g cm$^{-3}$).

Soil particle size was determined using the pipette method. The determination was made on the sample collected from the greatest depth in each soil pit. The soil sample



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was crushed and homogenized using a mortar and pestle, then sieved through 2 mm mesh to remove particles larger than sand. All mineral particles passed through the sieve, but some pieces of organic matter, such as roots, were caught and removed.

Organic matter was digested by adding hydrogen peroxide to the soil samples and heating the samples to accelerate the reaction (Kalra and Maynard 1991. Sodium hexametaphosphate was added to the samples to prevent flocculation, and the samples were shaken overnight.

Samples were transferred into 1 L graduated cylinders through a 0.05 mm mesh sieve and topped up to the 1 L mark with deionized water. The sand caught by the sieve was placed in a pre-weighed tin to dry. The soil suspension was stirred thoroughly with a plunger, and samples were pipetted from the cylinder at a depth of 10 cm at 4 minutes and 38 seconds, 1 hour and 14 minutes and 13 seconds, and 7 hours, 43 minutes and 49 seconds (Kalra and Maynard 1991). These times correspond to the falling time for diameters of <20 μm (silt), <5 μm (fine silt), and <2 μm (clay) respectively. Pipetted samples were dried and weighed.

### 3.6.2 Soil nutrient analysis

Soluble cations were determined in pore water samples. Distilled-deionized water was added to the 60 °C dried grab samples for 5-10 cm depth, and 0-20 cm depth for auger samples collected from saturated sites. Water was added to the soil at a 1:10 ratio and allowed to settle for 12 hours. Supernatant water was collected with a syringe and filtered through a 0.45 μm cellulose filter. Samples were placed into scintillation vials and shipped to the Taiga Environmental Laboratory in Yellowknife. Samples were analyzed for concentrations of $Na^+$, $K^+$, $Mg^{2+}$, $Ca^{2+}$, $Cl^-$, $NO_2^-$, $NO_3^-$, $SO^{2-}{}_4$, dissolved N, and dissolved P. The results for soluble cations and anions were expressed in mg $L^{-1}$.

### 3.6.3 Soil pH and electrical conductivity

Soil pH and electrical conductivity were measured to investigate the influence of chemical properties on vegetation community development. The core soil samples dried at 105 °C from a depth of 5-10 cm were used. These samples were pretreated using water as the suspension medium at a ratio of 1:4 for mineral soils and 1:8 for organic soils (Kalra and Maynard 1991). The pH was measured with the B30PCI SymphHony™ Benchtop Meter (VWR, Pittsburgh, PA) after calibration with reference pH 4 and pH 7 solutions. The electrical conductivity was determined using the B30PCI SymphHony™ Benchtop Meter but with a conductivity probe attached. Probe calibration was made using 100 µS, 1000 µS, and 1413 µS solutions.

### 3.6.4 Plant species identification

Plant species were identified in the field using Cody (2000). To confirm identifications, plants were collected and pressed in the field and compared with specimens at the National Herbarium of Canada. Comparison was assisted by Paul Sokoloff and Dr. Jeff Saarela.

## 3.7 Statistical analysis

All statistical analysis was conducted in R 3.3.2 (R Core Team, Vienna, Austria) or Primer 7 statistical software (Quest Research Ltd, Auckland, NZ).

### 3.7.1 Vegetation composition and cover

Vegetation composition and cover were analyzed from the surveys completed in 1985, 1993, and 2001 and in 2016. Surveys in 1985, 1993, and 2001 did not cover every grid point at Illisarvik, and as a result, there are only 31 sites that recurred in all survey years. For vegetation succession analysis the 31 recurring sites were used and compared between survey years. For the 2016 vegetation analysis all 67 vegetation survey sites were used and grouped by vegetation units.

#### 3.7.1.1 Species Diversity

Species richness, evenness, and diversity were determined using Primer software. Species richness was determined as the total number of species present at a site. Species diversity was determined using the Shannon index (Shannon 1948), calculated by

$$(2)\ \ H' = -\sum_i p_i \log(p_i)$$

where $p_i$ is the proportion of the total cover arising from the *i*th species. Evenness is expressed by how evenly the individuals are distributed among the different species at a site. For example, if two samples each comprising 100 individuals and five species had species abundances of 20, 20, 20, 20, 20 and 96, 1, 1, 1,1 the former has perfect evenness with low species dominance, while the latter has low evenness with high species dominance. The evenness was calculated using Pielou's evenness index (Pielou 1966):

$$(3)\ \ J' = H' / H'_{max} = H' / \log S$$

where $H'_{max}$ is the maximum possible value of the Shannon index, and $S$ is the total number of species (species richness).

A Kruskal-Wallis analysis of variance ('stats' package, R, R Core Team, 2016) was conducted to determine the significant differences among survey years, and among vegetation units in 2016, for richness, diversity, and evenness. This was followed by a post hoc Dunn's test ('FSA' package, R, R Core Team, 2016) to reveal significant differences among the mean values for richness, diversity, and evenness.

#### 3.7.1.2 NMDS ordination

Non-metric multidimensional scaling (NMDS) represents samples in 2-d space such that the distances between points are as closely matched to the relative dissimilarities as possible. In this analysis, the distances were based on the Bray-Curtis similarity matrix. The matrix values can range from 0-100, with sites that have no species similarities receiving a value of 0 and sites that have identical representation of species a value of 100. The NMDS ordination figure has axes with arbitrary values, but the closer points are to each other the more similar is their community composition.

The NMDS analysis was completed with PRIMER 7 and R software. The percent cover data for vegetation were square root transformed prior to ordination to reduce noise and ordination stress. To explore differences between survey years, PRIMER was used for NMDS ordination of the percent cover data. NMDS for the 2016 surveys was completed using the VEGAN package in R (Oksanen *et al*. 2017). The 2016 NMDS analysis was completed in R due to the capability of correlating environmental variables with the data, which will be discussed later in this chapter.

#### 3.7.1.3 Analysis of Similarities

ANOSIM (Analysis of Similarities) (Primer 7) was used to test whether species composition differed between years and the 2016 vegetation units. ANOSIM is analogous to Analysis of Variance (ANOVA) which allows for a test of the null hypothesis that there are no assemblage differences among groups. In order to compare vegetation composition among surveyed years, an ordered ANOSIM was used to test for a temporal trend, while a non-ordered ANOSIM was used to investigate the differences among the

2016 vegetation units. The $R_{ANOSIM}$ statistic was calculated by performing 999 permutations of the original data. The permutations generate *R* values to test the null hypothesis that similarities within years are smaller or equal to the similarities among years. The $R_{ANOSIM}$ statistic ranges from 0 to 1, 1 representing completely different assemblages and 0 being derived from identical assemblages. This analysis shows how well-separated the vegetation communities are (1) among years, to investigate changes with time, or (2) vegetation units, to see if units can be considered separate vegetation communities statistically.

#### 3.7.1.4 Similarity percentages

A similarity percentage (SIMPER) analysis (Primer 7) was conducted to identify the species making the largest contribution to similarities between sites within a group (year or vegetation unit). SIMPER analysis provides a mean similarity for the group which is a measure of the consistency in vegetation composition between all surveyed sites within the year. Additionally, the mean similarity of the species indicates the extent a species contributes to the overall mean similarity of the vegetation composition at survey sites within each group, i.e., how representative and consistent the species is within the group.

The SIMPER was used to calculate the percent contribution of each species to the similarity between sites within a year or vegetation unit grouping. The species identified in this analysis are those most consistently found within a given year or vegetation unit and that contribute most to the between-group Bray-Curtis similarity.

#### 3.7.1.5 Indicator species

An indicator species is one whose presence or absence is an indicator of environmental conditions in a habitat. A change in indicator species with time since lake drainage would indicate a change in environment to allow or inhibit the establishment of species. Indicator species between vegetation units would indicate that there are differing environmental conditions within the basin. To determine the vegetation that distinguishes the groups, such as the year or site, indicator species were determined using the INDVAL function within the INDICSPECIES package in R (Dûfrene and Legendre 1997). Indicator species analysis calculates an indicator value ($IV_{ij}$) for species $i$ in group $j$ based on relative abundance ($A_{ij}$) and relative frequency ($B_{ij}$):

$$(4)\ A_{ij} = \overline{x}_{ij}/\textstyle\sum_j \overline{x}_i$$

$$(5)\ B_{ij} = n_{ij}/n_j$$

$$(6)\ IV_{ij} = B_{ij}\ x\ A_{ij}\ x\ 100$$

where $\overline{x}_{ij}$ is the mean cover of species $i$ within group $j$, $\sum_j \overline{x}_i$ is the sum of the mean cover of species $i$ in all groups ($j$), $n_{ij}$ is the number of samples in group $j$ that are occupied by species $i$, and $n_j$ is the total number of samples (surveys) in the group. $IV_{ij}$ ranges from 0 to 100, with values >25 being strong indicators of a given group.

### 3.7.2 Environmental variable analysis

#### 3.7.2.1 Environmental variable ordination

In order to examine the correlations between vegetation units and abiotic parameters, the ENVFIT function within the VEGAN package for R was used to evaluate relations between NMDS scores and environmental variables. The matrix of environmental variables used included VWC, thaw depth, snow depth, LAI, percent bare ground, organic-matter thickness and vegetation height. The function adds arrows representing environmental variables to the NMDS ordination plot, in which the arrow shows the direction of the increasing gradient, with the length being proportional to the correlation coefficient between the variables and the ordination.

#### 3.7.2.2 Correlation analysis

Correlation matrices allow analysis of the amount of interdependence between environmental variables. A correlation matrix was produced using Spearman's rank correlation in R ('stats' package, R, R Core Team, 2016). The correlation matrix included all the environmental variables measured: active-layer depth, snow depth, vegetation height, organic-matter thickness, VWC, and percentage bare ground. To investigate differences between the tundra and the basin, correlation analysis was also carried out separately for data from these locations (n=67 for basin, n=43 for tundra).

#### 3.7.2.3 Correlation and regression tree

Correlation and regression trees (CART) ('tree' package, R, R Core Team, 2016) were used to isolate variables influencing thaw depth. When appropriate, trees were pruned to a size that produced the smallest mean standard error. Trees were created for all the environmental variables, and then for the basin and the tundra sites separately.

#### 3.7.2.4 Principal component analysis

Principal component analysis (PCA) was performed in R ('psych' package, R, R Core Team 2016) to further explore relations between the environmental variables. PCA was conducted on standardized environmental variables to provide equal weighting to each variable. The PCA was conducted to investigate the associations of variables with thaw depth.

### 3.7.3 Maps

All maps were created in ArcMap 10.4 (ESRI, Redlands, CA). An aerial image of the basin was acquired using an unmanned aerial vehicle courtesy of Dr. Lewkowicz. The image was georeferenced from GPS points taken at the grid points. All shapefiles were digitized by the author. Interpolated maps were created using spline interpolation to create the smoothest visual representation of the data.

# Chapter 4
# Vegetation Succession at Illisarvik

## 4.1 Introduction

In this chapter, the vegetation composition at four points in 1985-2016 (1985, 1993, 2001, and 2016) was examined. Vegetation composition was examined to determine the vegetational trajectory of the basin since drainage and to investigate whether it is approaching the vegetation composition of the surrounding undisturbed tundra. All surveys are referenced to the established grid (Figure 4.). This chapter also describes what species and plant functional types had become well-established within the basin over time.

## 4.2 Site characterization

The basin has become increasingly vegetated since lake drainage in 1978. The visual changes in plant cover are dominated by the physical growth of the vegetation, especially in the most recent 15 years (2001-2016).

In 1979, there was no vegetation present in the basin (Fig. 4.2a). In 1982, vegetation was present around the margins of North Pond. In the following year, grasses and sedges colonized the north end of the basin. The south end of the basin remained wind eroded and sparsely vegetated until the early 1990s, when shrubs as well as grasses began to colonize the area. The shrubs initially colonized the north end and the southern margins of the basin. The vegetation communities in these locations continued to be dominated by shrubs in 2016 (Fig. 4.2 and 4.3).

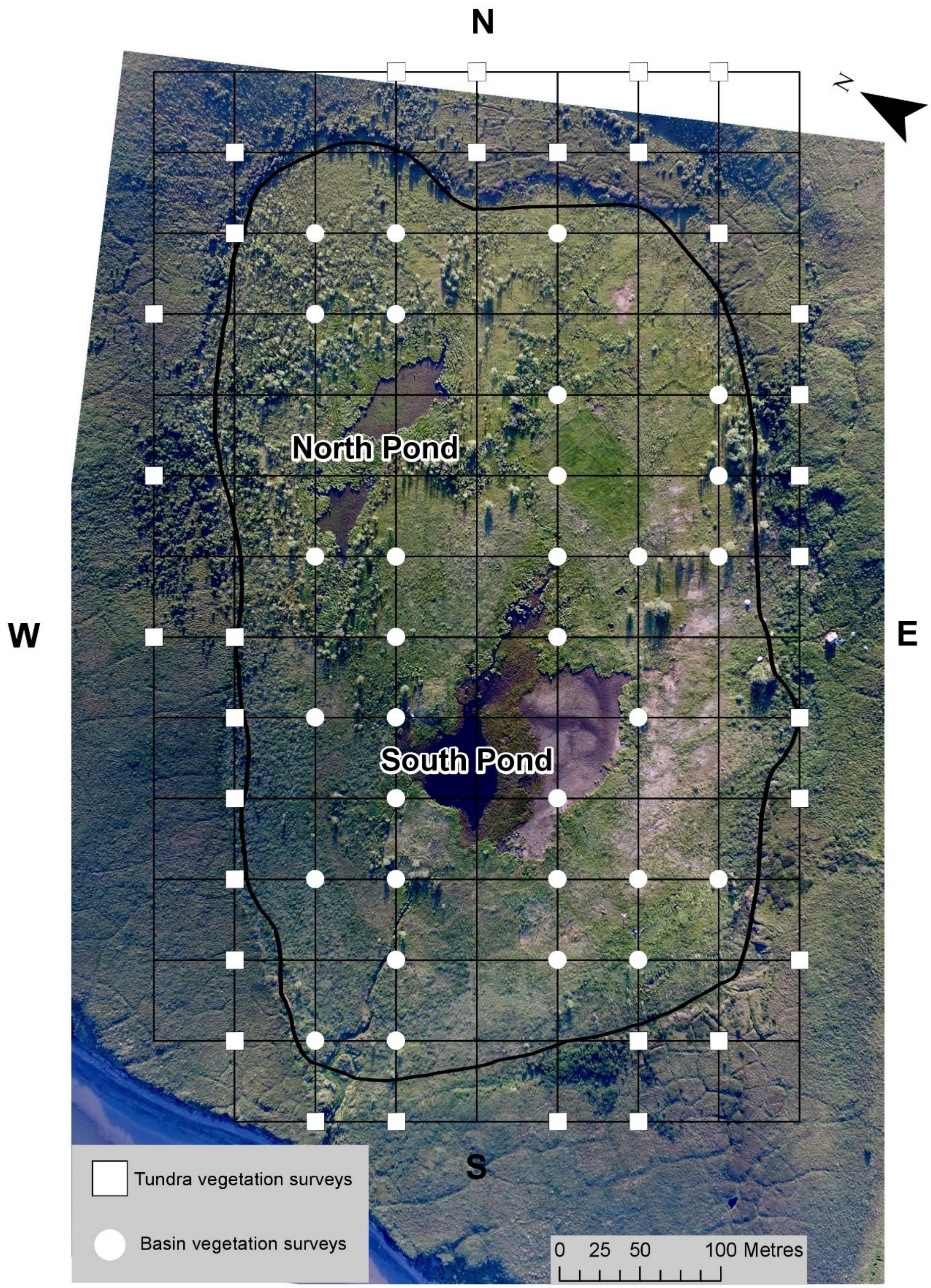



Figure 4.1 - Sites with vegetation surveys from 1985, 1993, 2001, and 2016. References to direction in text correspond to the grid, which was established for surveys in the basin by J.A. Hunter, Geological Survey of Canada, in 1979. Aerial image taken and reproduced with kind permission of A.G. Lewkowicz.

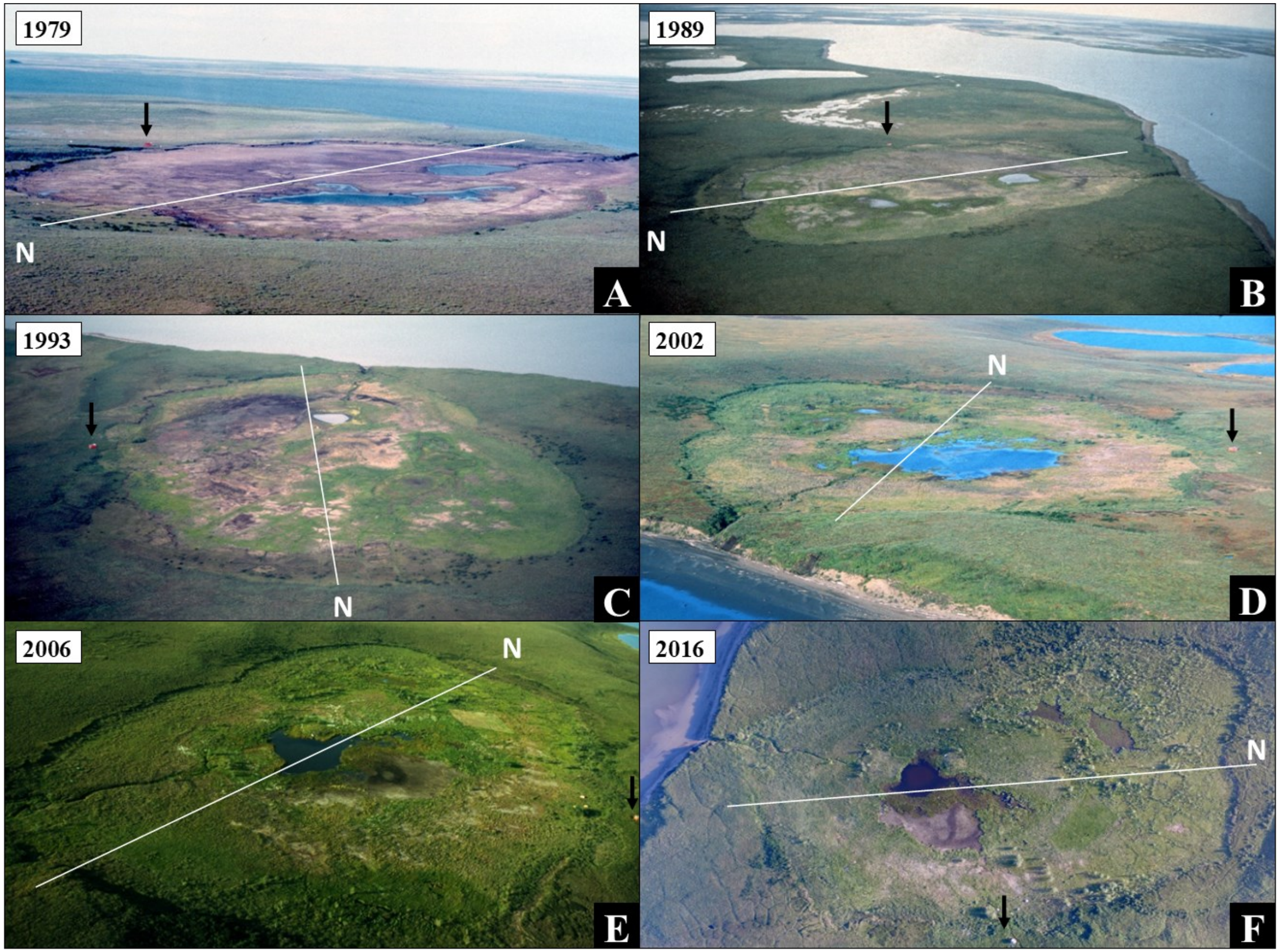



Figure 4.2 - Historical photographs of Illisarvik lake basin in 1979, 1989, 1993, 2002, 2006, and 2016. The arrow indicates the research cabin as a point of reference, and the line is the N-S grid line as shown in Fig. 4.3. Note the increase in vegetation cover and the fluctuation of pond sizes with time. Photos by J.R. Mackay (A-C), C.R. Burn (D-E), and A.G. Lewkowicz (F). Reproduced with kind permission of C.R. Burn and A.G. Lewkowicz.

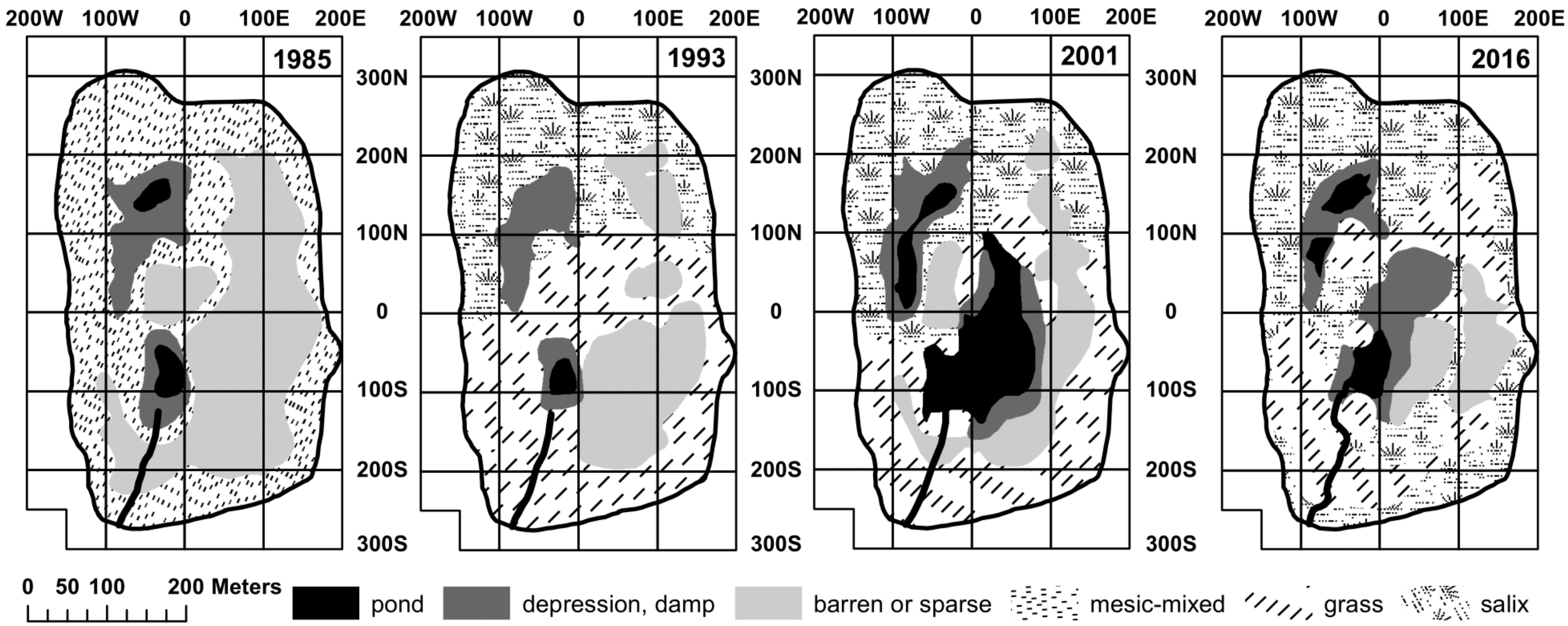



Figure 4.3 – Generalized vegetation and site conditions at Illisarvik in August 1985, 1993, 2001, and 2016 (Ovenden unpublished data). The drainage channel created to drain Lake Illisarvik is shown in the southwest corner of the lakebed. The 1985, 1993, and 2001 maps were modified from an unpublished manuscript kindly provided by L. Ovenden (cartography by Christine Earl).

Since drainage, Illisarvik has had two residual ponds surrounded by damp depressions that have been colonized by plants adapted to wet and seasonally flooded environments, such as sedges. The basin is drier towards the margins (Fig. 4.2 and 4.3). Bare surfaces have decreased in size since drainage as vegetation has established, but a large patch of unvegetated ground has persisted, and this area may be flooded in some summers by South Pond (Fig. 4.2 and 4.3).

The two residual ponds have fluctuated in size, indicating inter-annual variability in soil moisture and basin water balance. North Pond decreased in size after drainage, disappearing completely in 1993 (Fig. 4.2c). In 2002, the pond reappeared and was still present in 2006 and 2016. South Pond remained consistent in size following drainage and expanded in area in 2002. Fig. 4.2 indicates the inter-annual variability of the size of South Pond.

### 4.2.1 Vegetation change

In 1985, Ovenden (1986) identified these surface units in the basin: the depressions, the barren or sparsely vegetated areas, and the remainder as a mesic-mixed unit. The depressions had high water tables, or standing water, while the mesic-mixed unit was distinguished due to a more diverse vegetation in comparison with the rest of the basin. The vegetation units became more distinct with time. In 1993, Ovenden (unpublished) further sub-divided the mesic mixed unit into a *Salix* unit at the north end with a considerable *Equisetum* ground cover and a grass unit with minimal *Equisetum* at the south end of the basin. Grasses continued to dominate the southern portion of the basin, while in the northern half *Equisetum* and willow shrubs were prevalent in 1993. The *Salix* unit included *Juncus castaneus* in 1993 and then sedges (*Carex capillaris* and *Carex* *bigelowii*) in 2001 (Ovenden unpublished). In 2016, the *Salix* unit covered the north half of the basin but had also extended to the southern margins, including the south end of the large bare ground area.

In 1985, extensive areas of the eastern half of the lake bed were sparsely vegetated (Fig. 4.3). *Descurainia sophioides* and *Epilobium latifolium* were the dominant species present in these units in 1985 and 1993, respectively (Appendix B). By 2001, vegetation cover in this area had increased and retained several species only found in this unit including *Deschampsia caespitosa*, *Puccinellia* spp., *Suaeda calceoliformis*, *Epilobium latifolium*, *Lomatogonium rotatum*, and *Matricaria ambigua*. In 2016, the sparsely vegetated area directly beside South Pond continued to be primarily bare with the exception of a few scattered individuals of *Arctophila fulva.* The sparsely vegetated area further to the east continued to retain species from 2001 except for *Puccinellia* spp., *Suaeda calceoliformis*, and *Epilobium latifolium*. This unit decreased in area and was flooded in some years (such as 2001), but sites such as 50E-100S remained unvegetated (Fig. 4.4). This location experienced deflation before 1993 limiting the ability of plants to colonize (Ovenden 1986). Flooding, as in 2015, may have limited vegetation establishment as well as unfavourable soil chemistry discussed later in section 5.3.4.3.

The damp ground surrounding North and South ponds (labelled "depression, damp" in Fig. 4.3) were characterized by *Arctophila fulva* and *Senecio congestus* in 1985, followed by dense growth of *Carex aquatilis* from 1993 onwards. *Hippuris vulgaris* and *Ranunculus gmelinii* were common in shallow water (<30 cm) and in openings in the sedge marsh in 2001. *Hippuris vulgaris* continued to be the dominant vegetation in the shallow North Pond and was found in openings in the *Carex aquatilis* marsh by South

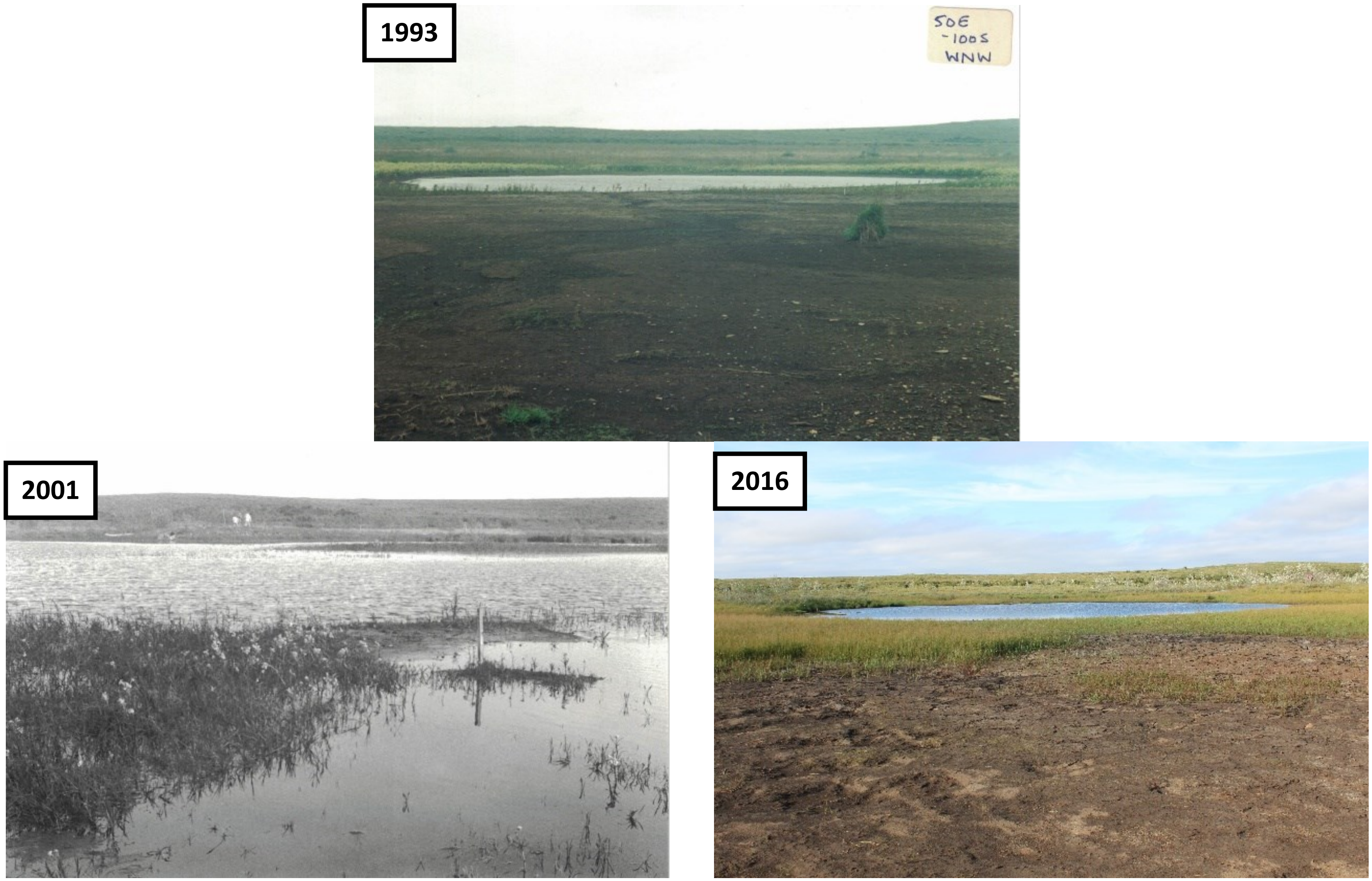



Figure 4.4 - Photos taken from stake 50E-100S in 1993, 2001, and 2016. This site has remained sparsely vegetated since date of drainage. Changes in the size and extent of South Pond result in variations from flooded to bare ground from year to year. Historical photos by Dr. L. Ovenden. Reproduced with kind permission of L. Ovenden.

Pond in 2016. While *Ranunculus gmelinii* was still present, it no longer characterized depression vegetation in 2016. The expansion of South Pond eastward in 2001 did not create any new marshes, but there was a scattered but discontinuous growth of *Arctophila fulva*, *Ranunculus gmelinii,* and *Senecio congestus*. This area was primarily bare ground in 2016, but the eastern side of South Pond contained a marsh of *Arctophila fulva*.

Visually, the grass unit on the southern end of the basin has remained relatively unchanged since the 1993 surveys (Fig. 4.5). Shrubs began to develop between 2001 and 2016, but grasses have remained the predominant vegetation. The most striking visual change with time in the basin has been the development of large woody shrubs *(Salix* spp. and *Alnus viridis* subsp. *crispa*), in the *Salix* unit (Fig. 4.3). *Salix* cover was evident in the north end of the basin in 1993, but the shrubs remained less than 1 m tall. The density of willow cover at the northernmost end of the basin has increased since 1993, but the willows there have been primarily *S. pulchra* and *S. glauca* which have not exceeded 1.5 m in height. In contrast, tall *Salix* (> 1 m) species dominated by *S. alaxensis* and *S. glauca* were abundant on the western margin of the basin in 2016 (Fig. 4.6 and 4.7).

### 4.3 Changes in cover abundance

The increase in vegetation cover over time evident in the photographic record is reflected by the vegetation surveys (Table 4.1). Assuming little change in tundra vegetation cover, difference between vegetation cover in the basin and the tundra had decreased to about 20% by 2016 (Table 4.1).

The vegetation at Illisarvik is grouped into eight PFTs: deciduous shrub, evergreen shrub, forb, grass, sedge, rush, moss, and lichen (Appendix A). Deciduous

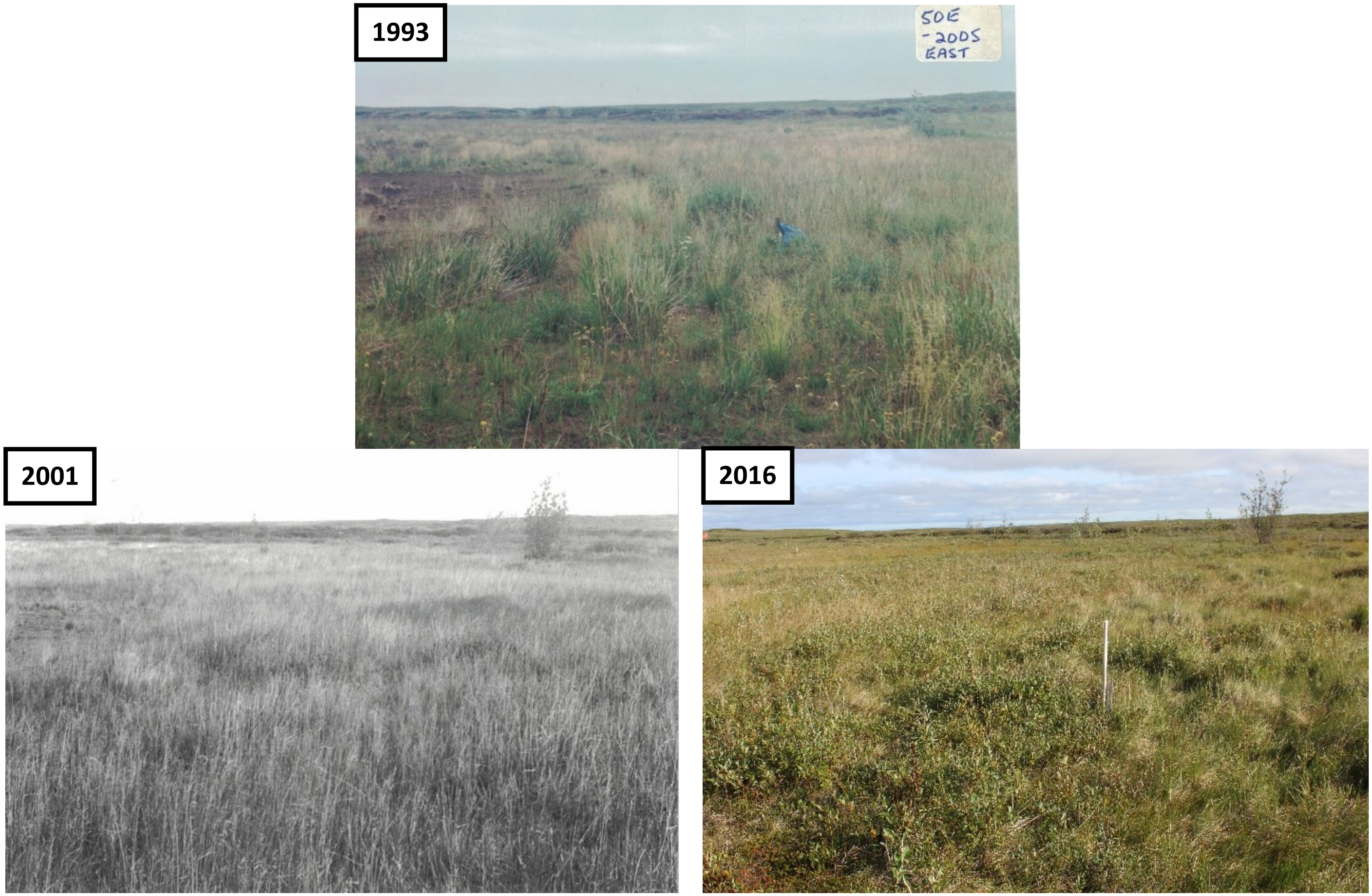



Figure 4.5 - Photos taken from stake 50E-200S in 1993, 2001, and 2016. This site is visually representative of the southern end of the basin grass unit. 1993 and 2001 photos by Dr. L. Ovenden. Reproduced with kind permission of L. Ovenden.


Figure 4.6 - Photos taken from above the grid north of the basin in 1993 (above) and 2016 (below). Note the development of shrubs within the basin in 2016, the growth of willows is shown by the arrow on the right in 2016.  Drainage outlet indicated by the black arrow. 1993 photo by Dr. L. Ovenden. Reproduced with kind permission of L. Ovenden.

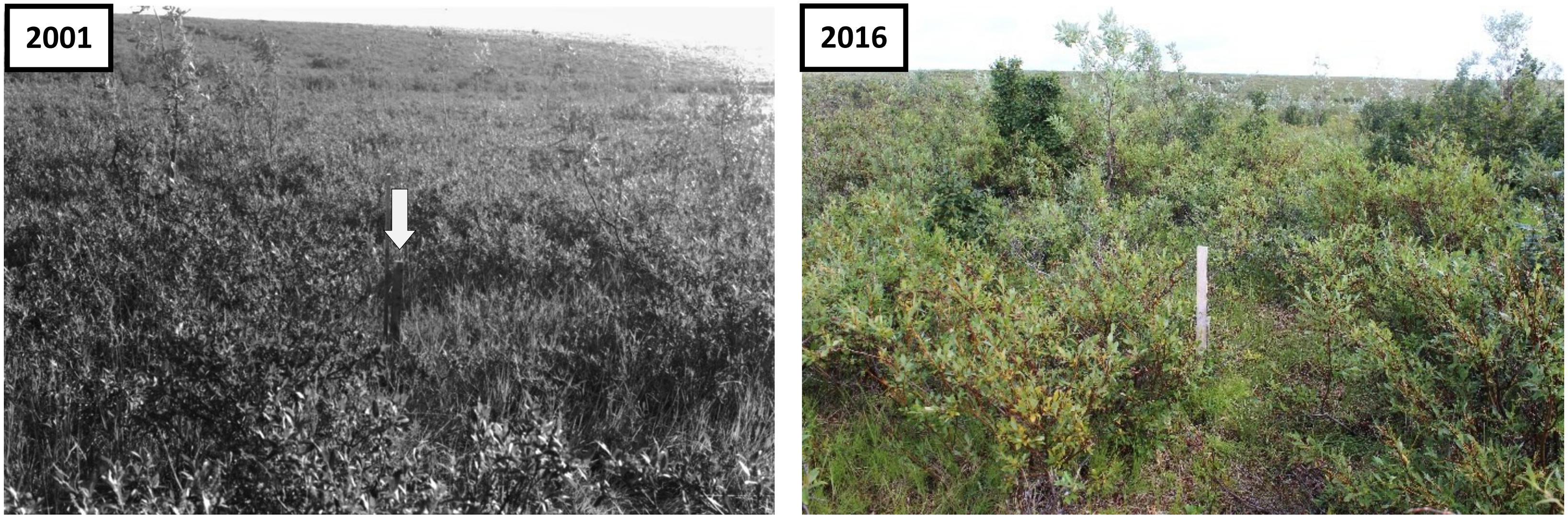



Figure 4.7 - Photographs of stake 150W-150N taken in 2001 (left) and 2016 (right) in the *Salix* vegetation unit. The arrow is pointing to the location of the stake. 2001 photo by Dr. L. Ovenden. Reproduced with kind permission of L. Ovenden.

Table 4.1 - Average % cover for repeated sites in all four years and the tundra ± 1 SE. Total cover may exceed 100% as several different strata are considered in vegetation at a site.

| **Site** | **% Cover** |
|---|---|
| **Basin** | |
| 1985 | 39 ± 6 |
| 1993 | 94 ± 10 |
| 2001 | 111 ± 8 |
| 2016 | 108 ± 5 |
| **Tundra** | |
| 2016 | 133 ± 4 |

shrub (primarily *Salix* spp.) cover increased substantially from 1993 to 2001 but has subsequently remained at ~20% (Fig. 4.8). Evergreen shrubs appeared in 2001 with a slight increase in cover in 2016 to ~8%, but well below the cover of ~25% measured in the tundra. Forb cover peaked in 1993 and 2001 when it was the dominant PFT but declined to its lowest level in 2016 with values remaining slightly greater than the tundra. Grass and sedge cover have increased since drainage, while rush and lichen cover showed little difference among years or compared with the tundra sites. Moss coverage varied from ~7-10% from 1993 to 2016 and remained below tundra values. The visual increase in plant cover is supported by the decrease in bare ground cover with time. The most rapid contraction of the bare ground units occurred between 1985 and 1993 with little change since 2001. Overall, shrub, grass, and sedge cover increased, bare ground cover decreased since drainage, and forb cover decreased since 2001 (Fig. 4.8).

The vegetation succession in the basin is documented in Table 4.2, which indicates the change in species composition with time. The table represents the species lists compiled in 1985, 1993, 2001, and 2016 by survey year and grouped by PFT. Early successional species, such as *Descurainia sophioides*, *Juncus arcticus*, and *Epilobium angustifolium*, were not observed in later surveys, while deciduous and evergreen shrub species remained in the basin once established.

### 4.4 Species diversity

Species richness was significantly different amongst the surveys ($\chi^2$ = 92.57 and p <0.001), with the fewest species in 1985. Species richness in 2016 was significantly different from 1993, 2001, and the tundra (Table 4.2, Fig. 4.9). Species diversity (as

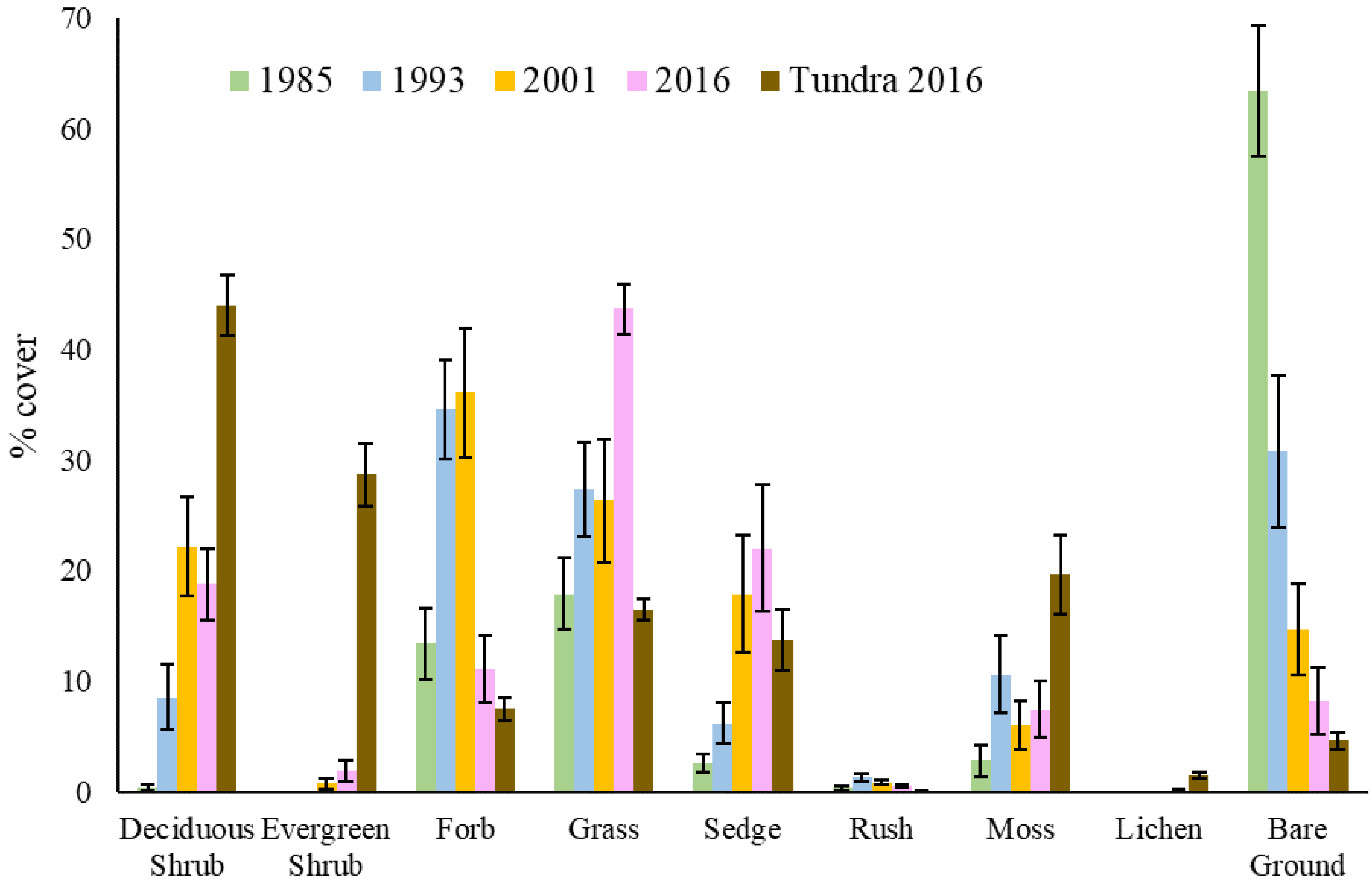



Figure 4.8 - Percent cover of major plant functional types (PFT) at Illisarvik basin from 1985 to 2016. Data are means ± 1 SE (n=31 for basin and n=43 for tundra sites). Tundra sites surveyed in 2016 only.

Table 4.2 - Presence of vascular species at Illisarvik in 1987, 1993, 2001, 2016 and the surrounding tundra. Species are ordered by first appearance and disappearance from the site.

| | 1985 | 1993 | 2001 | 2016 | Tundra |
|---|---|---|---|---|---|
| **Forb** | | | | | |
| *Epilobium angustifolium* | X | | | | X |
| *Descurainia sophioides* | X | X | | | |
| *Senecio congestus* | X | X | X | | |
| *Cochlearia officinalis* | X | X | X | | |
| *Draba glabella* | X | X | X | | |
| *Matricaria ambigua* | X | X | X | | |
| *Suaeda calceoliformis* | X | X | X | | |
| *Artemisia tilesii* | X | X | X | X | X |
| *Equisetum arvense* | X | X | X | X | X |
| *Hippuris vulgaris* | X | X | X | X | |
| *Pedicularis sudetica* | X | X | X | X | X |
| *Stellaria longipes s.l.* | X | X | X | X | X |
| *Braya humilis* | | X | | | |
| *Stellaria calycantha* | | X | | | |
| *Ranunculus cymbalaria* | | X | | | |
| *Bistorta vivipara* | | X | X | | X |
| *Caltha palustris* | | X | X | | |
| *Cerastium beeringianum* | | X | X | | |
| *Epilobium latifolium* | | X | X | | |
| *Lomatogonium rotatum* | | X | X | | |
| *Rumex arcticus* | | X | X | | |
| *Saxifraga hirculus* | | X | X | | X |
| *Silene uralensis* | | X | X | | |
| *Castilleja raupii* | | X | X | X | X |
| *Parnassia kotzebuei* | | X | X | X | X |
| *Ranunculus gmelinii* | | X | X | X | |
| *Stellaria crassifolia* | | X | X | X | |
| *Astragalus alpinus* | | | X | | |
| *Amerorchis rotundifolia* | | | | X | |
| *Epilobium palustre* | | | | X | |
| *Orthillia secunda* | | | | X | |
| *Oxytropis campestris* | | | | X | |
| *Tofieldia pusilla* | | | | X | X |

| | 1985 | 1993 | 2001 | 2016 | Tundra |
|---|---|---|---|---|---|
| **Forb (continued)** | | | | | |
| *Lupinus arcticus* | | | | | X |
| *Pedicularis capitata* | | | | | X |
| *Petasites frigidus* | | | | | X |
| *Saussurea angustifolia* ssp. *Angustifolia* | | | | | X |
| *Senecio atropurpureus* | | | | | X |
| **Grass** | | | | | |
| *Puccinellia* spp. | X | X | X | | |
| *Arctagrostis latifolia* | X | X | X | X | X |
| *Arctophila fulva* | X | X | X | X | |
| *Festuca* spp. | X | X | X | X | |
| *Deschampsia caespitosa* | X | X | X | X | X |
| *Dupontia fisheri* | X | X | X | X | X |
| *Poa* spp. | X | X | X | X | X |
| *Trisetum spicatum* | X | X | X | X | |
| *Alopecurus alpinus* | | X | X | | |
| *Calamagrostis stricta* | | X | X | X | X |
| *Kobresia myosuroides* | | | | X | X |
| *Anthoxanthum monticola* ssp. *Alpinum* | | | | | X |
| **Sedge** | | | | | |
| *Carex capillaris* | X | X | X | | |
| *Carex aquatilis* | X | X | X | X | X |
| *Carex bigelowii* ssp. *lugens* | X | X | X | X | X |
| *Eriophorum scheuchzeri* | X | X | X | X | |
| *Carex krausei* | | X | | | |
| *Carex maritima* | | X | X | | |
| *Carex saxatilis* | | X | X | | |
| *Eriophorum angustifolium* | | X | X | | |
| *Carex atrofusca* | | | X | | |
| *Carex lachenalii* | | | | X | X |
| *Eriophorum vaginatum* | | | | | X |

Table 4.2 - Continued

| | 1985 | 1993 | 2001 | 2016 | Tundra | | 1985 | 1993 | 2001 | 2016 | Tundra |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Rush** | X | | | | | **Deciduous Shrub** | | | | | |
| *Juncus arcticus* | X | X | X | | | *Salix alaxensis* | X | X | X | X | X |
| *Juncus castaneus* | | X | | | | *Salix glauca* | X | X | X | X | X |
| *Juncus biglumis* | | X | X | | | *Salix niphoclada* | | X | X | | |
| *Luzula arctica ssp. arctica* | | X | X | X | X | *Salix ovalifolia* | | X | X | | |
| *Juncus balticus* | | | X | | | *Salix planifolia* | | | X | | |
| *Luzula confusa* | | | | X | X | *Alnus viridis* subsp. *crispa* | | | X | | X |
| *Luzula nivalis* | | | | | X | *Betula glandulosa* | | X | X | X | X |
| *Luzula multiflora* | | | | | | *Salix arbusculoides* | | X | X | X | X |
| | | | | | | *Salix arctica* | | X | X | X | X |
| **Evergreen Shrub** | | | X | X | X | *Salix lanata* | | X | X | X | X |
| *Empetrum nigrum* | | | X | X | X | *Salix pulchra* | | X | X | X | X |
| *Pyrola grandiflora* | | | | X | X | *Arctostaphylos rubra* | | | X | X | X |
| *Dryas integrifolia* | | | | X | X | *Vaccinium uliginosum* | | | X | X | X |
| *Ledum palustre* subsp. *decumbens* | | | | X | X | *Rubus chamaemorus* | | | | | X |
| *Vaccinium vitis-idaea* | | | | | X | *Salix reticulata* | | | | | X |
| *Andromeda polifolia* | | | | | X | | | | | | |
| *Cassiope tetragona* | X | | | | | | | | | | |

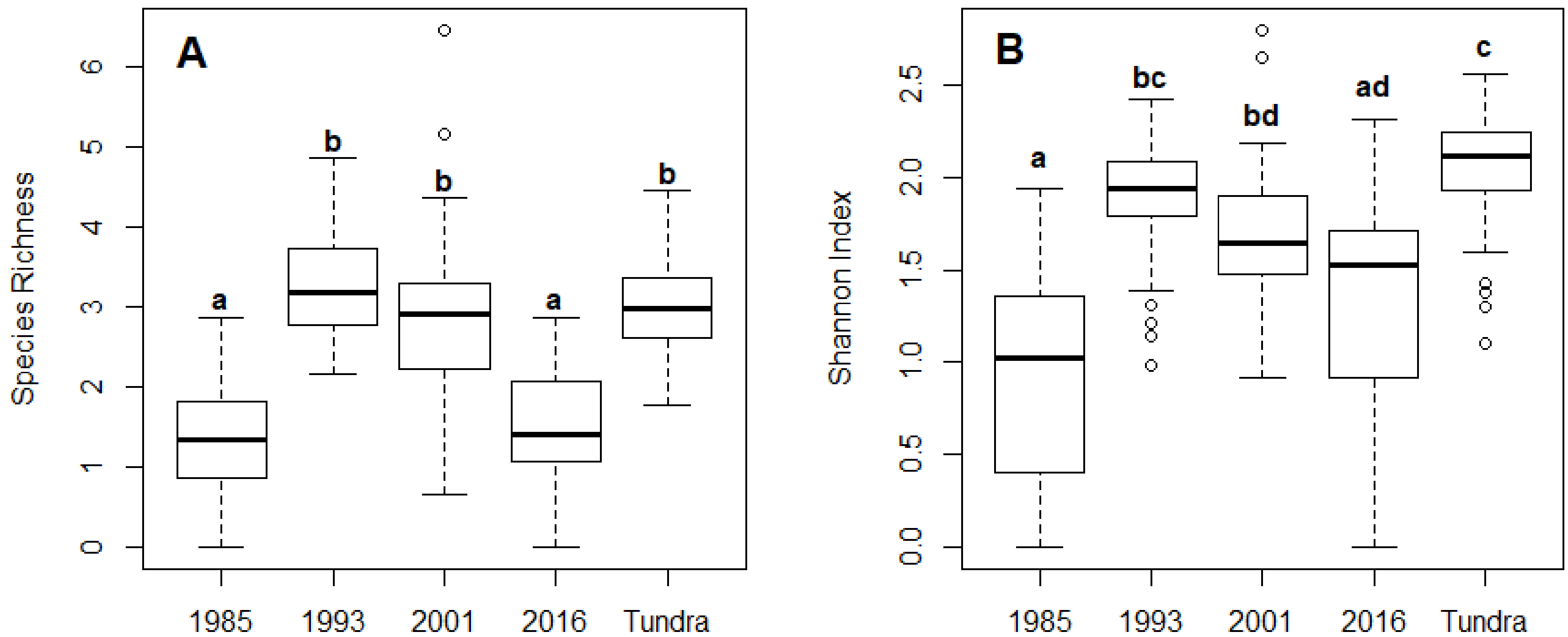



Figure 4.9 - Boxplots across years for (A) species richness and (B) the Shannon index of alpha diversity. Different letters represent significant differences in species richness and diversity determined using a post-hoc Dunn’s test. Boxes represent the lower and upper quartiles, solid horizontal lines are the median value, and the whiskers are the minimum and maximum values or if there are outliers it is 1.5 the interquartile range.

measured using the Shannon H index) was significantly different between the years ($\chi^2$ =73.73, p <0.001). Diversity was lowest in 1985, increased in 1993 to a comparable diversity with the tundra, decreased in 2001, and continued to decrease towards 2016, but still had a value higher than 1985. Species evenness was not significantly different amongst survey years ($\chi^2$ = 8.20, p = 0.08), suggesting that species richness is the main influence on the species diversity values (Fig. 4.9).

## 4.5 Vegetation composition

### 4.5.1 Transition with time

Ordination was used to compare vegetation composition at Illisarvik in four survey years and at tundra sites in 2016, as well as to determine any quantitative or statistical compositional differences in plant cover. Figure 4.10 is the ordination plot for these data obtained through non-metric multidimensional scaling (NMDS). This plot demonstrates the statistical progression over time within the vegetation cover data, and the distinctive statistical nature of the tundra in this phase space. For data from the lake basin, scores on the first axes decline and on the second axis increase over time. NMDS revealed compositional differences between each year and the tundra (Fig. 4.10) for none of the basin sites in any year overlapped with the tundra cluster.

### 4.5.2 Compositional differences between years

Analysis of Similarities (ANOSIM) was used to determine if there are statistically significant compositional differences among the survey years and the tundra. ANOSIM indicated significant differences (p<0.001) between each survey year and the tundra (Table 4.3). Despite significant p-values for each group in the ANOSIM analysis, most groups cannot be well-separated or individually distinguished using the $R_{ANOSIM}$ values.

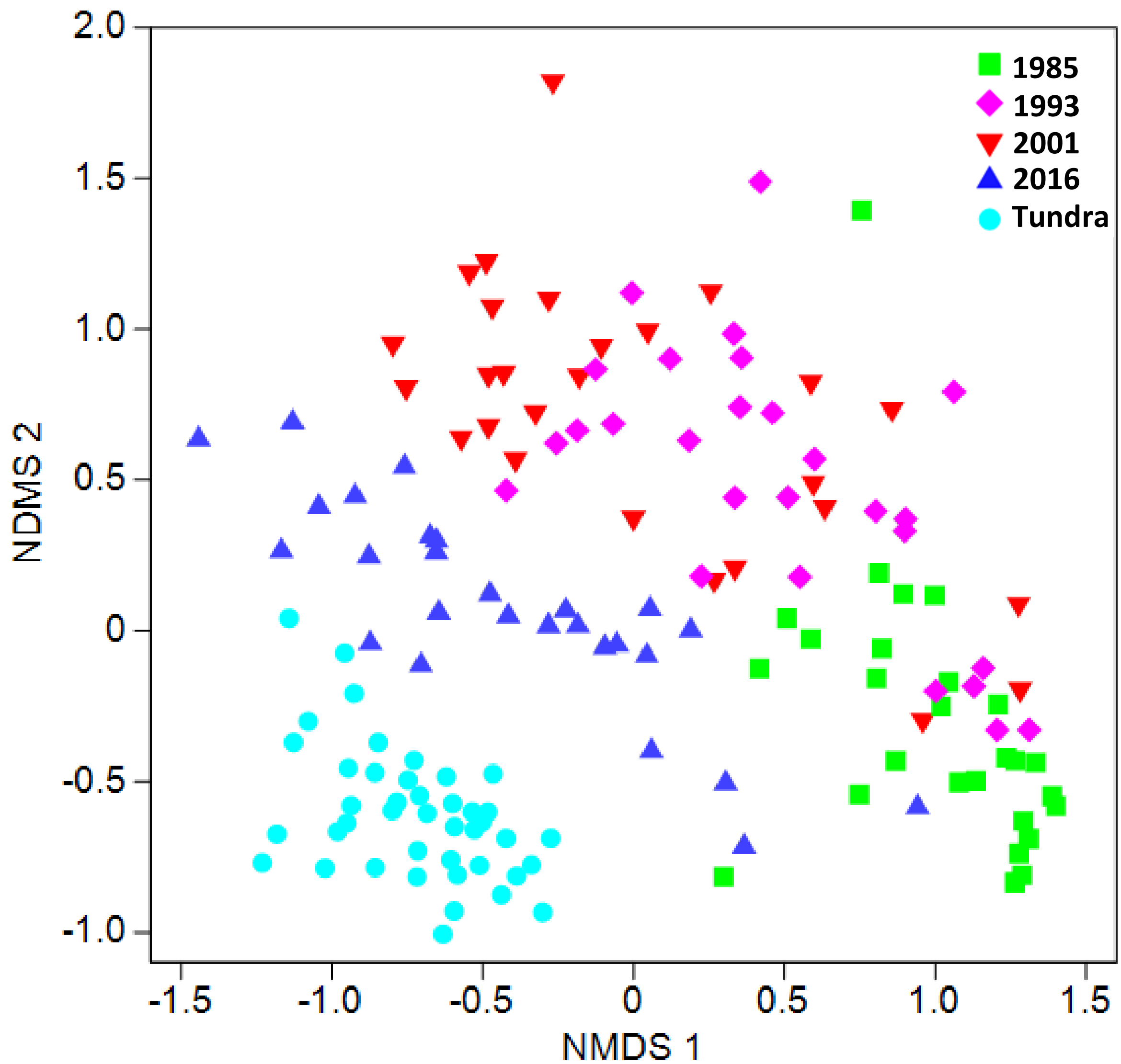



Figure 4.10 - Non-metric multidimensional scaling (NMDS) ordination of plant community composition based on Bray-Curtis similarity matrices (stress = 0.21, k=2). Results are shown for all repeat sites from 1985, 1993, 2001, and 2016 sites as well as tundra sites.

Table 4.3 - Pair-wise comparisons of plant community composition between years and the tundra surveys using the ANOSIM procedure. $R_{ANOSIM}$ values in bold (higher than 0.75) indicated well-separated groups, values between 0.50 to 0.75 describe overlapping but distinguishable groups, and values less than 0.25 represent groups that cannot be separated (Clarke and Gorley 2001).

| | **1985** | **1993** | **2001** | **2016** | **Tundra** |
|---|---|---|---|---|---|
| **1985** | - | | | | |
| **1993** | 0.35 | - | | | |
| **2001** | 0.46 | 0.14 | - | | |
| **2016** | 0.67 | 0.65 | 0.38 | - | |
| **Tundra** | **0.85** | **0.93** | **0.81** | **0.76** | - |

Only tundra was well-separated from the basin in all years. Since 1993 the compositions have converged as the $R_{ANOSIM}$ values decrease. None of the basin years can be well-separated, indicating that there is compositional overlap between years (Table 4.3).

### 4.5.3 Similarities between years

Using Similarity Percentages (SIMPER) analysis, each group was compared to determine the species contributing to the greatest similarity within years (Table 4.4). Table 4.4 shows the top five species that contribute to the similarity of sites within each group (years and tundra). Mean similarity (Table 4.4, second column) is the amount a species contributes to the average similarity within the group. The more abundant the species within the group, the more it will contribute to intra-group similarities and, secondly, the more evenly distributed the species is in its greater abundance, the more it will typify the group. *Arctagrostis latifolia* has been an important component of the vegetation cover during every survey year. *Puccinellia* spp. were important in 1985 and 1993 and *Carex aquatilis* from 1993 to 2016. Vegetation composition in 1985 was primarily characterized by the early successional species *Descurainia sophioides*, *Senecio congestus* and *Arctophila fulva*. *Puccinellia* spp. and *Arctagrostis latifolia* dominated the basin in the early years, but *Puccinellia* spp. and *Senecio congestus* decreased in cover after 1985, and were not found in 2016. *Equisetum arvense* has been a dominant component of the cover since 1993. While *Salix glauca* became dominant in the basin from 2001, it is the only vascular plant species to be found in both basin and tundra SIMPER analysis. Each year had some compositional overlap with other years (Fig. 4.10, Table 4.3, Table 4.4), due to species that persisted in the basin such as *Carex aquatilis*, *Salix glauca*, and *Arctagrostis latifolia*. Differences in

Table 4.4 - Results of SIMPER analysis characterizing similarity in community composition between the re-surveyed sites each year and in the tundra. The table shows the top five species (or species groups) that make the greatest contribution to the between-group Bray-Curtis similarity for each year. Mean similarity is a measure of the consistency in vegetation composition between all surveyed sites within the year. The mean cover (untransformed) of each species is shown in the second column.

| **Survey Year/ Species** | **Mean cover (%)** | **Mean similarity †** | **Sim/SD‡** | **Percent contribution §** | **Cumulative similarity** |
|---|---|---|---|---|---|
| 1985: Mean similarity = 16.51; n=31 | | | | | |
| * *Puccinellia* spp. | 10.9 | 10.38 | 0.78 | 65.60 | 65.60 |
| *Descurainia sophioides* | 3.7 | 1.85 | 0.23 | 11.22 | 76.82 |
| *Senecio congestus* | 3.0 | 0.90 | 0.35 | 5.46 | 82.28 |
| - *Arctagrostis latifolia* | 3.0 | 0.83 | 0.27 | 5.02 | 87.30 |
| *Arctophila fulva* | 3.4 | 0.52 | 0.18 | 3.15 | 90.45 |
| 1993: Mean similarity = 20.88; n=31 | | | | | |
| - *Arctagrostis latifolia* | 13.9 | 4.28 | 0.70 | 20.48 | 20.48 |
| *Equisetum arvense* | 15.3 | 3.26 | 0.43 | 15.61 | 36.09 |
| * *Puccinellia* spp. | 5.8 | 2.07 | 0.45 | 9.92 | 46.01 |
| *Deschampsia caespitosa* | 5.1 | 1.82 | 0.67 | 8.70 | 54.71 |
| Moss | 10.3 | 1.56 | 0.35 | 7.45 | 62.17 |
| 2001: Mean similarity = 16.31; n=31 | | | | | |
| *Equisetum arvense* | 18.8 | 3.51 | 0.36 | 21.55 | 21.55 |
| ● *Carex aquatilis* ssp. *stans* | 12.6 | 2.63 | 0.38 | 16.15 | 37.70 |
| - *Arctagrostis latifolia* | 14.8 | 2.40 | 0.31 | 14.72 | 52.43 |
| + *Salix glauca* | 8.7 | 1.69 | 0.39 | 10.34 | 62.77 |
| *Artemisia tilesii* | 3.4 | 0.76 | 0.38 | 4.67 | 67.44 |
| 2016: Mean similarity = 18.55; n=31 | | | | | |
| ● *Carex aquatilis* ssp. *stans* | 21.0 | 7.09 | 0.39 | 38.57 | 38.57 |
| *Equisetum arvense* | 9.5 | 2.66 | 0.46 | 14.46 | 53.03 |
| + *Salix glauca* | 5.6 | 1.86 | 0.41 | 10.09 | 63.12 |
| - *Arctagrostis latifolia* | 4.6 | 1.80 | 0.39 | 9.78 | 72.90 |
| Moss | 7.4 | 1.49 | 0.35 | 8.11 | 81.01 |
| Tundra: Mean similarity = 35.71; n=43 | | | | | |
| Moss | 19.6 | 6.34 | 0.79 | 17.76 | 17.76 |
| + *Salix glauca* | 14.3 | 6.21 | 1.01 | 17.40 | 35.15 |
| *Betula glandulosa* | 13.6 | 5.65 | 0.94 | 15.81 | 50.97 |
| *Cassiope tetragona* | 11.7 | 4.09 | 0.80 | 11.45 | 62.42 |
| *Carex bigelowii ssp. lugens* | 5.4 | 2.15 | 0.85 | 6.01 | 68.43 |

† Mean similarity in this column describes how the species contributes to the overall mean similarity of surveyed sites within each year, and how representative and consistent the species is within the group.

‡ Sim/SD is a species mean similarity divided by its standard deviation. Higher values indicate that the species not only contributes to within group similarity but does so consistently.

§ The percent contribution is the species mean similarity divided by the year mean similarity.

vegetation composition were caused by transient species such as the early successional species, *Senecio congestus*, *Puccinellia spp*., and *Descurainia sophioides*, their reduction in cover may have been due to changes in environmental variables or species competition. Nevertheless, the higher cumulative similarity in 1985 (Table 4.4) suggests greater homogeneity within the basin than in years requiring more species to reach the same cumulative similarity values. This is supported by Fig. 4.9, in which 1985 has the lowest species diversity and richness.

### 4.5.4 Distinct yearly species

Indicator species are ones that are most representative of a group of sites, as a combination of species relative abundance and relative frequency. The strongest indicator species are found at all sites in a group and not at sites of other groups (Dûfrene and Legendre 1997). In 1985, the indicator species were the early successional species *Descurainia sophioides*, *Senecio congestus*, and *Arctophila fulva* (Table 4.5). Indicator species for 1993 were *Matricaria ambigua*, *Cochlearia officinalis*, *Draba glabella*, *Silene uralensis* and *Juncus castaneus*. Three indicator species were found for 2001: *Ranunculus gmelinii, Hippuris vulgaris*, and *Luzula arctica*. There were no indicator species for 2016, while the tundra had 23. All species present in 2016 in the basin were found in other groups (e.g. years), implying that no new and well colonized species had established within the basin since 2001. The lack of indicator species in 2016 and the numerous indicator species for the tundra sites indicate that there is still a large compositional difference between the basin and surrounding tundra. The tundra is a better environment for evergreen shrubs.

Additional analysis of indicator species was conducted with pairs of years, in

Table 4.5 - Indicator species analysis results for the different survey years.

| Year | Species | Indicator Value | p-value | A † | B ‡ |
|---|---|---|---|---|---|
| 1985 | | | | | |
| | *Descurainia sophioides* | 0.604 | 0.001 | 0.9440 | 0.3871 |
| | *Senecio congestus* | 0.585 | 0.001 | 0.7598 | 0.4516 |
| | *Arctophila fulva* | 0.451 | 0.001 | 0.6994 | 0.2903 |
| 1993 | | | | | |
| | *Matricaria ambigua* | 0.743 | 0.001 | 0.7444 | 0.7419 |
| | *Cochlearia officinalis* | 0.662 | 0.001 | 0.6797 | 0.6452 |
| | *Draba glabella* | 0.543 | 0.001 | 0.7037 | 0.4194 |
| | *Silene uralensis* | 0.492 | 0.001 | 0.7500 | 0.3226 |
| | *Juncus castaneus* | 0.415 | 0.004 | 0.5938 | 0.2903 |
| 2001 | | | | | |
| | *Ranunculus gmelinii* | 0.410 | 0.003 | 0.8674 | 0.1936 |
| | *Hippuris vulgaris* | 0.369 | 0.011 | 0.8431 | 0.1613 |
| | *Luzula arctic* | 0.321 | 0.020 | 0.8000 | 0.1290 |
| 2016 | | | | | |
| | None | | | | |
| Tundra § | | | | | |
| | *Cassiope tetragona* | 0.889 | 0.001 | 1.000 | 0.7907 |
| | *Arctostaphylos rubra* | 0.854 | 0.001 | 0.8950 | 0.8140 |
| | *Betula glandulosa* | 0.833 | 0.001 | 0.8286 | 0.8372 |
| | Lichen | 0.795 | 0.001 | 0.9371 | 0.6744 |
| | *Carex bigelowii* | 0.788 | 0.001 | 0.7425 | 0.8372 |

† 'A' values indicate how representative species is of the year. If only found in that year, the index would have a value of 1.

‡ 'B' values indicate how pervasive the species are of the sites in that year. If the species is found in all the sites, the index would have a value of 1.

§ For the tundra unit other indicator species from highest to lowest value are: *Lupinus arcticus*, *Vaccinium uliginosum*, *Dryas integrifolia*, *Ledum palustre* subsp. *decumbens*, *Pyrola grandiflora*, *Empetrum nigrum*, *Eriophorum vaginatum*, *Rubus chamaemorus*, *Petasites frigidus*, *Sausserea angustifolia*, *Senecio atropurpureus*, *Pedicularis capitata*, *Andromeda polifolia*, *Salix reticulat*a, *Tofieldia pusilla*, *Bistorta vivipara* and *Alnus viridis* subsp*. crispa*.

which indicator species were determined that are representative of several survey years. The analysis illustrated the development of indicators that are less transitory within the basin (Table 4.6). For instance, *Puccinellia* spp. were indicator species for 1985 and 1993 when combined, but they were not present in 2016. *Salix* spp. were indicator species for 1993, 2001, 2016, and the tundra (*Salix glauca*, *Salix pulchra*, *Salix arctica*, and *Salix lanata*), while *Salix alaxensis* remained an indicator within the basin from 1993 onwards.

### 4.6 Succession in drained lake basins

In the Arctic, the general successional model for drained thaw lake basins is that re-vegetation and then peat accumulation follows drainage (Bliss and Peterson 1991; Eisner *et al.* 1998; Hinkel *et al.* 2005; Jones *et al.* 2012; Lantz *et al.* 2017). At other sites, wet, graminoid vegetation establishes within 5-10 years, and peat accumulation begins 20-100 years following drainage (Jones *et al.* 2012). Over time, basin productivity decreases as graminoid vegetation communities are replaced by ericaceous bogs and tussock-tundra ecosystems. Younger basins have been shown to have higher gross primary production than older basins (Zona *et al.* 2010). The vegetation succession occurs as available nutrients decrease in abundance, and permafrost aggradation limits rooting depth and liquid water availability (Zona *et al.* 2010; Jones *et al.* 2012).

Overall at Illisarvik, peat accumulation has not begun in the drained lake basin. The organic matter horizon was less than 1 cm thick at most of the sites surveyed. In terms of vegetation productivity, the basin decreased in species richness and diversity after 1993.

Table 4.6 - Indicator species analysis results for groupings of years.

| Year | Species | Indicator Value | p-value | A † | B ‡ |
|---|---|---|---|---|---|
| 1985 and 1993 | | | | | |
| | *Puccinellia* spp. | 0.789 | 0.001 | 0.8762 | 0.7097 |
| 1993 and 2001 § | | | | | |
| | *Artemisia tilesii* | 0.747 | 0.001 | 0.8654 | 0.6452 |
| | *Deschampsia caespitosa* | 0.722 | 0.001 | 0.8967 | 0.5806 |
| | *Stellaria longipes* | 0.639 | 0.001 | 0.9043 | 0.4516 |
| | *Castilleja raupii* | 0.580 | 0.001 | 0.8678 | 0.3871 |
| | *Stellaria crassifolia* | 0.574 | 0.001 | 0.9712 | 0.3387 |
| 2001 and 2016 | | | | | |
| | *Parnassia kotzebuei* | 0.530 | 0.001 | 0.8297 | 0.3387 |
| 1993, 2001, and 2016 ¶ | | | | | |
| | *Carex aquatilis* | 0.767 | 0.001 | 0.9123 | 0.6452 |
| | *Arctagrostis latifolia* | 0.757 | 0.008 | 0.8872 | 0.6452 |
| | *Equisetum arvense* | 0.710 | 0.001 | 0.8843 | 0.5699 |
| | *Salix alaxensis* | 0.648 | 0.001 | 0.9773 | 0.4301 |
| | *Poa* spp. | 0.621 | 0.001 | 0.8155 | 0.4731 |
| 1993, 2001, 2016 and tundra | | | | | |
| | Moss | 0.785 | 0.001 | 0.9970 | 0.6176 |
| | *Salix glauca* | 0.739 | 0.001 | 0.9641 | 0.5662 |
| | *Salix pulchra* | 0.636 | 0.001 | 1.0000 | 0.4044 |
| | *Salix arctica* | 0.507 | 0.009 | 1.000 | 0.2574 |
| | *Salix lanata* | 0.470 | 0.031 | 1.0000 | 0.2206 |

† 'A' values indicate how representative the species are of the year grouping. If only found in that year, the index would have a value of 1.

‡ 'B' values indicate how representative the species are of the sites in that year grouping. If the species is found in all the sites, the index would have a value of 1.

§ For the 1993 and 2001 grouping other indicator species from highest to lowest indicator value after those in the table are: *Salix ovalifolia*, *Trisetum spicatum*, *Epilobium latifolium, Eriophorum angustifolium*, *Alopecurus alpinus*, and *Carex maritima*.

¶ For the 1993, 2001, and 2016 grouping other indicator species from highest to lowest indicator value after those in the table are: *Calamagrostis stricta* and *Juncus balticus* ssp. a*laskanus*.

### 4.6.1 Vegetation succession model

The vegetation succession within the basin is best described by a directional species replacement model, in which biological driving forces are greater than environmental resistance. The evidence for this model includes the change in indicator species over time and the decrease in the similarity of the basin vegetation over time. Billings and Peterson (1980) and Lantz (2017) also used successional replacement to explain changes in vegetation composition at lake basins in Alaska and Old Crow Flats (OCF), YK. Billings and Peterson (1980) state that on the coastal tundra of northwestern Alaska, grasses (*Dupontia fisheri* and *Arctophila fulva*) and *Eriophorum scheuchzeri* predominate in the lakebeds for the first few decades following drainage (Billings and Peterson 1980). The successional pathway appears to proceed to a mossy sod of *Carex aquatilis* hundreds of years later. In the OCF, early vegetation succession was dominated by the rapid development of dense willow stands (Lantz 2017). In the youngest basin, that was three years old, Lantz (2017) found early colonizers with small seeds that are rapidly dispersed (*Epilobium palustre*, *Eriophorum russeolum*, *Salix* spp., *Senecio congestus*, and *Stellaria longipes*).

The early successional species in Alaska (Bilings and Peterson 1980) of *Dupontia fisheri*, *Eriophorum scheuchzeri*, and *Arctophila fulva* correspond with the 1985 survey at Illisarvik. *Arctophila fulva* was an indicator species for the basin in 1985, while the early colonizing species of *Dupontia fisheri* and *Eriophorum scheuchzeri* were still present within the basin in 2016. However, in the OCF basins the earliest basin (three-years-post-drainage) was dominated by *Senecio congestus* (Lantz 2017), which is an indicator for Illisarvik in 1985, and *Carex aquatilis*, which became a characterizing species at

Illisarvik 15 years following drainage.

Of the early successional species found at Illisarvik and the basins researched by Lantz (2017) and Billings and Peterson (1980), only *Senecio congestus* and *Puccinellia* spp. are no longer present. Other species that were well established but have diminished in abundance in the Illisarvik basin include *Epilobium angustifolium*, *Cochlearia officinalis*, *Suaeda calceoliformis*, and *Descurainia sophioides*. This indicates that Illisarvik is still in the early successional stages, and that other species are not out-competing some of the colonizing species yet. *Equisetum arvense* has been a dominant species in Illisarvik after 2001 and was present in the OCF basins ranging from 12 - 43 years of age (Lantz 2017).

Willow establishment at Illisarvik has been consistent with reports from the OCF (Lantz 2017), but not with the field studies from the North Slope (Billings and Peterson 1980). In OCF, willows were well established in one basin within two years of drainage and were found in all the basins studied under 44 years of age (Lantz 2017). The rapid growth of willows resulted in the exclusion of most other species in the OCF. At Illisarvik, willows were established within the basin by 1993, and became an indicator from 1993 onwards, characterizing the basin coverage from 2001 onwards.

There are some indications that Illisarvik vegetation communities are becoming more compositionally similar to the tundra. A few species that are characteristic of the tundra have established within the basin, such as *Arctostaphylos rubra*, *Empetrum nigrum*, *Dryas integrifolia*, *Ledum palustre* subsp. *decumbens*, *Vaccinium vitis-idaea*, and *Vaccinium uliginosum*. However, these species have still only established near the margins of the basin and present low percent coverage in comparison with other vegetation. *Vaccinium vitis-idaea* and *Ledum palustre* subsp. *decumbens* are characterizing species at an 83-year-old basin (Lantz 2017). If Illisarvik continues in its current trajectory more tundra species may establish within the basin, with a continued succession towards the vegetation composition of the surrounding tundra.

Trends in species replacement at Illisarvik suggest that willow shrubs and *Carex aquatilis* have been the most effective competitors in the early stages of succession (Ovenden, unpublished), and this trend continued in 2016. Ovenden (unpublished) speculated that prominence of *Descurainia*, *Senecio*, *Matricaria*, *Puccinellia*, and *Arctophila* was due to seed dispersal of these species from the nearby seashore or the former shoreline of Lake Illisarvik, or even in bird feces. Bird feces are an important factor in primary succession environments, particularly for grass dispersal (Magnússon *et al.* 2014), but the close proximity of tundra vegetation in relation to the basin, likely makes wind dispersal the primary form of seed transport. The gradual replacement of the early colonizer species by *Arctagrostis*, *Equisetum*, *Carex aquatilis*, and *Salix* spp., suggests that they competed less effectively for the resources as more vegetation has become established (Ovenden, unpublished).

### 4.6.2 Succession trajectory

The environment at Illisarvik is closer to that of the North Slope than that of OCF in terms of climate and undisturbed tundra vegetation, but the species found within the basin more closely resemble that of those in OCF. The basins in the North Slope are dominated by hydrophilic graminoids; *Dupontia fisheri*, *Eriophorum scheuchzeri*, and *Arctophila fulva* (Billings and Peterson 1980; Zona *et al.* 2010). This suggests that local climates may not play as important a role as the available species pool, which may alter the direction of succession following drainage.

The relation between sites with high soil moisture and *Carex aquatilis* establishment suggests that direction of succession is primarily dominated by the soil moisture regime. Waterlogged sites would limit the establishment of willows and shrubs that typically thrive at disturbances, as well as species requiring a drier substrate (Johnstone and Kokelj 2008; Kemper and Macdonald 2009, Lantz *et al.* 2009; Lantz *et al.* 2010). Indeed, at Illisarvik the depressions surrounding the ponds were dominated by *Carex aquatilis* in 1993, 2001, and 2016.

In 2016, willows were widespread within Illisarvik basin, with new younger growth established at the south end of the basin near the ponds and bare ground areas. The current trajectory indicates that there will be continued willow growth at Illisarvik, but most of the older basins on Richards Islands are over several hundred years old but do not have any erect shrub development. Willow may not persist indefinitely, for intraspecific competition will drive self-thinning in stands (Verwijst 1996; Bullard *et al.* 2002; Lantz 2017), and these stands will likely be replaced by other plant communities. The lack of willow dominated older basins indicates that they are a seral community (Ovenden 1982; Lantz 2017). However, successional trajectory of the basin vegetation either towards one similar to the tundra or towards another assemblage is unknown, and the presence of willows may persist in this new trajectory due to climate change. A limited understanding of succession on a centennial and millennial time scale, in conjunction with the influence of a changing climate and ground conditions makes prediction of future successional trajectories difficult (Bartleman *et al.* 2001; Johnstone and Chapin 2003; Lantz *et al.* 2009; Lantz 2017).

### 4.7 'Climax' vegetation

A climax community is the natural vegetation that exists in an area at the end of vegetation succession. It is indicated by the establishment of a vegetation community that is stable, self-maintaining, self-reproducing, and in equilibrium with the environment (Park and Allaby 2017). This species composition will remain undisturbed through time, so long as the environment remains unchanged since the growth of other species is inhibited by competition for food, energy, nutrients, and space. The tundra surrounding Illisarvik may be considered a climax community, but in order for a climax community to exist the environment cannot change. Yet, the climate is changing, particularly in Arctic regions. Temperatures in the Mackenzie Delta are increasing relatively rapidly (Lantz and Kokelj 2008; Burn and Kokelj 2009), and there is a predicted increase in precipitation in the near-shore Beaufort region which would influence the moisture regime at Illisarvik (Bonsal and Kochtubajda 2009).

Unfortunately, the surrounding tundra had not been surveyed until 2016, and so it is not possible to determine if there is any change in vegetation characteristic of the climax community of the upland tundra. However, there is indication of change through photographs, particularly in the establishment and propagation of alders in the tundra north and west of the basin. This is illustrated in photographs (Fig. 4.3) where the growth of alder from 1993 to 2016 at the north end of the grid is evident.

Studies of vegetation succession in the western Arctic use space-time substitution (side-by-side comparisons) examining basins of different ages to represent the stages of succession. Space-time substitution assumes that, under certain circumstances, sampling in space can be the equivalent to sampling through time (Chorley and Kennedy 1971).

This method ignores process and spatial variation within sites, and that contingent factors like boundary conditions, initial conditions at the beginning of the system, and the particular order of events over time at a given site may all impact the subsequent trajectory of the system (Pickett 1989). Space-time substitution assumes constant soil conditions, microclimate, and history at all sites. This is not a valid assumption as climate is not constant over time, and rarely are site histories and physiography the same among locations. To date, Illisarvik is the only known longitudinal vegetation succession study in western Arctic Canada.

# Chapter 5
# Vegetation and the Environment

## 5.1 Introduction

In this chapter, the relations between vegetation composition and distribution and other environmental variables including snow depth, ground temperatures, active-layer thickness, and soil properties are examined. These variables were examined to investigate the influence on vegetation distribution and to determine the influence of vegetation and other environmental variables on the active-layer thickness and near-surface thermal regime within the basin.

## 5.2 Vegetation units

Illisarvik basin was divided into vegetation units based on the dominant visual species or plant functional type. In 2016, the basin was roughly divided into bare ground, sparsely vegetated, grass, sedge, and shrub units (Fig. 5.1 and 5.2). The shrub unit was further sub-divided into three sub units based on the visually dominant species: *Salix alaxensis* (Tall Willow), *Salix glauca* (Low Willow), and *Alnus viridis* subsp. *crispa* (Alder). These units were identified by walking through the basin along the gridlines and noting changes in dominant species in the canopy and/or understorey. Only seven units within the basin can be statistically investigated as the Pendant Grass unit did not intersect with any of the grid points and, therefore, does not have any vegetation survey data.

The most striking visual difference in composition was between the basin and the surrounding undisturbed tundra. The basin was dominated by grasses and willows, with a

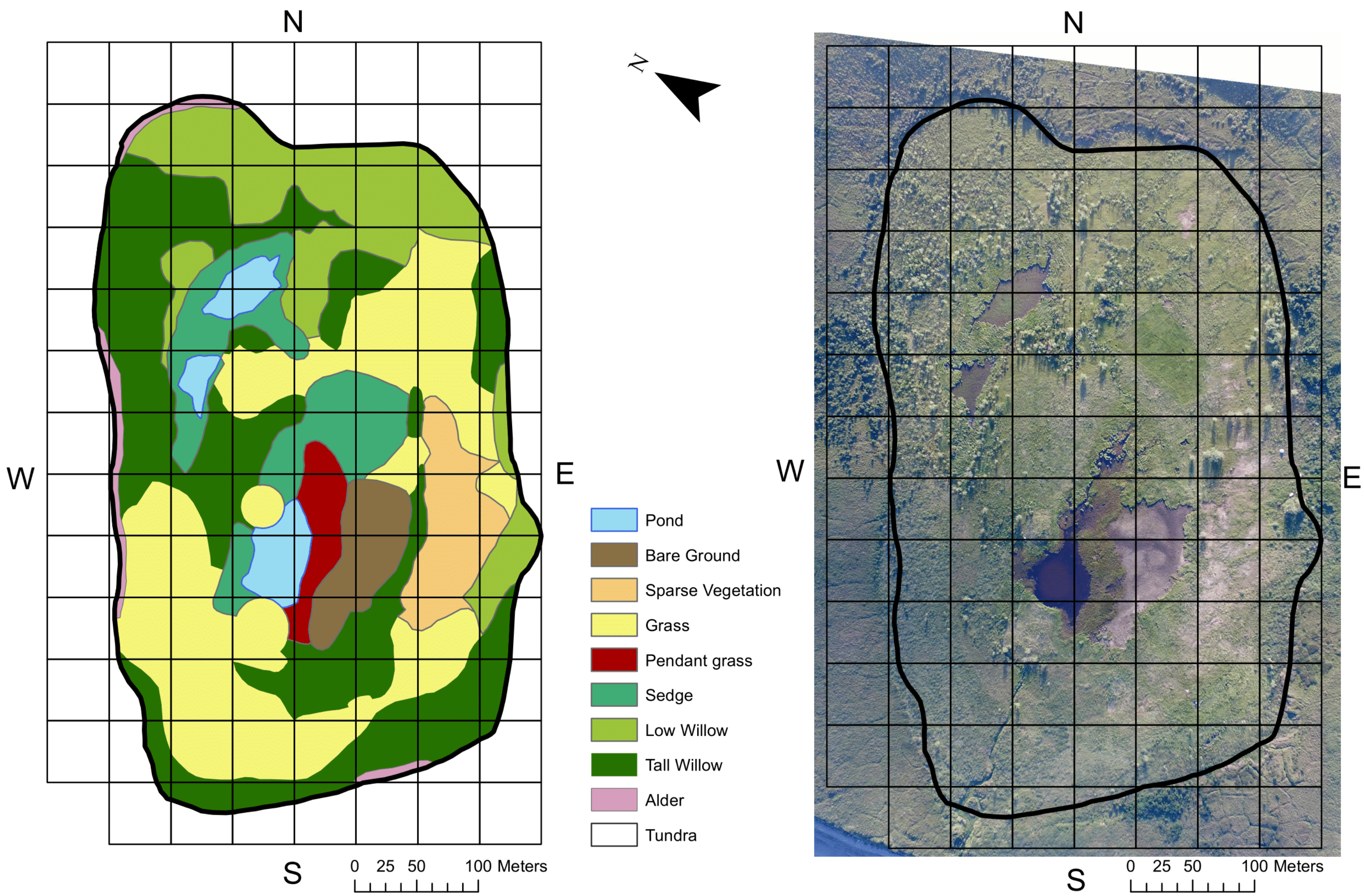



Figure 5.1 - Vegetation map of Illisarvik illustrating the vegetation units used for analysis (left) and aerial imagery of Illisarvik from 2016 (right).

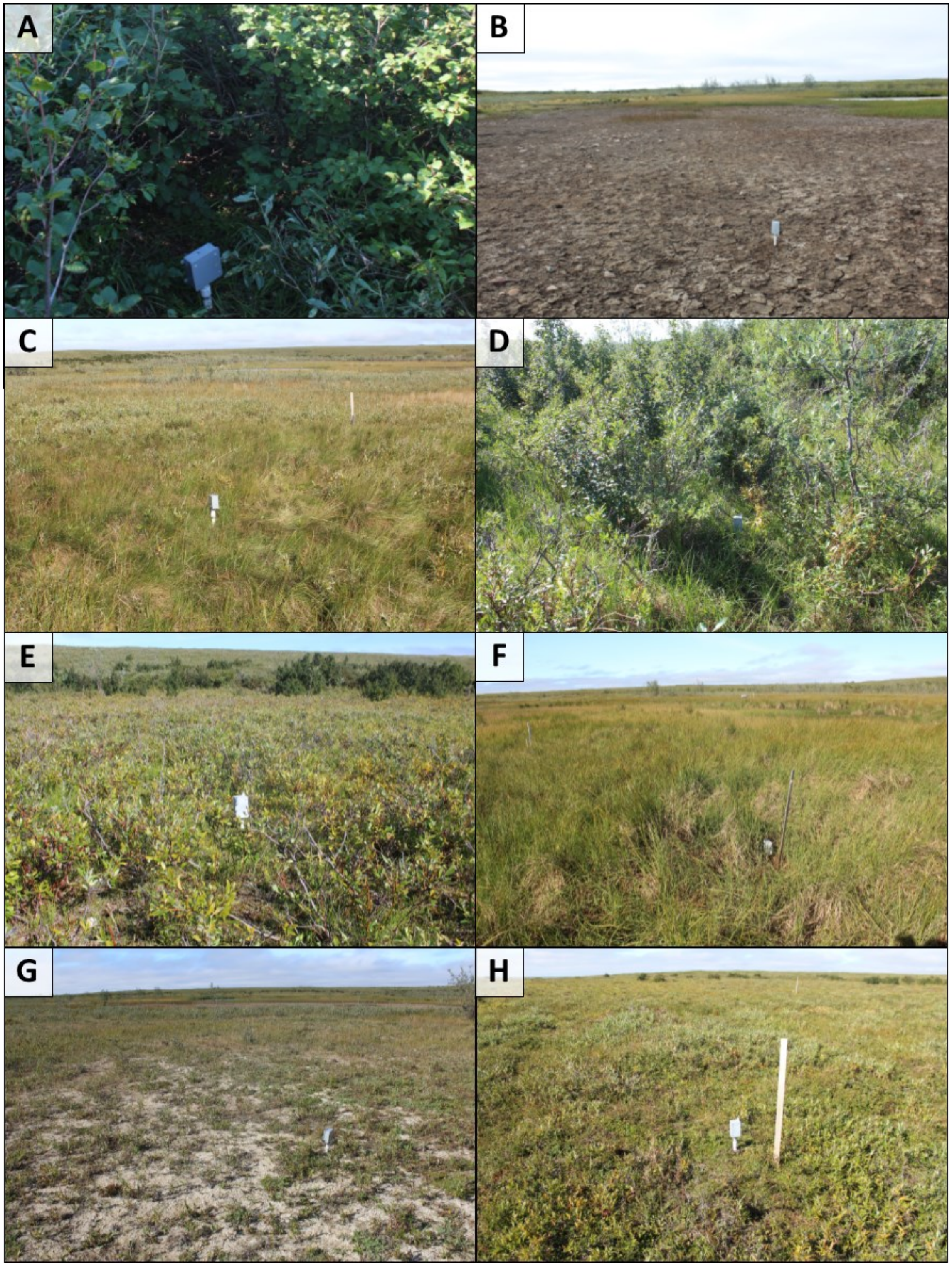



Figure 5.2 - Illisarvik vegetation units: A) Alder (M6), B) Bare Ground (I6), C) Grass (L6), D) Tall Willow (F2), E) Low Willow (B3), F) Sedge (H6), G) Sparse Vegetation (I8), and H) Tundra (H1). The photos are taken at the location of the ground temperature loggers within each vegetation unit. See Fig. 3.8, p.59, for location of these sites.

large unvegetated area. The tundra had little to no unvegetated ground and was dominated by dwarf or prostrate shrubs, moss cover, and a few grasses. Statistically, the units that were the most compositionally distinct on the basis of vegetation were the Bare Ground, Sedge, Sparse Vegetation and Tundra units. A more detailed analysis of the vegetation composition is found in Appendix D. The following analyses are based on 67 vegetation surveys conducted within the basin and 42 surveys at tundra grid points.

## 5.3 Environmental variables

### 5.3.1 Soil texture

The soil texture varies little in the Illisarvik lake basin. The majority of the basin is either loam or silt loam, with sandy loam being found closer to the margins, such as in the Alder and Sparse Vegetation units (Table 5.1), as well as the Bare Ground unit.

### 5.3.2 Volumetric water content

Overall, the basin had higher 0-20 cm VWC than the tundra, and it was highest in the north end of the basin (Fig. 5.3). Volumetric water content distribution roughly corresponded with depressions within the unit, drainage towards the outlet, and poor drainage at the north end. An analysis of variance revealed differences in VWC between units, with the differentiation being statistically significant between the drier Sparse Vegetation and Tundra units and all the other units ($\chi^2 = 59.13$, $p<0.001$). The Sedge was the wettest unit, but its VWC was not statistically significantly different from VWC in Bare Ground, Grass, or Salix units (Table 5.1).

### 5.3.3 Conductivity and pH

The soil electrical conductivity varied throughout the basin with the highest value found

Table 5.1 – Mean values of environmental characteristics of the vegetation units at Illisarvik in 2016, ± 1 SE.

| | Alder | Bare | Grass | Tall Willow | Low Willow | Sedge | Sparse | Tundra |
|---|---|---|---|---|---|---|---|---|
| **OM Thickness (cm)** | 14.3 ± 10.4 | 0 | 2.3 ± 1.3 | 3.4 ± 1.0 | 2.0 ± 0.9 | 2.8 ± 1.0 | 0.4 ± 0.2 | 13.0 ± 1.5 |
| **% Vegetation cover** | 160 ± 39 | 19 ± 12 | 106 ± 7 | 120 ± 4 | 126 ± 12 | 93 ± 10 | 95 ± 9 | 132 ± 4 |
| **Vegetation height (cm)** | 193 ± 59 | 23 ± 7 | 82 ± 10 | 157 ± 13 | 74 ± 17 | 72 ± 16 | 79 ± 12 | 56 ± 6 |
| **Area ($m^2$)** | 2,803 | 6,058 | 47,074 | 50,683 | 25,950 | 15,295 | 8,567 | - |
| **% of total basin area** | 1.7 | 3.6 | 28.2 | 30.4 | 15.6 | 9.2 | 5.1 | - |
| **0-20 cm VWC (%)** | 47.1 ± 5.2 | 57.6 ± 7.4 | 52.6 ± 2.0 | 52.7 ± 1.6 | 55.8 ± 2.5 | 65.7 ± 2.0 | 32.7 ±7.7 | 42.6 ±1.6 |
| **LAI** | 3.44 ± 0.8 | 0.19 ± 0.1 | 2.34 ± 0.3 | 2.40 ± 0.2 | 3.00 ± 0.3 | 4.01 ± 0.5 | 0.66 ± 0.1 | 1.96 ± 0.1 |
| **Snow depth (cm)** | 127 ± 24 | 16 ± 3 | 38 ± 5 | 74 ± 7 | 52 ± 4 | 62 ± 14 | 27 ± 2 | 47 ± 5 |
| **Active-layer (cm)** | 87 ± 12 | 112 ± 9 | 75 ± 8 | 84 ± 5 | 78 ± 7 | 63 ± 7 | 112 ± 12 | 52 ± 3 |
| **Conductivity (µS/cm)** | 381.0 ± 148.0 | 2113.5 ± 1466.5 | 1395.9 ± 853.8 | 258.1 ± 24.9 | 323.7 ±127.1 | 1148.7 ± 163.1 | 188.3 ± 41.7 | 133.0 ±244.2 |
| **pH** | 5.9 ±0.4 | 5.3 ± 2.0 | 5.8 ± 0.2 | 6.2 ± 0.3 | 5.6 ± 0.2 | 6.0 ± 0.6 | 7.3 ± 0.1 | 6.3 ± 0.3 |
| **% Bare ground** | 1.7 ±1.7 | 87.7 ± 6.7 | 7.7 ± 3.1 | 5.2 ± 1.3 | 16.0 ± 2.5 | 8.3 ± 4.2 | 34.0 ± 8.0 | 5.4 ± 0.8 |
| **Soil texture *** | Sandy Loam | Sandy Loam | Silt Loam | Loam | Loam | Silt Loam | Sandy Loam | Sandy Loam |

* The proportions of silt, sand, and clay at each site in addition to a soil textural triangle can be found in Appendix E.

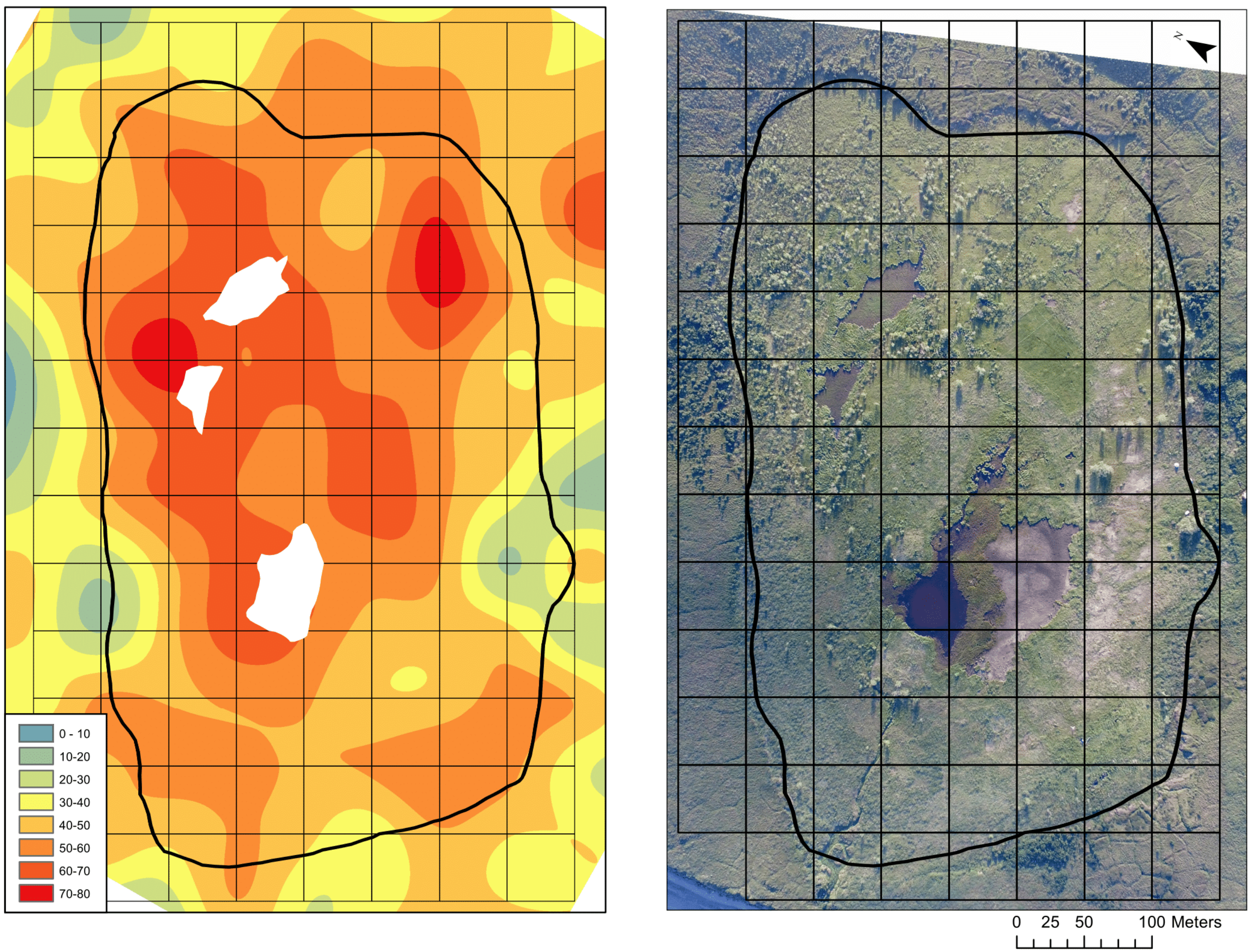



Figure 5.3 – Volumetric water content (%) at Illisarvik. Interpolation created using spline in ArcGIS.

within the Bare Ground unit (1851.78 μS/cm). Conductivity values were all <500 μS/cm for the Tundra, Alder, Sparse Vegetation, and Willow units. The soil acidity is defined by the pH, where pH >7.4 is alkaline soil, while acidic soil has a pH <5.5 (Soil Classification Working Group 1998). The average pH for the vegetation units indicates neutral soils with the exception of the acidic Bare Ground (Table 5.1).

The pH value for the Bare Ground unit in Table 5.1 of 5.29 is an average from two different sampling locations; one soil sample provided a pH of 7.26, while the other site had an ultra acidic soil (pH = 3.31). Other sites had acidic soils but with pH ranges from 4.8 to 5.5 in the Grass, Tall Willow, Low Willow, Sedge, and Tundra units. The tundra samples with acidic soils were all from the peat plateau at the north end of the basin. The specific sites in the other units with acidic soils also had acid-tolerant vegetation, such as *Equisetum arvense*, which is the dominant understorey vegetation. The grass site with acidic soil was dominated by the sedge *Eriophorum scheuchzeri,* which frequently grows in acidic soils (pH 3.5 to 5.5) (Ladyman 2006; Aiken *et al.* 2007). Overall, the majority of the basin had neutral pH, suitable for a wide range of vascular plant species. The majority of acidic sites were still well within a range that certain species have adapted to withstand.

The low pH in the bare ground could be due to the soil being sandier than the other soils in the basin. Sandier soils have a decreased buffering capacity and increased leaching rate. pH may hinder vegetation development as low pH restricts nitrification rates and is associated with toxic to levels of some elements, such as aluminum (Gough *et al.* 2000). Gough *et al.* (2000) and Roland *et al.* (2017) indicate that there is lower species richness with increasing acidity, and the Bare Ground unit represents an end member on this scale.

### 5.3.4 Nutrients

Overall, there were no large differences in cation and anion availability between the vegetation units, with the exception of the Bare Ground site based on PRS probe adsorption rates (Appendix F). The Bare Ground is the only site with available $NO_3^-$ (41.32µg 10 $cm^{-2}$ 4 $weeks^{-1}$) and is high in $Al^+$ (27.99µg 10 $cm^{-2}$ 4 $weeks^{-1}$). $Al^+$ in large amounts is toxic to vegetation and can be a serious limiting factor for plant productivity in acidic soils as it inhibits root growth, and it may explain the lack of vegetation in tis unit (Panda *et al.* 2009). As discussed previously, one of the soil samples in the bare ground site had ultra acidic soil (pH = 3.3), and the highest plant available $Al^+$. Many plants are sensitive to micro molar concentrations of $Al^+$ in phytotoxic forms (phytotoxic refers to forms that are poisonous and/or inhibit the growth of plants). Aluminum solubilization into phytotoxic form ($Al(OH)_2^+$, $Al(OH)^{2+}$, and $Al^{3+}$) is enhanced by low pH (Delhaize and Ryan 1995; Kinraide 1997). It enters root tip cells inhibiting cell elongation and division, reducing water and nutrient uptake and, therefore, the development of the plant. The presence of available $NO_3^-$ only at this location may be because $Al^+$ has inhibited the establishment of plants within the bare ground unit and there is no vegetation to take up $NH_4^+$, which instead may undergo nitrification by nitrifying bacteria. Overall, tundra soil was generally lower than the soils at basin sites in nutrient availability, in both macronutrients (Ca, Mg, and S) and micronutrients (Fe, Mn, and Al).

Pore-water concentrations of $Mg^{2+}$, $NO_3^-$, and $SO^{2-}{}_4$ were all significantly higher in soils from the Bare Ground unit. Otherwise, there were no other significant differences

(Fig. 5.4, Appendix F). Pore-water concentrations of Na, N, and P were lowest within the Bare Ground unit. $Cl^-$ and $K^+$ concentrations were higher in the saturated Sedge and Pendant Grass units. $Na^+$ and $Cl^-$ values were expected to be higher in the saturated (Sedge and Pendant Grass) and Bare Ground units, due to repeat flooding and the potential for saline water to be expelled from the freezing talik below the basin. However, $Na^+$ concentrations were slightly higher for the Sedge unit, but lower for the Pendant Grass and Bare Ground units. Chloride values were highest in the saturated units, but the Bare Ground values were comparable with the other units within the basin. High electrical conductivities values in the Bare Ground were likely due to increased concentrations in Ca and Mg sulphates, but the values are well below those for slightly saline soils.

**5.3.5 Leaf area index**

The leaf area index (LAI) differs amongst units (Table 5.1). An analysis of variance revealed significant differences between units ($\chi^2 = 41.47$, $p<0.001$). Post-hoc analysis showed that the Bare Ground and Sparse Vegetation had the lowest LAI values, significantly less than all other sites except Low Willow. The highest LAI values were recorded in Alder and Sedge units and were statistically significantly different from all the other sites (Fig. 5.5).

**5.3.6 Snow depth**

The snow depth at Illisarvik is greatest on the lee side of slopes, such as the W margins of the basin, and where it accumulates in drifts in the basin center near tall willows (Fig. 5.6). A Kruskal-Wallis analysis of variance revealed significant differences between the vegetation units ($\chi^2 = 39.516$; $p<0.001$). A post-hoc analysis showed that the bare ground

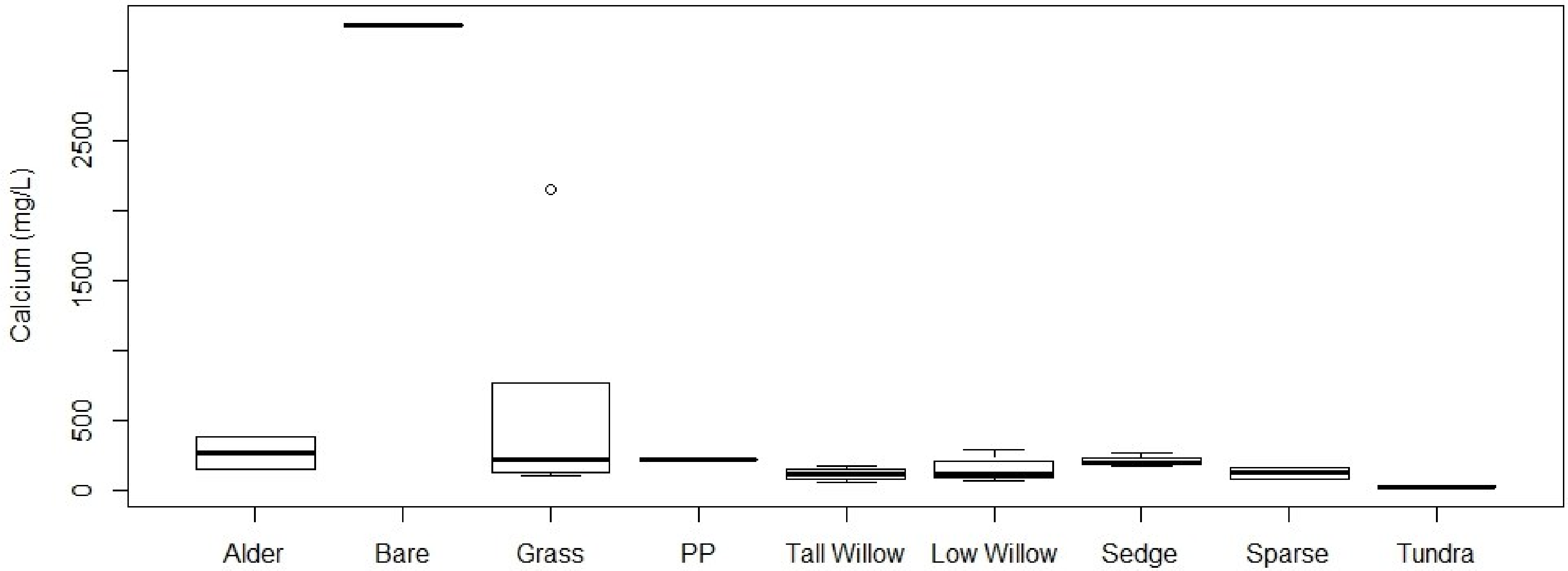



Figure 5.4 - Concentrations of calcium ions in the Illisarvik vegetation units. The pattern in concentration between sites is similar to values for $Mg^{2+}$ and $SO^{2-}{}_{4}$. The PP unit is the peat plateau.

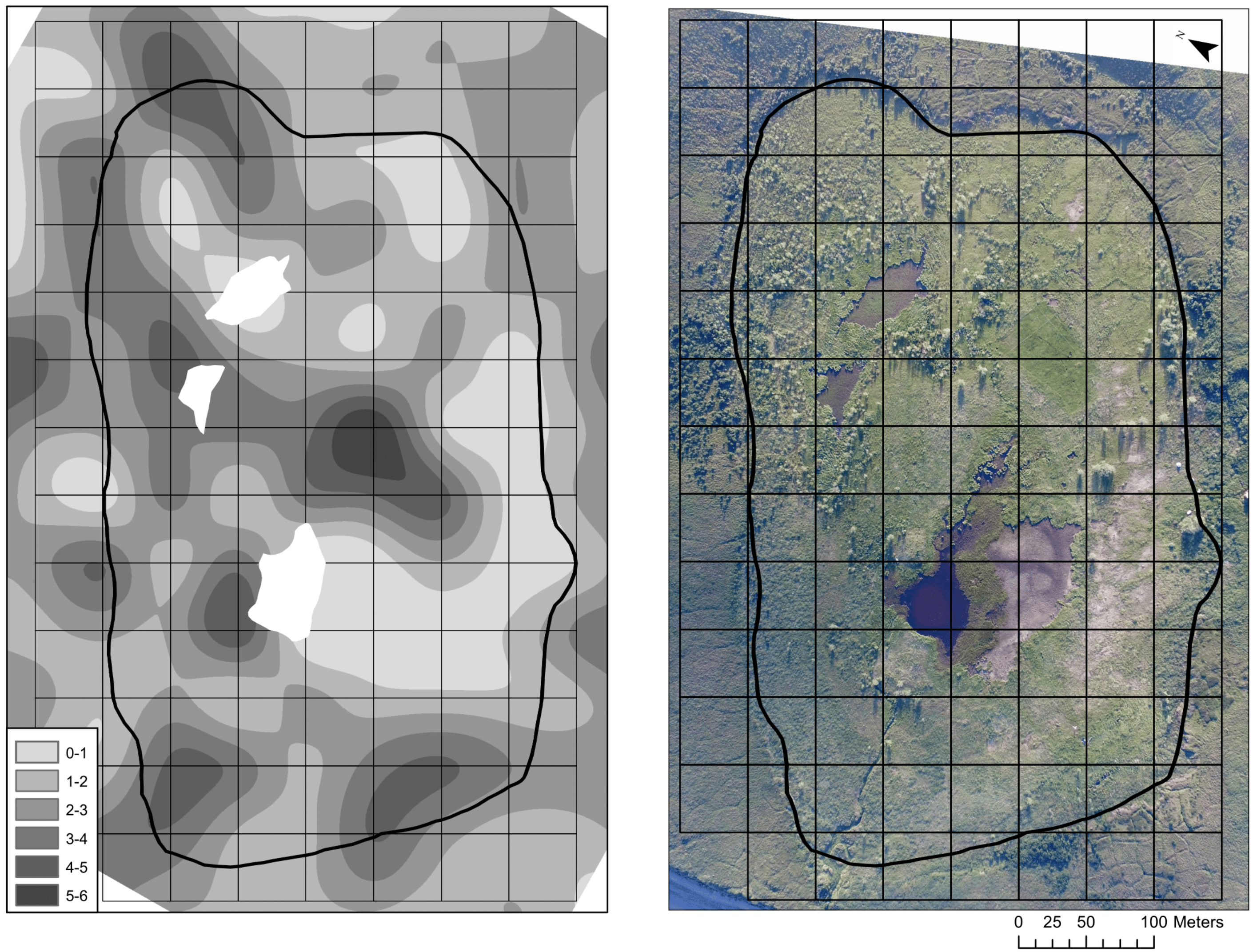



Figure 5.5 – LAI at Illisarvik. Interpolation created using spline in ArcGIS.

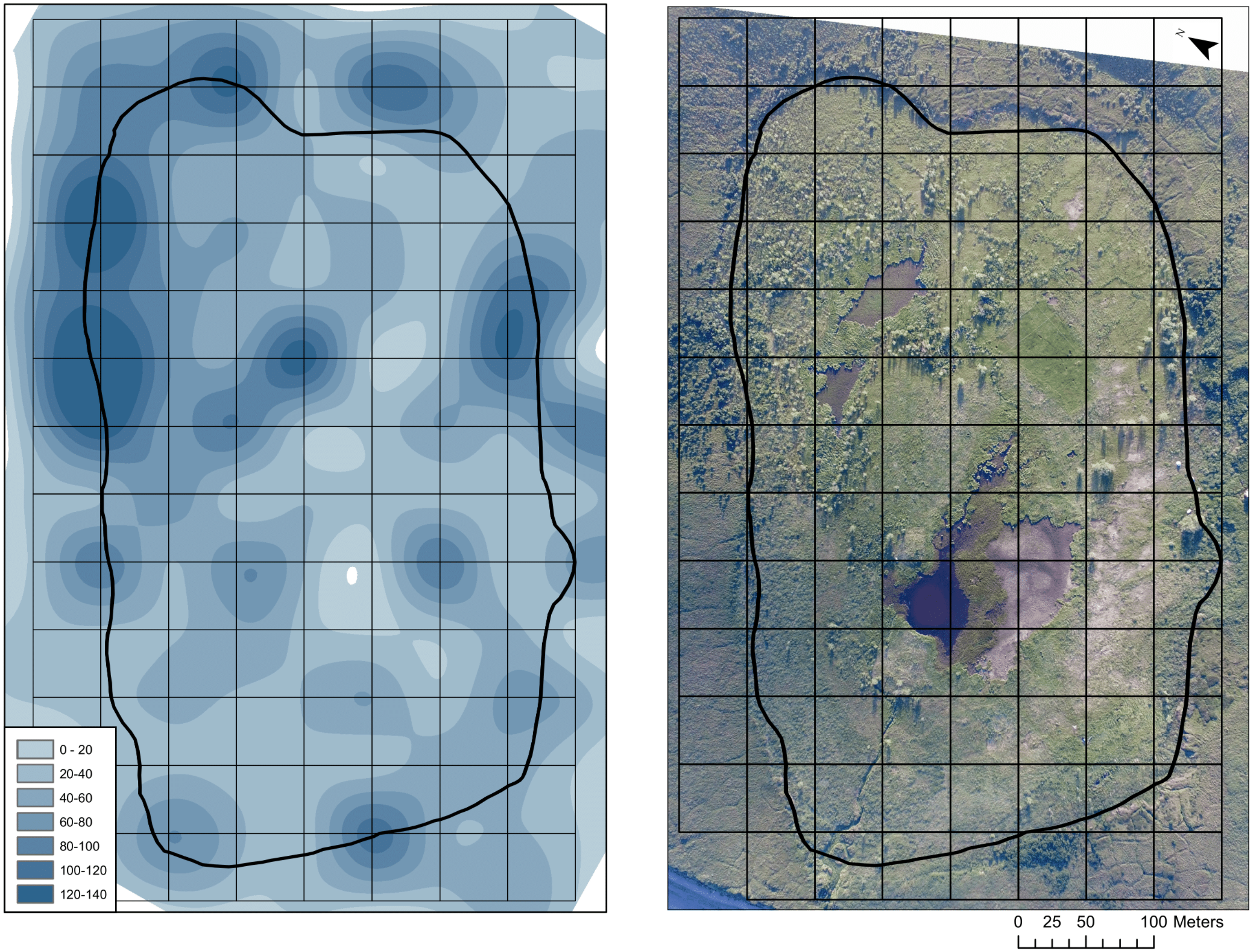



Figure 5.6 – Snow-depth (cm) at Illisarvik in April 2017. Interpolation created using spline in ArcGIS.

site had significantly lower snow depths than the Alder, Sedge, and Willow units. Overall, the Sedge, Alder, and Willow units had the highest mean snow depths while the sites with little to no vegetation had the lowest values (Table 5.1, Fig. 5.7). Spatial variations in snow depth have been related to deciduous shrub cover at other sites (e.g., Sturm *et al.* 2001; Bewley *et al.* 2010).

### 5.3.7 Active layer

The active-layer thickness was greatest along the eastern margins of the basin and in the bare ground and sparse vegetation units (Fig. 5.7c). An analysis of variance was conducted to determine if there were significant differences between the Bare Ground and Sparse Vegetation units in comparison with the other units. There was a significant difference in mean active-layer thickness between the vegetation units ($\chi^2 = 56.19$, $p<0.001$). The post-hoc analysis revealed that although the Bare Ground and Sparse Vegetation had the thickest active layer (Table 5.1), they were only significantly different from the Tundra and Sedge vegetation units.

## 5.4 Vegetation and environmental variable interactions

The ENVFIT function in VEGAN package for R (Oksanen *et al.* 2017; R, R Core Team 2016) was used to examine correlations between community structure and environmental variables at each plot. The approach taken was to evaluate relations between the environmental variables and the NMDS scores (Fig. 5.8). NMDS shows the similarity of sites within 2-d space, where sites that are more similar in vegetation composition are ordinated closer together. The axes and orientation in the plot are arbitrary. Environmental variables have been correlated with the vegetation plots using the NMDS

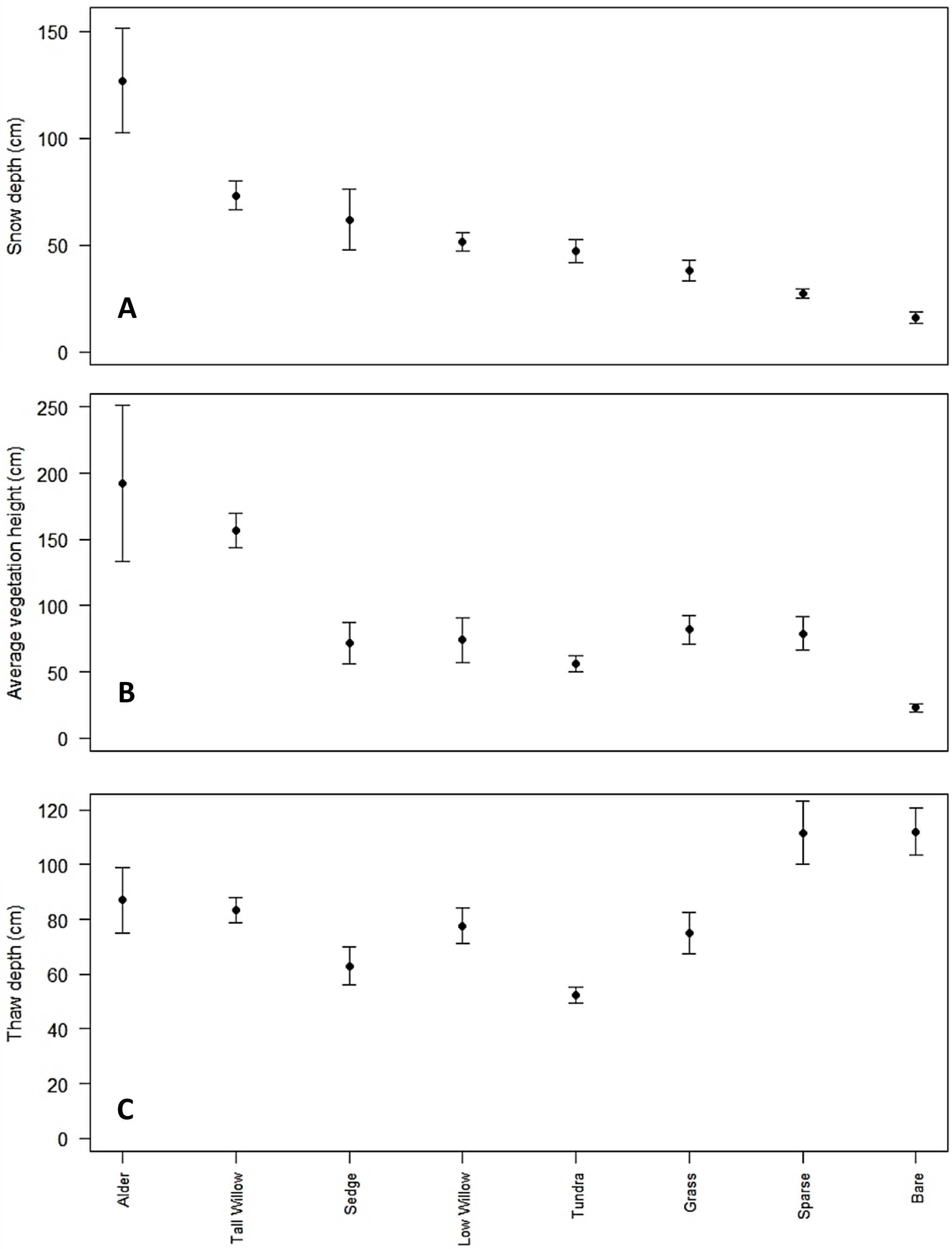



Figure 5.7 - (A) snow depth (cm), (B) vegetation height (cm), and (C) thaw depth (cm) at the different vegetation units. Thaw depth and snow depth values for each site within the unit are the median of five measurements. The vertical lines represent ±1 standard error.

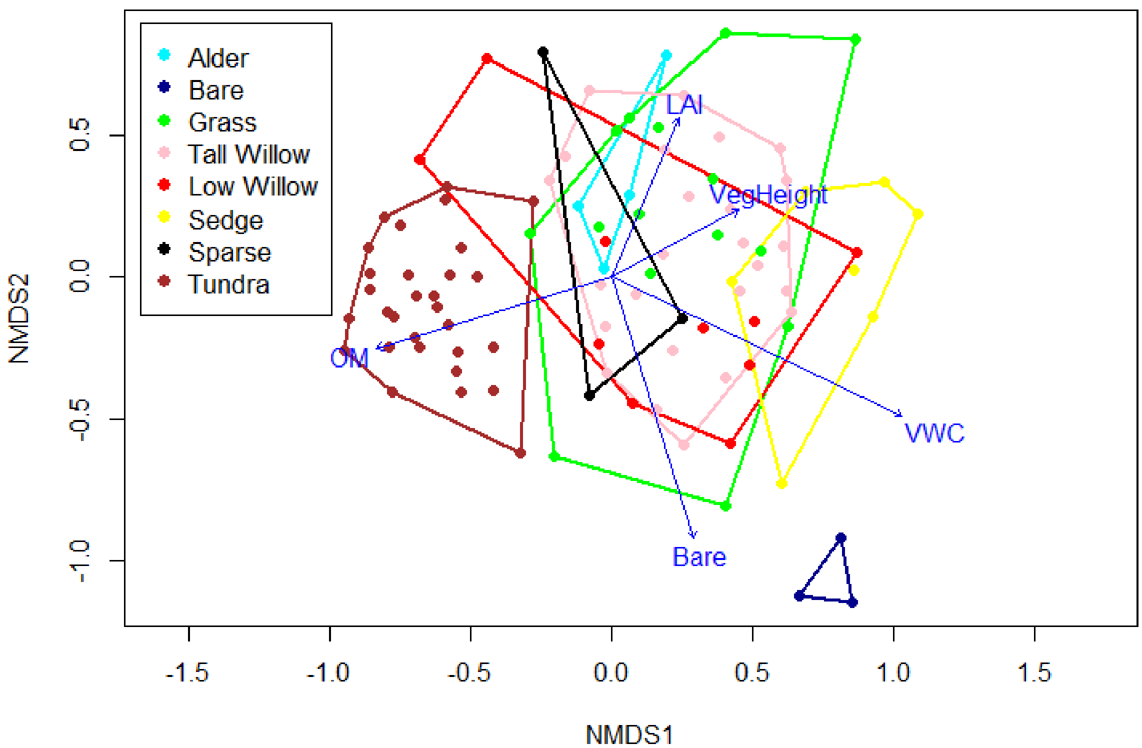



Figure 5.8 - Non-metric multidimensional scaling (NMDS) ordination of plant community composition within the basin vegetation units based on Bray-Curtis similarity matrices (stress = 0.21, k=2). The arrows show environmental variables with a significant correlation to the NMDS scores. LAI is the leaf-area index, OM is the thickness of the organic matter (cm), VegHeight is the average of the tallest vegetation within a 1 m, 1-3 m, 3-5, and 5-7 m radius of the site, and Bare is the % bare cover.

scores. The longer the arrow to the environmental variable on Fig. 5.8, the stronger the correlation, with only significant correlations shown in the diagrams. The environmental variables investigated were snow depth, thaw depth, vegetation height, soil moisture (volumetric water content), organic-matter thickness, leaf-area index, and percent cover bare ground at each plot. The only variables that were not significantly correlated with NMDS scores were snow depth and thaw depth.

Snow depth is likely not statistically significant in relation to vegetation composition because sites with thin snow cover had high but opposite NMDS values on both axes (Fig. 5.8), such as the sites in the Tundra, Sparse, and Bare Ground units.

The lack of correlation with thaw depth indicates that there is no specific vegetation composition associated with greater thaw depths. The Bare Ground sites have a large thaw depth, as do several sites in the Tall Willow unit.

NMDS 1 appeared to represent a gradient in soil moisture values, while NMDS 2 is a gradient in LAI. The sites found primarily within the Alder and Tall Willow units were positively correlated with LAI, due to the multiple layers of canopy shading the ground surface. Not surprisingly, soil moisture was associated with the Sedge unit, and the greater percent cover of bare ground is associated with the Bare Ground unit, and negatively correlated with the upland tundra surrounding the lake basin.

To better understand factors that could be influencing vegetation communities, nutrient data were investigated in relation to the vegetation units. Nutrients are a limiting factor in northern environments, and the ability of plants to take advantage of nutrients is an important factor in plant community development. Nutrient data were collected at one representative location within the vegetation units and, therefore, there are only single nutrient values for each unit. The nutrient data at sites within the vegetation units (Appendix F) were correlated against the NMDS values of average species vegetation covers in each vegetation unit. The only nutrients that had a significant correlation with the vegetation NMDS were the $NO_3^-$, Ca, and $SO^{2-}_4$ collected from the pore water samples (Fig. 5.9). None of the PRS probe data were significantly correlated with vegetation units.

$SO^{2-}_4$ and $Ca^+$ concentrations were associated with the Bare Ground unit, and Sparse Vegetation, while the $NO_3^-$ was positively correlated with the Sedge unit. The Sedge unit was dominated by *Carex aquatilis* spp. *stans*, this could be due to the higher concentrations of available $NO_3^-$ since species in the *Carex* genus preferentially utilize $NO_3^-$ in comparison to $NH_4^+$ (McKane *et al.* 2002; Iversen *et al.* 2015). Oddly, $Ca^+$ concentrations are usually inhibited by low soil pH but this site had the lowest recorded pH in the basin.

### 5.5 Snow-shrub interactions

Snow depth and the average vegetation height in all the sites had a significant positive relationship (Spearman rank-order $\rho = 0.59$; $p<0.001$; $n = 126$) (Fig. 5.10 A). A curvilinear logarithmic distribution between vegetation height and snow depth is expected when a maximum supply of snow is reached for a region (e.g., Palmer 2007 Fig.4.7; Palmer *et al.* 2012). In this context, snow depth increases with vegetation height to a maximum value. For vegetation height greater than this there is no further increase in snow depth due to limitation in the supply. The linear relation at Illisarvik indicates that the maximum snow depth was not reached, even with a theoretically unlimited supply of

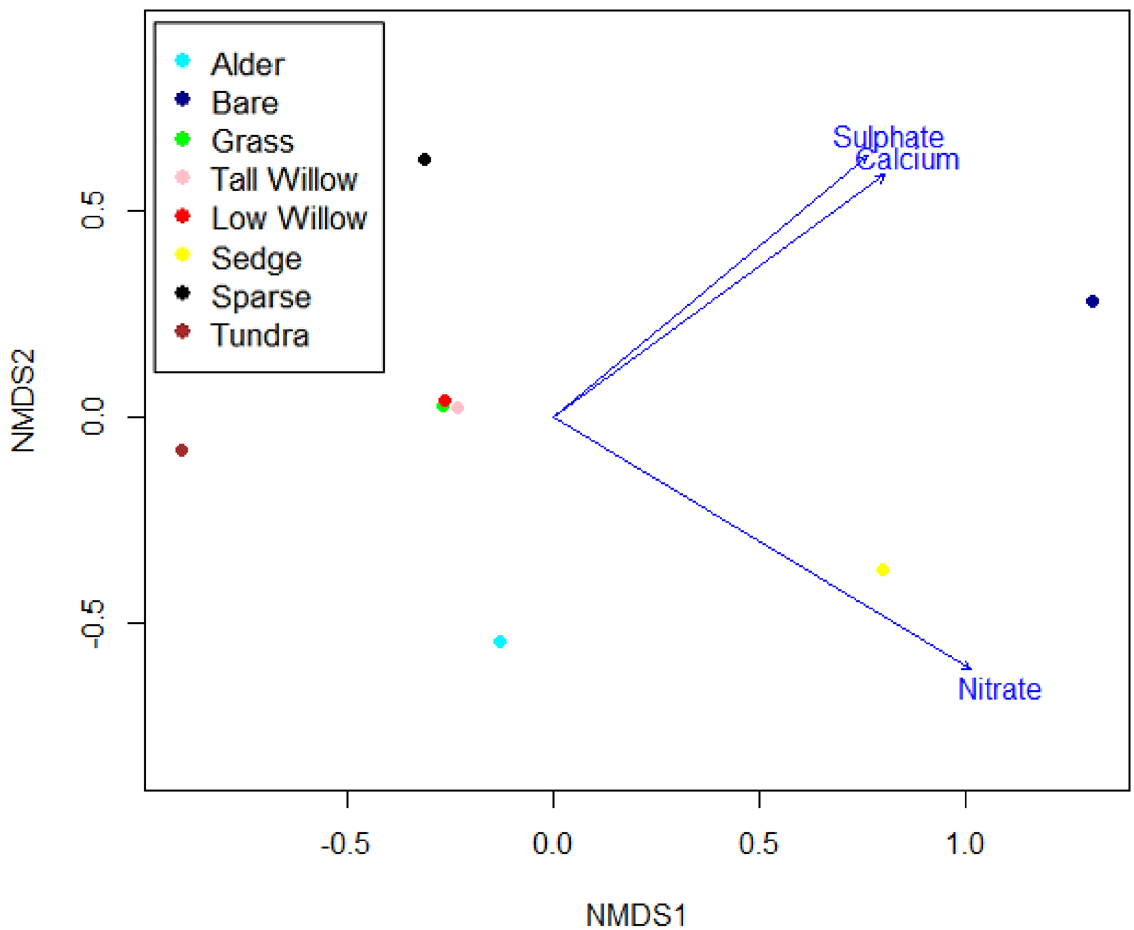



Figure 5.9 - Non-metric multidimensional scaling (NMDS) ordination of plant community composition within the basin vegetation units based on Bray-Curtis similarity matrices. The arrows show abiotic variables with a significant correlation to the NMDS scores (p-value <0.05). Each site is an average of the percent cover of species within the vegetation unit.

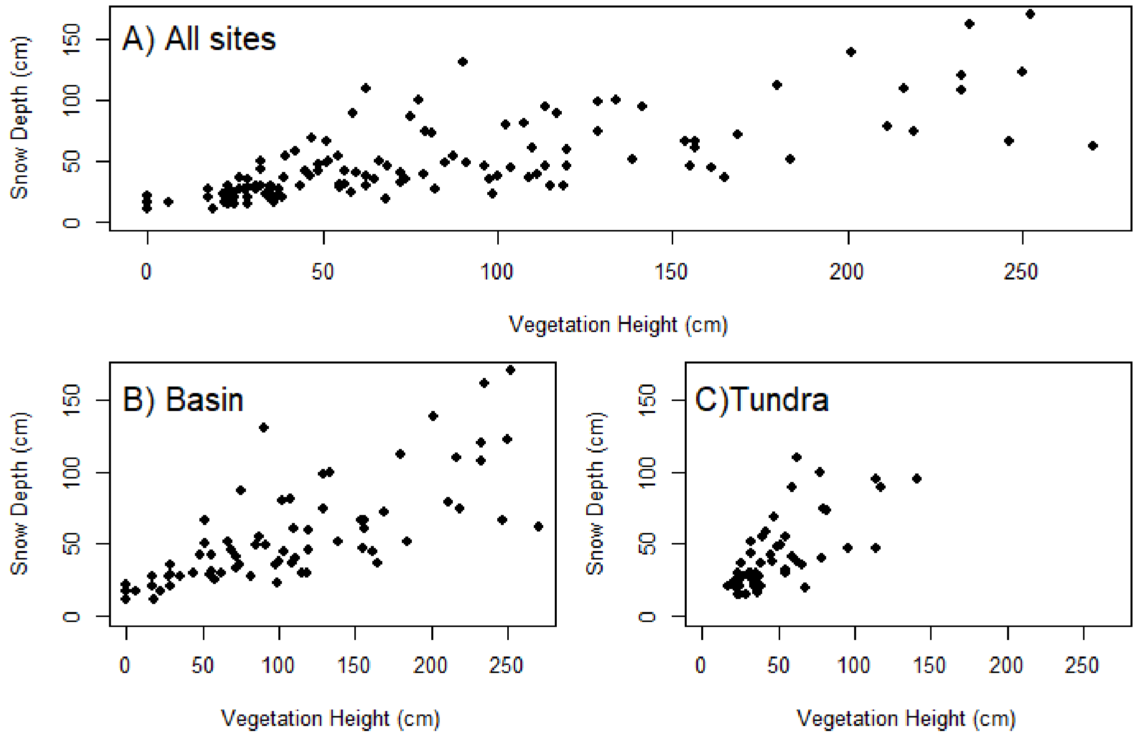



Figure 5.10 - Snow depth and average maximum vegetation height: (A) all sites at Illisarvik (n=110), (B) the basin sites (n=67), and (C) the tundra sites (n=43). The average maximum vegetation height is the maximum height of vegetation within 1 m, 1-3 m, 3-5 m, and 5-7 m of a grid point averaged to provide a representative maximum height for the location.

blowing snow from the surrounding tundra. There are differences in the snow-vegetation relations between the basin and the tundra (5.9 B and C). Vegetation height explains slightly more of the variation in snow depth in the basin (adjusted $\rho^2 = 0.61$) than the tundra (adjusted $\rho^2 = 0.48$) potentially due in part to the greater range in vegetation heights in the basin.

### 5.5.1 Insulating depth hoar

Snow pits were dug near each of the ground temperature loggers in April 2017 to investigate the snow stratigraphy, particularly the depth hoar. Depth hoar is a poorly bonded and highly insulative type of snow (Sturm and Benson 1997) created by metamorphism in response to strong temperature gradients, and its low thermal conductivity makes it an efficient insulator close to the ground surface (Akitaya 1974; Sturm *et al.* 2001).

The depth hoar thickness at Illisarvik ranges from 14-48% of the total snowpack (Table 5.2). The depth hoar at Illisarvik is highest at the Tundra, Cottongrass, Sedge, and Low Willow units, which present a range in vegetation types and structure (Table 5.2). At the sedge, cottongrass, and tundra sites, the depth hoar is inter-mingled with the dense ground cover vegetation and is no thicker than the vegetation height. Additionally, these sites also have some of the thinnest snow packs. Interestingly, the tall willow, bare ground, and sparse sites had the lowest percentage depth hoar, despite these sites having the thickest active layers. This indicates that, although the depth hoar has a low thermal conductivity making it an efficient insulator, it is not likely a primary influencing factor on active-layer thickness at Illisarvik, due to absolute variations in snow depth.
Sturm *et al*. (2001) found in Arctic Alaska that the depth hoar was 70% of the snow pack

Table 5.2 - Ground temperature logger site characteristics. Temperatures recorded at 25 cm below the surface in different vegetation communities at Illisarvik.

| | **Alder** | **Bare Ground** | **Cottongrass** | **Tall Willow** | **Low Willow** | **Sedge** | **Sparse** | **Tundra** | **Peat Plateau** |
|---|---|---|---|---|---|---|---|---|---|
| **Snow depth (cm)** | 115 | 7 | 20 | 160 | 27 | 33 | 37 | 12 | 16 |
| **Depth hoar (cm)** | 35 | 1 | 9 | 18 | 13 | 14 | 9 | 5 | 4 |
| **% Depth hoar** | 30.4 | 14.3 | 45.0 | 11.3 | 48.1 | 42.4 | 24.3 | 41.7 | 25.0 |
| **Thaw depth (cm) †** | 40 | >95 | 83 | >92 | >112 | 37 | >110 | 60 | 35 |
| **VWC % †** | 26.3 | 44.2 | 52.1 | 52.3 | 52.1 | 64.4 | 23.4 | 33.6 | 51.1 |
| **Date of freeze-back at depth** | Oct. 28$^{th}$ | Oct. 11$^{th}$ | Oct. 19$^{th}$ | Dec. 1$^{st}$ | Nov. 26$^{th}$ | Nov. 28$^{th}$ | Oct. 10$^{th}$ | Oct. 23$^{rd}$ | Nov. 26$^{th}$ |
| **Duration of fall zero curtain (days)** | 26 | 9 | 7 | 61 | 55 | 57 | 8 | 21 | 55 |
| **Temperature range (°C)** | 12.2 | 35.0 | 19.4 | 8.0 | 13.8 | 13.3 | 24.9 | 24.7 | 19.3 |
| **Mean (°C)** | -2.6 | -4.7* | -3.5* | -0.8 | -0.8 | -2.4 | -2.5 | -5.4 | -4.7 |
| **Min (°C)** | -7.3 | -23.2 | -13.3 | -3.4 | -6.8 | -8.9 | -12.9 | -18.1 | -14.8 |
| **Max (°C)** | 4.8 | 11.8 | 6.1 | 4.6 | 7.0 | 4.4 | 12.0 | 6.9 | 4.5 |
| **Mean freezing season temperature (°C)** | -4.1 | -10.8 | -7.5 | -1.8 | -3.0 | -3.9 | -7.1 | -8.8 | -6.7 |
| **Mean thawing season temperature (°C)** | 3.2 | 5.7* | 2.7* | 2.3 | 3.4 | 1.9 | 6.0 | 3.2 | 2.0 |

* The bare ground and cottongrass loggers stopped recording ground temperature measurements on May 24$^{th}$ and May 14$^{th}$ respectively. They were gap-filled with the ground temperature data that they most closely followed in August 2016, which were the sparse vegetation temperatures for bare ground, and low willow for cottongrass.

† These measurements were taken at time of logger installation on August 4$^{th}$, 2016 before installation.

at shrub sites in comparison with 55% in tussock tundra. Roy-Léveillée *et al*. (2014) obtained similar results with 16-75% depth hoar at sites in taiga with low and tall shrub vegetation in the Old Crow Flats (OCF). Palmer *et al.* (2011) noted a higher percentage of depth hoar in tundra sites with smaller vegetation (40-60%) than at shrub and spruce tree dominated sites (23-53%) in the uplands east of the Mackenzie Delta.

### 5.5.2 Snow drifts

Evidence for the accumulation of snow in areas with large shrubs is shown in drift formation on the lee side of shrubs (Sturm *et al.* 2001). Two large snow drifts, 110 and 60.5 m long, were surveyed in April 2017 in the center of Illisarvik (Fig. 5.11, and 5.12). These drifts were located adjacent to lines of tall *Salix alaxensis* shrubs on flat ground. These drifts show that shrubs influence snow accumulation at Illisarvik. However, the majority of the thick snow packs were found along the basin margins, particularly on the west side of the basin. These western snow packs were likely influenced by the topography, being located along slopes in the lee of the dominant wind. Sturm *et al.* (2000) indicated that snow depths as much as 10 m downwind from a shrub may be affected by it. Increased snow trapping allows for increased winter ground temperatures further from the shrub creating warmer environments for more shrubs to establish, as well as protecting plant buds and tissues from low winter temperatures (Bokhorst *et al.* 2008).

## 5.6 Ground temperature

One full year of active-layer temperatures at 25 cm depth were recorded to investigate relations between active-layer thermal regimes and vegetation communities. The ten instrumented sites were divided into tundra, shrub, graminoid, and unvegetated

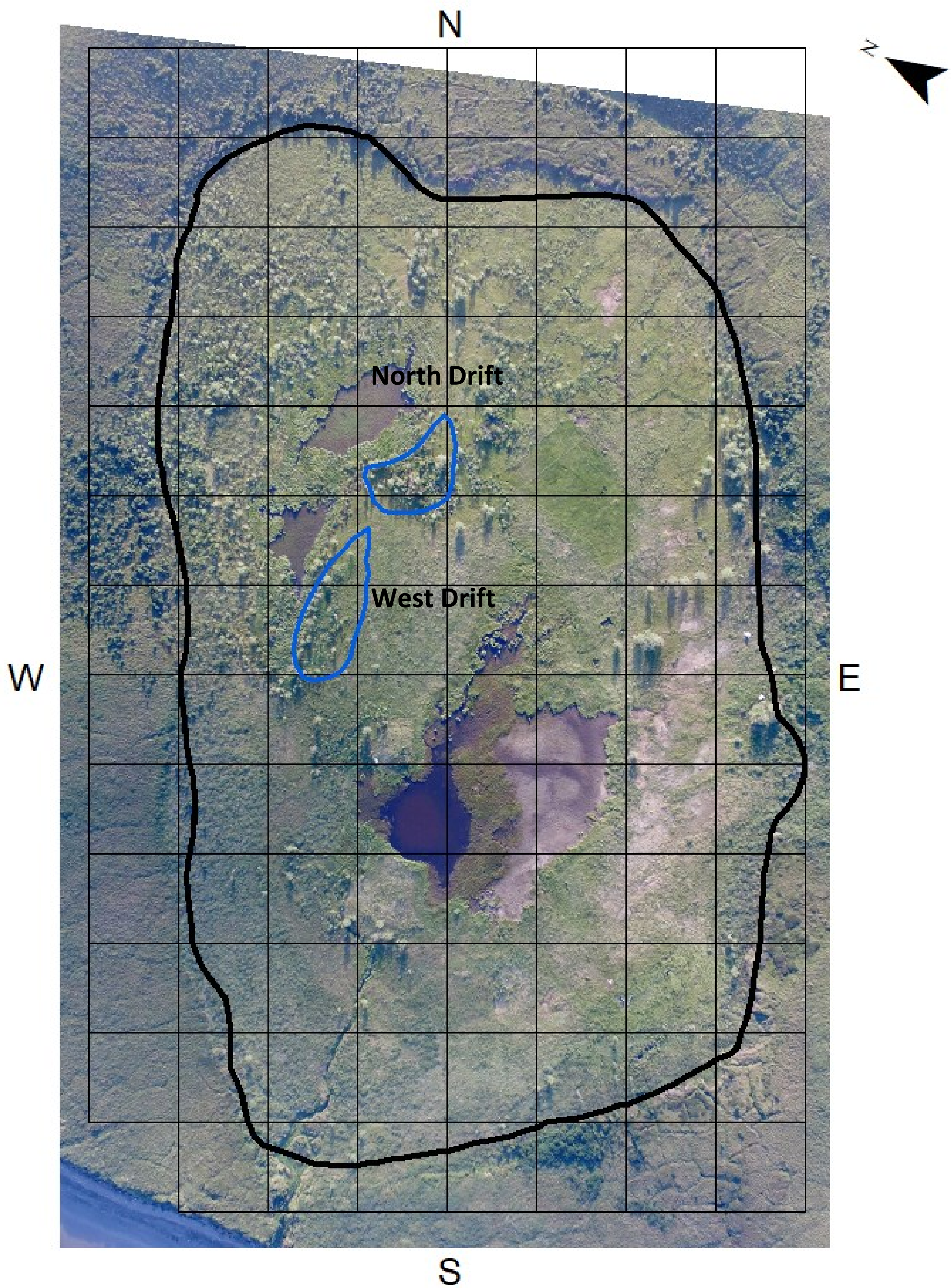



Figure 5.11 - Locations of the west and north snow drifts that were surveyed.

A B

Figure 5.12 - West snow drift. (A) illustrates the height of the drift along the W-E axis (B) illustrates the drift height from the N-S axis.

environments.

Overall, from August 2016 - 2017 the data from the sites indicated substantial variations in ground temperatures ($T_g$) (Fig. 5.13). Mean annual $T_g$ varied from -0.8 °C in the Tall Willow site to -5.4 °C in the tundra (Table 5.2). The Spearman rank correlation between annual $T_g$ and snow depth at the sites was 0.8 (p-value <0.05). This suggests variables influencing temperatures in winter may be more important in determining annual $T_g$ than variables influencing thaw season temperatures.

### 5.6.1 Tundra

The tundra sites (tundra and peat plateau) were expected to have the lowest annual $T_g$, due to the insulating properties of the organic matter in summer and thinner snow pack caused by lower vegetation. Minimum $T_g$ was lower at the tundra loggers than all other sites except Bare Ground, with the upland tundra site recording the second lowest minimum temperatures. Additionally, these sites had the lowest annual $T_g$. The tundra site had a lower VWC than the peat plateau site, limiting latent heat release, lowering ground temperatures more rapidly than at the peat plateau, which had the longest zero curtain of 55 days (Table 5.2, Fig. 5.13). Furthermore, the tundra permafrost is colder than the former lake talik in the basin because freezing of pore water in the talik releases latent heat at depth resulting in warmer near surface permafrost in the basin. The colder tundra permafrost had little latent heat to supply to the active layer in winter and, therefore, its temperature decreased more rapidly than in the basin (Figs. 5.13 and 5.14).

### 5.6.2 Unvegetated

The unvegetated sites (Bare Ground and Sparsely Vegetated units) had the largest range of active-layer temperatures. The 25 cm temperature at these sites varied most closely

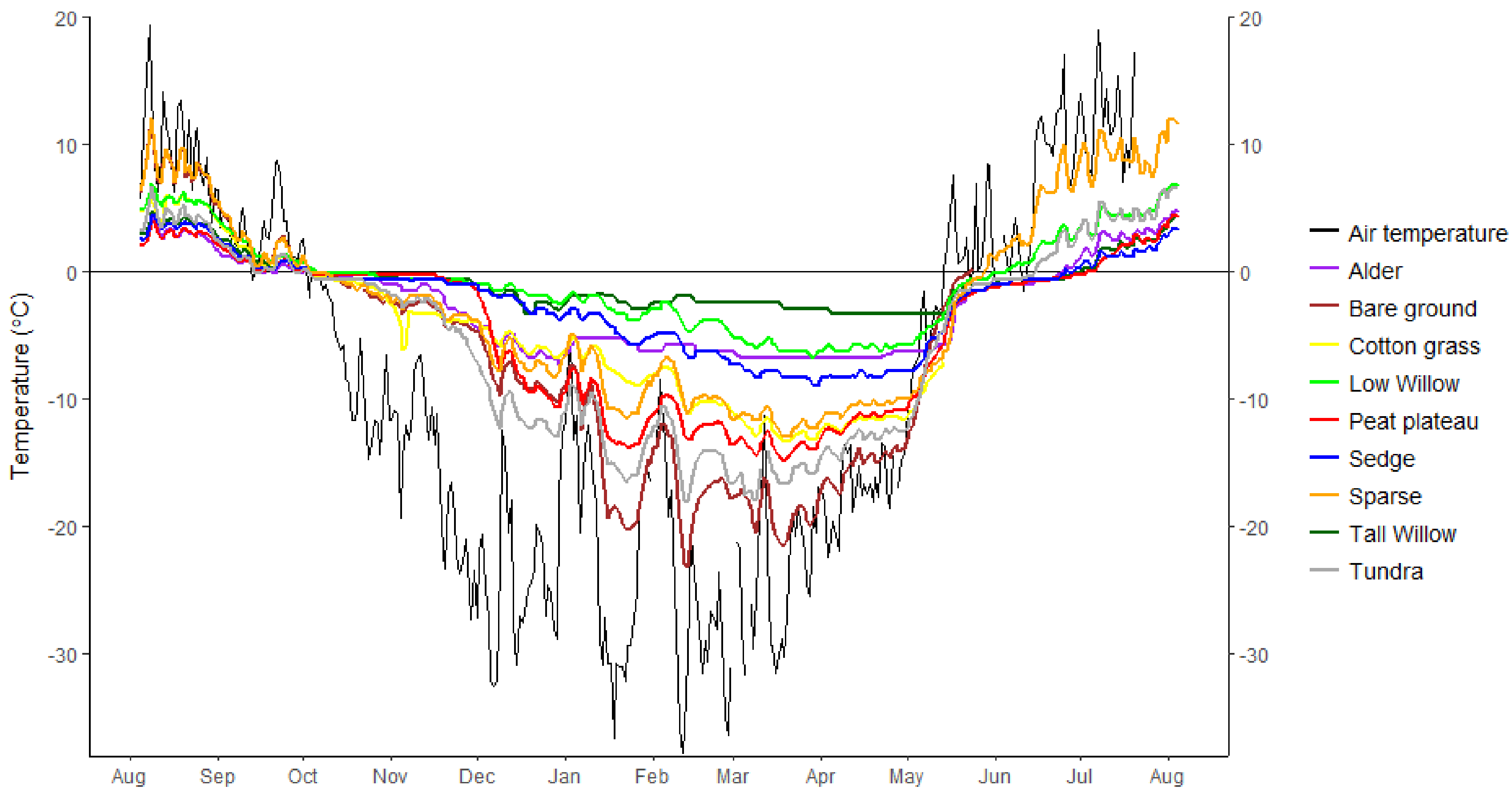



Figure 5.13 - Active-layer temperatures at 25 cm depth for different sites in the basin representing various vegetation units. Air temperature is from the Tuktoyaktuk weather station. The year of data is from August 5th, 2016 to August 4th, 2017.

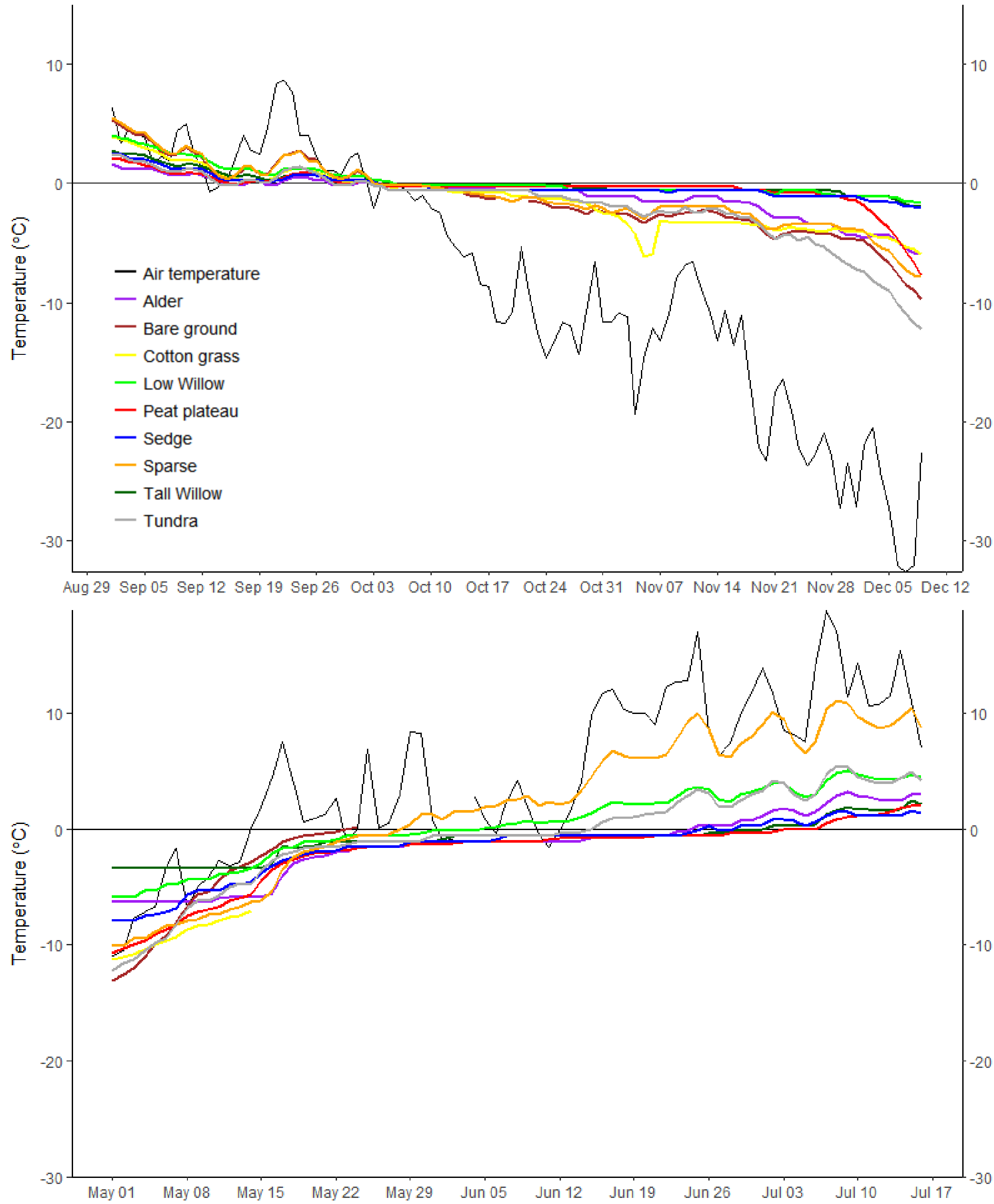



Figure 5.14 - Active-layer temperatures at 25 cm depth for different sites in the basin representing various vegetation units during the freeze-back and thaw period in 2016 and 2017 respectively. Air temperature is from the Tuktoyaktuk weather station.

with air temperatures throughout the year (Table 5.2, Fig. 5.13). The longer freezing season at the Bare Ground site contributed to the lowest $T_g$ within the basin (~ -4.7°C). $T_g$ at the Sparse Vegetation was higher (~ -2.5 °C) as the site was downwind from a tall *Salix alaxensis* shrub, whose drift increased the snow depth at the logger site (Table 5.2). The large range in soil temperatures at these sites is due to decreased albedo, little to no shading or insulation in summer, moist but not saturated mineral soil, and a decreased snow cover in winter.

### 5.6.3 Graminoid

The graminoid sites (Sedge and Cottongrass) were all dominated by similar vegetation structure and were located some distance from the influence of shrubs. The Sedge had higher freezing season temperatures due to a fall zero curtain 38 days longer than that at the Cottongrass site (Table 5.2, Figs. 5.13 and 5.14), and a thicker snow pack by ~10 cm. The Sedge did have lower thawing season temperatures than the Cottongrass, likely due to greater LAI, reducing the solar radiation reaching the ground surface throughout the growing season, as well as increased VWC.

### 5.6.4 Shrub

The Willow units (Tall and Low Willow) had $T_g$ > 1°C, making them the warmest of the sites overall (Table 5.2). The higher temperatures are attributed to increased snow trapping. At the Alder unit, $T_g$ of -2.6 °C, is close to the middle of the distribution from nine sites (Table 5.2). The Alder temperatures decreased more rapidly than the Willow sites. Environments with greater winter LAI, such as boreal forests, may intercept snow fall creating a thinner snowpack (Yi *et al.* 2007). On average, alders lose their leaves later than other shrubs, sometimes well after the first snowfall; this provides the large LAI to trap snow above the ground surface (Rozell 2015). The snow held aloft in the alder branches provides pockets of air and a thin snow cover at the ground surface, increasing conductive heat loss in winter. With increased snowfall and alder leaf fall, a thick (115 cm) snow pack developed at the site. $T_g$ at the Alder site decreased more rapidly than the other shrub sites following the first permanent snow on October 15$^{th}$, 2016 (Fig. 5.14).

The Tall Willow site had a higher $T_g$ and smaller range in temperatures than the Low Willow site (Table 5.2, Fig. 5.13), similar to results from other studies where dense shrubs had higher $T_g$ (Lantz *et al.* 2013; Kokelj *et al.* 2017). The Tall Willow had a snow pack over 130 cm thicker than the Low Willow site, which dampened the influence of air temperatures in the freezing season more efficiently (Fig. 5.13). The Tall Willow site did not reach temperatures below -3.4 °C at 25 cm depth. With an active layer of >92 cm at the site, higher temperatures indicate a low thermal gradient and suggest the potential for unfrozen ground above permafrost throughout the winter (Table 5.2).

**5.6.5 Snow depth and ground temperatures**

Snow depth plays an important role in insulating ground in winter at Illisarvik as shown in Fig. 5.13. The ground thermal regime is more sensitive to changes in snow depth where snow is thin and dense (Mackay and Mackay 1974; Osterkamp 2007). Depth hoar development increases the thermal resistance of the snow pack significantly, so that the depth hoar and total thickness are the primary controls on the thermal regime (Zhang 1993). The depth hoar varied among the sites, being thickest at the sites with the thinnest snow packs (Table 5.2), which may have increased the thermal resistance from these sites. However, as shown in Fig. 5.15, there is a positive curvilinear relation between snow depth and minimum freezing season ground temperatures. The curvilinear relation

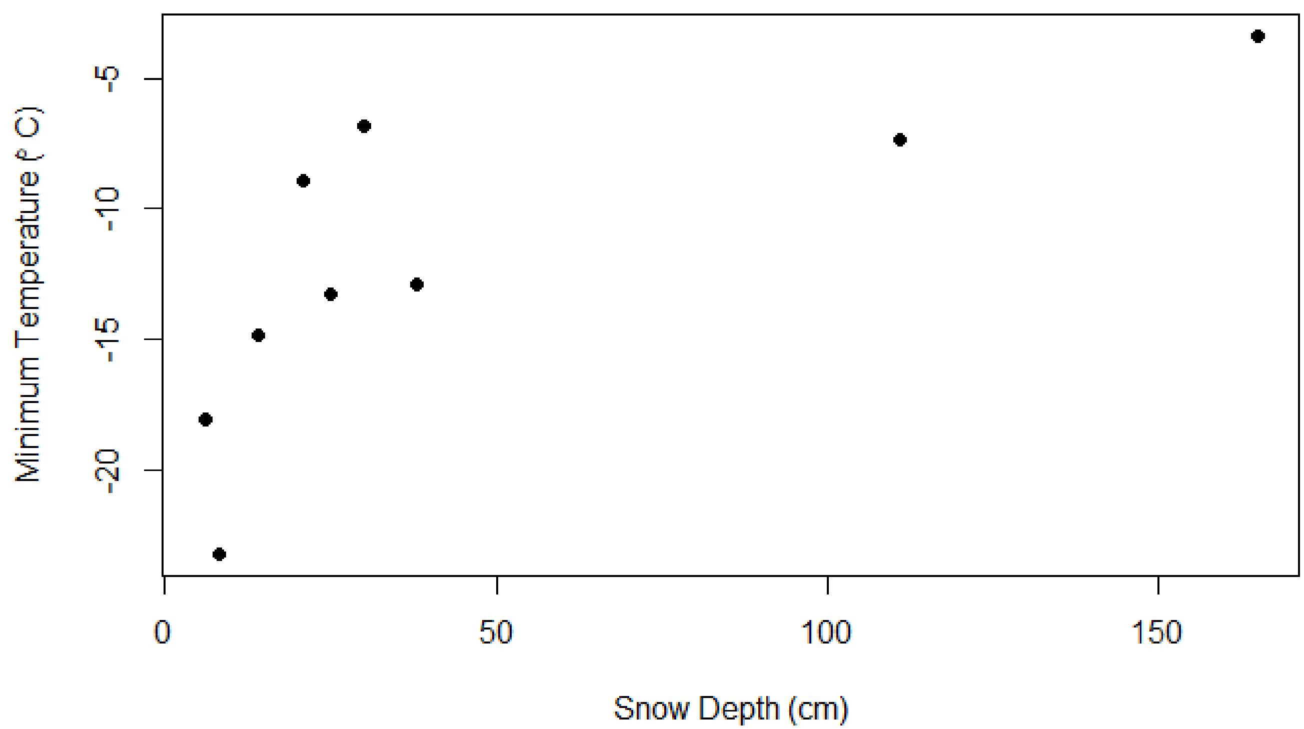



Figure 5.15 - Relation between snow depth and minimum recorded temperature at the 25 cm depth active-layer temperature logger sites.

indicates that the maximum thermal effect of the snow pack was reached at about 50 cm thickness, the same thickness determined by Harris (1981) in Alberta. The variations in the points were likely caused by variations in the density of the snow pack, as dense snow would have lower thermal resistance and increased thermal conductivity. This was shown at the Sparse Vegetation site where, despite the third thickest snowpack, lower freezing season temperatures were recorded, potentially due to the very densely packed snow drift beneath which it was located (Table 5.2).

### 5.7 Factors influencing active-layer thickness

Active-layer thickness measured at Illisarvik ranged from ~36 cm to 160 cm in the basin to 21 cm in the tundra. Thaw depths were greatest along the eastern margins of the basin grid (Fig. 5.16) and in the Bare Ground and Sparse Vegetation units (Table 5.1). These areas had greatly different vegetation heights as well as snow depths, indicating that a number of environmental factors governed spatial variations in the active layer.

#### 5.7.1 Leaf area index

Increased LAI may reduce the radiation reaching the ground surface in summer, thus reducing active-layer thickness (Marsh *et al.* 2010). A Spearman rank-order correlation between LAI and active-layer thickness had a negative significant correlation with the basin sites ($\rho = -0.66$; $p = <0.001$; $n = 67$) (Table 5.3). The negative relation continues in the correlation and regression tree (CART) and principal component analysis (PCA) used to examine variables driving the active-layer thickness (Figs. 5.17 and 5.18). LAI is the first leaf node in the CART and loads negatively against the active layer in PCA. High LAI values are found in the Sedge and Alder units which also have the shallowest active-

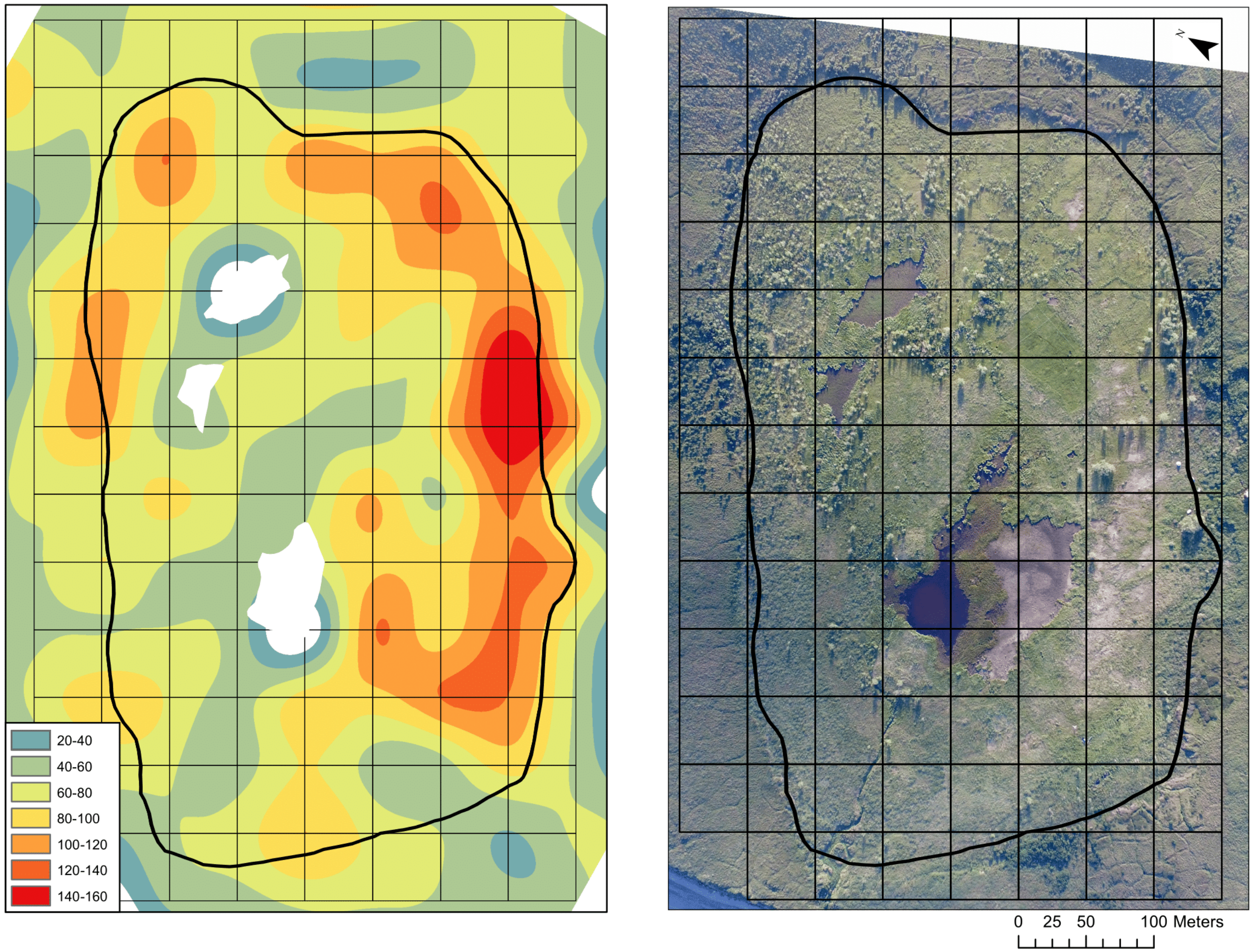



Figure 5.16 - Interpolation of median of five thaw depth measurements (cm) at each grid point taken at the end of August 2017. Interpolation created using spline in ArcGIS.

Table 5.3 - Spearman rank correlation matrix of environmental variables at Illisarvik in the tundra (n=43) and in the basin (n=67). Highlighted values have a correlation with a p-value >0.05. OM is the organic matter thickness, LAI is leaf-area index, AL is active-layer thickness, VWC is volumetric water content, and Vegetation Height is average maximum vegetation height.

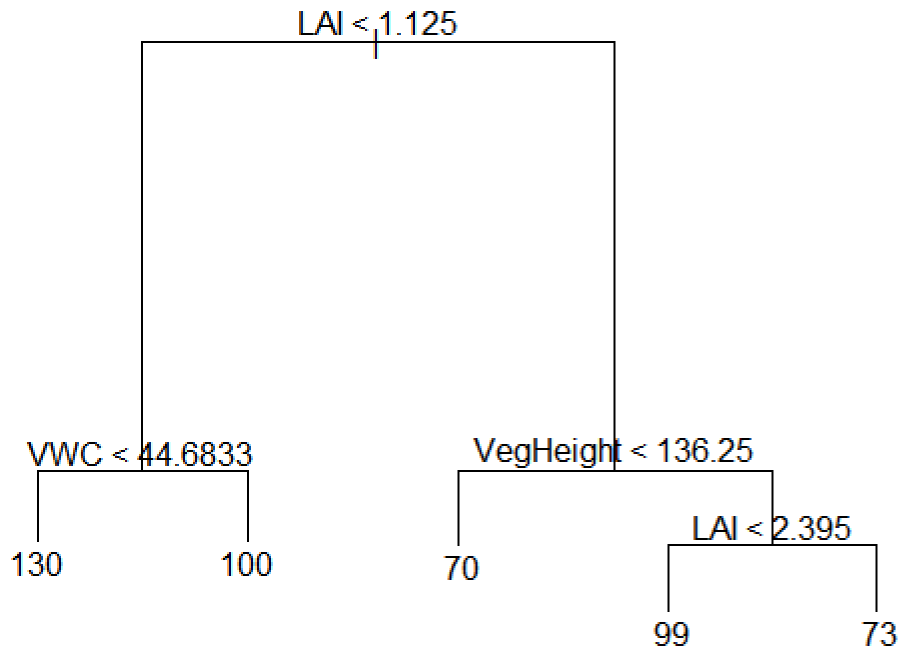
**Tundra**

| | OM | Snow Depth | LAI | AL | VWC | Vegetation Height |
|---|---|---|---|---|---|---|
| **Snow** | 0.07 | | | | | |
| **LAI** | -0.1 | 0.15 | | | | |
| **AL** | **-0.61** | -0.04 | -0.16 | | | |
| **VWC %** | 0.23 | 0.02 | **-0.34** | -0.26 | | |
| **Vegetation Height** | 0.07 | **0.72** | 0.14 | -0.01 | 0.19 | |
| **% Bare Cover** | **0.38** | -0.08 | 0.05 | **-0.35** | 0.09 | -0.23 |

**Basin**

| | OM | Snow Depth | LAI | AL | VWC | Vegetation Height |
|---|---|---|---|---|---|---|
| **Snow** | 0.4 | | | | | |
| **LAI** | **0.64** | 0.3 | | | | |
| **AL** | 0.33 | -0.01 | **-0.66** | | | |
| **VWC %** | 0.1 | 0 | **0.29** | **-0.38** | | |
| **Vegetation Height** | 0.26 | **0.75** | 0.14 | 0.04 | -0.09 | |
| **% Bare Cover** | -0.48 | **-0.26** | **-0.38** | **0.31** | 0.1 | **-0.24** |

**Basin**




**Tundra**

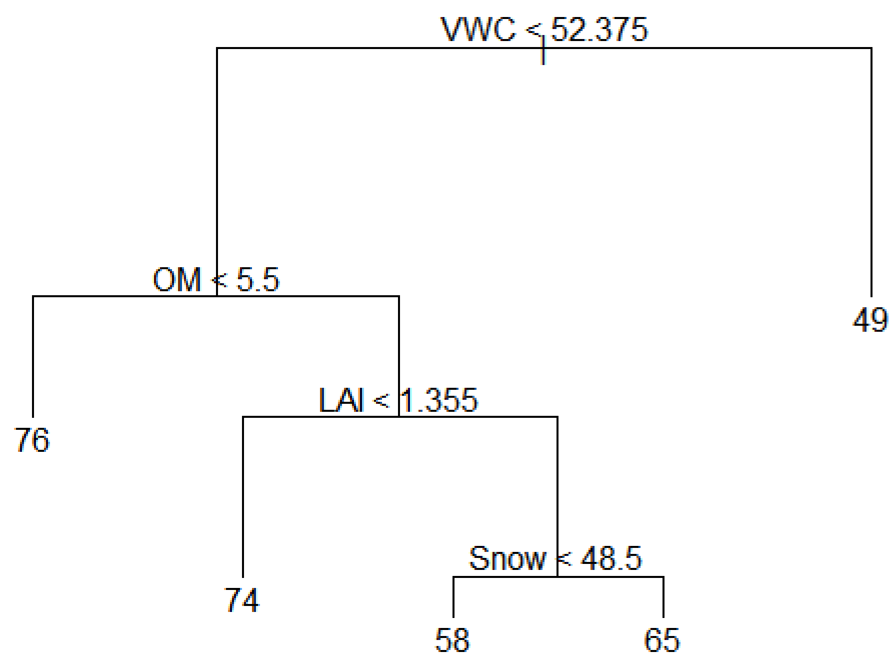



Figure 5.17 - Correlation and regression tree (CART) analysis for predicting thaw depth (cm). Top is for basin sites and bottom is for tundra sites. LAI is the leaf-area index, OM is the thickness of the organic matter (cm), and VegHeight is the average of the tallest vegetation within a 1 m, 1-3 m, 3-5, and 5-7 m radius of the site. The regression tree predicts the active-layer thickness (cm) based on the values of environmental variables.

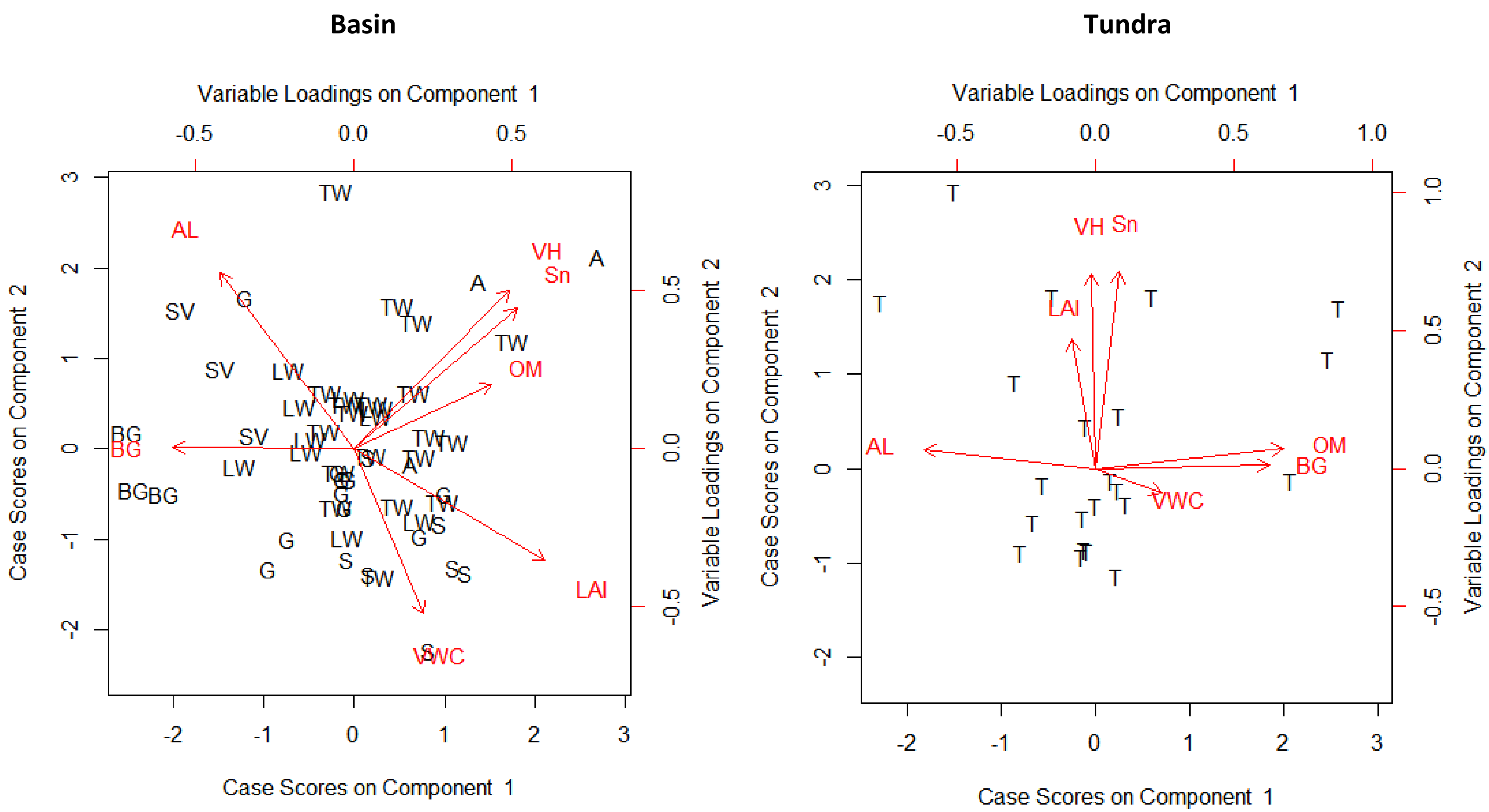



Figure 5.18 - Principal component analysis for the basin and tundra sites. The environmental variables are VWC, LAI, active-layer thickness (AL), mean maximum vegetation height (cm) (VH), snow depth (cm) (Sn), and percent cover of bare ground (BG). The vegetation units are Alder (A), Bare Ground, (BG), Sparse Vegetation (SV), Grass (G), Sedge (S), Tall Willow (TW), and Low Willow (LW).  The variable loadings can be found in Appendix G.

layers within the basin (Table 5.1), as reported by Kade and Walker (2008) and Blok *et al.* (2010). Shrubs are more structurally complex than graminoids, and increased complexity would increase snow trapping and winter insulation, by increasing vegetation height and limiting the collapse of vegetation under the snow load.

### 5.7.2 Snow

However, snow depth did not have a significant correlation with either the basin or the tundra active layer (Table 5.3) and only appeared as the fourth leaf node in the CART analysis for the tundra (Fig. 5.17). The relation between increased snow cover and greater thaw depth is shown in several studies (Sturm *et al.* 2001; Zhang 2005; Lafrenière *et al.* 2012). Vegetation height may be an important environmental variable in determining active-layer thickness as a proxy for snow depth. Vegetation height loads highly with active layer in the PCA component 2 for the basin (Fig. 5.18) and is an environmental factor in CART analysis (Fig. 5.17).

### 5.7.3 Organic matter

There was a negative relation between organic-matter thickness and active-layer development, as obtained by Lantz (2017) and Billings and Peterson (1991). The tundra sites surrounding Illisarvik represent a stable surface that has had time to develop a thick organic layer. There was a strong negative rank correlation between organic-matter and active-layer thicknesses in the tundra sites ($\rho = -0.61$; $p<0.001$) (Table 5.3) as well as a strong negative relation with active layer in component 1 of the PCA (Fig. 5.18).

### 5.7.4 Soil Moisture

Active-layer had a significant negative correlation with soil moisture in the basin ($\rho = -0.38$; $p = 0.001$) but not the tundra (Table 5.3). In the basin, the relation with soil moisture was illustrated by component 2 of the PCA (Fig. 5.18) and in the CART analysis for both the tundra and basin (Fig 5.17). Increased soil moisture increases latent heat release in early winter, which prolongs the zero curtain (French 2007). Therefore, sites with greater soil moisture will have higher $T_g$. However, this does not necessarily translate into greater active-layer depths. An active layer with a high soil moisture will have a high frozen ice content once freeze back occurs. The summer temperature gradient allows moisture migration to the frost table, creating an ice-rich layer at the top of permafrost (Shur *et al*. 2005; French 2007). The following summer as the thaw front encounters ice, energy will be used for phase change rather than active-layer deepening, slowing thaw penetration. This occurred at the Sedge unit, which had a higher $T_g$ than the Cottongrass site, yet the lowest average thaw depth within the basin (Table 5.2, Fig. 5.13).

### 5.7.5 Salinity

Salinity does not influence active-layer thickness but can influence the measured value using the thaw probe method. Increasing salinity results in increased dissolved salts which will depress the freezing point of soil water (Williams and Smith 1989). This freezing-point depression is usually only about 0.1 °C or so below 0 °C. However, since the thaw probe is pushed to the point of refusal, it may be pushed past the depth of 0 °C if there is little or no ice in the soil (Mackay 1977). According to Mackay (1977), errors can occur when probing fine-grained soil, such as found at Illisarvik, resulting in the probe being pushed several decimeters past the frost table. In late summer when thaw depth is near the maximum, frictional resistance in these soils may also make probing insensitive to the frost table. However, the salinity was only significantly different at one bare ground site, which had an active-layer of 118 cm in comparison to the other bare ground site of 95 cm.

### 5.8 Summary

The relative influence of environmental variables on active-layer thickness and temperatures differed between the basin and tundra sites. The tundra was primarily influenced by organic matter and percent vegetation cover while the basin active-layer was primarily influenced by LAI, vegetation height, and soil moisture content. Snow did not appear as an important influencing factor, despite it likely being the cause of the higher active-layer temperatures (Fig. 5.15). However, the vegetation height variable may act as a proxy for snow depth due to their collinearity. The cause of the greater active-layer depths at the Sparse and Bare Ground unit was not apparent in this analysis, but the characterizing variables for these units were the low albedo, a substrate primarily composed of sandy loam (O’Neill 2011), and a water table of ~35-50 cm below the surface in 2015.

# Chapter 6
# Summary and Conclusions

## 6.1 Summary of results

This research provided a unique opportunity to investigate longitudinal vegetation succession in an Arctic environment. The creation of Illisarvik and continuous monitoring by J.R. Mackay and previous studies by Dr. Ovenden made this possible. The thesis examined 38 years of vegetation succession in the Illisarvik drained lake basin and the influence of vegetation on near-surface ground temperatures and active-layer thicknesses.

### 6.1.1 Illisarvik vegetation succession

Shortly following drainage, the basin was dominated by grasses and sedges; shrubs began to colonize the basin in the 1990s and became visually dominant in the early 2000s. The early colonizers, such as *Senecio congestus* and *Descurainia sophioides*, decreased in abundance until they were only sparsely present in the basin in 2016. Vegetation cover increased up to 2001 but has remained less than in the tundra. Grass, sedge, and shrub cover has increased with time, and forb coverage has decreased since 2001, while species richness and diversity have slowly decreased since 1993, as was observed in the study by Billings and Peterson (1980) (Fig. 2.3). Species composition has changed, becoming closer to the undisturbed tundra, but is still significantly different. Species that characterized the basin at seven years post-drainage were primarily ruderal species, with only *Arctagrostis latifolia* widely present in every survey between 1985-2016. *Equisetum arvense* has characterized the basin understorey since 1993, while *Salix glauca* and *Carex aquatilis* have been dominant species since 2001. No new species were able to populate the basin widely in 2016. However, following 1993 four *Salix* spp. have become indicator species for the basin; prior to 2001 the indicator species were primarily forbs.

### 6.1.2 Vegetation association with environmental variables

In order to investigate the influence of vegetation on the active layer and near-surface ground temperatures, the basin was divided into eight vegetation units based on the visually dominant vegetation: Alder, Tall Willow, Low Willow, Grass, Pendant grass, Sedge, Sparse Vegetation, and Bare Ground. The units varied with factors such as nutrient availability, soil moisture, vegetation height, snow depth, active-layer thickness, and near-surface ground temperatures. The Bare Ground unit which is periodically flooded, had one site with ultra acidic pH (3.3) and a high concentration of $Al^{+}$ which may have caused soil toxicity and may help explain the lack of vegetation within the unit. The majority of the basin had a neutral pH, was not saline, and was not limited in nutrients. The soil moisture was highest in the Sedge unit indicating a strong association between soil moisture and species adapted to wet conditions, such as *Carex aquatilis*.

Snow depth was positively correlated with average maximum vegetation height ($\rho$=0.59), which was determined to be an important factor influencing thaw depth and active-layer temperatures ($T_g$). The vegetation acted as a proxy for snow depth as snow depth insulated the ground surface in winter, and the vegetation height influenced the surrounding environment through the creation of drifts. However, the insulating influence of snow diminished once drifts were greater than ~ 50 cm deep.

The other important environmental factor was soil moisture. Soil moisture was positively associated with $T_g$, with increased soil moisture lengthening the zero curtain in autumn through increased latent heat release and was negatively associated with active-layer thickness as more energy was required to melt ground ice. The Bare Ground and Sparse Vegetation units had thick active layers but little to no vegetation and thin snow packs. The active layer at these sites may be influenced more by their low albedo, sandy soil, and moisture at depth.

## 6.2 Conclusions

The following six conclusions can be drawn from the examination of the vegetation succession and association with environmental variables:

1. A gradual shift was observed towards undisturbed tundra characteristics in the basin vegetation 38 years following drainage. However, the vegetation communities in the basin remained compositionally distinct from the undisturbed tundra.
2. There has been a distinct increase in willow cover and height within the basin. Species of erect shrubs such as *Salix glauca, Salix lanata*, and *Salix alaxensis* have been characteristic of the basin since 1993.
3. *Carex aquatilis* subsp. *stans* cover has increased with time and dominates most of the saturated areas. Should lake basin drainage decrease, *Carex aquatilis* would continue to expand and likely dominate newly saturated environments.
4. A reduction in coverage of early colonizing species indicates a directional replacement model of succession, in which inter-species competition influences vegetational species success.
5. Illisarvik is a good site for erect willow establishment. After drainage it was a largely unvegetated substrate close to the Mackenzie Delta, a source of willow

seeds.

6. The soil moisture regime and vegetation were the primary environmental factors controlling active-layer thickness and ground temperatures within the basin, while these variables were primarily controlled by organic-matter thickness in the tundra. Snow depth was of subsidiary influence and primarily controlled by vegetation height. Increased ground temperatures and thicker active layers were found at sites dominated by tall willows.

### 6.3 Broader implications

Vegetation relates to snow thickness (Sturm et al. 2001; Mackay and Burn 2002a), as documented at the taller, more densely vegetated willow sites. These sites will continue to maintain higher ground temperatures than other sites and the tundra. Increased surface temperatures will decrease the rate of peat accumulation through increased microbial decomposition. The majority of old drained lake basins in the low Arctic are characterized by thick peat; reduced peat development due to shrub growth may influence the successional trajectory of the basin.

Illisarvik drained lake basin is a field experiment (Mackay 1997). In that context, drainage was controlled to allow for the study of permafrost and permafrost related topics such as ice-wedge growth. Maintaining the drainage of the basin influences the basin hydrology which in turn influences the vegetation. However, despite the modification of the drainage, it is expected that the same vegetation would occur but the species distribution differ. For instance, the sedge meadows would be a larger portion of the basin due to increased flooding, but the more elevated margins would still be less saturated allowing for grasses and shrubs to establish and grow. The modification of the environment results in a modified vegetation succession and, therefore, the results cannot be simply generalized to surrounding basins. However, Illisarvik provides an unparalleled record that enables hypotheses to be tested that are associated with change over time. This is advantageous over a chronosequence study where a comparison of several basins in a region may have differing vegetative trajectories due to site specific differences such as substrate, soil moisture, and size, and thus, may obscure the temporal trends (Burt 1994). At Illisarvik, the geographic location remains the same, and regional and site-specific changes occur together. It is difficult to state that Illisarvik is a regional indicator for the outer Mackenzie Delta region but it provides the only documented empirical evidence of vegetation succession in a drained lake basin in the region. It is a useful study site as the basin is changing at the same time as the surrounding environment and, therefore, the future vegetation trajectory and its implications can be further investigated.

### 6.4 Future research

There are three future research avenues to explore following this project. The first is the reason for the Bare Ground unit within the basin. A more intensive data collection from different locations within the unit could be conducted with interest in pH, conductivity, and nutrient availability. The two sites sampled in 2016 have varying results for pH, and there is only one sample site for nutrient data. An analysis of the aluminum toxicity causing the lack of vegetation could be examined. Analysis of a soil depth profile would also be of interest. This research might determine the reasons for uncolonized ground at Illisarvik nearly 40 years after drainage.

The second research topic is related to the active-layer freeze back in the locations that have thick active-layers and are dominated by tall willows or by a lack of vegetation. These locations may not freeze back completely each year and may be locations of supra-permafrost taliks. The specific conditions causing the thick active layers are not known, as the Bare Ground and Sparse Vegetation sites have contradictory data with the Tall Willow sites. The Bare Ground, Sparse Vegetation, and eastern margins of the basin have sandier soils and soil moisture at depth that may influence the thickness. Ground temperatures measured continuously at various depths throughout the year at these sites, as well as an analysis of the soil moisture and soil texture at depth, may provide greater insight. These activities would contribute to understanding of permafrost degradation within Illisarvik, a site where, uniformly, aggradation was expected after drainage.

Lastly, this study should be continued with the same methodology in another 20 years or so. Vegetation succession will continue and Illisarvik provides a unique and valuable dataset that should be further developed. Further research may investigate changes in not only the vegetation but also the environmental variables that change with time in conjunction with the vegetation. Additional drained basins of similar ages to Illisarvik on the Tuktoyaktuk Peninsula or Richards Island may also be surveyed to determine if there has been similar vegetation succession in the region. With a changing climate, a longitudinal study may provide important insight into the responses of vegetation succession after a disturbance and divergence from formerly predicted trajectories.

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## Appendix A

Flora of Illisarvik from 1985-2016

| Species | Common Name | Plant Functional Type |
|---|---|---|
| *Achillea millefolium* | common yarrow | Forb |
| *Alnus viridis* subsp. *crispa* | mountain alder | Deciduous shrub |
| *Alopecurus alpinus* | alpine meadow-foxtail | Grass |
| *Amerorchis rotundifolia* | roundleaf orchid | Forb |
| *Andromeda polifolia* | bog rosemary | Evergreen shrub |
| *Anthoxanthum monticola* subsp. *Alpinum* | alpine sweetgrass | Grass |
| *Arctagrostis latifolia* | wideleaf polargrass | Grass |
| *Arctophila fulva* | pendant grass | Grass |
| *Arctostaphylos rubra* | red fruit bearberry | Deciduous shrub |
| *Artemisia tilesii* | Tilesius' wormwood | Forb |
| *Astragalus alpinus* | alpine milkvetch | Forb |
| *Betula glandulosa* | resin birch | Deciduous shrub |
| *Bistorta vivipara* | alpine bistort | Forb |
| *Braya humilis* | rockcress | Forb |
| *Calamagrostis stricta* | slimstem reedgrass | Grass |
| *Caltha palustris* | yellow marsh marigold | Forb |
| *Carex aquatilis* subsp. *stans* | water sedge | Sedge |
| *Carex atrofusca* | darkbrown sedge | Sedge |
| *Carex bigelowii* subsp. *lugens* | Bigelow's sedge | Sedge |
| *Carex capillaris* | hair-like sedge | Sedge |
| *Carex krausei* | Krause's sedge | Sedge |
| *Carex lachenalii* | twotipped sedge, hare's foot sedge | Sedge |
| *Carex maritima* | curved sedge | Sedge |
| *Carex saxatilis* | rock sedge | Sedge |

**Appendix A -** continued

| **Species** | **Common Name** | **Plant Functional Type** |
|---|---|---|
| *Cassiope tetragona* | white Arctic mountain heather | Evergreen shrub |
| *Castilleja raupii* | Raup's indian paintbrush | Forb |
| *Cerastium beeringianum* | Bering chickweed | Forb |
| *Cochlearia officinalis* | Danish scurvygrass | Forb |
| *Deschampsia caespitosa* | tufted hairgrass | Grass |
| *Descurainia sophioides* | northern tansy mustard | Forb |
| *Draba glabella* | smooth draba | Forb |
| *Dryas integrifolia* | entireleaf mountain-avens | Evergreen shrub |
| *Dupontia fisheri* | Fisher's tundragrass | Grass |
| *Empetrum nigrum* | black crowberry | Evergreen shrub |
| *Epilobium angustifolium* | fireweed | Forb |
| *Epilobium davuricum* | Dahurian willowherb | Forb |
| *Epilobium latifolium* | dwarf fireweed, river beauty | Forb |
| *Epilobium palustre* | marsh willowherb | Forb |
| *Equisetum arvense* | field horsetail | Forb |
| *Eriophorum angustifolium* | tall cottongrass | Sedge |
| *Eriophorum scheuchzeri* | white cottongrass, dense cottongrass, sheatled cotton-grass | Sedge |
| *Eriophorum vaginatum* | tussock cottongrass | Sedge |
| *Festuca* spp. | fescue | Grass |
| *Hippuris vulgaris* | common mare's-tail | Forb |
| *Juncus arcticus* | arctic rush | Rush |
| *Juncus balticus* subsp. *Alaskanus* | Alaska rush | Rush |
| *Juncus biglumis* | two flowered rush | Rush |
| *Juncus leucochlamys* | chestnut rush | Rush |
| *Kobresia myosuroides* | Bellardi bog sedge | Grass |

**Appendix A -** continued

| Species | Common Name | Plant Functional Type |
|---|---|---|
| *Ledum palustre* subsp. *decumbens* | marsh Labrador tea | Evergreen shrub |
| *Lomatogonium rotatum* | marsh felwort | Forb |
| *Lupinus arcticus* | arctic lupine | Forb |
| *Luzula arctica ssp.arctica* | arctic woodrush | Rush |
| *Luzula confusa* | northern woodrush | Rush |
| *Luzula multiflora* | common woodrush | Rush |
| *Luzula nivalis* | wideleaf arctic woodrush | Rush |
| *Luzula wahlenbergii* | Wahlenberg's woodrush | Rush |
| *Matricaria ambigua* | false mayweed | Forb |
| *Orthilia secunda* | sidebells wintergreen | Forb |
| *Oxytropis campestris* | field locoweed | Forb |
| *Parnassia kotzebuei* | Kotzebue's grass of Parnassus | Forb |
| *Pedicularis capitata* | capitate lousewort | Forb |
| *Pedicularis sudetica* | sudetic lousewort | Forb |
| *Petasites frigidus* | arctic sweet coltsfoot | Forb |
| *Poa* spp. | bluegrass | Grass |
| *Potamogeton filiformis* | pondweed | Forb |
| *Puccinellia spp.* | alkaligras | Grass |
| *Pyrola grandiflora* | largeflowered wintergreen | Evergreen shrub |
| *Ranunculus aquatilis* | white water crowfoot | Forb |
| *Ranunculus cymbalaria* | alkali buttercup | Forb |
| *Ranunculus gmelinii* | Gmelin's buttercup | Forb |
| *Ranunculus hyperboreus* | high northern buttercup | Forb |
| *Rubus chamaemorus* | cloudberry | Deciduous shrub |
| *Rumex arcticus* | arctic dock | Forb |
| *Salix alaxensis* | feltleaf willow | Deciduous shrub |
| *Salix arbusculoides* | littletree willow | Deciduous shrub |

**Appendix A -** continued

| **Species** | **Common Name** | **Plant Functional Type** |
|---|---|---|
| *Salix arctica* | arctic willow | Deciduous shrub |
| *Salix glauca* | gray willow, grayleaf willow | Deciduous shrub |
| *Salix hastata* | halberd willow | Deciduous shrub |
| *Salix lanata* subsp. *richardsonii* | Richardson's willow | Deciduous shrub |
| *Salix niphoclada* | barrenground willow | Deciduous shrub |
| *Salix ovalifolia var.arctolitoralis* | oval-leaf willow | Deciduous shrub |
| *Salix planifolia* | diamondleaf willow | Deciduous shrub |
| *Salix pulchra* | tealeaf willow | Deciduous shrub |
| *Salix reticulata* | net-veined willow, netleaf willow | Deciduous shrub |
| *Saussurea angustifolia* subsp. *angustifolia* | narrowleaf saw-wort | Forb |
| *Saxifraga hirculus* | yellow marsh saxifrage | Forb |
| *Senecio atropurpureus* | arctic groundsel | Forb |
| *Senecio congestus* | marsh fleabane | Forb |
| *Senecio tundricola* | fuscate groundsel | Forb |
| *Silene uralensis* | apetalous catchfly | Forb |
| *Stellaria calycantha* | northern starwort | Forb |
| *Stellaria crassifolia* | fleshy starwort | Forb |
| *Stellaria longipes* | longstalk starwort | Forb |
| *Suaeda calceoliformis* | Pursh seepweed | Forb |
| *Tofieldia pusilla* | Scotch false asphodel | Forb |
| *Trisetum spicatum* | spike trisetum | Grass |
| *Vaccinium uliginosum* | bog blueberry, bog bilberry | Deciduous shrub |
| *Vaccinium vitis-idaea* | lingonberry, mountain cranberry | Evergreen shrub |

## Appendix B

Vegetation surveys

List of all the vegetation surveys at Illisarvik by site. The sites are ordered from west to east, using the basin grid starting at the northernmost row, and then progressing southward row by row. The sites vegetation units are listed, the first vegetation unit is the vegetation unit in the amalgamated map in Chapter 5 (Fig. 5.1) and throughout the text of thesis, the second one listed is the vegetation unit as stated by the more detailed vegetation map (Appendix C).

Site: 50W-350N

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| Bare ground | - | - | - | 8 |
| *Betula glandulosa* | - | - | - | 17 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 3 |
| *Cassiope tetragona* | - | - | - | 47 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 1 |
| *Lichen* | - | - | - | 5 |
| Litter | - | - | - | 6 |
| *Lupinus arcticus* | - | - | - | 7 |
| Moss | - | - | - | 20 |
| *Petasites frigidus* | - | - | - | 10 |
| *Pyrola grandiflora* | - | - | - | 2 |
| *Salix alaxensis* | - | - | - | 1 |
| *Salix arctica* | - | - | - | 1 |
| *Salix glauca* | - | - | - | 5 |
| *Saussurea angustifolia* subsp. *angustifolia* | - | - | - | 1 |
| *Senecio atropurpureus* | - | - | - | 1 |
| *Vaccinium uliginosum* | - | - | - | 4 |
| *Vaccinium vitis-idaea* | - | - | - | 9 |

Site: 0-350N

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctostaphylos rubra* | - | - | - | 6 |
| Bare ground | - | - | - | 5 |
| *Betula glandulosa* | - | - | - | 6 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 1 |
| *Cassiope tetragona* | - | - | - | 17 |
| *Dryas integrifolia* | - | - | - | 3 |
| *Equisetum arvense* | - | - | - | 1 |
| Litter | - | - | - | 12 |
| *Lupinus arcticus* | - | - | - | 2 |
| Moss | - | - | - | 50 |
| *Pedicularis capitata* | - | - | - | 1 |
| *Petasites frigidus* | - | - | - | 5 |
| *Pyrola grandiflora* | - | - | - | 1 |
| *Salix arctica* | - | - | - | 1 |
| *Salix glauca* | - | - | - | 10 |
| *Saussurea angustifolia* subsp. *angustifolia* | - | - | - | 1 |
| *Senecio atropurpureus* | - | - | - | 1 |
| *Stellaria crassifolia* | - | - | - | 1 |
| *Vaccinium uliginosum* | - | - | - | 14 |

Site: 100E-350N

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 1 |
| *Arctostaphylos rubra* | - | - | - | 11 |
| Bare ground | - | - | - | 7 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 8 |
| *Cassiope tetragona* | - | - | - | 11 |
| *Dryas integrifolia* | - | - | - | 32 |
| *Empetrum nigrum* | - | - | - | 2 |
| Lichen | - | - | - | 3 |
| Litter | - | - | - | 7 |
| *Lupinus arcticus* | - | - | - | 5 |
| Moss | - | - | - | 10 |
| *Poa arctica* | - | - | - | 1 |
| *Pyrola grandiflora* | - | - | - | 3 |
| *Salix glauca* | - | - | - | 30 |
| *Saussurea angustifolia* subsp. *angustifolia* | - | - | - | 1 |
| *Vaccinium uliginosum* | - | - | - | 2 |

Site: 150E-350N

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 1 |
| *Arctostaphylos rubra* | - | - | - | 17 |
| Bare ground | - | - | - | 6 |
| *Bistorta vivipara* | - | - | - | 1 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 3 |
| *Cassiope tetragona* | - | - | - | 35 |
| *Dryas integrifolia* | - | - | - | 13 |
| Lichen | - | - | - | 1 |
| Litter | - | - | - | 4 |
| *Lupinus arcticus* | - | - | - | 10 |
| Moss | - | - | - | 3 |
| *Pedicularis capitata* | - | - | - | 1 |
| *Pedicularis sudetica* | - | - | - | 1 |
| *Salix glauca* | - | - | - | 19 |
| *Saussurea angustifolia* subsp. *angustifolia* | - | - | - | 1 |

Site: 150W-300N

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 1 |
| *Arctostaphylos rubra* | - | - | - | 4 |
| Bare ground | - | - | - | 5 |
| *Betula glandulosa* | - | - | - | 7 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 11 |
| *Cassiope tetragona* | - | - | - | 17 |
| *Eriophorum vaginatum* | - | - | - | 9 |
| Lichen | - | - | - | 4 |
| Litter | - | - | - | 25 |
| *Lupinus arcticus* | - | - | - | 1 |
| Moss | - | - | - | 3 |
| *Petasites frigidus* | - | - | - | 3 |
| *Pyrola grandiflora* | - | - | - | 1 |
| *Salix glauca* | - | - | - | 6 |
| *Senecio atropurpureus* | - | - | - | 1 |
| *Vaccinium uliginosum* | - | - | - | 20 |

Site: 100W-300N

Vegetation unit: Alder, Alder

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Alnus viridis* subsp. *Crispa* | - | - | - | 50 |
| *Artemisia tilesii* | - | - | - | 10 |
| Bare ground | - | - | - | 5 |
| *Betula glandulosa* | - | - | - | 48 |
| *Empetrum nigrum* | - | - | - | 5 |
| *Equisetum arvense* | - | - | - | 8 |
| Litter | - | - | - | 90 |
| *Salix glauca* | - | - | - | 50 |
| *Vaccinium uliginosum* | - | - | - | 10 |

Site: 50W-300N

Vegetation unit: Alder, Alder

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Alnus viridis subsp. Crispa* | - | 1 | 1 | 2 |
| *Alopecurus alpinus* | - | 1 | 1 | |
| *Arctagrostis latifolia* | - | 20 | 10 | 5 |
| *Arctophila fulva* | - | 1 | | |
| *Arctostaphylos rubra* | - | | | 1 |
| Bare ground | - | 5 | | |
| *Betula glandulosa* | - | | 5 | 6 |
| *Carex aquatilis* subsp. *stans* | - | 1 | 5 | 3 |
| *Carex bigelowii* subsp. *lugens* | - | | 15 | |
| *Castilleja raupii* | - | 1 | 1 | |
| *Empetrum nigrum* | - | 1 | 35 | 15 |
| *Equisetum arvense* | - | 50 | 30 | 10 |
| *Eriophorum angustifolium* | - | 1 | | |
| *Eriophorum scheuchzeri* | - | 1 | | |
| Litter | - | | | 35 |
| Moss | - | 5 | | 5 |
| *Pedicularis sudetica* | - | 1 | 1 | |
| *Poa* spp. | - | 1 | | |
| *Pyrola grandiflora* | - | 1 | | |
| *Salix arbusculoides* | - | | | 3 |
| *Salix glauca* | - | 1 | 15 | 5 |
| *Salix lanata* | - | | 15 | |
| *Salix pulchra* | - | 15 | 20 | 8 |
| *Stellaria longipes s.l.* | - | 1 | | |
| *Vaccinium uliginosum* | - | | 1 | |

Site: 0-300N

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Alnus viridis* subsp. *Crispa* | - | - | - | 5 |
| *Andromeda polifolia* | - | - | - | 4 |
| *Arctostaphylos rubra* | - | - | - | 2 |
| Bare ground | - | - | - | 7 |
| *Betula glandulosa* | - | - | - | 8 |
| *Calamagrostis stricta* | - | - | - | 40 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 6 |
| *Cassiope tetragona* | - | - | - | 1 |
| *Empetrum nigrum* | - | - | - | 8 |
| *Eriophorum vaginatum* | - | - | - | 2 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 1 |
| Litter | - | - | - | 10 |
| Moss | - | - | - | 50 |
| *Rubus chamaemorus* | - | - | - | 2 |
| *Salix pulchra* | - | - | - | 7 |
| *Tofieldia pusilla* | - | - | - | 1 |
| *Vaccinium uliginosum* | - | - | - | 7 |

Site: 50E-300N

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Alnus viridis* subsp. *Crispa* | - | - | - | 20 |
| *Andromeda polifolia* | - | - | - | 2 |
| Bare ground | - | - | - | 16 |
| *Betula glandulosa* | - | - | - | 15 |
| *Cassiope tetragona* | - | - | - | 4 |
| *Empetrum nigrum* | - | - | - | 3 |
| *Eriophorum vaginatum* | - | - | - | 4 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 3 |
| Lichen | - | - | - | 1 |
| Litter | - | - | - | 25 |
| Moss | - | - | - | 70 |
| *Rubus chamaemorus* | - | - | - | 1 |
| *Salix arctica* | - | - | - | 2 |
| *Vaccinium uliginosum* | - | - | - | 25 |
| *Vaccinium vitis-idaea* | - | - | - | 1 |

Site: 100E-300N

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctostaphylos rubra* | - | - | - | 5 |
| Bare ground | - | - | - | 13 |
| *Betula glandulosa* | - | - | - | 20 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 8 |
| *Cassiope tetragona* | - | - | - | 1 |
| *Equisetum arvense* | - | - | - | 1 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 4 |
| Litter | - | - | - | 13 |
| *Petasites frigidus* | - | - | - | 3 |
| *Pyrola grandiflora* | - | - | - | 2 |
| *Salix arctica* | - | - | - | 2 |
| *Salix glauca* | - | - | - | 5 |
| *Salix pulchra* | - | - | - | 2 |
| *Salix reticulata* | - | - | - | 2 |
| *Vaccinium uliginosum* | - | - | - | 30 |

Site: 150E-300N

Vegetation unit: Tundra, Tundra

| **Vegetation** | **1985** | **1993** | **2001** | **2016** |
|---|---|---|---|---|
| *Arctostaphylos rubra* | - | - | - | 3 |
| Bare ground | - | - | - | 2 |
| *Betula glandulosa* | - | - | - | 9 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 5 |
| *Cassiope tetragona* | - | - | - | 80 |
| *Empetrum nigrum* | - | - | - | 3 |
| *Equisetum arvense* | - | - | - | 1 |
| *Eriophorum vaginatum* | - | - | - | 4 |
| Litter | - | - | - | 6 |
| *Lupinus arcticus* | - | - | - | 8 |
| *Pyrola grandiflora* | - | - | - | 1 |
| *Rubus chamaemorus* | - | - | - | 1 |
| *Salix glauca* | - | - | - | 50 |
| *Saussurea angustifolia* subsp. a*ngustifolia* | - | - | - | 1 |
| *Stellaria crassifolia* | - | - | - | 1 |
| *Vaccinium uliginosum* | - | - | - | 5 |

Site: 150W-250N

Vegetation unit: Tundra, Tundra

| **Vegetation** | **1985** | **1993** | **2001** | **2016** |
|---|---|---|---|---|
| *Arctostaphylos rubra* | - | - | - | 3 |
| Bare ground | - | - | - | 2 |
| *Betula glandulosa* | - | - | - | 9 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 5 |
| *Cassiope tetragona* | - | - | - | 80 |
| *Empetrum nigrum* | - | - | - | 3 |
| *Equisetum arvense* | - | - | - | 1 |
| *Eriophorum vaginatum* | - | - | - | 4 |
| Litter | - | - | - | 6 |
| *Lupinus arcticus* | - | - | - | 8 |
| *Pyrola grandiflora* | - | - | - | 1 |
| *Rubus chamaemorus* | - | - | - | 1 |
| *Salix glauca* | - | - | - | 50 |
| *Saussurea angustifolia* subsp. *Angustifolia* | - | - | - | 1 |
| *Stellaria crassifolia* | - | - | - | 1 |
| *Vaccinium uliginosum* | - | - | - | 5 |

Site: 100W-250N

Vegetation unit: Low Willow, Salix glauca and Equisetum

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | 3 | 10 | 1 | |
| *Artemisia tilesii* | 5 | 1 | | |
| Bare ground | 10 | | | |
| *Betula glandulosa* | | | 1 | |
| *Calamagrostis stricta* subsp. *stricta* | | | 1 | |
| *Carex aquatilis* subsp. *stans* | 1 | 5 | 5 | 6 |
| *Carex bigelowii subsp. lugens* | 10 | 15 | | |
| *Deschampsia caespitosa* | | 1 | | |
| *Draba glabella* | 2 | | | |
| *Dupontia fisheri* | 1 | | | |
| *Equisetum arvense* | | 35 | 50 | 45 |
| *Eriophorum angustifolium* | | 1 | | |
| *Juncus arcticus* | 2 | | | |
| *Juncus balticus* subsp. *alaskanus* | | 5 | | |
| Litter | | | | 20 |
| *Matricaria ambigua* | 1 | | | |
| Moss | 40 | 85 | | 35 |
| *Pedicularis sudetica* | 1 | | | |
| *Puccinellia* spp. | 15 | | | |
| *Salix alaxensis* | | 5 | 1 | 7 |
| *Salix arbusculoides* | | | 15 | 15 |
| *Salix arctica* | | | 5 | |
| *Salix glauca* | 8 | 30 | 35 | 17 |
| *Salix lanata* | | 1 | 20 | |
| *Salix niphoclada* | | | 1 | |
| *Salix ovalifolia* var. *arctolitoralis* | | 15 | | |
| *Salix pulchra* | | 30 | 15 | 14 |
| *Senecio congestus* | 2 | | | |
| *Stellaria longipes s.l.* | 2 | | | |
| *Vaccinium uliginosum* | | | 1 | |

Site: 50W-250N

Vegetation unit: Low Willow, Salix glauca and Sedge

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | 2 | 2 | | |
| *Artemisia tilesii* | | 1 | | |
| Bare ground | 40 | | | |
| *Betula glandulosa* | | 1 | | |
| *Calamagrostis stricta* subsp. *stricta* | | 1 | 1 | |
| *Carex aquatilis* subsp. *stans* | 5 | 5 | 15 | 80 |
| *Carex bigelowii* subsp. *lugens* | 1 | 1 | 1 | |
| *Castilleja raupii* | | 1 | 1 | |
| *Deschampsia caespitosa* | | 10 | 1 | |
| *Equisetum arvense* | 40 | 85 | 90 | 1 |
| *Eriophorum angustifolium* | | 1 | 1 | |
| *Eriophorum scheuchzeri* | | 1 | 1 | |
| *Juncus biglumis* | | 1 | | |
| *Juncus castaneus* | | 1 | | |
| Litter | | | | 32 |
| *Matricaria ambigua* | | 1 | | |
| Moss | 10 | 1 | | |
| *Poa* spp. | | 10 | 2 | 1 |
| *Puccinellia* spp. | 5 | | | |
| *Salix alaxensis* | | 1 | 1 | |
| *Salix arbusculoides* | | | 1 | |
| *Salix arctica* | | 1 | 1 | |
| *Salix glauca* | | 3 | 2 | |
| *Salix lanata* | | 1 | 5 | |
| *Salix ovalifolia* var. *arctolitoralis* | | 1 | | |
| *Salix pulchra* | | 5 | 10 | 18 |
| *Senecio congestus* | 2 | | | |
| *Silene uralensis* | | 1 | | |
| *Stellaria calycantha* | | 1 | | |
| *Stellaria crassifolia* | | 1 | | |

Site: 0-250N

Vegetation unit: Low Willow, Salix glauca

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctostaphylos rubra* | - | - | - | 1 |
| Bare ground | - | - | - | 7 |
| *Betula glandulosa* | - | - | - | 1 |
| *Carex aquatilis* subsp. *stans* | - | - | - | 10 |
| *Equisetum arvense* | - | - | - | 19 |
| *Festuca rubra* subsp. *arctica* | - | - | - | 1 |
| *Juncus balticus* subsp. *alaskanus* | - | - | - | 4 |
| Litter | - | - | - | 8 |
| Moss | - | - | - | 86 |
| *Pedicularis sudetica* | - | - | - | 2 |
| *Poa* spp. | - | - | - | 1 |
| *Salix glauca* | - | - | - | 7 |
| *Salix lanata* | - | - | - | 17 |
| *Salix pulchra* | - | - | - | 35 |
| *Trisetum spicatum* | - | - | - | 3 |

Site: 50E-250N

Vegetation unit: Low Willow, Salix glauca and Sedge

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Anthoxanthum monticola* subsp. *alpinum* | 5 | | | |
| *Arctagrostis latifolia* | | 20 | 1 | |
| *Artemisia tilesii* | | | 2 | |
| *Astragalus alpinus* | 80 | | | |
| Bare ground | | 35 | | 25 |
| *Calamagrostis stricta* | | 1 | | 1 |
| *Carex aquatilis* subsp. *stans* | | | 1 | |
| *Carex bigelowii* subsp. *lugens* | 1 | | 5 | |
| *Carex capillaris* | | | 10 | |
| *Carex krausei* | | | | 5 |
| *Castilleja raupii* | | 1 | 2 | |
| *Deschampsia caespitosa* | | 5 | | |
| *Epilobium palustre* | 1 | | | |
| *Equisetum arvense* | | 20 | 75 | 15 |
| *Eriophorum angustifolium* | 5 | | 1 | |
| *Eriophorum scheuchzeri* | | 2 | | 1 |
| *Juncus balticus* subsp. *alaskanus* | | | | 3 |
| *Juncus biglumis* | 1 | | | |
| *Juncus castaneus* | | 1 | | |
| Litter | | | | 20 |
| *Lomatogonium rotatum* | | 1 | | |
| *Matricaria ambigua* | | 1 | | |
| Moss | | 20 | | |
| *Parnassia kotzebuei* | | 1 | 1 | |
| *Pedicularis sudetica* | | | | 1 |
| *Potamogeton filiformis* | 10 | | | |
| *Puccinellia* spp. | | 10 | | |
| *Salix arctica* | | | 5 | 21 |
| *Salix glauca* | | | 5 | |
| *Salix lanata* | | | 2 | 3 |
| *Silene uralensis* | | 1 | 1 | |
| *Stellaria longipes* s.l. | | | 1 | |
| *Tofieldia pusilla* | | | | 1 |

Site: 100E-250N

Vegetation unit: Low Willow, Salix glauca and Equisetum

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | | 1 | 1 | |
| *Arctophila fulva* | 5 | | | |
| *Arctostaphylos rubra* | | | | 2 |
| *Artemisia tilesii* | | | 1 | |
| Bare ground | 45 | 25 | | |
| *Calamagrostis stricta* | | | 1 | 1 |
| *Carex aquatilis* subsp. *stans* | 1 | 1 | | 4 |
| *Carex atrofusca* | | | 1 | |
| *Castilleja raupii* | | | 1 | |
| *Deschampsia caespitosa* | 5 | 1 | | |
| *Draba glabella* | 1 | | | |
| *Dryas integrifolia* | | | 1 | |
| *Equisetum arvense* | 25 | 60 | 70 | 6 |
| *Eriophorum angustifolium* | | 1 | | |
| *Eriophorum scheuchzeri* | | 1 | | |
| *Festuca* spp. | | 1 | | |
| *Juncus balticus* subsp. *alaskanus* | | | 1 | 2 |
| *Juncus castaneus* | | 1 | | |
| Litter | | | | 15 |
| *Matricaria ambigua* | 1 | | | |
| Moss | 5 | 2 | | 95 |
| *Parnassia kotzebuei* | | | 1 | |
| *Pedicularis sudetica* | | 1 | 1 | |
| *Poa* spp. | | 1 | 1 | 1 |
| *Puccinellia* spp. | 2 | | | |
| *Pyrola grandiflora* | | | | 1 |
| *Salix alaxensis* | 1 | 1 | | |
| *Salix arbusculoides* | 1 | | 2 | |
| *Salix arctica* | | 1 | 5 | |
| *Salix glauca* | | 10 | 50 | 20 |
| *Salix lanata* | | 1 | 10 | |
| *Salix niphoclada* | | | 1 | |
| *Salix pulchra* | | 5 | 10 | 5 |
| *Salix reticulata* | | 1 | 2 | 1 |
| *Senecio congestus* | 5 | | | |
| *Tofieldia pusilla* | | | 1 | |
| *Vaccinium uliginosum* | | | | 1 |

Site: 150E-250N

Vegetation unit: Tundra, Peat plateau

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 1 |
| *Arctostaphylos rubra* | - | - | - | 5 |
| Bare ground | - | - | - | 6 |
| *Betula glandulosa* | - | - | - | 60 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 1 |
| *Cassiope tetragona* | - | - | - | 1 |
| *Dryas integrifolia* | - | - | - | 1 |
| *Empetrum nigrum* | - | - | - | 4 |
| *Kobresia myosuroides* | - | - | - | 1 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 1 |
| Lichen | - | - | - | 1 |
| Litter | - | - | - | 15 |
| *Poa arctica* | - | - | - | 4 |
| *Salix arbusculoides* | - | - | - | 2 |
| *Salix pulchra* | - | - | - | 2 |
| *Stellaria crassifolia* | - | - | - | 1 |

Site: 200W-200N

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 1 |
| *Betula glandulosa* | - | - | - | 16 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 10 |
| *Cassiope tetragona* | - | - | - | 3 |
| *Empetrum nigrum* | - | - | - | 6 |
| *Eriophorum vaginatum* | - | - | - | 35 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 1 |
| Litter | - | - | - | 36 |
| Moss | - | - | - | 17 |
| *Rubus chamaemorus* | - | - | - | 2 |
| *Salix arbusculoides* | - | - | - | 5 |
| *Salix lanata* | - | - | - | 8 |
| *Salix pulchra* | - | - | - | 30 |
| *Vaccinium uliginosum* | - | - | - | 8 |
| *Vaccinium vitis-idaea* | - | - | - | 3 |

Site: 150W-200N

Vegetation unit: Tall Willow, Tall Salix alaxensis and Salix glauca

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Betula glandulosa* | - | - | - | 1 |
| *Carex aquatilis* subsp. *stans* | - | - | - | 30 |
| Litter | - | - | - | 80 |
| Moss | - | - | - | 6 |
| *Petasites frigidus* | - | - | - | 3 |
| *Salix pulchra* | - | - | - | 40 |
| *Vaccinium uliginosum* | - | - | - | 1 |

Site: 100W-200N

Vegetation unit: Tall Willow, Tall Salix alaxensis and Salix glauca

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | | 1 | | |
| *Artemisia tilesii* | | 2 | | 1 |
| Bare ground | 90 | 50 | | |
| *Calamagrostis stricta* subsp. *stricta* | | 5 | 10 | |
| *Carex capillaris* | 1 | | 1 | |
| *Cochlearia officinalis* | 1 | 2 | | |
| *Deschampsia caespitosa* | | 5 | | |
| *Draba glabella* | 1 | 1 | | |
| *Empetrum nigrum* | | | 1 | |
| *Equisetum arvense* | | 5 | 80 | 41 |
| *Juncus balticus* subsp. *alaskanus* | | 2 | 2 | |
| *Juncus castaneus* | | 2 | | |
| Litter | | | | 45 |
| *Luzula confusa* | | | 1 | |
| *Matricaria ambigua* | | 1 | | |
| Moss | 2 | 30 | | 10 |
| *Parnassia kotzebuei* | | | 1 | 1 |
| *Poa pratensis* | | | | 3 |
| *Puccinellia* spp. | 10 | | | |
| *Salix alaxensis* | | | 1 | |
| *Salix arbusculoides* | | | 1 | |
| *Salix arctica* | | | 5 | |
| *Salix glauca* | | 10 | 35 | 9 |
| *Salix lanata* | | 1 | 10 | |
| *Salix ovalifolia* var. *arctolitoralis* | | 2 | | |
| *Salix pulchra* | | 5 | 35 | 7 |
| *Senecio congestus* | 1 | | | |
| *Silene uralensis* | | 5 | | |
| *Stellaria longipes* s.l. | | 1 | 1 | |

Site: 50W-200N

Vegetation unit: Tall Willow, Tall Salix alaxensis and Salix glauca

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | 30 | 1 | 1 | |
| *Arctophila fulva* | 10 | | | |
| Bare ground | | 60 | 25 | 4 |
| *Carex aquatilis* subsp. *stans* | | 1 | 1 | 75 |
| *Carex bigelowii* subsp. *lugens* | 10 | | | 2 |
| *Carex capillaris* | 4 | | | |
| *Castilleja raupii* | | 1 | 1 | |
| *Cochlearia officinalis* | | 1 | | |
| *Deschampsia caespitosa* | | 1 | 2 | |
| *Draba glabella* | | 1 | | |
| *Dupontia fisheri* | | | 1 | |
| *Epilobium angustifolium* | 5 | | | |
| *Equisetum arvense* | 2 | 25 | 40 | 6 |
| *Eriophorum scheuchzeri* | 10 | 1 | | 1 |
| *Juncus balticus* subsp. *alaskanus* | | | 1 | |
| *Juncus castaneus* | | | 1 | |
| Litter | | | | 40 |
| *Matricaria ambigua* | | 1 | 1 | |
| *Poa* spp. | | | 1 | 1 |
| *Salix alaxensis* | | 5 | 30 | |
| *Salix arbusculoides* | | 1 | | |
| *Salix glauca* | | | 2 | |
| *Salix lanata* | | 1 | | |
| *Salix ovalifolia* var. *arctolitoralis* | | 10 | 10 | |
| *Senecio congestus* | 1 | | 1 | |
| *Silene uralensis* | | 1 | | |
| *Stellaria crassifolia* | | 1 | | 1 |
| *Stellaria longipes* s.l. | 2 | 1 | | |
| *Trisetum spicatum* | | 1 | 1 | |

Site: 0-200N

Vegetation unit: Tall Willow, Tall Salix alaxensis and Salix glauca

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Carex aquatilis* subsp. *stans* | - | - | - | 40 |
| *Equisetum arvense* | - | - | - | 7 |
| *Eriophorum angustifolium* | - | - | - | 1 |
| Litter | - | - | - | 45 |
| Moss | - | - | - | 8 |
| *Parnassia kotzebuei* | - | - | - | 2 |
| *Salix alaxensis* | - | - | - | 1 |
| *Stellaria crassifolia* | - | - | - | 1 |

Site: 50E-200N

Vegetation unit: Low Willow, Salix glauca and Sedge

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Bare ground* | 99 | - | - | |
| *Carex aquatilis* subsp. *stans* | | - | - | 25 |
| *Empetrum nigrum* | | - | - | 1 |
| *Equisetum arvense* | | - | - | 22 |
| *Eriophorum angustifolium* | | - | - | 1 |
| *Eriophorum scheuchzeri* | | - | - | 4 |
| *Juncus balticus* subsp. *alaskanus* | | - | - | 9 |
| Litter | | - | - | 17 |
| Moss | | - | - | 35 |
| *Poa pratensis* | | - | - | 3 |
| *Puccinellia* spp. | 1 | - | - | |
| *Salix alaxensis* | | - | - | 2 |
| *Salix pulchra* | | - | - | 7 |

Site: 100E-200N

Vegetation unit: Low Willow, Bare ground

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | 1 | |
| *Arctostaphylos rubra* | - | - | 1 | |
| Bare ground | - | - | 97 | 75 |
| *Betula glandulosa* | - | - | 1 | |
| *Carex aquatilis* subsp. *stans* | - | - | | 1 |
| *Carex krausei* | - | - | | 10 |
| *Deschampsia caespitosa* | - | - | 1 | |
| *Draba glabella* | - | - | 1 | |
| *Empetrum nigrum* | - | - | 1 | |
| *Equisetum arvense* | - | - | 1 | 30 |
| *Juncus balticus* subsp. *alaskanus* | - | - | | 1 |
| *Matricaria ambigua* | - | - | 1 | |
| *Parnassia kotzebuei* | - | - | 1 | |
| *Pedicularis sudetica* | - | - | 1 | |
| *Puccinellia* spp. | - | - | 1 | |
| *Salix lanata* | - | - | 1 | |
| *Suaeda calceoliformis* | - | - | 1 | |

Site: 150E-200N

Vegetation unit: Low Willow, Salix glauca and Equisetum

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Alnus viridis* subsp. *crispa* | - | - | - | 7 |
| *Arctagrostis latifolia* | - | - | - | 1 |
| *Arctostaphylos rubra* | - | - | - | 6 |
| *Artemisia tilesii* | - | - | - | 2 |
| *Betula glandulosa* | - | - | - | 33 |
| *Carex krausei* | - | - | - | 3 |
| *Castilleja raupii* | - | - | - | 1 |
| *Dryas integrifolia* | - | - | - | 2 |
| *Empetrum nigrum* | - | - | - | 8 |
| *Equisetum arvense* | - | - | - | 21 |
| *Eriophorum vaginatum* | - | - | - | 2 |
| *Luzula multiflora* | - | - | - | 1 |
| *Pyrola grandiflora* | - | - | - | 6 |
| *Salix glauca* | - | - | - | 15 |
| *Salix pulchra* | - | - | - | 1 |
| *Salix reticulata* | - | - | - | 5 |
| *Stellaria crassifolia* | - | - | - | 1 |
| *Tofieldia pusilla* | - | - | - | 1 |
| *Vaccinium uliginosum* | - | - | - | 2 |

Site: 200E-200N

Vegetation unit: Tundra, Peat plateau

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Andromeda polifolia* | - | - | - | 1 |
| *Arctostaphylos rubra* | - | - | - | 2 |
| Bare ground | - | - | - | 1 |
| *Betula glandulosa* | - | - | - | 2 |
| *Carex aquatilis* subsp. *stans* | - | - | - | 80 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 7 |
| *Dryas integrifolia* | - | - | - | 2 |
| *Dupontia fisheri* | - | - | - | 1 |
| *Equisetum arvense* | - | - | - | 1 |
| *Juncus balticus* subsp. *alaskanus* | - | - | - | 1 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 1 |
| Lichen | - | - | - | |
| Litter | - | - | - | 27 |
| Moss | - | - | - | 2 |
| *Petasites frigidus* | - | - | - | 1 |
| *Rubus chamaemorus* | - | - | - | 3 |
| *Salix arbusculoides* | - | - | - | 3 |
| *Salix pulchra* | - | - | - | 1 |
| *Salix reticulata* | - | - | - | 6 |
| *Saxifraga hirculus* | - | - | - | 1 |

Site: 150W-150N

Vegetation unit: Tall Willow, Tall Salix alaxensis and Salix glauca

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Alnus viridis* subsp. *crispa* | - | - | 1 | |
| *Arctagrostis latifolia* | - | - | 15 | 6 |
| *Artemisia tilesii* | - | - | 1 | |
| Bare ground | - | - | | 15 |
| *Betula glandulosa* | - | - | | 1 |
| *Carex aquatilis* subsp. *stans* | - | - | 1 | 3 |
| *Carex bigelowii* subsp. *lugens* | - | - | 10 | |
| *Dupontia fisheri* | - | - | 1 | |
| *Empetrum nigrum* | - | - | | 1 |
| *Equisetum arvense* | - | - | 1 | 8 |
| *Juncus balticus* subsp. *alaskanus* | - | - | 1 | |
| Moss | - | - | 5 | 45 |
| *Petasites frigidus* | - | - | | 2 |
| *Salix alaxensis* | - | - | 5 | |
| *Salix arbusculoides* | - | - | 1 | 17 |
| *Salix glauca* | - | - | 15 | 11 |
| *Salix pulchra* | - | - | 60 | 25 |
| *Vaccinium uliginosum* | - | - | 1 | 1 |

Site: 100W-150N

Vegetation unit: Tall Willow, Tall Salix alaxensis and Salix glauca

| **Vegetation** | **1985** | **1993** | **2001** | **2016** |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | 1 | 1 | |
| *Artemisia tilesii* | - | 5 | 1 | |
| Bare ground | - | | | 15 |
| *Betula glandulosa* | - | | 1 | 4 |
| *Carex aquatilis* subsp. *stans* | - | 1 | | 4 |
| *Carex capillaris* | - | 1 | 10 | |
| *Castilleja raupii* | - | 1 | 1 | |
| *Cerastium beeringianum* | - | 1 | | |
| *Deschampsia caespitosa* | - | 5 | 1 | |
| *Draba glabella* | - | 1 | | |
| *Empetrum nigrum* | - | 5 | 2 | |
| *Equisetum arvense* | - | 20 | 80 | 35 |
| *Eriophorum angustifolium* | - | | 1 | |
| *Festuca* spp. | - | | 1 | |
| *Juncus balticus subsp. alaskanus* | - | | 1 | |
| *Juncus castaneus* | - | 1 | | |
| *Luzula arctica ssp.arctica* | - | | 1 | |
| *Matricaria ambigua* | - | 1 | | |
| Moss | - | 40 | | 80 |
| *Poa* spp. | - | 1 | | |
| *Pyrola grandiflora* | - | 2 | 5 | |
| *Salix alaxensis* | - | 25 | 30 | 20 |
| *Salix arbusculoides* | - | | 1 | 8 |
| *Salix arctica* | - | 1 | 10 | |
| *Salix glauca* | - | 10 | 25 | 12 |
| *Salix hastata* | - | | 10 | |
| *Salix lanata* | - | 2 | 20 | 3 |
| *Salix ovalifolia* var. *arctolitoralis* | - | 1 | | |
| *Salix pulchra* | - | 10 | 5 | 3 |
| *Salix reticulata* | - | 1 | | |
| *Silene uralensis* | - | 1 | | |
| *Stellaria longipes* s.l. | - | 1 | | |
| *Trisetum spicatum* | - | 2 | 1 | |
| *Vaccinium uliginosum* | - | | 1 | |

Site: 50W-150N

Vegetation unit: Pond, Pond

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctophila fulva* | - | 15 | 80 | - |
| Bare ground | - | | 15 | - |
| *Caltha palustris* | - | 1 | | - |
| *Equisetum arvense* | - | | 1 | - |
| *Hippuris vulgaris* | - | 2 | 10 | - |
| *Ranunculus gmelinii* | - | 80 | 5 | - |
| *Ranunculus hyperboreus* | - | | 1 | - |
| *Senecio congestus* | - | 5 | | - |

Site: 0-150N

Vegetation unit: Low Willow, Salix glauca and Sedge

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Calamagrostis stricta* | - | - | - | 1 |
| *Carex aquatilis* subsp. *stans* | - | - | - | 7 |
| *Equisetum arvense* | - | - | - | 25 |
| *Juncus balticus* subsp. *alaskanus* | - | - | - | 1 |
| Litter | - | - | - | 50 |
| Moss | - | - | - | 7 |
| *Salix arbusculoides* | - | - | - | 4 |
| *Salix arctica* | - | - | - | 5 |
| *Salix lanata* | - | - | - | 8 |
| *Salix pulchra* | - | - | - | 10 |

Site: 50E-150N

Vegetation unit: Tall Willow, Tall Salix alaxensis and Salix glauca

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Alnus viridis* subsp. *crispa* | | | 1 | |
| *Alopecurus alpinus* | | 1 | 1 | |
| *Arctagrostis latifolia* | 15 | 15 | 2 | 3 |
| *Artemisia tilesii* | 1 | 5 | 1 | |
| Bare ground | 30 | | | 20 |
| *Calamagrostis stricta* subsp. *stricta* | | 15 | 1 | |
| *Carex aquatilis* subsp. *stans* | 10 | 1 | 10 | 6 |
| *Carex atrofusca* | | | 1 | |
| *Carex bigelowii* subsp. *lugens* | | 2 | 1 | |
| *Carex capillaris* | | 1 | | |
| *Carex lachenalii* | | 1 | | |
| *Castilleja raupii* | | 1 | 1 | |
| *Deschampsia caespitosa* | | 1 | | |
| *Draba glabella* | 1 | | | |
| *Equisetum arvense* | 1 | 60 | 90 | 33 |
| *Eriophorum angustifolium* | | 1 | | |
| *Eriophorum scheuchzeri* | | 1 | | |
| *Juncus balticus* subsp. *alaskanus* | | 1 | 1 | |
| *Juncus biglumis* | | | | |
| *Juncus castaneus* | 7 | 5 | | |
| Litter | | | | 10 |
| *Matricaria ambigua* | | 1 | | |
| Moss | 20 | 20 | | 55 |
| *Parnassia kotzebuei* | | 1 | | |
| *Poa* spp. | | 1 | 1 | |
| *Puccinellia* spp. | 10 | | | |
| *Salix alaxensis* | | | 1 | |
| *Salix arbusculoides* | | 2 | 15 | 20 |
| *Salix arctica* | | | 1 | |
| *Salix glauca* | 1 | 40 | 35 | 25 |
| *Salix lanata* | | | 1 | |
| *Salix pulchra* | | 1 | 2 | 25 |
| *Senecio congestus* | 5 | | | |
| *Silene uralensis* | | 1 | 1 | |
| *Stellaria crassifolia* | | 1 | | |
| *Stellaria longipes* s.l. | 1 | | | |

Site: 100E-150N

Vegetation unit: Grass, Cottongrass

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | | 1 | 1 | |
| *Artemisia tilesii* | | 1 | | |
| Bare ground | 99 | 95 | 90 | 41 |
| *Carex aquatilis* subsp. *stans* | | | 1 | |
| *Cochlearia officinalis* | | 1 | 1 | |
| *Deschampsia caespitosa* | | 1 | 5 | 3 |
| *Epilobium latifolium* | | 1 | 1 | |
| *Equisetum arvense* | | | | 8 |
| *Eriophorum scheuchzeri* | | | | 40 |
| *Juncus balticus* subsp. *alaskanus* | | | 1 | 3 |
| Litter | | | | 4 |
| *Lomatogonium rotatum* | | | 1 | |
| *Matricaria ambigua* | | 1 | | |
| *Pedicularis sudetica* | | | 1 | |
| *Puccinellia* spp. | 1 | 1 | 1 | |
| *Salix glauca* | | | 1 | 2 |
| *Senecio congestus* | | 1 | | |
| *Suaeda calceoliformis* | | | 1 | |

Site: 150E-150N

Vegetation unit: Tall Willow, Tall Salix alaxensis and Equisetum

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Alopecurus alpinus* | | 1 | 1 | |
| *Arctagrostis latifolia* | 5 | 10 | | |
| *Artemisia tilesii* | | 1 | 1 | |
| Bare ground | 10 | 5 | 0 | |
| *Betula glandulosa* | | | 5 | |
| *Calamagrostis stricta* | | | 1 | 60 |
| *Carex aquatilis* subsp. *stans* | | 1 | 1 | |
| *Carex capillaris* | | | 1 | |
| *Castilleja raupii* | | 1 | 2 | |
| *Deschampsia caespitosa* | | 1 | | |
| *Equisetum arvense* | 84 | 90 | 85 | 5 |
| *Juncus balticus* subsp. *alaskanus* | | | 1 | |
| *Juncus castaneus* | | 2 | | |
| Litter | | | | 10 |
| *Luzula arctica* subsp. *arctica* | | | 1 | |
| *Matricaria ambigua* | | 1 | | |
| Moss | | | | 25 |
| *Parnassia kotzebuei* | | 1 | 1 | |
| *Poa* spp. | | 5 | 2 | |
| *Puccinellia* spp. | 1 | | | |
| *Pyrola grandiflora* | | | 1 | |
| *Salix arctica* | | 1 | 5 | |
| *Salix lanata* | | | 1 | |
| *Salix ovalifolia* var. *arctolitoralis* | | 1 | | |
| *Salix pulchra* | | | | 2 |
| *Stellaria crassifolia* | | | | 1 |

Site: 200E-150N

Vegetation unit: Tundra, Peat plateau

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Alnus viridis* subsp. *crispa* | - | - | - | 10 |
| *Arctostaphylos rubra* | - | - | - | 4 |
| *Betula glandulosa* | - | - | - | 13 |
| *Bistorta vivipara* | - | - | - | 1 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 2 |
| *Cassiope tetragona* | - | - | - | 25 |
| *Dryas integrifolia* | - | - | - | 4 |
| *Kobresia myosuroides* | - | - | - | 1 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | |
| Lichen | - | - | - | 1 |
| Litter | - | - | - | 17 |
| *Lupinus arcticus* | - | - | - | 3 |
| Moss | - | - | - | 17 |
| *Petasites frigidus* | - | - | - | 4 |
| *Salix glauca* | - | - | - | 25 |
| *Saussurea angustifolia* subsp. *angustifolia* | - | - | - | 1 |
| *Senecio atropurpureus* | - | - | - | 1 |
| *Stellaria crassifolia* | - | - | - | 1 |

Site: 200W-100N

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Alnus viridis* subsp. *crispa* | - | - | - | 5 |
| *Arctagrostis latifolia* | - | - | - | 2 |
| *Arctostaphylos rubra* | - | - | - | 3 |
| Bare ground | - | - | - | 10 |
| *Betula glandulosa* | - | - | - | 22 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 3 |
| *Cassiope tetragona* | - | - | - | 25 |
| *Empetrum nigrum* | - | - | - | 10 |
| *Equisetum arvense* | - | - | - | 1 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 1 |
| Lichen | - | - | - | 1 |
| Litter | - | - | - | 10 |
| Moss | - | - | - | 8 |
| *Pyrola grandiflora* | - | - | - | 1 |
| *Salix glauca* | - | - | - | 25 |
| *Tofieldia pusilla* | - | - | - | 2 |
| *Vaccinium uliginosum* | - | - | - | 20 |
| *Vaccinium vitis-idaea* | - | - | - | 17 |

Site: 150W-100N

Vegetation unit: Alder, Alder

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 6 |
| *Artemisia tilesii* | - | - | - | 2 |
| *Betula glandulosa* | - | - | - | 3 |
| *Calamagrostis stricta* | - | - | - | 10 |
| *Empetrum nigrum* | - | - | - | 1 |
| *Equisetum arvense* | - | - | - | 10 |
| Litter | - | - | - | 40 |
| Moss | - | - | - | 5 |
| *Petasites frigidus* | - | - | - | 2 |
| *Salix alaxensis* | - | - | - | 4 |
| *Salix lanata* | - | - | - | 25 |
| *Salix pulchra* | - | - | - | 2 |
| *Vaccinium uliginosum* | - | - | - | 1 |

Site: 100W-100N

Vegetation unit: Sedge, Sedge

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctophila fulva* | 20 | - | | |
| Bare ground | 20 | - | 30 | 10 |
| *Carex aquatilis* subsp. *stans* | | - | 30 | 65 |
| *Equisetum arvense* | 1 | - | 1 | |
| *Eriophorum angustifolium* | | - | 40 | |
| *Hippuris vulgaris* | 1 | - | | |
| Litter | | - | | 20 |
| *Matricaria ambigua* | 1 | - | | |
| Moss | 10 | - | | |
| *Puccinellia* spp. | 40 | - | | |
| *Senecio congestus* | 10 | - | | |
| Standing water | | - | | 35 |
| *Stellaria crassifolia* | | - | 1 | |

Site: 50W-100N

Vegetation unit: Tall Willow, Salix glauca and Equisetum

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | 2 | 15 | 10 | |
| *Arctophila fulva* | 25 | | | |
| *Artemisia tilesii* | | 2 | | |
| Bare ground | | | | 3 |
| *Betula glandulosa* | | | 1 | |
| *Carex aquatilis* subsp. *stans* | 1 | | 5 | |
| *Cochlearia officinalis* | | 5 | | |
| *Deschampsia caespitosa* | | 5 | | |
| *Dupontia fisheri* | | 2 | | |
| *Equisetum arvense* | | 30 | 30 | 20 |
| *Eriophorum angustifolium* | | 1 | | |
| *Festuca* spp. | | 1 | | |
| *Hippuris vulgaris* | 1 | | | |
| Litter | 30 | | | 42 |
| *Luzula nivalis* | | | | 3 |
| Moss | 2 | | | |
| *Pedicularis sudetica* | | 1 | | |
| *Poa* spp. | | 1 | 2 | |
| *Puccinellia* spp. | 5 | | | |
| *Salix alaxensis* | | 1 | 1 | |
| *Salix arbusculoides* | | 1 | 1 | |
| *Salix arctica* | | 20 | 30 | 8 |
| *Salix glauca* | | 2 | 10 | 6 |
| *Salix lanata* | | | 5 | 7 |
| *Salix ovalifolia* var. *arctolitoralis* | | | 1 | |
| *Salix pulchra* | | 5 | 20 | 6 |
| *Saxifraga hirculus* | | 1 | 1 | |
| *Senecio congestus* | 15 | | | |
| *Silene uralensis* | | 1 | | |
| *Stellaria crassifolia* | | 10 | | |
| *Stellaria longipes* s.l. | | 10 | | |
| *Trisetum spicatum* | | 1 | 1 | 7 |

Site: 0-100N

Vegetation unit: Sedge, Sedge

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| Bare ground | - | - | - | 32 |
| *Carex aquatilis* subsp. *stans* | - | - | - | 45 |
| Moss | - | - | - | 2 |
| *Salix glauca* | - | - | - | 4 |
| Standing water | - | - | - | 22 |

Site: 50E-100N

Vegetation unit: Grass, Cottongrass

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | | | - | 7 |
| Bare ground | 99 | 65 | - | 6 |
| *Carex aquatilis* subsp. *stans* | | | - | 1 |
| *Carex capillaris* | 1 | | - | |
| *Carex krausei* | | | - | 4 |
| *Cerastium beeringianum* | | 1 | - | |
| *Cochlearia officinalis* | | 1 | - | |
| *Deschampsia caespitosa* | | 2 | - | |
| *Descurainia sophioides* | 1 | | - | |
| *Draba glabella* | | 1 | - | |
| *Equisetum arvense* | | | - | 7 |
| *Eriophorum scheuchzeri* | | 1 | - | 2 |
| *Juncus balticus* subsp. *alaskanus* | | | - | 1 |
| Litter | | | - | 60 |
| *Luzula nivalis* | | | - | 1 |
| *Matricaria ambigua* | | 1 | - | |
| *Moss* | | 1 | - | |
| *Pedicularis sudetica* | | 1 | - | |
| *Poa arctica* | | | - | 3 |
| *Puccinellia* spp. | | 35 | - | |
| *Salix alaxensis* | | | - | 2 |
| *Salix arctica* | | | - | 4 |
| *Salix glauca* | | 1 | - | 4 |
| *Stellaria crassifolia* | | | - | 1 |

Site: 100E-100N

Vegetation unit: Grass, Low Salix alaxensis

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | 1 | - | 3 |
| *Artemisia tilesii* | - | 5 | - | |
| *Bare ground* | - | 80 | - | 10 |
| *Carex aquatilis* subsp. *stans* | - | 1 | - | 8 |
| *Cochlearia officinalis* | - | 1 | - | |
| *Deschampsia caespitosa* | - | 2 | - | |
| *Descurainia sophioides* | - | 1 | - | |
| *Draba glabella* | - | 1 | - | |
| *Equisetum arvense* | - | | - | 20 |
| *Juncus balticus* subsp. *alaskanus* | - | | - | 1 |
| Litter | - | | - | 37 |
| *Matricaria ambigua* | - | 5 | - | |
| *Parnassia kotzebuei* | - | | - | 2 |
| *Puccinellia* spp. | - | 5 | - | |
| *Salix alaxensis* | - | | - | 18 |
| *Salix arctica* | - | | - | 4 |
| *Suaeda calceoliformis* | - | 2 | - | |

Site: 150E-100N

Vegetation unit: Tall Willow, Tall Salix alaxensis and Equisetum

| **Vegetation** | **1985** | **1993** | **2001** | **2016** |
|---|---|---|---|---|
| *Alopecurus alpinus* | | 1 | 1 | |
| *Arctagrostis latifolia* | | | 1 | |
| *Artemisia tilesii* | | | 2 | |
| Bare ground | 100 | 65 | | |
| *Betula glandulosa* | | | 1 | |
| *Calamagrostis stricta* subsp. *stricta* | | 1 | 1 | |
| *Carex aquatilis* subsp. *stans* | | 1 | 2 | 1 |
| *Carex maritima* | | 1 | 1 | |
| *Castilleja raupii* | | | 1 | |
| *Cochlearia officinalis* | | 1 | | |
| *Deschampsia caespitosa* | | 2 | | |
| *Epilobium latifolium* | | 1 | | |
| *Equisetum arvense* | | 30 | 95 | 27 |
| *Juncus balticus* subsp. *alaskanus* | | | 1 | |
| Litter | | | | 3 |
| *Matricaria ambigua* | | 1 | | |
| Moss | | | | 75 |
| *Parnassia kotzebuei* | | 1 | 1 | 1 |
| *Pedicularis sudetica* | | | 1 | |
| *Poa* spp. | | 1 | 1 | 3 |
| *Puccinellia* spp. | 1 | | | |
| *Pyrola grandiflora* | | | 1 | |
| *Salix alaxensis* | | 1 | 1 | |
| *Salix arctica* | | 1 | 1 | |
| *Salix glauca* | | | | 4 |
| *Salix lanata* | | | 1 | |
| *Salix pulchra* | | | 1 | |
| *Silene uralensis* | | | 1 | |
| *Trisetum spicatum* | | | | 5 |

Site: 200E-100N

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 5 |
| *Arctostaphylos rubra* | - | - | - | 5 |
| *Calamagrostis stricta* | - | - | - | 1 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 2 |
| *Cassiope tetragona* | - | - | - | 20 |
| *Dryas integrifolia* | - | - | - | 25 |
| Lichen | - | - | - | 1 |
| Litter | - | - | - | 10 |
| *Lupinus arcticus* | - | - | - | 20 |
| Moss | - | - | - | 5 |
| *Pedicularis capitata* | - | - | - | 1 |
| *Salix glauca* | - | - | - | 18 |

Site: 150W-50N

Vegetation unit: Alder, Alder

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Alnus viridis* subsp. *crispa* | - | - | - | 3 |
| *Arctagrostis latifolia* | - | - | - | 6 |
| Bare ground | - | - | - | 20 |
| *Betula glandulosa* | - | - | - | 12 |
| *Empetrum nigrum* | - | - | - | 10 |
| *Equisetum arvense* | - | - | - | 17 |
| Lichen | - | - | - | 2 |
| Litter | - | - | - | 35 |
| *Salix arctica* | - | - | - | 2 |
| *Salix lanata* | - | - | - | 7 |
| *Vaccinium uliginosum* | - | - | - | 7 |

Site: 100W-50N

Vegetation unit: Tall Willow, Tall Salix alaxensis and Salix glauca

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | | 2 | 10 | |
| *Arctophila fulva* | 1 | | | |
| *Artemisia tilesii* | | 1 | 1 | |
| Bare ground | 85 | | | 2 |
| *Calamagrostis stricta* subsp. *stricta* | | | 10 | |
| *Carex aquatilis* subsp. *stans* | | 5 | 70 | 37 |
| *Carex bigelowii* subsp. *lugens* | | | 1 | |
| *Carex maritima* | | 40 | 1 | |
| *Cochlearia officinalis* | | 1 | | |
| *Deschampsia caespitosa* | | 10 | | |
| *Descurainia sophioides* | 1 | | | |
| *Equisetum arvense* | | 20 | 20 | 5 |
| *Eriophorum angustifolium* | | | 10 | |
| *Eriophorum scheuchzeri* | | | 1 | |
| *Juncus balticus* subsp. *alaskanus* | | 1 | 1 | |
| *Juncus castaneus* | | 5 | | |
| Litter | | | | 70 |
| *Matricaria ambigua* | | 1 | | |
| Moss | 1 | 2 | 2 | |
| *Poa* spp. | | 1 | | |
| *Puccinellia* spp. | 11 | | | |
| *Salix alaxensis* | | 1 | 3 | |
| *Salix arctica* | | 1 | 1 | |
| *Salix glauca* | | 2 | 3 | 8 |
| *Salix lanata* | | 1 | 1 | |
| *Salix pulchra* | | | 1 | |
| *Senecio congestus* | 2 | | | |
| *Stellaria crassifolia* | | 5 | | |
| *Stellaria longipes* s.l. | 1 | 1 | 1 | |
| *Trisetum spicatum* | | | 1 | |

Site: 0-50N

Vegetation unit: Tall Willow, Tall Salix alaxensis grass and birch

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 15 |
| *Artemisia tilesii* | - | - | - | 1 |
| *Carex aquatilis* subsp. *stans* | - | - | - | 20 |
| *Empetrum nigrum* | - | - | - | 1 |
| Litter | - | - | - | 70 |
| *Parnassia kotzebuei* | - | - | - | 1 |
| *Salix arbusculoides* | - | - | - | 4 |
| *Salix lanata* | - | - | - | 1 |
| *Salix pulchra* | - | - | - | 3 |
| *Salix reticulata* | - | - | - | 2 |

Site: 50E-50N

Vegetation unit: Sedge, Sedge

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | | 15 | - | |
| *Artemisia tilesii* | | 1 | - | |
| Bare ground | 55 | 10 | - | |
| *Carex aquatilis* subsp. *stans* | | | - | 85 |
| *Cochlearia officinalis* | | 15 | - | |
| *Deschampsia caespitosa* | | 30 | - | |
| *Descurainia sophioides* | 30 | | - | |
| *Draba glabella* | | 1 | - | |
| *Epilobium latifolium* | | 1 | - | |
| *Equisetum arvense* | | 1 | - | |
| *Juncus balticus* subsp. *alaskanus* | | 1 | - | |
| *Juncus castaneus* | | 1 | - | |
| Litter | | | - | 15 |
| *Matricaria ambigua* | | 25 | - | |
| Moss | | 1 | - | |
| *Puccinellia spp.* | 15 | | - | |
| *Salix alaxensis* | | 1 | - | |
| *Salix glauca* | | 1 | - | |
| *Salix pulchra* | | 1 | - | |
| *Senecio congestus* | 1 | | - | |
| *Stellaria crassifolia* | | 5 | - | |
| *Stellaria longipes* s.l. | | 1 | - | |

Site: 100E-50N

Vegetation unit: Tall Willow, Low Salix alaxensis

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | | 1 | | 5 |
| Bare ground | 99 | 95 | 90 | 8 |
| *Carex aquatilis* subsp. *stans* | | 1 | | 12 |
| *Castilleja raupii* | | | 1 | |
| *Cochlearia officinalis* | | 1 | 1 | |
| *Deschampsia caespitosa* | | 1 | 1 | |
| *Descurainia sophioides* | 1 | 1 | | |
| *Draba glabella* | | 1 | | |
| *Epilobium latifolium* | | 1 | | |
| *Eriophorum scheuchzeri* | | | | 1 |
| *Juncus balticus* subsp. *alaskanus* | | | | 1 |
| Litter | | | | 65 |
| *Matricaria ambigua* | | 1 | 1 | |
| Moss | | | | 7 |
| *Parnassia kotzebuei* | | | | 1 |
| *Poa* spp. | | | 1 | |
| *Puccinellia* spp. | | 1 | 1 | |
| *Salix alaxensis* | | | | 8 |
| *Stellaria crassifolia* | | | | 1 |
| *Stellaria longipes* s.l. | | 1 | 1 | |
| *Suaeda calceoliformis* | | | 5 | |

Site: 150E-50N

Vegetation unit: Grass, Cottongrass

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | 5 | 5 | 2 | |
| *Arctostaphylos rubra* | | | | 13 |
| *Artemisia tilesii* | | 2 | 5 | |
| Bare ground | 75 | 5 | 5 | 20 |
| *Betula glandulosa* | | | 1 | 2 |
| *Calamagrostis stricta* | | | | 3 |
| *Calamagrostis stricta* subsp. *stricta* | | 2 | 1 | |
| *Carex aquatilis* subsp. *stans* | 2 | 20 | 60 | 3 |
| *Carex capillaris* | | | 1 | |
| *Carex maritima* | | 1 | 1 | |
| *Castilleja raupii* | | | 5 | |
| *Deschampsia caespitosa* | | 30 | | |
| *Descurainia sophioides* | 2 | | | |
| *Draba glabella* | | 1 | 1 | |
| *Dryas integrifolia* | | | | 7 |
| *Empetrum nigrum* | | | 1 | 1 |
| *Equisetum arvense* | | 20 | 20 | 7 |
| *Juncus balticus* subsp. *alaskanus* | | 1 | | 1 |
| *Juncus castaneus* | | 1 | | |
| *Luzula arctica* subsp. *arctica* | | | 1 | |
| *Matricaria ambigua* | | 5 | 5 | |
| Moss | | 10 | 10 | 45 |
| *Orthillia secunda* | | | | 2 |
| *Pedicularis sudetica* | | | 1 | |
| *Poa* spp. | | 2 | 1 | |
| *Puccinellia* spp. | 15 | 10 | | |
| *Pyrola grandiflora* | | | 1 | 1 |
| *Salix alaxensis* | | 1 | | |
| *Salix glauca* | | 1 | 1 | |
| *Salix lanata* | | | | 3 |
| *Salix niphoclada* | | 1 | | |
| *Salix pulchra* | | | 1 | |
| *Stellaria crassifolia* | | 1 | | |
| *Stellaria longipes* s.l. | | 1 | 1 | |
| *Vaccinium uliginosum* | | | 1 | |

Site: 200E-50N

Vegetation unit: Tundra, Salix glauca

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctostaphylos rubra* | - | - | - | 1 |
| *Artemisia tilesii* | - | - | - | 3 |
| *Betula glandulosa* | - | - | - | 4 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 2 |
| *Castilleja raupii* | - | - | - | 1 |
| *Empetrum nigrum* | - | - | - | 2 |
| Litter | - | - | - | 90 |
| *Lupinus arcticus* | - | - | - | 2 |
| Moss | - | - | - | 10 |
| *Parnassia kotzebuei* | - | - | - | 1 |
| *Pyrola grandiflora* | - | - | - | 1 |
| *Salix glauca* | - | - | - | 80 |
| *Vaccinium uliginosum* | - | - | - | 1 |

Site: 200W-0

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 5 |
| *Arctostaphylos rubra* | - | - | - | 5 |
| Bare ground | - | - | - | 4 |
| *Betula glandulosa* | - | - | - | 28 |
| *Dryas integrifolia* | - | - | - | 10 |
| *Empetrum nigrum* | - | - | - | 16 |
| *Kobresia myosuroides* | - | - | - | 1 |
| Lichen | - | - | - | 3 |
| Litter | - | - | - | 30 |
| *Lupinus arcticus* | - | - | - | 5 |
| Moss | - | - | - | 20 |
| Mushroom | - | - | - | 2 |
| *Pedicularis sudetica* | - | - | - | 1 |
| *Pyrola grandiflora* | - | - | - | 3 |
| *Salix glauca* | - | - | - | 25 |
| *Senecio atropurpureus* | - | - | - | 2 |
| *Vaccinium vitis-idaea* | - | - | - | 3 |

Site: 150W-0

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 3 |
| *Arctostaphylos rubra* | - | - | - | 8 |
| *Bare ground* | - | - | - | 2 |
| *Betula glandulosa* | - | - | - | 17 |
| *Cassiope tetragona* | - | - | - | 12 |
| *Dryas integrifolia* | - | - | - | 3 |
| *Empetrum nigrum* | - | - | - | 2 |
| *Eriophorum vaginatum* | - | - | - | 15 |
| *Litter* | - | - | - | 50 |
| *Lupinus arcticus* | - | - | - | 10 |
| *Moss* | - | - | - | 13 |
| *Pedicularis sudetica* | - | - | - | 1 |
| *Pyrola grandiflora* | - | - | - | 2 |
| *Rubus chamaemorus* | - | - | - | 4 |
| *Salix glauca* | - | - | - | 7 |
| *Salix pulchra* | - | - | - | 3 |
| *Senecio atropurpureus* | - | - | - | 1 |
| *Stellaria crassifolia* | - | - | - | 1 |
| *Tofieldia pusilla* | - | - | - | 2 |
| *Vaccinium uliginosum* | - | - | - | 7 |

Site: 100W-0

Vegetation unit: Tall Willow, Tall Salix alaxensis and Salix glauca

| **Vegetation** | **1985** | **1993** | **2001** | **2016** |
|---|---|---|---|---|
| *Bare ground* | - | - | - | 10 |
| *Carex aquatilis* subsp. *stans* | - | - | - | 34 |
| *Equisetum arvense* | - | - | - | 6 |
| Litter | - | - | - | 45 |
| *Salix alaxensis* | - | - | - | 8 |
| *Salix glauca* | - | - | - | 7 |
| *Salix pulchra* | - | - | - | 20 |

Site: 50W-0

Vegetation unit: Tall Willow, Low Salix alaxensis

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | | 1 | 1 | 2 |
| Bare ground | 96 | 95 | 95 | 10 |
| *Betula glandulosa* | | | 1 | |
| *Carex aquatilis* subsp. *stans* | | 1 | 1 | |
| *Castilleja raupii* | | | 1 | 1 |
| *Cochlearia officinalis* | | 1 | 1 | |
| *Deschampsia caespitosa* | | 1 | 5 | 4 |
| *Draba glabella* | | 1 | | |
| *Equisetum arvense* | | | | 7 |
| *Eriophorum scheuchzeri* | | | | 15 |
| *Juncus balticus* subsp. *alaskanus* | | | | 1 |
| Litter | | | | 50 |
| *Lomatogonium rotatum* | | | 1 | |
| *Matricaria ambigua* | | | 1 | |
| Moss | | | 1 | |
| *Parnassia kotzebuei* | | | 1 | |
| *Poa* spp. | | 1 | 1 | |
| *Puccinellia* spp. | 3 | 5 | 1 | |
| *Salix alaxensis* | | 1 | 1 | 12 |
| *Salix arctica* | | | | 2 |
| *Salix lanata* | | | 5 | |
| *Salix pulchra* | | | 1 | 4 |
| *Senecio congestus* | | | 1 | |
| *Stellaria longipes* s.l. | | 1 | | |
| *Suaeda calceoliformis* | | | 2 | |
| *Trisetum spicatum* | | | 1 | |

Site: 0-0

Vegetation unit: Sedge, Sedge

| **Vegetation** | **1985** | **1993** | **2001** | **2016** |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 30 |
| *Arctophila fulva* | - | - | - | 4 |
| Bare ground | - | - | - | 5 |
| *Carex aquatilis* subsp. *stans* | - | - | - | 30 |
| *Eriophorum scheuchzeri* | - | - | - | 1 |
| Litter | - | - | - | 50 |
| *Stellaria crassifolia* | - | - | - | 1 |

Site: 50E-0

Vegetation unit: Sedge, Sedge

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | | 10 | | 6 |
| *Arctophila fulva* | | | 5 | 1 |
| *Artemisia tilesii* | | 1 | | |
| Bare ground | 100 | 70 | 30 | 6 |
| *Carex aquatilis* subsp. *stans* | | | 10 | 40 |
| *Cochlearia officinalis* | | 1 | | |
| *Deschampsia caespitosa* | | 1 | | |
| *Equisetum arvense* | | 1 | | |
| *Eriophorum scheuchzeri* | | 1 | | 6 |
| *Hippuris vulgaris* | | | 15 | 1 |
| *Juncus castaneus* | | 1 | | |
| Litter | | | | 30 |
| *Matricaria ambigua* | | 5 | | |
| *Moss* | | 1 | | |
| *Puccinellia* spp. | 1 | 5 | | |
| *Ranunculus gmelinii* | | | 70 | 1 |
| *Salix glauca* | | 1 | | |
| *Senecio congestus* | | 1 | | |
| Standing water | | | | 7 |
| *Stellaria crassifolia* | | 10 | | |

Site: 100E-0

Vegetation unit: Grass, Dry grass

| **Vegetation** | **1985** | **1993** | **2001** | **2016** |
|---|---|---|---|---|
| *Calamagrostis stricta* | - | - | - | 80 |
| Litter | - | - | - | 20 |

Site: 150E-0

Vegetation unit: Sparse vegetation, Sparse vegetation

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctostaphylos rubra* | | - | - | 7 |
| Bare ground | 100 | - | - | 25 |
| *Betula glandulosa* | | - | - | 4 |
| *Carex aquatilis* subsp. *stans* | 1 | - | - | |
| *Carex krausei* | | - | - | 4 |
| *Castilleja raupii* | | - | - | 1 |
| *Descurainia sophioides* | 1 | - | - | |
| *Empetrum nigrum* | | - | - | 1 |
| *Juncus balticus* subsp. *alaskanus* | | - | - | 1 |
| Litter | | - | - | 30 |
| Moss | | - | - | 40 |
| *Puccinellia* spp. | 1 | - | - | |
| *Salix alaxensis* | | - | - | 15 |
| *Tofieldia pusilla* | | - | - | 2 |

Site: 150W-50S

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 4 |
| *Artemisia tilesii* | - | - | - | 2 |
| *Betula glandulosa* | - | - | - | 45 |
| *Cassiope tetragona* | - | - | - | 2 |
| *Empetrum nigrum* | - | - | - | 7 |
| *Eriophorum vaginatum* | - | - | - | 10 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 5 |
| Litter | - | - | - | 6 |
| *Lupinus arcticus* | - | - | - | 7 |
| *Pyrola grandiflora* | - | - | - | 2 |
| *Salix arctica* | - | - | - | 4 |
| *Salix glauca* | - | - | - | 18 |
| *Salix pulchra* | - | - | - | 6 |
| *Vaccinium vitis-idaea* | - | - | - | 10 |

Site: 100W-50S

Vegetation unit: Grass, Tall Salix alaxensis grass and birch

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | 1 | 10 | 90 | 5 |
| *Artemisia tilesii* | 7 | 5 | 10 | 3 |
| Bare ground | 35 | 20 | | 7 |
| *Betula glandulosa* | | | 10 | 9 |
| *Bistorta vivipara* | | | 1 | |
| *Calamagrostis stricta* subsp. *stricta* | | | | 15 |
| *Carex aquatilis* subsp. *stans* | 1 | | | 1 |
| *Deschampsia caespitosa* | | 5 | | |
| *Draba glabella* | 1 | 1 | | |
| *Empetrum nigrum* | | 1 | | |
| *Equisetum arvense* | | | | 2 |
| Litter | | | | 45 |
| *Matricaria ambigua* | | 1 | | |
| Moss | 1 | 40 | | 4 |
| *Parnassia kotzebuei* | | | 1 | 1 |
| *Poa* spp. | 3 | 5 | | |
| *Puccinellia* spp. | 55 | 25 | | |
| *Salix alaxensis* | | | 1 | |
| *Salix arctica* | | | | 4 |
| *Salix glauca* | 1 | 5 | 2 | 7 |
| *Salix lanata* | | | 1 | |
| *Salix ovalifolia* var. *arctolitoralis* | | | 1 | |
| *Salix pulchra* | | 2 | 1 | 3 |
| *Senecio congestus* | 1 | | | |
| *Stellaria crassifolia* | | | 5 | |
| *Stellaria longipes* s.l. | 1 | 20 | | |

Site: 50W-50S

Vegetation unit: Sedge, Sedge

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | 2 | - | - | 2 |
| *Arctophila fulva* | 4 | - | - | |
| Bare ground | 70 | - | - | 5 |
| *Carex aquatilis* subsp. *stans* | | - | - | 35 |
| *Descurainia sophioides* | 10 | - | - | |
| *Equisetum arvense* | | - | - | 3 |
| Litter | | - | - | 55 |
| *Puccinellia* spp. | 15 | - | - | |
| *Salix glauca* | | - | - | 5 |
| *Salix pulchra* | | - | - | 8 |
| *Senecio congestus* | 10 | - | - | |
| *Suaeda calceoliformis* | 5 | - | - | |

Site: 50E-50S

Vegetation unit: Bare ground, Bare ground

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctophila fulva* | | - | - | 1 |
| Bare ground | 100 | - | - | 98 |
| *Equisetum arvense* | | - | - | 1 |

Site: 100E-50S

Vegetation unit: Tall Willow, Low Salix alaxensis

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | | | 35 | 25 |
| *Artemisia tilesii* | | | 1 | |
| Bare ground | 100 | 95 | 5 | 5 |
| *Braya humilis* | | 1 | | |
| *Calamagrostis stricta* subsp. *stricta* | | | 5 | |
| *Carex aquatilis* subsp. *stans* | | | 1 | |
| *Cochlearia officinalis* | | | 1 | |
| *Deschampsia caespitosa* | | | 10 | |
| *Descurainia sophioides* | | 1 | | |
| *Draba glabella* | | | 1 | |
| *Epilobium latifolium* | | 2 | 2 | |
| *Equisetum arvense* | | | | 4 |
| *Juncus balticus* subsp. *alaskanus* | | | 2 | 2 |
| Litter | | | | 55 |
| *Matricaria ambigua* | | | 5 | |
| Moss | | | 10 | 7 |
| *Poa* spp. | | | 1 | |
| *Puccinellia* spp. | | 1 | 5 | |
| *Salix alaxensis* | | | 1 | 12 |
| *Senecio congestus* | | | 1 | |
| *Stellaria crassifolia* | | | 30 | |
| *Stellaria longipes* s.l. | | | 1 | |

Site: 150E-50S

Vegetation unit: Sparse vegetation, Sparse vegetation

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | | | - | 3 |
| *Arctostaphylos rubra* | | | - | 3 |
| *Artemisia tilesii* | | 2 | - | 2 |
| Bare ground | 95 | 15 | - | 50 |
| *Braya humilis* | | 1 | - | |
| *Castilleja raupii* | | | - | 7 |
| *Deschampsia caespitosa* | | 1 | - | |
| *Descurainia sophioides* | 2 | | - | |
| *Draba glabella* | | 2 | - | |
| *Dryas integrifolia* | | | - | 5 |
| *Epilobium latifolium* | | 80 | - | |
| *Festuca* spp. | | 5 | - | |
| *Matricaria ambigua* | | 1 | - | |
| Moss | | | - | 30 |
| *Oxytropis campestris* | | | - | 12 |
| *Parnassia kotzebuei* | | | - | 2 |
| *Poa arctica* | | | - | 1 |
| *Puccinellia* spp. | 3 | 1 | - | |
| *Salix alaxensis* | | | - | 10 |
| *Salix glauca* | | 1 | - | |
| *Salix reticulata* | | | - | 2 |
| *Stellaria longipes* s.l. | | 1 | - | |

Site: 200E-50S

Vegetation unit: Low Willow, Salix glauca and grass

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Artemisia tilesii* | - | - | - | 3 |
| Bare ground | - | - | - | 2 |
| *Betula glandulosa* | - | - | - | 2 |
| *Carex aquatilis* subsp. *stans* | - | - | - | 1 |
| *Castilleja raupii* | - | - | - | 1 |
| *Deschampsia caespitosa* | - | - | - | 3 |
| *Dryas integrifolia* | - | - | - | 6 |
| Lichen | - | - | - | 30 |
| *Lupinus arcticus* | - | - | - | 1 |
| Moss | - | - | - | 17 |
| *Poa arctica* | - | - | - | 1 |
| *Salix alaxensis* | - | - | - | 6 |
| *Salix arctica* | - | - | - | 5 |
| *Salix reticulata* | - | - | - | 2 |
| *Stellaria crassifolia* | - | - | - | 1 |

Site: 150W-100S

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctostaphylos rubra* | - | - | - | 6 |
| Bare ground | - | - | - | 5 |
| *Betula glandulosa* | - | - | - | 30 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 9 |
| *Cassiope tetragona* | - | - | - | 11 |
| *Dryas integrifolia* | - | - | - | 1 |
| *Empetrum nigrum* | - | - | - | 20 |
| *Epilobium angustifolium* | - | - | - | 2 |
| *Eriophorum vaginatum* | - | - | - | 4 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 2 |
| Lichen | - | - | - | 5 |
| Litter | - | - | - | 12 |
| *Lupinus arcticus* | - | - | - | 5 |
| Moss | - | - | - | 7 |
| *Pyrola grandiflora* | - | - | - | 2 |
| *Rubus chamaemorus* | - | - | - | 2 |
| *Salix glauca* | - | - | - | 9 |
| *Vaccinium uliginosum* | - | - | - | 1 |
| *Vaccinium vitis-idaea* | - | - | - | 7 |

Site: 100W-100S

Vegetation unit: Grass, Tall Salix alaxensis grass and birch

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 5 |
| Bare ground | - | - | - | 4 |
| *Betula glandulosa* | - | - | - | 15 |
| *Calamagrostis stricta* | - | - | - | 1 |
| *Carex aquatilis* subsp. *stans* | - | - | - | 21 |
| *Empetrum nigrum* | - | - | - | 10 |
| *Equisetum arvense* | - | - | - | 15 |
| Litter | - | - | - | 35 |
| *Salix arctica* | - | - | - | 7 |
| *Salix glauca* | - | - | - | 17 |

Site: 50W-100S

Vegetation unit: Sedge, Sedge

| **Vegetation** | **1985** | **1993** | **2001** | **2016** |
|---|---|---|---|---|
| *Alopecurus alpinus* | | 1 | | |
| *Arctagrostis latifolia* | | 30 | | |
| *Arctophila fulva* | 40 | | 1 | |
| *Artemisia tilesii* | 1 | 2 | | |
| Bare ground | 70 | 5 | | |
| *Calamagrostis stricta* | | | | 1 |
| *Carex aquatilis* subsp. *stans* | | 1 | 1 | 90 |
| *Carex saxatilis* | | 1 | | |
| *Cochlearia officinalis* | | 2 | | |
| *Deschampsia caespitosa* | | 1 | | |
| *Equisetum arvense* | | 40 | | |
| *Eriophorum angustifolium* | | 1 | | |
| Litter | | | | 15 |
| *Matricaria ambigua* | 2 | 2 | | |
| *Poa* spp. | | 15 | | 1 |
| *Puccinellia* spp. | | 1 | | |
| *Ranunculus gmelinii* | | | 1 | 3 |
| *Salix alaxensis* | | | 1 | |
| *Salix glauca* | | 1 | | |
| *Salix lanata* | | 1 | | |
| *Salix ovalifolia* var. *arctolitoralis* | | 1 | | |
| *Salix pulchra* | | 1 | 1 | |
| *Senecio congestus* | 40 | 1 | | |
| *Silene uralensis* | | 1 | | |
| *Stellaria crassifolia* | | 20 | | 1 |

Site: 50E-100S

Vegetation unit: Bare ground, Bare ground

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctophila fulva* | - | - | - | 3 |
| Bare ground | - | - | - | 90 |
| *Carex aquatilis* subsp. *stans* | - | - | - | 2 |
| *Deschampsia caespitosa* | - | - | - | 3 |
| *Epilobium palustre* | - | - | - | 1 |
| *Eriophorum scheuchzeri* | - | - | - | 1 |
| Litter | - | - | - | 1 |
| *Ranunculus gmelinii* | - | - | - | 1 |

Site: 100E-100S

Vegetation unit: Sparse vegetation, Sparse vegetation

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| Bare ground | - | - | - | 27 |
| *Castilleja raupii* | - | - | - | 2 |
| *Juncus balticus* subsp. *alaskanus* | - | - | - | 2 |
| Lichen | - | - | - | 10 |
| Litter | - | - | - | 40 |
| Moss | - | - | - | 4 |
| *Poa arctica* | - | - | - | 4 |
| *Salix alaxensis* | - | - | - | 5 |
| *Salix arctica* | - | - | - | 15 |
| *Salix glauca* | - | - | - | 20 |

Site: 150E-100S

Vegetation unit: Low Willow, Salix glauca and grass

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | 15 | 15 | |
| *Artemisia tilesii* | - | 1 | 1 | |
| Bare ground | - | 40 | 5 | |
| *Betula glandulosa* | - | | 1 | 6 |
| *Bistorta vivipara* | - | | 1 | |
| *Calamagrostis stricta* subsp. *stricta* | - | | 5 | |
| *Carex aquatilis* subsp. *stans* | - | | | 2 |
| *Castilleja raupii* | - | 1 | 1 | |
| *Deschampsia caespitosa* | - | 5 | 5 | |
| *Empetrum nigrum* | - | | 1 | 4 |
| *Eriophorum vaginatum* | - | | | 1 |
| *Festuca* spp. | - | 1 | | |
| *Juncus balticus* subsp. *alaskanus* | - | | 1 | |
| Litter | - | | | 40 |
| *Matricaria ambigua* | - | 10 | | |
| Moss | - | 60 | 10 | 20 |
| *Pedicularis sudetica* | - | | 1 | 2 |
| *Poa arctica* | - | | | 6 |
| *Poa* spp. | - | 5 | 15 | |
| *Puccinellia* spp. | - | 30 | | |
| *Salix alaxensis* | - | | 5 | 5 |
| *Salix arctica* | - | | 15 | |
| *Salix glauca* | - | | 10 | 5 |
| *Salix lanata* | - | | 10 | |
| *Salix niphoclada* | - | | 1 | |
| *Salix ovalifolia* var. *arctolitoralis* | - | 1 | 1 | |
| *Salix pulchra* | - | | 10 | 15 |
| *Silene uralensis* | - | 1 | | |
| *Trisetum spicatum* | - | 1 | 1 | |

Site: 200E-100S

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 2 |
| *Arctostaphylos rubra* | - | - | - | 4 |
| Bare ground | - | - | - | 12 |
| *Betula glandulosa* | - | - | - | 3 |
| *Cassiope tetragona* | - | - | - | 8 |
| *Dryas integrifolia* | - | - | - | 1 |
| *Empetrum nigrum* | - | - | - | 24 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 4 |
| Lichen | - | - | - | 2 |
| Litter | - | - | - | 5 |
| *Lupinus arcticus* | - | - | - | 28 |
| Moss | - | - | - | 2 |
| *Pedicularis sudetica* | - | - | - | 1 |
| *Pyrola grandiflora* | - | - | - | 4 |
| *Salix glauca* | - | - | - | 5 |
| *Vaccinium uliginosum* | - | - | - | 4 |
| *Vaccinium vitis-idaea* | - | - | - | 2 |

Site: 150W-150S

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 1 |
| *Arctostaphylos rubra* | - | - | - | 2 |
| Bare ground | - | - | - | 2 |
| *Betula glandulosa* | - | - | - | 30 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 2 |
| *Cassiope tetragona* | - | - | - | 7 |
| *Dryas integrifolia* | - | - | - | 2 |
| *Empetrum nigrum* | - | - | - | 13 |
| *Eriophorum vaginatum* | - | - | - | 5 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 2 |
| Litter | - | - | - | 20 |
| Moss | - | - | - | 10 |
| *Pedicularis sudetica* | - | - | - | 1 |
| *Petasites frigidus* | - | - | - | 8 |
| *Poa arctica* | - | - | - | 1 |
| *Pyrola grandiflora* | - | - | - | 2 |
| *Rubus chamaemorus* | - | - | - | 2 |
| *Salix arctica* | - | - | - | 2 |
| *Salix glauca* | - | - | - | 10 |
| *Vaccinium vitis-idaea* | - | - | - | 20 |

Site: 100W-150S

Vegetation unit: Grass, Tall Salix alaxensis grass and birch

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | | 10 | 70 | 27 |
| *Artemisia tilesii* | | 1 | 10 | 1 |
| Bare ground | 35 | | | |
| *Carex aquatilis* subsp. *stans* | | 1 | | |
| *Cochlearia officinalis* | | 1 | | |
| *Descurainia sophioides* | 15 | | | |
| *Draba glabella* | | 2 | | |
| *Juncus castaneus* | | | 1 | |
| *Kobresia myosuroides* | | | | 1 |
| Litter | | | | 70 |
| *Matricaria ambigua* | | 2 | | |
| *Parnassia kotzebuei* | | | 1 | 1 |
| *Pedicularis sudetica* | | | | 1 |
| *Poa* spp. | | 1 | 10 | |
| *Puccinellia* spp. | 50 | 65 | 2 | |
| *Pyrola grandiflora* | | | | 1 |
| *Salix alaxensis* | | | 1 | |
| *Salix arctica* | | | 1 | |
| *Salix glauca* | | | 15 | 30 |
| *Salix ovalifolia* var. *arctolitoralis* | | | 1 | |
| *Salix pulchra* | | | 1 | 3 |
| *Senecio congestus* | | 1 | | |
| *Silene uralensis* | | 1 | | |
| *Stellaria crassifolia* | | 1 | 5 | |
| *Stellaria longipes s.l.* | | 40 | 1 | |
| *Trisetum spicatum* | | | 1 | |

Site: 50W-150S

Vegetation unit: Grass, Tall Salix alaxensis grass and birch

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | | 2 | | 4 |
| *Arctophila fulva* | 1 | | | |
| *Arctostaphylos rubra* | | | | 2 |
| *Artemisia tilesii* | | 2 | 10 | 1 |
| Bare ground | 75 | 30 | | |
| *Betula glandulosa* | | | 1 | 1 |
| *Calamagrostis stricta* subsp. *stricta* | | 2 | 60 | |
| *Carex aquatilis* subsp. *stans* | 2 | 5 | 2 | |
| *Carex capillaris* | 1 | | | |
| *Castilleja raupii* | | | 1 | |
| *Cerastium beeringianum* | | | 1 | |
| *Cochlearia officinalis* | | 20 | | |
| *Deschampsia caespitosa* | | 2 | 10 | |
| *Descurainia sophioides* | 20 | | | |
| *Draba glabella* | | 5 | | |
| *Dupontia fisheri* | | | | 7 |
| *Empetrum nigrum* | | | | 3 |
| *Equisetum arvense* | | | 1 | |
| *Juncus balticus* subsp. *alaskanus* | | | | 1 |
| Litter | | | | 60 |
| *Matricaria ambigua* | | 10 | | |
| *Moss* | | | 30 | |
| *Parnassia kotzebuei* | | | 1 | 1 |
| *Poa* spp. | | | 1 | |
| *Puccinellia* spp. | 5 | 5 | | |
| *Salix alaxensis* | | | | 3 |
| *Salix glauca* | | 1 | 30 | |
| *Salix lanata* | | | | 35 |
| *Salix ovalifolia* var. *arctolitoralis* | | 2 | | |
| *Salix pulchra* | | | | 2 |
| *Senecio congestus* | | 1 | 1 | |
| *Silene uralensis* | | 2 | 1 | |
| *Stellaria crassifolia* | | 10 | 5 | |
| *Stellaria longipes* s.l. | | 5 | | |
| *Trisetum spicatum* | | | 1 | |

Site: 0-150S

Vegetation unit: Tall Willow, Low Salix alaxensis

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 30 |
| *Arctophila fulva* | - | - | - | 3 |
| *Artemisia tilesii* | - | - | - | 5 |
| *Betula glandulosa* | - | - | - | 2 |
| *Dupontia fisheri* | - | - | - | 2 |
| *Empetrum nigrum* | - | - | - | 1 |
| *Eriophorum scheuchzeri* | - | - | - | 1 |
| Litter | - | - | - | 45 |
| *Parnassia kotzebuei* | - | - | - | 1 |
| *Salix alaxensis* | - | - | - | 18 |
| *Salix pulchra* | - | - | - | 3 |

Site: 50E-150S

Vegetation unit: Tall Willow, Low Salix alaxensis

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | | | 15 | 5 |
| *Artemisia tilesii* | | | 10 | 3 |
| *Bare ground* | 99 | 100 | 5 | 5 |
| *Betula glandulosa* | | | | 2 |
| *Castilleja raupii* | | | | 2 |
| *Deschampsia caespitosa* | | | 5 | |
| *Descurainia sophioides* | 1 | 1 | | |
| *Draba glabella* | | | 1 | |
| *Epilobium latifolium* | | 1 | 30 | |
| Litter | | | | 7 |
| *Matricaria ambigua* | | 1 | 1 | |
| Moss | | | 15 | 10 |
| *Oxytropis campestris* | | | | 1 |
| *Poa arctica* | | | | 45 |
| *Poa* spp. | | | 2 | |
| *Puccinellia* spp. | | 1 | 35 | |
| *Salix alaxensis* | | | | 20 |
| *Salix arctica* | | | | 3 |
| *Stellaria crassifolia* | | | 15 | |
| *Stellaria longipes* s.l. | | | 2 | |

Site: 100E-150S

Vegetation unit: Grass, Dry grass

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | | 1 | | 10 |
| *Artemisia tilesii* | | | 15 | 1 |
| *Astragalus alpinus* | | | 10 | |
| Bare ground | 100 | 95 | 50 | 25 |
| *Calamagrostis stricta* | | | | 3 |
| *Castilleja raupii* | | | 1 | |
| *Cochlearia officinalis* | | 1 | | |
| *Deschampsia caespitosa* | | 1 | | |
| *Descurainia sophioides* | 1 | 1 | | |
| *Draba glabella* | 1 | 1 | 1 | |
| *Epilobium latifolium* | | 1 | 1 | |
| *Equisetum arvense* | | | | 2 |
| *Juncus balticus* subsp. *alaskanus* | | | | 2 |
| Lichen | | | | 3 |
| Litter | | | | 30 |
| *Matricaria ambigua* | | 1 | 1 | |
| Moss | | | 5 | |
| *Parnassia kotzebuei* | | | | 1 |
| *Poa* spp. | | | | 4 |
| *Puccinellia* spp. | 1 | 5 | 30 | |
| *Salix alaxensis* | | | | 3 |
| *Salix arctica* | | | | 7 |
| *Stellaria longipes* s.l. | | | 1 | |

Site: 150E-150S

Vegetation unit: Tall Willow, Tall Salix alaxensis and glauca

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Amerorchis rotundifolia* | | | | 1 |
| *Arctagrostis latifolia* | | 50 | 40 | |
| *Arctagrostis latifolia* subsp. *arundinaceus* | | | | 5 |
| *Artemisia tilesii* | | 10 | 2 | |
| Bare ground | 60 | | | 4 |
| *Betula glandulosa* | | | 1 | 4 |
| *Bistorta vivipara* | | 1 | | |
| *Calamagrostis stricta* subsp. *stricta* | | 1 | | |
| *Carex aquatilis* subsp. *stans* | 8 | 5 | 40 | 8 |
| *Castilleja raupii* | | 1 | 1 | |
| *Cochlearia officinalis* | | 1 | | |
| *Deschampsia caespitosa* | | 10 | | |
| *Descurainia sophioides* | 7 | | | |
| *Draba glabella* | | 1 | | |
| *Dupontia fisheri* | | | | 6 |
| *Empetrum nigrum* | | | 1 | 3 |
| *Equisetum arvense* | | 2 | 1 | 20 |
| *Festuca* spp. | 2 | 15 | | |
| *Juncus balticus* subsp. *alaskanus* | | | | 2 |
| Litter | | | | 28 |
| *Matricaria ambigua* | 1 | 1 | | |
| Moss | | 40 | | 5 |
| *Parnassia kotzebuei* | | | 1 | |
| *Pedicularis sudetica* | | 1 | 2 | 1 |
| *Poa* spp. | | 1 | | |
| *Puccinellia* spp. | 25 | | | |
| *Pyrola grandiflora* | | | 1 | |
| *Salix alaxensis* | | | 1 | |
| *Salix arbusculoides* | | | 1 | |
| *Salix arctica* | | 1 | 1 | |
| *Salix glauca* | | 5 | 25 | 15 |
| *Salix lanata* | | 1 | 5 | 5 |
| *Salix pulchra* | | 1 | 10 | 15 |
| *Senecio congestus* | 2 | | | |
| *Silene uralensis* | | | 1 | |
| *Stellaria longipes* s.l. | | | 1 | |
| *Trisetum spicatum* | | 1 | | |
| *Vaccinium uliginosum* | | | | 3 |

Site: 150W-200S

Vegetation unit: Tundra, Tundra

| **Vegetation** | **1985** | **1993** | **2001** | **2016** |
|---|---|---|---|---|
| *Arctostaphylos rubra* | - | - | - | 5 |
| Bare ground | - | - | - | 6 |
| *Betula glandulosa* | - | - | - | 15 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 8 |
| *Dryas integrifolia* | - | - | - | 8 |
| *Empetrum nigrum* | - | - | - | 30 |
| *Kobresia myosuroides* | - | - | - | 2 |
| Lichen | - | - | - | 2 |
| Litter | - | - | - | 10 |
| *Lupinus arcticus* | - | - | - | 5 |
| *Luzula nivalis* | - | - | - | 2 |
| *Petasites frigidus* | - | - | - | 6 |
| *Pyrola grandiflora* | - | - | - | 2 |
| *Salix glauca* | - | - | - | 4 |
| *Vaccinium uliginosum* | - | - | - | 10 |

Site: 100W-200S

Vegetation unit: Grass, Tall Salix alaxensis grass and birch

| **Vegetation** | **1985** | **1993** | **2001** | **2016** |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 6 |
| *Betula glandulosa* | - | - | - | 3 |
| *Empetrum nigrum* | - | - | - | 2 |
| Litter | - | - | - | 60 |
| Moss | - | - | - | 50 |
| *Pedicularis sudetica* | - | - | - | 1 |
| *Salix arctica* | - | - | - | 20 |
| *Salix glauca* | - | - | - | 25 |

Site: 50W-200S

Vegetation unit: Grass, Tall Salix alaxensis grass and birch

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | | 25 | 50 | 8 |
| *Arctostaphylos rubra* | | | 1 | |
| *Artemisia tilesii* | 1 | 15 | 15 | |
| Bare ground | 70 | | | |
| *Betula glandulosa* | | | 1 | 23 |
| *Carex aquatilis* subsp. *stans* | | 1 | 2 | 5 |
| *Carex bigelowii* subsp. *lugens* | | 1 | | |
| *Carex maritima* | | 1 | 1 | |
| *Castilleja raupii* | | | 1 | 1 |
| *Cerastium beeringianum* | | 1 | | |
| *Cochlearia officinalis* | | 1 | | |
| *Deschampsia caespitosa* | | | 1 | |
| *Descurainia sophioides* | 25 | | | |
| *Draba glabella* | | 1 | | |
| *Empetrum nigrum* | | | 15 | 23 |
| *Festuca* spp. | | 1 | 5 | |
| *Juncus balticus* subsp. *alaskanus* | | 1 | | |
| *Ledum palustre* subsp. *decumbens* | | | | 2 |
| Litter | | | | 20 |
| *Matricaria ambigua* | 2 | | | |
| Moss | | 25 | 35 | 12 |
| *Parnassia kotzebuei* | | | 1 | 1 |
| *Poa* spp. | | | 1 | |
| *Puccinellia* spp. | 5 | 25 | | |
| *Pyrola grandiflora* | | | | 2 |
| *Salix arctica* | | | 2 | |
| *Salix glauca* | | 1 | 10 | 10 |
| *Salix lanata* | | | 1 | |
| *Salix ovalifolia* var. *arctolitoralis* | | | 1 | |
| *Salix pulchra* | | | 1 | 2 |
| *Stellaria longipes* s.l. | | 15 | 20 | |
| *Trisetum spicatum* | | 5 | 10 | |
| *Vaccinium uliginosum* | | | | 2 |
| *Vaccinium vitis-idaea* | | | | 1 |

Site: 0-200S

Vegetation unit: Grass, Dry grass

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 20 |
| *Artemisia tilesii* | - | - | - | 6 |
| *Calamagrostis stricta* subsp. *stricta* | - | - | - | 10 |
| *Carex aquatilis* subsp. *stans* | - | - | - | 1 |
| *Carex maritima* | - | - | - | 1 |
| *Castilleja raupii* | - | - | - | 1 |
| Litter | - | - | - | 65 |
| *Parnassia kotzebuei* | - | - | - | 2 |
| *Senecio tundricola* | - | - | - | 2 |

Site: 50E-200S

Vegetation unit: Grass, Dry Grass

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | | 5 | 10 | |
| *Artemisia tilesii* | | 10 | 10 | 5 |
| Bare ground | 95 | 15 | | 2 |
| *Calamagrostis stricta* | | | | 1 |
| *Calamagrostis stricta* subsp. *stricta* | | | 60 | |
| *Carex aquatilis* subsp. *stans* | 3 | 25 | 1 | |
| *Cochlearia officinalis* | | 10 | 35 | |
| *Deschampsia caespitosa* | 1 | 10 | 20 | |
| *Descurainia sophioides* | | 2 | | |
| *Empetrum nigrum* | | | | 3 |
| Litter | 5 | | | 70 |
| *Matricaria ambigua* | | 2 | | |
| Moss | | | 15 | |
| *Parnassia kotzebuei* | | | 2 | 1 |
| *Poa* spp. | | 1 | | |
| *Puccinellia* spp. | 3 | 20 | | |
| *Salix alaxensis* | | | | 4 |
| *Salix arbusculoides* | | | | 5 |
| *Salix glauca* | | | | 8 |
| *Stellaria crassifolia* | | 1 | | 1 |
| *Suaeda calceoliformis* | | 1 | | |

Site: 100E-200S

Vegetation unit: Tall Willow, Sedge

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | | 10 | | 5 |
| *Arctophila fulva* | | 1 | | |
| *Artemisia tilesii* | | | 1 | |
| Bare ground | 95 | 20 | 15 | 5 |
| *Calamagrostis stricta* subsp. *stricta* | | 5 | 10 | |
| *Carex aquatilis* subsp. *stans* | | 5 | 30 | 10 |
| *Carex bigelowii* subsp. *lugens* | | 1 | | |
| *Carex saxatilis* | | | 1 | |
| *Deschampsia caespitosa* | | 10 | 2 | |
| *Dupontia fisheri* | | 1 | | |
| *Equisetum arvense* | | 15 | 20 | 3 |
| *Eriophorum scheuchzeri* | | 2 | 20 | |
| *Juncus balticus* subsp. *alaskanus* | | 1 | 5 | |
| Litter | | | | 75 |
| Moss | | 1 | | |
| *Parnassia kotzebuei* | | | 1 | |
| *Poa* spp. | | 20 | 30 | 1 |
| *Puccinellia* spp. | 2 | 10 | | |
| *Ranunculus cymbalaria* | | 1 | | |
| *Salix alaxensis* | | 1 | 5 | 4 |
| *Salix arctica* | | 5 | 15 | |
| *Salix glauca* | | | | |
| *Salix lanata* | | 1 | | |
| *Salix planifolia* | | | 5 | |
| *Senecio congestus* | 2 | | 1 | |
| *Stellaria crassifolia* | | 5 | | |

Site: 150E-200S

Vegetation unit: Tall Willow, Tall Salix alaxensis and glauca

| **Vegetation** | **1985** | **1993** | **2001** | **2016** |
|---|---|---|---|---|
| *Alopecurus alpinus* | | 1 | - | |
| *Arctagrostis latifolia* | 2 | 10 | - | 3 |
| *Artemisia tilesii* | 1 | 1 | - | |
| Bare ground | 85 | 30 | - | 10 |
| *Betula glandulosa* | | 1 | - | 17 |
| *Calamagrostis stricta* subsp. *stricta* | | 1 | - | |
| *Carex aquatilis* subsp. *stans* | 3 | 1 | - | 1 |
| *Carex atrofusca* | | 1 | - | |
| *Carex bigelowii* subsp. *lugens* | | 1 | - | |
| *Carex capillaris* | | 1 | - | |
| *Castilleja raupii* | | 5 | - | |
| *Draba glabella* | 2 | | - | |
| *Empetrum nigrum* | | 1 | - | |
| *Equisetum arvense* | | | - | 60 |
| *Festuca* spp. | 1 | | - | |
| Litter | | | - | 30 |
| *Luzula arctica subsp. arctica* | | 2 | - | |
| Moss | 5 | 20 | - | |
| *Pedicularis sudetica* | | 2 | - | |
| *Puccinellia* spp. | 1 | 2 | - | |
| *Pyrola grandiflora* | | 1 | - | |
| *Salix arctica* | | 5 | - | |
| *Salix glauca* | 4 | 35 | - | 7 |
| *Salix lanata* | 2 | 1 | - | |
| *Salix pulchra* | | 1 | - | |
| *Salix reticulata* | | | - | 1 |
| *Saxifraga hirculus* | 1 | 1 | - | |
| *Stellaria longipes* s.l. | 1 | 5 | - | |
| *Trisetum spicatum* | | 1 | - | |
| *Vaccinium uliginosum* | | 1 | - | 3 |

Site: 200E-200S

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctostaphylos rubra* | - | - | - | 1 |
| Bare ground | - | - | - | 5 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 1 |
| *Carex krausei* | - | - | - | 2 |
| *Cassiope tetragona* | - | - | - | 8 |
| *Dryas integrifolia* | - | - | - | 21 |
| *Empetrum nigrum* | - | - | - | 11 |
| Lichen | - | - | - | 1 |
| Litter | - | - | - | 4 |
| *Lupinus arcticus* | - | - | - | 19 |
| Moss | - | - | - | 5 |
| *Pedicularis capitata* | - | - | - | 1 |
| *Pedicularis sudetica* | - | - | - | 2 |
| *Pyrola grandiflora* | - | - | - | 2 |
| *Salix glauca* | - | - | - | 15 |
| *Saussurea angustifolia* subsp. *angustifolia* | - | - | - | 1 |
| *Senecio atropurpureus* | - | - | - | 1 |
| *Vaccinium uliginosum* | - | - | - | 10 |

Site: 150W-250S

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 3 |
| *Arctostaphylos rubra* | - | - | - | 2 |
| Bare ground | - | - | - | 20 |
| *Betula glandulosa* | - | - | - | 20 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 12 |
| *Empetrum nigrum* | - | - | - | 30 |
| Lichen | - | - | - | 3 |
| Litter | - | - | - | 10 |
| *Lupinus arcticus* | - | - | - | 3 |
| *Salix glauca* | - | - | - | 18 |
| *Vaccinium vitis-idaea* | - | - | - | 2 |

Site: 100W-250S

Vegetation unit: Tall Willow, Tall Salix alaxensis and glauca

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Alopecurus alpinus* | | 1 | 1 | |
| *Arctagrostis latifolia* | 20 | 20 | 45 | 30 |
| *Arctophila fulva* | 2 | | | |
| *Artemisia tilesii* | 1 | 15 | 10 | 2 |
| *Astragalus alpinus* | | | 1 | |
| Bare ground | 60 | | | |
| *Betula glandulosa* | | 1 | 1 | 15 |
| *Calamagrostis stricta* subsp. *stricta* | | 1 | 1 | |
| *Carex aquatilis* subsp. *stans* | | 1 | | |
| *Carex bigelowii* subsp. *lugens* | | 1 | 10 | |
| *Castilleja raupii* | | 1 | 2 | |
| *Deschampsia caespitosa* | 1 | 5 | | |
| *Empetrum nigrum* | | | 1 | 4 |
| *Festuca* spp. | | 1 | 5 | |
| Litter | | | | 60 |
| *Luzula arctica* subsp. *arctica* | | | 1 | |
| *Matricaria ambigua* | 1 | | | |
| Moss | | 50 | 2 | |
| *Poa* spp. | 5 | 50 | 1 | |
| *Puccinellia* spp. | 7 | | | |
| *Pyrola grandiflora* | | | | 5 |
| *Salix arbusculoides* | | | | 2 |
| *Salix glauca* | 1 | 10 | 35 | 25 |
| *Salix pulchra* | | 1 | 1 | |
| *Stellaria longipes* s.l. | 5 | 10 | 5 | |
| *Trisetum spicatum* | 1 | 2 | | |

Site: 50W-250S

Vegetation unit: Tall Willow, Tall Salix alaxensis and glauca

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Alopecurus alpinus* | | | 1 | |
| *Arctagrostis latifolia* | 5 | 80 | 75 | |
| *Arctophila fulva* | 5 | | | |
| *Artemisia tilesii* | 1 | 2 | 2 | 1 |
| Bare ground | 40 | | | |
| *Calamagrostis stricta* subsp. *stricta* | | | 1 | 2 |
| *Carex aquatilis* subsp. *stans* | 5 | | 15 | |
| *Castilleja raupii* | | 1 | | |
| *Cochlearia officinalis* | | 2 | | |
| *Deschampsia caespitosa* | 15 | 10 | | |
| *Descurainia sophioides* | 5 | | | |
| *Equisetum arvense* | | 1 | 10 | 75 |
| *Festuca rubra* subsp. *Arctica* | | | | 6 |
| Litter | | | | 30 |
| *Matricaria ambigua* | 1 | 1 | | |
| Moss | | 1 | | |
| *Parnassia kotzebuei* | | | 1 | |
| *Pedicularis sudetica* | | | 1 | |
| *Poa* spp. | | 1 | 1 | |
| *Puccinellia* spp. | 25 | 1 | | |
| *Pyrola grandiflora* | | | | 2 |
| *Salix alaxensis* | | 1 | 1 | |
| *Salix glauca* | | 1 | 5 | 8 |
| *Salix lanata* | | | 1 | |
| *Salix niphoclada* | | | 5 | |
| *Salix ovalifolia* var. *arctolitoralis* | | 1 | | |
| *Salix pulchra* | | 1 | 1 | 4 |
| *Stellaria longipes* s.l. | 1 | 5 | 5 | |
| *Trisetum spicatum* | | 1 | | |

Site: 0-250S

Vegetation unit: Tall Willow, Tall Salix alaxensis and glauca

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Betula glandulosa* | - | - | - | 2 |
| *Calamagrostis stricta* | - | - | - | 3 |
| *Carex aquatilis* subsp. *stans* | - | - | - | 4 |
| *Castilleja raupii* | - | - | - | 1 |
| Lichen | - | - | - | 2 |
| Litter | - | - | - | 27 |
| Moss | - | - | - | 50 |
| *Oxytropis campestris* | - | - | - | 5 |
| *Pyrola grandiflora* | - | - | - | 6 |
| *Salix glauca* | - | - | - | 25 |

Site: 50E-250S

Vegetation unit: Alder, Alder

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Alnus viridis* subsp. *crispa* | | - | - | 35 |
| *Arctagrostis latifolia* | 40 | - | - | |
| *Arctophila fulva* | 2 | - | - | |
| *Arctostaphylos rubra* | | - | - | 1 |
| *Artemisia tilesii* | 20 | - | - | 3 |
| Bare ground | 5 | - | - | |
| *Calamagrostis stricta* | | - | - | 8 |
| *Calamagrostis stricta* subsp. *stricta* | 2 | - | - | |
| *Carex aquatilis* subsp. *stans* | 8 | - | - | |
| Litter | | - | - | 90 |
| *Lomatogonium rotatum* | 1 | - | - | |
| *Matricaria ambigua* | 1 | - | - | |
| Moss | 1 | - | - | |
| *Pedicularis sudetica* | | - | - | 3 |
| *Puccinellia* spp. | 15 | - | - | |
| *Salix glauca* | 10 | - | - | |
| *Salix pulchra* | | - | - | 20 |

Site: 100E-250S

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Alnus viridis* subsp. *crispa* | - | - | - | 12 |
| *Arctostaphylos rubra* | - | - | - | 4 |
| Bare ground | - | - | - | 3 |
| *Betula glandulosa* | - | - | - | 8 |
| *Calamagrostis stricta* subsp. *stricta* | - | - | - | 1 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 9 |
| *Cassiope tetragona* | - | - | - | 17 |
| *Dryas integrifolia* | - | - | - | 1 |
| *Empetrum nigrum* | - | - | - | 2 |
| *Eriophorum vaginatum* | - | - | - | 7 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 1 |
| Lichen | - | - | - | 1 |
| Litter | - | - | - | 7 |
| Moss | - | - | - | 18 |
| *Pedicularis capitata* | - | - | - | 1 |
| *Pyrola grandiflora* | - | - | - | 1 |
| *Rubus chamaemorus* | - | - | - | 1 |
| *Salix glauca* | - | - | - | 8 |
| *Salix pulchra* | - | - | - | 9 |
| *Salix reticulata* | - | - | - | 1 |
| *Vaccinium uliginosum* | - | - | - | 3 |
| *Vaccinium vitis-idaea* | - | - | - | 2 |

Site: 150E-250S

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctostaphylos rubra* | - | - | - | 2 |
| Bare ground | - | - | - | 12 |
| *Betula glandulosa* | - | - | - | 11 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 7 |
| *Cassiope tetragona* | - | - | - | 1 |
| *Empetrum nigrum* | - | - | - | 1 |
| *Eriophorum vaginatum* | - | - | - | 50 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 6 |
| Lichen | - | - | - | 1 |
| Litter | - | - | - | 15 |
| Moss | - | - | - | 20 |
| *Pyrola grandiflora* | - | - | - | 1 |
| *Rubus chamaemorus* | - | - | - | 2 |
| *Salix glauca* | - | - | - | 3 |
| *Salix pulchra* | - | - | - | 9 |
| *Tofieldia pusilla* | - | - | - | 1 |
| *Vaccinium vitis-idaea* | - | - | - | 3 |

Site: 100W-300S

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctostaphylos rubra* | - | - | - | 20 |
| *Betula glandulosa* | - | - | - | 35 |
| *Dryas integrifolia* | - | - | - | 40 |
| *Dupontia fisheri* | - | - | - | |
| *Empetrum nigrum* | - | - | - | 12 |
| *Eriophorum vaginatum* | - | - | - | 2 |
| Lichen | - | - | - | 3 |
| Litter | - | - | - | 10 |
| *Lupinus arcticus* | - | - | - | 6 |
| *Pedicularis sudetica* | - | - | - | 3 |
| *Poa arctica* | - | - | - | 2 |
| *Pyrola grandiflora* | - | - | - | 3 |
| *Salix glauca* | - | - | - | 20 |

Site: 50W-300S

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Anthoxanthum monticola* subsp. *alpinum* | - | - | - | 2 |
| *Arctagrostis latifolia* | - | - | - | 2 |
| *Arctostaphylos rubra* | - | - | - | 18 |
| Bare ground | - | - | - | 1 |
| *Betula glandulosa* | - | - | - | 4 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 4 |
| *Carex krausei* | - | - | - | 7 |
| *Deschampsia caespitosa* | - | - | - | 2 |
| *Empetrum nigrum* | - | - | - | 3 |
| *Eriophorum vaginatum* | - | - | - | 7 |
| Lichen | - | - | - | 1 |
| Litter | - | - | - | 8 |
| Moss | - | - | - | 6 |
| *Pedicularis capitata* | - | - | - | 1 |
| *Pyrola grandiflora* | - | - | - | 1 |
| *Rubus chamaemorus* | - | - | - | 1 |
| *Salix arctica* | - | - | - | 3 |
| *Salix glauca* | - | - | - | 21 |
| *Salix reticulata* | - | - | - | 1 |
| *Saussurea angustifolia* subsp. *angustifolia* | - | - | - | 1 |
| *Stellaria crassifolia* | - | - | - | 1 |
| *Tofieldia pusilla* | - | - | - | 1 |
| *Vaccinium uliginosum* | - | - | - | 2 |

Site: 50E-300S

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 3 |
| *Arctostaphylos rubra* | - | - | - | 2 |
| *Betula glandulosa* | - | - | - | 21 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 2 |
| *Cassiope tetragona* | - | - | - | 13 |
| *Dryas integrifolia* | - | - | - | 27 |
| Lichen | - | - | - | 1 |
| Litter | - | - | - | 7 |
| *Lupinus arcticus* | - | - | - | 1 |
| Moss | - | - | - | 3 |
| *Pedicularis capitata* | - | - | - | 1 |
| *Pedicularis sudetica* | - | - | - | 1 |
| *Petasites frigidus* | - | - | - | 2 |
| *Poa arctica* | - | - | - | 1 |
| *Pyrola grandiflora* | - | - | - | 2 |
| *Salix glauca* | - | - | - | 25 |
| *Saussurea angustifolia* subsp. *angustifolia* | - | - | - | 2 |
| *Vaccinium uliginosum* | - | - | - | 11 |

Site: T1

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Andromeda polifolia* | - | - | - | 1 |
| *Arctostaphylos rubra* | - | - | - | 10 |
| *Carex aquatilis* subsp. *stans* | - | - | - | 4 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 2 |
| *Dryas integrifolia* | - | - | - | 1 |
| *Empetrum nigrum* | - | - | - | 2 |
| *Equisetum arvense* | - | - | - | 7 |
| *Eriophorum vaginatum* | - | - | - | 2 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 1 |
| Litter | - | - | - | 3 |
| Moss | - | - | - | 95 |
| *Salix arctica* | - | - | - | 2 |
| *Salix lanata* | - | - | - | 8 |
| *Salix reticulata* | - | - | - | 3 |
| *Saxifraga hirculus* | - | - | - | 1 |
| *Tofieldia pusilla* | - | - | - | 2 |
| *Vaccinium vitis-idaea* | - | - | - | 1 |

Site: T2

Vegetation unit: Tundra, Tundra

| **Vegetation** | **1985** | **1993** | **2001** | **2016** |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 3 |
| *Arctostaphylos rubra* | - | - | - | 4 |
| Bare ground | - | - | - | 4 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 3 |
| *Cassiope tetragona* | - | - | - | 15 |
| *Dryas integrifolia* | - | - | - | 4 |
| *Eriophorum vaginatum* | - | - | - | 8 |
| Lichen | - | - | - | 2 |
| Litter | - | - | - | 5 |
| *Lupinus arcticus* | - | - | - | 5 |
| *Moss* | - | - | - | 70 |
| *Rubus chamaemorus* | - | - | - | 1 |
| *Salix glauca* | - | - | - | 16 |
| *Salix reticulata* | - | - | - | 2 |
| *Senecio atropurpureus* | - | - | - | 2 |

Site: T3

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
| --- | --- | --- | --- | --- |
| *Andromeda polifolia* | - | - | - | 1 |
| *Arctagrostis latifolia* | - | - | - | 2 |
| *Arctostaphylos rubra* | - | - | - | 3 |
| Bare ground | - | - | - | 3 |
| *Betula glandulosa* | - | - | - | 9 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 8 |
| *Cassiope tetragona* | - | - | - | 18 |
| *Eriophorum vaginatum* | - | - | - | 4 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 2 |
| Lichen | - | - | - | 4 |
| Litter | - | - | - | 5 |
| *Lupinus arcticus* | - | - | - | 1 |
| Moss | - | - | - | 25 |
| *Pyrola grandiflora* | - | - | - | 2 |
| *Salix arctica* | - | - | - | 6 |
| *Salix glauca* | - | - | - | 12 |
| *Saussurea angustifolia* subsp. *angustifolia* | - | - | - | 1 |
| *Senecio atropurpureus* | - | - | - | 1 |
| *Vaccinium uliginosum* | - | - | - | 2 |
| *Vaccinium vitis-idaea* | - | - | - | 3 |

Site: T4

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Betula glandulosa* | - | - | - | 20 |
| *Bistorta vivipara* | - | - | - | 1 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 16 |
| *Cassiope tetragona* | - | - | - | 20 |
| *Empetrum nigrum* | - | - | - | 2 |
| *Eriophorum vaginatum* | - | - | - | 6 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 2 |
| Lichen | - | - | - | 2 |
| Moss | - | - | - | 32 |
| Mushroom | - | - | - | 1 |
| *Pedicularis sudetica* | - | - | - | 1 |
| *Pyrola grandiflora* | - | - | - | 2 |
| *Salix glauca* | - | - | - | 10 |
| *Saussurea angustifolia* subsp. *Angustifolia* | - | - | - | 1 |
| *Stellaria crassifolia* | - | - | - | 1 |
| *Vaccinium vitis-idaea* | - | - | - | 11 |

Site: T5

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 1 |
| *Arctostaphylos rubra* | - | - | - | 2 |
| *Betula glandulosa* | - | - | - | 11 |
| *Bistorta vivipara* | - | - | - | 1 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 5 |
| *Cassiope tetragona* | - | - | - | 14 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 2 |
| Lichen | - | - | - | 1 |
| Litter | - | - | - | 5 |
| *Lupinus arcticus* | - | - | - | 1 |
| Moss | - | - | - | 28 |
| *Petasites frigidus* | - | - | - | 2 |
| *Pyrola grandiflora* | - | - | - | 1 |
| *Rubus chamaemorus* | - | - | - | 9 |
| *Salix glauca* | - | - | - | 25 |
| *Saussurea angustifolia* subsp. *Angustifolia* | - | - | - | 1 |
| *Vaccinium uliginosum* | - | - | - | 2 |
| *Vaccinium vitis-idaea* | - | - | - | 3 |

Site: T6

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctograstis latifolia* subsp. *latifolia* | - | - | - | 3 |
| *Arctostaphylos rubra* | - | - | - | 2 |
| *Betula glandulosa* | - | - | - | 18 |
| *Bistorta vivipara* | - | - | - | 1 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 30 |
| *Cassiope tetragona* | - | - | - | 9 |
| *Dryas integrifolia* | - | - | - | 1 |
| *Equisetum arvense* | - | - | - | 1 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 1 |
| Lichen | - | - | - | |
| Litter | - | - | - | 16 |
| Moss | - | - | - | 25 |
| *Petasites frigidus* | - | - | - | 4 |
| *Poa arctica* | - | - | - | 1 |
| *Pyrola grandiflora* | - | - | - | 6 |
| *Rubus chamaemorus* | - | - | - | 2 |
| *Salix glauca* | - | - | - | 7 |
| *Salix pulchra* | - | - | - | 1 |
| *Vaccinium uliginosum* | - | - | - | 5 |

Site: T7

Vegetation unit:

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctostaphylos rubra* | - | - | - | 3 |
| *Bare ground* | - | - | - | 5 |
| *Betula glandulosa* | - | - | - | 2 |
| *Bistorta vivipara* | - | - | - | 1 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 2 |
| *Cassiope tetragona* | - | - | - | 2 |
| *Dryas integrifolia* | - | - | - | 1 |
| *Empetrum nigrum* | - | - | - | 2 |
| *Eriophorum vaginatum* | - | - | - | 47 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 1 |
| Litter | - | - | - | 6 |
| Moss | - | - | - | 22 |
| *Rubus chamaemorus* | - | - | - | 6 |
| *Salix glauca* | - | - | - | 4 |
| *Salix lanata* | - | - | - | 20 |
| *Salix pulchra* | - | - | - | 5 |
| *Senecio atropurpureus* | - | - | - | 1 |
| *Vaccinium uliginosum* | - | - | - | 3 |
| *Vaccinium vitis-idaea* | - | - | - | 1 |

Site: T8

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctostaphylos rubra* | - | - | - | 12 |
| *Betula glandulosa* | - | - | - | 2 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 1 |
| *Cassiope tetragona* | - | - | - | 14 |
| *Eriophorum vaginatum* | - | - | - | 33 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 4 |
| Lichen | - | - | - | 1 |
| Litter | - | - | - | 4 |
| Moss | - | - | - | 40 |
| *Petasites frigidus* | - | - | - | 2 |
| *Salix alaxensis* | - | - | - | 1 |
| *Salix arbusculoides* | - | - | - | 4 |
| *Salix lanata* | - | - | - | 9 |
| *Senecio atropurpureus* | - | - | - | 1 |
| *Vaccinium vitis-idaea* | - | - | - | 8 |

Site: T9

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 5 |
| *Arctostaphylos rubra* | - | - | - | 3 |
| *Betula glandulosa* | - | - | - | 23 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 1 |
| *Cassiope tetragona* | - | - | - | 12 |
| *Dryas integrifolia* | - | - | - | 2 |
| *Empetrum nigrum* | - | - | - | 2 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 2 |
| Lichen | - | - | - | 2 |
| Litter | - | - | - | 20 |
| *Lupinus arcticus* | - | - | - | 3 |
| *Luzula multiflora* | - | - | - | 1 |
| *Moss* | - | - | - | 77 |
| *Petasites frigidus* | - | - | - | 2 |
| *Poa arctica* | - | - | - | 1 |
| *Pyrola grandiflora* | - | - | - | 1 |
| *Salix glauca* | - | - | - | 13 |
| *Saussurea angustifolia* subsp. *angustifolia* | - | - | - | 1 |
| *Vaccinium uliginosum* | - | - | - | 2 |
| *Vaccinium vitis-idaea* | - | - | - | 3 |

Site: T10

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
| --- | --- | --- | --- | --- |
| *Bare ground* | - | - | - | 3 |
| *Betula glandulosa* | - | - | - | 9 |
| *Bistorta vivipara* | - | - | - | 1 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 22 |
| *Cassiope tetragona* | - | - | - | 5 |
| *Empetrum nigrum* | - | - | - | 10 |
| *Ledum palustre* subsp. *decumbens* | - | - | - | 3 |
| Lichen | - | - | - | 3 |
| Litter | - | - | - | 6 |
| Moss | - | - | - | 28 |
| *Petasites frigidus* | - | - | - | 2 |
| *Pyrola grandiflora* | - | - | - | 1 |
| *Salix glauca* | - | - | - | 15 |
| *Vaccinium vitis-idaea* | - | - | - | 8 |

Site: T11

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Arctagrostis latifolia* | - | - | - | 4 |
| *Arctostaphylos rubra* | - | - | - | 15 |
| Bare ground | - | - | - | 9 |
| *Betula glandulosa* | - | - | - | 2 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 8 |
| *Cassiope tetragona* | - | - | - | 9 |
| *Dryas integrifolia* | - | - | - | 4 |
| *Empetrum nigrum* | - | - | - | 8 |
| *Eriophorum vaginatum* | - | - | - | 2 |
| Lichen | - | - | - | 4 |
| Litter | - | - | - | 9 |
| *Lupinus arcticus* | - | - | - | 1 |
| Moss | - | - | - | 6 |
| *Pedicularis sudetica* | - | - | - | 1 |
| *Pyrola grandiflora* | - | - | - | 1 |
| *Salix glauca* | - | - | - | 20 |
| *Saussurea angustifolia* subsp. *angustifolia* | - | - | - | 1 |
| *Senecio atropurpureus* | - | - | - | 1 |
| *Vaccinium uliginosum* | - | - | - | 9 |
| *Vaccinium vitis-idaea* | - | - | - | 1 |

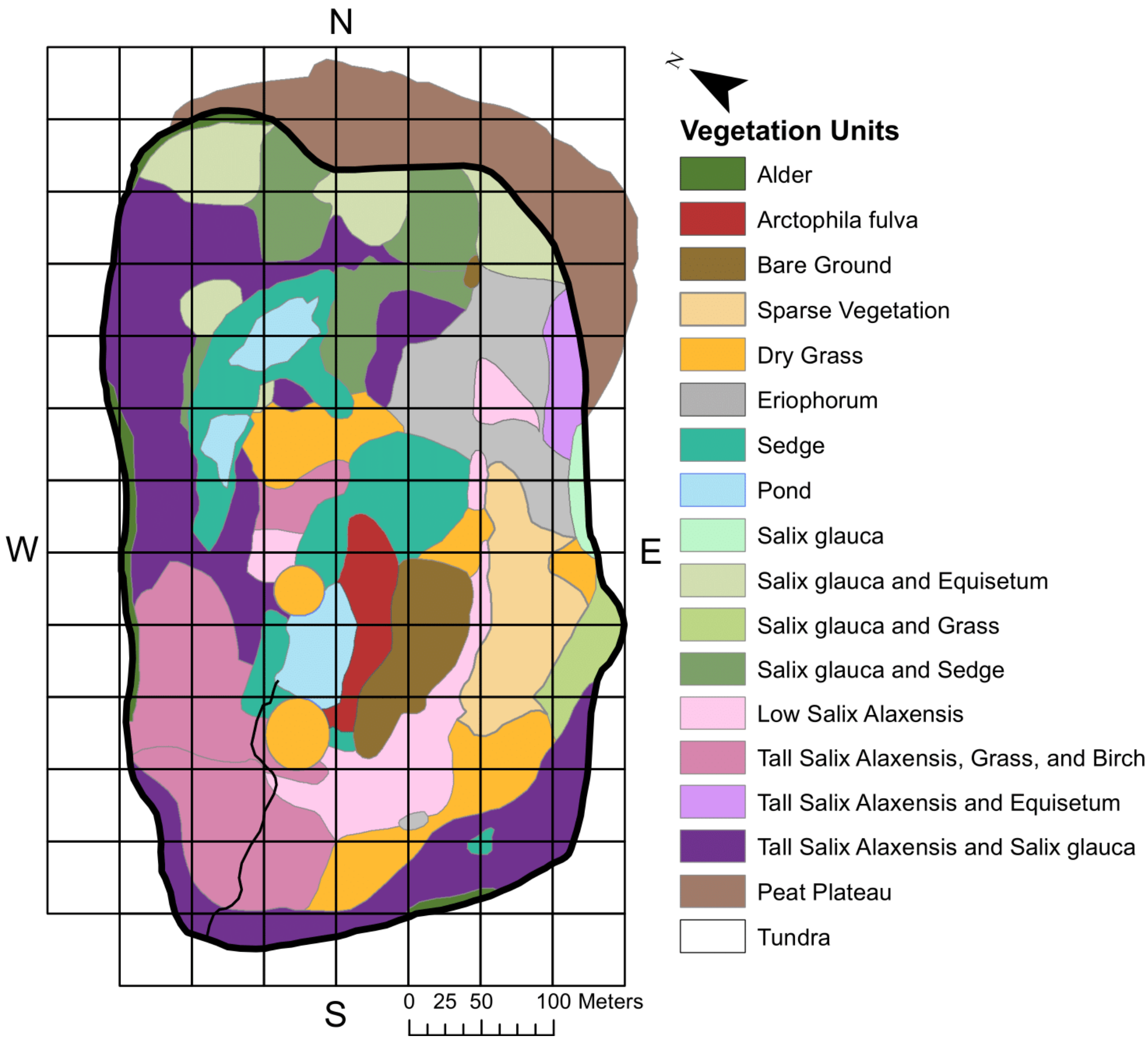
Site: T12

Vegetation unit: Tundra, Tundra

| Vegetation | 1985 | 1993 | 2001 | 2016 |
|---|---|---|---|---|
| *Andromeda polifolia* | - | - | - | 4 |
| *Arctagrostis latifolia* | - | - | - | 2 |
| Bare ground | - | - | - | 11 |
| *Betula glandulosa* | - | - | - | 8 |
| *Carex bigelowii* subsp. *lugens* | - | - | - | 4 |
| *Cassiope tetragona* | - | - | - | 9 |
| *Dryas integrifolia* | - | - | - | 27 |
| *Empetrum nigrum* | - | - | - | 4 |
| Lichen | - | - | - | 2 |
| Litter | - | - | - | 6 |
| *Lupinus arcticus* | - | - | - | 5 |
| Moss | - | - | - | 7 |
| *Pedicularis capitata* | - | - | - | 1 |
| *Poa arctica* | - | - | - | 1 |
| *Pyrola grandiflora* | - | - | - | 3 |
| *Salix glauca* | - | - | - | 19 |
| *Salix pulchra* | - | - | - | 4 |

**Appendix C**

Detailed vegetation map of Illisarvik



**Appendix D**

2016 Illisarvik Vegetation

Analysis of vegetation within the lake bed in 2016 is presented in this appendix. The vegetation surveys that followed the procedures outlined in chapter 4 to investigate the vegetation composition within the basin are described. This includes 36 more basin sites that were not used in the vegetation succession analysis.

## D.1 Basin and tundra vegetation

Overall, the basin had lower average vegetation cover than the tundra by ~ 16%; the tundra is 137 ± 4% vegetated in comparison with the basin at 122 ± 4%. Both had vegetation covers greater than 100% due to the presence of canopy and below canopy vegetation. ANOSIM between the basin and tundra were statistically significant ($p < 0.001$), but the $R_{ANOSIM}$ value of 0.52 indicates that there was not a complete separation between the two communities.

SIMPER analysis for the basin provide the same top five species as the analysis reported in chapter 4 (Table 4.4), indicating that vegetation at the 36 additional points was consistent with conditions at the 31 sites discussed previously. The SIMPER analysis indicates that there is still some compositional overlap between the two communities in terms of the most representative species for each respective group. The top five species produced by the SIMPER analysis are shown in Table D.1. Both moss and *Salix glauca* contribute to the similarity between plots within both the tundra and the basin. Moss contributed greatest to the between group dissimilarities, due to the higher percent cover in the tundra than in the basin. The same applies to *Salix glauca* which was the third

Table D.1 - Results of SIMPER analysis characterizing similarity in community composition between the vegetation units. The table shows the top five species (or species groups) that make the greatest contribution to the between-group Bray-Curtis similarity for each vegetation type. Mean similarity is a measure of the consistency in vegetation composition between all surveyed sites within the year. The mean cover (untransformed) of each species is shown in the second column. Mean similarity in the second column describes how much the species contributes to the overall mean similarity of survey sites within each group, which indicates how representative and consistent the species is within the group. Sim/SD is a species' mean similarity divided by its SD. Higher values indicate that the species not only contributes to within group similarity but does so consistently. The percent contribution is the species mean similarity divided by the group mean similarity.

| **Vegetation Unit/ Species** | **Mean cover (%)** | **Mean similarity** | **Sim/SD** | **Percent contribution** | **Cumulative similarity** |
|---|---|---|---|---|---|
| Basin (Mean similarity = 18.29) | | | | | |
| *Carex aquatilis* subsp. *stans* | 14.12 | 4.38 | 0.35 | 23.92 | 23.92 |
| *Equisetum arvense* | 9.81 | 3.35 | 0.50 | 18.33 | 42.25 |
| * Moss | 13.28 | 2.86 | 0.37 | 15.65 | 57.90 |
| + *Salix glauca* | 6.16 | 1.84 | 0.43 | 10.04 | 67.93 |
| *Arctagrostis latifolia* | 4.30 | 1.56 | 0.34 | 8.52 | 76.46 |
| Tundra (Mean similarity = 35.71 | | | | | |
| * Moss | 19.62 | 6.34 | 0.79 | 17.76 | 17.76 |
| + *Salix glauca* | 14.33 | 6.21 | 1.01 | 17.40 | 35.15 |
| *Betula glandulosa* | 13.57 | 5.65 | 0.94 | 15.81 | 50.97 |
| *Cassiope tetrogona* | 11.74 | 4.09 | 0.80 | 11.45 | 62.42 |
| *Carex bigelowii* subsp. *lugens* | 5.43 | 2.15 | 0.85 | 6.01 | 68.43 |

greatest contributing species to the dissimilarity. Both *Equisetum arvense* and *Carex aquatilis* which were representative species of the basin found in wet and moist environments created by the low-lying basin, while the elevated tundra was a drier environment. Lastly, *Arctagrostis latifolia* continued to be a representative species of the basin throughout the years and is likely due to it being a successful colonizing species in the western Arctic (Bliss and Peterson 1992).

### D.1.1 Distinguishing species

Indicator species were identified for the basin and the tundra (Table D.2). The tundra continued to have the most indicator species (18 species) in comparison with the basin (7 species). Of the 18 tundra indicator species, the majority were either forbs or evergreen shrubs. Every evergreen shrub that was found at Illisarvik appeared as an indicator species for the tundra. The deciduous shrub indicators in the tundra, were low-lying, and none of them *Salix* spp. The basin was distinguished primarily by moist environment species, such as *Carex aquatilis*, *Equisetum arvense*, *Eriophorum scheuchzeri*, and *Juncus balticus*. The striking visual difference between tundra and basin is the presence of tall *Salix alaxensis* shrubs in the basin, which was an indicator.

## D.2 Vegetation units

### D.2.1 Alder unit

The Alder unit was characterized by the presence of *Alnus viridis* subsp. *crispa* (Alder) (Fig. 5.2A). It was located along the margins of the basin along the grid north, south, and west and was the smallest unit covering approximately 1.7% of the basin. The unit was surveyed at four grid points, and it had the highest average organic-matter thickness,

Table D.2 - Indicator species analysis results for Illisarvik and the surrounding undisturbed tundra.

| Vegetation Unit | Species | Indicator Value | p-value | A † | B ‡ |
|---|---|---|---|---|---|
| Basin | | | | | |
| | *Equisetum arvense* | 0.761 | 0.001 | 0.9694 | 0.5970 |
| | *Carex aquatilis* subsp. *stans* | 0.732 | 0.001 | 0.8759 | 0.6119 |
| | *Salix alaxensis* | 0.581 | 0.001 | 0.9833 | 0.3433 |
| | *Juncus balticus* subsp. *alaskanus* | 0.508 | 0.001 | 0.9597 | 0.2687 |
| | *Artemisia tilesii* | 0.483 | 0.009 | 0.9670 | 0.2687 |
| | *Parnassia kotzebuei* | 0.454 | 0.007 | 0.9225 | 0.2239 |
| | *Eriophorum scheuzeri* | 0.423 | 0.018 | 1.000 | 0.1791 |
| Tundra § | | | | | |
| | *Carex bigelowii* subsp. *lugens* | 0.923 | 0.001 | 0.9945 | 0.8571 |
| | *Cassiope tetragona* | 0.900 | 0.001 | 1.0000 | 0.8095 |
| | *Arctostaphylos rubra* | 0.866 | 0.001 | 0.8991 | 0.8333 |
| | *Betula glandulosa* | 0.832 | 0.001 | 0.8080 | 0.8571 |
| | *Lupinus arcticus* | 0.770 | 0.001 | 0.9962 | 0.5952 |
| | *Pyrola grandiflora* | 0.738 | 0.001 | 0.7882 | 0.6905 |
| | *Vaccinium uliginosum* | 0.736 | 0.001 | 0.9142 | 0.5952 |

† ‘A’ values indicate how representative species occurrence is of the group. If only found in that group, the index would have a value of 1.

‡ ‘B’ values indicate how pervasive the species are in the group. If the species are found in all the sites, there would be a value of 1.

§ For the tundra unit other indicator species from highest to lowest value are: *Dryas integrifolia*, *Ledum palustre* subsp. *decumbens*, *Empetrum nigrum*, *Vaccinium vitis-idaea*, *Eriophorum vaginatum*, *Rubus chamaemorus*, *Sausserea angustifolia* subsp. *angustifolia*, *Petasites frigidus*, *Senecio atropurpureus*, *Pedicularis capitata*, and *Andromeda polifolia.*

tallest average vegetation height, and highest percent vegetation cover within the basin (Table 5.1). The alder shrubs were over 1.5 m tall, a mean maximum vegetation height of 1.8 m (Fig. D.1). The unit was primarily covered by deciduous shrub and forb plant functional groups (Table D.4) and had the highest percent cover of evergreen shrubs within the basin; likely due to the units' proximity to the basin margins and, therefore, the tundra. The deciduous shrub cover was ~22% *Alnus viridis subsp. crispa* and ~14% for both *Betula glandulosa* and *Salix pulchra*. *Equisetum arvense* was the highest forb cover followed by *Artemisia tilesii*, with the latter having highest average cover in this unit. *Betula glandulosa*, *Salix pulchra*, *Alnus viridis* subsp. *crispa*, and *Equisetum arvense* were characterizing species for the unit determined by SIMPER analysis, in addition to the grass *Calamagrostis stricta* (Table D.6). Lastly, the two indicator species for the unit were *Alnus viridis* subsp. *crispa* and *Artemisia tilesii* (Table D.7).

**D.2.2 Bare ground unit**

The bare ground unit was characterized by a lack of vegetation (Fig. 5.2B). The unit was located to the east of South Pond, covering ~ 3.6% of the basin, and was measured at three grid points. This unit had the lowest vegetation cover, with an average of ~19%, no organic-matter cover, and a mean maximum vegetation height of ~11 cm (Table 5.1). The few plants that grew in the unit were primarily within the forb and grass functional groups. The forb cover was composed of three species, dominated by *Equisetum arvense*, while the grass cover was primarily *Arctophila fulva* and *Deschampsia caespitosa*, though still < 1% cover (Table D.5). The characterizing species for this unit were *Arctophila fulva*, *Equisetum arvense*, and *Carex aquatilis* subsp. *stans*, which account for 100% of the cumulative similarity (Table D.6).

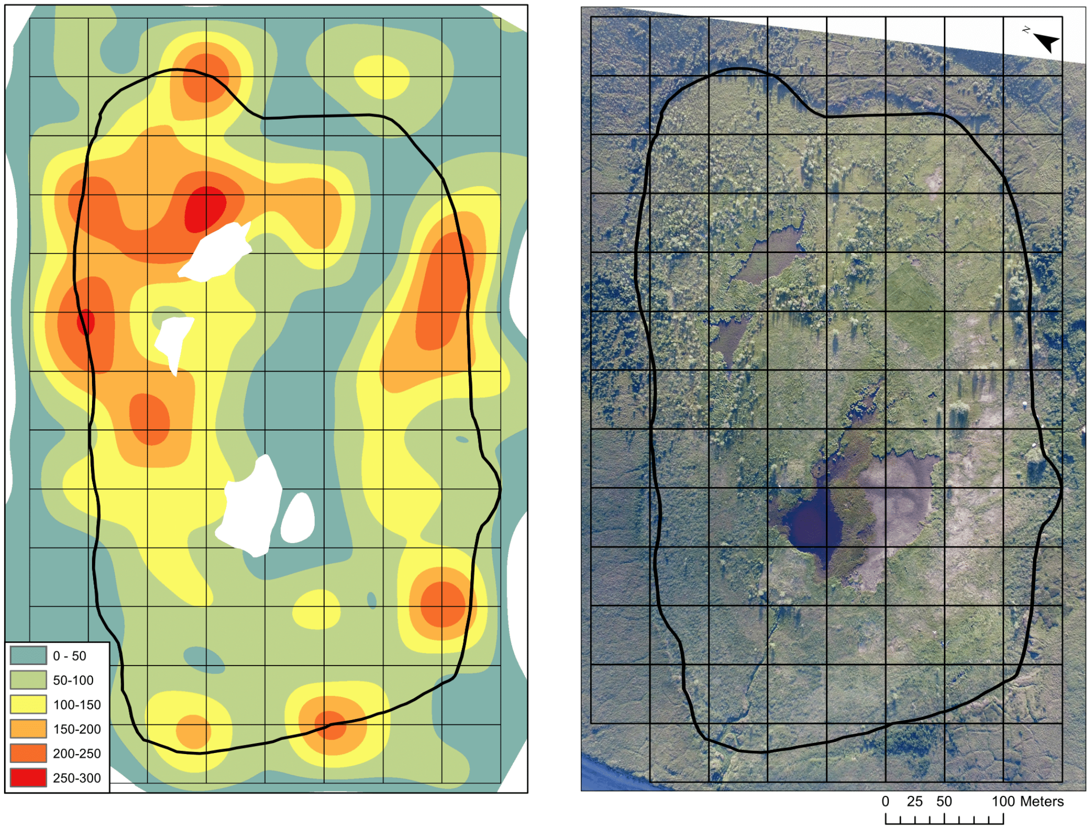



Figure D.1 – Interpolated mean maximum vegetation height map (left) and aerial image of Illisarvik in 2016 (right). The mean maximum vegetation height map was created using a spline interpolation in ArcGIS, using an average from the tallest vegetation within a 1 m, 1-3 m, 3-5 m, and 5-7 m radius of each grid point.

Table D.4 - Percent cover of major plant functional types (PFT) in Illisarvik from eight different vegetation units. Data are means ± SE (n=67 for the basin and n=43 for the tundra sites).

| PFT | Alder | Bare | Grass | Tall Willow | Low Willow | Sedge | Sparse | Tundra |
|---|---|---|---|---|---|---|---|---|
| Deciduous Shrub | 68.50± 30.5 | 0 | 22.00 ± 4.2 | 23.68 ± 3.7 | 33.60 ± 6.4 | 2.83 ± 2.1 | 27.00 ± 7.2 | 44.02 ± 2.8 |
| Evergreen Shrub | 5.25 ± 3.4 | 0 | 3.71 ± 1.9 | 0.96 ± 0.4 | 2.10 ± 1.1 | 0 | 2.00 ± 1.5 | 27.02 ± 2.8 |
| Forb | 12.00 ± 2.6 | 11.00 ± 9.5 | 7.36 ± 1.6 | 17.32 ± 3.9 | 17.80 ± 4.5 | 1.00 ± 0.5 | 9.33 ± 6.8 | 8.81 ± 1.1 |
| Grass | 7.25 ± 3.4 | 2.33 ± 1.9 | 50.57 ± 8.4 | 50.32 ± 5.2 | 22.60 ± 5.2 | 7.17 ± 5.5 | 26.00 ±11.7 | 16.93 ± 2.6 |
| Sedge | 0.75 ± 0.8 | 1.33 ± 0.9 | 12.43 ± 6.7 | 12.88 ± 3.9 | 15.20 ± 8.3 | 80.17 ± 7.6 | 0 | 13.69 ± 2.8 |
| Rush | 0 | 0.33 ± 0.3 | 0.71 ± 0.3 | 0.36 ± 0.2 | 2.00 ± 0.9 | 0 | 1.00 ± 0.6 | 0.10 ±0.1 |
| Moss | 2.50 ± 1.4 | 0 | 9.00 ± 4.6 | 15.32 ± 5.0 | 29.50 ± 11.0 | 0.33 ± 0.3 | 24.67 ± 10.7 | 19.62 ± 3.6 |
| Lichen | 0 | 0 | 0.21 ± 0.2 | 0.16 ± 0.1 | 3.00 ± 3.0 | 0 | 3.33 ± 3.3 | 1.48 ± 0.2 |
| Bare Ground | 1.25 ± 1.3 | 87.67 ± 6.7 | 8.21 ± 3.3 | 5.44 ± 1.3 | 3.40 ± 2.5 | 9.67 ± 4.7 | 34.00 ± 8.0 | 4.60 ± 0.8 |

Table D.5 - Vascular species composition of Illisarvik in the various vegetation units in 2016. Values are average percent cover of species within 1 x 3 m vegetation survey plots.

| | Alder | Bare | Grass | Tall Willow | Low Willow | Sedge | Sparse | Tundra |
|---|---|---|---|---|---|---|---|---|
| **Forb** | | | | | | | | |
| *Amerorchis rotundifolia* | | | | 0.04 | | | | |
| *Artemisia tilesii* | 3.75 | | 1.13 | 0.52 | 0.50 | | 0.67 | 0.12 |
| *Bistorta vivipara* | | | | | | | | 0.17 |
| *Castilleja raupii* | | | 0.13 | 0.16 | 0.20 | | 3.33 | 0.02 |
| *Epilobium angustifolium* | | | | | | | | 0.05 |
| *Epilobium palustre* | | 0.33 | | | | | | |
| *Equisetum arvense* | 7.00 | 10.33 | 4.13 | 15.16 | 15.40 | 0.43 | | 0.31 |
| *Hippuris vulgaris* | | | | | | 0.14 | | |
| *Lupinus arcticus* | | | | | 0.10 | | | 3.88 |
| *Orthillia secunda* | | | 0.13 | | | | | |
| *Oxytropis campestris* | | | | 0.24 | | | 4.00 | |
| *Parnassia kotzebuei* | | | 0.67 | 0.28 | | | 0.67 | 0.02 |
| *Pedicularis capitata* | | | | | | | | 0.19 |
| *Pedicularis sudetica* | 0.75 | | 0.13 | 0.04 | 0.50 | | | 0.31 |
| *Petasites frigidus* | 0.50 | | | 0.20 | | | | 1.29 |
| *Pyrola grandiflora* | | | 0.27 | 0.52 | 0.70 | | | 1.33 |
| *Ranunculus gmelinii* | | 0.33 | | | | 0.57 | | |
| *Saussurea angustifolia* subsp. *Angustifolia* | | | | | | | | 0.36 |
| *Saxifraga hirculus* | | | | | | | | 0.05 |
| *Senecio atropurpureus* | | | | | | | | 0.33 |
| *Senecio tundricola* | | | 0.13 | | | | | |
| *Stellaria longipes* s.l. | | | 0.13 | 0.16 | 0.20 | 0.29 | | 0.17 |
| *Tofieldia pusilla* | | | | | 0.20 | 0.00 | 0.67 | 0.21 |
| **Sedge** | | | | | | | | |
| *Carex aquatilis* subsp. *stans* | 0.75 | 1.00 | 8.67 | 11.40 | 13.50 | 55.71 | | 2.00 |
| *Carex bigelowii* subsp. *lugens* | | | | 0.08 | | | | 5.43 |
| *Carex krausei* | | | | 0.64 | 0.80 | 0.57 | | 0.17 |
| *Carex maritima* | | | 0.07 | | | | | |
| *Eriophorum angustifolium* | | | | 0.04 | 0.10 | | | |
| *Eriophorum scheuchzeri* | | 0.33 | 2.87 | 0.72 | 0.50 | 1.00 | | |
| *Eriophorum vaginatum* | | | | | 0.30 | | | 6.10 |
| **Rush** | | | | | | | | |
| *Juncus balticus* subsp. *alaskanus* | | 0.33 | 0.60 | 0.24 | 1.90 | | 1.00 | 0.02 |
| *Luzula multiflora* | | | | | 0.10 | | | 0.02 |
| *Luzula nivalis* | | | 0.07 | 0.12 | | | | 0.05 |
| **Grass** | | | | | | | | |
| *Anthoxanthum monticola* subsp. *alpinum* | | | | | | | | 0.05 |
| *Arctagrostis latifolia* | 2.75 | | 6.33 | 5.60 | 0.10 | 5.43 | 1.00 | 1.31 |
| *Arctophila fulva* | | 1.33 | | 0.12 | | 0.71 | | |
| *Calamagrostis stricta* | 4.50 | | 7.53 | 2.60 | 0.30 | 0.14 | | 1.00 |
| *Deschampsia caespitosa* | | 1.00 | 0.20 | 0.16 | 0.30 | | | 0.05 |
| *Dupontia fisheri* | | | 0.47 | 0.32 | | | | 0.02 |
| *Festuca* spp. | | | | 0.24 | 0.10 | | | |
| *Kobresia myosuroides* | | | 0.07 | | | | | 0.12 |
| *Poa* spp. | | | 0.53 | 2.12 | 1.30 | 0.14 | 1.67 | 0.29 |
| *Trisetum spicatum* | | | | 0.48 | 0.30 | | | |
| **Deciduous shrub** | | | | | | | | |
| *Alnus viridis* subsp. *crispa* | 21.75 | | | 0.12 | 0.70 | | | 1.24 |
| *Arctostaphylos* | 0.50 | | 1.00 | | 0.90 | | 3.33 | 4.79 |
| *Betula glandulosa* | 14.25 | | 3.53 | 2.40 | 4.20 | | 1.33 | 13.57 |
| *Rubus chamaemorus* | | | | | | | | 0.93 |
| *Salix alaxensis* | 1.00 | | 2.07 | 4.12 | 2.00 | | 10.00 | 0.05 |
| *Salix arbusculoides* | 0.75 | | 0.33 | 2.04 | 1.90 | | | 0.33 |

Table D.5 - continued

| | Alder | Bare | Grass | Tall Willow | Low Willow | Sedge | Sparse | Tundra |
|---|---|---|---|---|---|---|---|---|
| **Deciduous shrub (continued)** | | | | | | | | |
| *Salix arctica* | | | 3.20 | 0.60 | 3.10 | | 5.00 | 0.55 |
| *Salix glauca* | 6.25 | | 2.53 | 0.92 | 2.80 | | | 1.07 |
| *Salix lanata* | 7.50 | | 0.87 | 6.28 | 10.50 | 1.14 | | 1.88 |
| *Salix pulchra* | 13.75 | | 6.87 | 6.48 | 6.40 | 1.29 | 6.67 | 14.33 |
| *Salix reticulata* | | | | 0.12 | 0.80 | | 0.67 | 0.36 |
| *Vaccinium uliginosum* | 2.75 | | 0.13 | 0.60 | 0.30 | | | 4.93 |
| **Evergreen shrub** | | | | | | | | |
| *Andromeda polifolia* | | | | | | | | 0.31 |
| *Cassiope tetragona* | | | | | | | | 11.74 |
| *Dryas integrifolia* | | | 0.47 | | 0.80 | | 1.67 | 5.57 |
| *Empetrum nigrum* | 5.25 | | 2.80 | 0.96 | 1.30 | | 0.33 | 5.69 |
| *Ledum palustre* subsp. *decumbens* | | | 0.13 | | | | | 1.21 |
| *Vaccinium vitis-idaea* | | | 0.07 | | | | | 2.81 |

Table D.6 - Results of SIMPER analysis characterizing similarity in community composition between the re-surveyed sites each year and in the tundra. The table shows the top five species (or species groups) that make the greatest contribution to the between-group Bray-Curtis similarity for each year. Mean similarity is a measure of the consistency in vegetation composition between all surveyed sites within the year. The mean cover (untransformed) of each species is shown in the second column.

| Survey Year/ Species | Mean cover (%) | Mean similarity † | Sim/SD‡ | Percent contribution § | Cumulative similarity |
|---|---|---|---|---|---|
| Alder: Mean similarity = 22.64; n=4 | | | | | |
| *Alnus viridis* subsp. *crispa* | 21.8 | 5.42 | 0.49 | 23.95 | 23.95 |
| *Salix pulchra* | 7.0 | 4.64 | 0.78 | 20.49 | 44.43 |
| *Equisetum arvense* | 7.5 | 2.98 | 0.64 | 13.14 | 57.57 |
| *Betula glandulosa* | 14.3 | 1.96 | 0.85 | 8.67 | 66.24 |
| *Calamagrostis stricta* | 4.5 | 1.89 | 0.41 | 8.35 | 74.59 |
| Bare ground: Mean similarity = 7.9; n=3 | | | | | |
| *Arctophila fulva* | 1.3 | 5.13 | 0.58 | 64.90 | 64.90 |
| *Equisetum arvense* | 10.3 | 1.52 | 0.58 | 19.18 | 84.08 |
| *Carex aquatilis* subsp. *stans* | 1.0 | 1.26 | 0.58 | 15.92 | 100.00 |
| Grass: Mean similarity = 16.64; n=15 | | | | | |
| *Arctagrostis latifolia* | 6.3 | 3.96 | 0.65 | 23.81 | 23.81 |
| *Salix glauca* | 6.9 | 2.72 | 0.49 | 16.32 | 40.13 |
| *Equisetum arvense* | 4.1 | 1.67 | 0.43 | 10.04 | 50.17 |
| Moss | 8.4 | 1.26 | 0.24 | 7.58 | 57.76 |
| *Salix arctica* | 3.2 | 1.21 | 0.44 | 7.30 | 65.05 |
| Tall Willow*:* Mean similarity = 22.13; n=25 | | | | | |
| *Equisetum arvense* | 15.2 | 5.78 | 0.66 | 26.10 | 26.10 |
| *Carex aquatilis* | 11.4 | 4.18 | 0.39 | 18.87 | 44.98 |
| Moss | 15.3 | 3.46 | 0.43 | 15.64 | 60.62 |
| *Salix glauca* | 6.5 | 2.22 | 0.52 | 10.04 | 70.65 |
| *Arctagrostis latifolia* | 5.6 | 2.12 | 0.38 | 9.56 | 80.22 |
| Low Willow*:* Mean similarity = 26.8; n=10 | | | | | |
| Moss | 29.5 | 8.66 | 0.74 | 32.27 | 32.27 |
| *Equisetum arvense* | 15.4 | 6.72 | 0.79 | 25.06 | 57.33 |
| *Salix pulchra* | 10.5 | 4.10 | 0.81 | 15.28 | 72.61 |
| *Carex aquatilis* subsp. *stans* | 13.5 | 2.56 | 0.63 | 9.54 | 87.78 |
| *Salix glauca* | 6.4 | 1.51 | 0.46 | 5.62 | 89.71 |
| Sedge: Mean similarity = 62.48; n=7 | | | | | |
| *Carex aquatilis* subsp. *stans* | 55.7 | 61.03 | 3.98 | 97.67 | 97.67 |

† Mean similarity in this column describes how the species contributes to the overall mean similarity of surveyed sites within each year, and how representative and consistent the species is within the group.

‡ Sim/SD is a species mean similarity divided by its standard deviation. Higher values indicate that the species not only contributes to within group similarity but does so consistently.

§ The percent contribution is the species mean similarity divided by the year mean similarity.

Table D.6 - Continued

| **Survey Year/ Species** | **Mean cover (%)** | **Mean similarity †** | **Sim/SD‡** | **Percent contribution §** | **Cumulative similarity** |
|---|---|---|---|---|---|
| Sparse: Mean similarity = 30.41; n=3 | | | | | |
| Moss | 24.7 | 17.02 | 0.88 | 55.98 | 55.98 |
| *Salix glauca* | 10.0 | 9.22 | 2.70 | 30.31 | 86.30 |
| *Castilleja raupii* | 3.3 | 1.88 | 2.18 | 6.20 | 92.49 |
| *Arctostaphylos rubra* | 3.3 | 1.32 | 0.58 | 4.33 | 96.82 |
| Tundra: Mean similarity = 35.71; n=43 | | | | | |
| Moss | 19.6 | 6.34 | 0.79 | 17.76 | 17.76 |
| *Salix glauca* | 14.3 | 6.21 | 1.01 | 17.34 | 35.15 |
| *Betula glandulosa* | 13.6 | 5.65 | 0.94 | 15.81 | 50.97 |
| *Cassiope tetragona* | 11.7 | 4.09 | 0.80 | 11.45 | 62.42 |
| *Carex bigelowii* subsp. *lugens* | 5.4 | 2.15 | 0.85 | 6.01 | 68.43 |

† Mean similarity in this column describes how the species contributes to the overall mean similarity of surveyed sites within each year, and how representative and consistent the species is within the group.

‡ Sim/SD is a species mean similarity divided by its standard deviation. Higher values indicate that the species not only contributes to within group similarity but does so consistently.

§ The percent contribution is the species mean similarity divided by the year mean similarity.

Table D.7 - Indicator species for the different vegetation communities at Illisarvik.

| Vegetation Unit | Species | Indicator Value | p-value | A † | B ‡ |
|---|---|---|---|---|---|
| Alder | | | | | |
| | *Alnus viridis* subsp. *crispa* | 0.828 | 0.002 | 0.9136 | 0.7500 |
| | *Artemisia tilesii* | 0.648 | 0.031 | 0.5606 | 0.7500 |
| Bare Ground | | | | | |
| | *Arctophila fulva* | 0.640 | 0.013 | 0.6151 | 0.6667 |
| Grass | | | | | |
| | None | | | | |
| Tall Willow | | | | | |
| | None | | | | |
| Low Willow | | | | | |
| | None | | | | |
| Sedge | | | | | |
| | None | | | | |
| Sparse Vegetation | | | | | |
| | *Castilleja raupii* | 0.930 | 0.001 | 0.8657 | 1.0000 |
| | *Salix alaxensis* | 0.721 | 0.009 | 0.5199 | 1.0000 |
| | *Oxytropis campestris* | 0.561 | 0.032 | 0.9434 | 0.3333 |
| Tundra § | | | | | |
| | *Carex bigelowii* subsp. *lugens* | 0.919 | 0.001 | 0.9855 | 0.8571 |
| | *Cassiope tetragona* | 0.900 | 0.001 | 1.0000 | 0.8095 |
| | *Lupinus arctica* | 0.762 | 0.008 | 0.9749 | 0.5952 |
| | *Ledum palustre* subsp. *decumbens* | 0.702 | 0.004 | 0.9011 | 0.5476 |
| | *Vaccinium vitis-idaea* | 0.699 | 0.011 | 0.9768 | 0.5000 |

† 'A' values indicate how representative species occurrence is of the vegetation unit. If only found in that unit, the index would have a value of 1.

‡ 'B' values indicate how pervasive the species are in the vegetation unit. If the species are found in all the sites, the index would have a value of 1.

§ For the tundra unit other indicator species from highest to lowest value are: *Eriophorum vaginatum* and *Rubus chamaemorus*

### D.2.3 Grass unit

The grass unit was delineated due to a dominant cover of graminoids (Fig. 5.1), the unit contained willow shrubs, but they were not visually dominant (Fig 5.2 C). This unit is largely in the SW and E portions of the basin and had measurements at 15 grid points. The S portion of this unit had higher shrub cover and appeared to be drier than the N portion due to more efficient drainage. The unit was primarily composed of species within the grass and deciduous shrub plant functional groups, with a cover of ~51% and ~22% respectively (Table D.4). The highest average cover was by the grasses *Calamagrostis stricta* and *Arctagrostis latifolia*, and by the willow *Salix pulchra* (Table D.5). *Both Arctagrostis stricta* and *Salix pulchra* were characterizing species according to SIMPER analysis (Table D.6). *Calamagrostis stricta* was not a characterizing species as it was dominant in the S portion of the unit, but not in the N part of the basin. *Equisetum arvense*, moss, and *Salix arctica* were also characterizing vegetation in the unit. There were no indicator species for the unit (Table D.7).

### D.2.4 Tall Willow unit

The Tall Willow unit was defined by the visual dominance of tall *Salix alaxensis* shrubs commonly inter-mixed with alders along the margins, and with lower erect shrubs such as *Salix pulchra* and *Salix glauca* (Fig. 5.2 D). This unit occurred primarily along the W and S margins of the basin, but there had been recent development of the unit east of the Bare Ground with dense but young *Salix alaxensis* shrubs <1 m in height. Overall, the unit covered ~30.4% of the basin, making it the largest vegetation unit, with measurements taken at 25 grid points. The unit had the second highest vegetation cover and mean maximum vegetation height in the basin after the Alder unit.

The unit was primarily composed of deciduous shrubs, grasses, sedges, and forbs (Table D.4). *Salix lanata* and *Salix pulchra* had higher percent shrub cover in the unit, with *Salix alaxensis* being the third most common shrub cover. The understorey was primarily composed of *Equisetum arvense*, *Arctagrostis latifolia*, and *Carex aquatilis* subsp. *stans* which account for the forb, grass, and sedge plant functional groups respectively (Table D.5). The characterizing species were the same as those most commonly found in the understory, as well as moss. The characterizing willow in the unit was *Salix glauca* (Table D.6), with no indicator species for this unit (Table D.7).

While the unit was defined by *Salix alaxensis*, it did not have the greatest percent cover, nor was it a characterizing or indicator species within the unit, it was, however, the most dominant vegetation visually due to its height. *Salix glauca* and *lanata* are both willows that have many branches, creating thickets and, therefore, have high specific surface areas. *Salix alaxensis* does not create similarly dense thickets and does not cover as much area on a per shrub basis.

**D.2.5 Low Willow unit**

The Low Willow unit was defined by the presence of significant low to medium-height shrub cover, primarily *Salix glauca* and *pulchra* of 1 m in height (Fig. 5.2 E). Its understorey varied, but the three main types were forb (*Equisetum arvense*), sedge (*Carex aquatilis* subsp. *stans*), and grasses. This unit was located in the N of the basin and in a few thin sections on the E margins (Fig. 5.1). The unit area was ~16% of the basin, with measurements taken at 10 grid points.

The Low Willow unit was composed dominantly of species of the deciduous shrub, grass, and forb plant functional groups, in addition to having the highest percent cover of moss of all the units (Table D.4). The dominant deciduous shrub cover was *Salix lanata* and *pulchra*; *glauca* is only the fourth highest willow in terms of cover (Table D.5). Grass cover was highest in *Poa* species, while ground cover was dominated by *Equisetum arvense* and *Carex aquatilis* subsp. *stans*.

### D.2.6 Sedge unit

The Sedge unit was delineated by the dominant vegetation cover of sedges, specifically *Carex aquatilis* (Fig. 5.2 F). This vegetation unit was located around the North and South ponds in wet depressions characterized by a high water table (Fig. 5.1). The unit's area was ~9% of the total basin, with measurements taken at 7 grid points (Table D.3). Willows *Salix pulchra* and *lanata* were present but not common. Despite *Carex aquatalis* being such a dominant species within the unit, it was not an indicator species for the unit due to its prevalence throughout the other units in the basin (Table D.7)

### D.2.7 Sparse vegetation unit

The Sparse Vegetation unit was defined by the presence of vegetation, but with a large proportion of bare ground, as shown in Fig. 5.2(G). Visually, this unit appeared to be a mixture of solitary grass tufts and forbs, with some low-lying or prostrate willows. The unit was one of the driest in the basin located at a slightly higher elevation well-drained location east of the Bare Ground unit (Fig. 5.1). The Sparse Vegetation unit had increased deciduous shrub, grass, and moss plant functional group cover (Table D.4). The dominant ground cover species *Poa* spp. and *Arctagrostis latifolia* for the grasses, and *Salix alaxensis*, *Salix pulchra*, and *Salix arctica* for the willows (Table D.5). This unit also has the most indicator species of all the units in the basin: *Castilleja raupii, Salix alaxensis*, and *Oxytropis campestris* (Table D.7).

## D.3 Vegetation unit compositional differences

### D.3.1 Vegetation characteristics

Overall there are differences between the vegetation characteristics of the units. A Kruskal-Wallis analysis of variance was used to test the significance of differences between vegetation characteristics (organic matter thickness, vegetation height, and vegetation percent cover), followed by a Dunn's post-hoc test to reveal differences among mean values. The organic-matter thickness was statistically significantly different between units, $\chi^2 = 75.42$ and $p<0.001$. The post-hoc test revealed that the tundra had statistically higher organic-matter thickness than all the basin units with the exception of Alder. An interpolation of the organic-matter thickness data supports this as the tundra had thicker organic matter than the basin, and the thicker organic matter along the margins within the basin corresponds with the alder unit (Fig. D.2). The vegetation height was also statistically different between the units ($\chi^2 = 55.85$, $p<0.001$). The lowest vegetation heights were in the Bare Ground, Sedge, and Tundra units, which were statistically different from the Alder, Grass, and Willow units. Lastly, percent cover between the vegetation units was significantly different ($\chi^2 = 29.71$, $p<0.001$). The Bare Ground has significantly lower vegetation cover than the Tundra, Alder, and Willow units. The Grass and Sedge units had significantly lower cover than the Tundra unit.

### D.3.2 Vegetation composition

The units had statistically significant different vegetation compositions (Table D.6). ANOSIM between the vegetation units indicated that all units were well-separated from the Tundra unit (Table D.8). The sedge was statistically significant from the other vegetation units but has some low $R_{ANOSIM}$ values with the Tall Willow unit indicated a

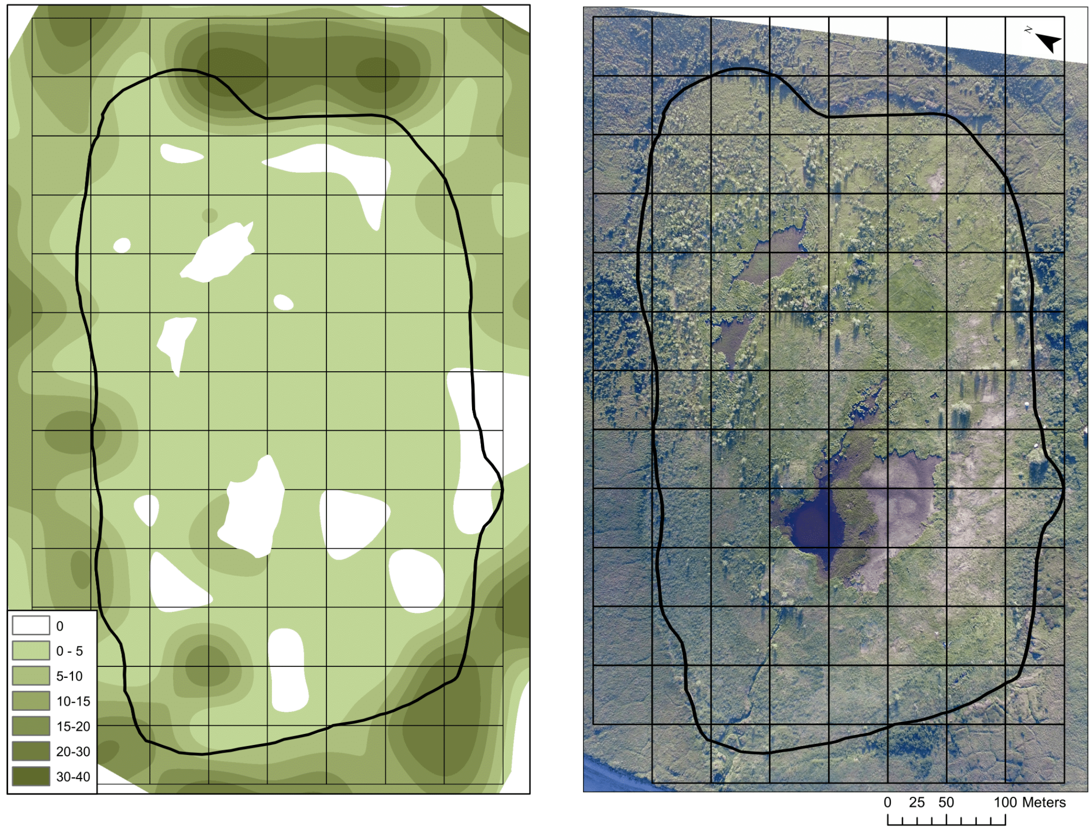



Figure D.2 - Organic matter thickness using spline interpolation in ArcGIS.

Table D.8 - Pair-wise comparisons of plant community composition between vegetation units using the ANOSIM procedure. $R_{ANOSIM}$ values higher than 0.75 indicated well-separated groups, values between 0.50 to 0.75 describe overlapping but distinguishable groups, and values less than 0.25 represent groups that cannot be separated (Clarke and Gorley 2001)

| | Tundra | Sedge | Bare | Sparse | Low Willow | Tall Willow | Grass |
|---|---|---|---|---|---|---|---|
| **Alder** | **0.77** | **0.96** | **0.87** | **0.89** | 0.26 | 0.12 | 0.01 |
| **Grass** | **0.78** | **0.41** | **0.55** | 0.12 | 0.08 | 0.09 | |
| **Tall Willow** | **0.77** | **0.27** | **0.49** | **0.31** | -0.02 | | |
| **Low Willow** | **0.79** | **0.60** | **0.56** | 0.25 | | | |
| **Sparse** | **0.85** | **1.00** | 0.96 | | | | |
| **Bare** | **1.00** | **0.91** | | | | | |
| **Sedge** | **0.98** | | | | | | |

* values in bold indicate p-values < 0.05 (significant)

large amount of compositional overlap. The Bare Ground is the only unit not separated from the Sparse Vegetation (p=0.1), but the $R_{ANOSIM}$ value of 0.963 indicated two well-separated groups. This separation was supported by the NMDS conducted on the data, in which the Bare Ground and Sparse units were well-separated on both axes (Fig. D.3). Low Willow unit had the greatest overlap with other units, and could not be separated from Tall Willow, Alder, Grass, or the Sparse Vegetation units. This compositional overlap was clearly displayed in the NMDS ordination (Fig. D.3). Therefore, the units that were the most distinguishable, on the basis of vegetation composition, were the Bare Ground, Sedge, and Sparse Vegetation units, while all the units were well-distinguished from the surrounding tundra.

**D.3.3 Species diversity**

Species richness, evenness, and diversity were determined for each vegetation unit. A Kruskal-Wallis analysis of variance indicated that species richness differed significantly among units ($\chi^2 = 73.43$, $p<0.001$). Dunn's post-hoc test (Fig. D.4) revealed differences among the mean values with the fewest species in the Bare Ground, Sedge, and Tall Willow units, and highest in the tundra. Species evenness was significantly different between the Bare Ground and Tundra ($\chi^2 = 27.49$, $p<0.001$), with Bare Ground containing the lowest evenness values and tundra the highest (Fig. D.4). Lastly, the Shannon diversity index was significantly different among units, where the Bare Ground, Sedge, and Willow units were all significantly less diverse than the Tundra ($\chi^2 = 63.05$, $p<0.001$).

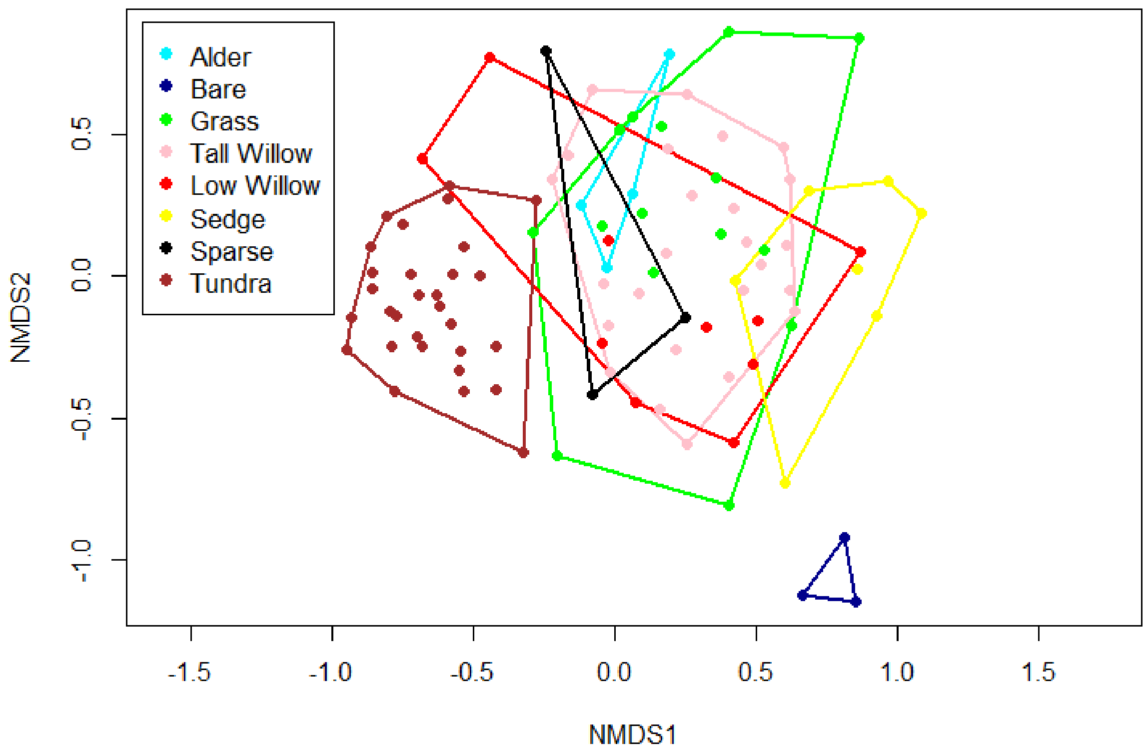



Figure D.3 - Non-metric multidimensional scaling (NMDS) ordination of plant community composition based on Bray-Curtis similarity matrices (stress = 0.23, k = 2). Results show the vegetation units at Illisarvik and the clustering of the sites within these units.

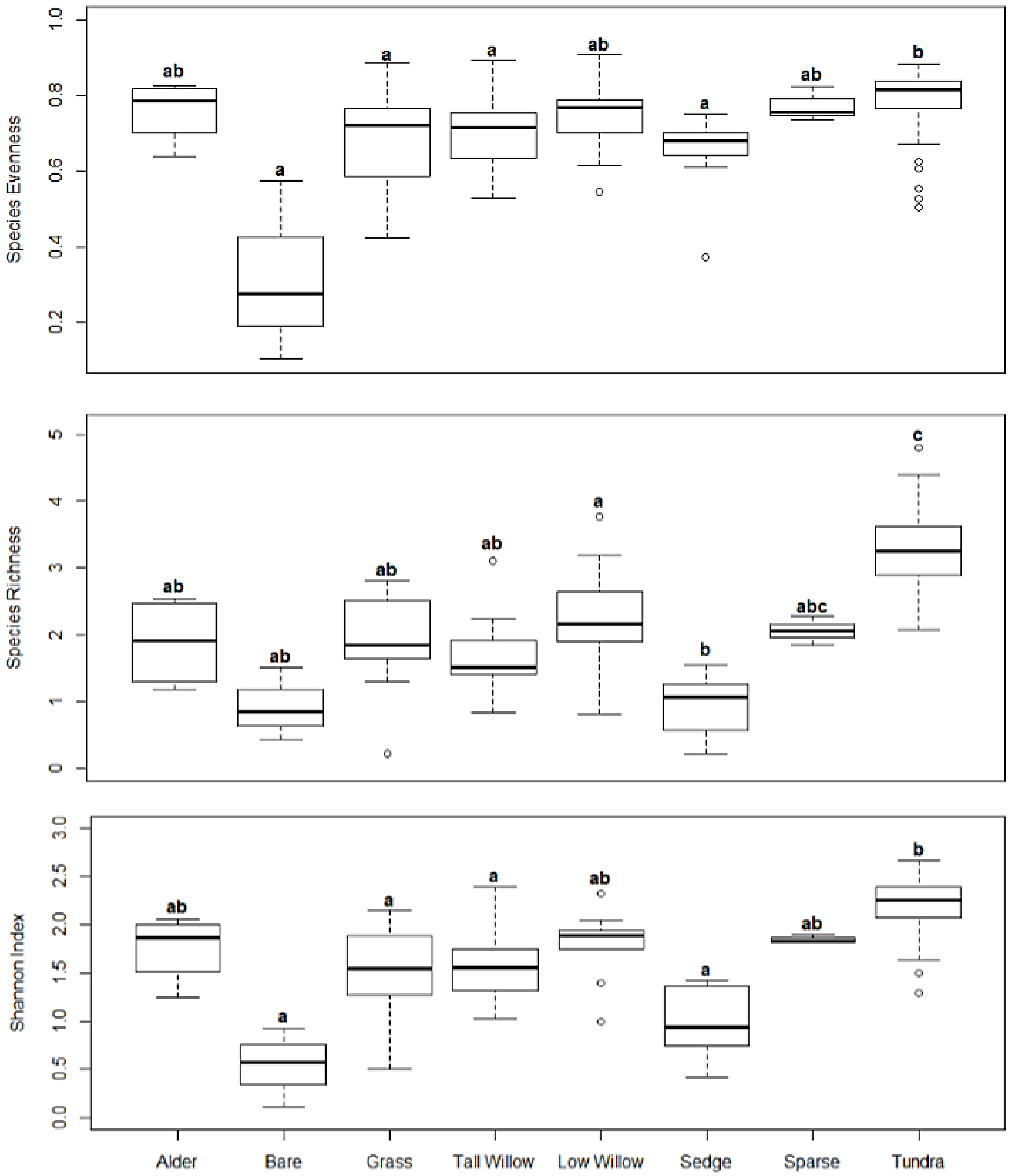



Figure D.4 – Boxplots of the vegetation units for species richness, species evenness and the Shannon index of alpha diversity. Different letters represent significant differences in species richness, evenness, and diversity. Boxes represent the lower and upper quartiles, solid horizontal lines are the median value, and the whiskers are the minimum and maximum values or if there are outliers it is 1.5 times the interquartile range.

## Appendix E

Soil texture

Table E.1 - Soil texture analysis. Soils taken from the top of permafrost were analyzed by O'Neill (2011).

| Unit | Depth (cm) | % Sand | % Silt | % Clay | Soil Texture |
|---|---|---|---|---|---|
| Alder | 20 | 48.3 | 39.1 | 12.6 | Loam |
| Alder | 20 | 73.7 | 21.3 | 4.9 | Sandy Loam |
| Arctophila fulva | 10 | 26.1 | 65.9 | 8.1 | Silt Loam |
| Arctophila fulva | Top of permafrost | 0.5 | 78.5 | 21.0 | Silt Loam |
| Bare Ground | 20 | 47.4 | 40.9 | 11.7 | Loam |
| Bare Ground | 20 | 49.6 | 44.9 | 5.5 | Sandy Loam |
| Bare Ground | Top of permafrost | 79. | 16.3 | 4.7 | Loamy Sand |
| Grass | 20 | 64.1 | 26.4 | 9.5 | Sandy Loam |
| Grass | 20 | 81.9 | 11.7 | 6.5 | Loamy Sand |
| Grass | 25-30 | 43.7 | 48.8 | 7.5 | Loam |
| Grass | Top of permafrost | 8.8 | 73.2 | 18.0 | Silt Loam |
| Grass | Top of permafrost | 58.8 | 32.7 | 8.5 | Sandy Loam |
| Grass | Top of permafrost | 26.8 | 62.0 | 11.2 | Silt Loam |
| Grass | Top of permafrost | 1.5 | 76.4 | 22.1 | Silt Loam |
| Grass | Top of permafrost | 7.6 | 75.1 | 17.3 | Silt Loam |
| Grass | Top of permafrost | 0.7 | 77.0 | 22.3 | Silt Loam |
| Grass | Top of permafrost | 7.3 | 76.7 | 16.0 | Silt Loam |
| Tall Willow | 20 | 40.5 | 44.8 | 14.7 | Loam |
| Tall Willow | 20 | 87.1 | 8.9 | 4.0 | Sand |
| Tall Willow | 20 | 38.3 | 45.8 | 15.8 | Loam |
| Tall Willow | 20 | 46.9 | 35.8 | 17.3 | Loam |
| Tall Willow | 25-30 | 49.7 | 34.7 | 15.6 | Loam |
| Tall Willow | Top of permafrost | 49.1 | 43.3 | 7.6 | Loam |
| Tall Willow | Top of permafrost | 0.0 | 76.2 | 23.8 | Silt Loam |
| Tall Willow | Top of permafrost | 0.0 | 77.6 | 22.4 | Silt Loam |
| Tall Willow | Top of permafrost | 0.0 | 76.4 | 23.7 | Silt Loam |
| Tall Willow | Top of permafrost | 3.2 | 82.7 | 14.1 | Silt Loam |
| Tall Willow | Top of permafrost | 0.0 | 76.7 | 23.3 | Silt Loam |
| Tall Willow | Top of permafrost | 0.0 | 74.2 | 25.8 | Silt Loam |
| Tall Willow | Top of permafrost | 15.5 | 71.0 | 13.5 | Silt Loam |
| Tall Willow | Top of permafrost | 0.0 | 77.4 | 22.6 | Silt Loam |
| Tall Willow | Top of permafrost | 0.0 | 72.6 | 27.4 | Silty Clay Loam |
| Low Willow | 20 | 33.0 | 54.7 | 12.3 | Silt Loam |
| Low Willow | 20 | 86.6 | 8.1 | 5.3 | Loamy Sand |
| Low Willow | 20 | 57.4 | 41.3 | 1.3 | Sandy Loam |
| Low Willow | 20 | 23.5 | 62.1 | 14.4 | Silt Loam |
| Low Willow | 20 | 82.4 | 10.9 | 6.8 | Loamy Sand |
| Low Willow | 20 | 76.4 | 15.1 | 8.5 | Sandy Loam |
| Low Willow | 20 | 44.2 | 43.0 | 12.8 | Loam |
| Low Willow | 20 | 71.7 | 23.5 | 4.8 | Sandy Loam |
| Low Willow | Top of permafrost | 30.0 | 58.4 | 11.7 | Silt Loam |

Table E.2 - continued

| Unit | Depth (cm) | % Sand | % Silt | % Clay | Soil Texture |
|---|---|---|---|---|---|
| Low Willow | Top of permafrost | 3.1 | 80.4 | 16.5 | Silt Loam |
| Low Willow | Top of permafrost | 54.1 | 36.0 | 9.9 | Sandy Loam |
| Low Willow | Top of permafrost | 65.3 | 27.8 | 6.9 | Sandy Loam |
| Low Willow | Top of permafrost | 14.0 | 72.0 | 14.0 | Silt Loam |
| Low Willow | Top of permafrost | 7.3 | 74.5 | 18.3 | Silt Loam |
| Sedge | 30 | 49.6 | 37.5 | 13.0 | Loam |
| Sedge | 15 | 25.1 | 73.8 | 1.2 | Silt Loam |
| Sedge | 20 | 40.2 | 57.1 | 2.7 | Silt Loam |
| Sedge | 30 | 43.7 | 53.9 | 2.5 | Silt Loam |
| Sedge | Top of permafrost | 9.1 | 71.7 | 19.2 | Silt Loam |
| Sparse Vegetation | 20 | 90.6 | 5.9 | 3.5 | Sand |
| Sparse Vegetation | 20 | 9.7 | 80.4 | 9.9 | Silt |
| Tundra | 20 | 33.3 | 52.7 | 14.0 | Silt Loam |
| Tundra | 20 | 91.8 | 3.6 | 4.6 | Sand |

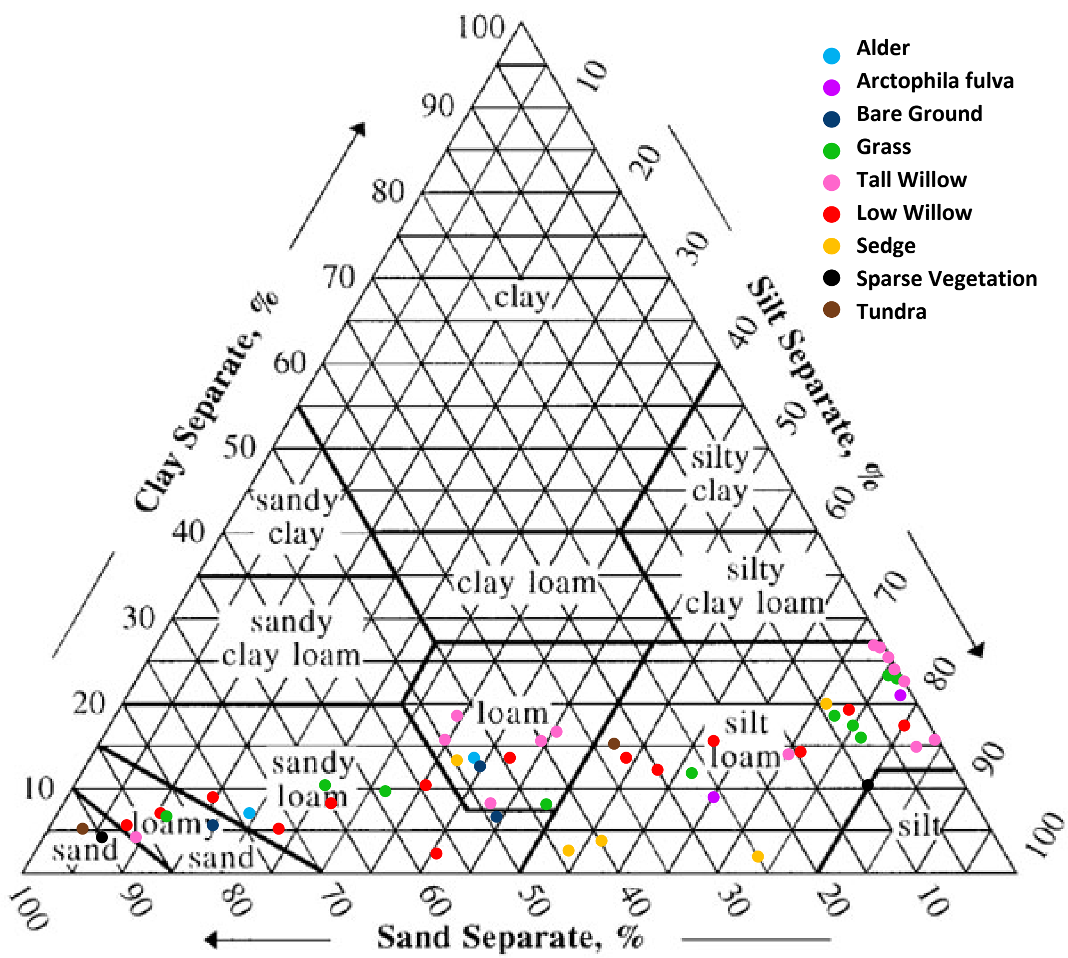



Figure E.1 - Illisarvik texture analysis on the texture triangle (USDA 2017)

## Appendix F

Nutrient data

Table F.1 – Nutrient supply rates (μg 10 $cm^{-2}$ 4 $weeks^{-1}$) for summer buried period. PRS probes inserted into top 10 cm of soil at the three sites. Values for the Tall Willow, Grass, Sedge, and Tundra sites are a mean of two sites.

| Nutrient | Tall willow | Low Willow | Grass | Bare Ground | Sedge | Tundra |
|---|---|---|---|---|---|---|
| **$NO_3^-$** | 1.22 | 0.00 | 1.26 | 41.32 | 0.80 | 1.69 |
| **$NH_4$-** | 3.65 | 2.96 | 1.30 | 1.58 | 6.22 | 1.00 |
| **Ca** | 1622.72 | 2353.34 | 1992.67 | 1656.99 | 1893.08 | 1024.09 |
| **Mg** | 444.48 | 547.19 | 662.86 | 603.30 | 485.90 | 417.71 |
| **K** | 22.10 | 12.57 | 9.47 | 23.86 | 6.50 | 24.45 |
| **P** | 3.51 | 4.82 | 1.24 | 1.19 | 3.57 | 1.42 |
| **Fe** | 175.12 | 854.81 | 123.42 | 36.33 | 538.78 | 23.28 |
| **Mn** | 8.00 | 30.26 | 11.66 | 21.27 | 24.67 | 1.01 |
| **Cu** | 0.83 | 0.92 | 0.24 | 0.58 | 0.01 | 0.06 |
| **Zn** | 1.25 | 2.33 | 0.78 | 1.84 | 0.36 | 0.58 |
| **B** | 0.80 | 3.26 | 0.49 | 0.59 | 2.00 | 0.15 |
| **S** | 168.00 | 77.54 | 1213.60 | 1127.53 | 250.78 | 14.99 |
| **Pb** | 0.34 | 0.96 | 0.03 | 0.05 | 0.00 | 0.07 |
| **Al** | 10.51 | 12.71 | 11.56 | 27.99 | 11.59 | 6.04 |
| **Cd** | 0.01 | 0.00 | 0.01 | 0.01 | 0.03 | 0.03 |

Table F.2 - Pore-water nutrients at 10-20 cm depth for each vegetation unit. Values are mg $L^{-1}$.

| Nutrient | Alder | Tall Willow | Low Willow | Pendant Grass | Grass | Sedge | Sparse | Bare Ground | Tundra |
|---|---|---|---|---|---|---|---|---|---|
| **Na** | 175.53 | 98.29 | 109.23 | 110.54 | 168.57 | 181.24 | 41.27 | 65.03 | 68.63 |
| **K** | 71.08 | 12.98 | 25.69 | 52.58 | 23.28 | 29.32 | 26.71 | 30.32 | 14.94 |
| **Mg** | 109.01 | 50.95 | 67.95 | 73.60 | 234.85 | 83.46 | 19.29 | 688.07 | 46.96 |
| **Ca** | 268.73 | 112.23 | 149.84 | 507.98 | 596.24 | 212.56 | 123.21 | 3333.90 | 90.55 |
| **Cl** | 78.78 | 80.89 | 92.82 | 166.56 | 126.42 | 251.66 | 43.07 | 98.09 | 35.84 |
| **$NO_2^-$** | 0.56 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| **$SO^{2-}_4$** | 117.85 | 155.90 | 386.80 | 1245.58 | 2144.74 | 471.23 | 197.68 | 9839.70 | 48.17 |
| **$NO_3^-$** | 6.59 | 3.10 | 1.79 | 2.07 | 2.66 | 8.62 | 0.71 | 11.71 | 1.08 |
| **Dissolved P** | 0.33 | 0.29 | 0.40 | 0.12 | 0.23 | 0.36 | 0.06 | 0.06 | 0.16 |
| **Dissolved N** | 11.42 | 7.84 | 15.14 | 11.55 | 11.51 | 14.69 | 1.84 | 13.15 | 3.64 |

## Appendix G

Principal component analysis (PCA)

Table F.1 - PCA variable loadings for the basin sites.

| | PC1 | PC2 | PC3 | PC4 |
|---|---|---|---|---|
| **OM** | 0.544 | 0.257 | -0.585 | 0.502 |
| **Snow** | 0.644 | 0.557 | 0.352 | 0.111 |
| **LAI** | 0.755 | -0.441 | | |
| **AL** | -0.531 | 0.695 | 0.158 | |
| **VWC** | 0.272 | -0.441 | 0.537 | 0.326 |
| **Veg Height** | 0.612 | 0.695 | 0.267 | |
| **% Bare** | -0.716 | -0.652 | 0.122 | 0.603 |
| | | | | |
| **SS loadings** | 2.523 | 1.874 | 0.869 | 0.734 |
| **Proportion variance** | 0.360 | 0.268 | 0.124 | 0.105 |
| **Cumulative variance** | 0.360 | 0.628 | 0.752 | 0.857 |

Table F.2 - PCA variable loadings for the tundra sites.

| | PC1 | PC2 | PC3 | PC4 |
|---|---|---|---|---|
| **OM** | 0.849 | | | 0.345 |
| **Snow** | 0.107 | 0.893 | 0.196 | |
| **LAI** | -0.109 | 0.584 | -0.633 | -0.397 |
| **AL** | -0.775 | | 0.140 | 0.462 |
| **VWC** | 0.298 | -0.110 | 0.799 | -0.395 |
| **Veg Height** | | 0.882 | 0.303 | |
| **% Bare** | 0.786 | | -0.363 | 0.172 |
| | | | | |
| **SS loadings** | 2.052 | 1.944 | 1.328 | 0.684 |
| **Proportion variance** | 0.293 | 0.278 | 0.190 | 0.098 |
| **Cumulative variance** | 0.293 | 0.571 | 0.761 | 0.858 |